The evolution of interacting spiral galaxy NGC 5194

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ABSTRACT

NGC 5194 (M51a) is a grand-design spiral galaxy and undergoing interactions with its companion. Here, we focus on investigating main properties of its star formation history (SFH) by constructing a simple evolution model, which assumes that the disc builds up gradually by cold gas infall and the gas infall rate can be parameterizedly described by a Gaussian form. By comparing model predictions with the observed data, we discuss the probable range for free parameter in the model and then know more about the main properties of the evolution and SFH of M51a. We find that the model predictions are very sensitive to the free parameter and the model adopting a constant infall-peak time $t_p = 7.0$ Gyr can reproduce most of the observed constraints of M51a. Although our model does not assume the gas infall time-scale of the inner disc is shorter than that of the outer disc, our model predictions still show that the disc of M51a forms inside-out. We find that the mean stellar age of M51a is younger than that of the Milky Way, but older than that of the gas-rich disc galaxy UGC 8802. In this paper, we also introduce a ‘toy’ model to allow an additional cold gas infall occurred recently to imitate the influence of the interaction between M51a and its companion. Our results show that the current molecular gas surface density, the star formation rate and the UV-band surface brightness are important quantities to trace the effects of recent interaction on galactic star formation process.

Key words: galaxies: abundance – galaxies: evolution – galaxies: individual: M51a – galaxies: photometry – galaxies: spiral.

1 INTRODUCTION

M51a is one of the nearest galaxies with grand-design spiral arms. The outstanding point of this galaxy is that it is known to be interacting with its companion galaxy NGC 5195 (the interacting system NGC 5194 + NGC 5195 is often called as M51). Coupled with its large angular size, nearly face-on inclination, high surface brightness and kinematic complexity, many studies about M51a have been carried out using various wavelengths and methods.

With respect to dynamic study, M51a is a very good target to explore the nature and origin of spiral structure. Two opposite scenarios dominate the discussion in the literature. One theory considers that the spiral arms are a long lasting pattern that slowly evolves and rotates with a single angular speed (Lin & Shu 1964), while the other assumes the arms to be transient disturbances generated, e.g. by the tidal interaction with a companion (Toomre & Toomre 1972). In the seminal kinematic study of M51a, Tully (1974) identified the spiral pattern in the outer disc as transient feature, while the inner arms are thought to be in a steady state. Indeed, Colombo et al. (2014) showed the kinematic evidence of an $m = 3$ wave in the inner disc of M51a, which may suggest the density-wave nature of the main spiral structure of M51a. On the other hand, many kinematic and hydrodynamical models showed evidence that, instead of quasi-steady density wave, the internal structure of M51a drives from the complicated and dynamical interaction with its companion (Salo & Laurikainen 2000; Theis & Spinneker 2003; Dobbs et al. 2010).

In addition to its dynamics, M51a is also a test bed to understand the effects of galaxy interacting on its star formation (SF)
process by investigating its stellar populations. Early observations have already shown that the blue and yellow–red stellar populations within M51 are spatially separate structures (Zwicky 1955). Later investigations of star clusters in M51a revealed that the star cluster formation rate increased significantly during the period of 100–250 Myr ago, which is consistent with the epoch of the dynamic encounters of these two galaxies (Lee, Chandar & Whitmore 2005; Hwang & Lee 2008, 2010). Kaleida & Scowen (2010) also found that there was an enhancement in the number of young stellar associations in the northern arm closest to the companion, most likely triggered by the interaction of M51a and NGC 5195. Through the spectral energy distribution modelling of the multibands images of the M51 system, Mentuch Cooper et al. (2012) revealed a burst of SF occurred in both galaxies roughly 340–500 Myr ago, which is in agreement with the results of the colour–magnitude diagrams of individual stars (Tikhonov, Galazutdinova & Tikhonov 2009). Moreover, Lee et al. (2011) found evidence that the tidal interaction between M51a and its companion appeared to enhance the SF process at the tidal bridge connecting the two galaxies.

