THE GROWTH OF THE DISK GALAXY UGC8802

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Received 2012 May 10; accepted 2012 May 30; published 2012 June 13

ABSTRACT

The disk galaxy UGC8802 has high neutral gas content and a flat profile of star formation rate compared to other disk galaxies with similar stellar mass. It also shows a steep metallicity gradient. We construct a chemical evolution model to explore its growth history by assuming its disk grows gradually from continuous gas infall, which is shaped by a free parameter—the infall-peak time. By adopting the recently observed molecular surface density related star formation law, we show that a late infall-peak time can naturally explain the observed high neutral gas content, while an inside-out disk formation scenario can fairly reproduce the steep oxygen abundance gradient. Our results show that most of the observed features of UGC8802 can be well reproduced by simply “turning the knob” on gas inflow with one single parameter, which implies that the observed properties of gas-rich galaxies could also be modeled in a similar way.

Key words: galaxies: evolution – galaxies: photometry – galaxies: stellar content

Online-only material: color figures

1. INTRODUCTION

Understanding the content and distribution of cold gas in galaxies is an important step to understand the formation and evolution of galaxies. UGC8802 is an interesting target selected from the GALEX Arecibo SDSS Survey (GASS; Garcia-Appadoo et al. 2009; Catinella et al. 2010). One interesting aspect is its cold gas content. UGC8802 is a disk galaxy with stellar mass $M_* \approx 2 \times 10^{10} M_\odot$, while its H$_i$ mass is estimated to be as high as $2.1 \times 10^{10} M_\odot$ (Springob et al. 2005) and its molecular gas mass is only about one-tenth of its H$_i$ mass (Moran et al. 2010). Compared to other disk galaxies in this stellar mass range, the high neutral gas content of UGC8802 is uncommon (Giovanelli et al. 2007; Garcia-Appadoo et al. 2009; Catinella et al. 2010). Why UGC8802 has such high neutral gas fraction and how UGC8802 acquires its cold gas are still open questions (Moran et al. 2010).

Another interesting aspect of UGC8802 is the flat profile of its star formation rate (SFR; Moran et al. 2010). The SFR surface densities of “normal” disk galaxies typically decrease (sometimes exponentially) from the center to the outer regions of the disk, such as in the Milky Way, M31, etc. (Bigiel et al. 2008; Fu et al. 2009; Yin et al. 2009). Aside from the flat SFR profile, Moran et al. (2010) found that UGC8802 shows a steeper radial oxygen gradient than the average gradient of the GASS sample.

Therefore, it is interesting to explain these observed results under the framework of the current models of galaxy formation and evolution. For an individual disk galaxy, parameterized modeling has been proven to be fruitful in exploring their galactic formation and evolution (Tinsley 1980; Chang et al. 1999; Boissier & Prantzos 2000; Chiappini et al. 2001; Colavitti et al. 2009; Yin et al. 2009). In this Letter, we construct such a parameterized model to investigate the radial-dependent star formation history (SFH) of UGC8802 so as to explore its growth history.

2. THE MODEL

Our model is based on that of Chang et al. (2010). Here we emphasize the main ingredients of the model, especially some revisions. We adopt the standard cold dark matter cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

We assume that the galactic disk is sheet-like and composed of a set of independent rings, each 500 pc wide. The disk originates through continuous gas infall from the dark halo. We assume that the disk begins to form at 12.5 Gyr ago, which roughly corresponds to $z \sim 6$ under standard cosmology. At a given radius $r$, the gas-infall rate $f_{in}(r, t)$ (in units of $M_\odot$ pc$^{-2}$ Gyr$^{-1}$) is assumed to be Gaussian in time (Chang et al. 1999, 2010):

