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Origin of optically passive spiral galaxies with dusty star-forming regions: Outside-in truncation of star formation?

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ABSTRACT

Recent observations have revealed that red, optically-passive spiral galaxies with little or no optical emission lines, harbour significant amounts of dust-obscured star formation. We propose that these observational results can be explained if the spatial distributions of the cold gas and star-forming regions in these spiral galaxies are significantly more compact than those in blue star-forming spirals. Our numerical simulations show that if the sizes of star-forming regions in spiral galaxies with disk sizes of R_d are $\sim 0.3R_d$, such galaxies appear to have lower star formation rates as well as higher degrees of dust extinction. This is mainly because star formation in these spirals occurs only in the inner regions where both the gas densities and metallicities are higher, and hence the dust extinction is also significantly higher. We discuss whether star formation occurring preferentially in the inner regions of spirals is closely associated with the stripping of halo and disk gas via some sort of environmental effect. We suggest that the “outside-in truncation of star formation” is the key to a better understanding of apparently optically-passive spirals with dusty star-forming regions.

Key words: stars:formation – galaxies:spiral – infrared:galaxies – galaxies:evolution

1 INTRODUCTION

Since the discovery of significant numbers of galaxies in distant ($z \sim 0.2$ – 0.5) clusters with a spiral morphology but with no apparent on-going star formation based on the absence of any emission lines in their optical spectra (e.g., Couch et al. 1994, 1998; Dressler et al. 1999; Poggianti et al. 1999), the origin of these so-called “optically-passive” spirals (or “k-type” spirals) has received considerable attention both observationally and theoretically (e.g., Bekki et al. 2002; Goto et al. 2003; Yamauchi & Goto 2004; Moran et al. 2006; Masters et al. 2010). For example, Goto et al. (2003) found that such passive spirals are located anywhere between 1 – 10 virial radii from the centres of clusters and suggested that their formation is closely associated with cluster-related physical processes. In contrast, Masters et al. (2010) recently found that passive spirals exist preferentially in intermediate density regimes, and that there are no

obvious correlations between their physical properties and their environment.

A further important and yet puzzling observational result is that some of the passive spirals contain significant amounts of *obscured* star formation (e.g., Wolf et al. 2005; Wilman et al. 2008; Wolf et al. 2009). The star formation rates in these cases are a factor of ~ 4 lower than those in blue spirals with the same mass. More specifically, the ratio of the star formation rate inferred from their infrared emission (SFR_{IR}) to that inferred from their UV emission (SFR_{UV}) is typically a factor of ~ 3 larger than that for blue spirals (Wolf et al. 2009), implying that the passive spirals have a significantly higher ($\times \sim 2$) level of dust extinction. However, it remains unclear how and when such dust extinction occurs in spiral galaxies when their star formation rates are significantly lower.

The purpose of this paper is to show how optically-passive spirals with lower yet substantial star formation rates can have higher degrees of dust extinction, based on numerical simulations of star-forming disk galaxies. In particular, we demonstrate that if the sizes of actively star-

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Table 1. The ranges of model parameters.

model no	f_g^a	$R_g (\times R_d)^b$	$\Sigma_{g,g} (M_\odot \text{ pc}^{-2})^c$	$\Sigma_{g,d} (M_\odot \text{ pc}^{-2})^d$	\bar{a}_v^e	$\bar{a}_{v,n}^f$	$\bar{b}_{\text{sf}} (M_\odot \text{ yr}^{-1})^g$	$\bar{b}_{\text{sf},n} (M_\odot \text{ yr}^{-1})^h$
Model 1	0.05	0.3	37.42	3.37	0.306	0.186	8.55	3.37
Model 2	0.20	1.0	12.47	12.47	0.067	0.056	15.17	10.90

^a The initial gas mass fraction of a disk galaxy.

^b The initial gas disk size of a disk galaxy measured in units of R_d , where R_d (=17.5 kpc) is the initial (stellar) disk size of the galaxy.

^c The initial mean surface gas density of a disk galaxy within R_g .

^d The initial mean surface gas density of a disk galaxy within R_d .

^e The value of the extinction parameter a_v averaged over all time steps in a simulation.