On the other hand, although the parametrized models have already been applied to several individual galaxies and proven to be fruitful tools to explore galactic formation and evolution (Tinsley 1980; Chang et al. 1999; Boissier & Prantzos 2000; Chiappini, Matteucci & Romano 2001; Yin et al. 2009; Chang, Shen & Hou 2012; Kang et al. 2012), there is still lack of similar investigation on M51a partially due to the complexity caused by the on-going interacting between M51a and its companion. In this paper, we construct a simple evolution model for M51a to build a bridge between its star formation history (SFH) and its observed properties, especially the radial distributions of cold gas surface density, metallicity, and the radial profiles of surface brightness in multibands. We present a parametrized description of the gas cooling process of the disc of M51a and adopt the local SF law in the model to calculate its star formation rate (SFR) using the cold gas surface density. Then, our model can predict the SFH, the chemical and colour evolution of M51a, with the help of stellar population synthesis (SPS) method. By comparing model predictions with the observed data, we can discuss the probable ranges for free parameters in the model and then know more about the main properties of the evolution and SFH of M51a.

The paper is structured as follows. Section 2 describes the observed features of M51a disc, including the surface brightness, the cold gas content, the SFR and the metallicity. In Section 3, we present the main assumptions and ingredients of our model in details. The comparisons between model predictions and observations and our main results are shown in Section 4. Our main conclusions are presented in Section 5.

2 OBSERVATIONS

M51a is one of the closest (the distance: $D \sim 8.0$ Mpc; Walter et al. 2008), face-on (inclination: $i \sim 20^\circ$; Tully 1974) SA(s)b spiral galaxy and many of its basic quantities have already been measured (Hu, Shao & Peng 2013). A summary of the main properties of M51a is shown in Table 1, most of which are adopted to constrain our model.

In this Section, we summarize the current available observations of M51a, especially the radial distributions along the disc, including the surface densities of gas mass and SFR, surface brightness and metallicity.

### Table 1. The main properties of M51a.

| Property          | Value          |
|-------------------|----------------|
| Hubble type       | SA(s)b         |
| Distance          | 8.0 Mpc        |
| Inclination       | 20$^\circ$     |
| $M_K$             | -24.19 mag     |
| Stellar mass      | $3.6 \times 10^{10}$ M$_\odot$ |
| H$_\alpha$ mass   | $2.8-3.9 \times 10^9 M_\odot$ |
| H$_2$ mass        | $2.52-7.1 \times 10^9 M_\odot$ |
| $f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\text{star}}}$ | $(0.13-0.23)$ |
| SFR$_\text{FUV+24\mu m}$ | $3.125 M_\odot$ yr$^{-1}$ |
| SFR$_\text{Ks}$   | $5.4 M_\odot$ yr$^{-1}$ |
| SFR$_{\text{RC-20\mu m}}$ | $2.56 M_\odot$ yr$^{-1}$ |

RefS: (1) NED; (2) Walter et al. (2008); (3) Tully (1974); (4) Jarrett et al. (2003); (5) Leroy et al. (2008); (6) Miyamoto, Nakai & Kuno (2014); (7) Kennicutt et al. (2003); (8) Schuster et al. (2007).

2.1 Radial profiles of surface brightness

The radial surface brightness profiles in multiband of a spiral galaxy contain fossil information about the SFH along the galactic disc and provide strong constraints on the models of galactic formation and evolution.

The catalogue data of the radial profiles of surface brightness for M51a in the ultraviolet bands (UV; Galaxy Evolution Explorer, GALEX for short), optical bands (Sloan Digital Sky Survey, SDSS for short), and near-infrared bands (NIR; Two-Micron All-Sky Survey, 2MASS for short) have been published by Muñoz-Mateos et al. (2009, MM09) hereafter, but all these values were only corrected for foreground Galactic extinction and still in lack of internal extinction correction. We adopt the method presented by Lin et al. (2013) to estimate the internal extinction profile in the FUV band $A_{\text{FUV}}$. Then, following the prescriptions of Boselli, Gavazzi & Sanvito (2003) and Cortese et al. (2008), we calculate the internal extinction in other wavelengths by assuming a given extinction law and a geometry for the distribution of stars and dust. The radial surface brightness profiles in FUV, NUV, u, g, r, i, z, J, H and K band are plotted in the left-hand side of Figs 3 and 4, where the open circles show the observed profiles only corrected for the Galactic extinction and the filled ones also include a correction for the radial variation of internal extinction.