$$f_{in}(r, t) = \frac{A(r)}{\sqrt{2\pi} \sigma} e^{-(t-t_p(r))^2/2\sigma^2},$$

where $t_p$ is the infall-peak time and $\sigma$ is the scatter. We adopt $t_p$ to be free and set $\sigma = 3$ Gyr since the model results are insensitive to varying $\sigma$ in the 2–4 Gyr range (Chang et al. 2010). The $A(r)$ are a set of separate quantities normalized by the stellar mass surface density of present-day $\Sigma_g(r, t_p)$, where $t_p$ is the cosmic age and set to be $t_p = 13.5$ Gyr according to the adopted cosmology. The stellar mass of UGC8802 and its disk scale length at the present time are adopted to be $M_* = 2 \times 10^{10} M_\odot$ and $r_d = 5.8$ kpc (Moran et al. 2010). We assume that the galaxy UGC8802 at present is a pure-disk system and $\Sigma_g(r, t_p)$ follows an exponential profile, and so that the central stellar mass surface density is given as $\Sigma_g(0, t_p) = M_*/(2\pi r_d^2)$. The star formation (SF) law is one of the key ingredients of our disk galaxy formation model. Kennicutt (1998) found a power-law relationship between the galaxy-averaged SFR surface density and the galaxy-averaged total gas surface density, which is often called the classical Kennicutt–Schmidt SF law and has been widely used in the chemical evolution models of the disk galaxy formation. Later, extended analyses to kpc-scale regions within several Local Group galaxies show that the SFR surface density correlates more strongly with the surface density of molecular hydrogen than that of atomic hydrogen (Wong & Blitz 2002; Bigiel et al. 2008; Leroy et al. 2008). In this study, we adopt a recently observed molecular surface density related SF law (hereafter, it is termed as the $\Sigma_{H_2}$-based SF law), that is, the SFR surface density $\Psi(r, t)$ is linearly proportional to the molecular...
hydrogen surface density $\Sigma_{H_2}(r,t)$:

$$\Psi(r,t) = \frac{\Sigma_{H_2}(r,t)}{\tau_{dep}},$$

where $\tau_{dep}$ is the molecular gas depletion time. Bigiel et al. (2008) and Leroy et al. (2008) derived a constant molecular gas depletion time as $\tau_{dep} = 2$ Gyr in their sample, while Saintonge et al. (2011) found non-universality of $\tau_{dep}$ in galaxies in the CO Legacy Database for the GASS (COLD GASS) sample. Saintonge et al. (2011) found that the strongest dependence of $\tau_{dep}$ is on the stellar mass and the mean $\tau_{dep}$ is parameterized as $\log(\tau_{dep}/\text{yr}) = 0.36(\log M_*/M_\odot - 10.7) + 9.3$. According to this relation, we adopt $\tau_{dep} = 0.77$ Gyr for UGC8802. Regarding the molecular-to-atomic mass fraction $R_{\text{mol}}(r,t)$, Blitz & Rosolowsky (2006) obtained an empirical fit relation:

$$R_{\text{mol}}(r,t) = \frac{\Sigma_{H_2}(r,t)}{\Sigma_{H_2}(r,t)} = (P_h/P_{h,0})^{\gamma},$$

where $P_h$ is the mid-plane pressure, $P_{h,0}$ and $\gamma$ are the fitting constants, and we adopt $P_{h,0}/k = 1.7 \times 10^4$ cm$^{-3}$ K and $\gamma = 0.8$ (Leroy et al. 2008). The pressure is estimated to include gas self-gravity (Elmegreen 1989; Leroy et al. 2008):

$$P_h = \frac{\pi}{2} G\Sigma_{\text{gas}} \left( \frac{\sigma_g}{\sigma_{g,z}} \right),$$

where $\sigma_g$ is the total gas surface density, and $\sigma_g$ and $\sigma_{g,z}$ are the vertical velocity dispersion of gas and stars. We adopt $\sigma_g = 11$ km s$^{-1}$ (Ostriker et al. 2010), while $\sigma_{g,z}$ is estimated as (see Appendix B of Leroy et al. 2008 for details)

$$\sigma_{g,z} = \sqrt{\frac{2\pi G r_d}{7.3}} \Sigma_{g,z}^{0.5}.$$

A similar $\Sigma_{H_2}$-based SF law has been successfully adopted in the semi-analytical model of galaxy formation by Fu et al. (2010). Kang et al. (2012) also use the $\Sigma_{H_2}$-based SF law to explore the chemical evolution and SFH of M33 and find that, compared to the model adopting the classical Kennicutt–Schmidt SF law, the model adopting the $\Sigma_{H_2}$-based SF law predicts steeper color and metallicity gradients, which are more consistent with the observations. Other components of the model, such as the initial mass function (IMF), chemical evolution, etc., are the same as that of Chang et al. (2010). We also consider the contribution of the gas outflow process by assuming that the gas outflow rate is proportional to the SFR and the coefficient is set to be $b_{out} = 0.007$ according to the mass-dependent model of Chang et al. (2010). We point out that our final results are insensitive to the variation of $b_{out}$ since UGC8802 is a massive galaxy and the gas outflow process is not a dominant process of its chemical evolution.

