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 disc sizes of \( R_d \) are \( \sim 0.3 R_d \), 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 disc 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: evolution – galaxies: spiral – infrared: galaxies.

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 ongoing 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, Shioya & Couch 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, Gray & Meisenheimer 2005; Wilman et al. 2008; Wolf et al. 2009). The star formation rates (SFRs) in these cases are a factor of \( \sim 4 \) lower than those in blue spirals with the same mass. More specifically, the ratio of the SFR inferred from their infrared emission (SFR\(_{IR}\)) to that inferred from their UV emission (SFR\(_{UV}\)) is typically a factor of \( \sim 3 \) 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 SFRs are significantly lower.

The purpose of this Letter is to show how optically passive spirals with lower yet substantial SFRs can have higher degrees of dust extinction, based on numerical simulations of star-forming disc galaxies. In particular, we demonstrate that if the sizes of actively star-forming regions \( (R_{sf}) \) in galaxies with disc sizes of \( R_d \) are significantly more compact than \( R_d \), then they will exhibit both lower SFRs 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 & Kenney (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\(_\alpha\) emission (from star-forming regions). We discuss how \( R_{sf} \) can be more compact in some star-forming passive spirals in Section 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 disc 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 disc galaxies; the details of this new code will be described in future papers (e.g. Bekki et al., in preparation).

The masses of the disc, 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:

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

where $r$, $\rho_0$ and $r_s$ are the spherical radius, the characteristic density of a dark halo and the scalelength of the halo, respectively. We adopted $c = 7.8$ (the ratio of $r_v$ to $r_s$ where $r_v$ 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 disc (with size $R_d$) were assumed to be proportional to $\exp(-R/R_{d,0})$, with scalelength $R_{d,0} = 0.2 R_d$, and $Z R_{d,0}$, with scalelength $Z_{d,0} = 0.04 d$ in our units, respectively; both the stellar and gaseous discs follow this exponential distribution. In addition to the rotational velocity caused both by the gravitational fields of the disc and dark halo components, the initial radial and azimuthal velocitydispersions were assigned to the disc component according to the epicyclic theory with Toomre’s parameter $Q = 1.5$.

The mass ratio of the bulge to the disc ($f_b$) and the scalelength ($R_{b,0}$) of the stellar bulge represented by the Hernquist profile were fixed at 0.167 and 0.04$R_d$, 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 $R_d$ and modelled using SPH particles. The mass fraction of the isothermal ISM in the disc ($f_g$) 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 disc 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 $10^{88}$ 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 disc based on the ages and metallicities that are estimated for the Galactic open clusters. We therefore allocated metallicity to each disc star according to its initial position as follows:

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

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

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

$$A_\lambda = -2.5 \log \frac{F_\lambda}{F_\lambda(0)} = 1.086 N_d Q_\lambda \sigma_\lambda,$$

where $F_\lambda$, $F_\lambda(0)$, $N_d$, $Q_\lambda$ and $\sigma_\lambda$ are the observed radiative 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 $\sigma_\lambda$ and the dimensionless factor $Q_\lambda$ 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 ($A_\lambda$) around a new star to be proportional to $N_d Z_\lambda$, which in turn is proportional to $\rho_g Z_\lambda$, where $\rho_g$ and $Z_\lambda$ are the 3D gas density and the gaseous metallicity around the star, respectively. Thus we defined the dust extinction parameter ($a_\lambda$) for each individual $i$th new star as follows:

$$a_{\lambda,i} = \rho_g Z_{\lambda,i},$$

where $\rho_g$ and $Z_\lambda$ 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 $a_\lambda$ of new stars and the star formation rate ($b_S$) over a 0.28-Gyr time interval in each simulation. We estimated the mean values of $a_\lambda$ and $b_S$ in star-forming disc galaxies over the last 0.1 Gyr ($a_{\lambda,0}$ and $b_{S,0}$, 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 $a_\lambda$ and $b_S$ estimated for all time-steps ($\bar{a}_\lambda$ and $\bar{b}_S$, respectively), because strong starbursts can occur initially in the inner regions of the discs for most models, owing to very high gas densities there. Thus our estimates pertain to those times when star formation and chemical evolution proceed steadily in the discs.

The two key parameters in the present study are $f_g$ and $R_d$ which control the sizes of the star-forming regions ($R_d$). Although we have run numerous models with different $f_g$ and $R_d$ 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 disc is important in determining the mean SFR 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 SFR and higher level of dust extinction, and Model 2, which refers to a blue spiral with a higher SFR and lower level of dust extinction. We also briefly describe the dependences of mean $a_\lambda$ on model parameters ($f_g$ and $R_d$). The mass and scale resolutions of the present simulations are $3 \times 10^7 \, M_\odot$ and 193 pc, respectively, so that we can estimate $a_\lambda$ for local gaseous regions ($\sim 100$ pc).