^f The value of the extinction parameter a_v averaged over the last 0.1 Gyr in a simulation.

^g The value of the star formation rate averaged over all time steps in a simulation.

^h The value of the star formation rate averaged over the last 0.1 Gyr in a simulation.

forming regions (R_{sf}) in galaxies with disk sizes of R_d are significantly more compact than R_d , then they will exhibit both lower star formation rates and heavier dust extinction. We assume that R_{sf} varies amongst spiral galaxies in the local and distant universe, and thus we treat R_{sf} as a free parameter in this study. This assumption is consistent with the recent observations of Koopmann & Kenny (2004) which showed that isolated spirals as well as those in the Virgo cluster are extremely diverse in the radial distribution and extent of their H α emission (from star-forming regions). We discuss how R_{sf} can be more compact in some star-forming passive spirals in §4.

2 THE MODEL

We used the latest version of GRAPE (GRAvity PipE, GRAPE-7) – which is the special-purpose computer for gravitational dynamics (Sugimoto et al. 1990) – in order to investigate the chemodynamical evolution of star-forming disk galaxies. We have revised our original GRAPE-SPH code (Bekki 2009) for galaxy-scale hydrodynamical evolution so that we can investigate chemical evolution and star formation processes of disk galaxies; the details of this new code will be described in future papers (e.g., Bekki et al. 2010).

The masses of the disk, bulge, and dark halo components of our model galaxy are represented by M_d , M_b , and M_{dm} , respectively. The mass ratio of M_{dm} to M_d was fixed at 16.7 for all of the present models so that the models can mimic the mass distribution of the Galaxy with the total mass of $\sim 10^{12} M_\odot$ (e.g., Evans & Wilkinson 2000). We adopted an NFW halo density distribution (Navarro, Frenk & White 1996) suggested from CDM simulations:

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}, \quad (1)$$

where r , ρ_0 , and r_s are the spherical radius, the characteristic density of a dark halo, and the scale length of the halo, respectively. We adopted $c = 7.8$ (the ratio of r_{vir} to r_s , where r_{vir} is the virial radius) that is reasonable for the total masses ($\sim 10^{12} M_\odot$) investigated in the present study.

The radial (R) and vertical (Z) density profiles of the disk (with size R_d) were assumed to be proportional to $\exp(-R/R_{d,0})$, with scale length $R_{d,0} = 0.2R_d$, and $\text{sech}^2(Z/Z_{d,0})$, with scale length $Z_{d,0} = 0.04d$ in our units, respectively; both the stellar and gaseous disks follow this exponential distribution. In addition to the rotational veloc-

ity caused both by the gravitational fields of the disk and dark halo components, the initial radial and azimuthal velocity dispersions was assigned to the disk component according to the epicyclic theory with Toomre’s parameter $Q = 1.5$.

The mass ratio of the bulge to the disk (f_b) and the scale length ($R_{b,0}$) of the stellar bulge represented by the Hernquist profile were fixed at 0.167 and $0.04R_d$, respectively, for all models, which is consistent with that of the bulge model of the Galaxy. In the present study, we describe only the results of the models with $M_d = 6 \times 10^{10} M_\odot$ (thus $M_b = 1.0 \times 10^{10} M_\odot$) and $R_d = 17.5$ kpc (thus $R_{b,0} = 0.7$ kpc).

The cold interstellar medium (ISM) was distributed within R_g and modeled using SPH particles. The mass fraction of the isothermal ISM in the disk (f_g) was assumed to be a free parameter. The initial temperature of the ISM was assumed to be 10^4 K. We adopted the same method as that used in Bekki & Chiba (2005) for determining the radial dependence of gas mass fraction in a disk for a given f_g . We adopted the same chemical evolution model as those used in Bekki & Chiba (2005) and the chemical yield and the return parameter were set to 0.02 and 0.3, respectively. The star formation was assumed to follow the Schmidt law (Schmidt 1959) with an exponent of 1.5. Kinetic energy of 10^{51} erg per supernova is given to the ISM immediately after star formation occurs.