We emphasize that our model only has one free parameter, the infall-peak time $t_p$. In Chang et al. (2010), $t_p$ is assumed to be a function of galactic stellar mass and do not vary with radius. In the case of UGC8802, we assume that $t_p$ is a function of radius since we will further consider the radial profiles of UGC8802 rather than the global properties of galaxies as that in Chang et al. (2010). Since formalizing $t_p(r)$ regulates the shape of SFHs along the disk, we aim to get the constraints on $t_p(r)$ from the observed properties of UGC8802 and then obtain insights into its growth history.

3. OBSERVATIONS VERSUS MODEL PREDICTIONS

We present our results step by step. First, we summarize the main observational properties of UGC8802, and then explore the influence of the free parameter on our results. Finally, we present a viable model to discuss the radial-dependent SFH of UGC8802.

The observed data of the radial profiles of UGC8802 are adopted mainly from Moran et al. (2010) and plotted in Figure 1. Since our model only has the galactic-center distance and cannot distinguish the negative position from the positive one, we plot the observed data of the negative and positive positions as open triangles and filled squares in Figure 1, respectively. The NUV $- r$ color profile of UGC8802 is measured using Sloan Digital Sky Survey (SDSS) and GALEX photometry (Moran et al. 2010), but the data have not been corrected for dust attenuation. The observed data of oxygen abundance $\log(O/H) + 12$, the SFR surface density, and $D_N$ (4000) are obtained from the long-slit spectroscopy of UGC8802 (Moran et al. 2010). The data SFR/(SFR) are estimated from the observed SFRs and the stellar surface density $\Sigma_{*}(r,t_p)$ by assuming a $(1-R)$ fraction of the total formed stellar mass is locked in the stellar mass in the present day, where $R$ is the return fraction and we set $R = 0.3$ according to the adopted IMF.

The comparison between model predictions of the radial profiles and the observations are presented in Figure 1. The dashed and dash-dotted lines are model results of two limiting cases of $t_p = 0.1$ Gyr and $t_p = 15$ Gyr, respectively. The case $t_p = 0.1$ Gyr (dashed lines) corresponds to a time-decreasing gas-infall process that most of the gas has been accreted in the early stage of its history, while that of $t_p = 15$ Gyr (dash-dotted lines) represents a time-increasing gas accretion that there is still a large fraction of cold gas infall at the present time. Figure 1 shows that the model predictions are very sensitive to the adopted $t_p$. The model adopting the later infall-peak time (dash-dotted lines) predicts the higher surface density of $H_2$ and $H_1$, the higher SFR and specific SFR, the lower gas-phase metallicity, the older mean stellar age, and the bluer color. These results are straightforward, the later $t_p$ corresponds to a more recent gas infall and then results in a younger stellar population and a higher fraction of cold gas in the present.

Figure 1 also shows that the area between the dashed and dash-dotted lines almost covers the locations of the observed data. There is a trend that the observed data at the inner region approaches the dashed lines (the early $t_p$) and the data at the outer regions approach the dash-dotted lines (the late $t_p$). After a set of calculations and comparisons, we select a viable model by adopting an inside-out formation scenario $t_p(r)/Gyr = 1.5 r/r_d + 5.0$ and plot its model results as solid lines in Figure 1. This model predicts $M_{H_2} = 3.7 \times 10^9 M_\odot$ and $M_{H_1} = 1.5 \times 10^{10} M_\odot$, which is in good agreement with the observed values ($M_{H_2} = 2.1 \times 10^{10} M_\odot$, $M_{H_1} = 1.45 \times 10^{10} M_\odot$; Moran et al. 2010), considering the observed uncertainties. Our model-predicted NUV $- r$ colors are systematically bluer than the observed ones, which is also reasonable since the observed NUV $- r$ color has not been corrected for dust attenuation and our model predictions are dust free.

The good consistence between our model predictions and the observations implies that the continued-gas-infall model is also viable for the "peculiar" UGC8802, which has a steeper metallicity gradient, flatter SFR profile, and extraordinarily higher neutral gas fraction than normal disk galaxies. The key ingredient of this successful model is that the infall-peak time $t_p$ increases from 5 Gyr in the innermost disk to 12.5 Gyr at the outer region around $\sim 5r_d$. That means the formation of UGC8802 is quite late and the disk is still growing. In fact, this scenario is the well-known idea that the disk forms...
Figure 1. Comparisons of the radial profiles between the observations and the model predictions. The dashed and dash-dotted lines are model results adopting $t_p = 0.1$ Gyr and $t_p = 15$ Gyr, respectively. The solid lines plot the predictions of the viable model, which adopts $t_p(r)/\text{Gyr} = 1.5r/r_d + 5$. The observed data are described in details in the text.

