Active Galactic Nuclei: An Examination of Their Physical Environment and Properties

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Abstract

Here Be Monsters! At the heart of great island universes lurks a weighty inky abyss, by millions out-grossing the solar orb. Betimes, they are fed; their manna falls from the milky heaven and they burst to life and grow. Transforming darkness to light, they spew forth a portion of their nourishment. In turn, they sculpt and shape their habitation. Their effulgence deforms their unfortunate host; their enormity engenders stars in the firmament. Ere long, improvident as the foolish grasshopper who lays not up store for winter, they hollow out their own larder, languish and are faint.

Active galactic nuclei (AGN) and their host galaxies have a complex relationship during their evolution; at times symbiotic, at others parasitic. The modes by which they interact are the subject of close attention (both observational and theoretical) within the astrophysical community, as they are drivers of galaxy growth and stasis over cosmic time.

The paradigm of AGN (the Unified Model) is a super-massive black hole being fed by gas accretion and generating radiation and gaseous outflows, where the observational properties are constrained by the orientation to the line of sight of the AGN and its surrounding obscuring material, as well as its power level. This model is well-supported by observational evidence, but the details of the gas dynamics and star formation are only partially understood. Theoretical models are recently becoming available to probe the small spatial and time scales required to understand the physics, and these need constraining by observation.

This thesis examines galaxies that have observed nuclear activity to elucidate modes of star formation in their central regions, and to determine the details of outflow kinematics, energetics and excitation to explore feedback processes. It also investigates the morphology, excitation and kinematics of molecular gas, which is the source of the nuclear and star-forming fuel. It tests the Unified Model against our observations of AGN orientation and obscuring dust structures.

The results are compared with simulation models of star formation, gaseous outflows and energetics in the nuclear environment, which posit an evolutionary cycle of gas compression, star formation and AGN activity; the results also inform the development of these models. The emphasis is on observations of early-type galaxies, which have a minimum of nuclear obscuration and presumably simplified fueling.

The galaxies are sampled from a catalog of local, massive early-type galaxies with radio emission, which were subsequently determined to have strong nuclear near infrared
and optical emission lines. These are observed with Integral Field Spectrographs on 8 to
10 m class telescopes in the near infrared portion of the spectrum, penetrating nuclear
dust obscuration, and using adaptive optics to remove atmospheric blurring and allowing
the telescopes to observe at their full resolution capabilities. From this data, we derive
stellar and gaseous kinematics and distributions, gas excitation states and modes, stellar
populations and formation ages and dust obscuration.

Analysis of data from the Seyfert 2 galaxies NGC 2110 and NGC 5728, and the star-
burst galaxy IC 630 reveal a variety of star-forming and gas outflow morphologies. The
nuclear obscuration structures are delineated and gas masses, distributions, kinematics
and excitations measured. Despite being early-type galaxies, they are similar in their
astrophysical attributes (star formation rates, circumnuclear cold molecular gas masses,
AGN generated mass outflow rates or Eddington ratios) to others of the same observational
class. Our observations of the outflow and nuclear obscuration morphologies support the
Unified Model and a picture of cyclic evolution of low- to moderate-power AGNs and their
host galaxies in the local universe.

Principal Coordinating Supervisor: Professor Jeremy Mould, Centre for Astrophysics and Supercomputing, Swinburne University of Technology

Associate Supervisor: Associate Professor Michael Brown, School of Physics and Astronomy, Monash University
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I have found working at the Centre for Astrophysics and Supercomputing, Swinburne University, a wonderful experience; the faculty and my co-students have been nothing but friendly, helpful and collegial. The exposure to weekly seminars, especially, has expanded my astronomical horizons beyond measure. As a mature-age student, I was made to feel just the same as the ‘young-uns’. They were also most sympathetic and supportive during my period of illness.

I also thank Dr. Michael Brown, my co-supervisor, for helpful discussions, especially on the ‘big picture’ and also for detailed review of this thesis.

Finally, my profound thanks to my wife Elsa and my son Christopher, my sister Caroline and others in my extended family, whose unfailing support and interest has kept me going. Taking the Ph.D. study on as an older student has been a big challenge, and they backed me 100% of the way.
Declaration

The work presented in this thesis has been carried out in the Centre for Astrophysics &
Supercomputing at Swinburne University of Technology between 2013 and 2017. This
thesis contains no material that has been accepted for the award of any other degree
or diploma. To the best of my knowledge, this thesis contains no material previously
published or written by another author, except where due reference is made in the text of
the thesis. The content of the chapters listed below has appeared in refereed journals.

Alterations have been made to the published papers to correct errors, as noted at the
end of the respective chapters. Other alterations have been made in order to maintain
argument continuity and consistency of spelling and style. Some duplicated material has
been removed from the published papers to other chapters to avoid repetition of the same
material, especially introductory comments and data reduction procedures.

- Chapter 3 has been published as:
  *Young Star Clusters in the Circumnuclear Region of NGC 2110*

- Chapter 4 has been published as:
  102
  *IC 630: Piercing the Veil of the Nuclear Gas*

I was the foremost contributor to these papers, performing all data reduction and anal-
ysis, most of the telescope observations and most of the preparation of the text and figures.
The co-authors provided editing and support ideas and assistance with the manuscripts.

Mark Durré
Melbourne, Victoria, Australia
2017

Jeremy Mould, 2017

Michael Brown, 2017
Dedication

To Elsa, Christopher and Caroline,
and to the memory of my brother, Kit, and my parents, Betty and Alan.

Ulysses

...you and I are old;
Old age hath yet his honour and his toil;
Death closes all: but something ere the end,
Some work of noble note, may yet be done,
Not unbecoming men that strove with Gods.

...This is my son, mine own Telemachus,
To whom I leave the sceptre and the isle,—
Well-loved of me, discerning to fulfil
This labour,...

...—Come, my friends,
'Tis not too late to seek a newer world.
Push o'ff, and sitting well in order smite
The sounding furrows; for my purpose holds
To sail beyond the sunset, and the baths
Of all the western stars, until I die.

...Tho' much is taken, much abides; and tho'
We are not now that strength which in old days
Moved earth and heaven, that which we are, we are;
One equal temper of heroic hearts,
Made weak by time and fate, but strong in will
To strive, to seek, to find, and not to yield.

Alfred, Lord Tennyson, 1809–1892 (1842)
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Introduction

1.1 Purpose of the Thesis

This thesis is an observational study of the environments of active galactic nuclei (AGN). Specifically, it examines the physical parameters of the stars and gas, especially in the narrow-line region (20–1000 parsecs from the super-massive black hole). This is the region where feedback between the AGN and the rest of the galaxy is most effective for star-formation or gas heating. To that end, observations have been carried out on nearby active galaxies, using large (8–10 m) telescopes combined with infra-red integral field spectrographs and adaptive optics, to observe the spatially-distributed spectra of the galactic nuclei, examining nebular emission lines and stellar absorption features.

1.2 Thesis Outline

The thesis is organized into chapters numbered as follows:

1. Introduction (this chapter) - outlining the scientific rationale for the thesis, with an overview of active galactic nuclei and areas where current understanding can be improved by an observational program that also informs theoretical investigations. This also incorporates a review of the current literature in the field and the state of observations of these objects (focusing on infra-red integral field observations). The investigative program will be outlined, with the criteria for selection of objects.

2. Observations, data reduction and analysis methodologies - this describes the reasons why particular observing techniques are used, the instruments and methods used for observation, how the acquired data is reduced and calibrated, how various data products are derived from the reduced data and a toolbox of how the physical parameters of the gas and stars are deduced from this data.
3. NGC 2110 - the discovery of large, young star clusters in the nucleus of this object reveals one of the pathways for star formation near an AGN.

4. IC 630 - this star-burst galaxy would appear to have many characteristics of an AGN, but, while it has radio and X-ray emission combined with strong nebular lines and large, young, nuclear star-forming regions, there may be no super-massive black hole. Theoretical models of unstable nuclear gas disks, generating star-bursts in short timescales, are broadly compatible with the observations.

5. NGC 5728 - this paradigm of a Seyfert 2 galaxy exhibits biconal nuclear outflows at high velocity, excited by hard radiation from the active nucleus and shocks from gas turbulence. Hot and cold gas masses are both present in this highly complex object.

6. Conclusion - this draws together the deduced physical attributes of these AGNs, both common and dissimilar features, as well as fitting them within the broader context of all AGNs.

### 1.3 An Overview of Active Galactic Nuclei

In the review that follows, I will focus on the literature that studies nearby AGN, where resolved studies can reveal the inner workings of the interactions with their host galaxies, rather than on large statistical samples, especially in the high-redshift universe.

Some galaxies in the local universe emit unusual (i.e. non-stellar) electromagnetic radiation from their nuclear regions, extending from the radio to the gamma-ray parts of the spectrum. First observed over a century ago (Fath, 1909, in the galaxies NGC 1068 and M81), one of the characteristic signatures is bright nebular emission lines in the optical part of the spectrum; these are produced by gas at low density. Seyfert (1943) recognized a class of these galaxies, which also have very bright, compact nuclei; the emission line widths were sometimes very broad, showing characteristic velocities of 1000–8500 km s$^{-1}$. These objects were subsequently called Seyfert galaxies.

With the advent of radio-astronomy, some large local elliptical galaxies (e.g. Virgo A–M87 and Centaurus A–NGC 5128) were found to be extragalactic radio sources, but there were also some sources that had no identifiable optical counterpart. These were eventually identified (Schmidt, 1963, for the source 3C 273) as star-like objects, whose optical emission lines exhibited an extraordinary red-shift, indicating a large cosmological distance and a correspondingly prodigious power output. The were originally designated as ‘quasi-stellar radio sources’ (quasar); later it was found that most quasars (90%) were ‘radio-quiet’ and the alternative name became ‘quasi-stellar object’ (QSO). Deep images
eventually showed that these objects were also the very bright, compact nuclei of galaxies. Collectively, the quasars, radio galaxies, Seyfert galaxies and other unusual objects with non-stellar nuclear radiation are known as ‘active galactic nuclei’ (AGN).

Further observations showed that the radio emission was produced by synchrotron radiation from charged particles circulating in magnetic fields in jet structures, launched at significant fractions of the speed of light; in an astrophysical context, this was first proposed by Shklovsky in 1953 (see Burbidge, 1956). Synchrotron emission in the jet can be optical (e.g. Burbidge, 1956, in M87). Observations also revealed excess production of X-rays, ultraviolet (UV) and far infra-red (FIR) radiation.

There are numerous sub-classes of AGN from observational perspectives, with radio sources classified whether they had centrally concentrated or edge brightened radio lobes (FR-I or -II sources), whether optical quasars or Seyferts have broad (> 1000 km s\(^{-1}\)) or narrow permitted spectral lines or no spectral features at all (BL Lac objects). An AGN class may have several observational signatures, that may or may not overlap with other classes.

The emission regions are unresolvably small and the power output is variable on time-scales of years down to days, indicating very small production regions by galactic standards, from light-time arguments (see Peterson, 2001, for a review). The puzzle was to find a mechanism that produced so much power in such a small size. The high stellar and gas velocities close to the nucleus also indicated a large enclosed mass. Salpeter (1964) and Zel’dovich (1964) originally proposed that accretion of matter onto a super-massive black hole meets the requirements of size and power output, which is produced by the efficient conversion of gravitational potential and kinetic energy into radiation. A straight-forward calculation shows that matter infalling from a few kiloparsec to the Schwarzschild radius of a large black hole can release some 10% of its mass-energy, a much greater conversion efficiency than thermonuclear reactions (∼0.1%).

A ‘Unified Model’, i.e. a paradigm that encompasses all classes of AGN, was proposed by Antonucci (1993) and Urry & Padovani (1995), who brought together many lines of evidence in a model where the different observational classes of AGN were a single type of object observed under different conditions. In this model, the main difference between the major grouping of AGNs (Type 1 and 2, see below for definition) depends on the inclination of the torus to the line of sight (LOS), and other characteristics were dependent on the accretion rate and the presence or absence of a radio jet. The AGN components thus (in order of physical size, given in brackets for each item) consisted of:


- A super-massive black hole (SMBH) of mass $10^6 - 10^9$ M$_\odot$ (solar masses) with event-horizon radius of $0.02 - 2$ Astronomical Units (AU) / $10^{-7} - 10^{-5}$ parsec (pc).

- An accretion disk around the SMBH equator, where matter falling into the relativistically deep potential well is compressed by gravitational and frictional forces and is heated to temperatures of $> 10^5$ K. This releases approximately 10% of its rest-mass energy as thermal emission, with its spectral energy peaking in the far-UV/soft X-ray regime. Associated with the accretion disk is a high-temperature ($> 10^6$ K) corona, which emits high-energy X-rays. ($10^{-2}$ pc / 2000 AU).

- A broad-line region (BLR) with photo-ionized clouds of gas moving at orbital speeds of $2000 - 10000$ km s$^{-1}$ and temperatures of $\sim 10000$ K. The gas is at high enough density that forbidden spectral lines are not present (due to collisional de-excitation), and the electron density is in the range $10^8 < N_e < 10^{12}$ cm$^{-3}$ (0.1–1 pc).

- A dusty, molecular torus which absorbs about half the light from the accretion disk and is heated to $100 - 1000$ K, re-emitting the energy in the infra-red. This torus obscures the central engine from a range of viewing angles and collimates the accretion disk radiation (1 – 100 pc).

- A narrow-line region (NLR), with low enough gas density so forbidden lines are not collisionally de-excited ($10^3 < N_e < 10^6$ cm$^{-3}$). Characteristic velocities are of the order of a few 100 km s$^{-1}$ and temperatures are in the same range as the BLR. No region with intermediate physical parameters for the permitted lines between the BLR and NLR has been observed. There may also be an extended NLR to a few kiloparsec (kpc) (100–300 pc).

- Some AGNs have a relativistic jet produced by magnetic fields in the accretion disk, emitting synchrotron radiation ($10^3 - 10^6$ pc).

‘Permitted’ and ‘forbidden’ spectral lines are distinguished by their transition lifetimes, with the latter being much longer than the former. Forbidden lines have a low transition probability by the standard quantum-mechanical rules, and are only found in low-density ($< 10^8$ cm$^{-3}$) gas.

Fig. 1.1 illustrates the model, where the LOS determines the observational class.

- Edge-on, the torus obscures the central region; only the NLR is visible, showing both permitted and forbidden lines with low characteristic velocities (Type 2 objects).

- As the inclination decreases, the high-speed ionized clouds close to the central engine become visible, with broad permitted lines of the BLR added to the narrow lines of the NLR (Type 1 objects).
Looking ‘down the barrel’, the accretion disk light outshines all other emission, swamping any spectral features. Rapid output variations are seen if the SMBH feeding varies; material launched by the jet show superluminal velocities and brightening due relativistic effects (Blazars, BL Lac objects, optically violent variables).

Conventionally, a distinction is made between low-luminosity AGN (LLAGN) where \( \log(L_{\text{Bol}}) \leq 42 \), moderate-luminosity Seyferts \( (43 \leq \log(L_{\text{Bol}}) \leq 45) \) (e.g. Crenshaw et al., 2003) and high-powered quasars \( \log(L_{\text{Bol}}) \geq 46 \), where \( L_{\text{Bol}} \) is the bolometric (i.e. total) luminosity in erg s\(^{-1}\) (Ho, 2008). As a comparison, \( \log(L_{\text{Bol}}) = 33.6 \) for the Sun. Very low-luminosity sources sometimes lack a BLR, indicating a fundamental change in the central engine processes at low accretion rates (Ho, 2008).

AGNs have a short duty cycle of accretion \( \sim 10^{-2} \), Greene & Ho, 2007), so they spend the majority of their life in the low-luminosity state. Low-excitation emission line region (LINER) nuclei may have no or very little AGN activity; aging starbursts, post-

\[\text{Figure 1.1: AGN Unified Model (adapted from Urry \\& Padovani, 1995, sourced from https://fermi.gsfc.nasa.gov/science/eteu/agn/)}\]
asymptotic giant branch (AGB) stars and white dwarfs can make substantial contributions to the emission line flux (see Mason et al., 2015, and references therein).

The canonical Unified Model has been modified in light of later observations, especially in the size and configuration of the obscuring torus to a smaller (< 10 pc), clumpy structure (see Elitzur, 2006; Netzer, 2015, for reviews); at high powers, the higher fraction of Type 1 over Type 2 AGNs suggests the ‘receding torus’ model (Lawrence, 1991), where the covering fraction of the torus is reduced as the dust sublimation radius increases.

It is now recognized that the vast majority of galaxies in the local universe have some sort of non-stellar (i.e. detectable emission lines) nuclear activity. Originally thought to be < 10% (Roy, 1994), the current value is 86% (see Ho, 2008, and references therein), including all disk-type and >50% elliptical galaxies. This even includes our own galaxy as a LLAGN.

Seyfert galaxies are the brightest AGN in the sky in apparent magnitude at visual wavelengths and are the prime targets for high spatial detail observations. Fig. 1.2 shows some characteristics of the class. The Seyfert 1 galaxy Mrk 279 is shown from the HST WFPC2 F606W image. Even at a spatial resolution of 0.05, the nucleus is unresolved (as seen by the diffraction spikes) and saturated, indicating a very bright, compact core. The typical Seyfert 1 and 2 spectra show the permitted H recombination lines as broad and narrow (Seyfert 1) or narrow only (Seyfert 2), with only narrow forbidden lines of [O III] and [N II]. The Seyfert 1 (NGC 5548) Hα and Hβ lines show a combination of a broad line (2010 km s⁻¹) and a narrow line (200 km s⁻¹), which is the same width as the narrow forbidden lines. Intermediate classes are also recognized (Seyfert 1.2, 1.5, 1.8 and 1.9), based on the relative strength of the broad vs. narrow lines in the optical spectrum.

Conventional seeing-limited, ground-based optical and infra-red observations have a resolution of (at best) ~ 0.5. This corresponds to a scale of 0.02 pc at the center of the Milky Way and 250 pc at 100 Mpc; the closest AGN (the Circinus Galaxy) is 3 mega-parsec (Mpc), corresponding to a resolution scale of 7 pc. This can be improved by an order of magnitude using adaptive optics and large telescopes in the near infrared, very-long baseline interferometry (VLBI) in radio wavelengths, and near- and mid-infrared interferometry.

1.3.1 SMBHs, Their Host Galaxies and Star Formation

1.3.2 The AGN/Galaxy Linkage

Observationally, SMBH masses and their galaxy host properties are well correlated; these are the stellar velocity dispersion (Ferrarese & Merritt, 2000; Gebhardt et al., 2000),
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Figure 1.2: Seyfert Galaxies. Left panel: Mrk 279, a Seyfert 1 galaxy, HST image (Malkan et al., 1998). Note the unresolved, saturated nucleus. Right panel: Typical Seyfert 1 (top) and 2 (bottom) spectra; note the broad and narrow permitted lines of H\(\alpha\) and H\(\beta\) and the narrow (only) forbidden lines of [O III] and [N II].

galactic bulge mass (Kormendy, 1993), K-band luminosity (Kormendy & Richstone, 1995; Graham & Scott, 2013) and the light profile’s Sérsic index (Graham et al., 2001). As the ‘sphere of influence’ of the SMBH (the volume of the galaxy where the mass of the black hole outweighs that of the stars and gas) is tiny compared to the scale of the galaxy, mechanisms must link the two together, i.e. processes that involve growing the SMBH must also affect the galaxy star formation and subsequent stellar distributions and dynamics within the galaxy.

Three scenarios for the linkage present themselves:

- Star formation generates AGN activity and concomitant SMBH growth; this can come from gaseous outflows from stars, feeding the SMBH.

In this scenario, gas is driven into the nucleus of galaxies during gas-rich mergers (Springel et al., 2005; Hopkins & Quataert, 2010; Bournaud, 2011), which then generates a starburst (SB). The models of Norman & Scoville (1988) suggested a buildup of a massive central star cluster which then fed the SMBH through late evolution mass loss; Davies et al. (2007) similarly posit that outflows from AGB stars (rather than winds from young massive stars) are more efficiently accreted, because of the lower wind speeds and greater mass loss (50–70 % of their mass).
Alternately, an existing dense circumnuclear gas disk can gravitationally collapse into clumps and stars (Schartmann et al., 2017).

- AGN activity controls star formation; scenarios can be suggested where low-power outflows, radio jets or gravitational instabilities compress the ISM to enhance star formation (SF). Alternately, the AGN energetics may suppress SF, as the gas is heated by direct radiation (where high-energy radiation from the AGN can photo-ionize the gas or can heat it through absorption) or mechanical energy; the latter is in the form of winds or outflows from radiation pressure and subsequent entrainment of the interstellar medium (ISM); this can, in turn, heat gas masses through supersonic shocks (e.g. Tabor & Binney, 1993).

In this scenario, Zubovas et al. (2013) suggests that AGN outflows over-compress a gas-rich ISM and trigger SF (especially in late-type galaxies where the outflow intersects the disk), and that the terminating process is the stellar feedback (winds, SNe) counteracting the AGN outflow locally. Zubovas & King (2016) also suggest that the ‘coasting’ outflows (after AGN activity has shut off), powered by thermal expansion, can enhance SF at larger radii than the observed ≤ 10 kpc outflow radius. Zubovas & Bourne (2017) demonstrate the complexities of these processes by adding gas fragmentation and self-shielding. An additional factor may be the presence of nuclear star clusters, which are small (<5 pc) and of the order of the SMBH in mass; Naiman et al. (2015) found that the presence of these enhances the accretion rate in simulated galaxy mergers.

- Another physical phenomenon controls both SF and AGN activity simultaneously; for example, stellar bars or galactic mergers (both major and minor) drive gas towards the center, feeding the SMBH directly and also producing a starburst with stellar evolution generating a subsequent further inflow.

This scenario is thought to be unrealistic; the infalling gas encounters the ‘angular momentum problem’ (see Phinney, 1994, for review). There is no difficulty removing the angular momentum of gas by gravitational torques, merger events or other instabilities from the outer to ~ 100 pc from the AGN (Haan et al., 2009), the problem lies in removing 5 orders of magnitude of specific angular momentum from there to the accretion disk radius. Mediating inflow by star formation from a gas disk (as in the first scenario) seems more plausible (Davies et al., 2007, and references therein).

There is some evidence that galaxies with AGNs (especially Seyferts) differ from quiescent ones in stellar and gas kinematics and dust content and morphology; Hicks et al.
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(2013), from a matched sample of 5 active (Seyfert) and inactive galaxy pairs, deduce that Seyferts have a dynamically cold nuclear structure with young stars and a significant gas reservoir. Izumi et al. (2016) find a positive correlation between the mass of dense molecular gas (traced by the HCN radio emission line) and the AGN accretion rate in 10 Seyfert galaxies, with 100 pc-scale nuclear disks.

A matched sample of 34 active and 34 inactive early-type galaxies by Simões Lopes et al. (2007), found all the active galaxies have circumnuclear dust, while only 26% of the inactive ones did. AGN-hosting galaxies have higher stellar mass within the central kiloparsec (Tsai & Hwang, 2015, comparing 104 AGN and 119 normal galaxies with 200 Mpc); there is, however, a difference between radio-selected and non-radio-selected galaxies, with the former having higher star-formation rates (SFRs), indicating current as well as past activity.

1.3.2.1 Simulations

Theory indicates that if the gas causing star formation is also responsible for feeding the central black hole, then a positive correlation between AGN feedback and SF is expected. If powerful AGNs are responsible for the star formation quenching, then a negative correlation is expected. At high AGN powers (especially in the early universe), simulations suggest that there is enough energy transfer to the ISM to suppress SF. In the models of Croton et al. (2006), radio-mode AGN provide the required feedback to make the galaxy mass function compatible with observations at the high-mass end.

Both mechanical and radiative, rather than thermal, feedback is required to reproduce the properties of massive early-type galaxies, as suggested by the simulations of Choi et al. (2015). Ciotti et al. (2015) showed that feedback is intermittent on both temporal and spatial scale, and can be both negative and positive. The semi-analytic models of Gutcke et al. (2015) suggest that at high SF rates (starbursts) the correlation between SFR and AGN power is positive, where part of the gas that turns into stars is accreted on the SMBH; whereas at lower powers the correlation is negative.

Volonteri et al. (2015) find that the AGN accretion rate and galaxy-wide SFR are temporally uncorrelated and have different variability timescales, but the accretion rate is better correlated with the nuclear SFR. For barred spirals, the scenario is more complex; Robichaud et al. (2017) finds that the gas is driven in quickly and forms a starburst, as opposed to un-barred spirals where the SFR increases more gradually; star formation is then suppressed by negative feedback from which pushes the gas outwards, colliding with the inflows and forming a ring of enhanced SF. The relative timing of AGN feedback is
important; if it is turned on before SF is well started, it has a larger negative feedback effect.

In summary, the simulations suggest that the rate, timing and location of star formation, the presence or absence of a bar and AGN power and variability all have effects on the feedback processes (both positive and negative).

1.3.2.2 Observations

Do the observations support these theoretical predictions? At the highest powers and largest scales, AGN radio-mode heating is observed to supply enough energy for negative feedback (e.g. Fabian, 2010, for the Perseus cluster). However, as opposed to the general prediction that high-power AGNs will suppress SF (i.e. a negative correlation), many observations have found a positive correlation. For example, HST imaging on quasars at $z \sim 1 - 2$ (Floyd et al., 2013) finds that the host galaxies are UV-luminous and therefore highly star-forming, even at the most active phase of the AGN. For most of the time, AGN are in a low power mode; recent observations (Villar-Martín et al., 2016) suggest that even luminous AGNs have low to modest outflows, not enough to suppress SF.

Some AGNs have large-scale radio jets, extending many kpc. While radio galaxies are often hosted by passive elliptical galaxies (e.g., M87), the relationship between radio jets and star formation is not simple. Jet-induced SF is observed by van Breugel & Dey (1993) in 3C 285 at a projected $\sim 70$ kpc distance from the quasar. Mould et al. (2000a) find the similar SF mode for Cen A (NGC 5128); Salomé et al. (2017) finds modest star-formation in the ‘Vertical’ structure in the northern filaments of this galaxy, from ALMA observation of CO filaments spatially matched with GALEX FUV, Herschel FIR and H\textalpha emission features. Zinn et al. (2013) found that radio jets are statistically associated with enhanced SF in several hundred AGN in the Chandra Deep Field South; however they found a negative correlation of SF with X-ray strength, suggesting that feedback ‘works both ways’. Even at the galaxy cluster level, Russell et al. (2016) reports that the massive hot outflows in the Phoenix cluster are rimmed with lofted cold molecular hydrogen filaments that will eventually fall back towards the galactic center and feed SF.

Studies of nearby Seyferts show a positive correlation between AGN luminosity and nuclear star formation. In a sample of 43 Seyfert galaxies, Watabe et al. (2007) compared the circumnuclear and nuclear SF and AGN luminosities. They found that the nuclear SF and AGN Eddington normalized luminosity was more strongly correlated, suggesting that starbursts nearer the AGN have a greater effect on accretion. This is supported by Bernhard et al. (2016), with a sample of 1620 X-ray selected AGNs, who find that high
specific luminosity (high Eddington ratio) AGNs are more likely to reside in galaxies with enhanced levels of star formation. Similarly, in a large study, Chen et al. (2009) compared the Eddington ratio of the SMBH with the specific SF rate in circumnuclear regions for over 10,000 Type 2 AGNs in the redshift range $0.03 \leq z \leq 0.08$. They concluded that the strong correlation implied that supernova (SN) explosions played a role in the transport of gas to galactic center by increasing the turbulent viscosity in the ISM.

Circumnuclear rings and spirals of SF are prominent in many AGN; Malkan et al. (1998) found a variety of features (rings, spirals, dust lanes, filaments etc.). Storchi-Bergmann et al. (1996) investigated SF in 6 galaxies with AGNs and found spirals and rings associated with tidal resonances; gas motions were mostly circular and indicated an unusual central mass concentration. These rings have been explored in detail with integral field unit (IFU) observations in the near-infrared (NIR); NGC 7582 (Riffel et al., 2009b), NGC 613 (Falcón-Barroso et al., 2014; Böker et al., 2008), NGC 1068 (Storchi-Bergmann et al., 2012) and NGC 5248 (Böker et al., 2008).

Starbursts in the nuclei of active galaxies can supply significant fractions of the total bolometric luminosity of the galaxy; Müller Sánchez et al. (2006) estimates 1.4% for the Circinus galaxy. The nuclear starburst connection has been examined by several groups in the infrared at high resolution (e.g. Bedregal et al., 2009; Davies et al., 2007); they find a variety of formation mechanisms and black hole (BH) fueling scenarios. Jaeggli & Joseph (2007) constructed self-consistent models in 4 nearby Seyfert 2 AGN from NIR emission line and continuum diagnostics, confirming they have genuine starbursts. Diniz et al. (2017) dissected the stellar ages in the inner 500 pc of Mrk 573, finding a mixture of old and young stars close to the nucleus, with intermediate-age stars predominating further out (similarly to NGC 1068, Mrk 1157 and Mrk 1066 from the same group).

At higher redshifts ($0.02 < z < 0.3$) and with a large statistical sample from SDSS (22 623), Kauffmann et al. (2003) showed that the host galaxies of high-luminosity AGN (as measured by the [O III] luminosity), whether of Type 1 or 2, have a young stellar population compared to normal galaxies; a significant fraction have recent star formation.

Observations do not, in general, seem to support the hypothesis of negative correlation between AGN activity and SF. An alternative picture of galaxy downsizing (Cowie et al., 1996; Scannapieco et al., 2005), where stars in more massive galaxies form earlier, suggests a positive correlation, even in the early universe. SF activity is more difficult to observe at those distances, therefore correlations are harder to measure.

In summary, these observations support the scenario of gas inflowing the nuclear region forming stars and feeding the SMBH. At high powers the SMBH feeding and star formation
are simultaneous; at moderate and lower powers, there may be a two-stage process where stars are formed first and the subsequent winds from stellar evolution feeds the SMBH.

1.3.3 Molecular Hydrogen and Feeding

If star formation and subsequent or simultaneous AGN feeding are fueled by inflowing cold molecular gas, then we may expect molecular hydrogen (H$_2$) to be ubiquitous in Seyfert galaxies, as this is the immediate fuel for SF. Cold molecular hydrogen is not directly observable, but can be traced in the radio spectrum by CO emission. However, in the high-energy environment of galactic nuclei and AGNs, it is warmed to a temperature in the range 500–2500 K by a variety of mechanisms (shocks, X-ray heating into gas masses, UV florescence), and then cools by emission lines in the NIR (mainly in the K-band). The total H$_2$ masses and surface densities can then be estimated from scaling relations (e.g. Mazzalay et al., 2013b), plus other deductions about the excitation mechanisms can be made, as described in Section 2.6.4.2.

The kinematic signatures of inflows are more difficult to measure than outflows; a small mass accretion onto the central engine of the AGN powers much larger outflow masses, inflow velocities are lower than outflows (presenting spectral resolution issues) and the source of the inflowing gas is usually a dynamically cold disk or ring, often requiring modeling to remove the rotational component to see the residual inflow (e.g. Diniz et al., 2015, for NGC 2110).

Large molecular gas reservoirs were observed by Reunanen et al. (2001) for 14 local Seyferts with long-slit infra-red (IR) spectroscopy, usually in a plane perpendicular to outflows. This is supported by Davies et al. (2014), who find that circumnuclear H$_2$ disks are present around all (5/5) active, but only in two of the 5 comparable inactive galaxies. They also found two accretion modes, secular (i.e. sourced from the diffuse ISM and quasi-continuous on long time scales) and external (i.e. on a short time-scale with significant gas masses). The two inactive galaxies that have H$_2$ also have counter-rotating gas dynamics and chaotic dust morphologies, suggesting gas inflow (and presumably AGN triggering) in the near future. Similar results are presented by Quillen et al. (1999). However, Rosario et al. (2017), from the Luminous Local AGN with Matched Analogs (LLAMA) survey, could not find a statistical difference of gas fractions or central star formation efficiency between the active and inactive galaxies. Sani et al. (2012) finds that the Toomre-stability of this gas vitiates against rapid SF in the central 100 pc.

From the summarized observations of the AGNIFS group on 10 local AGN, Riffel et al. (2015) and Diniz et al. (2015) found that:
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- Ionized and molecular gas have distinct morphologies and kinematics, with, in general, the H$_2$ being in the galactic plane and dominated by rotations and inflows (with ionized gas tracing outflows and having disturbed morphology).

- Outflows can range from 0.01–10 M$_\odot$ yr$^{-1}$ for low-luminosity Seyfert and LINER types, up to 100–1000 M$_\odot$ yr$^{-1}$ for high-luminosity Seyferts; velocities are in the range 200–800 km s$^{-1}$ for ionized gas and $\sim$ 150 km s$^{-1}$ for molecular gas (c.f. Davies et al., 2014, for a similar conclusion).

- H$_2$ inflows are observed at rates of 0.1–10 M$_\odot$ yr$^{-1}$.

- Kinematically cold nuclear structures of young stars with gas are observed in Seyferts.

Molecular gas is observed in a wide variety of morphologies (rings, bars, central and off-center peaks) and kinematics (circular and stellar-bar affected oval flows, co-rotation with stars with spiral inflows) (Mazzalay et al., 2013b, 2014). There may be multiple disks at different alignment (e.g. PKS B1718-649, Maccagni et al., 2016). In some cases, the H$_2$ ring appears to be an extension of the inner torus (da Silva et al., 2017, NGC 1566). For MCG–6-30-15 (Raimundo et al., 2017), there is a counter-rotating core of both stars and H$_2$, indicating that this core formation was associated with inflows of external gas to the center.

A mechanism to transport gas from galactic scale distances to the nuclear region is required. From observing 7 nearby AGN galaxies with VLA (CO and H I) and NIR images, Haan et al. (2009) deduced that gravitational torques are very efficient at transporting gas into the inner $\sim$ 100 pc, ranging from 0.01–50 M$_\odot$ yr$^{-1}$, with the dominant kinematic mode being bar, oval or 2-armed spiral; some of the galaxies have nested bars. However, gravitational torque transport ceases in the inner 100 pc, requiring other mechanisms.

Asymptotic giant branch stellar outflows are observed forming a dense turbulent disk in the inner few pc of Seyfert galaxies (Davies et al., 2010). The actual mass loss from aging stellar populations in 6 quiescent active galaxies was computed by Soria et al. (2006), finding the rate to be $\sim$ 10$^{-4}$–10$^{-3}$ M$_\odot$ yr$^{-1}$, an order of magnitude greater than X-ray observed hot gas inflow. For NGC 1097, Davies et al. (2009) found that the net molecular inflow was small ($\sim$ 0.06 M$_\odot$ yr$^{-1}$); this could generate starbursts every 20–150 Myr, sustainable over a Gyr. NGC 1068 has an inflow rate of $\sim$ 15 M$_\odot$ yr$^{-1}$, along two linear structures leading to within a few pc of the AGN in elliptical or parabolic orbits (Müller Sánchez et al., 2009); they note however that the required feeding rate of the AGN from its bolometric luminosity, is only 0.001 of that rate. Müller-Sánchez et al. (2011) calculated the outflow vs. accretion mass ratio for seven Seyfert galaxies, and found it in the range
\( \sim 100 - 8000 \). The mass accretion needed to power the AGN is a smaller by 2-3 orders of magnitude than the observed inflows.

Overall, the results show that there are several modes of accretion of nuclear gas and subsequent star-formation and AGN feeding. Molecular gas reserves in the nuclear region are necessary but not sufficient to trigger AGN activity.

### 1.3.4 Feedback and Outflows

The physics of cosmic feedback, i.e. the transfer of energy to the nuclear ISM from the AGN, is thought to have two major modes (from the review by Fabian, 2010):

- ‘Quasar’ (or ‘Radiative’) mode, having high accretion rates, short time-scales, small spatial scales; this mode transforms galaxy morphologies (quenching) and regulates SMBH mass growth, and is thought to be triggered by gas-rich mergers,
- ‘Radio’ (or ‘Kinetic’) mode, having low accretion rates, long (Hubble time) time-scales, large (galaxy halo) scales; this maintains galaxy morphology and regulates galaxy mass, and is thought to be the result of ‘dry’ mergers.

Hopkins & Elvis (2010) proposes a ‘two-stage’ feedback model at moderate or high powers, where a relatively weak wind from the accretion disk shreds and expands cold clouds, which can then be driven to outflow by radiation pressure; the kinetic luminosity to AGN bolometric luminosity ratio must exceed \( \sim 0.5\% \) for this to occur. A strong wind from the accretion disk could drive the accelerating phase of the NLR outflows, with only a fraction of the disk wind energy being transferred to the clouds, the rest carried by hot, low-density winds. This was found in the numerical study of Mou et al. (2017) on the example of NGC 4151. A similar mechanism drives powerful mass outflows traced by high-excitation emission lines from the low-luminosity AGN in NGC 1386 (Rodríguez-Ardila et al., 2017).

Feedback in moderately powered AGN is often observed as outflows of ionized gas, traced by optical or NIR emission lines. The presence of outflows in Seyfert 2 AGN, as traced by \([\text{O III}]\) kinematics, are correlated with AGN luminosity, rising from 10\% at \([\text{O III}]\) luminosities of \( \sim 10^{39} \) erg s\(^{-1}\) to 50\% at \( \sim 10^{42} \) erg s\(^{-1}\) (Woo et al., 2016). The importance of mass loss in the overall picture of AGN is emphasized by Crenshaw et al. (2003), with UV and X-ray observations of outflowing clouds in a majority of moderate luminosity Seyfert galaxies. These outflows are often aligned with a radio jet, if one is present, e.g. NGC 5728 (this thesis), NGC 613 (Davies et al., 2017). There are counter-examples - Riffel et al. (2014a) for NGC 5929 and Le et al. (2017) for 6 radio Type 2 AGNs
find no evidence that the gas outflows are directly connected to the large scale radio jets. Outflows themselves are not, in general, aligned with the axes of the galaxies; the angle between the bicone axis and the normal to the host galaxy disk has a full range of all possible angles (Fischer et al., 2014).

Nevin et al. (2017) summarizes the results from the literature for the outflow energy diagnostics. Over 4 orders of magnitude of bolometric luminosity \(42 \leq \log(L_{\text{Bol}}) \leq 46\), they find that the mass outflow rate and kinetic energy increases with increased bolometric luminosity and that \(L_{\text{KE}}/L_{\text{Bol}}\) remains roughly constant, where \(L_{\text{KE}}\) is the kinetic luminosity or power. The slope of the log-log relationship between the outflow rate and bolometric luminosity from all reviewed sources is \(0.50 \pm 0.12\). The outflows are powerful enough to drive feedback in accordance with the Hopkins & Elvis (2010) model, even at the lower end of this luminosity range.

Not all \(H_2\) structures are in rotation or in-falling; Tadhunter et al. (2014), Dasyra et al. (2015) and Morganti et al. (2015) observe fast outflows accelerating molecular gas in IC 5063, Emonts et al. (2014) observed a molecular outflow rate of \(\sim 20\ M_\odot\ yr^{-1}\) in NGC 3256; ALMA has also observed these outflows with CO observations (e.g. García-Burillo et al., 2014, in NGC 1068). Davies et al. (2014) finds that molecular outflows are at lower velocity \((\sim 150\ \text{km s}^{-1} - \text{below the galaxy escape velocity and likely to fall back})\) vs. ionized gas outflows \((\sim 200 - 2000\ \text{km s}^{-1})\). Sakamoto et al. (2014) in fact finds two molecular outflows in the merger luminous infra-red galaxy (LIRG) NGC 3526 with ALMA and SMA observations, one driven by an AGN jet, the other by a starburst-driven superwind.

Summarizing observational results and possible signatures of AGN/SF linkage, Harrison (2017) concluded that, while local AGNs are capable of quenching SF via radio jets, mechanical outflows, shocks and heating, it is unclear if this is the case at early epochs. The timescales of various processes are uncertain, e.g. outflows are still visible but there are no signs of direct AGN activity. Villar-Martín et al. (2016), from VLT-FORS2 spectroscopy of 18 Type 2 Seyferts and quasars at \(0.3 < z < 0.6\) deduced that there is no evidence that the outflows affect the host galaxies ISM at spatial scales larger than 1–2 kpc. Fischer et al. (2017) found a similar restricted spatial scale for the outflow of Mrk 573.

The details of the interplay between AGN and star formation require elucidation. The complex, closely couple phenomena of AGN feeding and outflows with SF enhancement or suppression require further observations and modeling.
1.3.5 Obscuration and the Torus

In the Unified Model of AGN, the dusty torus has three main effects; to be the proximal source of material feeding the accretion disk, to obscure the central engine along some lines of sight (setting the observational classification of the AGN) and to collimate the radiation and material outflows from the central engine, producing ionization cones. The observed size of the dusty nuclear obscuring region varies with the wavelength, becoming larger at shorter wavelengths as absorption becomes more effective; at longer wavelengths, absorption changes to emission from the hot dust.

The simple model of a smooth torus has been overtaken by observations in recent years, and is now thought to be complex, clumpy (a smooth dust distribution cannot survive in the harsh AGN vicinity) and dynamical. An observation set of HST WFPC2 images of 256 local \((z < 0.035)\) active galaxies (Malkan et al., 1998) seemed to undermine one of the postulates of the simple Unified Model which makes no allowance for host galaxy properties; Seyfert 2 galaxies were more likely to show enhanced dust absorption on scales grater than the supposed torus. Several dozen object are changing-look AGNs at X-ray wavelengths (as measured by the strong changes in their X-ray spectral shape), with some extreme objects changing obscuration on timescales of days or weeks (Ramos Almeida & Ricci, 2017).

Fischer et al. (2014) studied 17 local AGNs, and showed that the Seyfert 1/2 dichotomy was not a hard cutoff; the clumpy nature of the torus just increases the probability of obscuration of the BLR as the inclination increases. Risaliti et al. (2011) and Bisogni et al. (2017) use the [O III] equivalent width to measure the inclination of the accretion disk to the LOS, as the [O III] flux is a good indicator of the bolometric luminosity of the AGN and the continuum light from a quasar is assumed to come (mostly) from the AGN which is dependent on the inclination. Even in some edge-on sources, the broad emission lines were visible, suggesting clumpy obscuration.

The hot dust emits predominantly in the mid IR; Alonso-Herrero et al. (2011) fitted the spectral energy distribution (SED) of 13 nearby Seyfert galaxies with CLUMPY torus models and mid IR spectrographic and photometric observations, and found that compact (1–6 pc) torus radii fitted the data well; their results also supported the observations of Fischer et al. (2014) with regard to the probabilistic nature of obscuration. The \(\text{H}_2\) disk is often co-planar with the dusty torus and with an inner stellar ring (Menezes & Steiner, 2015, for the Sombrero Galaxy). Hicks et al. (2009) traced the ISM by molecular hydrogen in thick, clumpy disks for 11 Seyfert and LINER galaxies, and deduced that these (on 10s of pc scales) contributes to AGN obscuration. The gas is mixed with the nuclear
stellar population. The overall picture would seem to be that obscuration happens on many different spatial scales, from close-in clumpy toroidal structures, to flared equatorial structures of $\sim 100$ pc scale, to nuclear and galaxy scale dust lanes.

The theoretical predictions of Elitzur & Shlosman (2006) posit the torus as the region of clumpy winds coming off the accretion disk, with optically thick and dusty clouds; the structure becomes thinner and weaker with lower AGN power. This is supported by the observations of the CO emission of NGC 1097 with ALMA (Izumi et al., 2017), and also by Müller-Sánchez et al. (2013), with observations of H$_2$ in 7 LLAGNs, which showed column densities about 3 times smaller than Seyferts. Going in the other direction, a matched sample of 34 active and 34 inactive early-type galaxies by Simões Lopes et al. (2007), found all the active galaxies has circumnuclear dust, while only 26% of the inactive ones did, showing a strong correlation between accretion and circumnuclear dust; the dust morphologies were mostly chaotic.

In addition to observational studies, some models are consistent with a patchy torus around the central black hole. The models of Wada et al. (2016) of a nuclear starburst around a LLAGN, with a SMBH mass of $10^6$ M$_\odot$, naturally produce a double hollow-cone structure from the radiation-driven fountain with SN feedback, without needing a thick torus around the central source. The cone has diffuse ionized gas in the center surrounded with thick atomic gas; molecular gas is in the equatorial plane, inflated by supernovae.

In conclusion, the canonical small ($\sim 1 - 10$ pc), smooth, dusty torus model has been replaced by a clumpy, flared, large (to 100s of pc), multi-component region, where the obscuration of the AGN central engine is probabilistic, not based solely on the inclination to our LOS.

1.3.6 AGN Evolution

Active galaxies can be thought of as having two main phases of their evolution. In the early universe, the SMBH were being fed at close to the Eddington limit by gas-rich mergers; this built up both the galaxy and the SMBH mass, producing the well-known scaling relationships and are visible as high-powered quasars. This build-up peaked at ‘Cosmic Noon’ ($z \approx 2$) and the rate has been in decline ever since (Kormendy & Ho, 2013). This picture is somewhat modified by hard X-ray luminosity function studies of AGN at high redshift ($z > 3$) (Silverman et al., 2008), which shows that the accretion rate onto SMBHs is not as high as expected compared with lower redshifts.
The other phase, in the local universe, is the ‘maintenance’ mode; this is driven by more infrequent, random events. Following Taniguchi (1999) and Tsai & Hwang (2015), the evolutionary scenario for this mode is:

1. A minor merger or other mechanism drives gas into the nucleus.
2. A nuclear starburst is triggered.
3. The AGN ‘lights up’ as a Seyfert galaxy of moderate luminosity and Eddington ratio.
   - Winds from the evolved stars in the starburst accrete onto the SMBH.
   - The galaxy has more stellar mass in the central 1 kpc than a comparable ‘normal’ galaxy.
   - There are stellar and dusty structures (spirals and rings) around and feeding the nucleus.
4. The AGN eventually consumes the available material.
   - The stellar structures dissolve over a 200 Myr time-scale.
   - As the AGN slows down, it becomes a LINER and radio-jets become more prominent.

In Section 1.4.2, the statistics of observed objects by morphology (related to evolutionary state) is examined. It is noted that ellipticals and irregulars are under-represented; this could be a reflection of the fact that these do not contain SMBHs (irregulars) or that they have shut down or are in non-star forming, radio jet mode (ellipticals). For ellipticals, their preferential location in cluster environments may be the cause. Decreased Seyfert fractions in ellipticals towards cluster centers (de Souza et al., 2016, as against no decrease for spirals), indicates that galaxies in cluster centers should be more stripped of cold gas (by ram pressure or other mechanisms). The spirals may hold on to their gas better due to the extra gravitational force from their bulges.

### 1.4 Science Program Rationale and Observations

#### 1.4.1 Some Outstanding Problems

While the Unified Model is an excellent explanation of multiple AGN phenomena, its physical validity must be tested by simulations. This can be done by building theoretical models and comparing them with observations. Three-dimensional, adaptive-mesh resolution (AMR) hydrodynamic simulation models can resolve the accretion disk, dusty torus,
broad and narrow line regions and large scale in- and out-flows in a range of time and space scales (Wada et al., 2009; Schartmann et al., 2009; Wada, 2015; Wada et al., 2016). Since these simulations resolve small spatial scales, observations must be carried out at similar scales, if possible.

The main effort in this thesis is to examine star formation and associated phenomena in the nuclear region of AGN host galaxies, by studying gas rich AGNs in early-type galaxies. As these galaxies typically have little or no star formation, the presence (or absence) of star formation is easier to interpret than for late-type AGN host galaxies.

While the evolutionary scenarios and the Unified Model given above give a reasonable and consistent picture of AGN, outstanding issues remain, mainly in details. The narrow-line region provides a laboratory for these issues, since this scale is well-resolved for nearby (<100 Mpc) galaxies. To date, the observational data set at this resolution is limited (see Section 1.4.2, below). We examine the following phenomena in this thesis from our observations of the selected objects:

- Star formation in the nuclear region, including morphology and evolution, examining signatures of stellar winds and and supernovae (SNe).
- Does the nuclear obscuration density and morphology and outflow geometries support the Unified Model of AGN?
- How is energy from the AGN coupled to surrounding matter? The details of outflow (excited atomic gas) dynamics and radio jet interactions are examined.
- Molecular gas masses, kinematics, excitations and distributions are examined, as this is the fuel for star formation.
- Local galaxies housing AGNs (‘classical’ Seyferts and LINERs) are usually late-types (i.e. spiral galaxies); are AGN-associated phenomena in early-type galaxies different?

The scientific goals requires an observational program to study the nuclear activity of selected galaxies; the material flows are mapped through 2D velocity structures and the gas excitation is studied to determine the relative contributions of the activity modes.

- Make a detailed exploration in the NIR at the finest spatial scales possible of the nuclear region of nearby galaxies that have radio emission and near IR and optical nebular lines.
- Explore gas dynamics, which can both feed the central engine and providing SF material and outflows (which can control SF both positively and negatively).
• Deduce SF and SN rates, excitation modes, and masses of ionized, atomic and molecular gas in the central region, differentiating between star-forming and AGN excitation.

• Use the results to inform 3D hydrodynamic simulation models resolved in the range of time and space that probe the full range of AGN scales, from the accretion disk to the extended narrow-line region. How do our observations compare with theoretical simulations?

1.4.2 NIR IFU Observations of AGN

The literature was reviewed to find all galaxies with AGN within 100 Mpc that have been observed by at least one of the three 8–10 m class adaptive optics (AO)-assisted NIR IFU instruments (see Section 2.2). These works were selected for studies of stellar or gas physics, and excluded those that were purely studying the SMBH mass. This resulted in a list of 106 objects. The activity type is grouped into (1) H II/starburst, (2) Seyfert 1 and 1.5, (3) Seyfert 1.8, 1.9 and 2, (4) LINERs. The morphology was categorized simply as ellipticals, lenticulars, spirals (Sa, Sb, Sc and Sd) plus irregulars. Barred galaxies were grouped with un-barred.

The activity and Hubble types were compiled from Vizier\(^1\) catalogs ‘The revised RC3 catalog’ (Catalog VII/155/rc3, de Vaucouleurs et al., 1991) and the ‘Quasars and Active Galactic Nuclei (13th Ed.)’ (Catalog VII/258/vv10, Véron-Cetty & Véron, 2006). Of the IFU observed 106 galaxies, 10 were included in the Brown et al. (2011) catalog (396 galaxies) and 13 were included in the Mould et al. (2012) observations (165 galaxies); of these, 5 were observed by Mould et al. (2012) but were not in the Brown et al. (2011) catalog.

As a population comparison, all galaxies hosting an AGN with \(z < 0.024\) (the highest redshift in the AO-observed list) were also categorized by activity and Hubble type, a total of 482 galaxies. Galaxies that did not have a definitive Hubble or activity type were excluded. Some galaxies (46) had an activity flag of ‘S’ (Seyfert) without sub-type; these were distributed proportionately to Sy1 and Sy2 types. Fig. 1.3 plots the comparison of IFU observed and all galaxies. This shows that elliptical galaxies are under-represented in the observed sample, and that Seyfert 2 types are also underrepresented. This means that useful work can be done with these groups; ellipticals have (in general) even less obscuration than lenticular galaxies, thus observing the NLR of Seyfert 2s is easier than for Seyfert 1s.

\(^{1}\)http://vizier.u-strasbg.fr/viz-bin/VizieR
1.4. Science Program Rationale and Observations

![Histograms showing AGN host type and activity type](image)

Figure 1.3: Comparisons of AGN host type and activity type. ‘Observed’ is all published NIR IFU galaxies (SINFONI, NIFS, OSIRIS). ‘All’ is all galaxies with AGN with $z < 0.024$. Left panel: Hubble type comparison. Right panel: activity type comparison.

