The evolution and star-formation history of M33

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ABSTRACT

We construct a parametrized model to explore the main properties of the star-formation history of M33. We assume that the disc originates and grows by primordial gas infall and adopt a simple form of gas accretion rate with one free parameter, the infall time-scale. We also include the contribution of the gas outflow process. A major update of the model is that we adopt a molecular-hydrogen-correlated star-formation law and calculate the evolution of the atomic and molecular gas separately. Comparisons between the model predictions and observational data show that the model predictions are very sensitive to the adopted infall time-scale, while the gas-outflow process mainly influences the metallicity profile. A model adopting a moderate outflow rate and an inside-out formation scenario can be in good agreement with most of the observed constraints of the M33 disc. We also compare model predictions based on a molecular-hydrogen-correlated star-formation law and that based on the Kennicutt star-formation law. Our results imply that the molecular-hydrogen-correlated star-formation law should be preferred to describe the evolution of the M33 disc, especially the radial distributions of both the cold gas and the stellar population.

Key words: galaxies: abundances – galaxies: evolution – galaxies: individual: M33 – galaxies: spiral.

1 INTRODUCTION

The NGC 598 (M33) galaxy is a low-luminosity, late-type disc galaxy in the Local Group. M33 is observed to be much smaller and less massive than the Milky Way galaxy, but has a much larger gas fraction. It also shows no signs of recent mergers and no presence of a prominent bulge and bar component (Regan & Vogel 1994; McLean & Liu 1996). In addition, due to its proximity, large angular size and rather low inclination, M33 is an excellent target for detailed observations of its cold gas, metallicity, star-formation rate (SFR) and stellar population, and thus provides an excellent chance to test models of galactic chemical evolution. The star-formation (SF) law is one of the important ingredients of the model. 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 ($\Psi (r, t)$) and the galaxy-averaged total gas surface density ($\Sigma_{gas}(r, t)$), which was termed the classical Kennicutt SF law. Later, observations of high spatial resolution (less than kpc-scale regions) showed that the SFR surface density correlated more strongly with the surface density of molecular hydrogen ($\Sigma_{HI}(r, t)$) than with that of atomic hydrogen ($\Sigma_{HI}(r, t)$) and the total gas (Wong & Blitz 2002; Kennicutt et al. 2007; Bigiel et al. 2008; Leroy et al. 2008). It was also shown that the SFR surface density is almost proportional to $\Sigma_{HI}(r, t)$:

$$\Psi (r, t) = \frac{\Sigma_{HI}(r, t)}{t_{dep}},$$  

(1)

where $t_{dep}$ is the molecular hydrogen depletion time. Hereafter, equation (1) is called the $\Sigma_{HI}$-based SF law in this paper.

Moreover, the gas-outflow process may influence the evolution of M33. Garnett (2002) concluded that a spiral galaxy with $V_{out} \leq 125$ km s$^{-1}$ may lose some amount of gas in supernova-driven winds and Tremonti et al. (2004) also confirmed this conclusion. The results of Chang et al. (2010) indicated that the gas-outflow process plays an important role in the chemical evolution of the disc galaxy, since it can bring part of the newly formed metal off the galactic disc. They show that a model assuming that gas outflow efficiency

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increases as stellar mass decreases can explain the observed mass–metallicity relation.

The chemical evolution of M33 has been studied by several groups in previous studies (Mollá, Ferrini & Díaz 1996; Magrini, Corbelli & Galli 2007a; Marcon-Uchida, Matteucci & Costa 2010). Magrini et al. (2007a) found that a model adopting an almost constant gas-infall rate can reproduce some of the observed properties of M33, especially the observed relatively high SFR and the shallow abundance gradients. Marcon-Uchida et al. (2010) compared the chemical evolution of the Milky Way, M31 and M33. They found that the model predictions of the Milky Way and M31 were in good agreement with the main features of the observations, while the model of M33 failed to reproduce the present-day gas surface density in the inner disc. The oxygen abundance was also overestimated by 0.25 dex in the whole disc of M33.

In this paper, we build a bridge between the observed data of M33 and its star-formation history (SFH) by constructing a parametrized model of its formation and evolution. A major update of the model is that we adopt a $\Sigma_{H_2}$-based SF law and this may be the first time a model of M33 has calculated separately the evolution of atomic and molecular gas.

This paper is organized as follows. Section 2 describes the observed features of the M33 disc, including the surface brightness, SFR, cold gas content, metallicity, etc. The main assumptions and ingredients of our model are presented in Section 3. Comparisons between model predictions and observations are shown in Section 4 and Section 5 summarizes our main conclusions.

2 THE OBSERVATIONS

In this section, we summarize the current available observations of the M33 galaxy, especially the radial distributions along the disc, including the surface densities of gas and SFR, surface brightness, colour and metallicity. Our model predictions will be compared with all these observed trends.

