THE SINFONI Mg II PROGRAM FOR LINE EMITTERS (SIMPLE): DISCOVERING STARBURSTS NEAR QSO SIGHT LINES

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ABSTRACT

Low-ionization transitions such as the Mg II λ2796/2803 doublet trace cold gas in the vicinity of galaxies. It is not clear whether this gas is part of the interstellar medium of large protodisks, part of dwarfs, or part of entrained material in supernova-driven outflows. Studies based on Mg II statistics, e.g., stacked images and clustering analysis, have invoked starburst-driven outflows where Mg II absorbers are tracing the denser and colder gas of the outflow. A consequence of the outflow scenario is that the strongest absorbers ought to be associated with starbursts. We use the near-IR integral field spectrograph SINFONI to test whether starbursts are found around z ~ 1 Mg II absorbers. For 67% (14 out of 21) of the absorbers with rest-frame equivalent width \( W'_{\lambda2796} > 2 \) Å, we do detect Hα in emission within \( \pm 200 \) km s\(^{-1}\) of the predicted wavelength based on the Mg II redshift, and with impact parameter ranging from 0.2" to 6.7" from the QSO. The star formation rate (SFR) inferred from Hα is 1–20 \( M_\odot \) yr\(^{-1}\), i.e., showing a level of star formation larger than in M82 by a factor of >4 on average. Our flux limit (3σ) is \( f_{\text{HI}} < 1.2 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \), corresponding to a SFR of \( \sim 0.5 \ M_\odot \text{ yr}^{-1} \), much below past ground-based Hα surveys of absorption-selected galaxies. We find evidence (at \( \geq 95\% \)) for a correlation between SFR and equivalent width, indicating a physical connection between starburst phenomena and gas seen in absorption. In the cases where we can extract the velocity field, the host galaxies of Mg II absorbers with \( W'_{\lambda2796} > 2 \) Å reside in halos with mean mass \( \langle \log M_\text{h}(M_\odot) \rangle \sim 11.2 \), in good agreement with clustering measurements.

Subject headings: cosmology; observations — galaxies: evolution — galaxies: halos — intergalactic medium — quasars: absorption lines

Online material: color figures

1. INTRODUCTION

In the era of large spectroscopic surveys such as SDSS (York et al. 2000), the Mg II λ2796/2803 doublet seen in background QSO spectra is particularly useful for selecting thousands of absorbing galaxies (e.g., York et al. 2006). Galaxies selected via their Mg II λ2796/2803 doublet have been used as proxies for studying H i–selected galaxies at \( z < 1.5 \) (e.g., Rao et al. 2006).

It is not clear whether this cold gas is part of the interstellar medium of large spirals (Wolfe et al. 1986), part of the halos of galaxies (Bahcall & Spitzer 1969), or part of dwarf galaxies (York et al. 1986) akin to the Magellanic Clouds. An alternative scenario for absorption-selected galaxies is that the gas seen in absorption is part of cold gas clumps in the host-galaxy halos entrained in outflows produced by supernovae (SNe) (Nulsen et al. 1998; Schaye 2001). Most likely all three scenarios play a role, but in what proportion for a given equivalent width or H i column density?

Using cross-correlation techniques, Bouché et al. (2006) statistically constrained the halo mass of \( \sim 2000 \) Mg II host galaxies, finding that the host halo mass \( (M_h) \) decreases with increasing Mg II rest equivalent width \( (W'_{\lambda2796}) \). Given that the equivalent width must be correlated with the line-of-sight velocity width, \( \Delta v \), as also verified observationally by Ellison (2006), these results imply that \( M_h \) and \( \Delta v \) are anticorrelated. This seems to show that the clouds responsible for the absorption are not virialized; otherwise, a \( M_h-\Delta v \) correlation would have been measured. A natural explanation for this is that the cold gas originates from SN-driven outflows, in which case the velocity width \( \Delta v \) may be related to the outflow kinematics or may be a measure of the mass outflow rate. In a few cases, evidence for superwinds is seen from the absorption profile (Bond et al. 2001; Ellison et al. 2003). Others, e.g., Prochter et al. (2006) and Martin (2006), arrived at the same conclusion that superwinds play a significant role in Mg II absorbers from very different perspectives.

The most important implication from the starburst scenario is that the selection of galaxies via the Mg II absorption signature may be equivalent to selecting starburst-producing superwinds. Equivalently, nondetections of the Hα signature of a starburst would enable one to rule out the starburst scenario, while the presence of Hα emission is no unambiguous proof of starburst-driven winds.