1.4.3 IFU Surveys of AGN

Since the first AO-assisted integral-field spectroscopic study of a Seyfert galaxy (the Circinus galaxy) was presented in Müller-Sánchez et al. (2006), there have been several studies of individual or small samples of nearby AGNs. Obviously, larger samples are needed to extract significant statistics on their properties. There are several such surveys that have been, or are being, conducted. None of these are ‘large-scale’ by the standards of other surveys, due to the large amount of observing time needed for each object, along with inherent complexities in the techniques. The surveys are:

The KONA (Keck/OSIRIS Nearby AGN) Survey

(Müller-Sánchez et al., 2017) The sample is of 40 nearby ($z < 0.035$) Seyferts, crucially selected on the presence of high-excitation emission lines in the NIR; these also show hard X-ray and/or radio sources and have line ratios consistent with the AGN diagnostics. The main scientific goals are to examine inflows (driving gas from hundred-parsec scales into the nucleus), outflows (how do accreting black holes influence their host galaxies?), the molecular torus and unification schemes, and nuclear property trends with AGN properties and Seyfert types.
Chapter 1. Introduction

The LLAMA (Luminous Local AGN with Matched Analogues) Survey
(Davies et al., 2015) This survey matches a volume limited sample of nearby active galaxies selected by their 14-195 keV X-ray luminosity from the Swift/BAT survey, with complementary sample of inactive galaxies, selected to match the AGN host galaxy properties (stellar mass, morphological type, inclination, presence of a bar, distance). These have been examined for nuclear stellar properties (Lin et al., 2017, for kinematics and luminosity distributions), star-formation efficiencies of nuclear molecular gas (Rosario et al., 2017), environmental dependence on AGN activity and the host galaxy (Davies et al., 2016a) and BLR properties and extinction (Schnorr-Müller et al., 2016). These galaxies have been observed with a variety of instruments; all have been or will be observed with SINFONI.

The AGNIFS (AGN Integral Field Spectroscopy) Group
While not a formal survey, this group (led by Prof. Thaisa Storchi-Bergmann) at the Universidade Federal do Rio Grande do Sul, Porto Alegre, and the Universidade Federal de Santa Maria in Brazil, has published many papers on ~ 20 AGNs using the Gemini NIFS and GMOS plus the VLT SINFONI instruments. This group also surveyed 10 LLAGNs is early-type galaxies (Ricci et al., 2014b,a, 2015, 2016), studying circumnuclear stellar kinematics and gas properties.

Other works with large samples have made use of archival data (e.g. Burtscher et al., 2015, using archival SINFONI data). Müller-Sánchez et al. (2017) also gives references to other work using IFU observations on AGN, without AO.

1.4.4 Galaxy Selection and Observations
The objects in this thesis are a subset of the Brown et al. (2011) early-type galaxy sample, selected by Mould et al. (2012) as follows:

- The hypothesis is that all massive galaxies exhibit radio heating from an AGN or other sources to prevent the ISM from cooling and forming stars. The Brown et al. (2011) sample is 396 elliptical or lenticular galaxies that have a 2MASS magnitude $K < 9$, with a declination $\delta > -40^\circ$ and a galactic latitude $|b| > 15^\circ$. All these galaxies are within 100 Mpc. The 1.4 GHz radio emission was measured from archival data. This sample is volume complete in the part of the sphere accessible from Hawaii (presuming the use of the Keck telescopes for follow-up). The conclusion from these

\[\text{http://www.mpe.mpg.de/llama}\]
1.4. Science Program Rationale and Observations

observations supported the hypothesis that all massive galaxies have an AGN or recent star formation.

- This conclusion was followed up to examine the AGN/SF association. From the sample, Mould et al. (2012) conducted long-slit spectroscopic observations, mainly on the Palomar Hale 200 inch telescope using the Triplespec NIR longslit spectrograph (Herter et al., 2008). As these galaxies are early-types, the fueling and stellar populations are likely to be simpler than spirals, stored gas is smaller and there is a minimum of nuclear obscuration. In this campaign, 165 objects were observed; about 20% of objects showed NIR emission lines; these have greater radio power for a given galaxy mass than those without such lines.

- From the galaxies that showed emission lines, those that had the strongest lines were chosen, so they could be observed in reasonable time on the 10 m-class telescopes. All the galaxies showing emission lines were within 140 Mpc; a distance limit of $<80$ Mpc was set, enabling AO-corrected IFU observations at sub-10 parsec resolution. The feasibility of studying these galaxies at the required spatial resolution and sensitivity was proven with observations of Mrk 3 (UGC 3426) in Nov. 2011.

- During the observing runs in the Southern hemisphere (SINFONI on the VLT), we extended the selection to objects that were not in the Brown et al. (2011) list that had $\delta < -40^\circ$ (southern hemisphere), selecting galaxies with known strong emission lines in the visible spectrum.

The complete list of objects that we observed are given in Table 1.1; the astrophysical data are from the NASA/IPAC Extra-galactic Database (NED)\(^3\), and the distances (D) values given in the table assume a flow corrected Virgo + GA + Shapley Hubble flow model (Mould et al., 2000b). The objects examined in detail in this thesis were those with the best quality data in terms of emission line strength and/or they have interesting radio morphology or known outflows.

\(^3\)http://ned.ipac.caltech.edu/
## Table 1.1: Objects observed by our program

<table>
<thead>
<tr>
<th>Object</th>
<th>RA</th>
<th>DEC</th>
<th>Morphology</th>
<th>T</th>
<th>Activity</th>
<th>z</th>
<th>D (Mpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 630</td>
<td>10:38:33.61</td>
<td>-07:10:13.9</td>
<td>S0 pec?</td>
<td>-3</td>
<td>HII</td>
<td>0.007277</td>
<td>33.3</td>
</tr>
<tr>
<td>Mrk 1239</td>
<td>09:52:19.10</td>
<td>-01:36:43.5</td>
<td>E-S0</td>
<td>-4</td>
<td>Sy1.5</td>
<td>0.019927</td>
<td>87.5</td>
</tr>
<tr>
<td>UGC 3426</td>
<td>06:15:36.36</td>
<td>+71:02:15.1</td>
<td>S0:</td>
<td>-3</td>
<td>Sy2</td>
<td>0.013509</td>
<td>57.8</td>
</tr>
<tr>
<td>NGC 0262</td>
<td>00:48:47.14</td>
<td>+31:57:25.1</td>
<td>SA(s)0/a:</td>
<td>-3</td>
<td>Sy2</td>
<td>0.015034</td>
<td>60.7</td>
</tr>
<tr>
<td>NGC 1052</td>
<td>02:41:04.80</td>
<td>-08:15:20.8</td>
<td>E4</td>
<td>-4</td>
<td>LINER</td>
<td>0.005037</td>
<td>19.9</td>
</tr>
<tr>
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<td>03:08:56.74</td>
<td>-02:57:18.5</td>
<td>S0- pec:</td>
<td>-3</td>
<td>HII</td>
<td>0.008079</td>
<td>32.0</td>
</tr>
<tr>
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<td>05:52:11.38</td>
<td>-07:27:22.4</td>
<td>SAB0-</td>
<td>-3</td>
<td>Sy2</td>
<td>0.007789</td>
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<td>+12:15:57.9</td>
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<td>HII</td>
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<td>26.6</td>
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<td>-13:24:53.0</td>
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<td>Sy1</td>
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<td>-49:50:12.9</td>
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<td>AGN</td>
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<td>HII</td>
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<td>HII</td>
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<td>+09:56:02.7</td>
<td>(R)SB(s)0+</td>
<td>-1</td>
<td>Sy2</td>
<td>0.005704</td>
<td>24.2</td>
</tr>
</tbody>
</table>

Note. — Col: (1) NED preferred name (2) and (3) J2000.0 co-ordinates (4) NED Homogenized Morphology (5) RC3 T Type (6) NED or SIMBAD Activity Type (7) Redshift (8) Flow corrected Virgo + GA + Shapley Distance (Mould et al., 2000b)
You can have data without information, but you cannot have information without data.

Daniel Keys Moran, 1962

2

Observations, Data Reduction and Analysis
Methodologies

This chapter describes the telescope/instrument combinations used for observations, and the reasons they were chosen. It also describes the methods used to reduce and calibrate the observations to produce data sets for analysis.

This analysis includes production of images of both stellar continuum and gas emission fluxes, as well as deriving kinematics by fitting models to emission and absorption line profiles.

From this analysis, we can deduce physical conditions and parameters of the gas around the central object. These include gas column densities (and by extension masses), the contribution of the various excitation mechanisms of the gaseous emission lines (including star-formation, AGN activity, shocks etc.) and the gas temperatures and densities. We can also deduce the AGN activity level, super-massive black hole mass and Eddington ratio. The kinematics enable us to work out mass inflow to and outflow from the AGN and its associated geometry. Star-formation and supernova rates can also be deduced.

2.1 Observational Methodology

The criteria for choosing the telescope/instrument combination for observations is as follows:

- NIR wavelength range, to penetrate dust obscuration, which usually increases closer to the AGN.
- Simultaneous spatial and spectroscopic observations, at the highest resolutions possible.
Chapter 2. Observations, Data Reduction and Analysis Methodologies

- The largest telescope aperture available, to acquire data in reasonable time and to get the best possible resolution.
- Adaptive optics, to remove the effect of blurring by the atmosphere (seeing).

Traditional long-slit spectroscopy is inefficient when observing extended objects, so the criterion of simultaneous spatial and spectral observations is met by a class of instruments known as integral field units (IFUs). These divide a field of view into small elements, each of which is then split into a spectrum. The field is sampled by a variety of means; bundled fiber optics, an array of lenslets or image-slicing techniques\(^1\). The end-result after data reduction is a data cube, a 3D representation of the spatial dimensions \((x\) and \(y\) co-ordinates) and the spectrum \((z\) co-ordinate).

An illustration of the power of the NIR to penetrate obscuration is the case where a Seyfert 2-type nucleus (where the broad BLR emission lines are not visible in the optical), has a broad Br\(\gamma\) line, which has penetrated the dust; Reunanen et al. (2001) finds several examples.

Adaptive optics (AO) is a suite of techniques to remove the blurring caused by turbulence in the various layers of the atmosphere. It is usually performed by a feedback loop between the observation of an object that is known to be a point on the sky (a star, an artificial star generated by a laser that excites the sodium layer in the upper atmosphere or by a point-like galactic nucleus) and a light-path correcting deformable mirror. AO performs best in the infrared, which also has the advantage of penetrating obscuring gas and dust to directly observe the nuclear region. The optical part of the spectrum thus suffers from obscuration and relative ineffectiveness of AO. References for each AO system used are given with the description of each AO-assisted instrument.

Currently, there are 3 instruments that meet the combined requirements of a telescope in the 8-10 m class, adaptive optics and a near infra-red IFU; these are SINFONI on VLT, NIFS on Gemini North and OSIRIS on Keck I.

2.2 Observing with Integral Field Units and Adaptive Optics in the Near Infra-Red

The observations in this thesis were carried out on four IFU instruments:

- OSIRIS (Larkin et al., 2006) (OH- Suppressing Infra-Red Imaging Spectrograph) on the Keck I 10 m telescope on Mauna Kea with laser guide star adaptive optics (LGSAO) (Wizinowich et al., 2006; van Dam et al., 2006). The IFU uses a lenslet

\(^1\)A good review of the subject and techniques is at http://ifs.wikidot.com/
array to sample a rectangular field at close to the telescope’s diffraction limit. It has four spatial scales (0".02, 0".035, 0".05 and 0".1), and can be combined with four broad-band filters (Z, J, K, H – the Z filter covers the range 1000–1180 nm) or 18 narrow-band filters, with a lenslet geometry of 19 × 64 (broad-band filters) or 48 × 64 (narrow-band filters), with a spectral resolution of ~ 3600.²

- NIFS (McGregor et al., 2003) (Near-Infrared Integral Field Spectrometer) on the Gemini North 8.1 m telescope with the ALTAIR LGSAO³ on Mauna Kea. It employs an image-slicing technique, and has a square field of view (FOV) of ~ 3 × 3 arcsec², divided into 29 slices with an angular sampling of 0.103 × 0.042 arcsec². It has four filters (Z, J, H and K) at a spectral resolution of ~ 5300.⁴

- SINFONI (Eisenhauer et al., 2003; Bonnet et al., 2004) (SINgle Faint Object Near-IR Investigation) on the VLT 8.2m UT4 (Yepun) telescope on Cerro Paranal. It uses an image slicer technique similar to NIFS and provides J, H, K and H+K gratings (with spectral resolution of 1500 to 4000), with spatial scales of 0".025, 0".1 and 0".25.⁵

- WiFeS Dopita et al. (2007) (Wide-Field Spectrograph) on the ANU 2.3 m telescope at Siding Springs. This is a visual (320 – 950 nm) IFU, with a 25 × 38" FOV at 0".5 spatial scale and a spectral resolution of 3000. As this does not use adaptive optics, data from this instrument is used for broad-scale diagnosis of kinematics and excitation⁶.

The main spectral windows (i.e. where the infrared radiation penetrates the atmosphere) in the NIR are J (1100 – 1400 nm), H (1500 – 1800 nm) and K (1950 – 2400 nm); a Z-band filter (940–1100 nm) is available on OSIRIS and NIFS. On the boundaries of these windows, the atmospheric transmission decreases, but in good conditions (e.g. low water vapor content) useful observations can be made. There are also several other (‘telluric’) absorption features in these bands, which must be corrected. The standard method of doing this is to make observations of a ‘standard’ star as close in time as possible to the object observations, at a similar airmass (i.e. elevation above the horizon). This star should, ideally, be of type B or A, which have few inherent spectroscopic features apart from hydrogen and helium lines. This is described in detail in Section 2.4.2.

²http://www2.keck.hawaii.edu/inst/osiris/
³See http://www.gemini.edu/sciops/instruments/altair/ for system documents
⁴http://www.gemini.edu/sciops/instruments/nifs/
⁵http://www.eso.org/sci/facilities/paranal/instruments/sinfoni.html
Apart from absorption, the night sky also emits spectral lines, mainly from OH radicals; these lines are brightest at wavelengths longer than 1500 nm and are time-dependent, being caused by waves in the upper atmosphere at a height of 85 km, and are usually many orders of magnitude brighter than extended astronomical sources (Rousselot et al., 2000). The standard technique to remove these is to take successive observations on (‘Object’) and off (‘Sky’) the target with the same exposure, then to subtract the two; this usually provides good correction. Care must be taken not to have too long exposures, as changing atmospheric conditions will cause errors in the correction; these are usually seen as contaminating sky lines. Techniques are available to reduce these errors (Davies, 2007). Caution must also be used for signal to noise measures at the skyline and other major telluric features wavelengths.

Adaptive optics observations can be carried out using either the laser or natural guide star modes, with the laser guide mode also requiring a tip-tilt star for guiding; each mode has constraints on the distance and brightness of the tip-tilt star from the FOV. Guiding can often be done on the observed object, for instance the bright point-like nucleus of the galaxy.

An observing sequence thus consists of an acquisition frame set (‘Object-Sky’, typically a minute or less) to confirm centering, then one or several science frame sets (‘Object-Sky-Object’, typically 10–15 minutes each). These observations are either preceded or followed by a standard star observation.

### 2.3 Data Reduction

Basic data reduction is done by data reduction pipelines (DRP) provided by the instrument designers.

- The OSIRIS DRP, in contrast to the other IFU instruments, does not need to have routine nightly calibration data, but uses rectification matrices (‘recmats’), which incorporate flat-fielding, wavelength calibration and spatial distortion into one matrix that converts the 2D CCD image to a 3D data cube. These recmats are stable over long periods (> 1 year). The pipeline subtracts the sky from the object frame, adjusts CCD channel levels, identifies glitches and removes cosmic rays, extracts the spectra (using the recmats), assembles the data cube and corrects for atmospheric dispersion. The recmats must be valid for the observation date, and are retrieved from the OSIRIS instrument website\(^7\).

\(^7\)http://www2.keck.hawaii.edu/inst/osiris/tools/index.php
2.3. Data Reduction

- The NIFS data reduction is done as a sequence of tasks in IRAF. Night-time ancillary calibration observations are arc, flat field, dark and Ronchi slit-mask (for spatial calibration) frames. The tasks consist of creating baseline calibration files, then reducing the object and standard star observations using these calibrations. Each on-target frame is subtracted by the associated sky frame, flat fielded, bad pixel corrected and transformed from a 2D image to a 3D cube using the spatial and spectral calibrations. The resulting data cubes are spatially re-sampled to 50×50 mas spaxels.

- For SINFONI data, the recommendations from the ESO SINFONI data reduction cookbook and the gasgano software pipeline (version 2.4.8) are followed. Bad read lines are cleaned from the raw frames using the routine provided in the cookbook. Calibration frames are reduced to produce non-linearity bad pixel maps, dark and flat fields, distortion maps and wavelength calibrations. Sky frames are subtracted from object frames, corrected for flat field and dead/hot pixels, interpolated to linear wavelength and spatial scales and re-sampled to a wavelength calibrated cube, at the required spatial scale. The sequence of reduced object cubes are mosaicked and combined to produce a single data cube.

- The WiFeS data are reduced using the PyWiFeS package (Childress et al., 2013). The CCD images are preprocessed (converted from ADU to photon counts, cosmetic defect removal and bias removal), the slitlets separated, cosmic rays rejected, flat-fielding performed and the data cube generated, including spatial zero-point correction, atmospheric differential refraction removal and coordinate rectification.

Subsequent cube manipulation and computation is done using the the cube data viewer and analysis application QFitsView (Ott, 2016), which incorporates the DUSER language. After the basic reduction, some manipulation of the science cubes is required. The OSIRIS cube axes are in the sequence $\lambda, x, y$ (i.e. wavelength, RA and Dec), rather than the standard $x, y, \lambda$; the axes are swapped around (using QFitsView procedure swapaxes). Since the OSIRIS FOV is rectangular, the observations are often carried out aligned to an object feature (e.g. the galaxy major axis). For convenience, all data cubes are rotated so that north is up and east is left.

8http://www.gemini.edu/sciops/instruments/nifs/data-format-and-reduction
9http://iraf.noao.edu/
10http://www.eso.org/sci/software/gasgano.html
2.4 Flux Calibration and Telluric Correction

2.4.1 Flux Calibration

The standard stars are used for both telluric correction and flux calibration. The procedure to get the flux calibration constant for each data cube is as follows:

- The star’s spectrum is extracted. To do this, the aperture to be used must be carefully determined. With a multiple elements in the optical train, the IFU image shows significant scattered light over more than 1" radius. In addition, bright stars are usually observed with the AO loops open, to prevent detector saturation. All of these effects lead to the stellar image taking up a large fraction of the FOV. The aperture is set manually from the cube median image, using logarithmic scaling. A region outside this aperture is chosen to set the background level offset. This is illustrated in Fig. 2.1, which shows the cube average image using both linear and logarithmic scaling with 95% scale range, with the aperture and the annulus for background subtraction.

- A segment of the spectrum is chosen that avoids telluric features and stellar absorption lines, on or near the effective wavelength for the filter (\(Z\)–1050 nm, \(J\)–1235 nm, \(H\)–1652 nm, \(K\)–2120 nm). The total counts in a 10 nm window centered on the chosen wavelength is extracted. This value is divided by the exposure time and the window wavelength width to get a value in counts s\(^{-1}\) nm\(^{-1}\) (Fig. 2.2).

- The standard star’s magnitude is found from the SIMBAD astronomical database\(^{11}\). These are derived from the 2MASS catalog (Skrutskie et al., 2006). The \(Z\) magnitude (if required) is taken to be the same as the \(J\) magnitude (as \(J - H \approx 0\), so \(Z - J = 0\) is a good approximation for A0 stars).

- The magnitude and wavelength chosen are converted to a flux density using the website ‘Conversion from magnitudes to flux, or vice-versa’\(^{12}\). As an example, the star HIP073266 has a \(H\) magnitude of 7.3, which measured at 1652 nm has a flux of 1.43 \(\times\) 10\(^{-12}\) erg cm\(^{-2}\) s\(^{-1}\) nm\(^{-1}\).

- The ratio of the flux and the counts s\(^{-1}\) nm\(^{-1}\) is the flux calibration constant. The data cube values are scaled by this constant and divided by the spectral channel width and the exposure time. OSIRIS data is already divided by the exposure time in the data reduction pipeline.

\(^{11}\)http://simbad.u-strasbg.fr/simbad/
\(^{12}\)http://www.gemini.edu/sciops/instruments/midir-resources/imaging-calibrations/
fluxmagnitude-conversion
2.4. Flux Calibration and Telluric Correction

The standard stars are (ideally) of spectral type A0, which only have hydrogen absorption lines in their spectrum; these are usually fast rotators showing Doppler broadening of the lines (Wood, 2003). The spectra can be modeled by a black-body curve for the appropriate temperature plus simple Gaussian or Lorentz profiles to remove the hydrogen lines. SINFONI standard stars were a range of stellar types, from B2 to A5. To get a more accurate model of these spectral classes, the stellar atmospheric models from Castelli & Kurucz (2003)\textsuperscript{13} were used. For standard main sequence stars of Solar metallicity, the ckp00 set of models was used. The models for temperatures 8000 to 30000 K were extracted for the wavelength range 901 to 2595 nm, and log-linearly interpolated to produce data for the temperature for each spectral type in the range B0 to A7. A black-body curve was then fitted to the models. The results are given in Table 2.1 below.

It is noted that the model spectra in the infrared do not fit a black-body curve with the same temperature as fitted in the visible part of the spectrum. The best fit blackbody vs. the nominal temperature for the spectral type is given in Table 2.1. This is an issue when applying a blackbody fit for telluric correction for standard data reduction. While the difference is not large, it is a potential source of error for stellar population models, where the spectral slope is important. The reason for this difference is that the hydrogen opacity (caused by bound-free and free-free interactions) is less at the infrared wavelength, and effectively we are seeing to lower (therefore hotter) layers in the stellar atmosphere.

A telluric spectrum is created as follows:

\textsuperscript{13}ftp.stsci.edu/cdbs/grid/ck04models/
Chapter 2. Observations, Data Reduction and Analysis Methodologies

Table 2.1: Model Stellar Spectra, Nominal Temperature and Black-Body Fit

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>BB Fit</th>
<th>Optical Temp. a</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0</td>
<td>42362</td>
<td>29200</td>
<td>1.45</td>
</tr>
<tr>
<td>B1</td>
<td>26902</td>
<td>23000</td>
<td>1.17</td>
</tr>
<tr>
<td>B2</td>
<td>24091</td>
<td>21000</td>
<td>1.15</td>
</tr>
<tr>
<td>B3</td>
<td>20600</td>
<td>17600</td>
<td>1.17</td>
</tr>
<tr>
<td>B4</td>
<td>19172</td>
<td>16400</td>
<td>1.17</td>
</tr>
<tr>
<td>B5</td>
<td>18161</td>
<td>15200</td>
<td>1.20</td>
</tr>
<tr>
<td>B6</td>
<td>17022</td>
<td>14300</td>
<td>1.19</td>
</tr>
<tr>
<td>B7</td>
<td>16392</td>
<td>13500</td>
<td>1.21</td>
</tr>
<tr>
<td>B8</td>
<td>15711</td>
<td>12300</td>
<td>1.28</td>
</tr>
<tr>
<td>B9</td>
<td>14987</td>
<td>11400</td>
<td>1.32</td>
</tr>
<tr>
<td>A0</td>
<td>12380</td>
<td>9600</td>
<td>1.29</td>
</tr>
<tr>
<td>A1</td>
<td>11965</td>
<td>9330</td>
<td>1.28</td>
</tr>
<tr>
<td>A2</td>
<td>11747</td>
<td>9040</td>
<td>1.30</td>
</tr>
<tr>
<td>A3</td>
<td>11545</td>
<td>8750</td>
<td>1.32</td>
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<tr>
<td>A4</td>
<td>11154</td>
<td>8480</td>
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<tr>
<td>A5</td>
<td>9617</td>
<td>8310</td>
<td>1.16</td>
</tr>
<tr>
<td>A6</td>
<td>9560</td>
<td>8120</td>
<td>1.18</td>
</tr>
<tr>
<td>A7</td>
<td>9505</td>
<td>7920</td>
<td>1.20</td>
</tr>
</tbody>
</table>

aValues from http://www.uni.edu/morgans/astro/course/Notes/section2/spectraltemps.html

- The flux calibration spectrum is divided by the black-body function at the spectral type temperature as given in Table 2.1.

- The hydrogen and helium lines are removed manually by Gaussian fitting, using the QFitsView emission line de-blend functionality.

- The spectrum is normalized (maximum value set to 1), avoiding noise values.

- Each science data cube spaxel (spatial pixel) is divided by this spectrum.

Fig. 2.2 illustrates the telluric correction process, showing the standard star spectrum divided by a black-body (at 15711 K for a B8 star), the hydrogen lines removed and the flux normalized. The bottom two panels show an example of a galaxy spectrum (NGC 5728, central 1", H+K filter), before and after telluric correction.
2.4. Flux Calibration and Telluric Correction

Figure 2.2: Telluric correction. Top left panel: standard star spectrum, with a blackbody spectrum (11571 K for B8 star) and the hydrogen absorption feature denoted. Top right panel: telluric spectrum after dividing by black-body, removing the absorption features and normalizing. Bottom panels: galaxy spectrum, before (left) and after (right) telluric correction. The noisy region in the range 1750–1900 nm is due to the heavy atmospheric absorption between the H and K bands.

2.4.3 Further Post-reduction Processing

All cubes are cleaned to remove bad pixels, obvious as either negative numbers or extreme excursions, from uncorrected cosmic rays or pipeline artifacts. Cleaning is done manually, especially over emission line wavelength ranges, where bad pixel regions are identified and removed by interpolation. For SINFONI data cubes, some spaxels towards the periphery have gaps in their spectra of approximately 35 pixels due to a ‘dead’ area on the CCD chip; these are also interpolated over - for our observations, these spaxels do not have significant data.

A sequence of observations in a contiguous data set are usually reduced using the same telluric correction and flux calibration; these are usually combined by averaging (after checking for image registration). Observations can also be carried out on an object over several sessions; these are combined after separate flux calibration and telluric correction.
Figure 2.3: SINFONI cube instrumental fingerprint. Left and middle panels: cube median image (i.e. median of all spectral pixels at each spaxel) before and after fingerprint removal (logarithmic scale); the $x$ and $y$ axes are spaxels. Right panel: residual image

A prominent feature (e.g. the brightest spaxel in the image created from the spectrally collapsed data cube) is chosen as a reference point. The cubes are then aligned to this point and averaged.

IFUs can have ‘instrumental fingerprints’ that are not corrected by the standard calibration techniques. Menezes et al. (2014, 2015) demonstrate this for SINFONI and NIFS data cubes; they use the principal component analysis (PCA) tomography technique to characterize the fingerprints (which on SINFONI data cubes show as broad horizontal stripes) and remove them. This fingerprint is the result of detector array persistence (see George et al., 2016). This is visible in our data cubes; we median collapse all wavelengths and display on a logarithmic scale. In fact we see two horizontal stripes at y axis pixels 11-24 and 48–51, as shown in Fig. 2.3 (left panel), and note this is different to the pattern found in Menezes et al. (2015). This fingerprint affects further results, especially for extinction measures.

Attempts to apply the PCA technique to remove the fingerprints can be unsuccessful, as the fingerprint amplitude is comparable to the data and appeared strongly in the tomogram corresponding to eigenvector E1 (which contains practically all of the continuum variation across the image); however the technique does identify the fingerprint, as it appears only in a few of the tomograms. As an alternative, we simply interpolated over the fingerprint in the $y$ axis direction at each spectral pixel. The resulting data cube median is also shown in Fig. 2.3 (middle panel). The right panel of Fig. 2.3 shows the median image of the ratio of the cubes in linear scale; the ratio can be significant, up to 60%.
2.4.4 Spectral Resolution and Wavelength Calibration

The spectral resolution of an instrument, \( R = \lambda / \Delta \lambda \), is published in the appropriate handbook; this can also be measured using the OH skylines, as these lines are assumed to have very narrow width. The technique to measure \( R \) from skylines is to reduce an off-target sky frame using the standard pipeline, against a master-dark exposure, which is created as part of the standard calibration sequence. The sky spectrum is then extracted from the data cube by collapsing it in the spatial directions. The width of the spectral lines is measured using the QFitsView Gaussian fitting facility. The individual lines are checked from Rousselot et al. (2000), to ensure that close multiplets are not measured. The results for each filter and plate scale used in our observations is given in Table 2.2. The calculated, rather than the published, value is used in further processing e.g. to correct the measured LOS velocity dispersion in emission line analysis.

Using the same data, the wavelength calibration can be checked for each observation session, and corrected as required. Using strong, easily identified lines, the Gaussian fit gives the central wavelength, which is compared against the value from Rousselot et al. (2000). A simple linear regression gives the slope and zero intercept, from which the correction in wavelength at the middle of the spectrum is calculated.

2.5 Data Analysis

2.5.1 Plotting Conventions

In this thesis, the image orientations are north is up, east is to the right (i.e. observer sky view) unless otherwise noted; also by convention, the RA axis is positive for increasing RA, so x axis plots will show decreasing values from left to right. The RA and Dec values are always relative to the nucleus of the object.

2.5.2 Continuum Imaging

The morphology of the inner regions of the observed galaxies is often complex, with in-feeding dust lanes, bars, arms, obscuring regions and nuclear clusters or disks. An original, linearly scaled image (e.g. from archival Hubble Space Telescope (HST) data) does not bring these features out very well when presented as printed images. These can be enhanced through various techniques; one of the most effective is the structure map (Pogge
Table 2.2: Instrument Spectral Resolutions

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Filter</th>
<th>Plate Scale (mas)</th>
<th>Measured Resolution</th>
<th>FWHM&lt;sup&gt;a&lt;/sup&gt; (km/s)</th>
<th>Sigma&lt;sup&gt;a&lt;/sup&gt; (km/s)</th>
<th>FWHM (nm)</th>
<th>Published Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIFS</td>
<td>H</td>
<td>50</td>
<td>5560</td>
<td>55</td>
<td>23</td>
<td>0.29</td>
<td>5300</td>
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<tr>
<td></td>
<td>J</td>
<td>50</td>
<td>5422</td>
<td>57</td>
<td>24</td>
<td>0.23</td>
<td>5300</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>50</td>
<td>5087</td>
<td>59</td>
<td>25</td>
<td>0.44</td>
<td>5300</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>50</td>
<td>5454</td>
<td>57</td>
<td>24</td>
<td>0.19</td>
<td>5300</td>
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<tr>
<td>OSIRIS</td>
<td>H bb</td>
<td>35</td>
<td>3177</td>
<td>96</td>
<td>41</td>
<td>0.52</td>
<td>3800</td>
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<tr>
<td></td>
<td>H n3</td>
<td>35</td>
<td>3110</td>
<td>97</td>
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<td>0.54</td>
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<tr>
<td></td>
<td>H n4</td>
<td>35</td>
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<td>85</td>
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<td></td>
<td>H n4</td>
<td>55</td>
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<td>86</td>
<td>36</td>
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<td>4138</td>
<td>74</td>
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</tr>
<tr>
<td></td>
<td>J n2</td>
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<td>62</td>
<td>26</td>
<td>0.25</td>
<td>3800</td>
</tr>
<tr>
<td></td>
<td>J n3</td>
<td>35</td>
<td>3612</td>
<td>84</td>
<td>36</td>
<td>0.35</td>
<td>3800</td>
</tr>
<tr>
<td></td>
<td>K bb</td>
<td>100</td>
<td>2994</td>
<td>102</td>
<td>43</td>
<td>0.73</td>
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<td></td>
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<td>76</td>
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<td>0.27</td>
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</tr>
<tr>
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<td>Z n3</td>
<td>50</td>
<td>3853</td>
<td>78</td>
<td>33</td>
<td>0.8</td>
<td>3800</td>
</tr>
<tr>
<td>SINFONI</td>
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<td>126</td>
<td>53</td>
<td>0.52</td>
<td>2360</td>
</tr>
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<td></td>
<td>K</td>
<td>250</td>
<td>1860</td>
<td>163</td>
<td>69</td>
<td>0.67</td>
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<td>H+K</td>
<td>50</td>
<td>1560</td>
<td>201</td>
<td>85</td>
<td>1.25</td>
<td>1950</td>
</tr>
</tbody>
</table>

<sup>a</sup>FWHM = Full width half-maximum of line; see Equation 2.3.

& Martini, 2002), which produces an image defined as:

\[
S = \left( \frac{I}{I \otimes P} \right) \otimes P_t
\]

(2.1)

where \( I \) is the original image, \( P \) is the HST camera point spread function (PSF) from the TinyTim software<sup>14</sup> (Krist et al., 2011), \( P_t \) is the transpose of the PSF and \( \otimes \) is the convolution operator. An example (for NGC 2110) from the WFPC2 camera is given in Fig. 2.4.

<sup>14</sup>http://www.stsci.edu/hst/observatory/focus/TinyTim

‘White light’ images are extracted from the IFU data cubes by collapsing the cube along the spectral axis, either over the whole wavelength range or over a spectral segment;
a single spectral element may not have a good signal to noise ratio. This reveals nuclear clusters or disks plus other features.

The continuum spectrum can be used to determine the stellar population, especially the relative contribution of young, intermediate and old stars. Full treatment of this requires a stellar population synthesis analysis; see Section 2.6.2 below.

2.5.3 Gas Kinematics

Gas kinematics, i.e. the line-of-sight velocity and dispersion, are derived from fitting a Gaussian model to strong emission lines in the spectrum. The main lines fitted are the atomic hydrogen recombination lines, molecular hydrogen rotational-vibrational lines and the forbidden ionised iron lines. Deriving the kinematic field from a single species is not sufficient, as each species traces gas in a different excitation conditions, e.g. atomic hydrogen is excited by UV photons, molecular hydrogen by a range of mechanisms, but at a lower temperature than atomic hydrogen, and ionised iron by collisional excitation.

To extract gas kinematics from data cubes, the basic procedure is to use the QFitsView velmap function. This fits a Gaussian curve for every spaxel at the estimated central wavelength and full width half maximum (FWHM). This generates maps of the best fit continuum level (C), height (H), central wavelength ($\lambda$) and FWHM. These are readily converted to the dispersion ($\sigma$), the flux ($F$) and the emission equivalent width ($EW$):

$$\sigma = \text{FWHM} / (2 \sqrt{2 \ln(2)})$$

$$= \text{FWHM} / 2.355$$

$$\sigma_{\text{True}} = \sqrt{\sigma_{\text{Obs}}^2 - \sigma_{\text{Ins}}^2}$$
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\[ F = H \times \text{FWHM} \times 1.06477 \]  
\[ EW = \frac{F}{C} \]  
\[ V = V_{\text{Sys}} + V_{\text{LOS}} \]  
\[ = c \times (\lambda/\lambda_R - 1) \]

where \( \lambda_R \) is the rest-frame wavelength of the emission line and \( c \) is the speed of light. The ‘true’ emission line width is convolved with the instrumental dispersion (2.4.4) to produce the observed dispersion; this recovered by subtracting the instrumental from the observed dispersions in quadrature (2.4).

Map values are accepted or rejected based on ranges on each of the derived parameters produced by the procedure, based on visual inspection of the fluxes and kinematic structures i.e. the derived values of continuum, line flux, LOS velocity or dispersion have to be within certain values. Single pixels may be rejected because of large excursions from their neighbours; the source of anomalous values is usually noise spikes in the data or low flux values, causing poor model fits. Rejected pixels are then interpolated over from neighbors or masked out, as appropriate.

A useful diagnostic is to plot histograms of the velocity and dispersion; this shows whether one species is kinematically ‘hotter’ or ‘colder’ than another, e.g. cold H\(_2\) is associated with star-forming rings, kinematically settled disks or inflows, whereas hotter gas is associated with outflows.

The velocity field consists of two components, the systemic velocity \( V_{\text{Sys}} \) (usually the galaxy’s Hubble flow) plus the peculiar line of sight \( V_{\text{LOS}} \) gas motion at each spaxel. The systemic velocity can be problematic to determine; the Hubble flow (redshift) may be derived from 21 cm H I radio or optical observations over the whole galaxy, which do not necessarily reflect the nuclear motions. \( V_{\text{Sys}} \) can be determined by using the average, median or flux-weighted average wavelength over the field, or by defining the velocity at a particular locus (e.g. the nucleus) as the zero-point. The systemic velocities for different species (e.g H I or [Fe II] vs H\(_2\)) may be not be the same, due to different dynamical structures. Thus, given \( \lambda_R \), we derive \( V_{\text{LOS}} + V_{\text{Sys}} \) as per Equation 2.7; fixing \( V_{\text{Sys}} \) then gives \( V_{\text{LOS}} \).

The simple 2D flux maps do not give the full 3D picture of the gas distribution and kinematics; these can be elucidated by combining several methods:

- The standard LOS velocity and dispersion, with a simple assumption of a Gaussian fit to the emission at each spaxel. This gives the peak velocity of the emission line at each spaxel; however, it is dependent on the relative intensities of different kinematic
components present. The peak emission will usually correspond to the kinematics of the components with the highest fluxes.

- Velocity-channel maps, which show the flux distribution at each velocity slice. Unlike the standard velocity and dispersion plots, these show how the gas at a certain velocity is distributed across the field; at a single LOS, the gas may have multiple kinematic components, not just a single component with an inherent dispersion, which the simple Gaussian model assumes.

- Position-velocity diagrams, which lay a slit over the cube aligned with a feature of interest, and plot the flux density by velocity at each position.

2.5.4 Stellar Kinematics

Stellar kinematics can be determined using stellar absorption lines; in the NIR, the most prominent are the CO band-heads in the range 2293–2355 nm from cool stars (K–M spectral types). Since these band-heads do not have simple single absorption peaks, a more sophisticated spectral fitting technique must be used. Commonly, the penalized pixel-fitting (pPXF) method of Cappellari & Emsellem (2004) is used. The Gemini spectral library of near-infrared late-type stellar templates from Winge et al. (2009) is used, specifically the NIFS sample version 2. The observed K-band data cube is reduced to the rest frame and normalized. Both the observations and templates are trimmed to the CO band-head wavelength range (2150–2420 nm, at $R = 5300 - 5900$). The example code for kinematic analysis from the website\footnote{http://www-astro.physics.ox.ac.uk/~mxc/software/#ppxf} is followed. This code outputs the stellar LOS velocity and dispersion and corresponding errors for each spaxel, along with the combined template fit and weights for each template. The same technique can be used in the optical spectrum; the standard templates in this case are usually the MILES models\footnote{http://miles.iac.es}.

2.6 Physical Parameters

2.6.1 Cosmology and Distances

This thesis uses the standard cosmology of $H_0 = 73 \text{ km s}^{-1}\text{Mpc}^{-1}$, $\Omega_{\text{Matter}} = 0.27$ and $\Omega_{\text{Vacuum}} = 0.73$. Distances to galaxies (and other object parameters) use NED values, assuming a Virgo + GA + Shapley Hubble flow model (Mould et al., 2000b). Object brightness is given in Vega magnitudes (unless otherwise stated), and distances refer to
luminosity distance rather than co-moving distance (as observations are in the low-redshift regime).

To convert from measured flux to luminosity, i.e. power output of the object, the relationship is:

\[ L = 4\pi FD^2 \]  

where \( D \) is the distance, \( F \) is the flux and \( L \) is the luminosity. For \( D \) in Mpc and \( F \) in cgs units, this becomes:

\[ L \left( \text{erg s}^{-1} \right) = 1.2 \times 10^{50} F D^2 \]  
\[ L \left( L_{\odot} \right) = 3.1 \times 10^{16} F D^2 \]  

2.6.2 Extinction

Interstellar extinction from dust is important for several reasons (Mathis, 1990):

- It differentially obscures radiation in the spectrum, especially in the UV and visible wavelengths; the absorbed energy is re-radiated at far infrared wavelengths. The ISM can be cooled if collisional heating of the dust is significant, which removes the gravitational energy of collapsing clouds, allowing star-formation.
- By shielding the UV radiation that causes molecular dissociation, the dust provides formation sites for \( \text{H}_2 \), the fuel for star formation. The molecule’s formation involves catalytic reactions on the surface of interstellar grains.
- AGN central engines can be completely obscured by the dust in the visible part of the spectrum, and the dust cloud geometry can collimate the accretion disk radiation, for example, the dusty torus of the Unified AGN Model.

Extinction is measured as the reduction in flux in the optical (V) spectral region (i.e. at an effective wavelength of 550 nm) in magnitudes, \( A_V \). The reddening, \( E(B-V) \), is either measured directly or derived from other observations, and is related to \( A_V \) by the total to selective extinction ratio \( R_V \):

\[ A_V = E(B-V) \times R_V \]  

From Cardelli et al. (1989), the empirical relations between the extinction at any wavelength \( \lambda \) and \( A_V \) is:

\[ A_\lambda/A_V = a(x) + b(x)/R_V \]
where, for infrared and optical wavelengths (where $x = 1/\lambda$ in $\mu$m):

Infrared — $900 \leq \lambda \leq 3300$ nm

\begin{align*}
a(x) &= 0.547x^{1.61} \\
b(x) &= -0.527x^{-1.61}
\end{align*}

Optical — $300 \leq \lambda \leq 900$ nm

\begin{align*}
y &= x - 1.82 \\
a(x) &= 1 + 0.17699y - 0.50447y^2 - 0.02427y^3 \\
&\quad + 0.72085y^4 + 0.01979y^5 - 0.7753y^6 + 0.32999y^7 \\
b(x) &= 1.41338y + 2.28305y^2 + 1.07223y^3 \\
&\quad - 5.38434y^4 - 0.62251y^5 + 5.3026y^6 - 2.09002y^7
\end{align*}

Emission line pairs at wavelengths $\lambda_1, \lambda_2$ with known flux ratios can be used to compute the extinction from the above equations, where, in general, the formula is as follows:

\[
A_V = -2.5 \times \log \left( \frac{[f(\lambda_1)/f(\lambda_2)]_O}{[f(\lambda_1)/f(\lambda_2)]_T} \right)
\]

where $[f(\lambda_1)/f(\lambda_2)]_O$ is the observed flux ratio and $[f(\lambda_1)/f(\lambda_2)]_T$ is the theoretical ratio. This equation reduces to:

\[
E_{B-V} = \alpha_{\lambda_1, \lambda_2} \log \left( \frac{R_{\lambda_1, \lambda_2}}{F_{\lambda_1}/F_{\lambda_2}} \right)
\]

where $R_{\lambda_1, \lambda_2}$ is the intrinsic emissivity ratio of the two lines and $\alpha_{\lambda_1, \lambda_2}$ extrapolates from the emission line wavelengths to $B-V$. From the Cardelli et al. (1989) reddening law, a value of $R_V = 3.1$ is used, the standard value for the diffuse ISM. From infrared and visual observations, there are several methods of deriving the extinction; the ratios between the several hydrogen recombination lines, and between the $[\text{Fe II}]$ emission lines at $\lambda = 1257$ nm and 1644 nm. The values of $\alpha_{\lambda_1, \lambda_2}$ and $R_{\lambda_1, \lambda_2}$ are given in Table 2.3 below for the individual line ratios.

The flux ratios for H$\alpha$, H$\beta$, Pa$\beta$, Pa$\gamma$ and Br$\gamma$ are determined by case B recombination and assuming an electron temperature $T_e = 10^4$ K and a density $n_e = 10^3$ cm$^{-3}$ (Hummer & Storey, 1987). The intrinsic flux ratio is a weak function of both temperature and density. Over a range $5,000 < T_e < 10,000$ K and $100 < n_e < 1000$ cm$^{-3}$, this varies by only 5%.
As the [Fe II] lines 1644 nm and 1257 nm share the same upper level, $a^4D \rightarrow a^6D$ and $a^4D \rightarrow a^4F$, respectively, their ratio is a function purely of the transition probabilities and wavelengths, i.e.

$$F(1257 \text{ nm})/F(1644 \text{ nm}) = A(1257 \text{ nm})/A(1644 \text{ nm}) \times 1644/1257$$  \hspace{1cm} (2.20)

where $A(\lambda)$ is the Einstein coefficient for the transition. From the NIST Atomic Spectra Database (Kramida et al., 2016), $A(1257 \text{ nm}) = 4.7 \times 10^{-3}$ and $A(1644 \text{ nm}) = 6.0 \times 10^{-3}$, giving an expected flux ratio of 1.03.

The values of intrinsic emissivity ratio of the two [Fe II] emission lines from the literature are discrepant; a value 1.36 is derived from Nussbaumer & Storey (1988) Einstein coefficients, while the values from Quinet et al. (1996), give a value to 1.03, which decreases the derived $E_{B-V}$ value by 1 mag and the $A_V$ value by about 3 mag (see further discussion in Koo et al., 2016; Hartigan et al., 2004; Smith & Hartigan, 2006). From Herbig-Haro 1 nebula observations, Bautista & Pradhan (1998) derived a value of 1.34. Smith & Hartigan (2006) in fact derive a ratio of 1.49 from measurements of [Fe II] emission lines around P Cygni, and specifically excluded the Quinet et al. (1996) value. This work will use the value of 1.36; using the 1.03 value usually makes the extinction derived from observation unphysical (i.e. less than 0) over the whole field.

**Table 2.3: Extinction calculation parameters for Equation 2.19.**

<table>
<thead>
<tr>
<th>Spectral Lines</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>$\alpha_{\lambda_1,\lambda_2}$</th>
<th>$R_{\lambda_1,\lambda_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa β–Br γ</td>
<td>1282.2</td>
<td>2166.1</td>
<td>5.22</td>
<td>5.88</td>
</tr>
<tr>
<td>[Fe II]</td>
<td>1256.7</td>
<td>1643.6</td>
<td>8.21</td>
<td>1.36 (1.03)</td>
</tr>
<tr>
<td>Pa γ–Pa β</td>
<td>1094.1</td>
<td>1282.2</td>
<td>10.32</td>
<td>0.55</td>
</tr>
<tr>
<td>Pa α–Br γ</td>
<td>1875.6</td>
<td>2166.1</td>
<td>26.55</td>
<td>12.15</td>
</tr>
<tr>
<td>H α–H β</td>
<td>656.3</td>
<td>486.1</td>
<td>2.33</td>
<td>2.86</td>
</tr>
</tbody>
</table>

Given the visual extinction, the flux at any infrared wavelength can be corrected as follows:

$$R_\lambda = 0.404 \times \left(\frac{\lambda}{1000}\right)^{-1.61}$$  \hspace{1cm} (2.21)

$$C = 10^{(0.4\times R_\lambda \times A_v)}$$  \hspace{1cm} (2.22)

$$F_T(\lambda) = F_O(\lambda) \times C$$  \hspace{1cm} (2.23)

where $R_\lambda$ is the Cardelli law relationship (with $R_V = 3.1$) and $F_O$ and $F_T$ are the observed and de-reddened (‘true’) flux values.
2.6. Physical Parameters

The Milky Way extinction for an object (from NED, Schlafly & Finkbeiner, 2011) is subtracted from the derived extinction to get the ‘true’ extinction (i.e. that due to the source).

The full treatment of stellar extinction requires stellar population synthesis, e.g. the STARLIGHT code of Cid Fernandas et al. (2005), which fits the continuum (excluding emission lines) by a combination of single stellar population (SSP) models, combined with an extinction model and, optionally, black-body (for warm dust) and power-law (for AGN featureless continuum) models. In lieu of this full treatment, and assuming a single stellar population in the field of view, an indication of the relative extinction can be derived by fitting a simple linear function to the continuum (masking out emission lines and regions of poor telluric correction); the slope will be shallower for higher extinction.

Extinction measures derived from emission lines are usually higher than those for stellar populations; Calzetti et al. (1994) found that Hβ/Hα extinction was a factor of 2 higher than the continuum extinction, due to hot stars being associated with dusty regions. Riefler et al. (2006), in the 0.8-2.4 μm atlas of AGNs, demonstrated poor correlation between the total extinction derived from [Fe II] and that from H I ratios, especially for starburst galaxies. Another consideration is that the emission lines arise within the obscuring material and therefore do not probe the full dust column.

2.6.3 Gas Emission

2.6.3.1 Gas Masses

The cold gas column density can be derived from the visual extinction value. The gas-to-extinction ratio, \( N_H/A_V \), varies from 1.8 (Predehl & Schmitt, 1995) to \( 2.2 \times 10^{21} \text{ cm}^{-2} \) (Ryter, 1996). Zhu et al. (2017) finds the Milky Way ratio for solar abundances to be \( \sim 2.1 \times 10^{21} \text{ cm}^{-2} \); this increases to \( \sim 2.5 \times 10^{21} \text{ cm}^{-2} \) for sub-solar abundances. We will use a value of \( 2.0 \times 10^{21} \text{ cm}^{-2} \). Using an average atomic/molecular weight of 1.4, we thus derive the relationship:

\[
\sigma_{\text{Gas}} = 22.1 \ A_V \ M_\odot \ pc^{-2}
\]  

(2.24)

We also derive the ionized hydrogen and warm/hot and cold H₂ gas masses, using the formulae from Riefler et al. (2013b, 2015):

\[
M_{\text{HII}} \approx 3 \times 10^{17} F_{\text{Brγ}} D^2 \ M_\odot
\]  

(2.25)

\[
M_{\text{H}_2(\text{hot})} \approx 5.0776 \times 10^{13} F_{\text{H}_2} D^2 \ M_\odot
\]  

(2.26)
Chapter 2. Observations, Data Reduction and Analysis Methodologies

\[
M_{H_2}(\text{cold}) \approx R \frac{L_{H_2}}{L_{\odot}} \frac{M_{\odot}}{D^2} \\
\approx 3.12 \times 10^{16} R F_{H_2} \text{ erg cm}^{-2} \text{s}^{-1}
\]

where \(D\) is the distance in Mpc and \(F\) is measured in erg cm\(^{-2}\) s\(^{-1}\). The constant \(R\) is given variously as 1174 (Mazzalay et al., 2013b) for 6 local galaxies, or 4000 (Muller Sánchez et al., 2006) from 17 LIRG/ULIRG galaxies, which gives \(M_{\text{Cold}}/M_{\text{Warm}}\) as \(7.2 \times 10^5\) and \(2.7 \times 10^6\), respectively. We will use the value of \(R = 1174\). For the Br\(\gamma\) emission, a standard electron temperature \(T = 10^4\) K and density \(n_e = 100\) cm\(^{-3}\) is assumed.

The \(H_2\) flux is that of the 2121 nm line. The cold-to-warm molecular gas mass ratio \((7.2 \times 10^5)\) is originally derived in Mazzalay et al. (2013b) from the observed CO radio emission with estimates of CO/\(H_2\) ratios (which can vary over a range \(10^5\) to \(10^7\)). At the centers of galaxies hosting AGN, this ratio could be substantially overestimated, as a greater proportion of the gas will be excited.

### 2.6.3.2 Star Formation

Star formation can be traced by the presence of hot O- and B-type stars, which emit copious UV radiation, ionising the atomic hydrogen in the vicinity. Star formation rates (SFR) can estimated using relationship between SFR and hydrogen recombination lines from Kennicutt et al. (2009), which is regarded as an ‘instantaneous’ trace of star formation, as the O- and B-type stars evolve rapidly. Assuming Case B recombination at an electron temperature \(T_e = 10^4\) K and a density \(n_e = 10^3\) cm\(^{-3}\) and applying the line-strength ratios from Hummer & Storey (1987), we get:

\[
SFR \ (M_\odot \ yr^{-1}) = 7.9 \times 10^{-42} L(H\alpha) \\
= 5.66 \times 10^{-40} L(\text{Br}\gamma) \\
= 1.40 \times 10^{-40} L(\text{Pa}\beta)
\]

where the luminosity values \(L\) are erg s\(^{-1}\). The Br\(\gamma\) measurement has the advantage that it requires minimal or no correction for extinction.