2.1 Surface brightness and radial distribution of colours

The surface brightness observed in multi-bands of a galaxy contains important information about its SFH. For example, since the surface brightness in the far-ultraviolet (FUV) band is very sensitive to the presence of recent SF activity and that in the near-infrared $K$ band strongly correlates with the accumulated SF in the galaxy, the observed radial distribution of FUV−$K$ colour provides tight constraints on the specific SFR of the galaxy.

Muñoz-Mateos et al. (2007) derived M33’s azimuthally averaged radial profiles in FUV−$K$ colour by using Galaxy Evolution Explorer (GALEX) UV-band surface brightness (Gil de Paz et al. 2007) and a deep Two-Micron All-Sky Survey (2MASS) image ($K < 21$ mag arcsec$^{-2}$). We show the measured FUV-band and $K$-band surface brightness as well as the FUV−$K$ colour profiles from Muñoz-Mateos et al. (2007) in Fig. 1. In the upper panel, we plot the surface brightness of FUV and $K$ bands as crosses (red in the online article), which have been corrected only for Galactic extinction. The lower panel shows radial profiles of FUV−$K$ colour: the open circles (cyan in the online article) have only been corrected for Galactic extinction and the filled circles (yellow in the online article) have been corrected for both Galactic and internal extinction. It can be seen from Fig. 1 that the negative gradient (after the extinction correction) implies an inside-out formation process, i.e. the stellar populations become relatively blue and young as radius increases.

The disc scalelength $r_d$ can be obtained from the radial profile, but it has some complexity since it is not only dependent on wavelength but also related to what we refer: gas disc, stellar disc or a total. Based on the surface-brightness profiles in the $B$ and $K$ bands, Regan & Vogel (1994) derived stellar scalelengths of 1.9 and 1.4 kpc respectively, while the CO (representing the molecular hydrogen distribution) radial scalelength is about 2.5 kpc (Corbelli 2003), larger than that of the stellar disc. Where the total gas mass surface density ($\Sigma_{H_2} + \Sigma_{HI}$) is concerned, the resulting scalelength is much larger (Corbelli 2003; Magrini et al. 2007a). In Table 1, we list the scalelengths for different disc components of M33. In general, the $K$-band luminosity reflects the stellar profile: a smaller value of $r_{d,K}$ implies that the stellar disc is more concentrated than the gas disc. In this paper we will adopt $r_d = 1.4$ kpc (Regan & Vogel 1994). The total stellar mass of M33 is estimated to be $\sim(3.0–6.0) \times 10^9 M_\odot$ (Corbelli 2003).

2.2 Profiles of cold gas, SFR and gas depletion time

During the past years, a number of data sets relating to the atomic and molecular gas distributions in M33 are becoming available. Imaging of molecular clouds has recently been carried out in M33 with the Berkeley–Illinois–Maryland Association (BIMA) interferometer and with the Five College Radio Astronomy Observatory (FCRAO) 14-m telescope using the CO $J = 1 – 0$ line transition (Corbelli 2003; Engargiola et al. 2003; Heyer et al. 2004; Verley et al. 2009). M33 was also observed by the Institute de RadioAstronomie Millimétrique (IRAM) 30-m telescope using the CO $J = 2 – 1$ line transition (Gardan et al. 2007; Gratier et al. 2010). The observed radial profiles of $H_2$ surface density are plotted in the top panel of Fig. 2, where the data are taken from Corbelli (2003) (filled triangles, green in the online article), Heyer et al. (2004) (filled squares, cyan in the online article), Verley et al. (2009) (filled
The cold gas distribution is tightly correlated with the distribution of the SFR. Several groups have already measured the SFR in several regions along the disc of M33 using different tracers, including Hα emission and luminosity in the FUV and far-infrared (FIR) bands (Engargiola et al. 2003; Hippelein et al. 2003; Heyer et al. 2004; Boissier et al. 2007; Gardan et al. 2007; Verley et al. 2009). The observed data of the radial distribution of SFR surface densities are plotted in the middle panel of Fig. 2. The data taken from Heyer et al. (2004) and Boissier et al. (2007) are shown by filled squares (FIR, cyan in the online article) and empty triangles (FUV, yellow in the online article), respectively. The data taken from Verley et al. (2009) are represented by empty pentagons (24 μm, red in the online article), asterisks (Hα, red in the online article), five-pointed stars (FUV, red in the online article) and filled pentagons (FIR, red in the online article).