In this Letter, we report the first results of our “SINFONI Mg II Program for Line Emitters” (SIMPLE), which is aimed at detecting Hα from the starburst galaxy using the integral field unit (IFU) SINFONI (Eisenhauer et al. 2003) available at the Very Large Telescope (VLT). The advantages of IFUs include the possibility of detecting the Mg II host at impact parameters smaller than the seeing disk, and of measuring the two-dimensional kinematics of galaxies.

We present our sample selection in § 2 and results in § 3. Throughout, we use the \( h = 0.7, \Omega_M = 0.3, \Omega_L = 0.7 \) cosmology.

2. SAMPLE SELECTION

Our sample of Mg II–selected galaxies is selected from the SDSS/2QZ databases and from the catalog of absorption-line...
systems of Ryabinkov et al. (2003) with the only physical criterion $W_{\lambda 2796} > 2 \, \AA$. We then ensured that the corresponding H$\alpha$ emission line would fall inside the SINFONI wavelength range and away from sky OH emission lines. The $W_{\lambda 2796} > 2 \, \AA$ criterion was used for the following two reasons. First, in the superwind scenario, the strongest absorbers (as measured by $W_{\lambda 2796}$) ought to have the largest star formation rates, hence the largest He$\alpha$ fluxes. Second, the $W_{\lambda 2796} > 2 \, \AA$ criterion is known to select the hosts with the smallest impact parameters, $\rho < 30 \, h^{-1} \, \text{kpc}$ (e.g., Steidel 1995; Bouche et al. 2006). At $z = 1$, this corresponds to $\sim 4 \, \text{kpc}$, which means that the host galaxy will fall within the field of view of SINFONI (8$''$).

We have obtained SINFONI observations toward 21 Mg $\text{II}$ absorbing galaxies all with absorption redshift $z_{\text{abs}} = 1$, i.e., corresponding the J-band filter. We focused on $z \sim 1$ systems because (1) this redshift range is close to the range used in Bouche et al. (2006) and (2) our flux sensitivity is enhanced in the J band compared to that in the K band. The latter point is due to the gain in luminosity distance compared to the loss in raw instrument throughput. For each QSO field we took 4 $\times$ 600 s exposures, placing the QSO in the four quadrants of the field of view. The total exposure time for the host galaxy thus varies between 10 and 40 minutes, depending on its location with respect to the QSO. The observations were all taken in seeing-limited mode with 0.125$''$ pixels, in moderate (optical) seeing conditions ($1'' - 1.5''$), yielding a point-spread function (PSF) of 0.8$'' - 1.2''$ in the J band.

The data reduction is based on pairwise subtraction of the frames as in F"orster Schreiber et al. (2006) using the MPE SINFONI pipeline (SPRED; Abuter et al. 2006 and references therein) and the OH sky line removal scheme of Davies (2007). The wavelength solution is obtained using the Ar lamp frames, and the absolute wavelength is obtained directly from the OH sky emission lines. Flux calibration is performed using telluric standard stars.

### 3. RESULTS

From the SINFONI data cubes, we detect an H$\alpha$ emitter within $\pm 200 \, \text{km s}^{-1}$ of the predicted location from the Mg $\text{II}$ redshift in 14 of the 21 fields down to a flux limit of $4 \times 10^{-18} \, \text{erg s}^{-1} \, \text{cm}^{-2}$ (1 $\sigma$) (see Table 1). In other words, we have a 67% detection rate. The undetected hosts are either fainter than our flux limit or outside the field of view. Figure 1 shows the H$\alpha$ flux maps for all of the detected host galaxies. In all frames, the QSO PSF (typically 0.8$''$–1.2$''$ FWHM) was subtracted from the H$\alpha$ flux maps and is shown as contours.

As seen from Figure 1, the impact parameters range from 0.2$''$ to 4$''$ (1 to 25 kpc), with one at $\sim 6.7''$ (J0841+2339). The very strong absorber ($W_{\lambda 2796} = 4.5 \, \AA$) toward the QSO 2QZ J0226–28 is detected with an impact parameter of 0.2$''$, well within the seeing disk. We can rule out the possibility of this emission line being from the QSO. Indeed, the emission line at 1.327 $\mu$m corresponds to 4185 $\AA$ in the rest frame of the QSO and therefore does not correspond to any known atomic transition. Furthermore, the emission line is clearly spatially offset from the QSO centroid. This shows that it is possible to decouple the intervening galaxy and the QSO owing to the information contained in the IFU data cube.