The Br\(\gamma\) and Pa\(\beta\) equivalent widths can be used to estimate the age of a star-burst, using the STARBURST99 models of Leitherer et al. (1999). These produce EW data for a range of metallicities and initial mass functions; all showing a static EW until about 3–5 Myr, then a rapid decrease to about 10 Myr. An example for instantaneous SF, an IMF power law index \(\alpha = 2.35\) and a mass upper limit of 100 M\(\odot\) is shown in Fig. 2.5, with a range metallicities \(Z = 0.008\) (sub-solar), 0.02 (solar) and 0.04 (super-solar). The ratio of
2.6. Physical Parameters

Figure 2.5: Age - Br $\gamma$ and pab EW diagram example with instantaneous SF, $\alpha = 2.35$ and $M_{\text{up}} = 100 M_\odot$. The range of metallicity values are given in the key.

H I to He I emission can be used as an indicator of relative age of star clusters, following Böker et al. (2008); as the He I ionization energy is 24.6 eV vs. 13.6 eV for hydrogen, the He I emission will arise in the vicinity of the hotter stars (B- and O-type), which will vanish fastest.

We can also derive the Lyman continuum flux and the number of O-type stars from the Br $\gamma$ flux using the scaling relationships cited in Brandl et al. (2012), derived from Ho et al. (1990):

$$N_{Lyc} = 8.7 \times 10^{57} F_{Br\gamma} D^2$$

(2.31)

$$\log(N_{O7V}) = \log(N_{Lyc}) - 48.75$$

(2.32)

where $N_{Lyc}$ is the number of Lyman continuum photons, $N_{O7V}$ is the number of O7-type stars, $D$ is the galaxy distance in Mpc and $F_{Br\gamma}$ is the Br $\gamma$ flux in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

Star formation rates can also be compared between various indicators, including radio, UV, mid and far infrared and X-rays. The indicators from the review by Brown et al. (2017) will be used in this thesis, unless otherwise noted.

Line-ratio diagnostics must be used to determine if hydrogen recombination emission lines at a particular locus are being excited by star formation or other mechanism (e.g. AGN radiation - see Section 2.6.4).
2.6.3.3 Supernovae

Rosenberg et al. (2012) presents a formula for the supernova rate, based on the measured \([\text{Fe II}] \, 1257\, \text{nm} \) flux. Supernova remnant shock fronts destroy dust grains by thermal sputtering, which releases the iron into the gas phase where it is singly ionized by the interstellar radiation field (Graham et al., 1987). In the extended post-shock region, \([\text{Fe II}] \) is excited by electron collisions (Mouri et al., 2000), making it a strong diagnostic line for tracing shocks. The relationship is:

\[
\log(\nu_{\text{SNR}}) = (1.01 \pm 0.2) \log(L_{[\text{Fe II}]1257}) - 41.17 \pm 0.9 \quad (2.33)
\]

where the rate \(\nu_{\text{SNR}}\) is in units of \(\text{yr}^{-1}\, \text{pc}^{-2}\) and the surface luminosity \(L\) is in units of erg \(\text{s}^{-1}\, \text{pc}^{-2}\). The presence of any AGN outflow shocks will, of course, reduced the derived rate.

2.6.4 Gas Excitation

Excitation mechanisms broadly falls into two categories (1) photo-ionization by a central, spectrally hard radiation field (from an AGN accretion disk) or by young, hot stars (UV ionization and recombination or collisional heating) or (2) thermal heating, which can be either by shocks (from AGN outflows, supernova remnants, star formation, AGB winds or radio jet interaction) or UV/X-ray heating of gas masses. \(\text{H}_2\) is also excited by UV pumping and fluorescence (Black & van Dishoeck, 1987). The emission line spectra flux ratios enable determination of the particular or mixture of mechanisms.

Of course, any one object will have a mixture of all these mechanisms, both over the whole object and region-by-region. Emission line flux ratios in any one parcel of gas are dependent on metallicity, temperature, density and excitation photon flux from star formation and evolutionary processes, plus the AGN engine energetics. Observationally, these fluxes are also dependent on the sum over the LOS of emission from different gas parcels (e.g. \(\text{H}_2\) in a nuclear disk, \([\text{Fe II}]\) jacketing outflows which are filled with ionized hydrogen and high-excitation metal species), plus observational uncertainties. The spread of pixels in the diagnostic diagram reflects these factors. For example Davies et al. (2017) for NGC 613 found that each spaxel’s emission line luminosities were consistent with a linear superposition of 3 basis spectra, one each of star forming, AGN and pure shock.
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2.6.4.1 Nuclear Activity Diagnostics

Nuclear activity for NIR emission line objects can be categorized by a diagnostic diagram (Larkin et al., 1998; Rodríguez-Ardila et al., 2005), where the log of the flux ratio of \( \text{H}_2/\text{Br}\gamma \) is plotted against that of \([\text{Fe II}] (1257 \text{ nm})/\text{Pa}\beta \). This is analogous to the BPT diagrams (Baldwin et al., 1981) commonly used in the optical regime (e.g. Kewley et al., 2006). Following the updated limits from Riffel et al. (2013a), the diagram is divided into three regimes for star-forming (SF) or starburst (SB), AGN and low-ionization nuclear emission line region (LINER) excitations, as set out in Table 2.4. Other objects outside these regimes are designated as ‘transition objects’ (TO). The diagnostic emission lines

<table>
<thead>
<tr>
<th>Excitation Mode</th>
<th>( \text{H}_2/\text{Br}\gamma )</th>
<th>([\text{Fe II}] 1257 \text{ nm}/\text{Pa}\beta )</th>
<th>([\text{Fe II}] 1644 \text{ nm}/\text{Br}\gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF/SB</td>
<td>&lt; 0.4</td>
<td>&lt; 0.6</td>
<td>&lt; 2.6</td>
</tr>
<tr>
<td>AGN</td>
<td>0.4 – 6</td>
<td>0.6 – 2</td>
<td>2.6 – 8.6</td>
</tr>
<tr>
<td>LINER</td>
<td>&gt; 2</td>
<td>&gt; 2</td>
<td>&gt; 8.6</td>
</tr>
</tbody>
</table>

are convenient; the pairs are close together in wavelength, removing the dependency on calibration accuracy and differential extinction. The table has been supplemented with the expected ratio regimes for \([\text{Fe II}] 1644 \text{ nm}/\text{Br}\gamma \) for \( H \) and \( K \) combined spectra, taking the ratios \( \text{Pa}\beta/\text{Br}\gamma = 5.88 \) and \([\text{Fe II}] 1257/1644 \text{ nm} = 1.36 \). If this ratio is used, the fluxes must be corrected for extinction.

In several examples, the excitation plot shows medium to strong correlations between the two sets of line ratios; this is seen in both the total nuclear spectrum of active galaxies (Larkin et al., 1998; Riffel et al., 2013a) as well as on a spaxel-by-spaxel basis (Colina et al., 2015, also see Chapter 4) . This indicates that the excitation mode can be reasonably well deduced with an observation in only one filter. The diagnostic diagrams requires the production of four sets of flux maps, alignment and scaling (if required) of the flux ratio maps, then smoothing to remove pixellation.

For optical observations, the updated BPT diagrams (Kewley et al., 2006) are used to diagnose the excitation modes; this uses ratios of \([\text{N II}]/H\alpha \), \([\text{S II}]/H\alpha \) and \([\text{O I}]/H\alpha \) vs. \([\text{O III}]/H\beta \) to separate \( \text{H II} \), AGN and composite excitations, and to further divide AGN into Seyfert and LINER modes. The regions on these diagrams are not simple rectangles, but are parameterized curves (see Kewley et al., 2006).
2.6.4.2 Molecular Hydrogen

Molecular hydrogen (H$_2$) is very important in the star-formation context of AGN activity, since it is the basic building block for stars. In the $K$ band, there are a whole series of rotational-vibrational emission lines, which can be used to examine the excitation mechanism for H$_2$, which can be either:

- UV photons (fluorescence) from star formation and/or AGN continuum emission (Black & van Dishoeck, 1987).
- Shocks from supernovae, AGN outflows or star-formation winds (Hollenbach & McKee, 1989).
- X-rays from the AGN irradiating and heating dense gas (Maloney et al., 1996).

In reality, all these different mechanisms occur together; however, the dominating mechanism can be estimated and the contributing fractions of different mechanisms can be constrained (Busch et al., 2017).

Following the method outlined in Wilman et al. (2005), for gas with density $n_T > 10^5$ cm$^{-3}$, the thermal (collisional) temperatures can be estimated. The occupation numbers of the excited ro-vibrational levels of the H$_2$ molecule will be in thermal equilibrium at a temperature $T_{exc}$ equal to the kinetic temperature of the gas. This leads to the relationship:

$$\ln \left( \frac{F_i \lambda_i}{A_i g_i} \right) = \text{constant} - \frac{T_i}{T_{exc}}$$

where $F_i$ is the flux of the $i$th H$_2$ line, $\lambda_i$ is its wavelength, $A_i$ is the spontaneous emission coefficient, $g_i$ is the statistical weight of the upper level of the transition and $T_i$ is the energy of the level expressed as a temperature. The left-hand side of this equation is equivalent to $\ln(N_{upper})$, the occupation number of the upper level of the H$_2$ transition. This relation is valid for thermal excitation, under the assumption of an ortho:para abundance ratio of 3:1. The $A_i$, $g_i$ and $T_i$ for each line was obtained from on-line data ‘Molecular Hydrogen Transition Data’.$^{17}$ A list of the relevant H$_2$ lines in the $K$ band is given in Table 2.5. The last column shows the expected flux ratio of the line vs. the 2121.8 nm line, for thermal equilibrium at 2000 K. At a particular location, plotting $\ln(N_{upper})$ vs. $T_i$ gives a linear relationship, where the negative inverse slope is the excitation temperature $T_{exc}$. Departures from linearity can be attribute to several causes:

- If the plot shows separate linear relationships for the lower-excitation (i.e. the $\nu = 1-0$) transitions vs. the higher-excitation ($\nu = 2-1$ and $\nu = 3-2$) transitions, this

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$^{17}$www.astronomy.ohio-state.edu/~depoy/research/observing/molhyd.htm
### Table 2.5: $K$ band $H_2$ transition lines

<table>
<thead>
<tr>
<th>Transition</th>
<th>$\lambda$ (nm)</th>
<th>$g$</th>
<th>$E_{\text{upper}}$ ($K_{T_i}$)</th>
<th>$A \times 10^{-7}$ s</th>
<th>$F/F_{2121}$ @2000 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1 S(5)</td>
<td>1944.9</td>
<td>45</td>
<td>15763</td>
<td>5.05</td>
<td>0.042</td>
</tr>
<tr>
<td>1-0 S(3)</td>
<td>1957.6</td>
<td>33</td>
<td>8365</td>
<td>4.21</td>
<td>1.022</td>
</tr>
<tr>
<td>1-0 S(2)</td>
<td>2033.8</td>
<td>9</td>
<td>7584</td>
<td>3.98</td>
<td>0.375</td>
</tr>
<tr>
<td>2-1 S(3)</td>
<td>2073.5</td>
<td>33</td>
<td>13890</td>
<td>5.77</td>
<td>0.083</td>
</tr>
<tr>
<td>1-0 S(1)</td>
<td>2121.8</td>
<td>21</td>
<td>6956</td>
<td>3.47</td>
<td>1.000</td>
</tr>
<tr>
<td>2-1 S(2)</td>
<td>2154.2</td>
<td>9</td>
<td>13150</td>
<td>5.6</td>
<td>0.031</td>
</tr>
<tr>
<td>3-2 S(3)</td>
<td>2201.4</td>
<td>33</td>
<td>19086</td>
<td>5.63</td>
<td>0.006</td>
</tr>
<tr>
<td>1-0 S(0)</td>
<td>2223.5</td>
<td>5</td>
<td>6471</td>
<td>2.53</td>
<td>0.211</td>
</tr>
<tr>
<td>2-1 S(1)</td>
<td>2247.7</td>
<td>21</td>
<td>12550</td>
<td>4.98</td>
<td>0.083</td>
</tr>
<tr>
<td>3-2 S(2)</td>
<td>2287.0</td>
<td>9</td>
<td>18386</td>
<td>5.63</td>
<td>0.002</td>
</tr>
<tr>
<td>1-0 Q(1)</td>
<td>2406.6</td>
<td>9</td>
<td>6149</td>
<td>4.29</td>
<td>0.699</td>
</tr>
<tr>
<td>1-0 Q(2)</td>
<td>2413.4</td>
<td>5</td>
<td>6471</td>
<td>3.03</td>
<td>0.233</td>
</tr>
<tr>
<td>1-0 Q(3)</td>
<td>2423.7</td>
<td>21</td>
<td>6956</td>
<td>2.78</td>
<td>0.701</td>
</tr>
</tbody>
</table>

indicates that there is a component of much hotter gas close to the $H_2$ dissociation temperature of $\sim$ 4000 K.

- The gas density is not high enough ($n_T > 10^5 cm^{-3}$ - the critical density for these transitions) to reach collisional excitation equilibrium; the gas is being heated by non-thermal fluorescent emission (Davies et al., 2003, 2005).

- Non-thermal emission due to excitation of the molecule by secondary electrons deep in the cloud.

The $H_2$ 2-1 S(3) (2073.5 nm) is diagnostic for X-ray excitation, which is expected to suppress the line, as the upper level of this transition is depopulated by a resonance with photons around the wavelength of Ly-$\alpha$ at 1216 Å, which are readily generated by X-ray heating (Black & van Dishoeck, 1987; Krabbe et al., 2000; Davies et al., 2005).

The flux ratio for the 2–1 S(1) (2247.7 nm) and 1–0 S(1) (2121.8 nm) lines is diagnostic for excitation by soft-UV photons (from star formation) vs. thermal processes (from shocks or X-ray heating), with a value of $\sim 0.1 - 0.2$ for thermal and $\sim 0.55$ for fluorescent processes (Mouri, 1994).

Independently, the rotational and vibrational temperatures can be determined from two ortho/para lines that belong to the same vibrational level, e.g. 1–0 S(0) (2223.5 nm) and 1–0 S(2) (2033.8 nm), whereas the vibrational excitation temperature can be determined by connecting two transitions with same J but from consecutive $\nu$ levels, e.g. 2–1 S(1) (2247.7 nm) and 1–0 S(1) (2121.8 nm) (Riffel et al., 2014b; Busch et al., 2017).
Chapter 2. Observations, Data Reduction and Analysis Methodologies

The formulas are:

\[
T_{\text{rot}(\nu=1)} = \frac{1113K}{1.130 + \ln \left( \frac{F_{1-0S(0)}}{F_{1-0S(2)}} \right)} \tag{2.35}
\]

\[
T_{\text{vib}} = \frac{5594K}{0.304 + \ln \left( \frac{F_{1-0S(1)}}{F_{2-1S(1)}} \right)} \tag{2.36}
\]

If the two temperatures are at variance, this indicates the gas is not in local thermodynamic equilibrium (LTE). Mouri (1994) presented a graphical method to determine the excitation temperature and mechanism, by plotting the two sets of ratios above, with the loci of excitation models; thermal (UV, X-ray, shock) and non-thermal (pure fluorescence). The plot template is shown in Fig. 2.6 (after Mouri, 1994; Krabbe et al., 2000), which also shows the line for LTE, with the temperatures marked along the trajectory.

The excitation mechanisms and observations on molecular hydrogen in AGN are further discussed in Mouri (1994); Krabbe et al. (2000); Rodríguez-Ardila et al. (2004a, 2005); Wilman et al. (2005); Storchi-Bergmann et al. (2009); Riffel et al. (2013a, 2014b); Davies et al. (2005); Smajić et al. (2015) and Mazzalay et al. (2013b).

2.6.4.3 [Fe II] Diagnostics

Iron (Fe) is abundant in astrophysical environments. The forbidden lines ([Fe II]) are the strongest low-ionisation metal lines in the NIR. Iron is bound up in dust grains and is released by sputtering from supernova or other shocks (Mouri et al., 2000). This is then excited by electron collisions in partially-ionized hydrogen zones. The ionization potential (IP) for \(Fe \rightarrow Fe^+\) is 7.9 eV vs. 13.6 eV for hydrogen; however \(Fe^+ \rightarrow Fe^{2+}\) is 16.2 eV, which means that Fe\(^+\) will not survive in a fully-ionized zone.

The partially-ionized zones are created by either power-law photo-ionization (where the electron temperature \(T_e \approx 8000\) K) or by shocks \((T_e \approx 6000\) K). The sequence of [Fe II] emission lines are mainly in the J and H bands from the \(a^4D, a^4F\) and \(a^6D\) levels; the most prominent lines are at 1256.7 nm \((a^4D \rightarrow a^4F)\) and 1643.6 nm \((a^4D \rightarrow a^6D)\). These sets of transitions are forbidden, i.e. the are not allowed by the usual quantum-mechanical selection rules, but are allowed via electric quadrupole or magnetic dipole transitions in low-density astrophysical gases. As mentioned above the 1257 nm and 1644 nm flux ratios can be used to derive the extinction.

The [Fe II] and [P II] 1188.6 nm emission lines can be used to diagnose the relative contribution of photo-ionization and shocks (Oliva et al., 2001; Storchi-Bergmann et al.,
2.6. Physical Parameters

Figure 2.6: $H_2$ excitation diagram, after Mouri (1994) and Krabbe et al. (2000). The secondary $x$ and $y$ axes show the equivalent $T_{vib}$ and $T_{rot}$ for the line ratios.

2009), where ratios $\sim 2$ indicate photo-ionization (as the [Fe II] is locked into dust grains), with higher values indicating shocked release of the [Fe II] from the grains (up to 20 for SNRs).

We can determine the electron density from the methods described in Storchi-Bergmann et al. (2009), by measuring the ratios of $H$-band emission lines for [Fe II] 1533/1644, 1600/1644, 1664/1644 and/or 1677/1644 nm. This plots the ratio against models of electron density and temperature. Above 1000 K, the ratio is relatively insensitive to temperature. Linear approximations for log($n_e$) are given for the [Fe II] line ratios over the range $n_e = 3 \times 10^3 - 8 \times 10^4$ cm$^{-3}$ from Koo et al. (2016), valid over a given flux ratio.

2.6.4.4 Other Emission Line Diagnostics

The ‘coronal’ lines are forbidden transitions with large ionization states, so called as they were first observed in the Solar corona. Their high ionization potential ($\geq 100$ eV) indicates that they are photoionized by soft X-rays (100–400 eV) from the AGN or are heated by fast shocks ($\geq 10^6$ K). The lines observed are [Si VI] (1964 nm – 167 eV), [Ca VIII] (2321
nm – 127 eV), [S IX] (1252 nm – 329 eV) and [Al IX] (2045 nm – 285 eV), and are thought to be associated with outflows in a coronal-line region (CLR), between the BLR and NLR.

The atomic structure of He I makes it a unique astrophysical tool. The 2s level of the triplet state is metastable with a lifetime of 2 hr, and it acts as a second ground state. The 2s level lies 19.75 eV above the ground state, and so it is populated by recombination. It is depopulated predominantly by collisions in photoionized gas. Although helium is abundant in astronomical gas, He I* is rare. One of every ~175,000 He+ ions is He I* in a typical plasma (Clegg, 1987). The emission line at 1083.0 nm (2s → 2p) can be the strongest line in the whole NIR spectrum. This can be used as a tracer of gas with high electron excitation temperature, i.e. close to the AGN.

Other optical emission line flux ratios can be used to estimate the electron temperature and density:

\[
R_O = \frac{I(\lambda 4949 + \lambda 5007)}{I(\lambda 4363)} \quad ([\text{O III}]) \quad (2.37)
\]
\[
R_N = \frac{I(\lambda 6548 + \lambda 6584)}{I(\lambda 5754)} \quad ([\text{N II}]) \quad (2.38)
\]
\[
R_S = \frac{I(\lambda 6717)}{I(\lambda 6731)} \quad ([\text{S II}]) \quad (2.39)
\]
\[
T_e = \frac{32900}{\ln\left(\frac{7.9}{R_O}\right)} \quad \text{(Kwok, 2007)} \quad (2.40)
\]
\[
T_e = \frac{25000}{\ln\left(\frac{8.3}{R_N}\right)} \quad \text{(Osterbrock & Ferland, 2006)} \quad (2.41)
\]
\[
N_e = 10^2 T_e \left( \frac{R_S - 1.49}{5.62 - 12.8 R_S} \right) \quad \text{(Acker & Jaschek, 1986)} \quad (2.42)
\]

where \( R_X \) is the flux ratio for the particular species. The temperature methods for the [O III] and [N II] flux ratios (Equations 2.40 and 2.41) are given as alternatives if one set is unmeasurable; they also do not include a term in \( N_e / \sqrt{T_e} \), which is negligible in these environments.

2.6.5 SMBH/Enclosed Mass Estimation

2.6.5.1 Velocity Profile Methods

If the stellar (or gas) velocity field shows ordered rotation, it can be used to estimate the enclosed mass, within the resolution constraints of the data. The simplest form for the velocity field is the Plummer model (Plummer, 1911) (see e.g. Riffel & Storchi-Bergmann,
2.6. Physical Parameters

\[ V_{LOS} = V_{Sys} + \sqrt{\frac{R^2GM}{(R^2 + A^2)^{3/2}}} \left[ \sin(i) \cos(\Psi - \Psi_0) \right] \]

\[ \cos^2(\Psi - \Psi_0) + \frac{\sin^2(\Psi - \Psi_0)^{3/2}}{\cos^2(i)} \]

(2.43)

where \( V_{LOS} \) and \( V_{Sys} \) are the observed line of sight and systemic velocities, \( R \) is the projected distance from the nucleus, \( \Psi \) is the position angle, \( \Psi_0 \) is position angle of the line of nodes, \( G \) is the gravitational constant, \( A \) is the scale length, \( i \) is the disk inclination (\( i=0 \) for face-on) and \( M \) is the enclosed mass. Including the location of the kinematic center, this equation has 6 free parameters. The kinematic center and line of nodes can be well-constrained from the observations. Standard techniques (e.g. Levenberg-Marquardt least-squares fitting algorithm) are used to solve for the parameters. Residuals from this model fit for gas can be a signature of non-rotation flows, i.e. inflow or outflow.

For a simple velocity profile, the standard Keplerian rotation (and the equivalent in astrophysical units) is given by Equations 2.44 and 2.45. Solving for the Plummer profile with \( \Psi = 0^\circ \) and \( i = 0^\circ \) at the scale length \( A \) gives a modified function Equations 2.46 and 2.47).

\[ M = \frac{R V^2}{G} \]

\[ M \ [M_{\odot}] = 232.8 \times R \ [pc] \ V^2 \ [km \ s^{-1}] \] \ (2.44)

\[ M = \frac{A V^2 R^{3/2}}{G} \]

\[ M \ [M_{\odot}] = 658.5 \times A \ [pc] \ V^2 \ [km \ s^{-1}] \] \ (2.45)

where \( R \) is half the peak-to-peak distance and \( V \) is half the peak-to-peak velocity difference.

2.6.5.2 The \( M - \sigma \) Relationship

The SMBH mass estimation can be derived from the stellar velocity dispersion (the \( M - \sigma \) relationship). The general form for the relationship (and the corresponding error equation), with the dispersion \( \sigma \) measured in km s\(^{-1}\) and with a systematic error \( \epsilon \) is:

\[ \log(M_{BH}) = \alpha + \beta \log\left(\frac{\sigma}{200}\right) \]

\[ \Delta \log(M_{BH})^2 = \log\left(\frac{\sigma}{200}\right)^2 \Delta \beta^2 + \Delta \alpha^2 + \left(\frac{\beta}{\ln(10)}\right)^2 \left(\frac{\Delta \sigma}{\sigma}\right)^2 + \epsilon^2 \]

(2.48) \ (2.49)

The parameters are given in Table 2.6 for several references and applicabilities.
2.6.5.3 Other Methods

There are other relationships between galaxy parameters and SMBH mass, e.g. $K$-band luminosity or Sérsic index; these can be used to cross-check results.

The $K$-band bulge luminosity relationship ($M - L_{K, sph}$) is of the form:

$$\log(M_{BH}) = (\alpha \pm \Delta \alpha) + (\beta \pm \Delta \beta) \log(M \pm \Delta M + \gamma) \pm \epsilon \quad (2.50)$$

$$\Delta \log(M_{BH})^2 = (M + \gamma)^2 \Delta \beta^2 + \Delta \alpha^2 + \beta^2 \Delta M^2 + \epsilon^2 \quad (2.51)$$

where $M$ is the absolute $K_S$ magnitude of the bulge (usually measured from the 2MASS image).

The Sérsic index ($n$) is fitted to the light profile, and has the scaling relationship (Savorgnan et al., 2013):

$$\log(M_{BH}) = \alpha + \beta \log\left(\frac{n}{3}\right) \quad (2.52)$$

$$\Delta \log(M_{BH})^2 = \log\left(\frac{n}{3}\right)^2 \Delta \beta^2 + \Delta \alpha^2 + \left(\frac{\beta}{\ln(10)}\right)^2 \frac{\Delta n}{n}^2 + \epsilon^2 \quad (2.53)$$

The spiral arm pitch angle is related to the SMBH mass in the form

$$\log(M_{BH}) = \alpha - \beta \left[|\phi| - \gamma^\circ\right] \quad (2.54)$$

where $\phi$ is the spiral pitch angle and $\gamma$ is the zero intercept of the relationship (both in degrees).

2.6.5.4 Black Hole Sphere of Influence

The ‘sphere of influence’ of a SMBH (i.e. the volume of space over which the gravity of the SMBH dominates those of the stars) is given by the formula:

$$R_I = \frac{GM_*}{\sigma^2} \quad (2.55)$$

$$R_I(\text{pc}) = 4.305 \times 10^5 \frac{M_* [10^8 M_\odot]}{\sigma^2 [\text{km s}^{-1}]} \quad (2.56)$$

For example, for a SMBH of $M_* = 10^8 M_\odot$ and a stellar velocity dispersion 150 km s$^{-1}$, the sphere of influence is $\sim 18$ pc.
### Table 2.6: Parameter values for Equations 2.48 to 2.54

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Application</th>
<th>$\alpha$</th>
<th>$\Delta \alpha$</th>
<th>$\beta$</th>
<th>$\Delta \beta$</th>
<th>$\epsilon$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graham et al. (2011)</td>
<td>Elliptical Galaxies</td>
<td>8.27</td>
<td>0.06</td>
<td>4.43</td>
<td>0.57</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>McConnell &amp; Ma (2013)</td>
<td>$\sigma \leq 200$ km s$^{-1}$</td>
<td>8.35</td>
<td>0.15</td>
<td>5.66</td>
<td>0.85</td>
<td>0.43</td>
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</tr>
<tr>
<td>Kormendy &amp; Ho (2013)</td>
<td>Core-Sérsic</td>
<td>8.5</td>
<td>0.049</td>
<td>5.42</td>
<td>0.294</td>
<td>0.28</td>
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<tr>
<td>Graham &amp; Scott (2013)</td>
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<td>0.92</td>
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</tr>
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<td>-0.44</td>
<td>0.08</td>
<td>0.44</td>
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</tr>
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<td>Savorgnan et al. (2013)</td>
<td>Sérsic bulges</td>
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<td>0.12</td>
<td>4.11</td>
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<td>2.23</td>
<td>1.50</td>
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<tr>
<td>Davis et al. (2017)</td>
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<td>0.07</td>
<td>0.171</td>
<td>0.017</td>
<td>0.30</td>
<td>15</td>
</tr>
</tbody>
</table>

#### 2.6.5.5 Bolometric Luminosity and Eddington Ratios

The total (bolometric) luminosity of the AGN can be problematic to compute from the spectral energy distribution (SED); however the following relationships can be used to derive the bolometric luminosity from the X-ray flux, the Eddington luminosity (i.e. the maximum luminosity possible from a SMBH of a given mass), plus the Eddington ratio and the accretion rate:

\[
L_{\text{Bol}} = 16 \times L_X [2 - 10 \text{ keV}] \quad \text{(Ho, 2009)} \tag{2.57}
\]

\[
\log(L_{\text{Bol}}) = 1.12 \log(L_X [14 - 195 \text{ keV}]) - 4.23 \quad \text{(Winter et al., 2012)} \tag{2.58}
\]

\[
L_{\text{Edd}} = 1.3 \times 10^{38} \frac{M_\bullet}{M_\odot} \text{ erg s}^{-1} \tag{2.59}
\]

\[
R_{\text{Edd}} = \frac{L_{\text{Bol}}}{L_{\text{Edd}}} \tag{2.60}
\]

\[
\dot{M}_{\text{acc}} \text{ [M}_\odot \text{ yr}^{-1}] = \frac{L_{\text{Bol}}}{c^2 \eta} \tag{2.61}
\]

\[
= 1.84 \times 10^{-46} L_{\text{Bol}} \text{ [erg s}^{-1}] \quad \text{(for } \eta = 0.1\text{)}
\]

where $L_X$ is the X-ray luminosity, $L_{\text{Bol}}$ is the bolometric luminosity, $M_\bullet$ is the BH mass and $\dot{M}_{\text{acc}}$ is the accretion rate. A standard efficiency rate $\eta$ of 0.1 is used. The X-ray luminosity in the 2–10 keV band can be affected by absorption, in which case the 14–195 keV measurement can be used; alternatively it can be corrected to the intrinsic 2–10 keV
luminosity by the relationship from Winter et al. (2009):

$$\log L_{2-10 \text{ keV}}^{\text{Int}} = 1.06 \times \log L_{14-195 \text{ keV}} - 3.08$$  \hfill (2.62)

An alternative proxy of the bolometric luminosity is the [O III] emission line luminosity, especially for heavily obscured Type 2 AGN. The emission line arises in the much larger narrow line region (NLR), where the gas is photoionized by the continuum radiation escaping within the opening angle of the torus. The observed flux is therefore weakly affected by the viewing angle relative to the torus and its luminosity provides an indication of the nuclear luminosity. The [O III] flux must be corrected for extinction; we use the relationships given in Lamastra et al. (2009) (with all flux measurements in erg s\(^{-1}\)):

$$L_{C[\text{O III}]} = L[\text{O III}] \left( \frac{H\alpha/H\beta}{3} \right)^{2.94}$$ \hfill (2.63)

$$L_{\text{Bol}} = C[\text{O III}] \times L_{C[\text{O III}]}$$ \hfill (2.64)

where

$$C[\text{O III}] = 87 \quad \log(L[\text{O III}]) = 38 - 40$$ \hfill (2.65)

$$= 142 \quad = 40 - 42$$

$$= 454 \quad = 42 - 44$$

where \(L\) and \(L_C\) are the observed and corrected luminosities and the part in the brackets is the Balmer decrement correction from the observed H\(\alpha\) and H\(\beta\) fluxes. \(C[\text{O III}]\) is the correction factor to convert [O III] to bolometric luminosity, given for [O III] luminosity ranges. As a note of caution, the [O III] flux can be contaminated by star formation.
Young Star Clusters in the Circumnuclear Region of NGC 2110

3.1 Introduction

The first object observed with IFU from the Mould et al. (2012) catalog, from the Palomar Triplespec IR spectroscopy observations, is NGC 2110. This object was chosen (apart from the strong emission lines) because of the well-known double radio jet (Ulvestad & Wilson, 1983). It is a SAB0− galaxy (i.e., weakly barred lenticular, de Vaucouleurs et al., 1991) with an activity type of Seyfert 1h which indicates ‘normal’ Seyfert 2 activity, but with a broad polarized Balmer lines (Véron-Cetty & Véron, 2006). Reunanen et al. (2001) detected weak broad-line Brγ emission. Others (e.g. Ferruit et al., 2004; Moran et al., 2007; Rosario et al., 2010; Storchi-Bergmann et al., 1999) state it is of Seyfert 2 type. From NED, the recession velocity is 2350 ± 24 km s\(^{-1}\) (Mould et al., 2000b) and a distance of 32.2 ± 2.3 Mpc. This is equivalent to a scale of 156 pc arcsec\(^{-1}\) and a distance modulus of 32.54 ± 0.15 mag. The AGN bolometric luminosity is \(L_{\text{Bol}} = 6.3 - 7.9 \times 10^{43} \text{ erg s}^{-1}\) with the absorbing column density \(N_H = 2.84 \times 10^{22} \text{ cm}^{-3}\) (Vasudevan et al., 2010, from the Swift/Burst Alert Telescope (BAT) survey).

Pogge (1989) detected extended H\(\alpha\) and [O III] emission (which seemed to follow the form of the radio structure). The ionization map, from the ratio of [O III]/H\(\alpha\), revealed an 8\(''\) ionization cone with an opening angle of 30° and a position angle (PA) = 10°, aligned with the radio jet. This was followed up by Mulchaey et al. (1994), who mapped this emission with the Hubble Space Telescope (HST), showing a curved inner jet of about 1\(''\) long.

Ferruit et al. (2004) combined HST STIS and WFPC2 observations, CFHT OASIS IFU observations and Keck-II NIRSPEC data to show that the ionized gas outflow ([O III]) is...
asymmetric about the nucleus (with the bulk of the emission to the north) and comes from the jet structure. This also contradicted the suggestion that the SMBH was kinematically and spatially offset from the nucleus (Mundell et al., 2001). González Delgado et al. (2002) supported the conclusion of Ferruit et al. (2004), and also suggested that the AGN activity was driven by a minor merger, as revealed in the HST F606W unsharp-masked image.

The radio power is $3.9 \times 10^{22}$ W Hz$^{-1}$ at 1.4 GHz (Ulvestad & Wilson, 1989). The nuclear radio emission is variable (Mundell et al., 2009, a ~38% decline in nuclear flux density over seven years); however Glass (2004) finds minimal near IR variability. With IRTF, Riffel et al. (2006) measured continuum fluxes in the range $1.9 - 2.8 \times 10^{14}$ erg cm$^{-2}$ s$^{-1}$ with a $0''.8 \times 15''$ slit in 1'' seeing, with a spectral resolution of 360 km s$^{-1}$.

Nandra et al. (2007), from XMM-Newton observations found an X-ray flux (2–10 keV) of $2.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is equivalent to a source power of $3.1 \times 10^{42}$ erg s$^{-1}$. NED values show variability of a factor of 2 over a 10-yr period (Ueda et al., 2005, with ASCA, $5.1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$). Evans et al. (2006) also find X-ray emission 4'' north of the nucleus, coincident with the edge of the radio jet and the H$\alpha$ and [O III] emission found with HST (Mulchaey et al., 1994). They consider that shock emission from the northern radio jet interacting with the ISM to be the favored X-ray production mechanism; the mechanism for the production to the southern side of the nucleus is unclear.

Schnorr-Müller et al. (2014) presented Gemini GMOS kinematics, finding multiple components of emitting gas; a warm disk, a cold disk, a northern cloud and a nuclear components. They estimated a cold gas inflow rate of $2.2 \times 10^{-2}$ M$_{\odot}$ yr$^{-1}$ and a ionized gas outflow rate of 0.9 M$_{\odot}$ yr$^{-1}$ in the inner 300 pc; their spatial resolution on the Gemini South telescope was about 100 pc. Using NIR Gemini-NIFS observations, Diniz et al. (2015) found H$_2$ flow rates of $4.6 \times 10^{-4}$ (inflow) and $4.3 \times 10^{-4}$ (outflow) M$_{\odot}$ yr$^{-1}$ in the inner 70 pc with a spatial resolution of 24 pc.

Fig. 3.1 (left panel) shows the combined Very Large Array (VLA) 6 cm image contour from Ulvestad & Wilson (1983, 1989)$^1$, overlaid on the structure map created from the HST F606W broad-band image (Malkan et al., 1998)$^2$. The over-plotted boxes represent the OSIRIS narrow-band (solid lines) and wide-band (dotted lines) filter fields of view (FOVs) for 0.035 arcsec pixel$^{-1}$ plate scale. Fig. 3.1 (right panel) shows the nucleus enlarged to the OSIRIS narrow-band FOV. The bright extension of the nucleus to the NW maps onto the inner H$\alpha$ jet.

This object was observed with the Triplespec IR spectrograph at the Mt. Palomar 200'' telescope as part of the Mould et al. (2012) program, with a 1'' wide longslit oriented

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$^1$VLA Archive http://archive.nrao.edu/nvas/

$^2$MAST HST archive http://archive.stsci.edu/
eastwest, with spectral resolution \( R = 2600 \). The resulting spectrum is plotted (reduced to rest frame) in Fig. 3.2, showing prominent emission lines of \( \text{He I} \) (1083 nm) and \( \text{[Fe II]} \) (1257 and 1644 nm); the continuum flux values are in line with those of Riffel et al. (2006). Other lines detected include \( \text{Pa} \beta, \text{Br} \gamma \) and \( \text{H}_2 \), plus the CO band-heads at 2290–2352 nm in absorption. The \( \text{Pa} \beta \) line showed a dispersion of about 210 km s\(^{-1}\), with no indication of Seyfert 1–type broadening. The line ratios for the IR AGN classification (Riffel et al., 2013a) are \( \log(\text{H}_2/\text{Br} \gamma) = 0.59 \) and \( \log(\text{[Fe II]}/\text{Pa} \beta) = 0.37 \). This places it on the AGN/LINER boundary. Note that the \( \text{H}\) recombination lines are weak in comparison to the \( \text{[Fe II]}\) lines; they also show multiple components, indicating outflows.

As a comparison, the nuclear spectrum from 6dF observations (Jones et al., 2009) is shown in Fig. 3.3, at 0.58 nm spectral resolution and a 6″.7 aperture. The spectrum has been reduced to rest-frame and the major emission lines are identified. The line ratios for the emission diagnostic diagram (Kewley et al., 2006) are \( \log(\text{[N II]}/\text{H}\alpha) = 0.107 \), \( \log(\text{[S II]}/\text{H}\alpha) = 0.02 \), \( \log(\text{[O I]}/\text{H}\alpha) = -0.41 \) and \( \log(\text{[O III]}/\text{H}\beta) = 0.73 \). The \( \text{[N II]}/\text{H}\alpha \) ratio sets it firmly in the AGN regime; the \( \text{[S II]}/\text{H}\alpha \) and \( \text{[O I]}/\text{H}\alpha \) ratios place it on the boundary between Seyfert and LINER classification, as does the NIR emission line classification. This shows that there is a significant shock excitation component as well as photo-ionization.
Chapter 3. Young Star Clusters in the Circumnuclear Region of NGC 2110

Figure 3.2: Mt. Palomar Triplespec near-IR spectrum, showing AGN excitation emission line ratios. OSIRIS filter bandwidths are shown (J
2, H
3, Z
b).

Figure 3.3: Optical spectrum of the nucleus of NGC 2110 from 6dF, with emission lines identified; again, the AGN excitation mode predominates.

3.2 Observations

NGC 2110 was observed with OSIRIS on 1 and 2 Nov. 2012, as set out in Table 3.1. A standard plate scale of 0′′.035 pixel−1 was used. The seeing over the two nights was in the range 0′′.4–0′′.6, with only one frame having worse than 0′′.9. The airmass was in the range 1.15–1.3. Each on-target frame had a 900 second exposure. The long axis of the FOV was left in the default position (i.e. N–S). We concentrated on the strong emission lines of He I and [Fe II] to give the best S/N ratio within the observing time constraints. Alternative emission lines (e.g., Pa β, Br γ or H2) were not observed.
3.2. Observations

The resulting data cubes have FOVs of $2''.31 \times 1''.785$ (66 $\times$ 51 pixels) and $2''.275 \times 0''.665$ (65 $\times$ 19 pixels) for the narrow- and wide-band filters, respectively. Data reduction, telluric correction, flux calibration and data cube cleaning were performed as described in Sections 2.3 and 2.4, above. Initially, the data sets for each filter were not mosaicked together, as it was apparent that the seeing varied considerably between sets.

### Table 3.1: NGC 2110 Observations, 2012 November 1 and 2

<table>
<thead>
<tr>
<th>Filter</th>
<th>Wavelength $\Delta \lambda / \lambda$ (nm)</th>
<th>Frames</th>
<th>Exp. (sec)</th>
<th>Standard Star</th>
<th>Target Line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Res. (nm)</td>
<td></td>
<td></td>
<td>Mag Eff. Temp K</td>
<td></td>
</tr>
<tr>
<td>$Jn2$</td>
<td>1228–1289 5050 0.15</td>
<td>4</td>
<td>3200</td>
<td>HD21875/HD27000\textsuperscript{a}</td>
<td>[Fe II] 1257 nm 7.476/8.045 12380</td>
</tr>
<tr>
<td>$Hn3$</td>
<td>1594–1676 3110 0.2</td>
<td>6</td>
<td>5400</td>
<td>HD21875</td>
<td>[Fe II] 1644 nm 7.492 12380</td>
</tr>
<tr>
<td>$Zbb$</td>
<td>999–1176 3960 0.12</td>
<td>2</td>
<td>1800</td>
<td>HD21875\textsuperscript{a}</td>
<td>He I 1083 nm 7.476 12380</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Standard stars for first and second night.

Additional archival NIR IFU data has also been used, as follows:

### Table 3.2: NGC 2110 Archival Observations

<table>
<thead>
<tr>
<th>Filter</th>
<th>Instrument</th>
<th>Program ID</th>
<th>Scale $''$</th>
<th>Obs. Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Jbb$</td>
<td>OSIRIS</td>
<td>K306OL</td>
<td>0.1</td>
<td>12 Nov 2010</td>
</tr>
<tr>
<td>$K$</td>
<td>NIFS</td>
<td>GN-2010B-Q-25\textsuperscript{a}</td>
<td>0.103 $\times$ 0.4</td>
<td>23 Nov 2010</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Published in Diniz et al. (2015).
Chapter 3. Young Star Clusters in the Circumnuclear Region of NGC 2110

3.3 Results

3.3.1 Circumnuclear Star Clusters

Our observations are confined to the nuclear region of this galaxy, encompassing the dusty torus and obscured AGN/BLR. The continuum \(Z_{bb}\), \(J_{n2}\) and \(H_{n3}\) images are shown in Fig. 3.4.

Star formation in the circumnuclear region of NGC 2110 was best resolved in the \(J\)-band continuum. This has the appearance, as shown in Fig. 3.5, of four star clusters (labeled ‘A’ to ‘D’) in a rough semi-circular ring, having a major axis of about 90 pc. In this and following maps, the location of the AGN is identified by ‘+’ marker near cluster ‘B’; see below for discussion of the identification. The clusters are best resolved in one of the \(J_{n2}\)-band data sets, the other \(J_{n2}\)-band and the \(H_{n3}\)-band data sets show them less clearly; seeing limitations are probably responsible. However, the ‘horseshoe’ shape of the light is visible in all the \(J_{n2}\) and \(H_{n3}\) images over both nights.

The clusters are not visible in the \(Z_{bb}\)-band images; the smaller FOV misses some of them, as well as there being reduced AO performance at shorter wavelengths. They are also not visible in either the \(HST\) images for the F606W and F200N filters; in the first case dust obscuration reduced the contrast and in the second the spatial resolution (0\(^{\prime\prime}.17\)) reduces the visibility. There is also no sign of them in the \(K\)-band NIFS observations of Diniz et al. (2015), probably because they are overwhelmed by the strongly-rising continuum.
3.3. Results

from the nuclear hot dust. For the $Jbb$ observations, the clusters are unresolved at a spatial resolution of 0\".1.

Figure 3.5: The circumnuclear clusters. The $Jn2$ continuum image with the best resolution, with surface brightness contours (in mag arcsec$^{-2}$). The flux density values are in units of $10^{-16}$ erg cm$^{-2}$ s$^{-1}$ nm$^{-1}$. Clusters are labeled `A' to `D'. The presumed AGN location is marked with `+'.

The cluster luminosities were measured as follows:

- A point-spread function was created from a $Jn2$-band telluric star observation on that night (with AO loops closed). The PSF was created by fitting a 2D Gaussian to the data cube median collapsed along the wavelength axis. The FWHM of the fitted Gaussian was $\sim$ 2 pixels.

- From the data cube, the average flux density was measured over the wavelength range 1240–1260 nm.

- The flux density image was de-convolved with the Lucy-Richardson (Lucy, 1974; Richardson, 1972) algorithm with 5 iterations using the QFitsView lucy functionality. The number of iterations was chosen by trial and error to enhance the image without introducing artifacts.

- Each cluster was fitted with a 2D Gaussian profile and the total flux density and FWHM sizes were estimated.
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- The total flux density was converted to magnitudes using the Gemini ‘Conversion from magnitudes to flux, or vice-versa’ calculator (see Section 2.4.1).

- The flux was converted to an absolute magnitude using the distance modulus of 32.2, and compared to the Solar J-band absolute magnitude of 3.64 (Binney & Merrifield, 1998).

- The clusters sizes were scaled at 5.5 pc pixel$^{-1}$.

Table 3.3 gives the results. These clusters can be compared to the Arches cluster in the center of the Milky Way (MW), with J-band luminosity $L = 6 \times 10^7 L_\odot$ (Figer et al., 2002) and the Hercules globular cluster M13, $L = 3.6 \times 10^5 L_\odot$ (from SIMBAD and NED). Subtracting the star cluster flux from the original image reveals a rather flat field with some loops and arc segments, but impression is of a ring with a weak central emission. Cluster ‘D’ is extended towards cluster ‘C’; there is probably a continuous arm or ridge connecting all the clusters. At a 2 pixel spatial resolution of 11 x 11 pc, these clusters are just resolved.

### 3.3.2 Gas Distribution and Kinematics

The gas emission line flux and kinematic plots presented above allow the determination of the source, flows and excitation of the various atomic and molecular species in the nuclear region.

The $Jn2$, $Hn3$, and $Zbb$ spectra of the central 0’’.5 (encompassing the clusters) are presented in Fig. 3.6; the wavelengths have not been reduced to the rest frame, as identification is unproblematic.

Fig. 3.7 shows the nuclear 0’’.5 spectra combined on one axis, including the $K$-band spectrum from the NIFS data cube (Diniz et al., 2015). This shows a rising continuum, now extending from 1000 to 2400 nm, due to the dusty torus emission. The ‘Atlas’ spectrum (Riffel et al., 2006) is shown for comparison; this was obtained from IRTF, using the SpeX spectrograph in cross-dispersed mode (SXD, 800–2400 nm).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Size (pc)</th>
<th>Flux ($\times 10^{16}$ erg cm$^{-2}$ s$^{-1}$)</th>
<th>mag J</th>
<th>Mag J</th>
<th>$L/L_\odot$ ($\times 10^7$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>16 x 12</td>
<td>4.3</td>
<td>17.1</td>
<td>-15.4</td>
<td>4.2</td>
</tr>
<tr>
<td>B</td>
<td>18 x 13</td>
<td>3.7</td>
<td>17.3</td>
<td>-15.3</td>
<td>3.7</td>
</tr>
<tr>
<td>C</td>
<td>12 x 15</td>
<td>2.5</td>
<td>17.7</td>
<td>-14.9</td>
<td>2.5</td>
</tr>
<tr>
<td>D</td>
<td>28 x 12</td>
<td>5.7</td>
<td>16.8</td>
<td>-15.7</td>
<td>5.6</td>
</tr>
</tbody>
</table>
3.3. Results

Figure 3.6: $Z_{bb}$, $Jn2$ and $Hn3$ spectra of the central $0''.5$. The $[\text{Fe} \, \text{II}]$ lines are reasonably symmetric, but the He I line shows a strong P Cygni-like blue-ward absorption feature. Some imperfectly corrected skylines have been masked from the $Hn3$ spectrum, for clarity.
Figure 3.7: Jn2, Hn3, and Zbb nuclear spectra combined with the archival K spectrum (NIFS), compared with the ‘Atlas’ spectrum of Riffel et al. (2006); the main spectral features are identified. The ‘Atlas’ spectrum is offset and scaled for visibility. The rising continuum slope of the nuclear spectrum (compared to the longslit) is indicative of an increasing component of hot dust emission in the nucleus.
3.3. Results

The flux, LOS velocity and dispersion maps for [Fe II] 1644 nm and He I are shown in Figs. 3.8 and 3.9. The maps for [Fe II] 1257 nm are not shown, due to the greater extinction. These maps are derived using the methods described in Section 2.5.3. The region of star formation can be seen in the shocked [Fe II] gas. The flux map shows a roughly elliptical region or broad bar, about $0''.55 \times 0''.35$, i.e. $85 \times 55$ pc, at the level where the flux is 50% of the maximum. The PA of the bar is $35^\circ - 215^\circ$, where $0^\circ$ is north and $90^\circ$ is east. At 20% of the maximum flux, it takes on the reverse S-shape as seen by HST in [O III] and H$\alpha$ (Mulchaey et al., 1994, e.g. their Plate 19) and with NIFS in Br$\gamma$ (Diniz et al., 2015). It has dimensions $1''.75 \times 0''.63$, i.e. $275 \times 100$ pc, and the overall alignment becomes N–S, in line with the radio jet. By comparison, the He I flux is somewhat more centrally concentrated; at 50% flux it is $60 \times 40$ pc, with the same orientation.

The [Fe II] LOS velocity map shows the outflows, with the northern component having a velocity towards us of 50–100 km s$^{-1}$, with corresponding motions away from us in the southern component and dispersion maps. The northern component velocities align with H$\alpha$/[O III] outflow, whereas the flux values align more with the radio jet. One can speculate that the [Fe II] excitation is caused by the radio jet, but some of the gas is entrained in the outflows. The dispersion is greatest at the nucleus, where the AGN excitation is strongest and there is a component of artificial broadening as the LOS penetrates both the N and S outflow components.

The maximum [Fe II] flux is not co-located with the clusters, but rather lies between them. This is the shocked inter-cluster medium that is radiating, excited by strong outflows, driven by star formation, evolved stellar winds and supernova (SN) shocks, plus the radio jet in the extended emission. The clusters seem embedded in the general gas velocity field.

The location of the nucleus of the galaxy (and presumably the AGN) in the Jn2 and Hn3 maps is an interesting problem, as there are no readily defined features to map onto (say) the HST image. To match the images, we mapped the [Fe II] fluxes over the HST structure map at the same scale (Fig. 3.10). The maps were manually aligned until the bright nucleus and jet features matched up, thus identifying the location of the AGN nucleus on the flux map, which is marked with a cyan ‘+’ on all the plots.

3.3.3 Extinction

The visual extinction is proportional to the column density of dust in the LOS, and the value is derived from the [Fe II] 1257/1644 nm flux ratio, as described in Section 2.6.2,
Figure 3.8: NGC 2110 [Fe II] kinematics. Flux, LOS velocity and LOS dispersion ($\sigma$) for [Fe II] 1644 nm. Units and contours as per Fig. 3.9. The approaching and receding outflows (NW and SE respectively) are visible in the velocity maps.

Figure 3.9: NGC 2110 He I kinematics. Flux, LOS velocity and LOS dispersion ($\sigma$) for He I. Flux values in units of $\times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, with contours at 10, 30, 50, 70 and 90% of maximum. Velocity and dispersion units are km s$^{-1}$. The receding velocities to the north and south are an artifact of the P Cygni absorption near the nucleus.
with the extinction calculated using the values in Table 2.3, with $R_{A_1,A_2} = 1.36$ and a MW extinction of 1.02 mag (Schlafly & Finkbeiner, 2011, through NED). The map is clipped for low flux values and unphysical extinction values less than zero. The resulting map is shown in Fig. 3.10. Despite deriving extinctions on a pixel-by-pixel basis being problematic (see Section 4.3.3), the extinction aligns very well to the dust lanes visible in the HST structure map, except at the nucleus, where it reaches $A_V$ values of 3 to 4 magnitudes in a bar of size $\sim 0''.35 \times 0''.175$, i.e. $55 \times 27$ pc. This compares with the value of $A_V \geq 4.6(+1.2,-1.7)$ mag, derived from HST F547M and F718M images by Mulchaey et al. (1994). The average extinction within the central $0''.5$ is 1.6 mag.

This central bar can be interpreted as a region of dust and gas obscuring the central engine, seen edge-on. Without this obscuration, the nucleus would dominate the visual image, as can be seen in the $K$-band observations (Diniz et al., 2015).