Since the observed SFR surface density ψ(r, t) and the molecular hydrogen surface density S_{HI}(r, t) are both available, it is easy to estimate the molecular gas depletion time t_{dep} according to the S_{HI}-based SF law. In practice, we first divide the observed data along the disc of M33 into 16 bins. Then, we calculate the mean values of both ψ(r, t) and S_{HI}(r, t) in each bin in logarithmic coordinates and show them as filled squares with error bars in the top and middle panels of Fig. 2, where the error bars represent the distribution dispersion in each bin. Using the mean values obtained, we calculate the molecular gas depletion time in each bin through t_{dep} = S_{HI}(r, t)/ψ(r, t) (according to the S_{HI}-based SF law) and plot them in the bottom panel of Fig. 2 as filled squares with error bars. It can be seen that t_{dep} is almost constant along most of the disc except in the outer region (r > 4σ1), where t_{dep} increases gradually as galactic radius increases. For the purpose of simplicity, we adopt the mean value of molecular gas depletion time and fix t_{dep} = 0.43 Gyr throughout this work.

The reciprocal quantity of the molecular gas depletion time 1/t_{dep} of a galaxy correlates to its star-formation efficiency (SFE), which describes the proportion of molecular gas turned into stellar mass in unit time. Leroy et al. (2008) explored the SFEs of 23 nearby galaxies and estimated that the average value of 1/t_{dep} is about 1.9 Gyr in large spirals. However, the case of M33 is slightly different. Gardan et al. (2007) found that M33 was more efficient in forming stars than large spirals in the local Universe and the molecular depletion time was about 0.11–0.32 Gyr. Gratier et al. (2010) also concluded that the SFE of M33 appeared to be 2–4 times higher than that observed in massive spiral galaxies. Our results of Fig. 2 also suggest that the SFE of M33 is almost constant along the disc and higher than the average value of SFE of large spirals investigated by Leroy et al. (2008).

The H\textsc{i} surface density profile has been derived from high-sensitivity observations with the Westerbork Synthesis Radio Telescope (WSRT)+Effelsberg 100-m (Deul & van der Hulst 1987), Arecibo (Corbelli & Schneider 1997; Putman et al. 2009) and Very Large Array (VLA) B, C and D (Gratier et al. 2010).

2.3 Disc abundance gradients

The abundance gradient is an essential ingredient in an accurate picture of galaxy formation and evolution. The existence of abundance gradients along the Milky Way has been proved by observations during the past 20 years using different tracers. Oxygen or/and iron abundance gradients about ~0.06 to ~0.07 dex kpc^{-1} were obtained by using various tracers, such as H\textsc{i} regions, B stars (see Rudolph et al. 2006 and references therein), planetary nebulae (PNe: Maciel, Lago & Costa 2006) and open clusters (Chen, Hou & Wang 2003; Chen et al. 2008). A radius-dependent SFR and an infall model with a disc formed by ‘inside-out’ scenarios could well reproduce the above gradients (Matteucci & Francois 1989; Boissier & Prantzos 1999; Hou, Prantzos & Boissier 2000; Chiappini, Matteucci & Romano 2001; Fu et al. 2009; Yin et al. 2009).

Nevertheless, the abundance gradients for different elements are different and the exact gradient value, especially its time evolution, for the Milky Way disc is still not very certain. This has prevented formation of a clear constraint for chemical evolution models. Therefore it is very important to have more data from extragalactic galaxies. Indeed, abundance gradients have been found in many other spiral galaxies (Zaritsky, Kennicutt & Huchra 1994). At present, the best studied extragalactic galaxies for abundance are M101 (Kennicutt, Bresolin & Garnett 2003), M31 and M33 (Rosolowsky & Simon 2008; Magrini et al. 2007b); this was achieved by observing a large sample of H\textsc{i} regions and young stars in their discs.
Figure 2. Observed profiles of the surface density of H$_2$ and SFR and the molecular gas depletion time for the M33 disc. Top panel: current surface-density profiles of H$_2$. Middle panel: current surface-density profiles of SFR. The mean values of both $\Psi(r, t)$ and $\Sigma_{H_2}$ in each bin are shown as filled squares with error bars, where the error bars represent the distribution dispersion in each bin. Bottom panel: the filled squares are the molecular gas depletion time estimated according to the $\Sigma_{H_2}$-based SF law and the error bars also represent the distribution dispersion in each bin. The observed data are described in detail in Section 2.2.

The observed abundance gradient of H II regions in M33 has been obtained by several authors. The first quantitative spectroscopic studies were carried out by Smith (1975), Kwitter & Aller (1981) and Vilchez et al. (1988). These observations, which were limited to the brightest and largest H II regions, implied a steep radial oxygen gradient of about $-0.1$ dex kpc$^{-1}$. Using the data from previous observations with derived electron temperatures, Garnett et al. (1997) re-determined the radial oxygen abundance and obtained an overall oxygen gradient of $-0.11 \pm 0.02$ dex kpc$^{-1}$, including the central regions of M33. Recent studies, such as those of Crockett et al. (2006), Magrini et al. (2007b, hereafter M07b), Rosolowsky & Simon (2008, hereafter RS08) and Magrini et al. (2010), seemed to converge to much shallower gradients, deriving the radial oxygen gradients as $-0.012 \pm 0.011$, $-0.054 \pm 0.011$, $-0.027 \pm 0.012$ and $-0.044 \pm 0.009$ dex kpc$^{-1}$, respectively.