It is extremely unlikely that all the 14 emission lines shown in Figure 1 be something else in relation to other intervening systems along the line of sight. For the strongest emitters (J0448, J0302, J0822, J0943), we do also detect [N $\text{II}$] $\lambda 6583$ and [S $\text{II}$] $\lambda\lambda 6717, 6731$, therefore lifting any ambiguity. In the cases where only one line is detected, we can reject the other possibilities (O $\text{II}$, O $\text{III}$, H$\beta$) for the following reasons.

### Table 1: Sample Properties

<table>
<thead>
<tr>
<th>Sight Line</th>
<th>$z_{\text{abs}}$</th>
<th>$W_{\lambda 2796}$ ($\AA$)</th>
<th>log $N_{\text{H}}/\rho$ ($\text{cm}^{-2}$)</th>
<th>PSF (arcsec)</th>
<th>$b$ (arcsec)</th>
<th>$\rho$ (kpc)</th>
<th>$f_{\text{HL}}$ ($\text{erg s}^{-1} \text{cm}^{-2}$)</th>
<th>SFR ($M_{\odot} \text{yr}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS J014717.76+125808.8</td>
<td>1.5030</td>
<td>4.025</td>
<td>1.0</td>
<td>1.9</td>
<td>15</td>
<td>$(1.7 \pm 0.4) \times 10^{-16}$</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>2QZ J022620.4–285751.1</td>
<td>2.171</td>
<td>4.515</td>
<td>...</td>
<td>0.25</td>
<td>2</td>
<td>$(1.5 \pm 0.3) \times 10^{-16}$</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2QZ J024824.4–310944.1</td>
<td>1.399</td>
<td>2.455</td>
<td>...</td>
<td>3.0</td>
<td>24</td>
<td>$(4.7 \pm 1.1) \times 10^{-17}$</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>2QZ J030249.6–321600.0</td>
<td>0.898</td>
<td>2.27</td>
<td>...</td>
<td>3.5</td>
<td>27</td>
<td>$(1.6 \pm 0.3) \times 10^{-16}$</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>J042703.7–130253.5</td>
<td>2.168</td>
<td>2.005</td>
<td>1</td>
<td>2.6</td>
<td>20</td>
<td>$(4.4 \pm 1.0) \times 10^{-17}$</td>
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</tr>
<tr>
<td>J044821.8+095017.1</td>
<td>2.115</td>
<td>3.169</td>
<td>1</td>
<td>1.8</td>
<td>14</td>
<td>$(3.8 \pm 0.8) \times 10^{-16}$</td>
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<tr>
<td>SDSS J082238.78+224318.9</td>
<td>1.620</td>
<td>2.749</td>
<td>1</td>
<td>3.1</td>
<td>24</td>
<td>$(4.7 \pm 0.9) \times 10^{-16}$</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>SDSS J083932.99+111206.6</td>
<td>2.966</td>
<td>0.32</td>
<td>0</td>
<td>3.7</td>
<td>29</td>
<td>$(1.2 \pm 0.2) \times 10^{-16}$</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>SDSS J084119.83+233904.9</td>
<td>1.5080</td>
<td>1.974</td>
<td>1</td>
<td>6.7</td>
<td>54</td>
<td>$(1.0 \pm 1.9) \times 10^{-16}$</td>
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<tr>
<td>SDSS J094309.66+103400.6</td>
<td>1.2390</td>
<td>3.525</td>
<td>1</td>
<td>3.0</td>
<td>24</td>
<td>$(3.3 \pm 0.7) \times 10^{-16}$</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>SDSS J142253.31–000149.0</td>
<td>1.0830</td>
<td>3.185</td>
<td>1</td>
<td>1.5</td>
<td>12</td>
<td>$(1.2 \pm 0.3) \times 10^{-16}$</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>SDSS J144104.91+044348.4</td>
<td>1.1120</td>
<td>2.22</td>
<td>1</td>
<td>1.4</td>
<td>11</td>
<td>$(4.5 \pm 1.0) \times 10^{-17}$</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>SDSS J233551.10+151453.2</td>
<td>0.8920</td>
<td>3.308</td>
<td>1</td>
<td>2.1</td>
<td>17</td>
<td>$(6.5 \pm 1.4) \times 10^{-17}$</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>2QZ J235714.9–273659.2</td>
<td>1.732</td>
<td>0.8149</td>
<td>...</td>
<td>1.0</td>
<td>8</td>
<td>$(8.6 \pm 1.7) \times 10^{-17}$</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ A "1" indicates that the system meets the Rao et al. (2006) criteria for being a DLA.