3.4 Discussion

3.4.1 Cluster Formation and Ages

The very large clusters we have found in the circumnuclear region of NGC 2110 can be compared to others found in our local region. The Arches cluster near the center of the MW has a mass of $2 \pm 0.6 \times 10^4$ $M_\odot$ (Espinoza et al., 2009), an age of 23 Myr, a luminosity $L = 6.3 \times 10^7$ $L_\odot$, and a small size of 0.2 pc; the intrinsic extinction (internal within the cluster) is not substantial (Figer et al., 2002). Assuming a similar age and mass-to-light
ratio, we have about 2.7 Arches masses, i.e. \( M = 5.3 \times 10^4 \) M\(_\odot\) in the circumnuclear region, equivalent to a star formation rate (SFR) of about 1.1 Arches clusters per Myr, i.e., about 0.02 M\(_\odot\) yr\(^{-1}\).

The star-formation rate can be determined from the hydrogen recombination lines. The Pa\( \gamma \) flux in the \( Zbb \) spectrum is weak and almost obscured by the He I line, and the Br\( \gamma \) flux in the \( K \) spectrum is heavily diluted by the hot dust continuum; however, we can use the value Pa\( \beta \) flux value of \( 2.5 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) from the Palomar Triplespec observations (Mould et al., 2012), giving a luminosity of \( 3.1 \times 10^{30} \) erg s\(^{-1}\). Using the Kennicutt relationship (Section 2.6.3.2, Equation 2.30) and ignoring any photo-ionization from the AGN, the SFR = 0.43 M\(_\odot\) yr\(^{-1}\), i.e. there is no difficulty forming these clusters in a few million years.

From the OSIRIS \( Jbb \) data, in the 0\(^{\prime\prime}.5 \) radius around the nucleus, the Pa\( \beta \) flux is \( 4.4 \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\); with \( A_V=1.6 \) mag, the de-reddened flux (Equation 2.22) is \( 6.6 \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\), which converts to a SFR of 0.12 M\(_\odot\) yr\(^{-1}\); again, more than adequate to form the clusters.

The dominant component of the IR emission line spectrum resembles the ‘Homunculus’ nebula around the Luminous Blue Variable \( \eta \) Car (Smith, 2002), with the powerful He I line and strong [Fe II] lines; NGC 2110 in fact has much weaker H recombination emission relative to those lines. We can compare the fluxes for the [Fe II] 1257 nm emission line between the two objects; the surface brightness of the brightest [Fe II] flux pixel is \( \sim 1.3 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\); the fluxes from Smith (2002) have a range of \( 1.2 - 38 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\). We can infer the presence of massive stars in the ring around the NGC 2110 nucleus and the consequent violent mass loss associated with their advanced evolution. From the OSIRIS \( Jbb \) Pa\( \beta \) equivalent width map (derived from the velmap procedure), the highest value is 1.6 nm, which translates to an age of 6–8 Myr (see Section 2.6.3.2) depending on metallicity. Hur et al. (2012) estimated the age of the clusters Tr 14 and Tr 16 associated with \( \eta \) Car at 1-3 Myr.

At the radius of the star cluster ring we would expect a speed of about \( \sim 150 \) sin\((i)\) km s\(^{-1}\) and a period of 1.2 Myr for a circular orbit, which means that the clusters are just a few dynamical times old and still to reach equilibrium with the BH. The low velocity amplitude would reflect that; furthermore we are observing shocked gas velocities toward the outside of a molecular obscuring region, rather than star clusters in a circular orbit.

Renaud et al. (2013), in their galactic hydrodynamical simulations, noted that star cluster formation close around the central BH seems to be controlled by tidal shear and resonances with spiral arms, and can produce matter condensations at \( \sim 40 \) pc at the
edge of a nuclear disk (‘bead on a string’). Just such a mechanism can be postulated for the formation of the observed clusters. Mould et al. (2000a) also observe star formation associated with the radio jet of Cen A and tentatively proposed photo-ionizing shocks from the jet as the physical mechanism.

The AGN polar biconal outflows (as seen in HST data) provide confinement and compression to the turbulent gassy/dusty torus, which triggers the formation of the observed massive clusters. They in turn provide the stellar winds (and occasional SN shocks) to cause the observed [Fe II] emission, as shown by the present data. This interaction occurs if the jets intersect the torus; Müller-Sánchez et al. (2011) shows that this commonly occurs and Rosario et al. (2010) propose this specifically for NGC 2110. Some of these cluster outflows feed the AGN, which helps to overcome the problem whereby gas in-falling from a large distance has too much angular momentum to impinge directly onto the BH/accretion disk. This scenario can be compared with the simulations described in Section 4.4.8.

### 3.4.2 Extinction and Gas Mass Estimation

Gas column densities are derived from the extinction. According to Smith (2002), η Car’s 1644/1257 nm flux ratio varies from 1.0 to 1.45 at three different locations in the nebula. We see a similar range of flux ratios, which implies $0 < E(J − H) < 0.5$. The expectation for normal reddening is $E(J − H)/E(B−V) = 0.37$ (Mathis, 1990). This gives $E(B−V)$ up to 1.4 mag, which is consistent with the measurements from Storchi-Bergmann et al. (1999). With an $R_V = 3.1$ reddening law (Schlafly & Finkbeiner, 2011) and a foreground MW galactic extinction $A_V$ of 1.02 (Schlafly & Finkbeiner, 2011, through NED), we obtain a total extinction value $A_V$ up to 3.2 mag. This is consistent with the value given by Alonso-Herrero et al. (1998), whose observations can be described by an evolved stellar population reddened by a foreground extinction of $A_V ≈ 2-4$ mag, which is also consistent with the values derived from HST images (Mulchaey et al., 1994). The MW galactic extinction value, however, has some uncertainty in it; the map of this low galactic latitude location ($l=213^\circ$, $b=-16^\circ$) (Schlafly & Finkbeiner, 2011) shows some patchiness. While we would not argue that the galactic reddening is zero, we can regard the value as an upper limit.

Our Palomar Triplespec spectrum (Fig. 3.2), averaged over the whole nuclear region with 1$''$ resolution (about the same spatial extent as our high-resolution maps), has flux values for the [Fe II] lines of $5.86$ (1257 nm) and $5.22$ (1644 nm) $\times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, which gives $A_V = 2.12$. Our measurements suggest that the massive star formation in
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NGC 2110's circumnuclear region is up to four times higher and at a similar level of extinction to that of the fan region of the η Car nebula.

Archival HST images of the nucleus (the F606W and F791W filters) with the Holtzman et al. (1995) calibration, yield $V - I \approx 1.8$ mag for the central tenth of an arcsec. Given the reddening calculated above, this suggests an intrinsic stellar population color of zero. The star clusters visible to OSIRIS in the NIR are not seen in Fig. 3.1, because of HST’s lesser resolution, the archival frames short exposure and over 3 mag of extinction.

The total gas mass can be calculated as described in Section 2.6.3.1. Table 3.4 presents the results. The SN rate is estimated from the [Fe II] flux using Equation 2.33. Table 3.5 presents the results, with the ‘Region’ column as per Table 3.4.

Table 3.4: Gas mass and surface density derived from extinction

<table>
<thead>
<tr>
<th>Region</th>
<th>$A_V$</th>
<th>Pixels</th>
<th>Area (pc$^2$)</th>
<th>Mass ($M_\odot$)</th>
<th>$\sigma_{Gas}$ ($M_\odot$pc$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Pixel</td>
<td>4.825</td>
<td>1</td>
<td>30</td>
<td>$3.23 \times 10^3$</td>
<td>106.6</td>
</tr>
<tr>
<td>50 pc</td>
<td>1.85</td>
<td>107</td>
<td>3236</td>
<td>$1.32 \times 10^5$</td>
<td>40.9</td>
</tr>
<tr>
<td>100 pc</td>
<td>1.52</td>
<td>296</td>
<td>8954</td>
<td>$3.01 \times 10^5$</td>
<td>33.6</td>
</tr>
<tr>
<td>Total</td>
<td>1.65</td>
<td>553</td>
<td>16728</td>
<td>$6.10 \times 10^5$</td>
<td>36.5</td>
</tr>
</tbody>
</table>

*Max. Pixel - pixel with highest value. 50/100 pc - pixels within 50/100 pc of AGN location. Total - all pixels over the whole field.

$^b$ $A_V$ averaged over all pixels in region.

$^c$ Number of valid pixels, i.e. $A_V > 0$

$^d$ Pixel dimension 5.5 pc.

Table 3.5: Supernova rates derived from [Fe II] flux.

<table>
<thead>
<tr>
<th>Region</th>
<th>[Fe II] Flux$^a$</th>
<th>[Fe II] Luminosity$^b$</th>
<th>SNR$^c$</th>
<th>SNR (yr$^{-1}$)</th>
<th>SN Interval (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Pixel</td>
<td>1.62</td>
<td>$2.02 \times 10^{37}$</td>
<td>14.3</td>
<td>$1.36 \times 10^{-4}$</td>
<td>7338</td>
</tr>
<tr>
<td>50 pc</td>
<td>232.3</td>
<td>$2.89 \times 10^{39}$</td>
<td>24.9</td>
<td>$1.95 \times 10^{-2}$</td>
<td>51</td>
</tr>
<tr>
<td>100 pc</td>
<td>551.6</td>
<td>$6.86 \times 10^{39}$</td>
<td>14.8</td>
<td>$4.64 \times 10^{-2}$</td>
<td>22</td>
</tr>
<tr>
<td>Total</td>
<td>815.6</td>
<td>$1.01 \times 10^{40}$</td>
<td>3.7</td>
<td>$6.86 \times 10^{-2}$</td>
<td>15</td>
</tr>
</tbody>
</table>

$^a$ Units of $10^{-16}$ erg cm$^{-2}$ s$^{-1}$

$^b$ Units of erg s$^{-1}$

$^c$ Units of $10^{-7}$ yr$^{-1}$ pc$^{-2}$
In the AGN Unified Model, the size of the cylindrically symmetric, smooth obscuring torus is usually given as of the order of several parsecs. What we observe is substantially larger (\(\sim 55 \text{ pc}\)). However, recent three-dimensional hydrodynamic simulations (Wada & Norman, 2002; Wada et al., 2009; Schartmann et al., 2008) suggest highly inhomogeneous and turbulent obscuring structures, with a radius of several tens of parsecs. Hicks et al. (2009) provide observational support for this scenario with their H\(_2\) gas data from a sample of nine local Seyfert 1 galaxies, showing thick, clumpy gas disks with a typical radius of about 30 pc. The presence of dust suggests NGC 2110 would repay investigation with ALMA of its molecular gas phase at this resolution.

### 3.4.3 Stellar Population

The stellar populations in the circumnuclear region are examined using extinctions and continuum colors. Fig. 3.11 displays the \(J - H\) magnitude image, derived by subtracting the \(Jn2\) and \(Hn3\) continua after alignment on the AGN location.

![Figure 3.11: Stellar population diagnostic map from \(J - H\) magnitude. The color map plots the \(J - H\) magnitude, with the overlayed contours in black showing the \(J\) magnitude, with values of 11.8, 11.9, 12, 12.25, 12.5 and 12.75. Dividing the image into the nucleus (central 0\(\prime\).5) and the field, the results for the average visual and \(J-H\) extinction, color and stellar color are shown in Table 3.6. The equivalent stellar spectral types are from Bessell & Brett (1988), tables II and III. The
clusters have a component of evolved stars (Alonso-Herrero et al., 1998), however for the nucleus the rising continuum from the hot dust, as can be seen from Fig. 3.7, will be significant at longer wavelengths.

**Table 3.6:** Extinction, $J - H$ and stellar colors.

<table>
<thead>
<tr>
<th>Region</th>
<th>$A_V$</th>
<th>$J - H$</th>
<th>$E(J - H)$</th>
<th>Stellar $J - H$</th>
<th>Spectral Type (Dwarf)</th>
<th>Spectral Type (Giant)</th>
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<tr>
<td>Nucleus</td>
<td>4.8</td>
<td>1.1</td>
<td>0.6</td>
<td>0.5</td>
<td>K2</td>
<td>G8</td>
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<tr>
<td>Field</td>
<td>1.6</td>
<td>0.25</td>
<td>0.2</td>
<td>0.05</td>
<td>A5</td>
<td>–</td>
</tr>
</tbody>
</table>

### 3.4.4 He I and the Nucleus

The He I emission allows examination of the conditions nearer to the center than the [Fe II] emission. The broadband $Zbb$ image and He I flux, velocity, and dispersion maps (Fig. 3.9) are different from the $Jn2$ image and [Fe II] 1644 nm maps. Both the morphology (more centrally concentrated) and the velocity dispersion (roughly 1.5 times) compared to [Fe II] support the conclusion that He I is closer to the photo-ionizing source. We note the NW extension of the bright central core is also seen on the HST image (Fig. 3.1 right panel).

The velocity map has a different structure, with an apparent red-shifted region in the center with blue-shifted wings to the N and S. On examination of the spectrum over the central $0".5$ (Fig. 3.6 bottom panel), we can see a P Cygni type profile (i.e. a blue-ward truncation in emission plus absorption) indicating an absorbing outflow in the line of sight. The LOS velocity from the velmap procedure at any pixel is derived from the peak of the emission; the absorbing outflow in the central region has the effect of red-shifting the velocity fit. To determine the relative velocities of the emitting and absorbing gas, a multi-component Gauss curve was fitted to the spectrum. It is noted that there seems to be a broad base of emission, as well as the main peak, so 3 Gaussian components were fitted, using the manual line fitting facilities in QFitsView. The results are given in Table 3.7 and the spectrum with the fits and residual are plotted in Fig. 3.12.

The velocity difference between the narrow emission line and the absorption is $\sim 600$ km s$^{-1}$. One could suggest that the dispersion of the ‘broad’ component is indicative of emission from the BLR breaking through the obscuration - this supports the classification of Seyfert 1h (Véron-Cetty & Véron, 2006). The broad and narrow emissions have essentially the same central velocity, within the uncertainties of the fits. Since this absorption
Table 3.7: He I Emission Line Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Height</th>
<th>λ Central (nm)</th>
<th>FWHM (nm)</th>
<th>σ (nm)</th>
<th>σ (km s(^{-1}))</th>
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</thead>
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<tr>
<td>Broad Emission</td>
<td>23.5 ± 1.1</td>
<td>1091.58 ± 0.34</td>
<td>21.07 ± 1.6</td>
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<td>2457</td>
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<tr>
<td>Narrow Emission</td>
<td>97.4 ± 3.7</td>
<td>1092.23 ± 0.15</td>
<td>4.08 ± 0.23</td>
<td>1.73</td>
<td>475</td>
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<tr>
<td>Absorption</td>
<td>64.6 ± 9.4</td>
<td>1090.07 ± 0.04</td>
<td>4.00 ± 0.16</td>
<td>1.70</td>
<td>467</td>
</tr>
</tbody>
</table>

component only occurs along the LOS, one would expect it to be more centrally concentrated than the emission; this is seen in the velocity field, where the absorption affects the derived velocity only within the central 0″.5 or so. As a comparison, the spectra of 3 positions, on the nucleus and 0″.63 north and south, are presented in Fig. 3.13. It can be seen that the N and S components show minimal or no P Cygni-type absorption.

Figure 3.12: P Cygni component fit to central 0″.5 He I emission. Top panel: Continuum subtracted observations and Gaussian fits, plus total fit. Bottom panel: residual (total fit – observation) plotted on same vertical scale. The fits show a broad and narrow emission line component, with foreground absorption with the gas approaching at ≈ 600 km s\(^{-1}\).

A similar outflow was also measured in He I in NGC 4151 by Iserlohe et al. (2013) for the 2058 nm line and by Storchi-Bergmann et al. (2009, 2010) for the 1083 nm line.
They found an absorption component at $\sim -460$ km s$^{-1}$, with again a greater central concentration than the main emission, which in this case was weaker than the absorption.

### 3.4.5 SMBH/Enclosed Mass

The mass in the nuclear region (including the SMBH) can be determined from the [Fe II] kinematics. Taking a cut across the [Fe II] velocity map centered on the nucleus along the line of the NW jet ($\sim 35^\circ$) produces the profile as shown in Fig. 3.14. This compares closely with the velocity curve from González Delgado et al. (2002). The enclosed mass, from the peak-to-peak positions (61 pc) and velocities ($132 \pm 52$ km s$^{-1}$) at the first turnover position, is calculated as $3.1(+2.9,-1.9) \times 10^7$ M$_{\odot}$ for a simple Keplerian model (Equation 2.45). The errors are derived from the velmap procedure fit, described above.

A Plummer model fitted to this data (Equation 2.43), assuming no inclination, gives a scale length $A = 42.6$ pc with a velocity of 76.2 km s$^{-1}$, which gives $M_\bullet = 1.6 \times 10^8$ M$_{\odot}$ (Equation 2.47).
3.4. Discussion

Figure 3.14: [Fe II] velocity profile and Plummer model fit across the nucleus, giving a SMBH mass of $3.1 \times 10^7$ M$_\odot$ from the data and $1.6 \times 10^8$ M$_\odot$ from the Plummer model.

This simplistic model will overestimate the BH mass, as there will be non-negligible stellar and gas mass within that radius. The velocity profile will also be affected by the outflows. We note, however, that for a stellar dispersion of 148 km s$^{-1}$ (derived above) and a BH mass of $2 \times 10^8$ M$_\odot$, the sphere of influence (Section 2.6.5) is about 40 pc, i.e., about the scale of the observed nuclear region.

Moran et al. (2007) also give a BH mass of $2 \times 10^8$ M$_\odot$, based on the $M - \sigma$ relationship and the measured stellar dispersion of 220 ± 25 km s$^{-1}$. The relationship (Section 2.6.5), with the parameter values from Graham et al. (2011) updated for elliptical galaxies and using the estimated stellar dispersion calculated above, gives a similar value of 2.85(+3.6,−1.6) $\times$ 10$^8$ M$_\odot$. The values for the Plummer and $M - \sigma$ models are in reasonable agreement; the simple Keplerian model underestimates the mass due to beam-smearing reducing the velocity gradient.

Riffel et al. (2013c) found a correlation between the stellar and [Fe II] gas dispersions:

$$\sigma_\star = (57.9 \pm 23.5) + (0.42 \pm 0.10) \times \sigma_{[\text{Fe II}]}$$  \hspace{1cm} (3.1)

Taking the dispersion in the nuclear region of the [Fe II] 1257 nm spectral line as 284 km s$^{-1}$, this correlation gives a stellar dispersion of 177 ± 52 km s$^{-1}$, giving a BH mass of 1.1(+3.6,−0.8) $\times$ 10$^8$ M$_\odot$. Krajnovic et al. (2007) have suggested that [Fe II] is not a good
tracer of the central potential and is not suitable for determination of BH mass; however in this case the derived value is compatible with that derived from the Keplerian rotation.

### 3.4.6 Conclusions

LGSAO resolution and IFU spectroscopy at the Keck Observatory of the nucleus of NGC 2110 have shown four massive young star clusters (the brightest of which has $L = 5.6 \times 10^7 \, L_{\odot}$) embedded in a disk of shocked gas, with an estimate of the enclosed mass of $2 \times 10^8 \, M_{\odot}$. Though NGC 2110 is a galaxy of type S0, its nuclear region is being fueled sufficiently on million year timescales to sustain an SFR of order $0.3 \, M_{\odot} \, yr^{-1}$, in line with the cluster formation rate we see.

The process that terminates galaxy growth by accretion is called feedback. BHs are integral to that process, found in all massive galaxies, and, when feedback is active, so are AGNs. Feedback activity classically embodies radio jets that can entrain and drive material clean out of galactic halos. But nuclear feedback can also be mediated as star formation, in which massive young stars eject a major fraction of their mass in powerful winds. In this galaxy we are witnessing one of the modes of AGN feedback at a few parsecs resolution, the formation of massive stars with energetic winds.

**Note**

This chapter has appeared originally as Durré & Mould (2014), but with modifications. The main differences are:

- An OSIRIS orientation problem was corrected, where the image should have been rotated by $90^\circ$ clockwise, changing the interpretation of the gas outflow alignment.
- Corrected flux calibration, which alters the derived values for the cluster masses, gas emission fluxes, continuum magnitudes and derived extinctions, gas masses and supernova rates.
IC 630: Piercing the Veil of the Nuclear Gas

4.1 IC 630 as a Starburst

IC 630 shows the second strongest NIR emission line flux in the Mould et al. (2012) spectroscopic observation program (after the well-studied Seyfert 1 galaxy UGC3426/Mrk 3). IC 630 (Mrk 1259) has a type of S0 pec (morphological type -2) from the RC3 catalog (de Vaucouleurs et al., 1991) with a redshift of 0.007277. The Virgo+GA+Shapley Hubble flow model (Mould et al., 2000b) gives a distance of 33.3 ± 2.3 Mpc, with a distance modulus of 32.6 mag. This is equivalent to a flux-to-luminosity ratio of $1.55 \times 10^{53}$ in cgs units, i.e., erg cm$^{-2}$ s$^{-1}$ to erg s$^{-1}$.

It has starburst type activity (Balzano, 1983), rather than the classical AGN-type high-excitation emission lines of Seyfert galaxies; in fact, it is classified as a ‘Wolf-Rayet’ galaxy with a super-wind, similar to M82 (Ohyama et al., 1997), with a high ratio of WR to O-type stars ($\sim 9\%$). The outflow is seen almost face-on, with the estimated velocity of $\sim 710$ km s$^{-1}$. Strong optical emission lines of hydrogen, [O III] and [N II] are seen, as well as N III, N V, He I and He II.

To illustrate global morphology and the relevant scales, Fig. 4.1 shows images for this object; the optical $g$ band image is from the MAST PanSTARRS image cutout facility\(^1\), the $H$ band near-infrared image is from the 2MASS catalog (Skrutskie et al., 2006) and the radio image at 1.4 GHz is from the VLA FIRST survey image cutout facility (Becker et al., 1995)\(^2\). The NIR and optical images is somewhat confused by the diffracted light from the nearby star HD92200, which has been masked out. The scale and orientation are the same in all images, as shown on the optical image (except for the top right panel). The 2MASS infrared image show a featureless spheroid with a published (NED, Skrutskie et al. 2006) ellipticity of about 0.5 at $PA \approx 70^\circ$. In the PanSTARRS $g$ optical image, the nucleus is

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\(^{1}\)https://archive.stsci.edu/
\(^{2}\)http://third.ucllnl.org/cgi-bin/firstcutout
off-center with respect to the disk, and shows dust lanes crossing SW to NE across the nucleus, with a suggestion of a shell structure (most prominent in the NE quadrant). We have also included the structure map generated from the PanSTARRS image, using a 2D Gaussian PSF fitted to the image artifacts; this image shows the central region at half the scale.

To delineate the non-symmetric nature of the isophotes, the galaxy PanSTARRS g was modeled using the IRAF ellipse and bmodel tasks. The results are shown in Fig. 4.2; the left panel shows the inner 1′ of the PanSTARRS g image, overlaid with the fitted elliptical contour model. The right panel shows the residual, i.e. the image minus the model. Dust lanes show as dark regions; this image reveals a quatrefoil pattern through the nucleus, similar to the structure map. These dust lanes/filaments are similar to other galaxies, thought to be feeding the central region (see e.g. Simões Lopes et al., 2007; Mezcua et al., 2015).

An estimate of the galaxy mass was calculated from the 2MASS H band photometry (from NED, 131".6 x 63".2 integration area), $m_H = 9.42$. With a distance modulus of 36.8, this gives $4.3 \times 10^9 \, M_\odot$ (assuming a M/L of 1 at $H$ and a solar magnitude of 3.3; Binney & Merrifield, 1998). From the Spitzer Heritage Archive 3.6 μm image and using the MOPEX tool\(^3\), the flux, with an aperture of 14″, is $5.83 \times 10^{-2}$ Jy, equivalent to $m_{3.6} = 9.2$, giving $4.44 \times 10^9 \, M_\odot$ (assuming a mass-to-light ratio of 0.8 at 3.6 μm and a Solar magnitude of 3.24; Oh et al., 2008). This low stellar mass (well below that of the MW and of the order of that of M33), combined with the presence of the bright nearby star interfering with the image, calls into question the morphological classification of S0.

To confirm the starburst characterization, the spectral energy distribution (SED) was compiled from existing data sources (Table 4.1), which is plotted in Fig. 4.3. The data were compiled from pre-existing catalogs listed in NED. This confirms the type, with the major peak at around 100 μm ($\sim 30$ K) being from dust heated by star formation. For comparison, the SED of the well-known starburst galaxy Arp 220 is also plotted, showing very similar features.

The SED was also fitted using the magphys package with the HIGHZ extension to fit the Planck observations (da Cunha et al., 2008, 2015); the fit estimates the galaxy mass at $\sim 1.5 \times 10^{10} \, M_\odot$ (somewhat higher then the mass estimate from the NIR photometry) and a SFR of $\sim 1.1 \, M_\odot \, yr^{-1}$. This is in line with the values in Table 4.2, which presents derived SFRs from various flux indicators. It is noted that the radio flux is about a factor of 4 above the fit; this could be as a result of the uncertainties associated with the fit,
Figure 4.1: Top left panel: Optical image (PanSTARRS $g$) with contour values of 11, 12, 12.5, 13 and 13.5 mag arcsec$^{-2}$, showing the non-circularity of the isophotes. Top right panel: PanSTARRS $g$ structure map central detail (note the different scale bars). The irregular dust-lane morphology is visible. The bright points in both the PanSTARRS images are artifacts. Bottom left panel: Infrared image (2MASS $H$); the nuclear morphology is a featureless ellipse. Bottom right panel: Radio (VLA FIRST 1.4 GHz) image; there is a hint of a lobe towards the NW. The optical and NIR units are magnitude per square arcsec. The contoured radio flux units are mJy; the circle in the bottom left of the plot is the beam size. The optical image shows the field of view (25 × 38") for the optical WiFeS IFU as a rectangle. The IR image also shows the field of view for the infrared IFU observations (3" × 3") as a small black square. The image sizes are 60" × 60", equivalent to ∼10 kpc (except for the top right panel).
which uses a prescription based on the far IR and radio correlation (da Cunha, private comm.) or from a highly obscured AGN.

Nuclear starbursts are usually the result of galaxy interactions (Bournaud, 2011) and the optical and residual images (Fig. 4.2) shows a disturbed morphology. An examination of images from various surveys around IC 630 does not reveal any candidate interacting galaxy, so we suggest that the starburst is generated by a minor merger.

4.2 Observations and Data Reduction

4.2.1 Observations

Our infrared observations were taken with NIFS on Gemini North in queue service observing mode and SINFONI on VLT-U4 (Yepun) in classical/visitor observing mode. Observations were carried out using adaptive optics with laser guide stars, as per Tables 4.3 and 4.4.

Each dataset consists of two 300 second observations, combined with a sky frame of 300 seconds, in the observing mode ‘Object-Sky-Object’. The NIFS observations used simple nodding to the sky position, which was 30" in both RA and Dec; for SINFONI the offset was 30" in Dec, plus a 0.05 jittering procedure.

The point spread function (PSF) for the instruments was estimated by fitting a 2D Gaussian to the collapsed cube of the standard star observations. For the SINFONI observations, the AO correction was not applied for the star, to prevent saturation; the PSF was estimated using an alternative star with a different spatial sampling, observed on the same night. The resulting Gaussian fits are somewhat elliptical; we use the major
### 4.2. Observations and Data Reduction

#### Table 4.1: IC630 Photometry

<table>
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<tr>
<th>Band</th>
<th>Source</th>
<th>Freq. (Hz)</th>
<th>λ (μm)</th>
<th>Flux (Jy)</th>
<th>ΔFlux (Jy)</th>
<th>log L (erg s⁻¹)</th>
<th>Ref</th>
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<td>MWA (150 MHz)</td>
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<td>Skymapper (v)</td>
<td>7.83E+14</td>
<td>3.83E-01</td>
<td>1.39E-02</td>
<td>2.21E-04</td>
<td>43.16</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Skymapper (u)</td>
<td>8.50E+14</td>
<td>3.53E-01</td>
<td>7.76E-03</td>
<td>1.95E-04</td>
<td>42.94</td>
<td>8</td>
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<tr>
<td>UV</td>
<td>GALEX (NUV)</td>
<td>1.30E+15</td>
<td>2.31E-01</td>
<td>4.07E-03</td>
<td>2.99E-05</td>
<td>42.85</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>GALEX (FUV)</td>
<td>1.95E+15</td>
<td>1.54E-01</td>
<td>2.32E-03</td>
<td>4.01E-05</td>
<td>42.78</td>
<td>9</td>
</tr>
<tr>
<td>X ray</td>
<td>ASCA (0.7–2 keV)</td>
<td>3.27E+17</td>
<td>9.18E-04</td>
<td>7.06E-08</td>
<td>3.53E-09</td>
<td>40.49</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>ASCA (0.7–7 keV)</td>
<td>9.35E+17</td>
<td>3.21E-04</td>
<td>4.19E-08</td>
<td>2.10E-09</td>
<td>40.72</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>ASCA (2–10 keV)</td>
<td>1.46E+18</td>
<td>2.06E-04</td>
<td>1.31E-08</td>
<td>6.55E-10</td>
<td>40.40</td>
<td>10</td>
</tr>
</tbody>
</table>


axis FWHM. The results listed in Table 4.4, showing the FWHM PSF in pixels, angular and spatial resolution.

Our optical observations were taken on using the WiFeS instrument (Dopita et al., 2010, 2007) on the Australian National University’s 2.3 m telescope at Siding Spring Observatory. The WiFeS IFU has a 25″ × 38″ field of view and 1″ × 1″ spaxels. The B3000 (3500-5800 Å) and R3000 (5300-9000 Å) gratings were used along with the RT560 dichroic. The instrument was used in ‘Classical Equal’ observation mode, with an average seeing of 2″.
Figure 4.3: Photometric data from Table 4.1 with magphys fit and example similar starburst SED (Arp220).

Table 4.2: Star formation rates for various indicators.

<table>
<thead>
<tr>
<th>Passband</th>
<th>Instrument</th>
<th>Flux</th>
<th>Luminosity</th>
<th>SFR (M_☉ yr⁻¹)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>150 MHz</td>
<td>0.22 Jy</td>
<td>2.1×10^{22} W Hz⁻¹</td>
<td>2.8</td>
<td>3</td>
</tr>
<tr>
<td>Radio</td>
<td>1.4 GHz</td>
<td>0.067 Jy</td>
<td>8.9×10^{21} W Hz⁻¹</td>
<td>3.6</td>
<td>2</td>
</tr>
<tr>
<td>Mid-IR</td>
<td>22.8 μm (W4)</td>
<td>3.9 Jy</td>
<td>6.8×10^{43} erg s⁻¹</td>
<td>10.3</td>
<td>1</td>
</tr>
<tr>
<td>Mid-IR</td>
<td>11.6 μm (W3)</td>
<td>0.7 Jy</td>
<td>2.4×10^{43} erg s⁻¹</td>
<td>5.8</td>
<td>1</td>
</tr>
<tr>
<td>Hα</td>
<td>6562.8 Å</td>
<td>2.77×10^{-12} erg cm⁻² s⁻¹</td>
<td>3.7×10^{41} erg s⁻¹</td>
<td>2.0</td>
<td>5</td>
</tr>
<tr>
<td>Far UV</td>
<td>1538.5 Å</td>
<td>2.20×10^{-13} Jy</td>
<td>5.8×10^{42} erg s⁻¹</td>
<td>2.9</td>
<td>4</td>
</tr>
<tr>
<td>X-ray</td>
<td>0.7-2 keV</td>
<td>2.30×10^{-13} erg cm⁻² s⁻¹</td>
<td>3.1×10^{40} erg s⁻¹</td>
<td>6.8</td>
<td>6</td>
</tr>
<tr>
<td>X-ray</td>
<td>0.7-10 keV</td>
<td>3.90×10^{-13} erg cm⁻² s⁻¹</td>
<td>5.2×10^{40} erg s⁻¹</td>
<td>13.0</td>
<td>6</td>
</tr>
</tbody>
</table>

References. — 1=IRSA AllWISE Catalog, (Wright et al., 2010), 2=NRAO VLA Sky Survey, Condon et al. (1998), 3=MWA GLEAM Survey, (Hurley-Walker et al., 2017), 4=GALEX DR7, 5=Oyakama NCS, Ohyama et al. (1997), 6=ASCA, Ueda et al. (2005).

Note. — Star formation rate indicators are from Brown et al. (2017), except † from Ranalli et al. (2003)
4.2. Observations and Data Reduction

Table 4.3: IC 630 Observation Log (1)

<table>
<thead>
<tr>
<th>Filter</th>
<th>Date</th>
<th>Telescope/Program ID</th>
<th>Standard Star</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wavelength (nm)</td>
<td>Instrument</td>
<td>mag</td>
</tr>
<tr>
<td></td>
<td>Spectral/Velocity Res.*</td>
<td>Spatial Res. (&quot;)</td>
<td>Eff. Temp (K)</td>
</tr>
<tr>
<td>J</td>
<td>11/04/2014</td>
<td>ESO 093.B0461(A)</td>
<td>HIP05501 (B2/B3 V)</td>
</tr>
<tr>
<td></td>
<td>1088-1412</td>
<td>SINFONI</td>
<td>7.88</td>
</tr>
<tr>
<td></td>
<td>2360 / 127</td>
<td>0.1 x 0.1</td>
<td>24000</td>
</tr>
<tr>
<td>H</td>
<td>6/05/2015</td>
<td>Gemini GN–2015A–Q–44</td>
<td>HD88766 (A0V)</td>
</tr>
<tr>
<td></td>
<td>1490-1800</td>
<td>NIFS</td>
<td>7.63</td>
</tr>
<tr>
<td></td>
<td>5300 / 57</td>
<td>0.103 x 0.04</td>
<td>12380</td>
</tr>
<tr>
<td>K</td>
<td>5/05/2015</td>
<td>Gemini GN–2015A–Q–44</td>
<td>HD88766 (A0V)</td>
</tr>
<tr>
<td></td>
<td>1990-2400</td>
<td>NIFS</td>
<td>7.63</td>
</tr>
<tr>
<td></td>
<td>5300 / 57</td>
<td>0.103 x 0.04</td>
<td>12380</td>
</tr>
<tr>
<td>Optical</td>
<td>18/11/2016</td>
<td>ANU 2.3 m 4160069</td>
<td>HD88766 (A0V)</td>
</tr>
<tr>
<td></td>
<td>350-900</td>
<td>WiFeS</td>
<td>7.90 (V)</td>
</tr>
<tr>
<td></td>
<td>3000 / 100</td>
<td>1 x 2</td>
<td></td>
</tr>
</tbody>
</table>

*a/Δλ and km s⁻¹

4.2.2 Data Reduction and Calibration

For the NIFS and SINFONI observations, the standard ancillary nightly calibration data were taken, and the routine data reduction, flux calibration and telluric correction were performed as described in Sections 2.3 and 2.4.1. The spectra were not reduced to the rest frame, as the target lines have good signal-to-noise (S/N), making identification unproblematic. The three final infrared data cubes (one each for J, H and K bands) conveniently all have the same native spatial sampling (0’.05); these were resized so all were 66x66 pixels (3".3 x 3".3), and re-centered to the brightest pixel (the nuclear core), with a field of view of ~540 x 540 pc at the galaxy. With this resolution, the plate scale is 8.2 pc pixel⁻¹.

The optical WiFeS data were reduced in the standard manner using the PyWiFeS reduction pipeline of Childress et al. (2013), with flat-fielding, aperture and wavelength calibration, and flux calibration from the standard star. The spatial pixel scale of 1" is equivalent to 164 pc; the whole field of view is 4.1 x 6.6 kpc. The data reduction produces a data cube for each of the blue and red filters. These were attached together in the wavelength axis and the red cube re-sampled to the same dispersion as the blue cube (0.0774 nm pixel⁻¹). The spectrum at each pixel showed considerable sky background, including skyline emission, especially red-ward of 7200 Å; this background was removed by subtracting the median spectrum of purely sky pixels.
Table 4.4: IC 630 Observation Log (2)

<table>
<thead>
<tr>
<th>Filter</th>
<th>On-target Exp. (s)</th>
<th>Seeing (&quot;(a))</th>
<th>PSF FWHM (pixel)(b)</th>
<th>PSF Res. (&quot;(b))</th>
<th>PSF Res. (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Datasets</td>
<td>Airmass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>600</td>
<td>1.1(c)</td>
<td>4.5</td>
<td>0.225</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1800</td>
<td>0.5</td>
<td>4.5</td>
<td>0.225</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>1800</td>
<td>0.7</td>
<td>5.2</td>
<td>0.26</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.16</td>
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</tr>
<tr>
<td>Optical</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.55</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(a\) Seeing from observer's report (SINFONI and WiFeS) or Mauna Kea Weather Center DIMM archive (NIFS)

\(b\) PSF estimate described below

\(c\) From the collapsed data cubes of the standard stars, the seeing was probably somewhat better; \(\sim 0.5\)"

It is well known that the flux calibration for IFU instruments can produce uncertainties of the order of 10%; our observations are also from 3 different instruments at four separate dates. We therefore cross-checked the calibration against the long-slit infrared observations from Mould et al. (2012). Using the longslit function in the data viewer and analysis package QFitsView (Ott, 2016), we extracted the spectra of a pseudo-longslit from each data cube with the same width and position angle as the Triplespec observations (1"=20 pixels, PA=208°) and compared it with the Mould et al. (2012) long-slit observations. These were plotted together as shown in Fig. 4.4; the three IFU observations are smoothly continuous, demonstrating good flux calibration. These are plotted against a polynomial fit of the Triplespec continuum. The Triplespec continuum is somewhat higher than the IFU fluxes (\(\sim 25\%\)); the long slit takes in more disk light than the 3’.3 IFU FOV, plus there is more scattered light in the IFU optics train. The spectral slopes are in good agreement; however the \(H\) band flux is somewhat higher than expected; this may be due to the minimum of \(H^-\) bound-free and free-free opacity in stellar atmospheres at \(\sim 1600\) nm, or to flux calibration uncertainties. The optical spectrum of the central 3’.3 from the WiFeS data cube is also plotted; the optical and NIR continua are also smoothly continuous.
4.2. Observations and Data Reduction

Figure 4.4: IC 630 Spectra. Top panel: NIR IFU spectra of nuclear region, with Triple-
spec smoothed continuum. The main nebular emission lines are marked, as well as the
molecular CO absorption band-heads in the K band. The vertical axis scales are: left axis
- IFU observations, right axis - Triplespec smoothed continuum fit. 2nd panel: Triplespec
spectrum. Extra nebular lines that are out of the IFU spectral ranges are also marked.
3rd panel: Ratio of IFU to Triplespec flux. Bottom panel: WiFeS optical spectrum, with
main emission lines marked. The emission line flux ratios indicate starburst type.
As described in Section 2.4.3, the SINFONI data cube showed an instrumental fingerprint. An attempt to apply the PCA technique to remove the fingerprints did not succeed, as the fingerprint amplitude is comparable to the data and appeared strongly in the tomogram corresponding to eigenvector E1. As an alternative, we simply interpolated over the fingerprint in the y-axis direction at each spectral pixel.

All plots in this chapter will use the same scale unless otherwise noted, i.e. $3'' \times 3''$. a side FOV (540 x 540 pc, 1 pixel = 8.2 pc), with North being up, and East to the left. For the WiFeS optical images, the plots are $20''$ a side FOV (3.3 x 3.3 kpc, 1 pixel = 164 pc). The RA and Dec values are given relative to the nuclear cluster center. Note the scale lengths of 0'0.5 and 50 pc.

### 4.3 Results

#### 4.3.1 Continuum Emission

The nuclear region stellar structure is revealed by the continuum emission. Fig. 4.5 presents the stellar light around the nucleus, showing the individual J, H, K and V band surface brightness maps in units of magnitude per square arcsec. These were extracted from the respective data cubes by averaging over the 10 nm around filter effective wavelengths, dividing by the pixel area and converting to magnitude (see Section 2.4.2).

In the NIR, the nuclear region (labeled ‘N’) presents as a central clump with half-light radius of about 50 pc. There are 3 secondary features, a ridge at PA=240° extending about 90 pc (labeled ‘2’) and two local light maxima at (PA/radius) 73°/130pc and 175°/125pc (labeled ‘1’ and ‘3’). The ridge extension has a hint of a spiral structure. These features are more prominent in the H and K bands than the J band, which is consistent with greater penetration through the dust at longer wavelengths. The H band data also has somewhat better spatial resolution than the K band.

The flux density for the nuclear cluster can be estimated by fitting a 2D Gaussian to the K band image (the least obscured data); this is $8.0 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ nm$^{-1}$. The Gemini Observatory flux to magnitude calculator converts this flux value to a magnitude of 14.4 for an effective wavelength of 2120 nm. At the distance magnitude of 32.6 (giving an absolute magnitude of -18.2) and the Solar K band magnitude of 3.28 (Binney & Merrifield, 1998), this gives a luminosity $L = 3.9 \times 10^8$ L$_\odot$.

Comparing a Gaussian fit to each of the secondary features, the FWHM of each is comparable to or just marginally larger than that of the standard star; therefore we cannot
4.3. Results

Figure 4.5: First, second and third panel: $J$, $H$ and $K$ band surface brightness. Labels (in blue) are the nuclear cluster/disk (‘N’), secondary clusters (‘1’ and ‘3’) and the ridge-like feature (‘2’). The contour values are chosen to delineate the features. Fourth panel: Optical ($V$) surface brightness - note the change of spatial scale. The central square indicates the NIR IFU fields of view. All values are in mag arcsec$^{-2}$.

say that these clusters are resolved. The optical surface brightness from the WiFeS data shows a featureless bulge; the nucleus is offset like the PanSTARRS $g$ image.

Stellar colors, indicative of population age and obscuration, are shown in the false-color continuum image (Fig. 4.6, left panel). This image was created by layering the $J$, $H$ and $K$ filter total flux values (using blue, green and red colors, respectively). The individual images have been smoothed by a 2D Gaussian at 2 pixels width to remove pixellation; the colors have also been enhanced to bring out the salient features. The slight east-west elongation of the features is due to the resizing of the SINFONI pixels in the data reduction process. The right-hand panel of Fig. 4.6 shows the $H - K$ magnitude; the $J$-band magnitude was not used, as the interpolation to remove the instrumental fingerprint obscures cluster ‘3’. Due to flux calibration uncertainties of $\sim 10\%$, the value of $H - K$ is...
uncertain by about 0.1 mag; however the relative magnitude differences will be the same. The $H$-band magnitude contours are over-plotted, with the same values as in Fig. 4.5.

The nucleus and other cluster features have lower $H - K$ magnitudes, indicative of bluer (younger) stellar populations. The extinction corrected colors can be used to assign a stellar type; see Section 4.4.5. The prominent band of redder color from W to NE is probably due to dust obscuration, rather than a stellar population difference; this can be seen as the dust band in Figs. 4.1 and 4.2 crossing north of the nucleus. This obscuration is also matched with the $H_2$ emission; see Section 4.4.2 below.

![Figure 4.6: Left panel: Continuum 3 Color Image ($J$=blue, $H$=green, $K$=red). Right panel: $H - K$ color (in mag). The black contour plot is the $H$-band surface brightness, as per Fig. 4.5 (second panel). The clusters have bluer colors, indicating younger stellar populations than the field.](image-url)

### 4.3.2 Stellar Kinematics

The stellar kinematics were investigated using the CO band-heads in the range 2293–2355 nm, using the penalized pixel-fitting (pPXF) method of Cappellari & Emsellem (2004). The Gemini spectral library of near-infrared late-type stellar templates from Winge et al. (2009) was used, specifically the NIFS sample version 2. The observed $K$-band data cube was reduced to the rest frame (using $z=0.007277$, equivalent to a velocity of $2182 \text{ km s}^{-1}$) and normalized. Both the observations and template trimmed to the wavelength range of 2270–2370 nm. We followed the example code for kinematic analysis from the website\(^4\). The ‘Weighted Voronoi Tessellation’ (WVT) (Cappellari & Copin, 2003) was used to

\(^4\)http://www-astro.physics.ox.ac.uk/~mxc/software/#ppxf
increase the S/N for pixels with low flux; we use the voronoi procedure in QfitsView. This aggregates spatial pixels in a region to achieve a common S/N. This needs both signal and noise maps; these are obtained from the fit and error of the stellar velocity dispersion value at each pixel calculated by the pPXF routine; in this case the S/N target was 250. Fig. 4.7 displays the results. The velocity field has a range of ±40 km s$^{-1}$ and shows no sign of ordered rotation. The zero value of the velocity was set as the median value returned from the pPXF code (31.5 km s$^{-1}$, compared to the instrumental velocity resolution of 57 km s$^{-1}$). The velocity dispersion range is 30–80 km s$^{-1}$.

![Figure 4.7: Stellar kinematics from CO band-heads, showing a lack of ordered rotation and reasonably flat dispersion distribution. Left panel: velocity. Right panel: velocity dispersion. Values in km s$^{-1}$. The contours are the K-band flux, in the range 10 – 90% in steps of 20% of the maximum value.](image)

The SMBH mass can be calculated as per Section 2.6.5. Using the $M - \sigma$ relationship with the Graham et al. (2011) parameters for elliptical galaxies and using a velocity dispersion of 43.9 (± 4.8) km s$^{-1}$ (the average value and standard deviation of the central 1'' of the velocity dispersion map), we obtained $M_\bullet = 2.25 (+5.1, -1.6) \times 10^5$ M$_\odot$. This should be regarded as an upper limit, as the relationship is derived only down to 60 km s$^{-1}$; however see Graham et al. (2016) on the galaxy LEDA 87300.

Other derivations of the $M - \sigma$ relationship are given in Table 2.6; for early-type galaxies (McConnell & Ma, 2013) we get $M_\bullet = 4.2 (+1.8, -3.4) \times 10^4$ M$_\odot$, from Kormendy & Ho (2013), $M_\bullet = 3.9 (+5.9, -2.4) \times 10^5$ M$_\odot$. These rather wide error estimates indicate the possibility that there is no SMBH in the nucleus of this galaxy (within 1.4, 1.2 and 1.6 $\sigma$, respectively). If a BH of that mass exists, the sphere of influence is less that 1 pc.
To confirm this small SMBH size, a Sérsic index was fitted to the 2MASS K$_S$ image, using the \texttt{Galfit3} application (Peng et al., 2009). This found an index of 0.824; using the relationship of Savorgnan et al. (2013), we derive $M_\bullet = 1.14 \times 10^5 \, M_\odot$, compatible with the value derived from the stellar velocity dispersion.

The possible mis-classification of this object’s morphology (S0), where there may be no or a very small bulge, is then consistent with the small BH size.

The bolometric luminosity, Eddington ratio and accretion rate are derived for this object, as described in Section 2.6.5. Using the X-ray flux of $1.9 \times 10^{-13} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ (Ueda et al., 2005) and the BH mass computed from the Graham et al. (2011) relationship, this gives the following results. The luminosity is within the range for a low-luminosity AGN (LLAGN) (Ho, 2008).

$$L_X = 2.53 \times 10^{40} \, \text{erg s}^{-1}$$
$$L_{Bol} = 4.05 \times 10^{41} \, \text{erg s}^{-1}$$
$$R_{Edd} = 1.4 \times 3.3, -0.98 \times 10^{-2}$$
$$M_{acc} = 7.4 \times 10^{-5} \, M_\odot \, \text{yr}^{-1}$$

If the AGN is heavily obscured, the value of $L_X$ (2–10 keV) will be underestimated (Winter et al., 2009). An alternative proxy of the bolometric luminosity is the [O III] emission line luminosity. We use Equations 2.63 and 2.65 with the observed fluxes from within 2″ radius of the nucleus from the WiFeS data cube. The [O III], H$\alpha$ and H$\beta$ fluxes are 3.02, 16.2 and $4.91 \times 10^{-13} \, \text{erg cm}^{-2} \, \text{s}^{-1}$. This gives a value for $L_C[\text{O III}] = 6.2 \times 10^{40} \, \text{erg s}^{-1}$ and $L_{Bol} = 8.8 \times 10^{42} \, \text{erg s}^{-1}$. This is over an order of magnitude higher than the value given by the $L_X$ relationship. The Eddington ratio and accretion rates are correspondingly increased, $R_{Edd} = 0.3$ and $M_{acc} = 1.63 \times 10^{-3} \, M_\odot \, \text{yr}^{-1}$. The Eddington ratio, in particular, seems unreasonably high for this class of object; the majority of the [O III] flux must be coming from vigorous nuclear star formation with the W-R stars providing the UV photo-ionizing flux, as indicated by the excitation regime. The BPT and IR classifications (as given in Section 4.3.4.2) supports this, showing minimal (if any) AGN activity.

### 4.3.3 Extinction

The visual extinction is proportional to the column density of dust in the LOS. The $H - K$ color map can be extended and quantified by using measures of extinction, as described in Section 2.6.2. The visual extinction is derived from the line ratios Pa$\beta$/Br$\gamma$, etc.
4.3. Results

Pa$\gamma$/Pa$\beta$, H$\alpha$/H$\beta$ and [Fe II]1257/1644 nm, with a galactic foreground extinction of 0.16 mag (Schlafly & Finkbeiner, 2011). The flux maps for the emission lines are shown in Fig. 4.8. The maps are presented in Fig. 4.9, showing the $A_V$ derived from the various line ratios. The values have been smoothed to reduce pixellation from misalignment. The values have a lower limit of zero (a negative number is unphysical or indicative of an incorrect theoretical line ratio). The average, maximum and minimum values derived from the various line ratios are shown in Table 4.5. The extinction from the [Fe II] lines
with a flux ratio of 1.03 has not been plotted, as it produces negative values over almost the whole field. For the NIR spectral lines, the plots show patchy extinction, but none of

**Table 4.5:** $A_V$ average, median, standard deviation and median deviation (magnitude, to 1 decimal place). For the [Fe II] derived extinction, the two values for the expected flux ratio are shown – 1.03 (Quinet et al., 1996) and 1.36 Nussbaumer & Storey (1988)

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa $\beta$/Br $\gamma$</td>
<td>0.9</td>
<td>0.9</td>
<td>0.6</td>
<td>0.5</td>
</tr>
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<td>[Fe II] (1.03)</td>
<td>1.2</td>
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<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>[Fe II] (1.36)</td>
<td>2.9</td>
<td>2.8</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Pa $\gamma$/Pa $\beta$</td>
<td>2.3</td>
<td>2.4</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>H $\beta$/H $\alpha$</td>
<td>0.9</td>
<td>0.8</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

the methods line up spatially with each other (except for the two areas of high extinction in [Fe II] 1257/1644 and Pa $\beta$/Br $\gamma$, at (0'''.45,-1'''.0) and (0''.75,0''.25) in relative RA and Dec. We hypothesize that this is caused by several effects:

- The [Fe II] and H recombination emissions come from gas in different excitation states which are not co-located and therefore have different LOS optical depths.
- The Pa $\beta$/Br $\gamma$ and the [Fe II] emissions are measured from different data cubes with pixel to pixel variations both from alignment and calibration. These are also subject to the instrumental fingerprint in the $J$-band cube mentioned above.
- The Pa $\gamma$/Pa $\beta$ ratios (which presumably do not suffer from calibration problems) are sensitive to flux measurement errors, which cause large variations since the wavelengths are close together, which sets a large value of $\alpha_{\lambda_{1},\lambda_{2}}$ in Equation 2.19 (see Table 2.3).
- While the theoretical flux ratios of the hydrogen recombination lines are weak functions of temperature and density, the intrinsic ratio to compute the Balmer decrement (i.e. the H $\alpha$/H $\beta$ ratio) can vary from 2.85 to 3.67 over the range ($10^4$ K, $10^4$ cm$^{-3}$) to ($10^3$ K, $10^2$ cm$^{-3}$) for ($T_e$, $n_e$). The standard values for H II regions is taken as 2.86, for AGN as 3.1 (Kewley et al., 2006). This can change the resulting $A_V$ by $\sim$0.5 mag.