Using PNe spectroscopy, Magrini et al. (2004) measured the element abundances of 11 PNe in M33. Magrini et al. (2007a, hereafter M07a) derived an oxygen radial gradient of $-0.11 \pm 0.04$ dex kpc$^{-1}$, while Magrini, Stanghellini & Villaver (2009, hereafter M09) presented a new result of $-0.031 \pm 0.013$ dex kpc$^{-1}$ from 91 PNe in M33. Adding their observed data of 16 PNe to the sample of 32 (out of 91) for M09, Bresolin et al. (2010) obtained an oxygen radial gradient of $-0.013 \pm 0.016$ dex kpc$^{-1}$ from this combined sample.

Abundance gradients in the M33 disc have also been estimated from B-type giants: for example, Monteverde et al. (1997) derived an oxygen radial gradient of $-0.16 \pm 0.06$ dex kpc$^{-1}$ and Urbaneja et al. (2005) obtained an oxygen radial gradient of $-0.06 \pm 0.02$ dex kpc$^{-1}$.

Clearly, the true situation of the abundance gradient in the M33 disc is still not fixed. Optical line spectroscopy is mainly concentrated on B stars and H II regions. The main uncertainty comes from the empirical calibrations used to derive electron temperatures in the nebula. Also, the stellar data suffer from lack of a large enough sample and the derived abundance gradient depends on the distance ranges. In any case, a larger and more homogeneous sample of H II regions that spreads over the whole M33 disc is needed in order to achieve conclusive results about the real gradients. Such a project...
is currently being undertaken by a couple of groups (Magrini et al. 2007b; Rosolowsky & Simon 2008).

In Table 2, we present most currently available oxygen abundance gradient measurements for the M33 disc. We plot the oxygen abundance observed in PNe, H II regions and B-type supergiants along the disc in Fig. 3. The observed data derived through PNe are denoted by open circles, where the 32 (out of 91) open circles coloured red in the online article are taken from Bresolin et al. (2010). The open squares represent the observed data obtained through H II regions, where the open squares coloured blue, cyan, green, yellow, magenta and red in the online article, respectively, are taken from RS08, M07b, Vilchez et al. (1988), Kwitter & Aller (1981), Crockett et al. (2006) and Bresolin et al. (2010). In addition, the observed data estimated from B-type supergiants are shown in the same panel via black empty triangles. In order to compare model predictions with observations, these data are also plotted in the bottom left panel of Fig. 4.

A clear property from Fig. 3 is that the M33 disc has a subsolar overall metallicity. This is consistent with the fact that low-mass galaxies have lower metallicity than high-mass systems, following the mass–metallicity relation among galaxies (Tremonti et al. 2004). Physically, the low metal content in low-mass galaxies can be interpreted as arising from the role of either high gas accretion (infall) or strong galactic winds (outflow), because both can change the metallicity of the galaxy disc and gas fraction (Dalcanton 2007). Since M33 is a low-mass system, we have reasons to assume that M33 is undergoing substantial galactic outflow processes during its evolution.

### 3 THE MODEL

Motivated by various observed properties available along the M33 disc, we build a bridge between the observations of M33 and its SFH by constructing a chemical evolution model. We assume that the disc has been embedded in a dark matter halo. Primordial gas ($X = 0.7571$, $Y_e = 0.2429$, $Z = 0$) within the dark halo cools down gradually to form a rotationally supported disc. The disc is basically assumed to be sheet-like and composed of a series of independent rings with width 500 pc. Since radial flows are still in the stage of lacking a well-understood description and will bring additional free parameters and uncertainties in the model, we do not consider radial flows in this paper. The details and essentials of our model are as follows.

#### 3.1 Gas infall rate

The gas infall process has been introduced in the formation model of the Milky Way disc due to the well-known ‘G-dwarf problem’, which means that a simple ‘closed-box’ model cannot explain the locally observed metallicity distribution function of long-lived stars (Pagel 1989). Recent observations, which were detected at 21 cm by Westmeier, Braun & Thilker (2005), also showed that the M33 disc is still in the process of accreting substantial gas.

