MODELS OF LATE-TYPE DISK GALAXIES: 1-D VERSUS 2-D

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Abstract. We investigate the effects of stochasticity on the observed galaxy parameters by comparing our stochastic star formation two-dimensional (2-D) galaxy evolution models with the commonly used one-dimensional (1-D) models with smooth star formation. The 2-D stochastic models predict high variability of the star formation rate and the surface photometric parameters across the galactic disks and in time.

Key words: galaxies: general – galaxies: evolution

1. INTRODUCTION

The studies of well resolved nearby disk galaxies demonstrate bursting nature of star formation (SF) events stochastically distributed across the galaxy disks (e.g., Harris & Zaritsky 2009). The effects of bursting SF are the most prominent in the outer disk regions (e.g., Barnes et al. 2013), however, photometric parameters, especially in the UV spectral region, are significantly altered throughout the entire disks (e.g., Simones et al. 2014). Despite that, the one-dimensional (1-D, resolved only along the radius of a galaxy) models, used for simulation of radial variations of the parameters of a disk galaxy, still employ a smooth SF prescription (e.g., Magrini et al. 2007; Marcon-Uchida et al. 2010; Kang et al. 2012).

In our previous paper (Mineikis & Vansevičius 2014), we used two-dimensional (2-D, resolved along the radius and azimuth of a galaxy) models downgraded to 1-D profiles and compared with the observed radial profiles of the galaxy M33. In this case, the presence of the so-called parameter “degeneracy valley” of 2-D models was demonstrated. In order to break those degeneracies, the necessity to use additional 2-D observational information was stressed.

In this study we explore the 2-D galaxy models with stochastic SF, which reproduce satisfactorily the observed radial profiles of the late-type spiral galaxy M33 (Mineikis & Vansevičius 2010, 2014). We use the 2-D models, with the parameters adjusted for M33, and compare them with the corresponding 1-D models with smooth SF in order to reveal SF stochasticity effects.
Table 1. PEGASE-HR parameters

| Parameter                  | Value                      | Reference                        |
|----------------------------|----------------------------|----------------------------------|
| Stellar library            | low-resolution             | Le Borgne et al. (2004)          |
| Initial mass function      | corrected for binaries     | Kroupa (2002)                    |
| Fraction of close binaries | 0.05                       | default PEGASE-HR value          |
| Ejecta of massive stars    | type B                     | Woosley & Weaver (1995)          |
| Nebular emission           | true                       | PEGASE-HR value                  |

2. THE MODELS

2.1. Smooth SF 1-D model

We construct 1-D galaxy disk model following the approaches developed for the nearby disk galaxies (e.g., Marcon-Uchida et al. 2010). The model is defined by dividing disk into concentric rings of 1 kpc in width. The disk grows by a gradual gas accretion from the reservoirs (attributed to each ring), where gas resides initially. The gas does not migrate in radial direction and always is well mixed. The individual evolution of each ring is computed by using the package PEGASE-HR (Le Borgne et al. 2004) and applying the Schmidt-Kennicutt type SF law (Kennicutt 1998):

\[
SFR_i = \frac{1}{\tau_{SF,i}} \cdot \left( \frac{\Sigma_{G,i}(t)}{\Sigma_{0,i}} \right)^n
\]

where SF rate in the ring \(i\), \(SFR_i\), is proportional to the gas density \(\Sigma_{G,i}\) normalized by the initial reservoir mass density \(\Sigma_{0,i}\); the star formation parameter \(\tau_{SF,i}\) defines the time-scale of the galaxy ring build up. The PEGASE-HR parameters used to generate 1-D and 2-D models are given in Table 1.

2.2. Stochastic SF 2-D model

We construct 2-D galaxy disk model following the prescription given in Mineikis & Vansevičius (2014). The disk is building up by a gradual gas accretion from the reservoir, where gas resides initially. The SF in the model is simulated by stochastic SF events in the model cells. The main model parameters determining stochastic SF are the probability of triggered SF, \(P_T\), and the efficiency of SF, \(\epsilon\) and \(\alpha\). \(P_T\) controls the intensity of propagating SF. The SF efficiency depends on two parameters and a gas density in a cell:

\[
SFE = \epsilon \cdot \left( \frac{\Sigma_G}{10 M_\odot/pc^2} \right)^\alpha
\]

where \(\Sigma_G\) is the gas surface density in a cell.

2.3. Calibration of the models

For the comparison with the 1-D models we use two different 2-D models taken from the parameter “degeneracy valley” (Mineikis & Vansevičius 2014). The 2-D models along the “degeneracy valley” have, on average, the radial profiles of gas surface density and \(i\) band photometry indistinguishable within 10% of accuracy. However, SF stochasticity (Fig. 1) and clustering of the SF regions (see Fig. 5 in Mineikis & Vansevičius 2014) are significantly different among them. The SF
Fig. 1. Radial profiles of the SFR standard deviation of the 2-D models. The SFR standard deviation was calculated in radial bins of 1 kpc in width for the galaxy ages from 10 to 13 Gyr with a time step of 10 Myr.

