STAR FORMATION AND CHEMICAL EVOLUTION OF M31

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ABSTRACT

In this work, we have established an inside-out infall bulge-disc formation model by assuming that the disc begins to form at different times at different radii, and the bulge forms by the disc instabilities. A radial dependent star formation prescription was adopted. It is found that no matter how the model parameters are adjusted, the M31 disc gas profile in the outer part could not be reproduced. This is different from situations in the Milky Way disc, in which the same SFR law can fairly reproduce a large number of observables. The model also predicts a steeper abundance gradient compared with observations. In order to alleviate these inconsistencies, the star formation efficiency in the outer M31 disc could be higher than that in the Milky Way disc. Furthermore, we found that to form a bulge mass comparable to what is observed in M31, the stability criterion must be less than 0.30. In this case, the model can also fairly reproduce the M31 disc rotational curve. It is possible that two giant spirals, the Milky Way and M31, in the Local Group, may form in a different way. For M31, our model calculations imply that disc instability is not an efficient mechanism for its bulge formation. We argue that fast accretion or early merger could be the alternative. Also, the outer part of the M31 disc may have been influenced by early interaction with satellite dwarfs. The Gaia satellite will certainly provide more insights into formation processes of M31 disc and bulge by resolving the underlying stellar populations.

Key words: Galaxies: formation, evolution, M31.

1. INTRODUCTION

As one of the three disc galaxies in the Local Group, M31 (Andromeda galaxy or NGC224) provides a unique opportunity for testing the theory of galaxy formation and evolution (Klypin et al. 2002; Widrow et al. 2003, Renda et al. 2004). According to the modern theory of disc galaxy formation, a galactic disc forms from baryonic gas which cools down from the halo with non-baryonic dark matter (Mo et al. 1998). Since halo gas must dissipate some of its energy before it can be accreted onto the disc, the disc would grow up with different timescales in different radii. A common framework is the inside-out scenario for disc formation and evolution, that is, the inner disc forms at an earlier time compared with the outer part. This has been considered the main mechanism of the existence of abundance and colour gradients in disc galaxies (Chang et al. 1999; Hou et al. 2000; Prantzos & Boissier 2000).

Owing to its long history of observations, M31 has provided a vast amount of observational data which could be used to constrain disc, bulge and/or halo formation models of M31 (Widrow et al. 2003). Recently, some observations toward M31 disc have been done with the help of HST or ground-based photometry in order to understand how star formation has influenced the evolution of the M31 disc (Bellazzini et al. 2003; Williams 2003a, 2003b). In particular, M31 has well observed disc surface brightness profiles and colour profiles in several bands (Walterbos & Kennicutt 1987, 1988). This provides unique constraints to the consistency of disc chemical and photometric evolution model for this galaxy.

In this paper, we apply an infall model to M31. We adopted a simple infall formulism to describe the growth of the disc with the advantage of ignoring complicated processes required in a LCDM cosmology. Apart from adopting a similar assumption of the radial dependence of infall timescale, we have introduced a disc formation timescale which is also radially dependent. Our motivation for the present model is to establish a proper formulism for both the infall time scale and disc formation timescale, which could be instructive for modelling a statistical sample of disc galaxies such as those from SDSS. We will also test the the Kennicutt star formation law with radial dependence (Kennicutt 1998) by comparing the predicted M31 disc gas profile and oxygen abundance gradient with observed ones. We also test the possible bulge formation mechanism by introducing a disc instability criterion.

2. THE INFALL MODEL

2.1. The Disc Formation

We assume that the M31 disc is as an ensemble of concentric, independently evolving rings, progressively built up by infall of primordial composition. The infall rate is assumed to be exponentially decreasing in time, i.e., $f(t, r) = A(r)\, e^{-t/\tau(r)}$, where $A(r)$ is the normalized function independent of time t. It can be obtained by normalizing the infall rate to the present-day disc profile. $\tau(r)$ is the infall time scale which is radially dependent. We will assume that the $\tau(r)$ increases outwards with an exponential law: $\tau(r) = a\ e^{b\ r}$, where a and b being free parameters, need to be determined. When $r = 0$, $\tau(0) = a$, which means a is just the infall duration of the center part of disc, or it reflects the formation of a bulge. Based on the metallicity distribution of K giants in the Milky Way bulge, Ferreras et al. (2003) suggest that the time scale of the Milky Way bulge formation will not exceed 0.5 Gyr with the durations of infall and star formation greater than 1 Gyr ruled out at the 90 per cent confidence level. Therefore, it is reasonable to assume that the M31 bulge forms at a similar infall time scale. In the following calculations, we will adopt a = 0.75 Gyr.