Since there is no definitive pattern of extinction, we will use a single average value ($A_V = 1.0$) over the whole field to derive the extinction correction. Using the Cardelli reddening law, the ratio $A_\lambda/A_V$ is 0.287, 0.178 and 0.117 (an increase in surface brightness of the same values in magnitudes) for the $J$, $H$ and $K$ band filters respectively. The de-reddened $H - K$ map values are decreased by only 0.06 magnitude.
4.3. Results

Figure 4.9: Extinction maps, using the emission line flux ratios as labeled. The color-bars give the $A_V$ value in magnitudes. The contour plot in the NIR ratio panels is the H-band flux, with the contours being 0.1–0.9 in steps of 0.2 of the maximum flux. For the visual ratio panels, the contour plot is the V-band flux with the same steps. Note the different axis scale for the V-band maps. The 1.36 flux ratio for the [Fe II] lines is preferred.

4.3.4 Gas Fluxes, Kinematics, Excitation and Star Formation

4.3.4.1 Nebular Emission

The nuclear gas structure is revealed using the techniques described in Section 2.5.3; the kinematic and flux maps were created from the data cubes. Table 4.6 shows the relevant
emission line fluxes that was measured at three locations, the nucleus and the locations of the [Fe II] and H₂ maxima. The absence of any flux from high ionization species indicates a lack of X-ray emission from an AGN; specifically [Ca VIII] 2321 nm with ionization potential (IP) = 127 eV is not present. Similarly, Table 4.7 shows the optical emission line fluxes.

Table 4.6: Integrated flux for emission lines for the nucleus (F₁), [Fe II] maximum (F₂) and H₂ (F₃) maximum locations, with their respective uncertainties (ΔF), within 0''0.25 × 0''0.25 apertures. Flux values are in 10⁻¹⁶ erg cm⁻² s⁻¹.

<table>
<thead>
<tr>
<th>Species</th>
<th>λ (nm) (Air)</th>
<th>λ (nm) (Obs)</th>
<th>F₁</th>
<th>ΔF₁</th>
<th>F₂</th>
<th>ΔF₂</th>
<th>F₃</th>
<th>ΔF₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa γ</td>
<td>1094.1</td>
<td>1102.1</td>
<td>160.28</td>
<td>2.69</td>
<td>120.62</td>
<td>1.66</td>
<td>77.86</td>
<td>1.10</td>
</tr>
<tr>
<td>[P II]</td>
<td>1188.6</td>
<td>1197.2</td>
<td>10.00</td>
<td>0.83</td>
<td>7.10</td>
<td>0.69</td>
<td>5.13</td>
<td>0.69</td>
</tr>
<tr>
<td>[Fe II]</td>
<td>1256.7</td>
<td>1265.8</td>
<td>22.83</td>
<td>1.03</td>
<td>26.21</td>
<td>0.76</td>
<td>21.79</td>
<td>0.48</td>
</tr>
<tr>
<td>Pa β</td>
<td>1282.2</td>
<td>1291.5</td>
<td>277.72</td>
<td>0.41</td>
<td>215.31</td>
<td>2.69</td>
<td>145.10</td>
<td>2.34</td>
</tr>
<tr>
<td>[Fe II]</td>
<td>1533.5</td>
<td>1544.7</td>
<td>4.13</td>
<td>0.69</td>
<td>3.79</td>
<td>0.44</td>
<td>2.51</td>
<td>0.31</td>
</tr>
<tr>
<td>[Fe II]</td>
<td>1643.6</td>
<td>1655.6</td>
<td>14.19</td>
<td>0.81</td>
<td>18.19</td>
<td>0.81</td>
<td>15.94</td>
<td>0.56</td>
</tr>
<tr>
<td>H₂ 1-0 S(9)</td>
<td>1687.7</td>
<td>1700.0</td>
<td>1.89</td>
<td>0.52</td>
<td>1.20</td>
<td>0.38</td>
<td>0.34</td>
<td>0.19</td>
</tr>
<tr>
<td>He I</td>
<td>2059.7</td>
<td>2074.7</td>
<td>27.28</td>
<td>0.66</td>
<td>18.80</td>
<td>0.56</td>
<td>13.41</td>
<td>0.56</td>
</tr>
<tr>
<td>H₂ 2-1 S(3)</td>
<td>2073.5</td>
<td>2088.6</td>
<td>0.50</td>
<td>0.14</td>
<td>0.44</td>
<td>0.09</td>
<td>0.42</td>
<td>0.09</td>
</tr>
<tr>
<td>H₂ 1-0 S(1)</td>
<td>2121.3</td>
<td>2136.7</td>
<td>1.51</td>
<td>0.19</td>
<td>1.38</td>
<td>0.19</td>
<td>1.65</td>
<td>0.09</td>
</tr>
<tr>
<td>Br γ</td>
<td>2166.1</td>
<td>2181.9</td>
<td>35.49</td>
<td>1.27</td>
<td>26.25</td>
<td>0.98</td>
<td>18.80</td>
<td>1.03</td>
</tr>
<tr>
<td>H₂ 1-0 S(0)</td>
<td>2223.3</td>
<td>2239.5</td>
<td>1.42</td>
<td>0.09</td>
<td>0.62</td>
<td>0.09</td>
<td>0.56</td>
<td>0.09</td>
</tr>
<tr>
<td>H₂ 2-1 S(1)</td>
<td>2247.7</td>
<td>2264.1</td>
<td>0.55</td>
<td>0.14</td>
<td>0.44</td>
<td>0.09</td>
<td>0.55</td>
<td>0.09</td>
</tr>
<tr>
<td>H₂ 1-0 Q(1)</td>
<td>2406.6</td>
<td>2424.1</td>
<td>1.37</td>
<td>0.14</td>
<td>1.60</td>
<td>0.19</td>
<td>1.86</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 4.7: Optical integrated flux for emission lines from nuclear region (2″ radius). Flux values are in 10⁻¹⁴ erg cm⁻² s⁻¹.

<table>
<thead>
<tr>
<th>Species</th>
<th>λ (Vac) (nm)</th>
<th>λ (Obs) (nm)</th>
<th>F</th>
<th>ΔF</th>
</tr>
</thead>
<tbody>
<tr>
<td>[O II]</td>
<td>372.7</td>
<td>375.4</td>
<td>47.30</td>
<td>2.88</td>
</tr>
<tr>
<td>H γ</td>
<td>434.2</td>
<td>437.3</td>
<td>10.36</td>
<td>0.85</td>
</tr>
<tr>
<td>H β</td>
<td>486.3</td>
<td>489.8</td>
<td>27.87</td>
<td>0.78</td>
</tr>
<tr>
<td>[O III]</td>
<td>496.0</td>
<td>499.6</td>
<td>15.13</td>
<td>0.38</td>
</tr>
<tr>
<td>[O III]</td>
<td>500.8</td>
<td>504.5</td>
<td>32.19</td>
<td>0.84</td>
</tr>
<tr>
<td>He I</td>
<td>587.7</td>
<td>592.0</td>
<td>5.00</td>
<td>0.29</td>
</tr>
<tr>
<td>[O I]</td>
<td>630.2</td>
<td>634.8</td>
<td>1.95</td>
<td>0.09</td>
</tr>
<tr>
<td>[N II]</td>
<td>655.0</td>
<td>659.8</td>
<td>10.98</td>
<td>1.12</td>
</tr>
<tr>
<td>H α</td>
<td>656.5</td>
<td>661.2</td>
<td>164.60</td>
<td>5.38</td>
</tr>
<tr>
<td>[N II]</td>
<td>658.5</td>
<td>663.3</td>
<td>30.62</td>
<td>0.91</td>
</tr>
<tr>
<td>He I</td>
<td>668.0</td>
<td>672.9</td>
<td>1.99</td>
<td>0.17</td>
</tr>
<tr>
<td>[S II]</td>
<td>671.8</td>
<td>676.7</td>
<td>11.02</td>
<td>0.37</td>
</tr>
<tr>
<td>[S II]</td>
<td>673.3</td>
<td>678.2</td>
<td>10.87</td>
<td>0.35</td>
</tr>
<tr>
<td>[S III]</td>
<td>907.1</td>
<td>913.2</td>
<td>21.86</td>
<td>0.59</td>
</tr>
</tbody>
</table>
4.3. Results

Figure 4.10: Emission lines fluxes and equivalent widths (corrected for extinction). Top row: emission line flux; scale bar is flux in units of $10^{-16}$ erg cm$^{-2}$ s$^{-1}$, contours are at 10, 25, 50 and 75% of the maximum value. Bottom row: equivalent width, scale bar in nm. The blue ‘+’ symbol marks the location of the nuclear cluster.

Fig. 4.10 presents the maps of emission line fluxes and equivalent widths for the main species; each column is labeled with the species and rest frame wavelength.

4.3.4.2 Gaseous Excitation

Gas emission line diagnostics allow the source of the excitation to be determined. We use the techniques from Section 2.6.4 to map the excitation regimes of excited gas; Fig. 4.11 maps the ratios for each pair of emission lines. Specific locations of interest are also plotted with symbols; the nucleus, the H$_2$ and [Fe II] flux maxima and clusters ‘1’ and ‘3’ from the continuum plots. The [Fe II]/Pa ratio has a range of 0.03 to 0.44, with the lowest value in the center and the highest value in the SW region, located about 215 pc from the center. The H$_2$/Br $\gamma$ ratio has a range 0.03 to 0.37, with a similarly located peak to the SW.

Fig. 4.11 also plots the density diagram for the values at each spaxel of log([Fe II]/Pa $\beta$) against log(H$_2$/Br $\gamma$), with the excitation mode regions (SF, AGN and LINER) delineated and with the locations of interest plotted with symbols. The straight-line fit to the points (the blue line in Fig. 4.11) is:

$$\log \left( \frac{\text{[Fe II]}}{\text{Pa} \beta} \right) = 0.558(\pm 0.1) \times \log \left( \frac{\text{H}_2}{\text{Br} \gamma} \right) - 0.130(\pm 0.091)$$
Figure 4.11: Infrared excitation diagram. Left panel: flux ratio \( [\text{Fe II}] / \text{Pa} \beta \), with H band flux is over-plotted with black contours. Middle panel: \( \text{H}_2 / \text{Br} \gamma \). Right panel: excitation map of log-log plot of flux ratios. Contour levels at 1, 5, 10 and 50% of maximum. The locations of interest are shown with symbols in the middle and right panel. The straight-line fit to the data is plotted in blue dashed line; the fit from Riffel et al. (2013a) as a green dashed line. The excitation is almost uniformly in the stellar photo-ionization regime, except for peripheral regions where the flux values are more uncertain.

The high correlation coefficient \( (r = 0.79) \) indicates that this relationship can be used to determine the excitation mode from just one set of measurements, e.g. from the \( J \) band spectrum when \( K \) band is not available. Similarly, Fig. 4.12 plots the BPT excitation diagram and the spaxel density diagram for the optical as defined in Kewley et al. (2006), using the \( [\text{N II}] / \text{H} \alpha \) and \( [\text{O III}] / \text{H} \beta \) flux ratios.

4.3.4.3 Gas Kinematics

Fig. 4.13 presents maps of the LOS velocities and dispersions of \( \text{Br} \gamma \), \( [\text{Fe II}] 1644 \) nm and \( \text{H}_2 \). All LOS velocities have been set so that the zero is the median value. The maps for \( \text{H} \alpha \) are presented in Fig. 4.14, showing the flux, equivalent width, LOS velocity and dispersion. The systemic velocity fields of the stars and gas from the central wavelength average around the nucleus were compared, after reduction to rest frame; these vary from \( +7 \) km s\(^{-1}\) (\( \text{Br} \gamma \)) to \( +40 \) km s\(^{-1}\) (stars). These are all within the measurement error (\( \pm 55 \) km s\(^{-1}\) for NIFS and \( \pm 125 \) km s\(^{-1}\) for SINFONI). Heliocentric corrections for different observations dates were \(< 7 \) km s\(^{-1}\).

4.3.4.4 Channel Maps

In order to map the flux distributions at all velocities covered by the emission line profiles and to assist delineating gas flows, we construct channel maps along the profile of the
4.3. Results

Figure 4.12: Optical excitation diagram. Left panel: flux ratio \([\text{N II}]/\text{H}\alpha\) (V-band flux overplotted in contours of 10, 30, 50, 70 and 90% of maximum). Middle panel: \([\text{O III}]/\text{H}\beta\) (white square is FOV of the NIR IFU instruments, for comparison). Right panel: excitation map of log-log plot of flux ratios. Contour levels at 1, 5, 10 and 50% of maximum. We can deduce the same conclusions as for the infrared diagram, i.e. the excitation is almost uniformly in the stellar photo-ionization regime.

\(\text{Br}\gamma, \text{[Fe II]}\ 1644\ nm\) and \(\text{H}_2\) emission. The maps were constructed by subtracting the continuum height, derived from the velocity map function \(\text{velmap}\), from the data cube. The spectral pixels are velocity binned and smoothed to reduce noise. Figs. 4.15, 4.16 and 4.17 show the derived channel maps for \(\text{Br}\gamma, \text{H}_2\) and \(\text{[Fe II]}\ 1644\ nm\), respectively. The \(\text{[Fe II]}\ 1644\ nm\) line is used rather than the \(\text{[Fe II]}\ 1257\ nm\) line, because of the \(J\) cube instrumental fingerprint. Note that the fluxes are rescaled on each map to bring out the structure, rather than share a common scale across all maps.
Figure 4.13: LOS velocity and dispersion for Br$\gamma$, [Fe II] 1656nm and H$_2$. Top row: velocity. Bottom row: dispersion. Bottom panels: velocity and dispersion histograms. All values are in km s$^{-1}$. The kinematics exhibit neither ordered rotation or organized outflows.
4.3. Results

Figure 4.14: H α flux and kinematic maps. Top left: flux (units of $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$) (V-band flux overplotted in contours of 10, 30, 50, 70 and 90% of maximum). Top right: equivalent width in nm. Bottom left: LOS velocity. Bottom right: LOS dispersion. Again, no evidence of organized rotation or outflows is visible.
Figure 4.15: Channel maps for Br $\gamma$. Each channel has a width of 60 km s$^{-1}$, with the channel central velocity shown in the top left corner of each plot. The blue cross is the position of the nucleus. Color values are fluxes in units of $10^{-18}$ erg cm$^{-2}$ s$^{-1}$. Positive velocities are receding, negative are approaching. The white contour on the +30 km s$^{-1}$ channel is the $K$ band continuum flux, at levels of 10, 25, 50, 75 and 90 % of maximum.
Figure 4.16: Channel maps for H₂. Channel widths are 40 km s⁻¹. Values are fluxes in units of 10⁻¹⁸ erg cm⁻² s⁻¹. Contours as per Fig. 4.15.
Figure 4.17: Channel maps for [Fe II] 1644 nm. Channel width are 60 km s\(^{-1}\). Values are fluxes in units of 10\(^{-18}\) erg cm\(^{-2}\) s\(^{-1}\). Contour is the \(J\) band continuum flux, as per Fig. 4.15
4.4 Discussion

4.4.1 Black Hole Mass and Stellar Kinematics

The stellar kinematic results presented above show no ordered rotation and have a flat velocity dispersion structure. We can therefore conclude that in the central region, the stellar dynamics are either face-on or pressure supported. The first is favored from the associated gas dynamics (see below), and the fact that this object is a S0 galaxy, which will have stellar rotation.

Ho (2008) sets out statistics for LLAGN (table 1 in the reference); the X-ray luminosity ($2.5 \times 10^{40}$ erg s$^{-1}$) indicates a spectral class somewhere between Seyfert 1 and 2. The measured Eddington ratio ($R_{Edd}$) is somewhat high for this class range, but this could be due to the uncertainties in the $M_\bullet$ measurement, plus emission from SN remnants and unresolved point sources, e.g high-mass X-ray binaries (Mineo et al., 2013). This could be the major component of the X-ray emission, with minimal contribution from any SMBH. It is also noted that the uncertainties in $R_{Edd}$ are not inconsistent with a value of zero, i.e. with no SMBH luminosity and X-ray emission solely from star formation/X-ray binaries.

4.4.2 Emission Line Properties and Diagnostics

The gas emission line flux and kinematic plots presented above allow the determination of the source, flows and excitation of the various atomic and molecular species in the nuclear region. The Br$\gamma$ and He I fluxes show strong central concentration, contiguous with the nuclear cluster. This emission is from star-forming regions. On the other hand, the [Fe II] and H$_2$ fluxes are located distinctly off-center. The [Fe II] peak is some 55 pc to the SW of the central cluster, roughly contiguous with the ridge feature ‘2’. The H$_2$ flux maximum is at a different location due west about 50–80 pc from the center.

The Br$\gamma$ and He I equivalent widths show a similar structure; there is relatively less star-formation in the nuclear cluster, with the peak being in a rough ring about 50–80 pc from the center. The [Fe II] and H$_2$ maximum values track their respective flux structures; the central ‘hole’ is also visible in these maps. These species are photo-ionized or dissociated by the UV flux from the young stars in the nuclear cluster.

To get a better sense of the relative locations of the emission from each species, we have constructed a color map (Fig. 4.18), where Pa$\beta$ is in blue, [Fe II] in red and H$_2$ in green. The colors have again been somewhat enhanced to reveal the features; this show the central concentration of ionized hydrogen, with the [Fe II] wrapping around it and the H$_2$ as a separate feature.
As described in Section 2.6.4.3, the [Fe II] and [P II] 1188.6 nm emission lines can be used to diagnose the relative contribution of photo-ionization and shocks. The flux ratio over the field varies from 2.7 in the nucleus to 7.4 at the highest [Fe II]/Pa β excitation ratio location (in the SW corner of the field); this indicates that photo-ionization is the main excitation mode over most of the field, with an increased shock contribution at the more AGN-like excitation locations.

To determine the electron density, we use the ratio of [Fe II] 1533/1644 nm and the method of Storchi-Bergmann et al. (2009). Measured over a region of 0″.25 × 0″.25 at the nucleus (0.27 ± 0.05) and at the location of the maximum [Fe II] emission (0.19 ± 0.02), values of \( \sim 3.2 \times 10^4 \text{ cm}^{-3} \) (at the nucleus) and \( \sim 0.8 \times 10^4 \text{ cm}^{-3} \) (at the [Fe II] maximum) were derived. Over the whole field, the [Fe II] 1533 nm flux was difficult to determine (having considerable noise), but values in the range \( 1.4 \times 10^4 < n_e < 6 \times 10^4 \text{ cm}^{-3} \) are obtained where it can be measured. These values are consistent with their findings for NGC 4151. We can also use the ratio [Fe II] 1533/1257 (using the Nussbaumer & Storey, 1988, ratio), and obtain similar values, \( 1 \times 10^4 < n_e < 3.2 \times 10^4 \text{ cm}^{-3} \).

As described in Section 2.6.4.2, the excitation mode for H\(_2\) (i.e. thermal vs. fluorescent processes) is diagnosed by the line ratio H\(_2\) 2–1 S(1)/1–0 S(1). At the location of the
maximum H$_2$ flux, the ratio is measured as 0.32 ± 0.05, indicating thermal processes. Since AGN-like excitation is minimal over the whole field and therefore X-rays from an accretion disk heating are absent, we conclude that shocks are the main excitation mode for H$_2$. The presence of the H$_2$ 2-1 S(3) indicates that no X-rays are present, supporting that conclusion.

We can also compute the ro-vibrational temperatures from the ratios H$_2$ 1-0 S(2)/1-0 S(1) (1.14 ± 0.38) and H$_2$ 2-1 S(1)/1-0 S(1) (Equations 2.35 and 2.36), and derive $T_{\text{rot}(\nu=1)} = 1115 ± 625$ K and $T_{\text{vib}} = 3860 ± 430$ K. The placement on the diagnostic diagram (Fig. 4.19) indicates that the H$_2$ is not in local thermodynamic equilibrium, and there is a significant contribution of non-thermal fluorescent excitation. Davies et al. (2003, 2005) shows that the lower $\nu = 1 − 0$ levels may be thermalised, but the $\nu = 2 − 1$ levels can be overpopulated due to fluorescent excitation by far-ultraviolet photons. This is consistent with the presence of large numbers of W-R stars.

![Figure 4.19: H$_2$ diagnostic diagram (Mouri, 1994) for the peak H$_2$ flux region, showing roughly equal thermal and non-thermal contributions.](image)

The excitation temperatures of the H$_2$ gas is derived from the method outlined in Wilman et al. (2005) (Section 2.6.4.2). To improve the signal to noise, the spaxels in the K-band data cube were summed where the H$_2$ flux was greater than $10^{-18}$ erg cm$^{-2}$ s$^{-1}$, and the fluxes of the resulting spectrum were measured by fitting a Lorentzian curve to each spectral line. As seen in Fig. 4.20, the observed fluxes fit a straight line reason-
able well. The resulting excitation temperature (the inverse of the fitted line slope) are $T_{\text{exc}} = 2565(\pm 145, -130)$ K. This is in line with the values for several Seyfert galaxies (e.g. Riffel et al. (2015); Storchi-Bergmann et al. (2009); Riffel et al. (2014b); Riffel & Storchi-Bergmann (2011); Riffel et al. (2010)) which are in the range 2100–2700 K. Checking whether the low vs. high excitation lines are significantly different, we derive temperatures of $720(\pm 695, -235)$ K and $1435(\pm 1340, -470)$ K, respectively. It is possible that there are multiple gas components present.

![Figure 4.20: H$_2$ temperature diagnostics using the relationship between $\ln(N_{\text{upper}})$ and $E_{\text{upper}}$ for the H$_2$ transitions. The fits are to the low-excitation (red) and high-excitation (blue) transitions, as well as for all transitions (black). The individual transitions are labeled.](image)

We have noticed a correlation between the locations of the H$_2$ and [Fe II] fluxes and the H – K colors; this is shown in Fig. 4.21, which maps the H$_2$ and [Fe II] equivalent width overplotted with contours of the H – K color; the EW-color correlation is more apparent than for flux-color. We speculate that this is due to the dust shielding the molecular gas from the photo-ionizing radiation of the young stars in the clusters; the [Fe II] ions can only exist in partially ionized regions that are some distance from the many W-R stars.

The electron temperature and density from the WiFeS optical spectrum can be calculated using the methods described in Section 2.6.4.4, using the [N II] flux ratios for temperature and the [S II] flux ratios for the density. In the inner 2'', the temperature is
4.4. Discussion

Figure 4.21: $H_2$ and [Fe II] equivalent width (color map) vs. $H - K$ color (contours). The white crosses are the cluster locations. The color-bar scales are the EW in nm. The shows the correlation between higher values of $H - K$ and the equivalent width of $H_2$ and [Fe II]. For $H_2$ this may be due to dust shielding molecular gas from the ionizing radiation of young stars. [Fe II] can only exist in partially ionized regions, away from the clusters.

$\sim 8630$ K and the density is $\sim 670$ cm$^{-3}$. In the annulus from 2 to 5", the temperature and density are calculations are more uncertain, due to the weakness of the [N II] $\lambda 5754$ line; they are $7500 \pm 2500$ K and $280 \pm 40$ cm$^{-3}$.

4.4.3 Gas Masses

The cold gas column density is derived from from the visual extinction value and the hot $H$ II and $H_2$ masses from the respective fluxes (Section 2.6.3.1). Using average extinction $A_V$ of 1 mag, the masses and surface densities in the central region are given in Table 4.8, as calculated from Equations 2.24 to 2.27.

Table 4.8: Gas Masses. Masses within the maximum value pixel, within 100 and 200 pc of center and over the whole field, plus the surface density within the central 100 and 200 pc.

<table>
<thead>
<tr>
<th>Species</th>
<th>Max. Pixel $^a$</th>
<th>$M_\odot$ 100 pc</th>
<th>$M_\odot$ 200 pc</th>
<th>$M_\odot$ (Total)$^b$</th>
<th>$M_\odot$pc$^{-2}$ 100 pc</th>
<th>$M_\odot$pc$^{-2}$ 200 pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$ II</td>
<td>426</td>
<td>$5.9 \times 10^6$</td>
<td>$1.02 \times 10^7$</td>
<td>$1.12 \times 10^7$</td>
<td>191</td>
<td>81</td>
</tr>
<tr>
<td>$H_2$ (warm)</td>
<td>$3.8 \times 10^{-3}$</td>
<td>69</td>
<td>149</td>
<td>184</td>
<td>$2.2 \times 10^{-3}$</td>
<td>$1.2 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

$^a$ Pixel with greatest flux or highest density.

$^b$ Over whole field where valid measurement.
The cold H$_2$ mass is estimated as $1.5 \times 10^8$ M$_\odot$. This estimate is greater than the ISM mass derived from extinction, even at the lower estimate of the scaling relationship with warm H$_2$. This could be because in this environment the dust grains which cause the extinction are being evaporated by the star formation photo-ionization, thus reducing the gas-to-dust/extinction ratio, and underestimating the ISM mass. An alternative hypothesis is that the extinction has been underestimated; the [Fe II] and H II emission lines do not probe the full gas column, thus underestimating the extinction-derived gas mass.

Schönell et al. (2017) summarizes results for 5 Seyfert 1, 4 Seyfert 2 and 1 LINER galaxies observed by the AGNIFS group; the range of H II surface densities is 1.5–125 M$_\odot$/pc$^2$ and of H$_2$ (cold+warm) surface densities is 526–9600 M$_\odot$/pc$^2$. Our values (191 and 1587 M$_\odot$/pc$^2$ within a radius of 100 pc, respectively) are comparable, with the H II value being somewhat higher than the range, probably because of the starburst nature of the object.

4.4.4 Star Formation and Supernovae

In this object, SF and SNe supply the bulk of gas excitation, with minimal AGN activity. The star formation rate is derived from the Kennicutt et al. (2009) relationship Equation 2.29, as shown in Table 4.9.

The star formation rates given in Table 4.2 above are mostly within a factor of 2, which is also in good agreement with the Br$\gamma$ derived rate as in Table 4.9. The exceptions are the WISE W4 and the X-ray derived values. The WISE color-color diagram (Wright et al., 2010) places this object in the starburst/luminous infra-red galaxy (LIRG) region. The X-ray flux from the nucleus could include AGN activity, which would reduce the derived SFR. There may be substantial highly obscured star formation which would only manifest in FIR and X-rays, which penetrate the dust.

From the magphys SED fitting, the derived SFR is about $\sim 1.1$ M$_\odot$ yr$^{-1}$. The SFR derived from the radio flux is in excellent agreement with the other indicators, showing there is no AGN component emission. Herrero-Illana et al. (2017) observed NGC 1614, a local starburst LIRG, with Very Long Baseline Interferometry (VLBI) and did not find a compact nuclear source, but found diffuse and compact (supernova remnant) emission from the starburst.

The supernova rate is computed from the Rosenberg et al. (2012) relationship (Equation 2.33). The results, using the de-reddened [Fe II] flux, are also shown in Table 4.9. The SN rate derived from radio emission using the indicator from Condon (1992) can be compared with that derived from the [Fe II] flux. The relationship (derived from Condon...
4.4. Discussion

(1992) Equation 18) is:

$$\nu_{\text{SNR}} \approx 0.077 \nu^\alpha \times L_N$$

(4.1)

where $\nu_{\text{SNR}}$ is the supernova rate per year, $\nu$ is the radio frequency in GHz, $\alpha$ is the radio spectral index ($=0.75$) and $L_N$ is the luminosity in units of $10^{22}$ W Hz$^{-1}$. For the VLSS (1.4 GHz) and MWA (150 MHz) fluxes (Table 4.1), $\nu_{\text{SNR}} = 0.089$ and 0.054 yr$^{-1}$, respectively. These are in reasonable agreement with the values derived from the [Fe II] emission (0.034 yr$^{-1}$).

Table 4.9: Star formation rate and supernova rate. Regions as for Table 4.8. The SNR is shown as the rate per year per pc$^2$, per year over the region and the interval between SN.

<table>
<thead>
<tr>
<th></th>
<th>Max. Pixel</th>
<th>100 pc</th>
<th>200 pc</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br $\gamma$ Flux ($\times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$)</td>
<td>0.86</td>
<td>180.2</td>
<td>307</td>
<td>337</td>
</tr>
<tr>
<td>SFR (M$_{\odot}$ yr$^{-1}$)</td>
<td>0.0065</td>
<td>1.4</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>[Fe II] Flux ($\times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$)</td>
<td>0.54</td>
<td>139</td>
<td>314</td>
<td>386</td>
</tr>
<tr>
<td>SNR (yr$^{-1}$ pc$^{-2}$ $\times 10^{-7}$)</td>
<td>7.2</td>
<td>3.95</td>
<td>2.25</td>
<td>2.0</td>
</tr>
<tr>
<td>SNR (yr$^{-1}$)</td>
<td>$4.8 \times 10^{-5}$</td>
<td>$1.25 \times 10^{-2}$</td>
<td>$2.8 \times 10^{-2}$</td>
<td>$3.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>SN Interval (yr)</td>
<td>20660</td>
<td>80</td>
<td>36</td>
<td>30</td>
</tr>
</tbody>
</table>

The star formation rate for the whole field given above can be compared with the rate derived from the WiFeS data. The H$\alpha$ flux from the nuclear 3$''$ per 3$''$ is $1.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, giving an emitted flux of $2 \times 10^{-39}$ erg s$^{-1}$. The SFR is determined from Equation 2.28, giving 1.1 M$_{\odot}$ yr$^{-1}$, in good agreement with the NIR-derived value.

4.4.5 Stellar Populations and Ages

The stellar populations and ages in the circumnuclear region are examined using emission line fluxes and continuum colors. Correcting the $H-K$ color map for the average visual extinction of 1 mag decreases the values by 0.06 mag, 95% of the pixels are in the range 0.02-0.28 mag and the average value is 0.14 mag. Given the uncertainties about the absolute flux calibration of the data cubes, caution must be exercised about assigning a stellar type to the colors (e.g. tables II and III of Bessell & Brett, 1988); however the relative differences are clear, with the clusters about 0.14 mag bluer than the rest of the field. The average color over the clusters is 0 mag, the color of an A0V star. The field average is the color of a K8V star (or K3III giant), going to an extreme of 0.33 mag (M5V or M8III).
The mass of the nuclear cluster can be estimated from the cluster size and velocity dispersion; using the virial formula:

\[ M \approx \frac{3}{2} \frac{\sigma_R^2 R}{G} \]  

where \( R \) is the cluster radius and \( \sigma_R^2 \) is the dispersion. Using the values of 50 pc and 44 km s\(^{-1}\), we derive a mass of \( \sim 3.4 \times 10^7 \) M\(_\odot\). This is a lower limit; any rotation will support more mass and the stars are probably not in virial equilibrium. Simulations (see Section 4.4.8) suggest that the stars settle into a thick disk, rather than a spherical cluster. The luminosity of \( 3.9 \times 10^8 \) L\(_\odot\), calculated above, gives a mass to light ratio of \( \sim 0.1 \). Given that this is a lower limit, is not inconsistent with an old stellar population (with a M/L of about 1) mixed with younger star formation.

In Balcells et al. (2007), the sizes of nuclear disks are measured by analyzing surface brightness profiles of S0–Sbc galaxies from HST NICMOS images. They find that the central star clusters are usually unresolvable at \( \sim 10 \) pc resolution, whereas the nuclear disks sizes are found to be in the range 25–65 pc (from their table 4). It can be deduced that the central object visible in our observations is more likely to be a disk than a spherical structure.

The ratio of H recombination to He I emission can be used as an indicator of relative age of star clusters, following Böker et al. (2008); as the He I ionization energy is 24.6 eV vs. 13.6 eV for hydrogen, the He I emission will arise in the vicinity of the hotter stars (B- and O-type), which will vanish fastest. It should be noted that the presence of significant numbers of W-R stars (as in this object) may increase the hard-UV radiation within the first \( \sim 10 \) Myr., weakening the age-He I relationship. (B. Groves, private comm.) Taking the ratio of the flux from Br\( \gamma \) and He I 2058 nm for the nuclear cluster and the two light concentrations and the ridge extension, the nuclear cluster shows a value of 0.72, while the other three show value of 0.60–0.63. Even though the differences are small, it is an indicator that the nuclear cluster is the youngest region (Fig. 4.22 left panel). This is also the bluest location in the \( H-K \) map (Fig. 4.6), and an obvious zone of avoidance for [Fe II] and H\(_2\).

We can estimate the stellar ages in the central region, using the methods of Brandl et al. (2012) and references therein, which examines the starburst ring in NGC 7552. They use the pan-spectral energy distribution of starburst models of Groves et al. (2007) to derive cluster ages based on Br\( \gamma \) EW. The map for Br\( \gamma \) (in Fig. 4.10) shows the central cluster and surrounding region have an EW in the range 2.5 to 4.5 nm. Using the STARBURST99 models with a Solar metallicity, a mass cutoff of 100 M\(_\odot\) (since there are
a large number of WF stars) and an IMF slope of 2.35, as described in Section 2.6.3.2, we derive an age in the range 5.5–6.5 Myr. This is the same as found in Ohyama et al. (1997) (and references therein), which derives the age from the $I(\text{He II} \lambda 4686)/I(\text{H} \beta)$ vs. $\text{EW}(\text{H} \beta)$ starburst model diagram ($\sim 5.5$ Myr).

Doherty et al. (1995) presented observations of the ratio $\text{He I}/\text{Br} \gamma$ in H II regions in starburst galaxies; from theoretical models and taking the ratio of He to H being 0.1 (solar equivalent) and the average ratio over the nuclear region in IC 630 being $\sim 0.71$, we estimate an effective temperature of $\sim 3.7 \times 10^4$ K from their figure 2. We can also derive the Lyman continuum flux, $N_{\text{LyC}} \approx 1.8 \times 10^{52}$ sec$^{-1}$ and the number of O7V-type stars, $N_{\text{O7V}} \approx 3200$, within a radius of 50pc from the peak emission (as per the methods in Section 2.6.3.2). This mixture of old and new stars in the nuclear cluster is by no means unique to this object; this is the case in our own galaxy (Do et al., 2009) and in NGC 4244 (Seth et al., 2008).

One can hypothesize that the starburst proceeded outward from the center in a wave, with shock winds from the young stars triggering star formation further out. This would also be supported by the observation that the [Fe II] flux seems to surround the H II region. The ratio of the equivalent width of $\text{He I}$ vs. $\text{Br} \gamma$, for the 150 pc around the nucleus, shows a lower value in the center (1.3–1.5) surrounded by a ring of higher value (1.9–2.1), also indicating a younger stellar population (Fig. 4.22). One could also hypothesize a period of AGN activity providing the initial compression wave.

**Figure 4.22:** $\text{He I}/\text{Br} \gamma$ Flux and EW Ratio for inner 150 pc, diagnosing relative ages for young, hot stars.
4.4.6 Excitation Mechanisms

The NIR excitation diagram (Fig. 4.11) shows that almost all pixels are within the ‘starburst’ regime, with minimal identifiable AGN activity (the pixels in the AGN region are located with low absolute flux values, with some corresponding uncertainty). The locations of interest, which are the nucleus, clusters ‘1’ and ‘3’ and the loci of maximum flux of H$_2$ and [Fe II], are all in the starburst region.

The excitation plot shows a tight correlation for the two line ratios, which is also seen for the nuclear spectrum of active galaxies (Larkin et al., 1998; Riffel et al., 2013a) as well as on a spaxel-by-spaxel basis (Colina et al., 2015), which concludes that the ISM excitation is determined by the relative flux contribution of the exciting mechanisms and their spatial location. The fit from our data (plotted in Fig. 4.11) is:

$$\log([\text{Fe II}] / \text{Pa } \beta) = 0.558 \log(\text{H}_2 / \text{Br } \gamma) - 0.13$$

This is consistent, within uncertainties, with the fit from Riffel et al. (2013a):

$$\log([\text{Fe II}] / \text{Pa } \beta) = 0.749 \log(\text{H}_2 / \text{Br } \gamma) - 0.207$$

which extends over a wider range of excitations, including AGNs and LINERs; their plot also shows that star-forming galaxies are consistently above this fit (as is the case for this object). The overall nuclear spectrum will have an excitation mode determined by the relative contribution of all sources.

In the optical (BPT) excitation diagram (Fig. 4.12, right panel), derived from the WiFeS data, again almost all pixels are in the starburst regime. At the NE and SW peripheries, some pixels exhibit ‘composite’ excitation, i.e. a mixture of pure starburst and pure AGN (see Kewley et al. (2006) and references therein), indicating there may be some contribution from AGN excitation; this is also possibly present in the infrared along the same axis. One can hypothesize AGN X-ray and shock excitation being obscured towards the line of sight by the starburst ionized outflow, but escaping along the galactic plane. An alternative explanation is presented by Ohyama et al. (1997), which posits a slowing-down super-wind scenario, where the earlier phase of the nuclear starburst generates fast winds (>200 km s$^{-1}$) which are now present in the outer regions, as versus the current slower shock velocities in the nucleus as the wind ceases.

Summarizing the excitation for each species:

- Hydrogen recombination emission is excited by UV photons from young stars.
4.4. Discussion

- [Fe II] is also photo-ionized from the young stars with minor contribution from shocks, as shown by the [Fe II]/[P II] ratios. The [Fe II] emission is not present around the clusters due to ionization by hot, young stars.

- H₂, by contrast, is excited by shocks (from the H₂ 2-1 S(1)/1-0 S(1) ratio), with some contribution from fluorescence. It is shielded from dissociation by photo-ionization from the clusters by dust.

4.4.7 Gas Kinematics

4.4.7.1 Velocity and Channel Maps

The LOS velocities do not show a simple bipolar structure that would be expected from disk rotation or outflow cones; instead it shows complicated multiple regions of both approaching and receding gas. Ohyama et al. (1997) considers the superwind to be at or nearly face-on to our LOS. This would also explain the lack of any ordered stellar rotation observed (see Fig. 4.7). The Brγ and [Fe II] velocity and dispersion fields are virtually identical, both in structure and distribution. The Brγ velocity distribution (as shown in the velocity histogram) is somewhat bi-modal, peaking around ±10 km s⁻¹. We suggest that most of the atomic hydrogen gas is in motion and that the apparent LOS velocity at any point is just the mass-weighted sum of the motions towards and away from us. The histograms also show that the H₂ velocity and dispersion is kinematically colder, with the dispersion peak at 30 km s⁻¹, half that of the Brγ and [Fe II]. The H₂ velocity distribution is also much lower.

The Brγ flux is strongly centrally concentrated, with the LOS velocity presenting a quadrupole pattern and with lower velocity dispersion in the center than at the periphery of the field. The [Fe II] flux is peaked at the periphery of the Brγ flux; this is compatible with the [Fe II] lines originating in less ionized material than the hydrogen recombination lines. The H₂ pattern is different; the velocity and dispersion maps and distributions are kinematically cooler. The H₂ velocity map shows almost the same pattern as the Brγ map, but the N-NW positive velocity region is reduced; this suggests that the two are kinematically de-coupled. This compares with Röffel et al. (2008) for NGC 4051, which also shows a similar channel map; they find the H₂ rotational structure to be dissimilar to the stellar rotation. Rodríguez-Ardila et al. (2004a), in a sample of 22 mostly Seyfert 1 galaxies, suggests that [Fe II] and H₂ originate in different parcels of gas and do not share the same velocity fields, with the [Fe II] flux locations, velocities and dispersions...
being different to the \( \text{H}_2 \); our results support this. Since IC 630 is close to face-on, it is uncertain if the \( \text{H}_2 \) is in the galactic plane.

The channel maps present a complex patchy picture (Figs. 4.15, 4.16 and 4.17). There is some evidence of structure in the NW (receding) to SE (approaching) directions. Given that the overall gas kinematics (Fig. 4.13) do not show the signatures of either biconal outflow or rotation, we can hypothesize that we are observing the outflows face-on, with streamers of gas rather than the gas filling a complete cone. In this case, the observed structure is again just the mass-weighted sum of the motions. At the extreme velocities, the \( \text{Br}\gamma \) and [Fe II] maps are similar; the difference appears at low velocity, reflecting the over-all flux distribution differences. The \( \text{H}_2 \) channel maps again are dissimilar; they are kinematically colder. The filamentary structures are similar (though at a smaller scale) to the outflows seen in M82.

### 4.4.7.2 Outflows

Let us examine the geometry of the outflows as delineated by the hydrogen recombination emission. The half-light radius (i.e. the radius of a circle from the center that covers half the total flux in each channel) increases from 100 pc to 115 pc over the velocity range 0 to ±270 km s\(^{-1}\). Within uncertainties, we can model this as a cylinder, as the half-light radius expands with height, rather than shrinks as a spherical shell expansion would display. The centroid position does not move much, except at extreme velocities where a patchy structure will have greatest effect, showing that the outflow is nearly face-on; this will not affect the outflow calculation, as the integrated flux is low at these velocities.

One can derive a ‘momentum’ measure by multiplying the gas flux and the LOS velocity at each channel; this is a maximum at ±90 km s\(^{-1}\) (equivalent to 9 \times 10^{-5} \text{ pc yr}^{-1} or 90 pc Myr\(^{-1}\)) and will be used to calculate the outflow. The radius of 90% of the flux for this channel is 205 pc which is an area of 1.3 \times 10^5 \text{ pc}^2, the flux total in both channels is 48.8 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} and the channel width is 60 km s\(^{-1}\), which is equivalent to 360 pc. Simplifying the geometry to a cylinder, this is a total volume of 9.5 \times 10^7 \text{ pc}^3 for both channels. We can calculate the mass of \( \text{H}II \) in the channel from Equation 2.25 above; this is 3.4 \times 10^5 \text{ M}_\odot; the density is thus 16 \times 10^{-3} \text{ M}_\odot \text{ pc}^{-3}. From these values, we obtain \( \dot{M} = 0.42 \text{ M}_\odot \text{ yr}^{-1} \). This is in line with the studies of other outflows from Seyferts and LINERs (0.01 – 10 \text{ M}_\odot \text{ yr}^{-1}) (Riffel et al., 2015).

The maximum kinetic power \( (L_{KE}) \) of the outflow is at the +150 km s\(^{-1}\) \( (8.4 \times 10^{38} \text{ erg s}^{-1}) \) and -210 km s\(^{-1}\) \( (18.3 \times 10^{38} \text{ erg s}^{-1}) \) channels. Integrating over all velocity channels, the total power is \( L_{KE} = 8.4 \times 10^{39} \text{ erg s}^{-1} \). This is an order of magnitude below
the estimates for Mrk 1157 (Riffel & Storchi-Bergmann, 2011) and NGC 4151 (Storchi-Bergmann et al., 2010) of 2.3 and $2.4 \times 10^{41}$ erg s$^{-1}$, respectively. These galaxies have significant AGN activity, rather than just star formation, generating larger outflows at higher velocities. However, the ratio $L_{KE}/L_{Bol} \approx 0.02$ is compatible with the literature as surveyed by Nevin et al. (2017); a major uncertainty being whether the bolometric luminosity in this case is from AGN or star-formation.

### 4.4.8 Simulations

Schartmann et al. (2017) present simulations of the evolution of circumnuclear disks in galactic nuclei. 3D Adaptive Mesh Resolution (AMR) hydrodynamical simulations with the RAMSES code (Teyssier, 2001) are used to self-consistently trace the evolution from a quasi-stable gas disk. This disk undergoes gravitational (Toomre) instability, forming clumps and stars. The disk is subsequently partially dispersed via stellar feedback.

The model includes a $10^7 \, M_\odot$ SMBH, with the disk located in a $8.5 \times 10^9 \, M_\odot$ galactic bulge, and includes SN feedback, which drives both a low gas density outflow as well as a high density fountain-like flow. The model finds that the gas forms a three component structure: an inhomogeneous, high density, molecular cold disc, surrounded by a geometrically thick distribution of molecular clouds above and below the disk mid-plane and tenuous, hot, ionized outflows perpendicular to the disk plane.

Star formation continues until the disk returns to stability, with the starburst dying away after $\sim 100$ Myr. This process cycles over $\sim 200 – 250$ Myr (depending on initial parameters); the starburst only consumes about half the gas and further inflows will feed the central region until instability is reached and the process can start again. This scenario can explain the observations of short-duration, intense, clumpy starbursts in Seyfert galaxies in their recent ($\sim 10$ Myr) history (Davies et al., 2007).

The results from Schartmann et al. (2017) show strong similarities to the IC 630 observations, with the initial formation of a few star clusters and clumps, and the outflows in filaments with a broad-based cone or cylindrical geometry reaching to similar scale heights of several hundred pc. The channel map at 30 Myr (Fig. 4.23) shows the filamentary structure, similar to that seen with IC 630, with coherent organization being traced through the velocity cuts. The simulations also suggest that the stellar velocity dispersion will be in the range of 40–50 km s$^{-1}$ in the first 10 Myr, which is consistent with the observations for IC 630.

The clumps and clusters dissolve at the end of star-formation period and a central disk forms, as seen with IC 630; we can suggest that it may have been through more than one
of these cycles. Seth et al. (2008) proposed two possible nuclear cluster formation mechanisms: (1) episodic accretion of gas from the disk directly onto the nuclear star cluster; or (2) episodic accretion of young star clusters formed in the central part of the galaxy due to dynamical friction. The simulation results suggest the second scenario as more likely; however the simulation indicates that the clusters are destroyed and redistributed through relaxation to the global potential, rather than dynamical friction.
4.5. Conclusions

A ‘life-cycle’ of nuclear gas, star formation and AGN activity can be posited.

- Gas flows in to the nucleus of a galaxy, through minor mergers or tidal torques, e.g. bars, where it collects in a disk in the bulge (and/or SMBH) gravitational potential.
- The gas disk becomes Toomre-unstable and starts collapsing into star-forming clumps and clusters. The SF rate peaks at about 6–30 Myr after the onset of instability. AGN activity may contribute to the instability.
- Stellar feedback, including supernovae and hot OB/WR stellar winds, partially disperses the gas disk and drives filamentary outflows with a scale height of several hundred pc, with the maximum flow at about 10–30 Myr. These winds do not fuel any significant AGN activity (Davies et al., 2007).
- At about 150 Myr, star formation declines, with the gas-disk approaching Toomre-stability within the following 20–30 Myr. The stars settle into a nuclear disk about 40–100 pc across.
- AGB winds efficiently feed any SMBH and AGN activity starts about 50–100 Myr after the starburst. The SMBH grows by this feeding and tidal friction infall from the gas disk. AGN outflows may trigger further star formation and the activity continues until all available gas is consumed.

IC 630 has been caught in the phase between the starburst and AGN activity.

4.5 Conclusions

In this chapter, we have mapped the gas and stellar flux distribution, excitation and kinematics from the inner ∼ 300 pc radius of the starburst S0 (?) galaxy IC 630, using NIR $J$, $H$ and $K$-band integral-field spectroscopy at a spatial resolution of 37–43 pc (0.23 – 0.26″), plus additional optical IFS data. The main conclusions of this chapter are as follows.

- The nuclear region has a central cluster or disk (half-light radius of 50 pc) with at least two other light concentrations (clusters) within 130 pc. The central stellar population is a mixture of young (∼ 6 Myr) and older stars.
- The stellar kinematics show a SMBH of $M_\bullet = 2.25(\pm 5.1, -1.6) \times 10^5$ M$_\odot$ (within 1.4 $\sigma$ of there being no central black hole). The AGN-like bolometric luminosity of the galaxy (radio and X-rays) is mostly from star formation, rather than BH activity.
- Within 200 pc of the nucleus, the mass of the cold ISM, as derived from extinction, is $M_{ISM} \approx 2.8 \times 10^6$ M$_\odot$, the mass of ionized gas is $M_{HII} \approx 1.7 \times 10^7$ M$_\odot$ while the
mass of the hot molecular gas is $M_{H_2} \approx 230 \, M_\odot$ and the estimated cold molecular gas mass is $M_{H_2}(\text{cold}) \approx 1.5 \times 10^8 \, M_\odot$. The cold H$_2$ mass estimate is greater than that of the ISM as derived from extinction; the ISM mass may be underestimated due to the emission lines being used to derive the extinction do not probe the full gas column; alternatively, star formation photo-ionization and the high excitation temperature may have sublimated the dust grains.

- The star formation rate is $2.3 \, M_\odot \, \text{yr}^{-1}$, with the SN rate of 1 per 36 years in the central 200 pc, producing X-ray and radio emission and releasing iron from dust grains, which is subsequently photo-ionized and shock heated.

- Emission line diagnostics show that the vast majority of gas excitation is due to star formation, with minimal input from AGN activity. For the main species, hydrogen recombination emission is excited by UV photons from young stars, [Fe II] is also photo-ionized from the young stars with minor contribution from shocks, whereas H$_2$ is excited mainly by shocks, with possibly some contribution from X-ray heating from star formation.

- The [Fe II] and hydrogen recombination emissions are closely coupled in velocity and dispersion, but the peak flux of the [Fe II] is at the periphery of the Br$\gamma$ flux. The H$_2$ is kinematically colder than those species, and is also not spatially co-located. Photo-ionization from the young stars in the clusters suppresses the [Fe II] and H$_2$ species; these are shielded by the presence of dust.

- A starburst $\sim 6$ Myr ago provided powerful outflow winds, with the ionized gas outflow rate at $0.42 \, M_\odot \, \text{yr}^{-1}$ in a face-on truncated cone geometry.

- Our observations are broadly comparable with simulations where a Toomre-unstable gas disk triggers a burst of star formation, peaking after about 30 Myr and possibly cycling with a period of about 200 Myr.

IC 630 is an example of a galaxy that has ‘AGN-like’ activity (radio and X-ray emission) but displays minimal AGN excitation. It has a high star formation rate in both the central region and over the whole galaxy. This object is an example of nuclear star-formation dominating the narrow-line region emission. The nuclear young stars and SN providing photo-ionization, stellar winds and shocks to excite the hydrogen, H$_2$ and [Fe II] emissions.
Note

This chapter has appeared as Durré et al. (2017), with modifications. The main differences are:

- The H$_2$ excitation temperature was estimated as $T_{exc} \approx 6135$ K (Section 4.4.2). Due to an error in computation, this value should have been $\sim 2600$ K. In this case, we do not need to invoke a two temperature model, and the result is now consistent with the range of values (2100 – 2700 K) found for other Seyfert galaxies (Riffel et al., 2015; Storchi-Bergmann et al., 2009; Riffel et al., 2014b; Riffel & Storchi-Bergmann, 2011; Riffel et al., 2010).

- The IFU flux calibration was corrected, where the values from the paper have to be multiplied by the following constants:
  1. $J$ - 6.9
  2. $H$ - 6.25
  3. $K$ - 4.7

This affected the extinction calculation (reducing $A_V$ over the field from 3.4 to 1.0 mag), the integrated flux values (Durré et al., 2017, Table 5 in) and the flux plots, with corresponding gas mass, star formation and supernova calculations and outflow rates - Tables 7 and 8 in the paper.
Dissecting the Outflows of NGC 5728

5.1 Introduction

Urry & Padovani (1995), in the seminal review paper on AGN unification, cited NGC 5728 the paradigm of a Type 2 AGN with ionization cones. These cones are predicted by the Unified Model of AGN, as radiation from the accretion disk is collimated by the surrounding dusty torus to impinge on the ISM, exciting the gas by photo-ionization and transferring mechanical energy to the gas by radiation pressure and disk winds. This makes it a prime target for investigation, particularly using IFU observations in the near infrared, allowing penetration of obscuring dust.

NGC 5728 is at a flow corrected distance (Virgo + GA + Shapley) of 41.1±2.9 Mpc, which is equivalent to a distance modulus of 33.07 mag (a flux-to-luminosity ratio of $2 \times 10^{53}$ in cgs units, i.e., erg cm$^{-2}$ s$^{-1}$ to erg s$^{-1}$) and a scale of 200 pc per arcsec; all values are from NED (Mould et al., 2000b). Apart from the AGN activity, the nucleus has a highly complex structure. The Spitzer Survey of Stellar Structure in Galaxies (S4G) (Buta et al., 2015) has the morphology (R1 )SB(r’l,bl,nr,ab)0/a, which indicates a barred spiral with a closed outer ring, an inner pseudo-ring/lens and a nuclear ring and bar/barlens. The morphology is important in the context of SF in the nuclear region, and in the determination of the SMBH mass.