Friel (1995) has derived the metallicity (Z) gradient of the Galactic stellar disk based on the ages and metallicities that are estimated for the Galactic open clusters. We therefore allocated metallicity to each disk star according to its initial position as follows:

$$[\text{m}/\text{H}]_R = [\text{m}/\text{H}]_{d,0} + \alpha_d \times R, \quad (2)$$

where $[\text{m}/\text{H}]_{d,0}$ is the central metallicity. If we adopt plausible values of -0.091 for the slope α_d (Friel 1995) and the central value of 0.48 for $[\text{m}/\text{H}]_{d,0}$, the mean metallicity of the disk is 0.0 in $[\text{Fe}/\text{H}]$.

In order to more quantitatively estimate dust extinction around each individual star in star-forming disk galaxies, we introduced a dimensionless parameter, a_v , which measures the degree of dust extinction for each new i -th stellar particle as follows: The dust extinction at wavelength λ (A_λ) around a star is described as follows (e.g., Spitzer 1978):

$$A_\lambda = -2.5 \log \frac{F_\nu}{F_\nu(0)} = 1.086 N_d Q_e \sigma_d, \quad (3)$$

where F_ν , $F_\nu(0)$, N_d , Q_e , and σ_d are the observed radia-

tive flux, the radiative flux in the absence of extinction, the column density (per cm^2) along the line of sight, the dimensionless extinction efficiency factor, and the geometrical cross section of a dust particle.

We assumed here that σ_d and the dimensionless factor Q_e are constant for all the models considered in this present study. Furthermore, previous models have shown that the dust mass of the Galaxy is linearly proportional to the total mass of the heavy elements (e.g., Dwek 1998). Therefore we took the degree of dust extinction (A_v) around a new star to be proportional to N_d , which in turn is proportional to $\rho_g Z$, where ρ_g and Z are the 3D gas density and the gaseous metallicity around the star, respectively. Thus we defined the dust extinction parameter ($a_{v,i}$) for each individual i -th new star as follows:

$$a_{v,i} = \rho_{g,i} Z_i, \quad (4)$$

where $\rho_{g,i}$ and Z_i are the 3D gas density and metallicity around the star. We here consider that the present model enables us to discuss the importance of initial gaseous distributions in determining the mean dust extinction of a galaxy without using our previous fully consistent model considering 3D dust distributions (Bekki & Shioya 2000).

We mainly investigated the time evolution of the mean a_v of new stars and the star formation rate (b_{sf}) over a 0.28 Gyr time interval in each simulation. We estimated the mean values of a_v and b_{sf} in star-forming disk galaxies over the last 0.1 Gyr ($\bar{a}_{v,n}$ and $\bar{b}_{\text{sf},n}$, respectively) and adopted them as reasonable indicators of the amount of dust extinction and global star formation for the galaxies. We consider that these mean values are better than the mean a_v and b_{sf} estimated for all time steps (\bar{a}_v and \bar{b}_{sf} , respectively), because strong starbursts can occur *initially* in the inner regions of the disks for most models, owing to very high gas densities there. Thus our estimates pertain to those times when star formation and chemical evolution proceeds steadily in the disks.

The two key parameters in the present study are f_g and R_g which control the sizes of the star-forming regions (R_{sf}). Although we have run numerous models with different f_g and R_g values, we show mainly the results for two representative models, the key parameter values for which are given in Table 1. This is mainly because these two comparative models show most clearly how the initial size of the gas disk is important in determining the mean star formation rate and the mean degree of dust extinction in a spiral galaxy. These two models are hereafter referred to as Model 1, which refers to a passive spiral with a lower star formation rate and higher level of dust extinction, and Model 2, which refers to a blue spiral with a higher star formation rate and lower level of dust extinction. We also briefly describe the dependences of mean a_v on model parameters (f_g and R_g). The mass and scale resolutions of the present simulations are $3 \times 10^5 M_\odot$ and 193 pc, respectively, so that we can estimate a_v for local gaseous regions (~ 100 pc).

Finally, we note that we are unable to discuss whether the simulated disks exhibit k-type spectra, because the present new chemodynamical simulation does not output spectrophotometric information. We will address this important point in our future papers using chemodynamical simulations with spectroscopic synthesis code like those in our previous work (Bekki et al. 2001).