We assume that the M33 disc is progressively built up by the infall of primordial gas from its dark matter halo. For a given radius $r$, the gas infall rate $f_{\text{in}}(r, t)$ (in units of $M_\odot$ pc$^{-2}$ Gyr$^{-1}$) is assumed to be

$$f_{\text{in}}(r, t) = A(r) \cdot e^{-t/\tau},$$

where $\tau$ is the infall time-scale and is a free parameter in our model. The $A(r)$ are actually a set of separate quantities constrained by the stellar mass surface density at the present time. In practice, we estimate $A(r)$ iteratively by requiring that the model–resulting stellar mass surface density at the present time is equal to its observed value (Chang et al. 2010; Chang, Shen & Hou 2012). The stellar disc of M33 is described by an exponential surface density profile, given by

$$\Sigma_\ast(r, t_g) = \Sigma_\ast(0, t_g) \exp(-r/r_d),$$

where $\Sigma_\ast(r, t_g)$ is the stellar mass surface density at the present time, $t_g$ is the cosmic age and we set $t_g = 13.5$ Gyr according to the standard cosmology. Here $\Sigma_\ast(0, t_g)$ is the central stellar mass surface density at the present time, $r_d$ is the radial scalelength of the stellar disc and we set $r_d = 1.4$ kpc. The total stellar mass of the M33 disc is given by

$$M_\ast(t_g) = \Sigma_\ast(0, t_g) 2\pi r_d^2.$$
Influence of free parameters on model predictions. On the left-hand side, from top to bottom are shown the $\text{H}_\text{I}$ surface density, total gas surface density, surface brightness in the FUV band and oxygen abundance radial profiles. On the right-hand side, from top to bottom are shown $\text{H}_2$ surface density, SFR surface density, surface brightness in the $K$ band, and FUV – $K$ colour radial profiles. Different line types correspond to various parameter groups: dashed lines ($\tau, b_{\text{out}}$) = (0.1 Gyr, 0), dotted lines ($\tau, b_{\text{out}}$) = ($\infty$, 0), solid lines ($\tau, b_{\text{out}}$) = ($\infty$, 2). The observed data are described in detail in Section 2.

We adopt $M_*(t_g) = 4.0 \times 10^9 M_\odot$ and we set $\Sigma_*(0, t_g) = 325 M_\odot \text{pc}^{-2}$ accordingly.

In previous models of the chemical evolution of disc galaxies, the gas infall rate is widely assumed to be exponentially decreasing with time (Hou et al. 2000; Chiappini et al. 2001; Yin et al. 2009). However, because of the small initial mass of M33, the disc may initially accumulate a small amount of gas; its accretion rate may gradually increase as its gravitational potential builds up and then start decreasing when the gas reservoir is depleted (Prantzos & Silk 1998). Therefore, we adopt another form of gas infall rate in this paper. Generally speaking, the gas infall rate we adopted is low at the beginning and gradually increases with time. It reaches a maximum value when $t = \tau$ and then slowly falls. We emphasize that the infall time-scale $\tau$, which regulates the shape of gas accretion history and then largely influences the main properties of SFH along the disc, is an important free parameter in our model.

### 3.2 Star-formation law

It is well known that almost all stars form in molecular clouds; therefore it is natural to expect that the SFR correlates more strongly with the molecular gas surface density than with the total one. Indeed, studies of spatially resolved SF laws show that the SFR correlates more strongly with the surface density of molecular hydrogen than with that of atomic hydrogen (Wong & Blitz 2002; Bigiel et al. 2008; Leroy et al. 2008). In this paper, we adopt a $\Sigma_{\text{H}_2}$-based SF law (see equation 1). We calculate the molecular hydrogen depletion time of M33 using the observed surface density of SFR and $\text{H}_2$ in Section 2.1 and we adopt $t_{\text{dep}} = 0.43$ Gyr throughout this work.

Regarding the ratio of molecular to atomic gas surface density of a galaxy disc $R_{\text{mol}}$, Blitz & Rosolowsky (2006) and Leroy et al. (2008) proposed that the midplane pressure of the interstellar medium (ISM) $P_{\text{b}}$ alone could determine $R_{\text{mol}}(r, t)$:

$$R_{\text{mol}}(r, t) = \frac{\Sigma_{\text{H}_2}(r, t)}{\Sigma_{\text{H}_1}(r, t)} = \left[ \frac{P_{\text{b}}(r, t)}{P_0} \right]^\alpha,$$

where $\Sigma_{\text{H}_1}$ and $\Sigma_{\text{H}_2}$ are the surface density of atomic and molecular hydrogen, respectively, and $P_{\text{b}}$ is the midplane pressure in the ISM.
where $P_0$ and $\alpha_P$ are constants derived from the observations. We adopt $P_0 = 4.3 \times 10^7 \text{ cm}^{-3} \text{ K}$ and $\alpha_P = 0.92$ (Blitz & Rosolowsky 2006).