The surface brightness in the K band has another application. Since the K-band luminosity is most sensitive to the old stellar population and less effected by dust attenuation than other bands, we adopt the K-band mass-to-light ratio to be $\Upsilon_\text{K}^*$ = 0.5 M$_\odot$/L$_\odot$K (Bell et al. 2003; Leroy et al. 2008), and then utilize the observed K-band surface brightness profile (MM09) to estimate the present-day stellar mass surface density profile $\Sigma(r, t_c)$, where $t_c$ is the cosmic age and we set $t_c = 13.5$ Gyr according to our adopted cosmology (see Section 3). We will use $\Sigma(r, t_c)$ derived here as our primary input parameter to constrain the total mass infalling to the disc.

2.2 Radial profiles of cold gas and SFR

During the past years, a number of data sets relating to the atomic and molecular gas surface density in M51a are becoming available.

In spirals, the CO line emissions are usually used to estimate the molecular gas mass surface density $\Sigma_{H_2}$. Imaging of molecular clouds has recently been carried out in M51a with the Berkeley-Illinois-Maryland Association (BIMA) interferometer using the CO $J = 1-0$ line transition (Helfer et al. 2003). Observations of the CO
The observed oxygen abundance profile of the M51a disc is shown in the bottom-right panel of Figs 3 and 4. The cycles represent the observed data obtained from Moustakas et al. (2010), where the open and filled circles are derived by the PT05 and KK04 calibration method, respectively. In the same panel, the data from Pilyugin et al. (2014) are shown as filled squares.

However, the true situation of the oxygen abundance gradient in the M51a disc is still not fixed. The main uncertainty comes from the calibration methods used to derive chemical abundance. In addition, the data might suffer from lack of large enough samples. In any case, a larger and homogeneous sample of H ii regions which spread the whole M51a disc is needed in order to have conclusive results about the real oxygen abundance gradients.

3 THE MODEL

Similar to previous models of the Milky Way (Chang et al. 1999; Chiappini et al. 2001; Matteucci et al. 2009) and other nearby disc galaxies (Boissier & Prantzos 2000; Mollá & Díaz 2005; Dalcanton 2007; Yin et al. 2009; Muñoz-Mateos et al. 2011; Chang, Shen & Hou 2012; Kang et al. 2012; Robles-Valdez, Carigi & Peimbert 2013), we assume that the M51a disc is progressively built up by the infall of primordial gas (X = 0.7571, Yp = 0.2429, Z = 0) from its dark matter halo. The disc is basically assumed to be sheet-like and composed of a series of independently evolved rings with width 500 pc, in the sense that no radial mass flows are considered.

Throughout this paper, we adopt the standard cold dark matter cosmology with H0 = 70 km s⁻¹ Mpc⁻¹, ΩM = 0.3, and ΩΛ = 0.7. Correspondingly, the cosmic time at z = 0 is 13.5 Gyr. The details and essentials of our model are described as follows.

3.1 Gas infall rate

We assume that there is a 1 Gyr time delay for the disc formation, which corresponds to z ~ 6 under the standard cosmology. After that, the disc originates and grows by continuous primordial gas infall from the dark matter halo. We adopt a Gaussian formula of the gas infall rate from Chang et al. (1999, 2012).

For the given radius r, the infall rate f_infall(r, t) (in units of M⊙ pc⁻² Gyr⁻¹) is assumed to be

\[ f_{\text{infall}}(r, t) = \frac{A(r)}{\sqrt{2\pi} \sigma} e^{-\left(t - \tau_p\right)^2/2\sigma^2}, \]