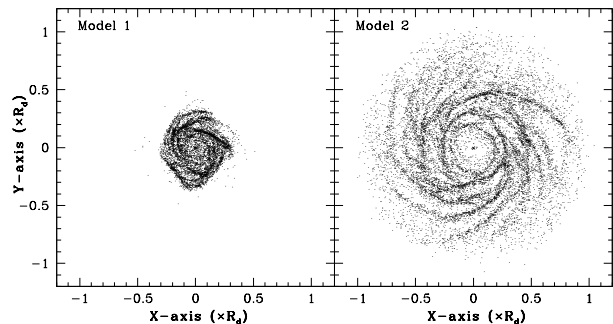


Figure 1. The distribution of new stars with ages less than 0.28 Gyr projected onto the x - y plane (i.e., the disk plane) for the two representative models, Model 1 (left) and Model 2 (right).

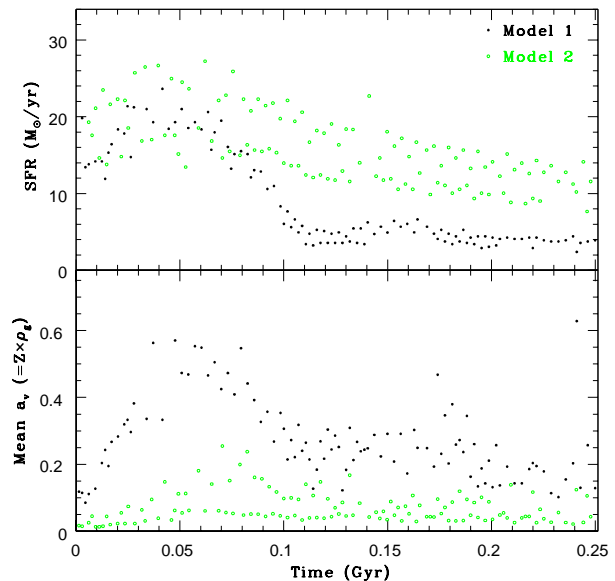


Figure 2. Time evolution of star formation rates (SFRs, upper) and mean a_v (extinction parameter, lower) for 0.28 Gyr in Model 1 (filled black) and 2 (open green).

3 RESULTS

Figure 1 shows that owing to the initially different gaseous distributions, the distributions of newly-formed stars are significantly different between the two models, Model 1 and 2. In Model 1, star formation can only proceed in the inner regions where both gas densities and metallicities are high. Owing to a larger gas mass fraction, new stars can be formed across the entire region of the disk in Model 2; star formation can occur not only in the inner regions with higher gas densities and metallicities, but also in the outer regions, even though the gas densities and metallicities are lower. The mean star formation rate in Model 2 ($10.9 M_\odot \text{yr}^{-1}$ for the last 0.1 Gyr) becomes significantly higher than that in Model 1 ($3.4 M_\odot \text{yr}^{-1}$) owing to the initially larger f_g . The spiral-like structure delineated by the very young stars with ages less than 0.28 Gyr in Model 2, suggests that well-defined

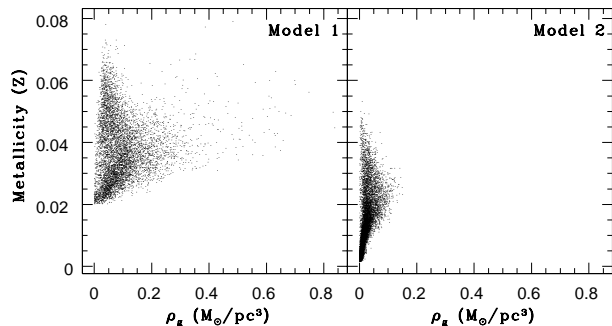


Figure 3. Plots of new stellar particles onto the $Z-\rho_g$ plane for Model 1 (left) and 2 (right). Here the metallicity (Z) and the local 3D gas density (ρ_g) around each individual new stellar particle is plotted.

