ARE LOW SURFACE BRIGHTNESS DISKS YOUNG?

PAOLO PADOAN
Theoretical Astrophysics Center, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark; padoan@tac.dk

RAUL JIMENEZ
Royal Observatory, Blackford Hill EH9-3HJ, Edinburgh, UK; raul@roe.ac.uk

AND

VINCENZO ANTONUCCIO-DELOGU
Osservatorio Astrofisico di Catania, Città Universitaria, Viale A. Doria 6, 95125 Catania, Italy

Received 1996 September 11; accepted 1997 March 3

ABSTRACT

We reconsider the problem of the age of the stellar disks of late-type low surface brightness galaxies (LSBs) by making use of a new IMF recently derived from numerical fluid dynamics simulations (Padoan, Nordlund, & Jones 1997), and a new synthetic stellar population code, based on Jimenez & MacDonald (1997) evolutionary tracks and Kurucz atmospheric models (Kurucz 1992).

We find that the disks of LSBs are not necessarily formed very recently. Their colors seem to indicate that the disks of LSBs started to form stars at least 7 Gyr ago, and more likely about 9 Gyr ago, and therefore contrary to what has been claimed in the literature disks of LSBs are not young.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: fundamental parameters

1. INTRODUCTION

Late-type low surface brightness galaxies (LSBs) are considered to be very young stellar systems, because of their rather blue colors (de Blok, van der Hulst, & Bothun 1995; McGaugh & Bothun 1996), very low oxygen abundances (McGaugh 1994), and the lack of any other suitable explanation. Based on these observational evidences, there have been recently theoretical suggestions that LSBs are formed inside dark matter halos that collapsed very recently, at \( z \leq 1 \), from density fluctuations of small amplitude (Dalcanton, Spergel, & Summers 1996; Mo, McGaugh, & Bothun 1994).

In this work we study the colors of LSBs from the point of view of synthetic stellar populations (SSP) and show that LSBs could be considerably older than claimed in the quoted literature. Recently, one of us (P. P.) has obtained a stellar initial mass function (hereafter P-IMF) starting from high-resolution numerical simulations of the supersonic random motions in the interstellar medium (Nordlund & Padoan 1997; Padoan, Jones, & Nordlund 1997). Here we will use this P-IMF into the latest version of our synthetic stellar population code, which is based on Jimenez & MacDonald (1997) evolutionary tracks and Kurucz atmospheric models (Kurucz 1992). Our synthetic stellar population models are better than the old Larson & Tinsley (1978) models used by McGaugh & Bothun (1996), since they incorporate the latest developments in stellar physics (Jimenez & MacDonald 1996), include all late stages of stellar evolution (red giant branch, horizontal branch, and asymptotic giant branch), and use a careful treatment of mass loss (Jimenez et al. 1996). In addition, the sampling of the late stages of stellar evolution is done much better, we use around \( 10^8 \) stars to compute a synthetic model. With this we compute synthetic colors for LSBs (§ 2), and we show how these can be used to set a lower limit on the ages of their stellar disks (§ 3). We also show that the total magnitude of the galaxies is consistent with our model and with estimates of oxygen abundance in the gas (§ 4).

2. SYNTHETIC STELLAR POPULATIONS FOR LOW SURFACE BRIGHTNESS GALAXIES

In the following, when we will refer to LSBs, we will always mean the sample of late-type disk galaxies observed by de Blok et al. (1995). For each galaxy of their sample the H i surface density, and the surface brightness profiles in several bands are published.

LSBs are found to be rather blue. De Blok et al. (1995) noted that it is difficult to understand the colors of LSBs, if their stellar population is old or forming at a declining rate. McGaugh & Bothun (1996), from the analysis of their sample, concluded that the stellar populations in LSBs must be very young, because of the very blue colors, the very low metallicity, and the lack of any other suitable explanation.

In order to verify these statements, we have produced models of LSBs made of exponential stellar disks, with the stellar IMF as predicted by the P-IMF. At variance with other IMF, the P-IMF contains no free parameters, and it is based on a model for the structure and dynamics of molecular clouds that has strong observational support (Padoan, Jones, & Nordlund 1997; Padoan & Nordlund 1997).