According to Elmegreen (1989, 1993), the midplane pressure of the ISM in disc galaxies can be expressed as

$$P_0(r, t) = \frac{\pi}{2} G \Sigma_{\text{gas}}(r, t) \left[ \Sigma_{\text{gas}}(r, t) + \frac{c_{\text{gas}}}{c_{\text{star}}} \Sigma_{\text{star}}(r, t) \right],$$

where $G$ is the gravitational constant and $c_{\text{gas}}$ and $c_{\text{star}}$ are the (vertical) velocity dispersions of gas and stars, respectively. Observations suggest that $c_{\text{gas}}$ is a constant along the disc and we adopt $c_{\text{gas}} = 11 \text{ km s}^{-1}$ (Ostriker, McKee & Leroy 2010), but $c_{\text{star}} = \sqrt{\frac{G M_\odot(z_0)}{z_0}}$, where $z_0$ is the scaleheight of the disc and we adopt $z_0 = 0.5 \text{ kpc}$ (Heyer et al. 2004).

### 3.3 Gas outflow rate

As we have already mentioned in the previous section, the outflow process may influence the evolution of M33. Indeed, Garnett (2002) suggested that spiral galaxies with $V_{\text{out}} \lesssim 125 \text{ km s}^{-1}$ may lose some amount of gas in supernova-driven winds. Spitoni et al. (2010) also concluded that the outflow may play a significant role, especially for galaxies with stellar mass less than $10^{10} \text{ M}_\odot$. To explain the observed correlation between the galactic gas-phase metallicity and its stellar mass, Tremonti et al. (2004) and Chang et al. (2010) suggested that it is necessary that the gas outflow efficiency of a galaxy increase as the galactic stellar mass decreases. Since M33 is a low-mass system with a rotation speed of about $110 \text{ km s}^{-1}$, the gas-outflow process should play an important role in its disc evolution.

Following Chang et al. (2010), we also assume that the outflow gas has the same metallicity as the ISM at that time and will not fall again to the disc. The gas outflow rate $f_{\text{out}}(r, t)$ (in units of $\text{M}_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}$) is assumed to be proportional to the SFR surface density $\Psi(r, t)$:

$$f_{\text{out}}(r, t) = b_{\text{out}} \Psi(r, t),$$

where $b_{\text{out}}$ is another free parameter in our model.

### 3.4 Stellar evolution and chemical evolution equations

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

Regarding the chemical evolution of the disc of M33, both the instantaneous-recycling approximation and instantaneous mixing of the gas with ejecta are assumed, i.e. 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):

$$\frac{d[\Sigma_{\text{gas}}(r, t)]}{dr} = f_{\text{in}}(r, t) - f_{\text{out}}(r, t),$$

$$\frac{d[\Sigma_{\text{star}}(r, t)]}{dr} = -(1 - R) \Psi(r, t) + f_{\text{in}}(r, t) - f_{\text{out}}(r, t),$$

$$\frac{d[Z(r, t) \Sigma_{\text{gas}}(r, t)]}{dr} = y(1 - R) \Psi(r, t) - Z(r, t)(1 - R) \Psi(r, t) + Z_\odot f_{\text{in}}(r, t) - Z_{\text{out}}(r, t) f_{\text{out}}(r, t),$$

where $\Sigma_{\text{out}}(r, t)$ is the total (star + gas) mass surface density and $Z(r, t)$ is the metallicity in the ring centred at galactocentric distance $r$ at evolution time $t$. $R$ is the return fraction and we set $R = 0.3$ according to the adopted IMF. $y$ is the stellar yield and we set $y = 1 Z_\odot$ (Chang et al. 2010). $Z_\odot$ is the metallicity of the infalling gas and we assume the infalling gas is primordial, i.e. $Z_{\text{in}} = 0$. $Z_{\text{out}}(r, t)$ is the metallicity of the outflowing gas, and that the outflow gas has the same metallicity as the ISM, i.e. $Z_{\text{out}}(r, t) = Z(r, t)$ (Chang et al. 2010).

In summary, the two free parameters in our model are the infall time-scale $\tau$ and the outflow coefficient $b_{\text{out}}$. The combination of gas infall rate and outflow rate determines the behaviour of the total (gas+star) mass surface density. We assume that the initial total mass surface density is zero; then we can numerically obtain the total mass surface density at any time after the free parameters are given. Adding the SF law, we can easily describe how much cold gas turns into stellar mass and then calculate numerically the chemical and colour evolution of the disc of M33.