where \( t_p \) is the infall-peak time and \( \sigma \) is the full width at the half-maximum of the peak. The \( A(r) \) is a set of normalized quantities constrained by the stellar mass surface density at the present time \( \Sigma_*(r, t_p) \). To explore how \( t_p \) and \( \sigma \) regulate the shape of the gas infall rate, Fig. 1 plots the normalized gas infall rate (upper panel) and the corresponding total infall gas surface density (lower panel), which is defined as how many cold gas have already been cooled to the given ring at time \( t \) and normalized to 1 at the present time. Different line types correspond to various parameter groups \((t_p, \sigma)\). We select \( t_p = 0.1 \) Gyr and \( t_p = 15 \) Gyr to represent the extreme case which corresponds to a time-decreasing infall rate and a time-increasing one, respectively. It can be seen from Fig. 1 that the degeneracy of \( t_p \) and \( \sigma \) does exist in that the combination of small \( t_p \) and large \( \sigma \) results in a similar shape of mass accretion curve comparing that of large \( t_p \) and small \( \sigma \). Since our main aim is to investigate the main trend of SFH for M51a but not to find the exact values of free parameters, for the purpose of simplicity, we choose to reduce the...
The normalized quantities 
\[ \frac{t_0}{t_{2012}} = \frac{t_0}{t_{2010}} \neq \frac{t_0}{t_{2007}} = \frac{t_0}{t_{2001}} = \frac{t_0}{t_{2000}} \] 
respectively. It shows that the \( A(r) \) does vary with \( t_0 \). But we do not treat \( A(r) \) as free parameter in our model since it is roughly fixed for given \( t_0 \).

Regarding the stellar mass profile at the present time, in our previous works such as Chang et al. (2012) and Kang et al. (2012), we assumed that the stellar disc is a pure exponential disc and the value of \( \Sigma_\star(r, t_0) \) is constrained by the quantities of total stellar mass and radial scalelength, which are usually obtained from the observed radial profiles of surface brightness plus the exponential disc assumption. In this paper, we regard \( \Sigma_\star(r, t_0) \) as a set of individual quantities and can be directly estimated from the observed radial profile of \( K \)-band surface brightness by adopting a constant mass-to-light ratio (see Section 2.1 for details). Since this method includes much more spatial structures than the previous ones, it permits us to more reasonably calculate the multiband radial profiles of surface brightness and compare with the observations in details.

### 3.2 Star formation law

SF process plays an important role in regulating the evolution of galaxies. Unfortunately, the SF process is so complicated that its underlying physical nature is still not completely understood (Kennicutt et al. 2007). Most models of the galactic evolution still rely on the empirical SF law, which connects the local cold gas surface density to the SFR surface density, to describe how much cold gas converts into stellar mass in each time step (Boissier & Prantzos 2000; Chiappini et al. 2001; Yin et al. 2009; Chang et al. 2012; Kang et al. 2012).

Based on the observed data of a sample of 97 nearby normal and starburst galaxies, Kennicutt (1998) found a power-law correlation between the galaxy-averaged SFR surface density and the galaxy-averaged total gas surface density, which was termed as the classical Schmidt–Kennicutt SF law and widely adopted in the studies of galactic formation and evolution. But a more fundamental way is to use spatially resolved measurements of the SFR and gas surface density to examine the correlations between the observables on a point-by-point basis within galaxies. Indeed, the studies of the spatially resolved SF law have been applied to several nearby spiral galaxies (Kennicutt et al. 2007; Bigiel et al. 2008; Leroy et al. 2009).
we adopted the SF law of M51a presented by Kennicutt et al. (2007):  
\[
\Psi(r, t) = 0.048 \Sigma_{gas}(r, t)^{1.56},
\]
where \(\Psi(r, t)\) (in units of \(\text{M}_\odot\text{ pc}^{-2}\text{ Gyr}^{-1}\)) is the SFR surface density, and \(\Sigma_{gas}(r, t)\) (in units of \(\text{M}_\odot\text{ pc}^{-2}\)) is the gas surface density, which is the sum of the surface density of the atomic and molecular gas. We assume that \(\Sigma_{gas}(r, t) = 1.36(\Sigma_{HI}(r, t) + \Sigma_{H2}(r, t))\), where \(\Sigma_{HI}(r, t)\) and \(\Sigma_{H2}(r, t)\) are the surface density of atomic and molecular hydrogen, and the factor 1.36 is to reflect the contribution of helium.

Regarding the ratio of molecular-to-atomic gas surface density \(R_{out}(r, t)\), we adopt the formula presented by Blitz & Rosolowsky (2006) and Leroy et al. (2008),  
\[
R_{out}(r, t) = \frac{\Sigma_{HI}(r, t)}{\Sigma_{H2}(r, t)} = \frac{P_h(r, t)}{P_0} e^{\alpha_p r},
\]
where \(P_h(r, t)\) is the mid-plane pressure of the interstellar medium (ISM), \(P_0\) and \(\alpha_p\) are constants derived from the observations. We adopt \(P_0/k = 1.92 \times 10^9\text{ cm}^2\text{ K}\) and \(\alpha_p = 0.87\) derived by Hirschfeld et al. (2009) for M51a.