$^b$ The 3 $\sigma$ upper limits for the nondetections are computed for an unresolved source spread over $\sim 200$ pixels, spread over 32 spatial pixels and spectral FWHM = 6 pixels = 9 $\AA$ (i.e., $R_{\lambda 500} = 0.4'' \approx 3$ kpc, and FWHM = 250 km s$^{-1}$). The same dust-correction was applied to the SFR limits.
[O III] $\lambda$5007 is a doublet easily identifiable at the SINFONI resolution $R \sim 2200$. [O III] $\lambda$3727 would not be resolved, but that would put the galaxy at a redshift higher than the QSO emission redshift. In most cases, the same argument applies for H$\beta$. When not, we have checked the QSO spectrum for possible corresponding absorbers (Mg II, Fe II) and found nothing in the QSO spectrum at the corresponding location.

After more than two decades, only <100 absorption-selected galaxies have been identified in emission, and mostly at $z \simeq 1$ (e.g., Kulkarni et al. 2006 and references therein) using broadband imaging (e.g., Le Brun et al. 1997; Chen & Lanzetta 2003). Low-redshift ($z < 1$) Mg II absorbers have been identified more easily (Bergeron & Boissé 1991; Steidel et al. 1994; Le Brun et al. 1997) than low-$z$ and high-$z$ damped Ly$\alpha$ absorbers (DLAs), which are all also Mg II absorbers (Rao et al. 2006). Our 67% detection rate of the host H$\alpha$ emission is thus in contrast to most previous H$\alpha$ studies of absorption-selected galaxies since our sample of strong Mg II absorbers ($W_{\lambda 2796} > 2 \text{ Å}$) is dominated by DLA “candidates” meeting the criterion of Rao et al. (2006) (see Table 1) and is due to several factors. If our careful avoidance of OH sky emission lines plays a significant role, it is the SINFONI throughput that enabled us to reach flux limits unavailable previously from the ground, reaching $1.2 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ or a SFR of $\sim 0.5 M_\odot$ yr$^{-1}$ at $z = 1$ in less than 1 hr. For comparison, previous H$\alpha$ surveys for $z > 2$ DLAs include the ground-based surveys of, e.g., Mannucci et al. (1998), unveiling several candidates down to $1.4 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ (3 $\sigma$); van der Werf et al. (2000), unveiling several candidates down to $1.7 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ (3 $\sigma$); Bunker et al. (1999), showing no detection down to $(7-16) \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (3 $\sigma$); the HST NICMOS survey of a $z = 0.656$ DLA ($W_{\lambda 2796} = 1.5 \text{ Å}$) by Bouché et al. (2001), showing no detections down to $3.7 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (3 $\sigma$); and the NICMOS survey of a $z = 1.89$ DLA by Kulkarni et al. (2001), showing no detection down to $1.4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (3 $\sigma$).

The large number of H$\alpha$ detections in this survey shows the relatively high star formation rates of the host galaxy given our shallow exposures. The averaged integrated H$\alpha$ luminosity for our sample is $L_{\text{H}\alpha} \simeq 6.4 \times 10^{41}$ erg s$^{-1}$ (median $4.2 \times 10^{41}$ erg s$^{-1}$), uncorrected for extinction. This is about 4 times that of the starburst M82 whose raw $L_{\text{H}\alpha} = 1.5 \times 10^{41}$ erg s$^{-1}$ (Lehnert et al. 1999). If we adopt a statistical correction of $A_v = 0.8$ mag as derived for local star-forming and starburst galaxies of similar H$\alpha$ luminosities (Kennicutt 1998; Buat et al. 2002), we infer an average (median) SFR of $\sim 12 (7) M_\odot$ yr$^{-1}$ using the Kennicutt (1998) flux conversion for a Salpeter IMF, and $\sim 7 (4) M_\odot$ yr$^{-1}$ using the Chabrier (2003) IMF (both from 0.1 to 100 $M_\odot$). Table 1 lists the derived properties of our sample.