### 4 MODEL RESULTS VERSUS OBSERVATIONS

Fig. 4 presents a comparison between model predictions and observations. The left-hand side of Fig. 4 shows the H$\alpha$ surface density, total gas surface density, surface brightness in the FUV band and oxygen abundance radial profiles. The right-hand side shows H$\beta$ surface density, SFR surface density, surface brightness in the $K$ band and FUV−$K$ colour radial profiles, respectively. The data of observed radial profiles of H$\alpha$ are taken from Corbelli (2003) (filled triangles, green in the online article), Heyer et al. (2004) (filled squares, cyan in the online article) and Gratier et al. (2010) (asterisks, blue in the online article). The data taken from Verley et al. (2009) are shown by empty circles (Westerbork) and filled circles (Arecibo), red in the online article. The left panel in the second row of Fig. 4 plots the total gas surface density, which is defined as $1.33(\Sigma_{\text{H}}(r, t) + \Sigma_{\text{H}_{2}}(r, t))$ (the factor of 1.33 considers the contribution of helium), where the data notation is the same as that for H$\alpha$. The data of total gas surface density taken from Verley et al. (2009) are calculated using the Arecibo data of $\Sigma_{\text{H}_{2}}$, except for the first four inner radii, where we used the values from Westerbork. The notation for the other panels of observed data is the same as described in detail in Section 2.

We explore the influence of free parameters on model results step by step. First, we do not consider the contribution of the gas-outflow process ($b_{\text{out}} = 0$), and explore the influence of $\tau$ on model results. The dashed and dotted lines in Fig. 4 denote the model predictions of two limiting cases of $\tau = 0.1 \text{ Gyr}$ and $\tau \rightarrow \infty$, respectively. The case of $\tau \rightarrow 0$ corresponds to a time-declining infall rate, which is very close to the ‘closed-box’ model, while $\tau \rightarrow \infty$ corresponds to a near-constant with a slight time-increasing gas inflall rate.

It can be seen from Fig. 4 that the model predictions are very sensitive to the adopted $\tau$. The model adopting a shorter $\tau$ predicts lower gas surface density (i.e. both H$\alpha$ and H$\beta$ components), lower SFR, lower surface brightness, redder colour and higher metallicity than that adopting a longer $\tau$. This is mainly due to the fact that, in our model, the setting of a short infall time-scale corresponds to a fast gas infall process and high SF process in the early period of galaxy evolution and then leads to an old stellar population, high metallicity and low cold gas content at the present day.

To investigate the influence of the gas-outflow process on the evolution of M33, the solid lines in Fig. 4 plot the model results adopting $\tau = \infty$ and $b_{\text{out}} = 2$. Comparison between solid and dotted lines shows that the gas-outflow process has no significant influence.
on the stellar population and the cold gas content but does reduce the gas-phase metallicity, since it takes a fraction of metals away from the disc. Therefore, the observed radial distribution of oxygen abundance may constrain the gas-outflow process of M33 tightly.

Another interesting point in Fig. 4 is that the area between the dashed and solid lines covers almost the whole region of the observations, which means that it is possible to construct an evolution model that can reproduce the main features of the observations of the M33 disc. Considering the observed trend that the inner stellar disc seems to be redder and metal-richer than that of the outer region, we adopt the inside-out disc formation scenario, i.e. a radius-dependent inflow time-scale $\tau = r/t_{\text{d}} + 5.0$ Gyr and a moderate outflow rate $b_{\text{out}} = 0.5$ as the viable model; its results are plotted as solid lines in Fig. 5. The observed data are the same as those of Fig. 4. It can be seen that the solid lines are in fair agreement with most observational data, which suggests that our viable model includes and describes reasonably well the important ingredients of the main processes that regulate the formation and evolution of M33.

The inflow time-scale is one of the important free parameters in our model. After exploring its influence on the radial profiles of M33 and computing several sets of combinations of free parameters, we finally choose the radius-dependent inflow time-scale in the viable model based on the balance that the model predictions can be consistent with most of the observed data. We emphasize that although the accurate values of free parameters in the viable model are not unique, the main trend that $\tau(r)$ increases from the inner disc to the outer parts is robust. In fact, this assumption is consistent with the well-known idea that the disc forms inside-out, already applied in previous models of the formation and evolution of disc galaxies (Matteucci & Francois 1989; Boissier & Prantzos 1999; Hou et al. 2000; Chiappini et al. 2001; Fu et al. 2009; Yin et al. 2009).

![Figure 5](https://example.com/fig5.png)

**Figure 5.** Comparison of the predictions of the viable model with the observations. The solid lines plot the viable model results, which adopt $(\tau, b_{\text{out}}) = (r/t_{\text{d}} + 5.0 \text{ Gyr}, 0.5)$ and the $\Sigma_{\text{H}_2}$-based SF law, while the dashed lines are with the same $(\tau, b_{\text{out}})$ but with the Kennicutt SF Law $\Psi(r, t) = 0.25\Sigma_{\text{gas}}^{1/4}(r, t)$. The observed data symbols are the same as those in Fig. 4.
In order to demonstrate clearly the property of the inside-out formation scenario, we plot the mean stellar age along the disc predicted by our typical model with solid lines in Fig. 6. It can be seen that the model predicts a decreasing mean stellar age from the inner disc to the outer region. The short infall time-scale means that a large fraction of stars formed at an early stage and hence high mean stellar age. Indeed, the ground-based observations of bright stars in M33 suggest that the outer disc of M33 may have formed at a late epoch and the SF process may be ongoing (Davidge 2003; Block et al. 2004; Rowe et al. 2005).