Since the disc grows progressively from the centre to the outer regions, we introduce a second time scale $t_0(r)$: the disc formation time scale, which is also a function of distance to galaxy centre. A linear variation with radius is assumed, that is: $t_0(r) = \beta \frac{r}{r_d}$, where r_d is the disc scale length, β is a free parameter. Clearly, this radial dependence of the timescale reflects a realistic inside-out formation of the galaxy disc.

The coefficient $A(r)$ is obtained by the requirement that at the present time T_g the current mass profile of the M31 disc $\Sigma(r)$ is obtained, i.e.,

$$\int_{t_0}^{T_g} f(t, r) dt \ = \ \Sigma(r) \tag{1}$$

with $\Sigma(r) = \Sigma_0 e^{-r/r_d}$, where Σ_0 is the central mass surface density of M31 disc. Notice that in Equation 1 the integration starts from t_0 which is radial dependent. The disc scale length r_d has some complexity since it is wavelength dependent. For example, the B-band scale length reflects mostly the SFR profile in the past $\sim$ 1 Gyr and the K-band reflects the total stellar population, cumulated over T_g = 15 Gyr. r_d is calculated according to the semi-analytical model of galaxy formation of Mo et al. (1998) and scaled to the Milky Way disc (Boissier & Prantzos 2000):

$$\frac{r_d}{r_{dMW}} = \frac{\lambda}{\lambda_{MW}} \frac{V_c}{V_{cMW}} \tag{2}$$

where r_{dWM} is the disc scale length of the Milky Way disc, (λ, V_c) and (λ_{MW}, V_{cMW}) are spin parameters and rotational velocities of the M31 and Milky Way halo, respectively. Therefore the r_d should correspond to the current disc scale length (close to K-band). Indeed, taking r_{dMW} = 2.6 kpc (K band) and λ_{MW} = 0.03 (Boissier & Prantzos 2000), V_{cMW} = 135 km s^{-1}(Efstathiou 2000), λ_{M31} = 0.038 and V_{cM31} = 175 km s^{-1}(Klypin et al. 2002), we have r_{dM31} = 4.2 kpc, which is similar to the observed value in the K band (Hiromoto et al. 1983).

2.2. The Bulge Formation

A disc that is self-gravitating tends to be unstable against bar formation. According to van den Bosch (1998), for a disc-bulge-halo system, the stability criterion can be written as

$$\varepsilon = V_d/(2V_c) < \varepsilon_{crit} \tag{3}$$

where V_d is the disc circular velocity, V_c is the circular velosity of composite bulge-disc-halo system. If $\varepsilon < \varepsilon_{crit}$ then the disc is stable against bar formation. In general, ε_{crit} is about 0.26 for stellar disc and 0.35 for gas disc (van den Bosch 1998).

3. STAR FORMATION AND CHEMICAL EVOLUTION

3.1. Star Formation

The star formation rate (SFR) is locally given by a Schmidt-type law, i.e., proportional to some power of the gas surface density Σ_g (Kennicutt law). According to the observations of Kennicutt (1998), it could also be it varies with distance from the galaxy centre r.

$$\Psi = \alpha \left[\frac{\Sigma_g}{M_\odot \mathrm{pc}^{-2}}\right]^{1.4} \left[\frac{V(r)}{220 \mathrm{kms}^{-1}}\right] \left[\frac{r}{10 \mathrm{kpc}}\right]^{-1} \tag{4}$$

where $\Psi(t, r)$ is the star formation per unit area (M$_\odot$Gyr^{-1}pc^{-2}). $V(r)$ is the circular velocity at radius r, α is the star formation efficiency. For the Milky Way disc, $\alpha = 0.1$.