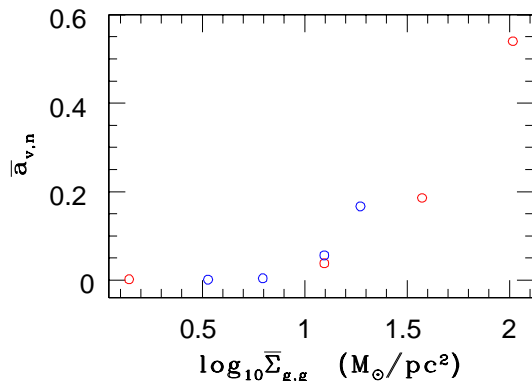


Figure 4. The dependences of $\bar{a}_{v,n}$ (mean dust extinction for new stars with ages less than 0.1 Gyr) on $\Sigma_{g,g}$ (initial mean gas density within R_g) for 8 different models. The models with $R_g = 0.3R_d$ and $R_g = R_d$ are shown in red and blue, respectively.

large spiral structures can be more clearly seen in disks with globally active star-forming regions.

In Figure 2 the time evolution of the mean star formation rate and extinction for Models 1 and 2 are shown. Here it can be clearly seen that the total star formation rate finally becomes as low as $\sim 3M_\odot\text{yr}^{-1}$ in Model 1, whereas its mean a_v becomes a factor of ~ 3 higher than that of Model 2 at $T = 0.28$ Gyr. The origin of this higher mean a_v in the disk of Model 1 can be explained via reference to Figure 3. This plots the 3D gas densities (ρ_g) and metallicities (Z) around the new stars formed within 0.28 Gyr in Models 1 and 2. Here it can be clearly seen that these two quantities are, on average, systematically higher in Model 1 than in Model 2. This is due to the fact that in Model 1 star formation occurs preferentially in the inner regions with higher gas densities and metallicities, whereas in Model 2 it occurs even in the lower-density and lower-metallicity outer regions of the disk. These results suggest that the observed higher dust extinction in passive spirals with lower star formation rates might be closely associated with more centrally-concentrated gas distributions within them.

In the present study, $\Sigma_{g,g}$ depending both on f_g and R_g is a key parameter that can determine $\bar{a}_{v,n}$. Figure 4 shows that the mean a_v for the very young stars formed within the last 0.1 Gyr ($\bar{a}_{v,n}$) depends on the initial mean gas densities within R_g ($\Sigma_{g,g}$) in such a way that $\bar{a}_{v,n}$ is higher in models with higher $\Sigma_{g,g}$. This figure also shows that models with $R_g = R_d$ can show higher $\bar{a}_{v,n}$, if $f_g \geq 0.3$ (corresponding to $\Sigma_{g,g} \geq 18.71M_\odot\text{pc}^2$). Furthermore, Figure 4 shows that $\bar{a}_{v,n}$ can be quite low in models with $R_g = 0.3R_d$ if f_g is lower (≤ 0.02): the star formation rates are also quite low in these models ($< 1M_\odot\text{yr}^{-1}$). This result suggests that passive spiral galaxies need to have a certain minimum amount of gas centrally concentrated in their disks if they are to show both lower yet substantial star formation rates and higher dust extinction relative to normal blue spirals.

We have shown that if star-forming regions are very strongly concentrated in the inner regions of spiral galaxy disks ($R_g \leq 0.2R_d$), then they appear to have rather low star formation rates ($< 1M_\odot\text{yr}^{-1}$) and high levels of dust extinction ($\bar{a}_{v,n} > 0.15$). For example, the model with $f_g = 0.007$ and $R_g = 0.1R_d$ shows $\bar{b}_{\text{sf},n} = 0.85M_\odot\text{yr}^{-1}$ and $\bar{a}_{v,n} = 0.30$. This result implies that if most of the gas in gas-poor disk galaxies (with $f_g < 0.01$) can be fueled to the nuclear regions and consumed rapidly there owing to some physical mechanism (e.g., galaxy-galaxy interaction), then such disk galaxies can be identified as passive spirals with nuclear star formation with higher degrees of dust extinction.