Table 2. The parameters of 2-D models

| Model                        | $P_T$ | $\epsilon$ | $\alpha$ |
|------------------------------|-------|-------------|----------|
| High stochasticity (HS)      | 0.30  | 1.0%        | 2        |
| Low stochasticity (LS)       | 0.34  | 0.2%        | 2        |

Table 3. The parameters of 1-D models

| $R$, kpc | $\log_{10}(\tau_{SF})$, Myr | $n$ |
|----------|------------------------------|-----|
| 1.5      | 1.6                          | 3   |
| 2.5      | 2.1                          | 3   |
| 4.5      | 3.0                          | 3   |
| 8.5      | 4.9                          | 3   |

The parameters of 2-D models used for the comparison with 1-D models are given in Table 2.

To compare 1-D and 2-D model predictions, we derived SF prescription for the 1-D models from the 2-D models fitted for the M33 galaxy. The 1-D model SF is based on the Schmidt-Kennicutt law and is controlled via two parameters, $n$ and $\tau_{SF}$. We used the parameter $n = 3$ derived from the observations (Heyer et al. 2004). The $\tau_{SF,i}$ parameter values for each ring were derived from the 2-D LS models by equation (1).

The evolution of $\tau_{SF,i}$ in the selected rings of the 2-D model is shown in Fig. 2. At the start of the galaxy simulation, the values of $\tau_{SF,i}$ tend to increase in all rings. This is due to slow SF rate because of low gas density in the cells, $\Sigma_G < \Sigma_C$ (for SF, the gas surface density threshold $\Sigma_C = 8 \ M_\odot/pc^2$). The gas density grows faster in the inner parts of the disk, therefore, the normal SF there occurs on a shorter time-scale. The derived median values of $\tau_{SF,i}$ for each ring are given in Table 3.
3. RESULTS

We succeeded to calibrate the smooth SF 1-D models and transform them to the system common to the stochastic SF 2-D models. Therefore, by comparing the evolution of the main SF parameters for both models, we were able to clearly demonstrate the large effects arising due to SF stochasticity, see Fig. 3 for the case of low stochasticity (LS) model.

We do not see strong stochasticity effects on the gas surface density and metallicity evolution. However, the effect of these parameters on the SF rate at the early ages is evidenced by strong discrepancy between the 1-D and 2-D models. This effect appears due to a low gas surface density, which is insufficient for normal self-propagating SF in the 2-D models. A huge scatter in the SF rate is prominent, being the largest in the central regions and outskirts of the galaxy disk. In the central disk regions the scatter is partly caused by a smaller number of cells forming the ring 1 kpc wide. In the disk outskirts the scatter is large because the low gas density prevents the steady self-propagating SF.
Fig. 3. The evolution of the gas surface density, SF surface density and gas metallicity in radial rings. The white line indicates a smooth SF in 1-D galaxy model based on the stochastic 2-D model (LS). The black dots represent eight independent runs of the LS model averaged within 1 kpc wide rings, the gray dots are for 0.1 kpc wide rings. The time step of the LS models is 10 Myr.

Fig. 4. The same as in Fig. 3, but for the HS model.
Fig. 5. Radial profiles of the gas surface density, SF surface density and metallicity at different time. The white circles indicate a smooth SF 1-D model. The black dots indicate the mean values of eight independent runs of the LS model averaged within 1 kpc wide rings; the error bars show the standard deviations in the scatter of the model values. The gray dots indicate the LS models averaged within 0.1 kpc wide rings. The time bin for averaging was 100 Myr.

Fig. 6. The same as in Fig. 5, but for the HS model.
Fig. 7. The same as in Fig. 3, but for the surface brightness in the GALEX $FUV$, $V$ and $K$ passbands.

Fig. 8. The same as in Fig. 7, but for the HS model.
Fig. 9. The same as in Fig. 5, but for the surface brightness in the GALEX FUV, V and K passbands.

Fig. 10. The same as in Fig. 9, but for the HS model.
Even stronger stochasticity effects on the SF rate are seen in the 2-D models of high stochasticity (HS), see Fig. 4. The smooth SF 1-D models, shown in all figures, are calibrated only versus the LS models, because the differences between the LS and HS calibrations are small.

In order to demonstrate the variations of stochasticity effects along the galaxy radius, we also show the same parameters displayed as radial profiles at different evolutionary times, see Fig. 5 (LS) and Fig. 6 (HS).

It is well known that spectral energy distributions of stellar populations are very sensitive to the bursting SF. The evolution of the surface brightness in the GALEX FUV, V and K passbands at different distances from the galaxy center, averaged within rings 1 kpc wide, are shown in Fig. 7 (LS) and Fig. 8 (HS). Naturally, the largest stochasticity effects are seen in the GALEX FUV passband. In the outskirts of the disk, however, a large scatter is seen even in the V and K passbands.

The variations of stochasticity effects along the galaxy radius for the same passbands, as radial profiles at different evolutionary times, are shown in Fig. 9 (LS) and Fig. 10 (HS). Note, that the stochastic effects almost vanish for the V and K passbands at the ages older than 5 Gyr. However, even such small photometric effects of stochasticity can be measured with the present-day observational technique.

4. CONCLUSIONS

We have demonstrated that our stochastic star formation 2-D galaxy models are, on average, consistent with the smooth star formation 1-D models, described by the empirical Schmidt-Kennicutt law. However, they show large variations of star formation rate and surface photometric parameters, especially in the UV range, across the disk and in time. The largest stochasticity effects are predicted to occur in the central regions and outer parts of the galaxy disk and during the first 1 – 2 Gyr from the beginning of the formation of the galaxy.

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