The mid-plane pressure of the ISM in disc galaxies can be expressed as (Elmegreen 1989; Leroy et al. 2008)  
\[
P_h(r, t) = \frac{\pi}{2} G \Sigma_{gas}(r, t) \left[ \Sigma_{gas}(r, t) + \frac{c_{gas}^2}{c_s^2} \Sigma_s(r, t) \right],
\]
where \(G\) is the gravitational constant, and \(c_{gas}\) and \(c_s\) are the (vertical) velocity dispersions of gas and stars, respectively. Observations reveal that \(c_{gas}\) is a constant along the disc and we adopt \(c_{gas} = 11\text{ km s}^{-1}\) (Ostriker, McKee & Leroy 2010), but \(c_s\) is estimated as \(c_s = \sqrt{\frac{\pi G M}{2 z_0}}\), where \(z_0\) is the scaleheight of the disc and we adopt \(z_0 = 1.0\text{ kpc}\) (Hirschfeld et al. 2009).

### 3.3 Other ingredients and basic equations

We also take into account the contribution of the gas outflow process in our model. According to the mass-dependent model of Chang et al. (2010), we assume that the gas outflow rate is proportional to the SFR and the coefficient is set to be \(b_{out} = 0.004\). It should be emphasized that our final results is not sensitive to the variation of \(b_{out}\) since the outflow process plays a relatively small role in the chemical evolution of such a massive galaxy as M51a (the stellar mass of M51a is about \(M_\star = 10^{10.7}\text{ M}_\odot\)).

We adopt the updated SPS model of Bruzual & Charlot (2003) (i.e. CB07) with the stellar initial mass function (IMF) being taken from Chabrier (2003) in our work. The lower and upper mass limits are adopted to be 0.1 \(\text{M}_\odot\) and 100 \(\text{M}_\odot\), respectively.

Regarding the chemical evolution of the disc of M51a, both the instantaneous recycling approximation and the instantaneous mixing of the gas with ejecta are assumed, that is, the gas in a fixed ring is characterized by a unique composition at each epoch of time. We take the classical set of equations of galactic chemical evolution from Tinsley (1980):  
\[
\frac{\text{d}[\Sigma_{gas}(r, t)]}{\text{d}t} = f_{in}(r, t) - f_{out}(r, t),
\]
where 
\[
\frac{\text{d}[Z(r, t)\Sigma_{gas}(r, t)]}{\text{d}t} = \frac{\pi}{2} G \Sigma_{gas}(r, t) \left[ \Sigma_{gas}(r, t) + \frac{c_{gas}^2}{c_s^2} \Sigma_s(r, t) \right],
\]
and 
\[
\frac{\text{d}[\Sigma_{gas}(r, t)]}{\text{d}t} = (1 - R)\Psi(r, t) + f_{in}(r, t) - f_{out}(r, t),
\]
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Comparisons of the radial profiles between model predictions and observations. The dashed and dotted lines are corresponding to the model results adopting $t_p = 0.1$ Gyr and $t_p = 15$ Gyr, respectively. In the left-hand panels, the open circles show the observed profiles only corrected for the Galactic extinction and the filled ones also include a correction for the radial variation of internal extinction. The observed data of radial distributions of molecular, atomic, and total gas mass surface density shown in panels of the right-hand side are taken from Schuster et al. (2007, filled circles), Kennicutt et al. (2007, filled triangles), Leroy et al. (2008, asterisks) and Miyamoto et al. (2014, filled diamonds), and the SFR surface density obtained from Schuster et al. (2007, filled circles), Heesen et al. (2014, filled pentagons), Leroy et al. (2008, asterisks) and Kennicutt et al. (2007, filled triangles) are displayed in the right-fourth panel. The observed oxygen abundances taken from Pilyugin et al. (2014) are shown as filled squares in the bottom-right panel, while the data taken from Moustakas et al. (2010) are plotted as open and filled circles corresponding to be derived by the PT05 and KK04 calibration method, respectively.