3.2. Chemical Evolution

We assume that the 'rings' of the disc are evolving independently from one another. The chemical evolution of each zone is followed by solving the appropriate set of integro-differential equations, with the Instantaneous Recycling Approximation adopted. The adopted stellar Initial Mass Function (IMF) is a Salpeter form (Salpeter 1955) in order to be consistent with the colour evolution. The basic equations of the chemical evolution is as follows (Pagel 1997):

$$\frac{d\Sigma_t}{dt} = f \tag{5}$$

$$\frac{d\Sigma_g}{dt} = f - (1 - R)\Psi \tag{6}$$

$$\frac{(\bar{Z}\Sigma_g)}{dt} = (y - \bar{Z})(1 - R)\Psi + Z_f f \tag{7}$$

where Σ_t, Σ_g is the total mass and gas surface density, Ψ is the star formation rate, $\bar{Z}$ is the average gas mass abundance, y is the effective stellar yield, which is assumed to be solar. R is the return fraction, which is the total mass fraction that is restored to the ISM by a stellar generation. For a Salpeter IMF, $R = 0.30$. Z_f is the metallicity of the infalling gas, which is assumed to be zero.

The colour evolution for each zone can also be followed once the chemical evolution was calculated. The spectrum of each zone at time t is treated in a standard way (Bruzual & Charlot 2003). Although the chemical and colour evolutions are calculated self-consistently, here we will only report the preliminary results of the chemical evolution.

4. DATA AND MODEL COMPARISON

4.1. Observational Data

For the Milky Way disc, there are plenty of observational data in the solar neighbourhood which provides strict constrains for all models concerning the Milky Way formation and evolution. For example, the G-dwarf metallicity distribution function is the basis of the necessity of infalling gas for the formation the Galaxy disc. The abundance gradient along the disc implies that the disc should be formed with inside-out scenario.

However, in the case of M31, we do not have a sample as in the 'solar neighbourhood', but we still have the observed radial profile for HI and H_2 gas surface density (Berkhuijsen 1977; Walterbos 1986; Koper et al. 1991; Loinard et al. 1999) and abundance gradient for several elements (Blair et al. 1982). Moreover, the colour profiles along the M31 minor and major axis in several wave bands are readily available (Hiromoto et al. 1983; Walterbos & Kennicutt 1988), which make it possible to consistently model both chemical and photometric profiles. But a real problem that concerns the colour evolution is the uncertainty of internal extinction of M31 as well as the foreground attenuation by the Milky Way disc. Also the M31 has a large bulge compared with the Milky Way galaxy, the effect of bulge pollution in disc colour profile should also be considered, either in the model or in the observed data. All those factors are not well determined, so we will select the gas profile and oxygen abundance gradient along the M31 disc as the main model constraints.

4.2. Gas and Abundance Profiles

We have run a number of models with different parameter combinations in order to test their effects on the resulted gas and abundance profiles along the M31 disc. The free parameters are (β, b, α).

First, we adopt the Milky Way disc star formation efficiency $\alpha = 0.1$, then the free parameters are (β, b). It is found that no matter how these two parameters are adjusted, the outer gas profile cannot be reproduced. The models always predict more gas in the outer part, mainly 12 kpc outward. But the inner profile can be well reproduced. Models with parameters $\beta = 0.5 \sim 1$ and $b = 0.05$ $\sim$ 0.1 can all predict acceptable profiles concerning the uncertainties in the observations. Figure 1 is an example for (β, b) =(1.0,0.1).

Secondly, the model predicts more steeper oxygen abundance gradient compared with the observations. In order to alleviate this inconsistency, the star formation efficiency in the outer M31 disc must be higher than that in the Milky Way disc.

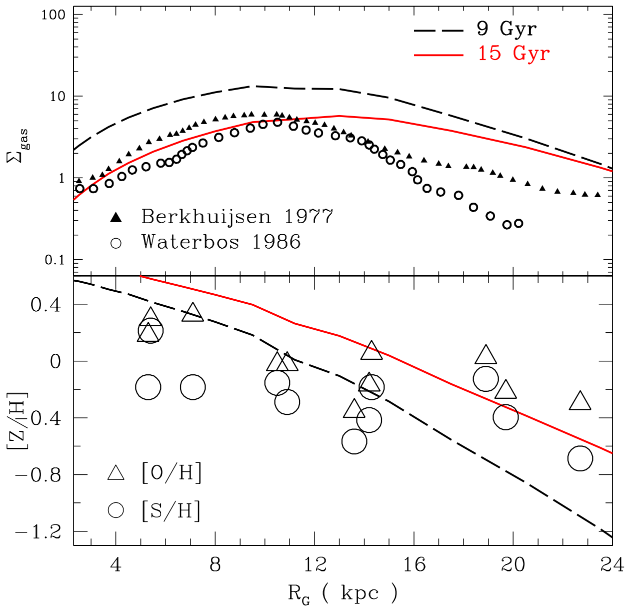

Figure 1. Radial profile of HI gas surface density (upper panel) and oxygen abundance gradient (lower panel) at 9 and 15 Gyr. The observed gas data comes from Berkhuijsen (1977) and Walterbos (1986). Abundance data comes from Blair et al. (1982). The model parameters in the Figure is (β, b, α) = (1.0,0.1,0.1).