Another method with which to test the inside-out formation scenario is to measure the radial distribution of the mean age of the stellar populations along the disc. Williams et al. (2009) presented resolved stellar photometry of four fields along the M33 disc and found that the age of the majority of the stars increases with increasing galactic distance, which is consistent with our model prediction. On the other hand, the investigation of the stellar age distribution in the far outer disc of M33 (outside the break radius $r > 8$ kpc) shows that the mean age of stars in the far outer disc is low ($\sim 3$ Gyr) but increases with radius (Barker et al. 2007, 2011). The explanation of the origin of this reverse age gradient in the far outer disc of M33 is still an open question and needs further investigation.

The SF law is another important component of the model that may largely influence the evolution of M33. In this paper, we adopt the $\Sigma_{\text{HI}}$-based SF law instead of the classic Kennicutt SF law (that is, $\Psi(r, t) = 0.25 \Sigma_{\text{gas}}^{1.4}(r, t)$) in previous studies. We compare the model predictions when using these two kinds of SF laws in Figs 5 and 6. The results of the Kennicutt SF law are shown by dashed lines. Other ingredients of the model, including the molecular-to-atomic ratio $R_{\text{mol}}$, are the same as those of the viable model. It can be seen that the solid lines can be clearly distinguished from the dashed lines, especially in the outer disc where the cold gas surface density is low. Compared with the model adopting the $\Sigma_{\text{HI}}$-based SF law, the model adopting the Kennicutt SF law predicts much flatter gradients of metallicity, mean stellar age and colour, but steeper gradients of $\Sigma_{\text{HI}}$, $\Sigma_{\text{H}_2}$ and $\Psi(r, t)$. These results suggest that, compared with the $\Sigma_{\text{HI}}$-based SF law, the SFE of the Kennicutt SF law is higher in the outer regions of the disc. This means that the cold gas in the outer regions will turn into stars more efficiently, which will result in an older stellar population. Indeed, previous works on the evolution of the Milky Way and M31 discs have shown that, in order to agree well with the observed metallicity gradient and its time evolution, it is necessary to adopt a modified Kennicutt SF law, such as $\Psi(r, t) \propto \Sigma_{\text{gas}}^{1.4}(r, t)/r$ (Boissier & Prantzos 1999; Chang et al. 1999; Fu et al. 2009; Yin et al. 2009). However, why the SFE should be inversely correlated directly with the galactic radius is not fully understood. Our results show that the model predictions based on a $\Sigma_{\text{HI}}$-based SF law are more consistent with observed trends, especially the radial distributions of both the cold gas and the stellar population.

5 SUMMARY

In this paper, we construct a parametrized model of the formation and evolution of the M33 disc by assuming that the disc originates and grows through primordial gas infall. The gas infall rate is described by a simple formula with one free parameter, the infall time-scale $\tau$. We also include the contribution of gas outflow. A molecular-hydrogen-correlated SF law is adopted to describe how much cold gas turns into stellar mass. We calculate the evolution of M33 numerically and compare the model predictions with observational data.

The main results of our model can be summarized as follows.

(i) Based on the observed $\Sigma_{\text{HI}}$ and SFR, we estimate the depletion time of molecular hydrogen $t_{\text{dep}}$ along the disc of M33. It is shown that $t_{\text{dep}}$ does not vary very much with radius, which suggests that the SFE of M33 is almost constant along the disc. We also show that the SFE of M33 is higher than the average value derived by Leroy et al. (2008) on the basis of a large sample of galaxies.

(ii) Our results show that the model predictions are very sensitive to the adopted infall time-scale. A long infall time-scale will result in blue colours, low metallicity, high $H_2$ and H I mass surface densities and high SFR surface density.

(iii) We also find that the outflow has relatively little effect on the disc stellar population and cold gas content. However, it has great influence in shaping the abundance profiles along the M33 disc, since it takes a fraction of metals away from the M33 disc due to its low-mass potential.

(iv) A model that adopts a moderate outflow rate and an inside-out formation scenario, i.e. an infall time-scale increasing with radius, can be in good agreement with most of the observed constraints on M33. Our results suggest that the formation of M33 is quiet and the galaxy may not have formed through a violent accretion process.

(v) We show that the model adopting the Kennicutt SF law predicts much flatter gradients of colour, metallicity and mean stellar age and steeper gradients of cold gas than that adopting an $\Sigma_{\text{HI}}$-based SF law. Our results imply that, compared with the Kennicutt SF law, an $\Sigma_{\text{HI}}$-based SF law would be more suitable to describe the evolution of the galactic disc, especially for radial distributions of both the cold gas and the stellar population.

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