From the 2MASS H-band absolute magnitude (Skrutskie et al., 2006) of -23.85 with a mass-to-light ratio of 1 at $H$ and a Solar absolute magnitude of $M_H = 3.3$ (Binney & Merrifield, 1998), the estimated galaxy mass is $7.2 \times 10^{10}$ M$_\odot$.

The Carnegie-Irvine Galaxy Survey (Ho et al., 2011) image (Fig. 5.1) clearly shows the outer ring with faint trailing spiral arms. The bar is weak, with the region between the nucleus and the outer ring being reasonably smooth with some faint dust rings. Rubin (1980), using H$\alpha$ emission line measurements, found that the rotation curve along the
NE-SW axis was flat and that the NE axis was approaching; that study concluded that the near side was to the NW, based on the trailing faint spiral arms. She also deduced that the non-circular velocities could be modeled equally well by an additional axisymmetric expansion, or by a displaced inner disk or spheroidal/triaxial inner bulge.

Figure 5.1: NGC 5728 star-cleaned color-composite image from CGS, created from the $B$, $V$ and $I$ images and cleaned of stars, as described in Ho et al. (2011). The image is oriented north up, east left. The sides of the image are 4′.6, equivalent to 55 kpc at the distance of NGC 5728. The features visible are the outer ring, faint arms trailing from SF peaks at the end of the major bar, a smooth disk with dust lanes, and the complex inner nuclear structure, composed of a ring with a bar.

NGC 5728 has outflows and ionization cones that are oriented across our line of sight. Gorkom (1982) first observed asymmetrical optical and radio emissions from this galaxy; their VLA 6 and 20 cm observations showed a diffuse 10″ region which was coextensive with the optical emission, with a compact nucleus and jet. These observations were followed up by Schommer et al. (1988); they concluded that the gas was streaming inwards, however their data did not exclude outward motions, as suggested by the double-peaked H$\alpha$ emission line region near the nucleus. Arribas & Mediavilla (1993) noted that the
kinematic center of the Hα, [N II] and [S II] emission lines and the radio flux did not coincide with the emission line flux maximum, suggesting that the nucleus was highly obscured. The Hα+[N II] and [O III] emission line images from the HST observations of Wilson et al. (1993) revealed a spectacular bi-conical structure with an overall extent of 1.8 kpc.

Mediavilla & Arribas (1995) explored the 2D kinematics of these emission lines using a fiber-fed optical spectrograph; however, they only observed the receding component of the cones in any detail. HST UV imaging polarimetry of the nucleus (Capetti et al., 1996), using the Faint Object Camera, revealed a centro-symmetric pattern of scattered light originating in the hidden nucleus; the polarization upper limit was 1.9%, in line with ground-based observations. This showed that the cones were much wider than that inferred from the emission lines (55–65°), implying that some of the torus is transparent to UV light while still blocking the ionizing radiation. The cone symmetry was used to locate the nucleus behind a dust lane. The activity type is classified as Seyfert 1.9 (Véron-Cetty & Véron, 2006), based on broad Hα Balmer line visibility.

The kinematics and excitation mechanisms of H2 and [Fe II] lines in a sample of active galaxies and using long-slit observations on the IRTF were studied by Rodríguez-Ardila et al. (2004a, 2005), which included this galaxy. They showed that, in general, the H2 was kinematically decoupled from the NLR, with this particular galaxy having the highest ratio of H2 to Brγ flux in their sample of 22 AGN. They estimated a warm H2 mass of ~900 M☉ in the nucleus. Rodríguez-Ardila et al. (2011) also detected the coronal line of [Si VI], however they did not observe any coronal lines in this object with an ionization potential (IP) > 167 eV, indicating a limit to the hard X-ray flux. From WiFeS optical IFU observations, Dopita et al. (2015) reported that the NLR was much more extended than from Wilson et al. (1993): 4.4 kpc rather than 1.8 kpc in extent.

Using the 0.8–2.4 μm IRTF Spex spectra from Rodríguez-Ardila et al. (2004a), which were taken with a 0″.8 × 15″ slit, Riffel et al. (2009a) deduced a mixture of 70% intermediate age (100 Myr to 2 Gyr) and 30% old (> 2 Gyr) stellar population contributions to the continuum for this object, with corresponding mass fractions of 25% and 75%, with no black-body dust component. All these observations indicate an obscured AGN with multiple gas kinematics including outflows, plus radio jets.
5.2 Observations, Data Reduction and Calibration

We obtained NIR IFU data from SINFONI on VLT-U4 (Yepun), both from our own observations ($J$-band filter) and from the MPE group ($H+K$-band filter) who kindly let us use the data from their LLAMA (Luminous Local AGN with Matched Analogues) survey. Each dataset consists of two object frames, combined with a sky frame with the same exposure, in the observing mode ‘Object-Sky-Object’. For the $J$-band SINFONI observations, the offset was 30" in Dec, plus a 0".05 jittering procedure; for the $H+K$ observations, the offset for the $H+K$ observations was was 60" in RA, plus a 0".1 jitter. Our NIR and optical observations are summarized in Table 5.1; it includes the details of the WiFeS S7 and MUSE TIMER program optical observations (see Section 5.3.2).

Data reduction, telluric correction, flux calibration and data cube cleaning were done as per Section 2.3 and 2.4. After telluric correction and flux calibration, the data cubes from the SINFONI $H+K$ were combined into single cubes. These were centered on the brightest pixel (in the image created by collapsing the cube along the wavelength axis). The `instrumental fingerprint' in the SINFONI $J$ data cube was corrected, as described in Section 2.4.3. Over the characteristic broad horizontal stripe, the flux correction was substantial, in places up to ±15%. For the final $H+K$ data cube, no fingerprint was visible in any of the tomograms, presumably because of the combination of cubes over 4 dates.

All the data cubes had some spikes and geometric artifacts, which are a product of the DRP or other noise which is not removed (e.g. cosmic rays). These were manually cleaned by interpolation over the offending pixels, especially over the emission lines wavelengths.

To check on the wavelength calibration, the OH skyline wavelengths were measured from the sky data cubes, as described in Section 2.4.4. This showed a wavelength shift of $\sim 0.44$ nm, equivalent to $\sim 62$ km s$^{-1}$; this value is used in Section 5.3.5 in the computation of the systemic velocity of the galaxy.

5.3 Results and Discussion

5.3.1 The Nucleus of NGC 5728

The nucleus of NGC 5728 is highly complex, as revealed by multi-wavelength images taken at high spatial resolution, with evidence of star formation, radio and X-ray jets and distorted kinematics. Fig. 5.2 shows the PanSTARRS $i$ band image from the MAST PanSTARRS image cutout facility\(^1\), overlaid with the VLA 20 cm large-scale map and the $HST$ F160W structure map combined with the VLA 6 cm map. The VLA data

\(^1\)https://archive.stsci.edu/
### Table 5.1: NGC 5728 Observation Log

<table>
<thead>
<tr>
<th>Date</th>
<th>Program ID</th>
<th>Filter</th>
<th>Exp. Time</th>
<th>Airmass</th>
<th>R&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Exp. Time&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Seeing&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Standard Star</th>
<th>ΔV&lt;sup&gt;f&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-Apr-14</td>
<td>093.B-0461(A)</td>
<td>J</td>
<td>300</td>
<td>1.085</td>
<td>2400</td>
<td></td>
<td></td>
<td>HIP091038</td>
<td></td>
</tr>
<tr>
<td>Mould</td>
<td>23-Feb-15</td>
<td>H+K</td>
<td>300</td>
<td>1.011</td>
<td>53</td>
<td></td>
<td></td>
<td>HIP073266</td>
<td>1560</td>
</tr>
<tr>
<td>093.B-0057(B)</td>
<td>SINFONI</td>
<td>0.25</td>
<td>1800</td>
<td>1.3</td>
<td>11.6</td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Davies</td>
<td>6-Mar-15</td>
<td>H+K</td>
<td>300</td>
<td>1.012</td>
<td>1560</td>
<td></td>
<td></td>
<td>HIP071451</td>
<td></td>
</tr>
<tr>
<td>093.B-0057(B)</td>
<td>SINFONI</td>
<td>0.1</td>
<td>1800</td>
<td>1.25</td>
<td>25.8</td>
<td></td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Davies</td>
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<td>H+K</td>
<td>300</td>
<td>1.016</td>
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<td>HIP078968</td>
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</tr>
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<td>093.B-0057(B)</td>
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<td>0.1</td>
<td>1800</td>
<td>1.25</td>
<td>-13.9</td>
<td></td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Davies</td>
<td>25-Jun-15</td>
<td>H+K</td>
<td>300</td>
<td>1.203</td>
<td>1560</td>
<td></td>
<td></td>
<td>HIP082670</td>
<td></td>
</tr>
<tr>
<td>093.B-0057(B)</td>
<td>SINFONI</td>
<td>0.1</td>
<td>1800</td>
<td>0.75</td>
<td>-21.8</td>
<td></td>
<td></td>
<td>8</td>
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</tr>
<tr>
<td>08-Apr-14</td>
<td>R and B</td>
<td>900</td>
<td>1.04</td>
<td>7000(R)/3000(B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1140018</td>
<td>WiFeS</td>
<td>1</td>
<td>1.2</td>
<td>13.5</td>
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<tr>
<td>Dopita</td>
<td>03-Apr-16</td>
<td>V</td>
<td>480</td>
<td>1.048</td>
<td>1800</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gadotti</td>
<td>09-Apr-16</td>
<td>V</td>
<td>480</td>
<td>. . .8</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Exposure time (sec) for each on-target frame.

<sup>b</sup>Measured spectral resolution.

<sup>c</sup>Seeing from the ESO Paranal Astronomical Site Monitoring (VLT) or the Mauna Kea Weather Center DIMM archive (Keck).

<sup>d</sup>Barycenter correction in km s<sup>-1</sup> from ‘Barycentric Velocity Correction’ website [http://astroutils.astronomy.ohio-state.edu/exofast/barycorr.html](http://astroutils.astronomy.ohio-state.edu/exofast/barycorr.html) (Wright & Eastman, 2014)

<sup>e</sup>SINFONI plate scale is re-binned to half size in the final data cube.

<sup>f</sup>Spectral velocity resolution (km s<sup>-1</sup>)

<sup>g</sup>Data not available
was originally published by Schommer et al. (1988); we acquired images from the NRAO Science Data Archive\textsuperscript{2} as set out in Table 5.2. There are 2 sets of 20 cm VLA data; large scale with 5" spaxels and small scale with 0".3144 spaxels; the beam size given is the half-power beam width for the antenna configuration and frequency (from the NRAO resolution table\textsuperscript{3}).

The \textit{HST} structure map was created as described in Section 2.5.2; it enhances the nuclear bar and ring, with the whole central structure looking like a miniature barred spiral. The spiral aspect appears close to face-on, which is different to the rest of the galaxy. Prada & Gutiérrez (1999) found that the core is counter-rotating with respect to the main galaxy, and considered that it was most probably caused by orbital instabilities associated with the secondary bar; however they could not rule out satellite or gas accretion with negative angular momentum. The filamentary dust lanes delineate the cold-phase fueling flows into the SMBH (see e.g. Simões Lopes et al., 2007; Mezcua et al., 2015).

The 20 cm large-scale map shows nuclear emission combined with two regions coincident with the star formation at the end of the galactic bar. At 6 cm, the higher spatial resolution nuclear emission shows an annulus structure, with the highest emission coincident with the structure map outer ring/arms. It also shows a jet in the NW-SE direction, aligned with the ionized gas emission.

\begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{figure5.2.png}
  \caption{Left panel: PanSTARRS $i$ image overlaid with VLA 20 cm large-scale flux contours with star-formation at the end of the main bar and nuclear AGN/SF emission. Right panel: HST F160W structure map overlaid with VLA 6 cm flux contours showing the AGN jet and the SF ring. Contour values in $\mu$Jy.}
\end{figure}

\begin{footnotesize}
\textsuperscript{2}https://archive.nrao.edu/archive/advquery.jsp
\textsuperscript{3}https://science.nrao.edu/facilities/vla/docs/manuals/oss/referencemanual-all-pages
\end{footnotesize}
5.3. Results and Discussion

Table 5.2: VLA observations for NGC 5728

<table>
<thead>
<tr>
<th>Obs. Date</th>
<th>Wavelength (cm)</th>
<th>Freq. (GHz)</th>
<th>Pixel Scale (&quot;)</th>
<th>Beam Size (&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Apr 1994</td>
<td>20</td>
<td>1.4</td>
<td>0.3144</td>
<td>1.3</td>
</tr>
<tr>
<td>23 Mar 1988</td>
<td>20.1</td>
<td>1.49</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>14 Jan 1984</td>
<td>6</td>
<td>4.86</td>
<td>0.3259</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Fig. 5.3 displays the VLA 6 cm fluxes at three different intensity scalings, to respectively enhance the jet and star-forming ring. Masking out all pixels that have a value >300 mJy (to remove the jet) (bottom left plot), the SF ring is seen as a string of emission features, each with roughly the same luminosity (∼2 mJy), which are probably individual supernova remnants. The VLA 20 cm map presents a very similar structure (not mapped here). Aligning the 6 cm and 20 cm maps allows measurement of the spectral index: this is also plotted in Fig. 5.3. The spectral index is computed

\[ \alpha = \frac{\log(S)}{\log(\nu)} \]

and is in the range -1.7 – -0.3, with a median value of -0.8, indicating non-thermal (i.e. synchrotron) emission.

If the total 6 cm flux is summed on the NE sector of the circle (since the jet interferes with the SW sector), a value of ∼ 70 mJy is obtained. At the distance of 41.1 Mpc, this translates to a luminosity of ∼ 1.4 × 10^{22} W Hz^{-1}. Using the SNR indicator of Condon (1992) (their equation 18) where \( \nu = 5 \) GHz and \( \alpha = -0.8 \), this is equivalent to a supernova rate (SNR) of ∼0.4 yr^{-1}; this value may well be high, as the jet emission may be contributing to the measured flux. The individual SNR luminosities are ∼ 4.4 × 10^{20} W m^{-2}; again the unmasked jet emission will contribute some of this luminosity. This can be compared to the SNRs in M82, which have luminosities in the range 0.02 – 1.7 × 10^{20} W m^{-2} (Muxlow et al., 1994). The spacing of the SNRs is reminiscent of the nuclear rings of star clusters; examples are cited in Brandl et al. (2012) and Pan et al. (2013) for NGC 7552 and Böker et al. (2008) for 5 nearby spiral galaxies.

Fig. 5.4 shows the elliptical model fit to the PanSTARRS image, using the IRAF stsdas.analysis.isophote ellipse and bmodel tasks. The parameters for the various features are given in Table 5.3. The ‘ellipticity’ is \( \epsilon = 1 - b/a \), where \( a \) is the major and \( b \) is the minor axis size (a smaller value means closer to circular); from which, assuming circular symmetry, the inclination \( i \) of the ellipse to the LOS can be derived. This will become important in determining the inclination to the LOS of the jet.

Fig. 5.5 shows the the [O III] MUSE flux image (see Section 5.3.2) overlaid with the Chandra X-ray contours (acquired from the Chandra Source Catalog, Evans et al. (2010),
Figure 5.3: AGN and circumnuclear SF activity from VLA 6 cm images. Top left: linear scaling (to enhance the jet). Top right: logarithmic scaling (to enhance star-forming ring). Bottom left: Jet masked to show point-source supernova remnant emission. All flux values are in mJy. Bottom right: Spectral index derived from 6 cm and 20 cm fluxes; the negative index indicates non-thermal (i.e. synchrotron) emission.
Figure 5.4: Elliptical model fit to isophotes, showing the complex structure of outer disk, inner ring and nuclear bar. Left panel: (top) outer, (bottom) inner parts of the galaxy, showing the centrally disturbed morphology. Right panel: Model residual (image–model); (top) outer, (bottom) inner. All color-bars and contours for isophote models have values in magnitudes arcsec$^{-2}$.

using the CSCView tool\textsuperscript{4}, and the VLA 6 cm contours. The X-ray and [O III] fluxes are co-spatial. The X-ray data have been smoothed by a Gaussian with a 2 pixel FWHM, to prevent pixellation. The X-ray orientation has the highest flux in the SE direction, counter to the radio jet; this can be explained by obscuration of the NW X-ray jet, plus relativistic beaming of the NW radio jet over the SE counter-jet. Rodríguez-Ardila et al. (2017), studying NGC 1368, deduce that the extended X-ray emission in that object is

\textsuperscript{4}http://cda.cfa.harvard.edu/cscview/, Dataset ID ADS/Sa.CXO#CSC/Reg/4077-1-P-2-0003
Table 5.3: Model fit to features. Col. 2 - the approximate limiting magnitude of the feature. The semi-major axis (SMA), position angle (PA) and ellipticity ($\epsilon$) are from the ellipse model fit. PA is N=0°, E=90°. $i=0°$ is face-on, 90° is edge-on to LOS.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Mag</th>
<th>SMA (pc)</th>
<th>PA°</th>
<th>$\epsilon$</th>
<th>$i°$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Bar</td>
<td>9.0</td>
<td>370</td>
<td>82</td>
<td>0.446</td>
<td>56</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>10.5</td>
<td>1045</td>
<td>20</td>
<td>0.128</td>
<td>29</td>
</tr>
<tr>
<td>Main Disk</td>
<td>12.5</td>
<td>4800</td>
<td>27</td>
<td>0.452</td>
<td>57</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>14.0</td>
<td>13200</td>
<td>32</td>
<td>0.580</td>
<td>65</td>
</tr>
</tbody>
</table>

caused by shocks greater than 200 km s$^{-1}$ producing free-free emission; as will be seen, the outflow velocities of NGC 5728 certainly exceed that value.

Figure 5.5: Chandra+VLA+[O III]. [O III] flux image (logarithmic scaling) from MUSE data (flux values as per color-bar), showing photo-ionized and shocked gas in the outflows. Chandra (0.5–7 keV) smoothed flux contours (green) with values of 0.1, 0.2, 0.5, 1, 2 and $5 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$; this shows the reflected AGN emission plus production from shocked gas. VLA 6 cm contours (blue) flux levels at 0.2, 0.5, 1 and 2 mJy, delineating the synchrotron emission from the relativistic jet. The X-ray, radio and emission-line gas are clearly aligned.
5.3. Results and Discussion

5.3.2 Optical IFU Observations

The complex structure of the inner region is further revealed with data collected in the Siding Spring Southern Seyfert Spectroscopic Snapshot Survey (S7)\(^5\) (Dopita et al., 2015; Thomas et al., 2017), using the WiFeS optical IFU. Emission line fitting products are computed for each object using the LZIFU toolkit (Ho et al., 2016), some of these are shown in Fig. 5.6. It also shows the WiFeS H\(\alpha\) and [O III] emission line images; the H\(\alpha\) clearly shows both the SF ring and the outflow, whereas the [O III] only shows the outflow. Note that the radio jet is aligned with, but in the opposite direction to, the side of the majority of the gas outflow; the high-excitation gas outflow shows up more clearly in the [O III]/H\(\beta\) ratio than the lower excitation [N II]/H\(\alpha\) ratio. The flux ratios for the Kewley et al. (2006) nuclear classification diagram are also plotted (Fig. 5.6 in Section 5.3.10).

In a similar manner to masking the VLA data, the star-forming H\(\alpha\) flux was computed by masking out pixels where the [O III] flux was \(\geq 5 \times 10^{-17}\) erg cm\(^{-2}\) s\(^{-1}\) (since the [O III] is only associated with the outflow). Over the SF ring, the H\(\alpha\) flux was \(1 \times 10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\), which, using the Kennicutt et al. (2009) relationship, is equivalent to a SFR of \(\sim 0.016\) M\(_{\odot}\) yr\(^{-1}\). This figure should be regarded as indicative only, as the masking processes are somewhat rudimentary, and H\(\alpha\) emission from the outflows cannot be excluded with certainty.

We also obtained archival data from the MUSE optical IFU instrument (Bacon et al., 2010) for the TIMER (‘Time Inference with MUSE in Extragalactic Rings’) survey (P.I. Dimitri A. Gadotti, European Southern Observatory); this data was reduced before release and is used, with the kind permission of Dr. Gadotti, for high resolution spectra close to the nucleus, to determine the Seyfert classification type.

5.3.3 The NIR and Optical Nuclear Spectrum

The nuclear spectrum was obtained by integrating the flux in a circular aperture of radius 0\(^{\prime\prime}\).5 around the brightest pixel in the continuum image for each data cube. Fig. 5.7 gives the spectra for the whole NIR wavelength range, showing the good flux calibration between the data cubes, taken at different dates and instruments. For comparison, the spectrum from the 0.8–2.4 \(\mu\)m atlas of AGN (Riffel et al., 2006) is also plotted (rescaled for clarity). Fig. 5.8 shows the detail for the main emission lines of interest. The prominent double peak of the [Fe II] 1257 nm line is caused by an imperfectly corrected telluric feature;  

\(^5\)https://miocene.anu.edu.au/S7/
Figure 5.6: AGN and circumnuclear SF activity from optical observations; WiFeS components derived from the LZIFU toolkit. First column: top - H\(\alpha\) flux, bottom - [O III] flux. Values in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$. The labels (‘N’, ‘1’ etc.) are locations for the excitation diagrams; see Section 5.3.10. Second column: Flux ratios top - log([N II]/H\(\alpha\)), bottom - log([O III]/H\(\beta\)). Third column: Stellar LOS, top - velocity, bottom - dispersion. Values in km s$^{-1}$.
5.3. Results and Discussion

subsequent results from of this line will be treated with caution. The optical WiFeS nuclear spectrum is presented in Fig. 5.9, showing the Seyfert 2-like narrow emission lines of hydrogen, oxygen, nitrogen and sulfur.

Véron-Cetty & Véron (2006) classify this galaxy as Seyfert 1.9 (i.e. broad-line components are only visible for \( H\alpha \)) based on the 6dF survey data (Jones et al., 2009); the nucleus was observed with a 6\".7 aperture at a spectral resolution of \( \sim 1000 \) (in poor seeing). The WiFeS observations show only narrow lines in \( H\alpha \); the mis-classification is caused by a large aperture (which incorporates the outflows), low spectral resolving power and overlap from the adjacent \([N\ II]\ lines. This will be further explored in Section 5.3.14.4.

5.3.4 Continuum Emission

We examine the nuclear structure, stellar populations and obscuring dust using continuum imagery. As the \( J \) band cube has poorer observational resolution (0\".25 with no AO), we will only use the \( H+K \) cube (0\".05 with AO). The \( H \) and \( K \) continuum magnitude images are derived from the cube by measuring the average flux over 10 nm around the filter effective wavelengths and converting to mag arcsec\(^{-2} \) for each pixel, and the color \( H-K \) was derived. Fig. 5.10 presents the magnitude and color maps for the central 3\".8 (760 \( \times \) 760 pc).

The dust-lane (starting at \( \Delta RA=+1'' \), \( \Delta Dec=0'' \), ending at \( \Delta RA=-0''.5 \), \( \Delta Dec=-0''.5 \)) shows up well in the \( H \)-band magnitude map; as expected, it is less prominent in the \( K \)-band. The central region is very red, \( H-K = 0.6 \) mag. The location of the peak of the central object appears to shift by \( \sim 0''.085 \) between \( H \) and \( K \). This is because of the increased dust penetration at longer wavelengths. The ‘true’ location of the AGN is discussed in Section 5.3.7; the shift in position with wavelength of the brightest peak indicates that determining this location is problematic.

The \( H-K \) image shows a broad bar aligned at \( PA = 40^\circ-220^\circ \), roughly 90\( ^\circ \) to the line of the jet/outflow. This is caused by the hot dust in the equatorial plane of the AGN, which also is the source of the very red colors at the nucleus; this is the equatorial toroidal obscuration component. The \( H-K \) image also shows reduced obscuration in the SE and NW quadrants; the edges of these (at < 0.2 mag) align very well to the edges of the outflow, especially in the SE (see Section 5.3.14.2 below for further discussion).

Fig. 5.11 (left panel) shows the structure map for the central 16\" of the \( HST \) F814W image, clearly showing the feeding filaments in the inner spiral structure. The right panel then overlays the \( K \)-band magnitudes contour over the central 3\".8. The dark lanes are seen as the extension into the center of the feeding filaments.
Chapter 5. Dissecting the Outflows of NGC 5728

**Figure 5.7:** Nuclear spectrum from central 1″ from SINFONI (J and H+K), plus the NIR atlas of (Riffel et al., 2006). Emission lines and CO absorption band-heads are marked. The NIR atlas spectrum is rescaled and offset for clarity. All spectra are reduced to rest-frame.

**Figure 5.8:** Enlarged SINFONI spectra from Fig. 5.7, showing the main lines. The [Fe II] line at 1257 nm is affected by a telluric feature. Spectra are reduced to rest-frame.

**Figure 5.9:** WiFeS spectrum of central 1″, showing the main lines. The spectrum is reduced to rest-frame.
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Figure 5.10: $H$ and $K$ surface magnitude and $H - K$ color map, as labeled. The magnitude colors are plotted with square-root scaling, to enhance contrast. The color-bar values are in mag arcsec$^{-2}$. The $H - K$ plot shows the AGN equatorial obscuration.

Figure 5.11: Left panel: *HST* F814W structure map, showing the feeding spirals, the bright central nucleus and the star-forming regions (bright points aligned with the outer edges of the dust lanes). The light green rectangles are the fields of view of SINFONI $H+K$ (inner) and $J$ (outer) observations. Right panel: Central 3".8 (760 pc) of the structure map overlaid with the $K$ magnitude contours; the $H - K$ obscuration matches the feeding filament.
AGN tori typically have hot (\(\sim 600 - 1000 \) K) dust emission; this can be seen as an increase in slope towards the end of the \( K \) band. Fig. 5.12 shows the ratio of the spectrum in annuli around the AGN location to that of a reference spectrum located 1\(^{\prime}\).3 NW of the nucleus, which is presumably representative of the underlying stellar population. This ratio is normalized at the shortest wavelength in the spectrum (1453 nm). The changing continuum slope is indicative of an increasing hot dust contribution at smaller radii. It should be emphasized that the actual continuum slopes are always negative; the inner slopes are relatively less negative.

The inner torus directly around the AGN is encompassed within the central pixel; we can find the temperature by fitting the \( K \)-band spectrum for this pixel with a linear combination of the reference spectrum described above and a black-body spectrum:

\[
S_C = \alpha S_R + \beta S_{BB}(T) + \gamma
\]

where \( S_C \) is the central pixel spectrum, \( S_R \) is the reference spectrum and \( S_{BB}(T) \) is a black-body spectrum at temperature \( T \); \( \alpha, \beta \) and \( \gamma \) are fitting constants. The equation was solved for \( T \) using the generalized reduced gradient algorithm (‘GRG Nonlinear’) implemented in the \texttt{MS-Excel} add-on \texttt{Solver}. The emission lines have been masked out from the central pixel spectrum. The best fit black-body spectrum is at a temperature of 870 K; this is shown in Fig. 5.12, bottom panel. Burtscher et al. (2015) report median hot dust temperatures of 1292 K for Seyfert 1 and 887 K for Seyfert 2 types for 51 local AGN; the value for NGC 5728 is in good agreement with this range.

### 5.3.5 Stellar Kinematics

The stellar kinematics help to disentangle the complex nuclear structure and also give an estimate for the SMBH mass. They are derived from the Si I line in the \( H \)-band at 1589.2 nm using the \texttt{velmap} procedure from \texttt{QFitsView}. This procedure is designed for emission lines; the spectrum was inverted to turn an absorption line into a peak. The resulting (cleaned) velocity and dispersion map is presented in Fig. 5.13. This shows a simple rotation around the east-west axis; the average dispersion in the central 0\(^{\prime}\).5 radius is 230 \( \pm \) 26 km s\(^{-1}\) and the systemic velocity is 2984 \( \pm \) 55km s\(^{-1}\). Combined with the wavelength calibration and the barycentric velocity corrections (derived above), our systemic velocity is 2937 km s\(^{-1}\), compared to the H I 21 cm velocity of 2786 km s\(^{-1}\) (Roth et al., 1991) and the H\(\alpha\)-derived velocity of 2804 km s\(^{-1}\) (Catinella et al., 2005).
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Figure 5.12: Hot dust contribution to the nuclear spectrum. Top panel: Ratio of continuum in annuli around the nucleus to a non-nuclear reference spectrum, showing the long-wavelength rise indicative of hot nuclear dust. The first and second plots are apertures of radius 0.1" and 0.25", then in annuli of 0.25" up to 1", around the nucleus. The reference spectrum is also plotted for comparison. The ratios have been offset for clarity. Bottom panel: Fit to nuclear flux from reference spectrum and black-body spectrum at 870 K. See text for an explanation of the fitting process. The vertical axis is in arbitrary flux units. The emission lines in the nuclear spectrum have been masked out. The residual flux is also plotted at the same scale.
Chapter 5. Dissecting the Outflows of NGC 5728

The difference can be ascribed to the H I measuring the velocity of the whole galaxy and the Hα velocity including gas with a non-zero peculiar velocity.

The stellar velocity field is modeled using the Plummer potential, as described in Section 2.6.5. The model was fitted with the generalized reduced gradient algorithm (‘GRG Nonlinear’) implemented in the MS-Excel add-on Solver. The systemic velocity was constrained to zero and the kinematic center to the AGN location. The model and residual results are also shown in Fig. 5.13. The axis PA is 1°.4 (i.e. the rotational equator is nearly edge-on to the LOS), with negligible inclination and a scale length of 1010 pc (i.e. off the edge of the field). A slice through the measured velocity field along the axis produces a velocity gradient of 205 km s⁻¹ over 140 pc, which implies an enclosed mass of \( \sim 3.5 \times 10^8 M_\odot \), assuming simple Keplerian rotation.

A solution was attempted using the CO band-heads in the K band spectrum in the range 2293–2355 nm, using the penalized pixel-fitting (pPXF) method of Cappellari & Emsellem (2004) and the Gemini spectral library of near-infrared late-type stellar templates (Winge et al., 2009), on both the OSIRIS K-band and SINFONI H+K-band data cubes. This produced poor results, as the relative strength of the CO lines was diluted by the rising AGN continuum.

Lin et al. (2017), using the same data set, found a central stellar velocity dispersion of 164 ± 4 km s⁻¹ from the CO band-heads; our use of a single absorption line, rather than spectral fitting, possibly overestimates the dispersion.

The kinematics of the inner ring and bar match (to first order) those of the molecular hydrogen (see Section 5.3.9.2); however, if this ring of star formation is a disk structure, then it appears not to be rotating about its normal axis, which would be almost along the LOS. Instead the Plummer model shows that the rotation axis is almost east-west and the disk is ‘tumbling’, mis-aligned to the main galactic plane rotation axis by \( \sim 60° \); these disturbed kinematics and morphology are possibly caused by an interaction, and would explain the star formation and AGN activity, as gas is driven into the nucleus.

5.3.6 SMBH Mass, Eddington Ratio and Accretion Rate

The black hole mass can be derived as described in Section 2.6.5, using various scaling relationships. The \( M - \sigma \) value is derived from our stellar kinematics using the Graham & Scott (2013) relationship. The Sérsic profile was fitted to the K continuum flux radial profile from the SINFONI data cube (see Fig. 5.14); as can be seen, the radial profile shows signs of a turn-over in the inner few pixels, indicative of a ‘core-Sérsic’ profile (see Graham & Scott, 2013; Savorgnan et al., 2013); the Sérsic index fit excludes the inner two
5.3. Results and Discussion

Figure 5.13: Top row: Stellar LOS velocity and dispersion from the Si I absorption line (1589 nm). Contours are the H-band normalized flux, from 30 to 90% of maximum, in steps of 10%. Velocity and dispersion values in km s\(^{-1}\). Bottom row: Plummer model fit and residual. This shows the ordered, tumbling rotation of the circumnuclear stellar structure, mis-aligned to the main galactic plane rotation axis by \(\sim 60^\circ\).

The Hyperleda database (Paturel et al., 2003) quotes the central velocity dispersion as \(210 \pm 15\) km s\(^{-1}\) from the [O III] emission line, obtained from Wagner & Appenzeller (1988), and is used to derive the mass using the \(M - \sigma\) relationship; however the standard cautions must be used for stellar vs. gaseous dispersions (e.g. Krajnovic et al., 2007), especially since [O III] is associated with the outflow. Given that, the SMBH mass value derived from the relationship is still reasonable (see Table 5.4).
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Figure 5.14: Top panel: radial profile data (points) with the Sérsic fit (index = 3.54). Bottom panel: residual (fit–data). Radius in logarithmic scale, flux is normalized. This implies a SMBH mass of $\sim 3.4 \times 10^8 \, M_\odot$.

The spiral arm pitch angle relationship of Davis et al. (2017) also yields a value for the SMBH mass comparable with the other relationships; these arms are faint ones that come from the end of the bar, not the ‘Outer Ring’ structure. I thank Dr. Benjamin Davis for providing the data, using the software SPIRALITY (Shields et al., 2015a,b), SpArcFiRe (Davis & Hayes, 2014) and 2DFFT (Davis et al., 2012). The de-projected galaxy image, with the fitted logarithmic spiral arcs, is shown in Fig. 5.15; the de-projection angle is 43°.

Table 5.4 gives the black hole mass measurements determined by the four different methods, as set out in Section 2.6.5. This shows that all values are consistent, within uncertainties. The $M - L_{K,sph}$ value may be low due to obscuration and a lack of a well-defined ‘classical’ bulge. The weighted mean value of the SMBH masses (using the inverse variances in each derived mass as the weights; these are then added to give the inverse variance on the weighted mean) is also given, and is used in calculation of the Eddington ratio.

The agreement between the different methods, all based on different astrophysical relationships, gives us confidence in the derived SMBH mass. The enclosed mass from the stellar velocity gradient, $\sim 3.5 \times 10^8 \, M_\odot$, from the Plummer model fit (derived above) is comparable with the average value of the SMBH mass $2.3 \times 10^8 \, M_\odot$, implying that the SMBH is the dominant component in the inner 150 pc.
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![Figure 5.15](image.png)

**Figure 5.15**: NGC 5728 de-projected image, showing the fitted logarithmic spiral arcs (red and blue), with the ‘Outer Ring’ with the magenta circle; the pitch angle relationship gives a SMBH mass of $\sim 3.4 \times 10^8 M_\odot$

**Table 5.4**: SMBH Mass derived from scaling relationships.

<table>
<thead>
<tr>
<th>Method</th>
<th>Value</th>
<th>$\log(M_\bullet)$</th>
<th>$M_\bullet(\times 10^8 M_\odot)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M - \sigma$</td>
<td>$230 \pm 26$ km s$^{-1}$ (Si I)</td>
<td>8.42 ± 0.46</td>
<td>3.35(+6.3, -2.19)</td>
</tr>
<tr>
<td></td>
<td>$210 \pm 15$ km s$^{-1}$ ([O III])</td>
<td>8.37 ± 0.41</td>
<td>2.33(+3.64, -1.42)</td>
</tr>
<tr>
<td>$M - L_{K_s, sph}$</td>
<td>$-23.25 \pm 0.01$ Mag</td>
<td>8.13 ± 0.49</td>
<td>1.36(+4.2, -0.45)</td>
</tr>
<tr>
<td>$M - n$</td>
<td>3.54</td>
<td>8.53 ± 0.42</td>
<td>3.39(+8.87, -1.3)</td>
</tr>
<tr>
<td>$M - \phi$</td>
<td>7.0 ± 0.3°</td>
<td>8.37 ± 0.37</td>
<td>2.34(+3.15, -1.34)</td>
</tr>
<tr>
<td>$\bar{M}$ (Weighted)</td>
<td></td>
<td>8.36 ± 0.20</td>
<td>2.3(+1.3, -0.8)</td>
</tr>
</tbody>
</table>

We calculate the bolometric luminosity, Eddington ratio, accretion rate and sphere of influence using the method described in Section 2.6.5 and the weighted average SMBH mass from Table 5.4. Using the 14–195 keV X-ray luminosity from Davies et al. (2015), this gives:

\[
L_X(14 - 195) = 1.62 \times 10^{42} \text{ erg s}^{-1}
\]

\[
L_{\text{Bol}} = 1.46 \times 10^{44} \text{ erg s}^{-1}
\]

\[
L_{\text{Edd}} = 3.0 (\pm 2.0, -1.2) \times 10^{46} \text{ erg s}^{-1}
\]

\[
R_{\text{Edd}} = 4.9 (\pm 3.2, -2.0) \times 10^{-3}
\]

\[
\dot{M}_{\text{acc}} = 2.7 \times 10^{-2} M_\odot \text{ yr}^{-1}
\]
R_I = 19 pc

Eddington ratios have a large range; the trend, as outlined by Ho (2008), is for higher luminosity AGNs to have higher ratios. Ricci et al. (2014a), in their discussion of emission line properties in 10 early-type galactic nuclei, noted that $R_{Edd} < 10^{-3}$ for all the galaxies that had AGN; however this sample were all LINERs. Storchi-Bergmann et al. (2010) found the ratio for NGC 4151 was 0.012 and Fischer et al. (2015) found 0.12 for Mrk 509 (both Seyfert 1.5); these however have a higher bolometric luminosities that NGC 5728. Vasudevan et al. (2010) gives an Eddington ratio for NGC 5728 of 0.028, however they underestimate the BH mass ($\log(M_\bullet) = 7.15$) and thus overestimate the ratio. Their range of values of the ratio for the complete sample of 63 Swift/BAT X-ray AGNs are $6 \times 10^{-3} \leq R_{Edd} \leq 7.3 \times 10^{-2}$. Ho (2008) gives a median $R_{Edd}$ for LLAGN of $1.1 \times 10^{-3}$ for Seyfert 1-type galaxies, and $5.9 \times 10^{-6}$ for Seyfert 2s; the bolometric luminosity for this galaxy ($1.46 \times 10^{44}$ erg s$^{-1}$) places it rather above the range for LLAGN.

In summary, NGC 5728 has a moderate-luminosity Seyfert 2 AGN, with Eddington ratio and accretion rate within the range of values found in the literature, powered by SMBH of $2.3 \times 10^8$ M$\odot$.

5.3.7 Locating the AGN

In Seyfert 2-type galaxies, the AGN is obscured by the dusty torus, so the small, unresolved BLR is not visible; this torus can extend from 1–100 pc. The position of the AGN is usually taken as the brightest pixel in the continuum (on the assumption that there is a nuclear cluster), but in this case there is a dust lane that obscures this location, as seen on the $H - K$ plot (Fig. 5.10). This lane is in addition to the supposed dusty torus, as it extends across the field for $\sim 400$ pc, and connects to the spiral feeding filaments.

Presumably, the outflows have their origin (both positionally and kinematically) at the AGN central engine; however there are issues that will affect the symmetry of the outflow fluxes and velocity fields:

- Obscuration; the dust lane is on the approaching outflow side; this will reduce the flux (and corresponding flux-weighted velocity).
- ISM impact; the SW velocity field shows an increase out from the AGN to a maximum of about 350 km s$^{-1}$ at 300 pc from the AGN and then a deceleration to 150 km s$^{-1}$ at 760 pc (projected distances); if the outflow encounters a more dense ISM (associated with increased obscuration), this will both reduce the distance to and the velocity of the maximum.
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- Velocity bias; even without obscuration, an outflow that has a significant component of velocity along the LOS will have the approaching velocities biased towards zero, as described by Lena et al. (2015), where approaching clouds preferentially show their non-ionized face to the observer; thus their line emission is attenuated by dust embedded in the cloud and the average velocity measured for the blue-shifted clouds is skewed toward smaller values.

We deduce the position of the AGN by 3 different methods, each of which is plotted on Fig. 5.16, which shows the magnified central region (1” = 20 pixels a side). These are derived from:

- The centroid/maximum of the H$_2$ flux, assuming this is kinematically cold and settled around the center of mass of the nucleus. The [Fe II], H$_2$ and Br $\gamma$ flux maxima locations are also plotted for comparison.

- The $H+K$-band flux ratio of [Fe II] and Br $\gamma$ shows that the [Fe II] jackets the Br $\gamma$, thus defining the edges of the outflow. The outflow edge center-lines and limits are plotted as lines; these are derived from the [Fe II] zero velocity channel map (see Section 5.3.9.3).

- The continuum centroid positions are plotted for $H+K$ wavelengths in the range 1460-2400 nm. This assumes that the flux peak moves closer to the AGN as the obscuration becomes less important.

All points are assumed to have a positional error of ±1 pixel. The H$_2$ flux, the continuum centroid trajectory and the outflow edge limits and centerline all seem to align to within ±2 pixels.

The final AGN location is taken to be the centroid of the locations of the H$_2$ centroid, the Br $\gamma$ centroid and the outflow edge limits and center; this is marked as the yellow star in Fig. 5.16. If we assume the AGN location is the same as the Chandra X-ray source, this is RA = 14h 42′ 23.897″, DEC = -17° 15′ 11.09″ (Evans et al., 2010, with typical 0″.6 precision).

We can set this AGN location on the $J$-band data cube by following the trajectory of the flux peak with wavelength. We equate the continuum centroid at 1350 nm in $J$ as the same as 1460 nm in $H+K$, displaced to follow the trend of the trajectory with wavelength. The $J$-band cube was resampled to the same resolution as the $H+K$ cube for the comparison. These positions are shown on previous and subsequent maps with a ‘+’ symbol.
Figure 5.16: AGN location derived by different methods: see text for explanation. The outflow edges as delineated by the [Fe II]/Br$\gamma$ ratio are shown as the black dotted line, with the centroid alignment shown by the dotted red lines. The axes are the data cube spatial pixels; 1 pixel = 10 pc = 0''.05 projected distance. The (0,0) position in RA, DEC is the center of the H+K image. Our preferred AGN location is shown as a yellow star, derived from H$_2$ and Br$\gamma$ centroids and the outflow edge limits and center.

5.3.8 Gaseous Nebular Emission

5.3.8.1 Nuclear Emission

Emission lines diagnose various physical parameters in the interstellar medium, including star formation and outflow dynamics, as well as the physical processes of excitation. Table 5.5 shows the flux (with uncertainty) for the observed emission lines in the central 1'' of the nucleus, from the $J$, $H+K$ and optical data cubes. It will be noted that the observed central wavelengths do not exactly correspond to the red-shifted air wavelengths, especially in the NIR. This comes from the biased wavelengths of the outflow, where the receding gas dominates over the approaching gas, with the ionized species lines in the outflow (hydrogen recombination, [Fe II] and [Si VI]) show a recession velocity 150–250 km s$^{-1}$ over systemic. The H$_2$ lines, which are not associated with the outflows, have wavelengths closer to the systemic values.
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Table 5.5: Integrated flux for emission lines for the central 1" (0.5 radius) aperture, with their respective uncertainties (ΔF). Flux values are in $10^{-16}$ erg cm$^{-2}$ s$^{-1}$. For the WiFeS S7 optical data, the flux is taken as the maximum value within 1 pixel (=1") of the position of the nucleus; values are taken from the LZUIFU toolkit data products, except for [O I] 630.0 flux, which was measured from the data cube. Line measurements are grouped by data source.

<table>
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<th>Data Source</th>
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<th>λ (Air)</th>
<th>F</th>
<th>ΔF</th>
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<td>372.6</td>
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<td>2.1</td>
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<td>23.2</td>
<td>3.7</td>
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<td></td>
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<td>1964.1</td>
<td>77.1</td>
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<td>2059.5</td>
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<td>45.6</td>
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<td>2154.2</td>
<td>4.4</td>
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<td>2166.1</td>
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<td>2423.7</td>
<td>36.5</td>
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</table>
5.3.8.2 Emission-line Flux Distribution

We derive maps of the gas emission fluxes and kinematics from the \textit{velmap} (velocity map) procedure in \textit{QFitsView} on the SINFONI data cubes ($J$ and $H+K$), as described in Section 2.5.3. Even though the OSIRIS $K$-band data cube has better wavelength resolution (R=3000 vs. R=1560), the SINFONI $H+K$ cube had better S/N, so that data will be used. Maps were obtained for the species $\text{Pa} \beta$ (1282 nm), $\text{Br} \gamma$ (2166 nm), $\text{[Fe II]}$ (1257 and 1644 nm), $\text{H}_2$ (2121 nm) and $\text{[Si VI]}$ (1964 nm).

The $\text{[Si VI]}$ maps were difficult to produce due to the close and strong $\text{H}_2$ (1957 nm) line; since the range of velocities over the whole field is fairly large, the \textit{velmap} routine was ‘locking on’ to the wrong line in places. This was solved by creating the maps for the $\text{H}_2$ line, then subtracting a Gaussian fit at each spaxel from the fitted parameters; this had the effect of removing the $\text{H}_2$ line from the data cube. Additionally the fitting procedure was done independently for the north and south halves of the data cube and then combined, as the $\text{H}_2$ velocity field is oriented in that direction. The $\text{[Si VI]}$ line was then fitted successfully.

Fig. 5.17 and 5.18 shows the flux and EW for each species. The $J$-band maps have a spatial extent of $7''.5$ square, as against the $H+K$-band of $3''$ (1.5 vs. 0.6 kpc). The hydrogen recombination emission, $\text{[Fe II]}$ and coronal $\text{[Si VI]}$ lines all show similar structure of a biconal outflow with a PA = 140–320$^\circ$; the equivalent width maps show this clearly (the EW is invariant to obscuration), displaying a distinct ‘waist’ at the outflow intersections.

By contrast, the $\text{H}_2$ is spatially distinct, presenting as a disk oriented roughly NS with ‘arms’ trailing to the NW and SE.

Assuming a uniform ISM, the $\text{[Fe II]}/\text{Br} \gamma$ and $\text{[Si VI]}/\text{Br} \gamma$ ratios plot the relative ionizing conditions for those species; these conditions will be explored in Sections 5.3.8.5 and 5.3.10. Fig. 5.19 plots the flux ratio of $\text{[Fe II]}$ (1644 nm), $\text{H}_2$ and $\text{[Si VI]}$ to $\text{Br} \gamma$. This shows that $\text{[Fe II]}$ becomes relatively stronger towards the end and around the edges of the outflow. The $\text{[Si VI]}$ is more concentrated near the AGN, however it is present the full length of the outflow. The $\text{H}_2$ emission is centrally concentrated, but as we will see, is kinematically disassociated from the outflow and ionized species.

5.3.8.3 The Outflow Bicones

The appearance of the two outflow cones is not the same; the SE one is reasonably continuous, whereas the NW one has a prominent break near the AGN, then restarts at about 260 pc from the nucleus.
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Figure 5.17: Bi-polar outflow structure as shown by the flux and equivalent width values for Pa\(\beta\) and [Fe II] (1257 nm). Flux values (shown in color-bar) in units of \(10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\). Contours are 10, 25, 50, 75 and 90% of the maximum flux. Equivalent width values in nm. Blue circles on the Pa\(\beta\) EW map are the locations for SF age measurement. The outer ring in the Pa\(\beta\) maps traces the star-forming ring around the nucleus, [Fe II] traces the outflow boundaries.
Figure 5.18: As for Fig. 5.17, but for Br$_\gamma$, H$_2$ (2121 nm), [Fe II] (1644 nm) and [Si VI]. The [Si VI] has nearly the same extent as the hydrogen recombination emission. The star-forming ring is outside the scale of the maps.
5.3. Results and Discussion

Figure 5.19: Flux ratios of [Fe II], H$_2$ and [Si VI] to Br$\gamma$, showing relative excitation. Contours on the [Fe II]/Br$\gamma$ plot are the K-band normalized flux, at 10, 25, 50, 75 and 90% of the maximum flux. [Fe II] is on the outflow boundaries, [Si VI] is more prominent closer to the AGN and H$_2$ and Br$\gamma$ emissions are disjoint.

Asymmetry in outflow cones can come from several sources (see Comerford et al., 2017, and references therein): blockage by high density clouds close to the AGN that absorb the outflow energy and promptly re-radiate it away or, alternately, discontinuous AGN outburst activity which can create asymmetries at source as seen in simulations. The first scenario is likelier with NGC 5728, as the limb-brightening that outlines the cones has the same length in both directions. The patch of emission at $\sim$ 320 pc NW would then be generated by the radio jet (which penetrates the clouds) impacting the ISM near the SF ring. The extended [O III] emission from the MUSE observations (Fig. 5.3) has discontinuities in both outflows to the full 2 kpc extent, which can be indicative of either turbulent entrainment of the ISM, flickering outflows within the symmetric outburst event or by obscuration by dust lanes in the galactic plane.

5.3.8.4 The Star-Forming Ring

The stellar age in the SF ring was determined from the Pa$\beta$ EW, using the STARBURST99 model data, as described in Section 2.6.3.2. Three locations in the ring, but out of the line of the outflows, were used, as shown in Fig. 5.17 top right panel (circles); the EW was averaged within a radius of 3 pixels. These values were in the range 0.16 – 0.42 nm, which is equivalent to 7.4 – 8.4 Myr for the model a Solar metallicity, a mass cutoff of 100 M$_\odot$ and an IMF slope of 2.35.
5.3.8.5 Coronal Line Emission

Emission lines of highly ionized species (e.g. [Si VI], [Ca VIII] and [S IX]) trace the direct photo-ionization either from EUV and soft X-rays from the AGN accretion disk, or by fast shocks. These species have ionization potentials (IP) up to several hundred eV, and are called coronal lines (CLs) and the emission locations are called coronal line regions (CLRs). This emission has the advantage of not being contaminated by photo-ionization from star formation i.e. it is diagnostic of AGN activity. For coronal species with an IP of \( \sim 100 - 150 \text{ eV} \), the emission exhibits a similar morphology and kinematics to lower ionization lines such as [O III]; however for species with IP \( > 250 \text{ eV} \), the emission is very compact.

Mazzalay et al. (2013a) found for NGC 1068 that the morphology and kinematics were consistent with being driven by the radio jet, and that shock mechanisms were favored over photo-ionization. A similar conclusion was deduced for NGC 1368 by Rodríguez-Ardila et al. (2017).

Apart from the [Si VI] emission, we also detect weak [S IX] and [Ca VIII] coronal lines. This is in contrast to Rodríguez-Ardila et al. (2011), who reported no detectable flux for those species for NGC 5728, in their coronal line study of 54 local AGN. We constructed flux maps these species by averaging the data cube along the spectral axis over the emission line profile, then subtracting the average continuum in a neighboring featureless spectral region; the result was multiplied by the line profile width to produce the flux. The weakness of the flux precluded using the standard \textit{velmap} procedure. Fig. 5.20 plots the flux maps; the weakness of the lines will cause some uncertainties, so the flux values should not be taken as very accurate, however the structure is clear.

The [S IX] emission (IP = 379 eV, \( \lambda = 83.3 \text{ nm} \)) showing a small extension along the line of the SW outflow, while the [Ca VIII] (IP = 147 eV, \( \lambda = 8.4 \text{ nm} \)) exhibits a more compact structure around the AGN location, with a possible extension along the NW outflow; both of these extensions are close to the observational resolution limits. Neither of these species shows the same spatial extent as [Si VI]; in the case of [Ca VIII] (which has a similar IP to [Si VI]), the low line strength means that the flux level drops below the detectable threshold; in the case of [S IX] an additional factor could be that the ISM fully absorbs the ionizing radiation closer to the AGN. We can also posit that the higher IP species are ionized directly by the AGN. The [Si VI] emission is also generated by shock excitation in the outflows, which do not have enough energy to excite the higher IP species.
Murayama & Taniguchi (1998) proposed a model of a clumpy CLR associated with the NLR, where the individual clumps are ‘matter-bounded’, i.e. the whole cloud is ionized and its extent is simply that of the gas cloud itself. Since, under this model, receding outflows (presumably the far side of the AGN) would preferentially show the highly-ionized face towards the observer, the emission should be more prominent on that side. However, our observations of the flux ratio $[\text{Si VI}]/\text{Br }\gamma$, as displayed in Fig. 5.19 do not show significant difference between the two outflows; this is further demonstrated by the plot of the average flux ratios for each channel (see Fig. 5.39).