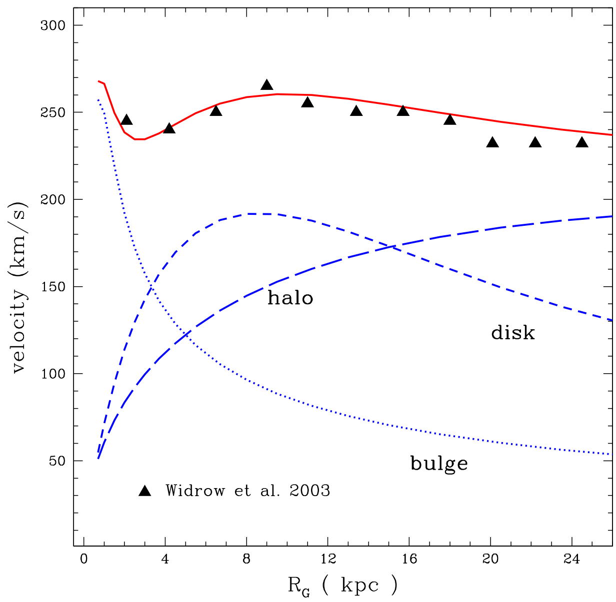

Figure 2. M31 disc rotational curve. Data comes from Widrow et al. (2003). The model parameters is the same as in Figure 1.

4.3. Bulge Mass and Disc Rotational Curve

If we assume the critical value is less than 0.30, then the bulge mass can be grown to 1.6 $\times$ 10^{10} $M_\odot$. In this case the final rotation curve can roughly be reproduced for the M31 disc. But this critical parameter is smaller than the generally adopted value in the galaxy formation model. We argue that the disc instability is not an efficient mechanism in the M31 bulge formation. In contrast, fast accretion or early merger could be the alternatives. This needs more detailed investigations.

5. SUMMARY

M31 is the largest spiral in the Local Group. Detailed studies, both theoretical and observational are necessary. In theory, previous chemical evolution work have been done by Dias & Tosi (1984); Josey & Arimoto (1992); Molla et al. (1996), all emphasizing the M31 disc evolution. Their common ideas are that the M31 disc and the Milky Way disc have a similar formation history and chemical evolution processes. Here we have established a disc infall model by introducing two time scales, one is the infall time scale, and the other is the disc formation time scale. We considered both chemical and colour formation processes, and also tested the efficiency of bulge formation by disc instability. Our preliminary results concerning star formation and chemical evolution are:

1. A Kennicutt star formation law with radial dependence could not reproduce the M31 gas profile in the outer part. Also, the model predicts a steeper abundance gradient. This is different from the case in the Milky Way disc where the same Kennicutt law can reproduce well the disc gas and abundance profile. In order to alleviate this inconsistency, the M31 outer disc needs higher star formation efficiency. We noticed that recent observations show that the M31 halo has a much higher metallicity than that in the Milky Way, which means that either the M31 halo has a much higher star formation efficiency or that the high metallicity results from a different origin, for example, a longer halo formation process. The M31 disc may have the similar underlying early history.

2. Disc instability may not be an efficient way to form the M31 bulge. We argue that the early merger could be an alternative. In this respect, we need more detailed modelling between the Milky Way bulge and the M31 bulge in order to see whether these two giant spirals have different early formation history.

Both above results could be clarified by more detailed resolved stellar population data, such as kinematics, metallicities and age distributions, all as a function of space. Although current ground-based and space telescopes have revealed some differences and also similarities between the Milky Way and M31, much more data is needed. For M31, Gaia should be able to reach bulge AGB stars, halo globular clusters, disc field stellar populations with enough accuracy. Thus Gaia is able to provide age, distance, kinematics and metallicity for different M31 populations, providing strong constraints on theoretical models of chemical evolution.

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