4 DISCUSSION AND CONCLUSIONS

If the scenario presented here (preferred star formation in inner regions of galaxies) is correct, this begs the question as to how the gas within disk galaxies might be truncated in this way in the course of their evolution. Previous numerical simulations show that ram pressure stripping by the hot intracluster medium can remove, quite efficiently, gas from the outer parts of spiral disks, so that their gas disk becomes much more compact than their stellar disk (e.g., Abadi et al. 1999; Kronberger et al. 2008). Furthermore, recent numerical simulations have shown that ram pressure stripping of halo gas, which is an important source of fuel for star formation in galactic disks, is more efficient in the outer parts of halos of disk galaxies in groups and clusters of galaxies (e.g., Bekki 2009). Thus it is possible that truncated gas disks can be formed as a result of halo and disk gas stripping, particularly in group and cluster environments.

Recently, the Galaxy Zoo project has revealed a large optical bar fraction in red spirals at low redshift ($70 \pm 5\%$ versus $27 \pm 5\%$ for blue spirals), and thus suggested that stellar bars are responsible for the truncation of star formation in this subset of the spiral galaxy population (Masters et al. 2010). Tidal interactions between galaxies can trigger the formation of bars and consequently transfer rapidly disk gas into the inner regions of the galaxies (e.g., Noguchi 1988). Therefore, the bars in disk galaxies can change the spatial distribution of gas such that the distribution can be much more centrally concentrated. Thus it could well also be possible that the origin of the proposed truncated gas disks has something to do with dynamical action of stellar bars in disk galaxies.

An important and possibly testable prediction of the

scenario presented here is that any emission associated with the star formation in optically-passive red spirals should be much more compact than that associated with star formation in blue spiral galaxies. On the other hand, the star formation rate per unit area (i.e., star formation density measured in units of $M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$) for these two different types of spirals should not be so different, because the star formation densities within the inner regions of passive spirals are expected to be as high as those in blue spirals. What is needed to test this is an emission line that traces star formation (and its rate) and is not heavily affected by dust extinction. Here, the $H\alpha$ line probably holds the most promise in terms of being the optical line least affected by dust extinction and one that can be readily mapped spatially and out to high redshifts via high resolution imaging and integral field unit spectroscopy.

As commented on above, a shortcoming of this study is its inability to show that disk galaxies with centrally-concentrated star formation exhibit passive k-type spectra. Although previous theoretical studies based on one-zone models and numerical simulations showed that e(a) and a+k/k+a spectra can be formed in dusty star-forming galaxies (e.g., Shioya & Bekki 2000; Bekki et al. 2001; Shioya et al. 2002), they did not clearly show k-type spectra can be formed from dusty star-forming galaxies. Thus it is crucially important that as a next step we conduct further numerical simulations that include spectrophotometric modeling which allow us to predict the spectroscopic signature associated with star formation that proceeds in the inner regions of disk galaxies.

If the star-forming regions of red passive spirals are as spatially extended as those in blue star-forming spirals, then it will be necessary to consider alternative scenarios to the one presented here. One such possibility worthy of brief mention here is that the upper-mass cutoff (m_{upp}) of the initial mass function (IMF) is significantly smaller (e.g., $< 20M_{\odot}$) in passive spirals. In this truncated IMF scenario, there are few or no massive O stars that can ionize the ISM (i.e., $> 20M_{\odot}$), such that (i) optical emission lines are very weak, and (ii) dust in the ISM can obscure star formation quite efficiently due to there being little destruction of dust by ionizing photons. This truncated IMF scenario has observational support through being able to explain the UV and $H\alpha$ properties of low surface brightness galaxies with low star formation rates (Meurer et al. 2009). More quantitative investigation based on numerical simulations of disk galaxy evolution with non-universal IMFs are required to test the viability of this scenario.

Recent observational studies of distant galaxies based on *Spitzer* 24 μm photometry and optical imaging by the *Hubble Space Telescope* have revealed the dusty nature of red galaxies and have provided new clues to the possible gradual truncation of galactic star formation in different environments (e.g., Gallazzi et al. 2009; Wolf et al. 2009). The present study suggests that truncation of star formation can occur more dramatically in the outer parts of disk galaxies, where environmental processes (e.g., tidal and ram pressure stripping) can be more effective. It also suggests that the possible inner dusty star-forming regions in passive spirals would be due to “outside-in truncation of star formation” in the course of disk galaxy evolution, in particular, in groups and clusters of galaxies.

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