Rodríguez-Ardila et al. (2004b) deduced that photo-ionization alone is not enough to generate coronal lines at the distances and velocities from the source that our observations show. In 5 of the 6 objects studied, the coronal line emission was significantly broader and asymmetric towards the blue than low-ionization lines. In contrast to their findings, the $[\text{Si VI}]$ FWHM for our observations is virtually identical to that of Br $\gamma$, both over the whole field and specifically along the the outflow axis.

The CLR, as delineated by the $[\text{Si VI}]$ emission, extends almost to full length of the NLR, out to 300 pc in each direction from the AGN. This indicates strongly collimated hard UV–soft X-ray flux from the AGN. While the $[\text{Si VI}]$ flux scales reasonably well with the Br $\gamma$ flux, there is an impression from the morphology that the production mechanism is different between the two outflows; the SE emission is in a conal form, as would be expected from direct ionization from the AGN EUV field. By contrast, the NW emission outlines, rather than infills, the cone, with the additional of the radio jet impact region (see Section 5.3.9.2); this is clearer in the equivalent width plots rather than the flux plots. This indicates that shock mechanisms predominate in the NW.

The X-ray jet observed by Chandra (especially in the soft X-rays) can contribute to the photo-ionization of CL species. The X-rays can be generated by several mechanisms; direct photo-ionization from the AGN, shocks with velocities $>200$ km s$^{-1}$ (Rodríguez-Ardila et al., 2017) and inverse Compton scattering of relativistic electrons associated with the radio jet. From the gas kinematics, velocities of the required magnitude are certainly present, and are aligned with the $[\text{Si VI}]$ emission generated by shocks. The absence of an X-ray jet in the NW outflow is most probably caused by higher gas column densities; this is certainly the region of the dust lane.

Rodríguez-Ardila et al. (2017) examined the powerful outflows in NGC 1386, and found that the $[\text{Si VI}]$ and $[\text{Ca VIII}]$ emission extended $\sim 150$ pc in one direction from the nucleus. This contrasts with Müller-Sánchez et al. (2011) for 7 Seyfert 1.5 – 2 galaxies, who found that the $[\text{Si VI}]$ emission had a mean FWHM size of 24 pc. The largest CLR so far is
that of NGC 5135 (Bedregal et al., 2009) of \( \sim 600 \) pc. The CLR of NGC 5728 certainly approaches that size.

Overall, the CLR is generated by a complex mixture of photo-ionization (both directly from the AGN and from shock-generated X-rays further along the outflow cone) and shocks. The morphology and kinematics of CLR species for each galaxy will depend on the AGN properties; photo-ionizing flux from the accretion disk, outflow dynamics and collimation to generate shocks and secondary X-rays produced by those shocks.

### 5.3.9 Gaseous Kinematics

#### 5.3.9.1 Line-of-sight Velocity and Dispersion

The kinematics of gas around the nucleus diagnose outflow, inflow and rotational structures in the nuclear region; combined with the emission-line flux, we can compute the energetics of this gas. Different species have different kinematics structures, e.g. outflows are prominent in hydrogen recombination and other ionized emission lines, whereas molecular hydrogen is usually in a rotating gas disk around the center.

In Figs. 5.21 and 5.22 we show the line-of-sight velocity and dispersion for the main emission lines in the \( J \) and \( H+K \) band. We use the kinematics of these lines to delineate outflows, rotations and (possible) feeding flows.

From the \( \text{Pa}\beta \) kinematics, the outflows have velocities reaching a maximum of about \(-250 \text{ km s}^{-1}\) at \(1.1\) NW (\( \sim 220 \text{ pc projected distance}\)) and \(270 \text{ km s}^{-1}\) at \(1.4\) (\( \sim 280 \text{ pc}\)).
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Figure 5.21: Kinematics for Pa $\beta$ and [Fe II] (1257 nm). Flux units $10^{-16}$ erg cm$^{-2}$ s$^{-1}$, EW units in nm. Both species show the strong bi-polar flow in velocity, with the nuclear dispersion being much higher for hydrogen recombination than [Fe II]. The zero velocity point is set at the AGN location (Section 5.3.7). White pixels are where the emission line was too weak to derive the kinematics.
Figure 5.22: As for Fig. 5.21 for Brγ, H$_2$ (2121 nm), [Fe II] (1644 nm) and [Si VI].
SE of the nucleus, then decelerating to -150/110 km s$^{-1}$ at double the respective distances from the nucleus. This profile suggests gas accelerated away from the AGN by radiation pressure, then decelerating as it interacts with the ISM and the radiation pressure drops off with increasing distance from the source. High absolute velocity values in the northern and southern parts of the field are due to the star-forming ring rotation, aligned with the stellar kinematics along a PA of $\sim 10^\circ$ (see Section 5.3.5).

Because of the telluric feature, the [Fe II] velocity field, while it displays a similar spatial extent, is biased towards higher recession velocity. A manual check of the velocity fit along the outflows, where the offending spectral pixels are masked out, shows that the velocity range is in line with the Pa $\beta$, i.e. $\pm 200$ km s$^{-1}$.

The Br $\gamma$, [Fe II] 1644 nm and [Si VI] velocity and dispersion maps show very similar structure, as is also the case for the flux and EW. Again, the H$_2$ kinematics do not align with the other species (see Section 5.3.9.2). For [Fe II] 1257 nm, the higher dispersion is more extended; around the SE outflow, the higher values outline the outflow, supporting an emission mechanism of a shock boundary. The Br $\gamma$, [Fe II] 1644 nm and [Si VI] dispersion plots show the same structure at higher spatial resolution.

We present histograms of the velocity and dispersion values in Figs. 5.23. All velocity histograms (except for [Fe II] 1257 nm, which has values contaminated by the telluric feature) show the characteristic double peak of outflows or rotation. The negative [Si VI] outflow velocities are somewhat higher than the Br $\gamma$ velocity; for the receding velocities, [Fe II] has higher values than Br $\gamma$ and [Si VI], with a modal value of $\sim 200$ km s$^{-1}$; there is a small group of pixels with a velocity of $-300$ to $-400$ km s$^{-1}$.

The [Fe II] dispersion distribution is more extended than Br $\gamma$. As it has a lower ionization potential than H I, it is only found in partially ionized media. In this case, it is on the edge of the outflows, which will broaden the line from the LOS components of the outflow velocity, and by turbulent entrainment at the outflow boundary. The [Si VI] dispersion values seem to be somewhat bi-modal, with high values more or less coincident with the high values for [Fe II] and lower values elsewhere; this may reflect the production mechanisms, i.e. photo-ionization where directly illuminated by the accretion disk, with low dispersion, and shocks (high dispersion) on the outflow boundaries.

The high dispersion values observed for Pa $\beta$ perpendicular to the outflows is attributed to the beam-smearing, causing the LOS to intersect both the approaching and receding outflows and broadening the line artificially; see Section 5.3.14.4 for a further discussion of this effect for the optical emission lines, which affect the Seyfert classification.
We plot the velocity and dispersion in a slice along the outflow centerline in Fig. 5.24. The velocity profile is virtually identical for all species, except for a region in the NW outflow (approaching) with a higher velocity for [Si VI].

For comparison, the [O III] and Hβ flux and kinematic maps from the MUSE archival data (seeing-limited at ~ $0''$.7) are also presented here. These were produced in the same manner as the SINFONI kinematic maps. Figs. 5.25 and 5.26 show the inner 9 × 9 kpc. The [O III] delineates the outflow, whereas the Hβ also includes the SF ring; the distortion in the LOS velocity field for Hβ from the combination of the SF ring and the outflows is clearly seen. Kinematic values are the same as from the SINFONI observations; however, the high values of the LOS dispersion aligned NE/SW across the nucleus are due to the overlapped outflow edges measured with limited ($0''$.2) plate scale resolution.
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Figure 5.23: Top panels: Velocity (left) and dispersion (right) distribution histograms for Paβ and [Fe II] (1257 nm). The higher [Fe II] dispersion is from line-broadening by LOS components of the outflow velocity and turbulent entrainment. Bottom panels: Velocity (left) and dispersion (right) distribution histograms for Brγ, H2 (2121 nm), [Fe II] (1644 nm) and [Si VI]. The H2 is kinematically colder than the other species.

Figure 5.24: LOS velocity and dispersion along the outflow centerline, centered on the AGN location, showing the steep gradient near the AGN and the asymptotic flattening further out.
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Figure 5.25: [O III] flux, equivalent width, LOS velocity and dispersion from MUSE archival data. Note the distance scale in the flux map. [O III] delineates the outflow.

Figure 5.26: As for 5.25, for H β. Hydrogen recombination emission delineates both the outflow and the SF ring.
5.3. Results and Discussion

5.3.9.2 Molecular Hydrogen Kinematics

Molecular hydrogen ($H_2$) is the direct source material for star formation; its location and kinematics help diagnose SF processes and AGN/SF linkages. Most $H_2$ structures in Seyfert galaxies are in rotating disks (Diniz et al., 2015). As we illustrated in Fig. 5.22, the $H_2$ velocity structure is aligned with a PA of $\sim 350^\circ$ while the outflows have a PA of $\sim 315^\circ$; the ordered $PV$ diagram also suggests simple rotation (see Section 5.3.9.4). Interestingly, this orientation is not in the plane either of the whole galaxy, or the inner structure (either disk or bar), unlike other examples (see e.g. NGC 4151, Storchi-Bergmann et al., 2010).

The $H_2$ LOS velocities and dispersions are kinematically colder than for [Fe II], Br$\gamma$ and [Si VI] (Fig. 5.23), reaching a maximum velocity of $\sim \pm 250$ km s$^{-1}$ vs. $\sim \pm 300$–400 km s$^{-1}$ for the ionic species, and a median (maximum) dispersion of $\sim 95$ km s$^{-1}$ (200 km s$^{-1}$) vs. $\sim 130$ km s$^{-1}$ (350 km s$^{-1}$) for Br$\gamma$. These trace different astrophysics; a cold molecular gas ring with kinematically associated star-formation vs. outflows.

We fitted a Plummer potential model to the $H_2$ velocity field, using the method described in Section 5.3.5. Initially, the five parameters (kinematic center $[X_0, Y_0]$, line of nodes, inclination and scale length) were left reasonably unconstrained. The fitted alignment was $347^\circ$, with the kinematic center located 0$''$.09 from the AGN position (equivalent to 17 pc projected distance). Fig. 5.27 shows the result. The model rotation axis is aligned at PA = $77^\circ$–$257^\circ$ (polar alignment $13^\circ$–$193^\circ$), with a very low inclination, i.e. almost edge-on. The scale length is approximately 0$''$.9, which corresponds to 180 pc.

We also fitted the model where we constrained the kinematic center to the position of the AGN (assuming that the SMBH is the center of rotation). The polar alignment was also constrained to align with the main NS ridge of the equivalent width plot (the line of nodes constrained to between 260–265$^\circ$). The results are shown in Fig. 5.28. The scale length and inclination are very similar to the unconstrained fit. Both residuals plots show a region to the east to SE of the nucleus of the gas disk which shows negative residual velocities; these are hypothesized to be gas entrained on the edges of the outflow. This is seen in the pronounced clockwise ‘twist’ of both the flux and velocity contours from the center. This is supported by the CO(1-0) radio emission morphology (which traces the extended molecular hydrogen), as reported by Combes & Leon (2002) from observations using the IRAM-30 m telescope.
Figure 5.27: Plummer model for H$_2$ velocity field with unconstrained parameters. Left panel: H$_2$ velocity field. Middle panel: Best fit Plummer model. Right panel: Residual velocity with H$_2$ equivalent width contours overplotted (in nm). All velocities shown in km s$^{-1}$.

Figure 5.28: Plummer model for H$_2$ velocity field with kinematic center and line of nodes constrained. Left panel: Best fit Plummer model. Right panel: Residual velocity with H$_2$ equivalent width contours overplotted (in nm). All velocities shown in km s$^{-1}$. These show ordered rotation broadly aligned with the stellar kinematics, plus the component of entrainment along the outflow edges.
5.3.9.3 Channel Maps

We further analyzed the gas kinematics using channel maps and position-velocity diagrams. These are similar, and are both used to reveal kinematic structures that are not visible in the LOS velocity and dispersion plots. The former slice the velocity axis across the LOS, while the latter slice it parallel to the LOS. Figs. 5.29 to 5.36 show the channel maps for the spectral lines \( \text{Pa} \, \beta \), \([\text{Fe II}] 1257\) nm (both from the \( J \) data cube), \([\text{Fe II}] 1644\) nm, \( \text{Br} \, \gamma \), \( \text{H}_2 2121\) nm and \([\text{Si VI}] 1964\) nm (from the \( H+K \) data cube). The maps were constructed by subtracting the continuum height, derived from the velocity map function \( \text{velmap} \), from the data cube. The spectral pixels are velocity binned and smoothed to reduce noise.

The \( J \)-band channel maps are at a larger scale, encompassing more of the star-forming ring, as well as the inner outflows, whereas the \( H+K \)-band maps show greater detail in the outflows. To separate the outflow and SF ring kinematics, we masked out the central 2\( '' \).5 around the AGN location where the bulk of the outflow emission is located (Fig. 5.32 - the channels are now 30 km s\(^{-1}\)). There is still some impact from the outflows (e.g. at the +45 and -135 km s\(^{-1}\) channels), but the maximum recession velocity is now in the SW quadrant, moving to the NE over the 450 km s\(^{-1}\) range, rather than the SE-NW direction of the outflows. This velocity range and orientation are compatible with stellar kinematics derived from the Si I absorption line (see Section 5.3.5 for a discussion of the anomalous kinematics). The star-forming ring has a greater velocity than the outflows, because its axis of rotation is perpendicular to our LOS, therefore we measure the full rotation velocity. By contrast, the outflows are inclined to our LOS (see Section 5.3.14.3) and we only measure the component velocity.

The \( J \)-band \([\text{Fe II}] \) channel maps (Fig. 5.30) are affected by the telluric absorption feature that could not be fully corrected; this shows as a reduced flux in the +112 km s\(^{-1}\) channel. The low velocity channels (-112 – +37 km s\(^{-1}\)) show the emission across most of the field; this is due to the common minimum value for the scaling for all channels, to enhance the high-velocity channels. These channels have been replotted in Fig 5.31 to suppress this noisy background; the -37 km s\(^{-1}\) show the ‘X’-shaped outline of the bicones. The +37 km s\(^{-1}\) channel has low flux levels, due to the imperfectly corrected telluric feature.
Figure 5.29: Channel map for Pa\(\beta\). Each channel has a width of 75 km s\(^{-1}\), with the channel central velocity shown in the top left corner of each plot. The cyan cross is the position of the AGN. Color values are fluxes in units of 10\(^{-18}\) erg cm\(^{-2}\) s\(^{-1}\), plotted with log scaling; all channels have the same maximum and minimum values. Positive velocities are receding, negative are approaching. The white contour on the +37 km s\(^{-1}\) channel is the J-band continuum flux, at levels of 30, 50, 70 and 90\% of maximum. Note the 200 pc scale on the -562 km s\(^{-1}\) channel. The outflow structure is prominent in the NW (approaching) and SE (receding), plus the SF ring component at the peripheries. The outflows, aligned NW-SE are visible, as well as the SF ring emission from -187 to +187 km s\(^{-1}\).
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Figure 5.30: As for Fig. 5.29, for [Fe II] 1257 nm. Note that the +112 km s$^{-1}$ channel has a lower flux, as this is affected by the imperfectly corrected telluric feature.

Figure 5.31: [Fe II] channel maps for low velocity with reduced scale range to enhance structure visibility. The ‘X’-shaped bicone boundaries are visible in the -37 km s$^{-1}$ channel - the +37 km s$^{-1}$ channel is affected by the imperfectly corrected telluric absorption.
Figure 5.32: As for Fig. 5.29, for Paβ, with the central 2''.5 around the AGN masked out. This enhances the SF ring features. The channel map velocity intervals are now 30 km s\(^{-1}\).
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**Figure 5.33**: Channel map for [Fe II] 1644 nm. The white contour on the +37 km s\(^{-1}\) channel is the H-band continuum flux, at levels of 30, 50, 70 and 90% of maximum. Note the 100 pc scale on the -562 km s\(^{-1}\) channel. The cross-shaped feature outlining the outflows is especially prominent in the -262 to +37 km s\(^{-1}\) channels. The [Fe II] emission is from partially ionized and shocked gas, which are the boundaries of the outflows where the accretion disk radiation is weaker and the shear turbulence between the outflows and the ISM is greatest.
Figure 5.34: As for Fig. 5.33, for Brγ. The white contour on the +37 km s$^{-1}$ channel is now the K-band continuum flux, at levels of 30, 50, 70 and 90% of maximum. This is confined to the outflows interior.
Figure 5.35: As for Fig. 5.34, for $\text{H}_2$ 2121 nm. The kinematics are oriented more NS, especially in the negative velocity channels, with some entrainment effect by the outflows.
Figure 5.36: As for Fig. 5.34, for [Si VI] 1964 nm, strictly confined to the outflow interior closer to the AGN than for Brγ.
Assuming that the [Fe II] and [Si VI] gas is co-moving with the Br $\gamma$, we can plot the channel flux ratio for those species. These are presented in Figs. 5.37 and 5.38. The [Fe II]/Br $\gamma$ channel ratio clearly shows that in the SE outflow, the [Fe II] ‘outlines’ the Br $\gamma$ emission, i.e. the flux ratios are higher to the SE, whereas the [Si VI]/Br $\gamma$ channel ratios are higher towards the nucleus. A check whether there is a difference between the outflows is shown in Fig. 5.39, which plots the average flux ratio for each velocity channel (with the standard deviation as uncertainties). There is a trend in the flux ratios towards the receding (positive) velocities for [Fe II]/Br $\gamma$, and an opposite trend for [Si VI]/Br $\gamma$, but with large uncertainties.

**Figure 5.37:** Flux ratio for [Fe II] 1644 nm/Br $\gamma$ for each velocity channel. The color-bar shows the flux ratio, with enhanced values (green and blue) at the peripheries of the outflows in the higher velocities, showing enhanced [Fe II] emission in partially ionised and shocked gas.
Figure 5.38: Flux ratio for [Si VI]/Br γ for each velocity channel, showing the more central concentration for the [Si VI] from direct photo-ionization from the AGN.

Figure 5.39: Average flux ratios for each velocity channel, with standard deviation as the uncertainty, showing no significant differences across velocities. This contradicts the model of Murayama & Taniguchi (1998) of a clumpy matter-bound CLR.
5.3.9.4 Position-Velocity Diagrams

Similarly to the channel maps, the position-velocity (PV) diagram can help to identify features in the outflows, like velocity and dispersion anomalies, that are not apparent in the standard kinematic maps. The PV diagram is generated by a ‘pseudo-longslit’ (the longslit function in QFitsView) along the outflow or the plane of rotation of the molecular gas. For Brγ, [Si VI] and [Fe II], the longslit was laid along a PA = 140–320° (NW–SE) centered on the AGN and aligned with the velocity extrema; for H$_2$ the line was along a PA = 170–350°, along the flux ridge line (presumably the plane of rotation). All slits are 2 pixels wide. The alignment of the longslits is shown in Fig. 5.40; slit 5 (blue and green) the one aligned with the AGN.

Fig. 5.41 shows the resulting plots for the central slit; the wavelength (on the X-axis) is converted to a velocity difference from the central pixel, and the Y-axis is the distance along the longslit in arcsec. To enhance the emission line features, the flux values have been divided by the median value along the slit position, otherwise the continuum variations would obscure the details; this is similar to the equivalent width of the emission line. The LOS velocity derived from the velmap procedure is overlaid on the relative flux; these delineate the centerline of the PV diagram at each position.

**Figure 5.40:** Longslit alignment, superimposed on [Fe II] flux map; the blue box is the slit for Brγ, [Si VI] and [Fe II] 1644 nm, the green for H$_2$. The white boxes are the off-nucleus pseudo-slits through the outflow, with the numbers corresponding to the plots in Figs. 5.42, 5.43 and 5.44.
The PV diagrams show a velocity gradient at the nucleus of ~330 (Br $\gamma$), 475 ([Si VI]) and 440 ([Fe II]) km s$^{-1}$ per 100 pc, with H$_2$ having a lower gradient of 175 km s$^{-1}$ per 100 pc. The H$_2$ velocity then levels off to a constant value of approximately ±200 km s$^{-1}$, presumably as it co-rotates with the stars. In the positive (receding) velocity direction, the Br $\gamma$, [Fe II] and [Si VI] all plateau or slightly decline at roughly the same velocity. However, in the negative (approaching) velocity direction, the Br $\gamma$ does not continue smoothly, presumably because of low flux values introducing uncertainties; the [Fe II] velocity continues rising and the [Si VI] shows a decline from a maximum of ~430 km s$^{-1}$ to ~320 km s$^{-1}$. It is noted that all three species plateau and the flux brightens at the edge of the field at this velocity; it is hypothesized that the source of this emission is the radio jet interacting with the ISM co-rotating with the inner disk, moving towards us at this velocity, rather than the direct outflow.

Figs. 5.42 and 5.43 shows the PV diagrams for [Fe II] and Br $\gamma$ at off-axis slits, aligned with the main axis at distances of 3 pixels in X and Y, i.e. 0''.2 = 40 pc apart. For both lines, panel 5 is identical to the corresponding diagrams in Fig. 5.41. For [Fe II], the off-axis plots look similar to the on-axis diagram. The Br $\gamma$ diagrams show a consistent patch of high flux in panels 4, 5 and 6; this is radio jet-ISM impact location. Figs. 5.44 shows the PV diagram of the flux ratios [Fe II]/Br $\gamma$; in this case the values have not been divided by the median. These diagrams show that [Fe II] has a relatively lower flux near the nucleus and becomes more important further along the outflows as the ionizing flux drops; e.g. panels 4, 5 and 6 have low ratios (~1.5) around slit position 0'' and high values (~3) at -1''.75.
5.3. Results and Discussion

**Figure 5.41:** PV diagrams for Br $\gamma$, [Fe II], [Si VI] and H$_2$, as described in the text. The slit position values are negative in the SE/S direction to positive in the NW/N position. The flux maps have different intensity for contrast enhancement. The LOS velocity derived from the velmap procedure is overlaid as white points. The Br $\gamma$ diagram shows significant discontinuities in the negative velocity outflow vs. the other species; this is also noted for the [O III] emission, as may be due to turbulent entrainment or flickering AGN activity.

**Figure 5.42:** Off-nucleus PV diagrams for [Fe II] through the outflow. The plots are numbered corresponding to the slits in Fig. 5.42. The flux maps all have the same intensity scale (color-bar in panel 9).
Figure 5.43: Off-nucleus PV diagrams for Brγ through the outflow. The plots are numbered corresponding to the slits in Fig. 5.42. The flux maps all have the same intensity scale (color-bar in panel 9). There are significant discontinuities, especially in the negative velocity flows; the main ‘hot-spot’ is the impact location on the star-forming ring.
Figure 5.44: Flux ratio [Fe II]/Brγ PV diagrams. The flux ratios all have the same range, given by the color-bar in panel 9. Higher values are where [Fe II] flux is relatively higher than Brγ; this shows the reduced importance close to the nucleus and increased ratio further along the outflows.
5.3.10 Gaseous Excitation

5.3.10.1 AGN Excitation

We derive excitation mode diagnostic diagrams from the emission line ratios \([\text{Fe II}]\) 1257 nm/\(\text{Pa}\)\(\beta\) and \(\text{H}_2/\text{Br}\)\(\gamma\), as described in Section 2.6.4. The diagrams are divided into 5 regions; star-forming (SF) or starburst (SB) (dominated by H II regions), AGN i.e. subjected to the radiation field from the accretion disk, LINER, where shocks from SN and outflows dominate and Transition Objects (TOs), which have a mixture of excitations. The TOs can be sub-divided by the diagnostic ratios into those where \([\text{Fe II}]\) dominates and those where \(\text{H}_2\) dominates.

As we do not have the \(K\)-band data at the same spatial scale, combined with the uncertainties in the \([\text{Fe II}]\) 1257 nm flux due to the telluric feature, the \(J\)-band diagnostic ratio \([\text{Fe II}]\) 1257 nm/\(\text{Pa}\)\(\beta\) is re-calibrated to the ratio \([\text{Fe II}]\) 1644 nm/\(\text{Br}\)\(\gamma\) in the \(H+K\)-band, using the ratios \([\text{Fe II}]\) 1257/1644 and (\(\text{Pa}\)\(\beta\)/\(\text{Br}\)\(\gamma\)) as given in Table 2.4. The \(H+K\)-band diagnostic ratios are shown in Fig. 5.45 (top left and right panels). Normally, extinction correction is not required as the line pairs are close together, however the \([\text{Fe II}]\) 1644 nm flux values must be multiplied by 1.17 to correct for the extinction relative to \(\text{Br}\)\(\gamma\) in this case, taking a value of \(A_V = 2.6\) from Section 5.3.12. Fig. 5.45 also shows (bottom right) the density of all pixels that have a measurement of both ratios on the excitation diagnostic diagram; the labels correspond to the positions on the \([\text{Fe II}]\) 1644 nm/\(\text{Br}\)\(\gamma\) map, i.e. the nucleus(‘N’), the two outflows (‘1’ and ‘2’) and an off-axis position (‘3’).

Overall, the excitation mode diagram show no ‘pure’ photo-ionization/SF mode, with the vast majority of pixels in the AGN mode region, with some LINER and TO excitation. Fig. 5.45 (bottom left) shows the predominating mode at each spatial location, as defined by the regions outlined in the bottom right panel. The colors denote the mode, as defined in the caption; the ‘TO’ regions have been divided into that which is dominated by excess \(\text{H}_2\) and that dominated by excess \([\text{Fe II}]\) emission. The plot shows the predominance of the AGN mode, with a TO ([\(\text{Fe II}\) excess]/LINER at the outflow end caps and TO (\(\text{H}_2\) excess) at the ‘waist’.

The correlation between the two sets of ratios is weak/non-existent \((R^2 = 0.044)\), unlike that found for e.g. IC 630 (Section 4.3.4.2, Durré et al., 2017) and for IC 4687, but similar to NGC 7130 (both Colina et al., 2015). This is due to the multi-component nature of this object; IC 630 is a starburst galaxy and IC 4687 a prototype star-forming LIRG, whereas NGC 7130 has a mixture of star-forming regions and compact AGN excitation.
Davies et al. (2016b) have presented computations of AGN and star-forming mixing ratio for NGC 5728 from WiFeS optical observations on a 1" scale (the S7 survey), where there is a clear trajectory of excitation. From our observations, this diagnostic is not possible for the nuclear region at high resolution because of the mixture of ionizing and thermal processes at any one location.

As a comparison, the excitation diagram from the S7 WiFeS data is shown in Fig. 5.46 (see Section 5.3.2 and Fig. 5.6 for the location labels). Both the [N II] and [S II] diagnostics are plotted (the [O I] flux was too weak to acquire a [O I]/Hβ ratio diagnostic); the [N II] diagnostic shows a mixture of star-formation and AGN mode, the [S II] diagnostic shows the AGN excitation is mainly ‘Seyfert’-type mode, rather than LINER. The [N II] diagnostic plot has already been presented in Davies et al. (2016b).

At the larger spatial extent (30" vs 3",6) and lower resolution (1" vs 0.1"), the star forming ring is included in the WiFeS field with the corresponding excitation mode, as against the SINFONI field, which shows none. Note that the positions marked by the labels ‘N’,‘1’ and ‘3’ are close together on the optical classification, but are well separated on the NIR diagram; this is due to the lower spatial resolution in the optical.

The standard division of the NIR excitation diagram into H II regions, AGNs, LINERs and TOs is a little misleading, as what is being plotted is excitation mechanism, i.e. photo-ionization and recombination versus thermal processes (heating plus shocks). Especially in the bottom-left corner of the diagram, the source can be either photo-ionization by young hot stars (UV) or accretion disk radiation (EUV/soft X-rays). In the [Fe II]1644 nm/Brγ ratio plots, the nuclear outflows shows low ratios, however these are not generated by hot, young stars, but by the AGN radiation field, as shown by the [Si VI] flux. [Si VI] has an IP = 167 eV (extreme UV/X-ray – 7.4 nm), which fully ionizes [Fe II] to [Fe III] (which has an IP 16.2 eV), therefore the ratio of [Fe II]/Paβ will be reduced in the outflow, which is exposed directly to the AGN radiation. This is also illustrated by the X-ray image (Fig. 5.5).

We distinguish between excitation sources at a particular location by examination of the continuum and emission line maps, as well as the diagnostic ratios. From Fig. 5.45 (panel 1), for the [Fe II]/Paβ ratios, we can see that there is almost no ‘pure’ star formation, except in the ring around the edge of the field (the 1.6 kpc ring). The outflows, unsurprisingly, show mainly AGN excitation, with a mixture of AGN and LINER excitation surrounding it. The actual mode in the periphery will be somewhat uncertain, as the flux values are low, with correspondingly larger uncertainties. By contrast, the H2/Brγ ratios have a different structure; this is due to the molecular hydrogen being decoupled
Figure 5.45: Excitation diagnostic maps from SINFONI $H+K$ data. Top left: $H_2/Br\gamma$ flux ratio map (log ratio). Black contours are $K$-band continuum flux, normalized to 10, 30, 50, 70 and 90% of the maximum. Color-bar labels show the excitation mode (H II–AGN–LINER). Top right: [Fe II]1644 nm/Br$\gamma$ flux ratio, corrected for reddening, black contours are the Br$\gamma$ flux; normalized to 10, 30, 50, 70 and 90% of the maximum. Bottom left: Spatial excitation mode; colors are red-AGN, green-LINER, orange-TO ($H_2$ predominating), purple-TO ([Fe II] predominating). Bottom right: Excitation pixel density map for log($H_2/Br\gamma$) vs. log([Fe II] 1644 nm/Br$\gamma$). Contour levels at 1, 5, 10, and 50% of maximum. The labels (‘N’, ’1’, ’2’, ’3’) correspond to positions on the [Fe II]/Br$\gamma$ ratio plot, as described in the text.
5.3. Results and Discussion

Figure 5.46: Optical excitation diagnostic diagrams from WiFeS S7 LZIFU component data. Left panel: log([N II]/Hα) vs. log([O III]/Hβ). Right panel: log([S II]/Hα) vs. log([O III]/Hβ). Labels correspond to the locations on Fig. 5.6. The majority of pixels have AGN/Seyfert-type excitation, plus the excitation from the star-forming ring. See the text for a commentary on the marked locations.

both spatially and kinematically from the outflows. This is also shown by the velocity and dispersion histograms; the [Fe II] and hydrogen recombination absolute velocity and dispersions peaks are higher than H$_2$.

We use the forbidden lines [Fe II] and [Si VI] as diagnostics for density, as above a critical density ($n_{cr}$) for each species the emission is suppressed because of rapid collisional de-excitation (Rodríguez-Ardila et al., 2011). For [Fe II], this is of the order $n_{cr} = 10^5$ cm$^{-3}$; for [Si VI] this is $n_{cr} = 6.3 \times 10^8$ cm$^{-3}$. This indicates that the densities inside and outside the outflows could be different by several orders of magnitude.

5.3.10.2 H$_2$ Excitation

We determined the excitation modes and temperatures for H$_2$ using the methods described in Section 2.6.4.2. The flux for the K-band lines was measured at several locations, as shown in Fig. 5.48 (left panel). The spectrum at each location was taken from a circular region 4 pixels wide and the flux measured from a Gaussian fit to the line, using QFitsView fitting facility. The locations were chosen to be the nucleus and 0''.5 N and S, in line with the rotation, plus other features visible in the flux map.

We could measure all of the low excitation lines ($\nu = 1-0$); however the high excitation line fluxes ($\nu = 2-1$ and $\nu = 3-2$) were more uncertain. At location P4, only the 2–1 S(3) line could be measured (see Fig. 5.47). The results for the derived parameters are given in Table 5.6 for the excitation temperatures and Table 5.7 for the ro-vib temperatures. Fig. 5.48 shows the excitation temperature plot derived from the method of Wilman et al.
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(2005) and Fig. 5.48 (right panel) shows the rotation and vibrational temperatures plotted on the Mouri (1994) excitation mechanism diagram. These results show that the gas is close to the LTE line, indicating predominantly thermal processes. The 2-1 S(3) line is present at all locations, however in most locations (P1, P2, P3 and P6) it is below the fitted line, indicating that X-rays make up a component of the excitation (e.g. Krabbe et al., 2000, for NGC 1275), with shocks probably the main contributor to the excitation.

Table 5.6: \( \text{H}_2 \) excitation temperatures.

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>( T_{exc} ) K, ( \nu = 1 - 0 )</th>
<th>( T_{exc} ) K, ( \nu = 2 - 1/3 - 2 )</th>
<th>( T_{exc} ) K, All</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Nucleus</td>
<td>1375 ± 35</td>
<td>4165 ± 510</td>
<td>2155 ± 30</td>
</tr>
<tr>
<td>P2</td>
<td>0\arcsec.5 S</td>
<td>1685 ± 160</td>
<td>4445 ± 445</td>
<td>2840 ± 50</td>
</tr>
<tr>
<td>P3</td>
<td>0\arcsec.5 N</td>
<td>1700 ± 100</td>
<td>1960 ± 560</td>
<td>2060 ± 80</td>
</tr>
<tr>
<td>P4</td>
<td>SE</td>
<td>1775 ± 210</td>
<td>...(^a)</td>
<td>1830 ± 165</td>
</tr>
<tr>
<td>P5</td>
<td>NW</td>
<td>1800 ± 185</td>
<td>2275 ± 400</td>
<td>7040 ± 310</td>
</tr>
<tr>
<td>P6</td>
<td>W</td>
<td>2085 ± 60</td>
<td>5620 ± 875</td>
<td>2840 ± 75</td>
</tr>
</tbody>
</table>

\(^a\)No slope could be determined; only 1 data point

Table 5.7: \( \text{H}_2 \) rotational and vibrational temperatures.

<table>
<thead>
<tr>
<th>Position</th>
<th>( T_{Rot} ) K</th>
<th>( T_{Vib} ) K</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1450 ± 10</td>
<td>2210 ± 72</td>
</tr>
<tr>
<td>P2</td>
<td>1870 ± 394</td>
<td>2262 ± 152</td>
</tr>
<tr>
<td>P3</td>
<td>2007 ± 463</td>
<td>2270 ± 198</td>
</tr>
<tr>
<td>P4</td>
<td>1542 ± 515</td>
<td>2512 ± 289</td>
</tr>
<tr>
<td>P5</td>
<td>1604 ± 674</td>
<td>2384 ± 379</td>
</tr>
<tr>
<td>P6</td>
<td>2225 ± 973</td>
<td>2050 ± 147</td>
</tr>
</tbody>
</table>

We calculate the excitation temperatures from the inverse slope of the low-excitation (\( \nu = 1 - 0 \)), high-excitation (\( \nu = 2 - 1/3 - 2 \)) and all lines, respectively. These are given in Table 5.6. The low-excitation temperatures are very similar (1740±50K), except for the nucleus and location P6. It can be hypothesized that the \( \text{H}_2 \) in the line of sight of the nucleus is shielded from some of the heating effect of the AGN by the circumnuclear torus or dusty bar that is visible in the \( H - K \) magnitude maps (Fig. 5.10). The radio jet impact on the ISM at location P6 could increase the excitation in that region.
If we include all the lines, the derived temperatures increase somewhat; however the high-excitation flux values are more uncertain. These temperatures now compatible with results for other Seyfert galaxies in the literature, in the range 2100–2700 K (e.g. Riffel et al., 2015; Storchi-Bergmann et al., 2009; Riffel et al., 2014b; Riffel & Storchi-Bergmann, 2011; Riffel et al., 2010). The temperature derived for P5 for all lines is would seem to be unphysical, being above the disassocation temperature for H₂. However, Davies et al. (2003, 2005) shows that the lower $ν = 1 − 0$ levels may be thermalised, but the $ν = 2 − 1$ and $ν = 3 − 2$ levels can be overpopulated due to fluorescent excitation by far-ultraviolet photons. If we fit just the $ν = 2 − 1$ and $ν = 3 − 2$ levels, we can see that the P5 location has a very high temperature ($\sim 7000$ K); this is in the NW outflow at the hypothesized point of impact of the radio jet with the ISM and is also presumably illuminated by the accretion disk radiation field where the fluorescent excitation is highest.

We also map the spatial distribution of the ratio H₂ 2248/2121 nm, which distinguishes between thermal processes (ratio of 0.1–0.2) vs. fluorescent ($\approx 0.55$) (following Riffel et al., 2014b, in their excitation study of NGC 1068). Fig. 5.48 (middle panel) shows this plot; where there is strong H₂ flux, the ratios indicate purely thermal processes. Higher values at the periphery reflect an increasing contribution of excitation by hot stars away from the X-ray heating and shocks in the nuclear region, plus uncertainties in the flux measurements.

### 5.3.10.3 Other Diagnostics

We can deduce the relative importance of photo-ionization vs shock excitation for [Fe II] by taking the flux ratio ([Fe II] 1257 nm /[P II] 1188 nm), as discussed in Section 2.6.4. This was determined at three locations with a 1″ aperture; the AGN (5.9 ± 1.2), the SE outflow maximum flux (5.8 ± 1.6) and the NW outflow maximum flux (3.9 ± 0.7). This shows the excitation is a mixture of shock and photo-ionization, with the latter predominating.

This result is confirmed by the diagnostics from Mouri et al. (2000), who calculated photo-ionization and shock heating models, and generated diagnostic diagrams for the ratios of [Fe II] 1257 nm/Pa $\beta$ vs. [O I]/H $\alpha$ for both power-law and blackbody photo-ionization, as well as shock heating models. From Table 5.5 values, the ratios within the inner 1″ are [Fe II] 1644 nm/Br $γ = 2.0$ (which translates to [Fe II] 1257 nm/Pa $\beta = 0.46$) and [O I]/H $α = 0.129$ (from the WiFeS S7 data). These values are compatible with both power-law photo-ionization and shock models (favoring photo-ionization), where the metal abundances are sub-solar and the ionization parameter is high, $U \geq 10^{-1.5}$ (see Fig. 3 of Mouri et al., 2000).
Figure 5.47: H$_2$ temperature plots. The value of the inverse slope of the relationship
between ln($N_{upper}$) and $E_{upper}$ is the excitation temperature of H$_2$ for LTE. The values
are plotted for each location, each with an offset for clarity. The transitions are labelled
below the plot. The $\nu = 1 - 0$ transition fits are plotted with solid lines, the $\nu = 2 - 1$
and $\nu = 3 - 2$ fits are plotted with dotted lines, those for all transitions with dashed lines.
Including the higher-excitation increases the derived temperatures, but these may not be
in LTE.

We attempted to measure the electron density from the [Fe II] line ratio, as described
in Section 2.6.4.3. However, the 1533, 1660, 1664 and 1677 nm lines were all very weak,
even at the location of the peak [Fe II] 1644 nm flux. The only one that could be measured
with reasonable certainty (the 1533 nm line) gave a low flux ratio (0.062 ± 0.01) which
Figure 5.48: Left panel: \( \text{H}_2 \) measurement locations on flux map. Contours are at 5, 10, 30 and 50 \% of maximum flux. Right panel: \( \text{H}_2 \) 2248/2121 nm flux ratio. Overplotted contours are \( \text{H}_2 \) 2121 nm flux, at levels of 5, 10, 20 and 50 \% of maximum. Thermal processes dominate at high \( \text{H}_2 \) flux, with an increasing contribution from UV fluorescence at lower fluxes. Bottom panel: Diagnostic diagram (Mouri, 1994) for \( \text{H}_2 \) locations. The green trajectory is for gas at LTE with the temperature indicated. The values for points P1–P6 are plotted. Thermal processes (X-ray heating and shocks) predominate.
indicated a low electron density ($< 1000 \text{ cm}^{-3}$). This is a firm upper limit, as the 1644 nm flux is strong. This low density is measured in the partially ionized [Fe II] line emitting region, and not close to the central engine, where it would be much higher.

### 5.3.11 Kinematic and Excitation Summary

Summarizing the association of each emission-line species with the nuclear phenomena:

- Hydrogen recombination emission ($\text{Pa} \beta$ and $\text{Br} \gamma$) is excited by photo-ionization both in the SF ring and in the outflows extending several kpc from the AGN, reaching a LOS velocity of $\pm 250 \text{ km s}^{-1}$. Some shock excitation in the locus of the radio-jet impact on the SF ring is also observed.
- The forbidden [Fe II] emission is observed in the partially ionized and shocked boundaries of the outflows, with higher and more extended dispersions than the hydrogen recombination emission.
- The high-excitation coronal line [Si VI] is photo-ionized directly by the AGN accretion disk radiation, with similar kinematics to the hydrogen recombination emission. Shock velocities at the outflow boundaries near the AGN are also high enough to excite this line. There is also weak [Ca VIII] and [S IX] emission close to the AGN, diagnostic of a strong X-ray radiation field. [O III] emission observed with the MUSE data also is associated with the outflows.
- The molecular hydrogen is kinematically distinct from and colder than the outflows, settled into a purely rotational disk, with some entrainment along the outflow boundaries. The low-excitation emission lines are in LTE at temperatures in the range 1400–2100 K, but there is evidence of fluorescent pumping in the high-excitation lines. X-ray heating and shocks are the main thermal processes.

### 5.3.12 Extinction

We can derive the extinction by dust from emission line flux ratios, as described in Section 2.6.2. For this object, it is problematic to use the [Fe II] 1257/1644 nm ratio, as the telluric feature in the 1257 nm emission line makes its flux values uncertain. The $\text{Pa} \gamma/\text{Pa} \beta$ ratio has the advantage that it is measured in the same band, but the $\text{Pa} \gamma$ gas kinematics are of poor quality due to the line being near the short end of the spectrum and close to the edge of the atmospheric window. An attempt at calculating the extinction using this ratio produced unphysical values over the whole field. We also suspect that there is some telluric contamination, as the line width is broader than $\text{Pa} \beta$. The $\text{Pa} \beta/\text{Br} \gamma$ ratio can only be
5.3. Results and Discussion

mapped over part of the whole central ring feature, as the $H+K$-band observations are at a smaller scale than the $J$-band ones; uncertainties are also introduced by the rescaling and any flux calibration uncertainties. The Pa$\alpha$/Br$\gamma$ ratio has the advantage that it is in the one data cube; however the Pa$\alpha$ line is in the atmospheric absorption region between the $H$ and $K$ bands. On examination of the cube, it was seen that the Pa$\alpha$ line is very strong, and the continuum is piece-wise smooth between the bands, so a definitive measurement can be made.

We derived the extinction value $A_V$ from the flux maps of Pa$\alpha$ and Br$\gamma$ and the constants as given in Section 2.6.2; unphysical values are masked out. This is shown in Fig. 5.49, where the left panel shows the color map of the Br$\gamma$ and the contour giving the Pa$\alpha$ flux. The extinction map is plotted in the right panel. The $A_V$ values range up to 19 magnitudes, and the extinction is strongly concentrated around the AGN, presenting as a roughly elliptical region or bar of size $64 \times 28$ pc (where the extinction is $>16$ mag), aligned at right angles to the outflow. This is comparable in size to the obscuring dust bar found for NGC 2110 at $55 \times 27$ pc (see Section 3.3.3). The average extinction over all valid pixels is 3.7. The extinction value towards the AGN implies a cold gas column density of $420 \, M_\odot \, pc^{-2}$ (Equation 2.24), equivalent to $N_H = 4 \times 10^{22}$ cm$^{-2}$. Davies et al. (2015) give the column density based on X-ray modeling as $N_H = 1.6 \times 10^{24}$ cm$^{-2}$, a factor of 40 times higher. This absorption is likely to be at the parsec scale in the BLR (Burtscher et al., 2016), i.e. it is probing a very narrow LOS, while the recombination lines are measured over a much more extended area; also, these lines will not penetrate very deep into the obscuration, as the high extinction will attenuate the emission lines so much that they will not contribute to the measured total.

Determining the extinction from the [Fe II] line ratio was more difficult, given the uncertainties mentioned above. The $H+K$ flux maps were rescaled and aligned to the $J$ maps, restricting the area to the central $4'' \times 4''$ around the AGN; the fluxes of the lines are shown in Fig. 5.49 (left panel - color map is [Fe II] 1257 nm flux, contours 1644 nm flux). The emissivity ratio of 1.36 was used for the [Fe II] line pair, as it matched the Pa$\beta$/Br$\gamma$ results most closely. The best results were in the regions of highest flux, i.e. for the most part in the outflows, with values in the maximum flux area up to 9.2 mag. The average extinction over all valid pixels is 3.2. These values should be treated with some caution, as it depends on the exact alignment of the two flux maps.

The extinction was also measured by taking a spectrum from the data cubes in an aperture of $1''$ diameter around the AGN location, showing $A_V = 14.9$ mag for Pa$\alpha$/Br$\gamma$, and 4.8 mag for [Fe II]. At the location $1''$ both south and east of the AGN, the extinction
was $\sim 4$ mag for [Fe II]; the Pa $\alpha$/Br $\gamma$ line ratios were not secure enough for measurement at this location.

The extinction maps are strikingly different, illustrating that the emitting gas regions for hydrogen recombination and [Fe II] lines are not co-located (Fig. 5.51). [Fe II] has minimal emission around the AGN in the strongly ionizing environment, whereas it traces the outflow cone, especially in the SE. From the channel maps, there appears to be no [Fe II] emission on the near wall of the SE cone, so the extinction for that species comes by traversing the whole cone radius.

For the hydrogen recombination extinction, apart from the high extinction around the AGN, there is a indication that it also traces the boundaries of the outflow cones; one can hypothesize that the dust (which causes the extinction) is sublimated in the main outflow. To check this, the [Si VI] flux, which presumably traces the high-ionization region, is plotted with the extinction from hydrogen recombination (Fig. 5.51, left panel); the extinction traces the boundaries of the [Si VI] except around the AGN; presumably this overlays the [Si VI] emission along our LOS.
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Figure 5.50: Extinction map from [Fe II]. Left panel: [Fe II] fluxes; color map and color-bar is 1257 nm flux, contours and labels are 1644 nm flux, both in units of $10^{-16}$ erg cm$^{-2}$ s$^{-1}$. Right panel: Visual extinction $A_V$ in magnitudes.

Figure 5.51: Left panel: Outflow extinction, as shown by $A_V$ from Pa $\beta$/Br $\gamma$ (color map - values given in color-bar) compared with [Si VI] flux (contours at 1, 2, 5, 10, 20 and 50% of maximum). Right panel: $A_V$ from [Fe II] 1257/1644 (color map - values given in color-bar) compared to $A_V$ from Pa $\alpha$/Br $\gamma$ (contours at 2, 7, 12 and 17 mag).
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5.3.13 Gas Masses

We derive the masses of ionized hydrogen (H II) and warm molecular hydrogen from the relationships in Section 2.6.3.1 (Equations 2.24 - 2.27). The ISM surface density is estimated from the extinction, $A_V$, derived in Section 5.3.12. Table 5.8 presents the results.

The surface density values for the inner 100 pc radius are within the ranges of the results from Schönell et al. (2017) (see Section 4.4.3). The values for the star formation rates and the supernova rates have not been calculated, as it is clear that both the hydrogen and iron excitation is caused by the AGN photo-ionizing source plus associated outflow shocks, rather than star formation.

**Table 5.8:** Gas masses for the cold ISM, H II and H$_2$, in the pixel with greatest flux/extinction and within a radius of 100 and 200 pc from the center and over the whole field, plus the 100 and 200 pc radius surface densities. The extinction/ISM is not measured outside the 100 pc radius.

<table>
<thead>
<tr>
<th></th>
<th>Max Pixel M$_{\odot}$pc$^{-2}$</th>
<th>M$_{\odot}$ 100 pc</th>
<th>M$_{\odot}$ 200 pc</th>
<th>M$_{\odot}$ (Total)</th>
<th>M$_{\odot}$pc$^{-2}$ 100 pc</th>
<th>M$_{\odot}$pc$^{-2}$ 200 pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISM ($\sigma_{\text{Gas}}$)</td>
<td>420</td>
<td>4.9 x 10$^6$</td>
<td>...</td>
<td>...</td>
<td>155</td>
<td>...</td>
</tr>
<tr>
<td>H II</td>
<td>110.0</td>
<td>7.93 x 10$^5$</td>
<td>1.31 x 10$^6$</td>
<td>1.92 x 10$^6$</td>
<td>25.2</td>
<td>10.4</td>
</tr>
<tr>
<td>H$_2$ (warm)</td>
<td>3.83 x 10$^{-2}$</td>
<td>388.5</td>
<td>695.6</td>
<td>957.2</td>
<td>1.24 x 10$^{-2}$</td>
<td>5.54 x 10$^{-3}$</td>
</tr>
</tbody>
</table>

The mass of warm H$_2$ over the whole field ($\sim$ 960 M$_{\odot}$) compares well with that found derived by Rodríguez-Ardila et al. (2005) (900 M$_{\odot}$); the estimated total (cold) H$_2$ mass is $7 \times 10^8 - 2.6 \times 10^9$ M$_{\odot}$. Combes & Leon (2002), from radio observations of CO(1-0), deduced a total H$_2$ mass of $3.1 \times 10^9$ M$_{\odot}$, which covers the whole galactic disk, including the extended nuclear region and the SF loci at the tips of the main bar.

5.3.14 Outflow Modeling and Kinematics

5.3.14.1 Velocity Models

There are various physical models of the gas kinematics in outflows from AGN. Crenshaw & Kraemer (2000) modeled the outflow NGC 1068 as a hollow bicone, with emitting material evacuated along the axis - the cone walls were clearly visible in the STIS G430L spectrum as a bifurcation. A similar model was applied to NGC 4151 (Das et al., 2005). Bae & Woo (2016) extended this to generalized bicone models, simulating emitted line profiles. They found that velocity dispersion increases as the intrinsic velocity or the bicone inclination increases, while apparent velocity (i.e., velocity shifts with respect to systemic
5.3. Results and Discussion

velocity) increases as the amount of dust extinction increases, since dust obscuration makes a stronger asymmetric velocity distribution along the LOS.

Das et al. (2005) also found that the outflow velocities could be modeled heuristically by a linear or square-root law, i.e. the velocity increases out from the origin to a turn-over point and then decreases back to systemic, in the form \( v = kr \) or \( v = k\sqrt{r} \) for the acceleration and \( v = v_{\text{max}} - k' r \) or \( v = v_{\text{max}} - k'\sqrt{r} \) for the deceleration, where \( k \) and \( k' \) are constants, \( v_{\text{max}} \) is the turn-over velocity and \( r \) is the radial distance. Müller-Sánchez et al. (2011) modeled 3 out of 7 of the galaxies (NGC 1068, NGC 3783 and NGC 7469) with a linear law, in their study of AGN outflow systems. Liu et al. (2015) modeled IRAS F04250-5718 and Mrk 509 as filled cones with constant velocity, in which case the maximum velocity dispersion would be expected along the bicone axis.

Fischer et al. (2013) modeled the inclination of 53 Seyfert galaxies from NLR kinematics using a full hollow bicone from [O III] imaging and STIS spectroscopy from HST. NGC 5728 kinematics were classified as ‘Ambiguous’, which means that it has anti-symmetric velocities, but could not classified as having a bicone. They explained this as either the two cones are not identical or that the filling factor is not 1 within the hollow cone and zero outside.