Finally, we note that we are unable to discuss whether the simulated discs 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, Shioya & Couch 2001).
Table 1. The ranges of model parameters.

| Model no. | $f_g^a$ | $R_g (\times R_d)^b$ | $\Sigma_{e,d}(M_\odot \text{ pc}^{-2})^c$ | $\Sigma_{e,d}(M_\odot \text{ pc}^{-2})^d$ | $\bar{a}_v^e$ | $\bar{a}_{v,b}^f$ | $\bar{b}_d (M_\odot \text{ yr}^{-1})^g$ | $\bar{b}_{d,e} (M_\odot \text{ yr}^{-1})^h$ |
|-----------|---------|----------------------|----------------------------------|----------------------------------|----------------|----------------|------------------|------------------|
| 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 disc galaxy.
$^b$The initial gas disc size of a disc galaxy measured in units of $R_d$, where $R_d (=17.5 \text{ kpc})$ is the initial (stellar) disc size of the galaxy.
$^c$The initial mean surface gas density of a disc galaxy within $R_g$.
$^d$The initial mean surface gas density of a disc 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 SFR averaged over all time-steps in a simulation.
$^h$The value of the SFR averaged over the last 0.1 Gyr in a simulation.

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

3 RESULTS

Fig. 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 disc 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 SFR 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 large spiral structures can be more clearly seen in discs with globally active star-forming regions.

In Fig. 2 the time evolution of the mean SFR and extinction for Models 1 and 2 are shown. Here it can be clearly seen that the total SFR finally becomes as low as $\sim 3$ $M_\odot \text{ yr}^{-1}$ in Model 1, whereas its mean $a_v$ becomes a factor of $\sim 3$ higher than that of Model 2 at $T = 0.28 \text{ Gyr}$. The origin of this higher mean $a_v$ in the disc of Model 1 can be explained via reference to Fig. 3. This plots the 3D gas densities ($\rho_g$) 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 disc. These results suggest that the observed higher dust extinction in passive spirals with lower SFRs might be closely associated with more centrally concentrated gas distributions within them.

In the present study, $\Sigma_{e,d}$ depending both on $f_g$ and $R_g$ is a key parameter that can determine $a_{v,b}$. Fig. 4 shows that the mean $a_v$ for the very young stars formed within the last 0.1 Gyr ($\bar{a}_{v,b}$)
lar bars are responsible for the truncation of star formation in this
disc galaxies (with \( R_{\text{d}} \geq 0.3 \) \( R_{\text{d}} \) and \( R_{\text{d}} = R_{\text{d}} \) are shown in red and blue, respectively.

depends on the initial mean gas densities within \( R_{\text{d}}(\Sigma_{\text{g}}) \) in such a way that \( a_{\text{d}} \) is higher in models with higher \( \Sigma_{\text{g}} \). This figure also shows that models with \( R_{\text{d}} = R_{\text{d}} \) can show higher \( a_{\text{d}} \), if \( f_{\text{g}} \geq 0.3 \) (corresponding to \( \Sigma_{\text{g}} \geq 18.71 \) \( M_{\odot} \) \( \text{kpc}^{-2} \)). Furthermore, Fig. 4 shows that \( a_{\text{d}} \) can be quite low in models with \( R_{\text{d}} = 0.3 \) \( R_{\text{d}} \) if \( f_{\text{g}} \) is lower (\( \leq 0.02 \)): the SFRs are also quite low in these models (\( < 1 \) \( M_{\odot} \) \( \text{yr}^{-1} \)). This result suggests that passive spiral galaxies need to have a certain minimum amount of gas centrally concentrated in their discs if they are to show both lower yet substantial SFRs 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 discs (\( R_{\text{d}} \leq 0.2 \) \( R_{\text{d}} \)), then they appear to have rather low SFRs (\( < 1 \) \( M_{\odot} \) \( \text{yr}^{-1} \)) and high levels of dust extinction (\( a_{\text{d}} > 0.15 \)). For example, the model with \( f_{\text{g}} = 0.007 \) and \( R_{\text{d}} = 0.1 \) \( R_{\text{d}} \) shows \( b_{\text{d}}/a_{\text{d}} = 0.85 \) \( M_{\odot} \) \( \text{yr}^{-1} \) and \( a_{\text{d}} = 0.30 \). This result implies that if most of the gas in gas-poor disc galaxies (with \( f_{\text{g}} < 0.01 \)) can be fuelled to the nuclear regions and consumed rapidly there owing to some physical mechanism (e.g. galaxy–galaxy interaction), then such disc galaxies can be identified as passive spirals with nuclear star formation with higher degrees of dust extinction.

\section*{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 disc 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 discs, so that their gas disc becomes much more compact than their stellar disc (e.g. Abadi, Moore & Bower 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 discs, is more efficient in the outer parts of halos of disc galaxies in groups and clusters of galaxies (e.g. Bekki 2009). Thus it is possible that truncated gas discs can be formed as a result of halo and disc 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 ± 5 per cent versus 27 ± 5 per cent 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 disc gas into the inner regions of the galaxies (e.g. Noguchi 1988). Therefore, the bars in disc 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 discs has something to do with dynamical action of stellar bars in disc 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 SFR 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 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 disc 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+b/a spectra can be formed in dusty star-forming galaxies (e.g. Shioya & Bekki 2000; Bekki et al. 2001; Shioya, Bekki & Couch 2001), 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 modelling which allow us to predict the spectroscopic signature associated with star formation that proceeds in the inner regions of disc 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 cut-off (\( m_{\text{upp}} \)) of the initial mass function (IMF) is significantly smaller (e.g. \( < 20 \) \( M_{\odot} \)) in passive spirals. In this truncated IMF scenario, there are a few or no massive O stars that can ionize the ISM (i.e. \( > 20 \) \( M_{\odot} \)), 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 SFRs (Meurer et al. 2009). More quantitative investigation based on numerical simulations of disc 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-\( \mu \text{m} \) 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 disc 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 disc galaxy evolution, in particular, in groups and clusters of galaxies.

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