Figure 2 shows the SFR as a function of $W_{\lambda 2796}$. It appears that there is a correlation between the SFR and $W_{\lambda 2796}$, which is significant at more than 2 $\sigma$; the Pearson correlation coefficient is $\rho = 0.59$ with a $P$-value $= 0.024 < 0.05$, and a Spearman rank test gives $\rho = 0.53$ and $P = 0.048$. The correlation is very consistent with the analysis of Zibetti et al. (2007), who found that the hosts of the strongest Mg II absorbers are bluer. If stronger starbursts produce larger outflows (whose signature is more clouds over a larger $\Delta r$), such a correlation would naturally arise in the outflow scenario. We will attempt to model this in more detail in N. Bouché et al. (in preparation).

The inferred SFRs are moderate, but whether or not the H$\alpha$ emitters seen in Figure 1 are producing winds depends on the SFR per unit area, $\Sigma$, not on the integrated SFR. For instance,
and we view this result as supporting the outflow scenario, but consistent with the prediction of the starburst-outflow scenario, at least for NGC 1569 (SFR $\sim 1 M_\odot$ yr$^{-1}$; Lehnert et al. 1999) and NGC 1569 (SFR $\sim 1 M_\odot$ yr$^{-1}$; Martin et al. 2002) have $\Sigma$ greater than the 0.1 $M_\odot$ yr$^{-1}$ kpc$^{-2}$ threshold for harboring SN-driven outflows (Heckman 2003), and do show strong outflows. Already, the majority of our sample meet this criteria. Higher spatial resolution data and better size constraints will enable us to test whether strong Mg $\ii$ selected galaxies always meet the outflow threshold and, in the cases where it does, to probe the outflow physical properties.

As stated in § 1, H$\alpha$ ought to be present and detected in the starburst-outflow scenario. Had we not detected H$\alpha$, this would have ruled out the outflow scenario. The high detection fraction thus prevents us from ruling out the outflow scenario. The relatively high average SFR (compared to M82) is in fact very consistent with the prediction of the starburst-outflow scenario, and we view this result as supporting the outflow scenario, but other interpretations are possible. Note that our conclusion only applies for galaxies selected with the strongest Mg $\ii$ absorption equivalent widths ($W_{\lambda2796} > 2 \AA$). Mg $\ii$ absorption systems with $W_{\lambda2796} < 2 \AA$ are much more numerous and may select a more diverse class of galaxies (e.g., Bergeron & Boissé 1991; Steidel et al. 1994).

Figure 3 shows an example of the two-dimensional velocity field for one of the Mg $\ii$ host galaxies. For the remainder of the sample, when we can extract the velocity field, we find that the host galaxy of Mg $\ii$ absorbers with $W_{\lambda2796} > 2 \AA$ reside in halos with masses ranging from $\log M_h(M_\odot) \sim 9.9$ to 11.9 with a logarithmic mean (log $M_h(M_\odot)$) $\sim 11.2$, once corrected for inclination. This is 10 times smaller than the Milky Way, and in good agreement with the halo masses predicted from the clustering analysis of Bouche´ et al. (2004, 2006). Here we are using the maximum velocity $V_{\text{max}}$ as a proxy for the circular velocity. In N. Bouche´ et al. (in preparation), we will present the kinematic results in detail.

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REFERENCES

Heckman, T. 2003, Rev. Mex. AA Ser. Conf., 17, 47
Steidel, C. C. 1995, in QSO Absorption Lines, ed. G. Meylan (Berlin: Springer), 139

Fig. 2.—SFR from the H$\alpha$ emission of Mg $\ii$ hosts as a function of rest-frame equivalent width $W_{\lambda2796}$. SFR and $W_{\lambda2796}$ may be correlated, indicating a physical connection between the host starburst and the gas seen in absorption. The cut at $W_{\lambda2796} = 2 \AA$ is due to our sample selection. Our SFR flux limit (SNR = 3) is shown as the dotted line.

Fig. 3.—Comparison between the H$\alpha$ emission map (left) and the two-dimensional velocity field (right) for one of our Mg $\ii$ host galaxies. The QSO continuum is shown as gray contours. The kinematics reveal that the kinematic major axis is perpendicular to the QSO–galaxy vector, i.e., the QSO is located along the minor axis, which is further evidence that the gas traced by Mg $\ii$ is part of the halo gas and not the disk. The maximum rotation velocity is $V_{\text{max}} \sim 80$ km s$^{-1}$ for this galaxy and is typical for our sample. Using $V_{\text{max}}$ as a proxy for the circular velocity, the inferred mean halo mass is (log $M_h(M_\odot)$) $\sim 11.2$ for the sample. [See the electronic edition of the Journal for a color version of this figure.]