(A color version of this figure is available in the online journal.)

inside-out and has also been applied to previous models of formation and evolution of disk galaxies (Chang et al. 1999; Boissier & Prantzos 2000; Chiappini et al. 2001; Colavitti et al. 2009; Fu et al. 2009; Yin et al. 2009; Wang et al. 2011).

The above results have shown that the inside-out growth scenario can nicely reproduce the main observed properties of UGC8802. In Figure 2, we show further predictions of the growth history of this established model of UGC8802. The upper panel of Figure 2 shows the model predicted time evolution of the half-size stellar mass $R_{50,*}$ (solid line), which is defined as the radius where half of the total stellar mass is contained. As we can see, our model predicts that the half-size of UGC8802 increases almost linearly with time, which is also globally consistent with the observations of the average size evolution trend of the massive galaxies ($r_e(z)/r_e(z=0) = (1+z)^{-1.1}$; van der Wel et al. 2008; dashed line). This size growth is actually another angle of view of the disk inside-out formation scenario.

In the bottom panel, we plot the model predictions of the evolution of the different mass components, which includes the stellar mass $M_*$ (solid line), the atomic hydrogen mass $M_{\text{HI}}$ (dashed line), and the molecular hydrogen mass $M_{\text{H}_2}$ (dotted line). The quantities are normalized by its value at the present day. The bottom panel of Figure 2 shows that, in the early epoch, with the continued infall of cold gas (mainly in the form of the atomic gas), the molecular gas accumulates faster, while the accumulation of stellar mass lagged behind. Later, the mass of the molecular gas becomes asymptotic, while the growth rate of the stellar mass speeds up. Indeed, half of the stellar mass has been accumulated during the last 4 Gyr. To sum up, our results suggest that UGC8802 is a young galaxy and still active in SF processes.

4. SUMMARY

In this work, we build a bridge for disk galaxy UGC8802 between its observed properties and its growth history by constructing a simple chemical evolution model. We find that a late infall-peak time $t_p$, which corresponds to a recent gas-infall process, is necessary to explain the observed high atomic and molecular gas content of UGC8802. The model adopting an inside-out formation scenario $t_p(r)/\text{Gyr} = 1.5r/r_d + 5.0$ and the $\Sigma_{\text{H}_2}$-based SF law can reproduce the observed radial profiles of UGC8802 very well. This consistency does encourage us that our simple model is viable for such a “peculiar” galaxy. This result implies that there should be no violent starburst process (e.g., the major merging) during the growth history of UGC8802. According to our model, half of the stellar mass of UGC8802 may have been accumulated during the last 4 Gyr and the SF process of the outer disk is still active. The physics behind the very young history of UGC8802 may related to its environment, however, which is beyond the scope of this Letter.

The success of our simple model in the case of UGC8802 implies that the observed properties of the gas-rich galaxies might also be well modeled by “turning the knob” on gas inflow with a single parameter. Indeed, Wang et al. (2011) and Moran et al. (2012) find that the color and metallicity of the outer region of the galaxies strongly correlate with its total atomic mass $M_{\text{HI}}$, i.e., the higher the $M_{\text{HI}}$, the bluer the color,
Figure 2. Growth history of UGC8802 predicted by the viable model. In the upper panel, the solid line shows the model predicted time evolution of the half mass size $R_{50}$, while the dashed line shows the observed trend of size evolution of massive galaxies. The bottom panel shows the normalized evolution history of different baryonic components, including the stellar mass (the solid line), the atomic hydrogen mass $M_{\text{HI}}$ (the dashed line), and the molecular hydrogen mass $M_{\text{H}_2}$ (the dotted line).

(A color version of this figure is available in the online journal.)

and the lower the metallicity. In our story, the high atomic gas fraction of gas-rich galaxy may be the result of a late and smooth gas accretion history, and the bluer color and lower metallicity of its outer region are embedded in the disk inside-out formation scenario. We will further explore these questions in a forthcoming paper.

We thank the anonymous referee for suggestions to greatly improve this Letter. This work is supported by the National Science Foundation of China No. 11173044, the Key Project No. 10833005 and No. 10878003, and the Group Innovation Project No. 10821302.

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