Interestingly, we can see from Fig. 3 that the area between the dashed and dotted lines brackets almost the whole region of the observations, which indicates that it is possible to construct a model that can reproduce the main features of the observations of the M51a disc. In fact, these two extreme cases ($t_p = 0.1$ Gyr and $t_p = 15$ Gyr) are bracketing the possible range of our model results, from where we can see the variation trends of the model predictions with different value of $t_p$. After a series of calculations and comparisons, we obtain a viable model by adopting the infall-peak time $t_p/Gyr = 7.0$ and plot its results as solid lines in Fig. 4.

The notation of observed data is the same as that of Fig. 3. We can see from Fig. 4 that the solid lines can basically reproduce most of the observational data, which indicates that our viable model includes and describes reasonably the key ingredients of the main processes that regulate the formation and evolution of M51a.

To further understand the effect of $t_p$ on the evolution of M51a, Table 2 summarizes the model predictions of the present total quantities of M51a, including the absolute $K$-band magnitude $M_K$, the
Figure 4. Comparisons of the model predictions with the observations. The solid lines plot the viable model results, while the dashed lines represent the ‘toy’ model results. The notation of the observational data is the same as that of Fig. 3.

Table 2. The model predictions of the total quantities of M51a with different parameters.

| $t_p$ (Gyr) | $M_K$ (mag) | $M_{H_2}$ ($10^9 M_\odot$) | $M_{HI}$ ($10^9 M_\odot$) | SFR ($M_\odot$ yr$^{-1}$) | $f_{gas}$ |
|------------|-------------|---------------------------|---------------------------|---------------------------|-----------|
| 0.1        | -24.17      | 1.86                      | 2.16                      | 1.04                      | 0.07      |
| 7.0        | -24.84      | 6.92                      | 2.96                      | 5.02                      | 0.17      |
| 15.0       | -26.08      | 38.22                     | 3.21                      | 49.75                     | 0.46      |

molecular gas mass $M_{H_2}$, the atomic gas mass $M_{HI}$, SFR and the gas fraction $f_{gas}$. Three different values of $t_p$ (0.1, 7.0, 15Gyr) are considered, which corresponds to the dashed, dotted lines in Fig. 3 and solid lines in Fig. 4. It can be seen from Table 2 that the model adopting a later infall-peak time predicts higher SFR and higher gas fraction. The predictions of the viable model adopting $t_p$/Gyr = 7.0 are in fairy agreement with the corresponding physical properties in Table 1 considering the observed uncertainties.

However, it can be seen from Fig. 4 that, contrary to the smoothness of the model predictions, the observed radial profiles of cold gas and SFR surface density show peaks at $R_G \sim 6$ kpc and the location of these peaks coincide with the location of the most active SF region in the disc of M51a (Scheepmaker et al. 2009). In addition, bumps obviously appear on the surface brightness radial profiles in the FUV, NUV and u band, and the intensity of the bump decreases gradually with the increase of the wavelength, which suggests that active SF process may take place in recent years around there.

Indeed, both kinematic and hydrodynamic modelling suggest that single or multiple encounters between these two galaxies are occurred 300–500 Myr ago (Salo & Laurikainen 2000; Thies & Spinneker 2003; Dobbs et al. 2010). Studies of stellar populations of M51a also revealed that a burst of SF occurred 340–500 Myr ago (Tikhonov et al. 2009; Mentuch Cooper et al. 2012). Moreover, Miyamoto et al. (2014) found that the local maximum at $R_G \sim 6$ kpc on the radial profiles of cold gas in M51a could be caused by
the kinks or fractures of the spiral arms by the interaction with its companion galaxy.

Correspondingly, we present a ‘toy’ model to imitate the influence of the interaction between M51a and its companion by allowing an additional cold gas infall (with constant rate $8.31 \, \text{M}_\odot \, \text{yr}^{-1}$) to the disc occurred recently (during the period $13.0 \leq t / \text{Gyr} \leq 13.2$) round the region $R_G \sim 6 \, \text{kpc}$. Other ingredients of the model are the same as those of the viable model. The results of the ‘toy’ model are shown by dashed lines in Fig. 4. It can be seen that the freshly infalling cold gas increases the mass surface density of both the molecular gas and the SFR, while has little effect on the atomic surface density and the gas-phase oxygen abundance. Moreover, the additional gas infall results in more luminous surface brightness in FUV, NUV and $u$ band, while the surface brightness in optical and near-infrared bands is less effected. Our results suggest that the molecular gas surface density, the SFR and the UV-band luminosity are important quantities to explore the effects of recent interaction on galactic SF process.