Following Das et al. (2005), we fitted the outflow velocity map (derived from the Pa\( \beta \) velmap procedure) with all combinations of square root and linear accelerations and decelerations. The Pa\( \beta \) map is used instead of Br\( \gamma \), as it encompasses a larger area and distance from the AGN, with the Br\( \gamma \) map only extending to the turnover distance. The best fit was found with the \( \sqrt{r} \) proportionality with a turnover velocity of 290 km s\(^{-1}\) at a distance of 200 pc from the nucleus. Fig. 5.52 shows the velocity values and fitted profile. As can be seen, the heuristic functional form is not a good fit around the turnover position; the competing forces on the gas of radiation pressure, magnetic fields, nuclear winds, gravity, ISM friction and gas pressure will produce a more complicated functional form than that given here. Müller-Sánchez et al. (2011) summarizes the state of knowledge of the dynamical models, noting that while drag forces can produce the required deceleration, the acceleration phase is more difficult to explain, with Everett & Murray (2006) suggesting an accelerated wind close to the AGN (at pc scales) subsequently interacting with and accelerating the ISM over several 100 pc. This is similar to the two-stage outflow model of Hopkins & Elvis (2010).
**Figure 5.52:** Pa$_\beta$ velocity and fitted profile along the outflow axis. The fit is for $\sqrt{r}$ proportionality.

### 5.3.14.2 The Bicone Geometry

We further examine the bicone geometry using the channel maps and PV diagrams. The channel map plot for [Fe II] (Fig. 5.33) shows clear signs of limb-brightening of the outflow (at velocities -337 to +187 km s$^{-1}$), which would be expected for a hollow cone model. This is best shown in the velocity range -187 to +37 km s$^{-1}$, as the prominent ‘X’-shaped figure with an opening angle of $\sim 70^\circ$. The near wall of the approaching cone (-412 to -112 km s$^{-1}$) is clearly seen, as is the far wall of the receding cone (+187 to +562 km s$^{-1}$). A puzzling aspect in the absence of the far (near) wall in the approaching (receding) cone. It is possible that this has been terminated by the interaction with the plane of the nuclear structure (the inner disk or mini-spiral), and the resulting outflow is a half-cone or fan shape.

By contrast, the Br$\gamma$ channel maps show little sign of the limb brightening, being more like a filled cone; supporting the concept of the [Fe II] jacketing the hydrogen recombination emission. The PV diagrams for Br$\gamma$ (Figs. 5.41 and 5.43) also show no or minimal signs of this structure.

If the [Fe II] outflow structure is a hollow bicone, then we should be able to separate the LOS velocities of the front and back walls. Instead of a single Gaussian fit (as from the velmap procedure), the asymmetric line profile of [Fe II] was fitted by a double Gaussian curve, as illustrated for the position 1” SE of the nucleus (Fig. 5.53); this shows a double
(green dashed line, with blue and red components) vs. a single Gaussian fit (black dashed line). The fits for each pixel along the centerline of the outflow is shown in Fig. 5.54, top panel, where the black line is the velocity from the velmap procedure, and the blue and red fits are the shorter and longer wavelength of the double Gaussian fits. For the double Gaussian fit, one of the fits always dominates and produces corresponding uncertainties in the other fit, as shown by the error bars. This also corresponds with the low flux of either the far or near wall visibility in the channel maps. The bottom panel of Fig. 5.54 shows the velmap measured velocity dispersion (i.e. that of the single Gaussian fit), with the uncertainties. Unlike the HST STIS data for NGC 1068 (Crenshaw & Kraemer, 2000), the line profiles do not show bifurcation, just a red or blue skewness.

From these velocity measurements, we can derive the outflow bicone parameters of internal opening angle and inclination to the LOS. The outflow is modeled as two cones truncated at the tip, and the sides aligned with the observed limb-brightening; this is shown in Fig. 5.55 - top left panel, where the colored map is the zero-velocity channel, the thick dashed lines are the sides of the outflow and the thin dotted line is the center-line of the outflow. The blue and red arrows illustrate the approaching and receding cones. The projected opening angle is measured from the zero velocity channel map at $\alpha = 71^\circ$; this is larger than the value derived for the emission lines by Capetti et al. (1996) (55–65$^\circ$) but somewhat narrower than the polarized continuum angle (94$^\circ$); the [Fe II] jacket of the main flow is the source of the higher opening angle.

The cone internal angle, $\beta$, and the inclination, $i$, (where $i=0^\circ$ means that the cone axis is in the plane of the sky and $i=90^\circ$ means that the cone is face-on) can be derived from the following relationships:

$$\tan(90 - \beta/2) = \tan(90 - \alpha/2)/\cos(i)$$  \hspace{1cm} (5.2)

$$V = V_F/\sin(i - \beta/2)$$ \hspace{1cm} (5.3)

$$= V_B/\sin(i + \beta/2)$$ \hspace{1cm} (5.4)

where $V_F$ and $V_B$ are the measured front and back wall LOS velocities and $V$ is the true outflow velocity. The parameters were derived at several points along the outflow centerline, ensuring that the velocity difference $|V_B - V_F|$ was over 230 km s$^{-1}$, where the two Gaussian components were clearly separated. The equations were solved using the ‘GRG Nonlinear’ algorithm, minimizing the difference between the outflow velocity derived from the front and back velocities, with the added check that the derived projected cone opening angle was close to the observed angle.
**Figure 5.53:** Outflow [Fe II] emission line profiles. Top panel: Single and double Gaussian fit to line profile at position 1" SE from the nucleus. Bottom panel: Fit residuals from single (black dots) and double (green crosses) Gaussian fits (at the same vertical scale).

**Figure 5.54:** [Fe II] kinematics of the front and back wall of hollow bicone outflow. Top panel: Velocities of double Gaussian fit (red and blue points) along the center-line of the outflow, with uncertainties. The black line is the velocity derived from the velmap procedure. The arrows indicate the position for the illustrative double Gaussian fit (Fig. 5.53). Bottom panel: Velocity dispersion from velmap procedure.
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The results at the several locations along the center-line agree very well, $\beta = 50^{\circ}.2 \pm 2^{\circ}.2$ and $i = 47^{\circ}.6 \pm 3^{\circ}.2$. It is noted that this inclination is close to that of the outer disk found in Section 5.3.1, Table 5.3 (48$^{\circ}$), i.e. the outflow is nearly co-planar to the main galactic plane. This is also close to the value for the de-projection angle for the spiral-arm pitch fit (Section 5.3.6) of 43$^{\circ}$. There is no requirement for AGN outflows to align to the galaxy geometry; Nevin et al. (2017), Müller-Sánchez et al. (2011) and Fischer et al. (2013) all find no alignment between outflow and galactic photometric axes.

The biconal interpretation is further supported at the -112 km s$^{-1}$ channel map slice, where a cone slice projected at the inclination can be overlaid on the elliptical feature (Fig. 5.55 - top right panel). Fig. 5.55 - bottom left panel shows a diagram of the bicone seen side-on across the plane of the sky.

Müller-Sánchez et al. (2011) examined the biconal outflows of 7 Seyfert galaxies, and found an anti-correlation between the half-opening angle of the cone and the outflow maximum velocity. The values for NGC 5728 (50$^{\circ}$ and 260 km s$^{-1}$/cos ($i$) = 380 km s$^{-1}$) place it on the trend on the plot (their figure 27) from the objects they measured. They also found an anti-correlation between the H$_2$ gas mass in the inner 30 pc and the half-opening angle; the H$_2$ mass for NGC 5728 within that radius is $0.6 \times 10^8$ M$_\odot$, placing it $\sim 0.5$ dex above the trend (their figure 28), but within uncertainties. The correlation between the opening angle and the gas mass (their figure 29) again places NGC 5728 $\sim 0.5$ dex above the trend. They posit that a higher H$_2$ mass provides increased confinement to the torus, which makes the outflow more highly collimated, which in turn increases the outflow velocity (see also Davies et al., 2006; Hicks et al., 2009; Müller Sánchez et al., 2009).

Fig. 5.56 shows cartoons of the model using the Shape 3D modeling software (Steffen et al., 2010), using the angular values and sizes derived here and in Section 5.3.1. The left panel shows the structures as seen by the observer, the right panel shows the view edge-on to the main galaxy disk. The black disk represents the ‘Main Disk’, with the assumption that the near side is to the NW, the blue (approaching) and red (receding) cones are the outflows and the ‘Inner Disk’ is in green. The left panel shows the galaxy and its structures as seen by the observer, the right panel shows an edge-on view. The model cone length is 1.8 kpc, and the main disk has a 4.8 kpc radius. As can be seen, the bicone, inner disk and main disk axes are not aligned. The outflow axis is almost in the plane of the main disk, with the blue-shifted (approaching) cone just behind the disk from our perspective. This is supported by the dust lanes crossing the outflow on our LOS. The nuclear stellar structure is almost perpendicular to the main disk.
Figure 5.55: Hollow bicone outflow model. Top left: observer view of outflow boundaries (thick dashed lines) and center-line (thin dotted line), superimposed on the zero velocity channel map. Blue and red arrows indicate approaching and receding outflow velocity directions, the cyan cross indicates the AGN position and the black arrow shows the viewing angle along the plane of the sky for the right panel diagram. Top right: -112 km s\(^{-1}\) channel map, with overplotted outflow boundary of a cone slice projected to the derived inclination angle of 47°. Bottom left: Side-on (plane of the sky) view of the outflow cones with the lines and blue and red arrows as for the left panel, with the opening angle and inclination as derived. The black arrow is the observer LOS and the green arrows indicate the LOS front and back wall velocities. Bottom right: \([\text{Fe II}]\) zero-velocity channel flux (contour) overlaid on the \(H - K\) color map. Contour values in \(10^{-18}\) erg cm\(^{-2}\) s\(^{-1}\), color-bar is \(H - K\) values. The association between the dust grain destruction and the \([\text{Fe II}]\) emission is shown by the anti-correlation.
5.3. Results and Discussion

<table>
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<th>Observer View</th>
<th>Galaxy Edge-on View</th>
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Figure 5.56: Model cartoon of galactic structure and outflows. Outflows: blue (approaching) and red (receding) cones. Main disk: black. Inner disk: green. Left panel: observer view. Right panel: edge-on to galactic plane view. The skewed morphology for the nuclear stellar structure vs. the main galactic plane is revealed.

It is noted that the condition for visibility of the BLR and thus a Seyfert 1 classification, i.e. \(|(i)| + \beta/2 > 90^\circ\), is not met, which supports the unified model of AGN, where the large-scale nuclear dust structures outside of the BLR collimates the ionizing radiation (see Müller-Sánchez et al., 2011).

As noted before (Section 5.3.4), the [Fe II] emission is well aligned with the $H - K$ color; this is shown in Fig. 5.55 - bottom right panel. The edges and other features of the emission flux are anti-correlated with the $H - K$ color (i.e. higher flux as aligned with lower color value). This shows that the dust is being removed at these locations. Alternative mechanisms are mechanical removal through entrainment in the outflows, or the grains being sublimated directly by high-energy photons or sputtered by shocks, releasing the iron to be excited by electron collisions (Mouri et al., 2000). The second process is probably the predominant one, given that the edges delineate the shock boundary of the outflows, as opposed to the lack of correlation between the [Fe II] velocity map and the $H - K$ color map. This is a different mechanism for releasing iron from grains than the standard supernova shock scenario, and is a striking illustration of the process.
5.3.14.3 Outflow Mass Rate and Power

The maximum outflow velocity observed from Pa $\beta$ of 290 km s$^{-1}$ gives a true outflow velocity of $\sim$ 390 km s$^{-1}$. We derive the mass outflow rate ($\dot{M}_{\text{out}}$) using the following procedure. To a first order, the cone can be modeled as a plane, where the LOS velocity and mass surface density represent the integrated chord through the cone. Each spaxel is considered as a cube ($0^\prime.05 = 10$ pc a side) moving at velocity $V = V_{\text{out}}/\sin(i)$, where $V_{\text{out}}$ is the observed LOS velocity. The mass in the cube is given by Equation 2.25; giving the density. Combined with the relationship $1$ km s$^{-1} = 1$ pc Myr$^{-1}$, and the distance of 41.1 Mpc, this gives:

$$\dot{M}_{\text{out}} = 6.9 \times 10^{13} V_{\text{out}} F_{B \gamma} \left[ \text{M}_\odot \text{ yr}^{-1} \right]$$

Fig. 5.57 shows the map of the outflow rates at each spaxel in the bicone in units of M$_\odot$ yr$^{-1}$. The field has been masked to the cone outline. The total outflow rate over the whole field is 38 M$_\odot$ yr$^{-1}$; the total for just the SE cone is 20 M$_\odot$ yr$^{-1}$, showing that the NE cone is not heavily obscured. However, the outflow rate distribution in each cone is dissimilar; the SE cone shows that the maximum rate is at $\sim$ 60 pc from the AGN, whereas the NW cone has it at the supposed radio jet impact region at $\sim$ 300 pc. It is possible that the NW cone has some obscuration from the dust lane and thus has a higher mass outflow rate than that measured.

We compute the kinetic power or luminosity $L_{KE}$ in the outflows (following e.g. Storchi-Bergmann et al., 2010) from Equation 5.6, which after conversion to cgs units and using Equation 5.5 becomes Equation 5.7, where $\dot{M}_{\text{out}}$ is in units of M$_\odot$ yr$^{-1}$ and $V_{\text{out}}$ and $\sigma$ are in km s$^{-1}$. It is assumed that the dispersion measure is due to turbulence; if it is not included the derived power value is reduced by 15%. The ratio of the accretion and outflow rates can also be computed.

$$L_{KE} = \dot{M}_{\text{out}} (V^2 + \sigma^2)/2$$
$$= 3.15 \times 10^{35} \dot{M}_{\text{out}} (V_{\text{out}}^2/\sin^2(i) + \sigma^2) \text{ erg s}^{-1}$$
$$\frac{\dot{M}_{\text{out}}}{\dot{M}_{\text{acc}}} = 38/(2.7 \times 10^{-2}) = 1185$$

This results in a total kinetic power of $\sim 1.5 \times 10^{42}$ erg s$^{-1}$, which is $\sim 0.01 L_{\text{Bol}}$.

The gas mass that can be expelled from the galaxy can be estimated, following Storchi-Bergmann et al. (2010). The projected outflow length and average velocity are 2 kpc and 175 km s$^{-1}$, respectively, which leads to the AGN active lifetime of at least 10$^7$ yr; this
5.3. Results and Discussion

Outflow Rate (M⊙/yr/spaxel)

<table>
<thead>
<tr>
<th>(arcsec)</th>
<th>0</th>
<th>0.025</th>
<th>0.05</th>
<th>0.075</th>
<th>0.1</th>
<th>0.125</th>
</tr>
</thead>
<tbody>
<tr>
<td>(arcsec)</td>
<td>−1.5</td>
<td>−1</td>
<td>−0.5</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
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Figure 5.57: Outflow rate for bicone in M⊙ yr⁻¹ spaxel⁻¹ for hydrogen derived from the Brγ flux and velocity fields, showing the SE peak close to the AGN and the NW feature at ~ 300 pc where the radio jet impacts the ISM in the SF ring.

This means a total kinetic energy of ~ 5 × 10⁵⁶ erg. We use the estimated galaxy mass of \( M_{\text{Galaxy}} = 7.2 \times 10^{10} \) M⊙ (derived above) and the relationship:

\[
M_{\text{Gas}} \approx \frac{E_{\text{Bind}} \times R_{\text{Gas}}}{G \times M_{\text{Galaxy}}}
\]  

(5.9)

where \( M_{\text{Gas}} \) is the expelled gas mass, \( E_{\text{Bind}} \) is the total kinetic energy (equated to the binding energy) and \( R_{\text{Gas}} \) is the observed outflow distance. This equates to \( M_{\text{Gas}} = 1.6 \times 10^8 \) M⊙. This is of the order of the total gas outflow through the bicones over the activity cycle of ~ 4 × 10⁸ M⊙, and is also of the order of the estimated mass of molecular gas in the nuclear region (7 × 10⁸ M⊙); this indicates that a large proportion of the gas will be blown away by the end of the AGN activity cycle, especially if the AGN lifetime is a few times that given here.

The kinetic-to-bolometric luminosity ratio is larger than values found in Barbosa et al. (2009) for 6 nearby Seyfert galaxies, which were in the range 10⁻⁵ ≤ \( L_{KE}/L_{Bol} \) ≤ 10⁻⁴; however, it is within the range of the values from Müller-Sánchez et al. (2011), who find 2 × 10⁻⁴ ≤ \( L_{KE}/L_{Bol} \) ≤ 5 × 10⁻² for 7 Seyfert galaxies with biconal outflows. In general, the former objects did not have collimated outflows and had significantly lower bolometric luminosities (1 × 10⁴² ≤ \( L_{\text{Bol}} \) ≤ 4.6 × 10⁴³ vs. 5 × 10⁴³ ≤ \( L_{\text{Bol}} \) ≤ 2.5 × 10⁴⁴ erg s⁻¹). The
mass outflow to bolometric luminosity ratio is also compatible with the relationship found by Nevin et al. (2017) from summarized literature values.

The ratio of the flow rates ($\dot{M}_{\text{out}}/\dot{M}_{\text{acc}}$) can be compared with the results from Müller-Sánchez et al. (2011), who find a range of $\sim 100 - 8000$; our value (only exceeded by one of their objects, NGC 2992) supports their conclusion that Seyferts with strong and collimated radio emission are also hosts of powerful outflows of ionized gas. The ratio of outflow energy to bolometric luminosity is also consistent with the Hopkins & Elvis (2010) models.

5.3.14.4 The Seyfert Classification

NGC 5728 has been variously classified as Seyfert 1.9 (Véron-Cetty & Véron, 2006) or as Seyfert 2 (Phillips et al., 1983); which is correct? The classification is based on whether H$\alpha$ shows a broad-line ($V_{\text{LOS}} \gtrsim 2000$ km s$^{-1}$) component (Seyfert 1.9) or not (Seyfert 2) at the nucleus; presumably because the very strong H$\alpha$ emission is only partially obscured and can ‘leak through’ the obscuration. This is important for support of the Unified Model; the orientation of the outflow and obscuration determines whether the BLR is visible, and hence the classification. Even with clumpy obscuration, the probability is high that the heavy obscuration observed will conceal the BLR.

All Seyfert Type 2 galaxies have [N II] emission lines of comparable strength to the NLR H$\alpha$, which can merge together with low spectral resolution observations, producing a false classification. If the combined narrow-line [N II] doublet ($654.805/658.345$ nm) and the H$\alpha$ ($656.279$ nm) are observationally blended, this will produce a minimum dispersion of $1620$ km s$^{-1}$; this will be larger with any intrinsic width in the emission lines. For instance, Balmaverde & Capetti (2014) found for 14 out of the 24 galaxies with a BLR as reported by Palomar ground-based spectra only required a wing to the narrow lines to reproduce the spectra just as well, when examined by HST STIS spectroscopy with comparisons between the [O I] and H$\alpha$+[N II] spectral-line complex.

Using the data from MUSE data cube at the nuclear location of NGC 5728, it can be seen that the narrow lines are split into two components separated by $\sim 535$ km s$^{-1}$, as delineated by a double Gaussian fit to the [O III] spectrum, as shown in Fig. 5.58. Fig. 5.59 shows the H$\alpha$+[N II] spectrum for the nuclear pixel; 6 narrow emission lines can be seen, two for each line corresponding to the two outflows (two of these, the red-shifted [N II] 654.805 nm and the blue-shifted H$\alpha$, are blended to produce a skewed line). To determine whether the H$\alpha$ contains a broad component, we compare 2 model fits. The first model (‘6G’) contains just the narrow-line features, each fitted with a Gaussian line profile, with
5.4. Conclusions

We have examined the nuclear region of NGC 5728 using data at multiple wavelengths and methods (X-ray, optical and NIR IFU spectra and radio), revealing a highly complex object showing gas and stars with multiple kinematics and excitation, driven by a powerful AGN. We have presented and analyzed emission line flux distribution, kinematics and excitation diagnostics, estimated stellar populations and ages and obscuration from continuum emission and emission line ratios and determined gas column densities, and found the SMBH mass.

In summary, the nuclear region has the following features.

- A star-forming ring with a diameter of 2 kpc and typical stellar age of $\sim 8$ Myr, with kinematics (face-on, tumbling spherical rotation around an east-west axis) that are different to the main galactic disk rotation (which has conventional disk rotation inclined at $65^\circ$ to the LOS at a PA of $32^\circ$).
Figure 5.58: Nuclear spectrum for [O III] (500.68 nm) from MUSE data, showing line splitting from the two outflows, separated by $\sim 535$ km s$^{-1}$. The blue dotted line shows a double Gaussian fit to the data.
5.4. Conclusions

Figure 5.59: Seyfert 1.9 or 2? Nuclear spectrum from MUSE, Hα+[N II] (654.805/658.345 nm) (black markers with error bars), plus fits (‘6G’ - red and ‘7G’ - blue dashed lines) and residuals. The black horizontal line is the continuum level. The individual best-fit narrow-line Gaussian line profiles (‘6G’ - red and ‘7G’ - blue fine dotted lines) and the ‘7G’ model broad Hα line (green) are also plotted. The respective residuals are plotted in the lower panel, at the same scale, illustrating no need to invoke broad-line emission to fit the data, i.e. the Seyfert 2 classification is correct.

- Dust lanes and spiraling filaments feed the nucleus, as revealed by the HST structure maps.
- A one-sided radio jet, impacting on the ISM at about 200 pc from the nucleus, combined with radio emission from the SN remnants in the SF ring.
- A SMBH of $2.3\times10^8 \, M_\odot$, powering an AGN with a bolometric luminosity of $1.5\times10^{46}$ erg s$^{-1}$, from accretion of material at $\sim 0.03 \, M_\odot \, yr^{-1}$, at an Eddington ratio of $5 \times 10^{-3}$.
- The AGN and BLR is hidden by a dust bar of size 64 $\times$ 28 pc, with up to 19 magnitudes of visual extinction, with an estimated dust temperature at the nuclear position of $\sim 870 \, K$. 
AGN-driven NLR outflows, analyzed by velocity and dispersion mapping through the line-of-sight, plus channel and position-velocity diagrams:

- A geometry of a bicone with at least a 2 kpc extent on each side, with an opening angle of \( \sim 50^\circ \) and an inclination to our LOS of \( \sim 46^\circ \); the outflow axis is not aligned with the galaxy rotational axis.
- A mass outflow rate of \( 38 \, M_\odot \, yr^{-1} \) with a kinetic power of \( \sim 1.5 \times 10^{42} \, erg \, s^{-1} \), about 1% of the total bolometric luminosity of the AGN; illustrating how feeding is dominated by feedback efficiency (over 1:1000 in mass flow rate).
- An active phase that has lasted at least 10 Myr, with enough kinetic power to unbind the majority of the available nuclear gas over that time-scale.
- EUV and X-ray ionizing radiation exciting [Si VI] in a CLR out to at least 300 pc from the AGN, with scattered and shock-excited 2–10 keV X-rays detectable along the outflow to over 1.8 kpc with a luminosity of \( 1.62 \times 10^{42} \, erg \, s^{-1} \).
- The bicone walls are delineated by [Fe II] emission, which is not present in the interior due to the high-ionization environment, with evidence that dust is sublimated by the outflow wall shocks, releasing the iron for subsequent excitation.

- The H\(_2\) gas is dynamically and spatially independent of the outflows, concentrated in a kinematically cold equatorial disk in the star-forming ring, but also showing entrainment along the sides of the bicone. The warm H\(_2\) has a mass of 960 \( M_\odot \), with an estimated \( 6 \times 10^8 \, M_\odot \) of cold H\(_2\) in the field of view. The gas is excited by thermal processes (shocks and radiative heating of gas masses) to temperatures in the range 1400–2100 K, with an increased ratio of fluorescent excitation towards the SF ring.

AGNs and their associated nuclear gas and stars must be studied at the highest resolution possible at multiple wavelengths to understand their complex natures.
The strongest affection and utmost zeal should, I think, promote the studies concerned with the most beautiful objects. This is the discipline that deals with the universe’s divine revolutions, the stars’ motions, sizes, distances, risings and settings...for what is more beautiful than heaven?

Nicolaus Copernicus, 1473–1543

Conclusions

6.1 Motivation

This thesis has focused on enhancing our understanding of the interactions between galaxies and the super-massive black holes that reside in their nuclei. The close association between SMBH mass and galaxy properties (mass, luminosity, nuclear stellar kinematics and light profile) mean that feedback processes (both positive and negative) must operate between them throughout their evolution, which manifests itself as AGN activity and star formation. In the early universe, AGN activity can be continuous and at high powers, which manifest as quasars, generating phenomena at galactic cluster scales and quenching star-formation over the whole galaxy. By contrast, in the local universe AGN activity is intermittent and at moderate to low powers.

While the effects of the AGN output (both mass and energy) can affect a huge range of spatial and temporal scales, it is imperative that they are probed at the smallest possible scale, that of the sphere of influence of the black hole, smaller than the size of the host galaxy by a factor of $10^8 - 10^9$. This requires a combination of adaptive optics to resolve these scales for even the closest AGN, simultaneous spectral and spatial information (using integral field spectroscopic units), the largest telescopes possible to acquire data in a reasonable time and observations in the near infrared to overcome dust obscuration.

The Unified Model paradigm of AGNs consists of infalling gas onto a SMBH accretion disk, which powers electromagnetic radiation and matter outflow. The SMBH is surrounded by a dusty obscuring region that constrains the observational properties depending on the orientation to our line of sight. This model has withstood observational examination well, with some modifications to the structure of, and the galactic-scale contribution to, the obscuration. However, the details of the closely coupled feedback processes between gaseous material flows and star formation are not well understood.
There seem to be several modes of these feedback processes. A cyclic evolution is suggested by the observations, where gas is compressed by instability-driven infall into the gravitational well of the nuclear region and generates stars; these evolve and generate winds which then feed the SMBH. The AGN outflow and radiation can, in turn, either enhance or suppress star formation, depending on collimation and power. The gas eventually is consumed or dissipated and the process shuts down, perhaps leaving a stable nuclear gas disk which is available to fuel the next cycle.

All AGNs that we can spatially resolve on scales of 10 pc or less are in the ‘maintenance mode’, i.e. their luminosities are modest or low by the standards of quasars ($< 10^{44}$ erg s$^{-1}$). The sample of AGNs that have been examined on this scale, with integral field units in the near-infrared spectral region, is limited; the published literature has $\sim 100$ objects. These observed galaxies are generally late (spiral) types, with early types (lenticular and especially elliptical morphology) underrepresented in the population of local AGN.

AGNs and their associated circumnuclear activity are definitely not simple objects. IFU observations in the NIR with adaptive optics are the most efficient way to study the nuclear region of AGN in detail. Wide-band photometry or single-slit spectra miss the richness and detail. IFU observations are required to determine:

- The gas kinematics and dynamics of the different ionic and molecular species to characterize inflows, outflows and rotations.
- Detailed star-formation morphology, populations and ages.
- The spatial distribution of the excitation modes of the various parcels of gas.
- The configuration and density of the dust that obscures the nucleus.
- The stellar kinematics to determine the mass, or indeed the very presence, of a super-massive black hole.

The sample of objects observed for this thesis was drawn from a population of massive, luminous local early-type galaxies with radio emission (diagnostic of either AGN or SF activity) and then observed for NIR emission lines. The galaxies with the strongest lines were then followed up by IFU spectroscopy in the NIR on 8–10 m class telescopes on either the Keck I OSIRIS, Gemini-N NIFS or VLT-4 SINFONI instruments at the highest spatial resolution possible, given the observational constraints. Three of those objects have been examined in detail for this thesis.
6.2 Summary of Results

NGC 2110 We found that this well-known Seyfert 2 AGN has four massive young star clusters in its nuclear region, the brightest of which has $L = 5.6 \times 10^7 L_\odot$. All the clusters are embedded in a disk of shocked gas, as delineated by the [Fe II] emission line. The maximum [Fe II] flux is not collocated with the clusters, but rather lies between them; the ISM is excited by strong outflows driven by star formation, evolved stellar winds and supernova (SN) shocks, plus the radio jet in the extended emission. Though it is an early type galaxy, its nuclear region is being fueled sufficiently on million year timescales to sustain an SFR of order $0.3 M_\odot$ yr$^{-1}$, in line with the implied cluster formation rate.

From the gaseous kinematics, the estimate of the central enclosed mass is $2 \times 10^8 M_\odot$. The central extinction value $A_V$ is up to 3.2 mag, as derived from [Fe II] line ratios; the obscuration morphology is a bar of dimensions $55 \times 27$ pc. The helium emission shows a strong P Cygni profile, indicative of a cold outflow at a velocity of $\sim 600$ km s$^{-1}$.

IC 630 This starburst S0 (?) galaxy has very strong nuclear emission lines of atomic and molecular hydrogen, iron and helium. It has a face-on presentation, making stellar and gaseous kinematics difficult to diagnose. The star formation rate is $2.3 M_\odot$ yr$^{-1}$, with the supernova rate of 1 per 36 years in the central 200 pc; this produces radio and X-ray emission. The hydrogen recombination and [Fe II] emissions are excited by photo-ionization from young stars, with an additional minor contribution by shocks to the [Fe II] emission. The stellar velocity dispersion shows that any SMBH must be small ($\sim 2 \times 10^5 M_\odot$ - possibly zero within errors); deducing an AGN presence, based on just the radio, X-ray and NIR emission-line radiation, would be spurious.

The inner 200 pc of this galaxy has $230 M_\odot$ of warm ($\sim 2300$ K) molecular hydrogen (implying $1.5 \times 10^8 M_\odot$ of cold H$_2$), $1.7 \times 10^7 M_\odot$ of gas ionized by star formation and $2.8 \times 10^6 M_\odot$ of neutral gas. The H$_2$ is excited by shocks with a minor contribution by X-ray heating; dust lanes shield this gas from the ionizing radiation of the young clusters that have many O-type and W-R stars.

The nuclear region has a central disk (half-light radius of 50 pc), plus other clusters within 130 pc. The stellar population consists of a mixture of young starburst ($\sim 6$ Myr old) and older stars. The starburst is generating a powerful outflow wind at a rate of $0.42 M_\odot$ yr$^{-1}$ in a face-on truncated cone geometry.
Chapter 6. Conclusions

NGC 5728 This SB0/a galaxy (barred lenticular/spiral) has radio and X-ray jets emanating from the nucleus, with a Seyfert 2 activity classification and distorted, counter-rotating inner stellar kinematics with a nuclear star-forming ring. The nuclear region of this galaxy is highly complex, with stars and gas having multiple kinematic and excitation components. Dust lanes and filaments spiral into the center; however the nearly face-on orientation does not allow inflow rates to be measured. The SMBH of mass $2.3 \times 10^8 M_\odot$ powers an AGN with a bolometric luminosity of $1.5 \times 10^{46}$ erg s$^{-1}$. It accretes $\sim 0.03 M_\odot$ yr$^{-1}$, at an Eddington ratio of $5 \times 10^{-3}$, typical of this class of object.

The AGN is generating a mass outflow of $38 M_\odot$ yr$^{-1}$ with a kinetic power of $\sim 1.5 \times 10^{42}$ erg s$^{-1}$, about 1% of the total bolometric luminosity. The outflow morphology is a bicone with a full opening angle of $\sim 50^\circ$ and an inclination to our line of sight of $\sim 46^\circ$. The gas in the cone interior is ionized by EUV and soft X-rays from the AGN plus shocks, showing coronal-line excitation in [Si VI] for at least 300 pc from the nucleus; the outflows boundaries sublimate dust through shock heating and are jacketed by [Fe II] emission in the partially ionized region.

The molecular gas is spatially distinct from the outflows, concentrated in a kinematically cold disk, equatorially aligned to the rotation of the star-forming ring, with entrainment where it interacts with the sides of the outflow. The warm-phase H$_2$ has a mass of 960 M$_\odot$, with a cold H$_2$ estimate of $6 \times 10^8 M_\odot$. The gas is excited, in the main, by thermal processes; shocks and radiative heating excite the gas masses to temperatures in the range 1400–2100 K, with some fluorescent excitation towards the SF ring.

The obscuring dust is concentrated in a bar of $64 \times 28$ pc around the AGN, causing up to 19 magnitudes of visual extinction; its estimated temperature at the nuclear position is $\sim 870$ K. A flared disk structure, aligned with the bar, extends away from the nucleus. This obscuring structure is aligned normal to the outflow bicones, consonant with the conventional equatorial torus model.

The bicone geometry supports the orientation aspect of the Unified Model, i.e. the LOS is not within the outflow opening angle and so we do not see the BLR. This AGN is definitively classed as a Seyfert 2-type AGN (rather than a Seyfert 1.9); analysis of MUSE spectral data shows that no broad component is required to fit the H$\alpha$ line profile at the nucleus, which shows multiple blended NLR outflow kinematic components.
6.3 Towards the Scientific Goals

In this thesis, we have examined in detail three galaxies with nuclear activity, contributing to the corpus of knowledge on these extra-ordinary objects. Even though these are early-type galaxies, there is plenty of nuclear gas available to generate star formation and nuclear activity.

The detailed examination of these objects has produced no evidence to contradict the Unified Model. On the contrary, the orientation and opening angle of the ionization cones of NGC 5728 and NGC 2110 and the structure and density of the observed nuclear obscuration match with the Seyfert 2 classification. The AGNs in early-type galaxies examined in this thesis are not unusual compared to the general population of Seyferts (which are usually hosted in late-type galaxies), with respect to star formation rates, circumnuclear cold molecular gas masses, AGN generated mass outflow rates or Eddington ratios.

Each galaxy presents a different circumnuclear star formation mode; large circumnuclear clusters (without an apparent nuclear cluster) for NGC 2110, a star-forming ring with a diameter of 1.8 kpc (with anomalous kinematics compared to the rest of the galaxy) for NGC 5728 and a large nuclear star-cluster with other smaller clusters within 130 pc of the nucleus for IC 630. Nuclear star-formation rates are difficult to deduce in the presence of AGN excitation; the estimates (in $M_\odot$ yr$^{-1}$) are 0.02 for NGC 5728, 0.3 for NGC 2110 and 2.3 for the starburst IC 630.

Our observations support a cyclic evolutionary model of AGN in maintenance mode (Taniguchi, 1999; Davies et al., 2007; Tsai & Hwang, 2015), thus:

1. A minor merger or other mechanism drives gas into the nucleus, forming into a thick nuclear disk of kinematically cold molecular gas with a radius of a few 100 pc (IC 630 and NGC 5728). Evidence of merger activity is seen in all three galaxies.

2. A nuclear starburst is triggered by instabilities in this quasi-stable gas disk.
   - These are generated by gravitational (Toomre) instabilities, either with (NGC 5728, NGC 2110) or without (IC 630?) the presence of a SMBH.
   - Stars form in clumps and clusters; stellar feedback, in the form of supernovae and hot OB/WR stellar winds, partially disperses the gas disk, with high-speed (250 km s$^{-1}$) broad-based outflows reaching to scale heights of several hundred pc, as seen in IC 630.
   - The clusters observed in our galaxies are young; 2–8 Myr.
These observations are compatible with the detailed modeling of Schartmann et al. (2017), which are hydrodynamical simulations of nuclear gas disks with energy input from density driven star formation and supernova bursts. AGN activity at this stage is minimal.

3. About 50–100 Myr after the starburst, the AGN ‘lights up’.

- Winds with relatively low speeds (10–30 km s\(^{-1}\)) from the evolved (AGB) stars in the starburst accrete onto the SMBH (NGC 2110, NGC 5728? - IC 630 has not evolved to that stage yet.)
- The AGN appears as a Seyfert galaxy of moderate luminosity (43 \(\leq\) log\(L_{\text{bol}}\) \(\leq\) 45 erg s\(^{-1}\)) and Eddington ratio (10\(^{-3}\) \(\leq\) \(R_{\text{Edd}}\) \(\leq\) 10\(^{-2}\)).
- There are stellar and dusty structures (spirals and rings) around and feeding the nucleus. (NGC 2110 and NGC 5278 have dusty feeding spirals, NGC 5728 has a star-forming ring, IC 630 has dusty lanes). This is more prevalent, in general, in early-type galaxies that have known AGN vs. those that do not (Simões Lopes et al., 2007).
- Material outflows, in the form of collimated ionization cones, are generated (NGC 5728, NGC 2110). At high enough kinematic powers, these may be produced in a two-staged process where the accretion disk wind shreds and expands cold gas, which is then accelerated by radiation pressure (Hopkins & Elvis, 2010). These outflows may extend for several kpc with speeds to 400 km s\(^{-1}\) and outflow rates of several 10s of solar masses per year (NGC 5728).
- The nuclear obscuration is organized into an equatorial toroidal structure, with a highly-obscured bar of size \(~ 60 \times 20\) pc (NGC 5728, NGC 2110) with a flared disk further away.
- The kinetic power of the outflow for both AGN and starbursts is of the order of 1–2% of the bolometric luminosity (NGC 5728, IC 630). The mass accretion rate required to produce the AGN bolometric and kinematic power is only a small fraction of that observed in the outflows, or indeed that observed flowing inwards from larger spatial scales.

4. The AGN starts to die away.

- The available material is eventually consumed or is blown away in the outflows. These outflows can unbind the available molecular gas from the nuclear region over its active lifetime, even from moderately-powered Seyferts (NGC 5728).
6.4. **Future Work**

- The stellar structures dissolve over a 200 Myr time-scale, settling into a nuclear disk.
- As the AGN slows down, its Eddington ratio decreases, it becomes a LINER and radio-jets become more prominent.

5. **5. This process may repeat on time-scales of \( \sim 200 - 250 \) Myr.**

- Gas gradually accumulates in the nuclear region through tidal forces from bars, giant molecular clouds etc.
- Alternatively, it is driven inwards by a stochastic event, such as a minor merger.

All the observed galaxies have disturbed morphology, such as distorted kinematics (NGC 5728), dust spirals (NGC 5728, NGC 2110) and lanes (IC 630) and irregular photometry (IC 630).

---

6.4 **Future Work**

The three objects presented in this thesis show how the circumnuclear environment of AGN are controlled by outflows, inflows and star formation. A larger sample set will enable these relationships to be more parameterized. To that end, the other IFU observed objects (\( \sim 15 \)) will be analyzed and published; these will be combined with archival data (an example is NGC 4438, which has a spectacular outflow and a molecular gas disk around the nucleus). The flux distributions of \( \text{H}_2 \) and \([\text{Fe II}]\) emission lines seem to be related to dust morphology; this will be explored further with NGC 7743, which seems to have an alignment of \( \text{H}_2 \) and dust lanes (as well as data from this thesis).

The complete set of spectra from the Mould et al. (2012) observations will be published as a community resource, and the results of that paper will be extended for star-formation rates (especially by stacking non-detections) and to determine nuclear stellar populations to compare with AGN activity. As well as galactic-scale stellar populations from the longslit data, the IFU \( K \) and \( H \)-band data will be re-analyzed using full stellar population modeling, giving better kinematic and extinction results than simplified CO band-head fitting.

The cold-phase \( \text{H}_2 \) gas around observed AGN will be examined directly (through CO emission) at small scale by observations with ALMA. These observations will be compared with forthcoming hydrodynamical simulations, extensions of the Schartmann et al. (2017) models. Examples of ALMA observations of nuclear gas and galactic-scale outflows are given in Oosterloo et al. (2017); Boizelle et al. (2017); Pozzi et al. (2017).
I am brain, Watson. The rest of me is a mere appendix.

Arthur Conan Doyle, 1859–1930

Acronyms and Glossary
### Table A.1: Astronomical/astrophysical acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGB</td>
<td>Asymptotic giant branch - stage of stellar evolution</td>
</tr>
<tr>
<td>AGN</td>
<td>Active galactic nucleus</td>
</tr>
<tr>
<td>AMR</td>
<td>Adaptive Mesh Resolution</td>
</tr>
<tr>
<td>AO</td>
<td>Adaptive optics</td>
</tr>
<tr>
<td>AU</td>
<td>Astronomical Unit (distance from Earth to the Sun)</td>
</tr>
<tr>
<td>BH</td>
<td>Black hole</td>
</tr>
<tr>
<td>BLR</td>
<td>Broad-line region</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-coupled device detector</td>
</tr>
<tr>
<td>CLR</td>
<td>Coronal-line region</td>
</tr>
<tr>
<td>DRP</td>
<td>Data reduction pipeline - software to reduce observational data to a calibrated spectrum, image or data cube</td>
</tr>
<tr>
<td>EW</td>
<td>Equivalent width of emission line</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of view</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width half maximum of an emission line fit.</td>
</tr>
<tr>
<td>IFU</td>
<td>Integral Field Unit</td>
</tr>
<tr>
<td>IP</td>
<td>Ionization potential</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>kpc</td>
<td>Kiloparsec</td>
</tr>
<tr>
<td>LGSAO</td>
<td>Laser guide-star adaptive optics</td>
</tr>
<tr>
<td>LINER</td>
<td>Low ionization nuclear emission region</td>
</tr>
<tr>
<td>LIRG</td>
<td>Luminous infra-red galaxy.</td>
</tr>
<tr>
<td>LLAGN</td>
<td>Low-luminosity AGN</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of sight</td>
</tr>
<tr>
<td>Mpc</td>
<td>Megaparsec</td>
</tr>
<tr>
<td>NIR</td>
<td>Near infrared region of the electromagnetic spectrum (1000–2500 nm)</td>
</tr>
<tr>
<td>NLR</td>
<td>Narrow-line region</td>
</tr>
<tr>
<td>NSC</td>
<td>Nuclear star cluster</td>
</tr>
<tr>
<td>PA</td>
<td>Position angle</td>
</tr>
<tr>
<td>pc</td>
<td>Parsec</td>
</tr>
<tr>
<td>PCA</td>
<td>Principle Component Analysis</td>
</tr>
<tr>
<td>Pixel</td>
<td>An element in array, either 1D (spectrum), 2D (image) or 3D (data cube). More specifically, an element in the spectral axis rather than spatial axes (spaxel).</td>
</tr>
<tr>
<td>pPXF</td>
<td>Penalized pixel-fitting method</td>
</tr>
<tr>
<td>PSF</td>
<td>Point spread function</td>
</tr>
<tr>
<td>SED</td>
<td>Spectral energy distribution</td>
</tr>
<tr>
<td>SF/SB</td>
<td>Star formation/starburst</td>
</tr>
<tr>
<td>SFR</td>
<td>Star formation rate</td>
</tr>
<tr>
<td>SMBH</td>
<td>Super-massive black hole</td>
</tr>
<tr>
<td>SN/SNe</td>
<td>Supernova (plural supernovae)</td>
</tr>
<tr>
<td>SNR</td>
<td>Supernova rate</td>
</tr>
<tr>
<td>Spaxel</td>
<td>A spatial element in a 3D data cube.</td>
</tr>
<tr>
<td>SSP</td>
<td>Single stellar population model</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet region of the electromagnetic spectrum (10–400 nm)</td>
</tr>
<tr>
<td>VLBI</td>
<td>Very Long Baseline Interferometry</td>
</tr>
<tr>
<td>WVT</td>
<td>Weighted Voronoi Tessellation</td>
</tr>
</tbody>
</table>
Table A.2: Instrument, telescope, observatory, survey or other facility acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MASS</td>
<td>Two Micron All Sky Survey</td>
</tr>
<tr>
<td>ALMA</td>
<td>Atacama Large Millimeter/Submillimeter Array</td>
</tr>
<tr>
<td>GALEX</td>
<td>Galaxy Evolution Explorer satellite observatory</td>
</tr>
<tr>
<td>GMOS</td>
<td>Gemini Multi Object Spectrometer on the Gemini telescopes</td>
</tr>
<tr>
<td>HST</td>
<td>Hubble Space Telescope</td>
</tr>
<tr>
<td>IRTF</td>
<td>NASA’s Infrared Telescope Facility (Hawaii)</td>
</tr>
<tr>
<td>MAST</td>
<td>Mikulski Archive for Space Telescopes</td>
</tr>
<tr>
<td>MUSE</td>
<td>The Multi Unit Spectroscopic Explorer optical IFU instrument on VLT</td>
</tr>
<tr>
<td>MWA</td>
<td>Murcheson Widefield Array radio telescope</td>
</tr>
<tr>
<td>NED</td>
<td>NASA/IPAC Extra-galactic Database</td>
</tr>
<tr>
<td>NICMOS</td>
<td>HST Near Infrared Camera and Multi-Object Spectrometer</td>
</tr>
<tr>
<td>NIFS</td>
<td>Near-Infrared Integral Field Spectrometer on the Gemini North telescope</td>
</tr>
<tr>
<td>OSIRIS</td>
<td>OH- Suppressing Infra-Red Imaging Spectrograph on the Keck I telescope</td>
</tr>
<tr>
<td>PanSTARRS</td>
<td>Panoramic Survey Telescope and Rapid Response System telescope</td>
</tr>
<tr>
<td>SINFONI</td>
<td>SNgle Faint Object Near-IR Investigation on the VLT-4 telescope</td>
</tr>
<tr>
<td>SMA</td>
<td>Sub-millimeter Array (Hawaii)</td>
</tr>
<tr>
<td>Triplspec</td>
<td>Infrared spectrometer, Mt Palomar</td>
</tr>
<tr>
<td>VLA</td>
<td>Very Large Array radio telescope</td>
</tr>
<tr>
<td>VLA FIRST</td>
<td>VLA Faint Images of the Radio Sky at Twenty-Centimeters survey</td>
</tr>
<tr>
<td>VLT</td>
<td>European Southern Observatory’s Very Large Telescope at Cerro Paranal</td>
</tr>
<tr>
<td>WFC3</td>
<td>HST Wide Field Camera 3</td>
</tr>
<tr>
<td>WFPC2</td>
<td>HST Wide Field and Planetary Camera 2</td>
</tr>
<tr>
<td>WiFeS</td>
<td>Wide-Field Spectrograph</td>
</tr>
<tr>
<td>WISE</td>
<td>Wide-Field Infrared Survey Explorer satellite observatory</td>
</tr>
</tbody>
</table>
This research has made use of the following facilities.

- The Jet Propulsion Laboratory, California Institute of Technology operates the NASA/IPAC Extragalactic Database (NED), under contract with the National Aeronautics and Space Administration.

- The SIMBAD Astronomical Database is operated by CDS, Strasbourg, France.

- IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

- The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

- The Pan-STARRS1 Surveys (PS1) and the PS1 public science archive have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg, and the Max Planck Institute for Extraterrestrial Physics, Garching, Johns Hopkins University, Durham University, the University of Edinburgh, the Queens University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under grant no. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation grant no. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), the Los Alamos National Laboratory, and the Gordon and Betty Moore Foundation.
Appendix B. Facilities

- The national facility capability for SkyMapper has been funded through ARC LIEF grant LE130100104 from the Australian Research Council, awarded to the University of Sydney, the Australian National University, Swinburne University of Technology, the University of Queensland, the University of Western Australia, the University of Melbourne, Curtin University of Technology, Monash University, and the Australian Astronomical Observatory. SkyMapper is owned and operated by the Australian National University’s Research School of Astronomy and Astrophysics. The survey data were processed and provided by the SkyMapper Team at ANU. The SkyMapper node of the All-Sky Virtual Observatory is hosted at the National Computational Infrastructure (NCI).

- GALEX is a NASA mission managed by the Jet Propulsion Laboratory.

- The scientific results reported in this article are based in part on data obtained from the Chandra Data Archive.

- Data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

- Our colleagues at Caltech are acknowledged for their ongoing support of the Triple-spec survey.

- The author is grateful for an Australian Postgraduate Award. The project also had the support of the Australian Research Council (ARC) through Discovery project DP140100435.

Observations were carried out on the following telescopes and proposals:
Table B.1: Observations

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Instrument</th>
<th>Proposal ID</th>
<th>Observation Date(s)</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemini:Gillett</td>
<td>NIFS</td>
<td>GN–2013B–Q–95</td>
<td>02/10/2013 &amp; 20/10/2013</td>
<td>Mould</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GN–2015A–Q–44</td>
<td>05/05/2015 &amp; 06/05/2015</td>
<td>Mould</td>
</tr>
<tr>
<td>VLT:Yepun (UT4)</td>
<td>SINFONI</td>
<td>093.B-0461(A)</td>
<td>10/04/2014</td>
<td>Cotter</td>
</tr>
<tr>
<td>Keck:Keck I</td>
<td>OSIRIS</td>
<td>W103OL</td>
<td>07/12/2011</td>
<td>Mould</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W017OL</td>
<td>01/11/2013 &amp; 02/11/2013</td>
<td>Mould</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W005OL</td>
<td>11/10/2014</td>
<td>Mould</td>
</tr>
<tr>
<td>ANU:2.3 m</td>
<td>WiFeS</td>
<td>4160069</td>
<td>17/11/2016 &amp; 14/01/2017</td>
<td>Mould</td>
</tr>
</tbody>
</table>
### C.1 The Electromagnetic Spectrum

This thesis designates regions of the electromagnetic spectrum as follows:

*Table C.1: Electromagnetic Spectral Regions*

<table>
<thead>
<tr>
<th>Spectral Region</th>
<th>Acronym</th>
<th>Wavelength (SI Units)</th>
<th>Frequency/ Energy (Typical)</th>
<th>Typical Astrophysical Phenomena</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td></td>
<td>&gt; 1 mm</td>
<td>&lt; 300 GHz</td>
<td>Synchrotron radiation</td>
</tr>
<tr>
<td>Sub-mm</td>
<td></td>
<td>100–1000 µm</td>
<td>3 THz–300 GHz</td>
<td>Very cold dust and gas</td>
</tr>
<tr>
<td>Far Infrared</td>
<td>FIR</td>
<td>15–100 µm</td>
<td>20–3 THz</td>
<td>Cold dust and gas</td>
</tr>
<tr>
<td>Mid Infrared</td>
<td>MIR</td>
<td>3–15 µm</td>
<td>100–20 THz</td>
<td>Warm dust</td>
</tr>
<tr>
<td>Near Infrared</td>
<td>NIR(^a)</td>
<td>1000–3000 nm</td>
<td>1 eV</td>
<td>Stars, gas</td>
</tr>
<tr>
<td>Optical</td>
<td></td>
<td>400–1000 nm</td>
<td>2 eV</td>
<td>Stars, gas</td>
</tr>
<tr>
<td>Near Ultraviolet</td>
<td>NUV</td>
<td>300–400 nm</td>
<td>3.5 eV</td>
<td>Hot stars, ionized gas</td>
</tr>
<tr>
<td>Far Ultraviolet</td>
<td>FUV</td>
<td>120–300 nm</td>
<td>8.5 eV</td>
<td>Hot stars, ionized gas</td>
</tr>
<tr>
<td>Extreme Ultraviolet</td>
<td>XUV</td>
<td>10–120 nm</td>
<td>35 eV</td>
<td>AGN accretion disks, corona</td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
<td>0.01–10 nm</td>
<td>1.25 keV</td>
<td>AGN accretion disks, corona</td>
</tr>
<tr>
<td>Gamma ray</td>
<td></td>
<td>&lt; 0.01 nm</td>
<td>&gt; 12.5 keV</td>
<td>Nuclear processes</td>
</tr>
</tbody>
</table>

\(^a\)The near-IR region is usually taken to start from 750 nm; however this thesis uses 1000 nm, as it relates to the instrumental techniques.
Appendix C. Astrophysical Properties

C.2 Ionization Potentials

This table contains the ionization potentials of elements of interest in this thesis, i.e. the energy required to produce the ionized species. These are taken from the CRC Handbook of Chemistry and Physics (Lide, 2003) through Wikipedia\(^1\).

\(\textbf{Table C.2:} \) Ionization potential (IP) for astrophysical species in this thesis.

<table>
<thead>
<tr>
<th>Species</th>
<th>IP (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H II</td>
<td>13.6</td>
</tr>
<tr>
<td>He II</td>
<td>24.6</td>
</tr>
<tr>
<td>N II</td>
<td>29.6</td>
</tr>
<tr>
<td>O II</td>
<td>35.1</td>
</tr>
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<td>O III</td>
<td>54.9</td>
</tr>
<tr>
<td>Al IX</td>
<td>284.6</td>
</tr>
<tr>
<td>Si VI</td>
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</tr>
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</tr>
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<tr>
<td>S III</td>
<td>23.3</td>
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<tr>
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<td>328.8</td>
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<tr>
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<td>Fe II</td>
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</tr>
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</table>

\(^1\)https://en.wikipedia.org/wiki/Ionization_energies_of_the_elements_(data_page)


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