4.2 Stellar populations along the disc

To further explore the properties of stellar population along the disc of M51a, we select four regions out and plot their viable model predictions of the SFHs and growth curves of stellar masses in Fig. 5, including 1–2 kpc (dashed line), 4–5 kpc (dotted line), 7–8 kpc (dash–dotted line), 10–11 kpc (solid line). Correspondingly, Fig. 6 displays their metallicity distribution function predicted by the viable model. Note that both the SFRs and stellar masses in Fig. 5 are normalized by their present-day values, and the horizontal dash–dotted line in the lower panel of Fig. 5 denotes the position that each component achieves 50 per cent of its final value.

Fig. 5 shows that the SFRs in the whole disc are very low at early stage and increase gradually due to the increase of gas infall rate. When the consumption rate of cold gas to form new stars is roughly balanced by the gas infall rate, the SFR reaches its peak and then drops down to its present-day value. It is interesting to see that the peak of the SFH moves gradually to later time from the inner to outer parts of disc. Moreover, Fig. 6 reveals that the inner disc contains a higher percentage of metal-rich stars than the outer disc. In other words, our model predictions show evidences that the disc forms inside-out. We will discuss this point again in next subsection.

4.3 Comparisons with the Milky Way and UGC 8802

The Milky Way and UGC 8802 are two disc galaxies containing comparable stellar mass with M51a, and we have already investigated SFHs of the two galaxies in previous works (Chang et al. 1999, 2012). In this section, we will compare the growth history of M51a predicted by the viable model with that of the Milky Way and UGC 8802. We referred to Chang et al. (1999, 2012) for a more indepth description of the models. Here, we only repeat main ingredients of the models such as the gas infall rate and the SF law, and present a summary of the models in Table 3.

In our previous models of the Milky Way and UGC 8802, a Gaussian formula of gas infall rate has been adopted. The input condition of UGC 8802 to constrain how much gas infalling to the disc is the stellar mass surface density at the present day, which is assumed to be pure exponential $\Sigma_*(r, t_0) = 93.7 \, \text{e}^{-r/\text{r}_{d,0}}$, with radial scalelength $r_{d,0} = 5.8 \, \text{kpc}$ (Chang et al. 2012). In the case of the Milky Way, the input parameter to constrain the gas infall rate is the total (gas+star) mass surface density at the present day, i.e.
(ii) The model adopting a constant infall-peak time, the model predictions also support the disc inside-out formation scenario. This trend also reinforces the recent analysis of the SFH of CALIFA galaxies, which shows that galaxies more massive than $10^{10}$ M⊙ grow inside-out (Pérez et al. 2013; González Delgado et al. 2014). In fact, this inside-out formation mechanism has already successfully applied to previous models of formation and evolution of disc galaxies (Chang et al. 1999, 2012; Boissier & Prantzos 2000; Hou et al. 2000; Chiappini et al. 2001; Yin et al. 2009; Kang et al. 2012) and supported by the observations for nearby disc galaxies (Muñoz-Mateos et al. 2007; Pérez et al. 2013).

### Table 3. A summary of the viable models for M51a, UGC 8802 and the Milky Way.

| Individual | M51a | UGC 8802 | Milky Way |
|------------|------|----------|-----------|
| Input properties | | | |
| $\mu_c$ | 0.048 | 55.0 e$^{-\left(r-r_c\right)/\Upsilon_L}$ | 55.0 e$^{-\left(r-r_c\right)/\Upsilon_L}$ |
| $\Upsilon_K$ | $0.5 \Sigma_{\odot}/L_{\odot}$ | $\Upsilon_K$ | $\Upsilon_K$ |
| $r_{d,\odot}$ | 5.8 kpc | $r_{d,\odot}$ | $r_{d,\odot}$ |
| SF law | $\Psi(r, t) = 0.048 \Sigma_{\text{gas}}(r, t)^{1.56}$ | $\Psi(r, t) = 0.048 \Sigma_{\text{gas}}(r, t)^{1.56}$ | $\Psi(r, t) = 0.048 \Sigma_{\text{gas}}(r, t)^{1.56}$ |
| Infall-peak time $t_p$ (Gyr) | 7.0 | $1.5 r/r_{d,\odot} + 5.0$ | 2.0 $r/r_{d,\odot}$ |

**Notes.**
(a) The observed K-band surface brightness profile taken from Muñoz-Mateos et al. (2009).
(b) The $K$-band mass-to-light ratio taken from Bell et al. (2003) and Leroy et al. (2008).
(c) $r_{\odot}$ is the solar Galactic radius, and $r_{d,\odot}$ is the disc scalelength of UGC 8802 (Chang et al. 2012).
(d) $\Upsilon_L$ is the disc scalelength of UGC 8802 (Chang et al. 2012).

The infall-peak time increases with radius (see Table 3), it is natural to see that both the dotted and dashed lines increase with time. In the case of M51a, although the model adopt a constant inflall-peak time, the model predictions also support the disc inside-out formation scenario. This trend also reinforces the recent analysis of the SFH of CALIFA galaxies, which shows that galaxies more massive than $10^{10}$ M⊙ grow inside-out (Pérez et al. 2013; González Delgado et al. 2014). In fact, this inside-out formation mechanism has already successfully applied to previous models of formation and evolution of disc galaxies (Chang et al. 1999, 2012; Boissier & Prantzos 2000; Hou et al. 2000; Chiappini et al. 2001; Yin et al. 2009; Kang et al. 2012) and supported by the observations for nearby disc galaxies (Muñoz-Mateos et al. 2007; Pérez et al. 2013).

#### 5 SUMMARY

M51a is a grand-design spiral galaxy and well known to be interacting with its companion. In this paper, we focus on investigating the SFHs of M51a by constructing a parametrized model and comparing model predictions with the observed data, especially the radial distributions of cold gas surface density, metallicity, and the radial profiles of surface brightness in multibands. Our main results can be summarized as follows.

(i) Our results show that the model predictions are very sensitive to the adopted infall-peak time $t_p$. A late infall-peak time $t_p$ results in more luminous surface brightness, low metallicity, high gas and SFR surface densities.

(ii) The model adopting a constant infall-peak time $t_p = 7.0$ Gyr can nicely reproduce most of the observed constraints of M51a. We also introduce a ‘toy’ model, which allows a small amount of additional cold gas infall to the disc in recent time, to imitate the influence of the interaction between M51a and its companion. Our results show that the additional gas infall could be attributed to the observed small bumps on the radial profiles of cold gas surface density, SFR surface density and surface brightness in the UV band.

(iii) Although we adopt a constant infall-peak time, our model predictions still show evidence that the disc forms inside-out. This is consistent with the results of Pérez et al. (2013) and González Delgado et al. (2014) that galaxies more massive than $10^{10}$ M⊙ grow inside-out.

(iv) We also compared the model predicted growth histories of M51a, the Milky Way and UGC 8802. We find that the mean stellar age of M51a is younger than that of the Milky Way, but older than that of the gas-rich disc galaxy UGC 8802. Our results also show that half of the total stellar mass of M51a may has been assembled during the last $\sim$5.0 Gyr and SF may still proceed actively in the disc of M51a.
Evolution of interacting spiral galaxy M51a

Figure 7. The growth history of M51a, UGC 8802 and the Milky Way predicted by their individual viable models. The upper panels plot the model predicted time evolution of $M_\star$ (left-hand panel) and $M_{H_\text{I}}$ (right-hand panel) of the three galaxies, The growth history of $M_{H_\text{II}}$ and the SFHS are displayed in the middle-left and middle-right panels, respectively. The model predicted evolution of the half-mass size $R_{50,\star}$ is displayed in the bottom-left panel. Each quantity is normalized to its value at the present day. The different line types correspond to different galaxies: solid lines for M51a, dashed lines for UGC 8802, and dotted lines for the Milky Way.

We emphasize that here we only present a parametrized model. Through the comparison between model predictions and observations, our ultimate goal is to present our story of the main properties of the formation and evolution of M51a. Although the accurate value of $t_p$ in the viable model is not unique, the main conclusions of our results are robust. However, since M51a belongs to a dynamically complicated system and maintains grand-designed spiral structure, it is a long way to go to clearly understand its origin and evolution.

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