The P-IMF is designed to model large-scale star formation, and contains a dependence on mean density \( n \), temperature \( T \), and velocity dispersion, \( \sigma_v \), of the star-forming gas. The mean stellar mass is given by

\[
M_* = 1.6 \times 10^7 \left( \frac{T}{10 \text{ K}} \right)^{1/2} \left( \frac{n}{10 \text{ cm}^{-3}} \right)^{-1/2} \left( \frac{\sigma_v}{5 \text{ km s}^{-1}} \right)^{-1} M_\odot.
\]

As a significant example we apply the P-IMF to a simple exponential disk model, with height scale equal to 100 pc, length scale equal to 5 kpc, and total mass equal to \( M_\odot = 3 \times 10^9 M_\odot \). The value of the mass is chosen as representative of the H i content of the galaxies (de Blok, McGaugh, & van der Hulst 1996). The value of the length scale is chosen to
reproduce the (low) surface density of the H I disks; the typical photometric length scale (de Blok et al. 1995) of the disks is a bit smaller than 5 kpc, but that can be understood as the effect of a higher star formation efficiency toward the center of the disks, than in their outer parts. The adopted velocity dispersion for the gas is the disk vertical velocity dispersion needed to match scale height. Our results about colors do not depend strongly on these particular values, however.

As a measure of the gas velocity dispersion we use the disk vertical velocity dispersion. We finally assume that all stars are formed in a cold gas phase, at $T = 5 \times 10^4$ K.

Figure 1 shows the IMF predicted for such a disk at 2 and 10 kpc from its center, compared with the Miller-Scalo IMF (Miller & Scalo 1979).

To compute the synthetic colors we used the latest version of our synthetic stellar population code (Jimenez et al. 1997). The code uses the library of stellar tracks computed with JMSTAR9 and the set of atmospheric models calculated by Kurucz (Kurucz 1992). A careful treatment of all evolutionary stages has been done following the prescriptions in Jimenez et al. (1995) and Jimenez et al. (1996). Different star formation rates and stellar IMF are incorporated in the code, so a large parameter space can be investigated.

We find that the star formation in LSBs can be adequately described with an initial burst, followed by a quiescent evolution up to the present time. It has been already remarked (van der Hulst et al. 1993) that LSBs’ gas surface densities are too low to allow efficient star formation according to Kennicutt criterion (Kennicutt 1980). Therefore, it is reasonable to argue that significant star formation is limited to an initial burst.

We find that the colors of LSBs are not difficult to reproduce.

Indeed, one can easily see, from the theoretical models by Kurucz (1992), that even a single star with low metallicity ($Z = 0.0002$) can reproduce the colors of LSBs. As an example, the colors of a typical galaxy from the sample of de Blok, van der Hulst, & Bothun, namely F568–V1, are $U - B = -0.16$, $B - V = 0.57$, $B - R = 0.91$, $V - I = 0.77$ (luminosity-weighted); the colors of a Kurucz model with temperature $T = 5500$ K, log $(g) = 4.5$, $Z = 0.0002$ are $U - B = -0.17$, $B - V = 0.56$, $B - R = 0.94$, $V - I = 0.75$. This model corresponds to a star of $\approx 1 M_\odot$ having a lifetime of $\approx 10$ Gyr. Obviously, the reason for such a good match does not lie in the fact that the stellar IMF does not contain any star more massive than $1 M_\odot$, as suggested in the past (Romanishin, Strom, & Strom 1983; Schombert et al. 1990), but simply in the fact that $1 M_\odot$ is an estimate of the mass at the turn-off for the stellar population of F568–V1, which gives an age for this galaxy of about 10 Gyr. We stress the fact that a low metallicity is required in order to fit all colors of the disks of LSBs.

### 3. THE AGE OF LOW SURFACE BRIGHTNESS GALAXIES

In Figure 2 we plot the time evolution of the colors for a very low metallicity ($Z = 0.0002$).

In order to compare the theoretical prediction with the observed colors, we have used the mean values of the luminosity-weighted colors listed in Table 4 of de Block et al. (1995). The error bars represent the dispersion around the mean, rather than the photometric uncertainty. It is clear that the fit is excellent for an age between 7 and 10 Gyr, while for an age younger than 7 Gyr, the theoretical $B - V$ and $B - R$ colors are too blue, compared with the data.

Since the colors $B - V$ and $B - R$ are the best ones to constrain the age of the galaxies, we show in Figure 3 the color-color diagram ($B - V$, $B - R$). The continuous line is the time trajectory of our model, from about 3 Gyr (left) to 12 Gyr (right). The two dashed lines divide the region with

![Figure 1](image1.png)  
**FIG. 1.—** Theoretical IMF at 2 and 10 kpc from the center of the disk (solid lines). The dashed line shows the Miller-Scalo IMF.

![Figure 2](image2.png)  
**FIG. 2.—** Time evolution of the colors in a model with metallicity $Z = 0.0002$ and star formation in a initial burst of $5 \times 10^7$ yr. The diamonds represent the observed mean values for the sample of LSBs (de Blok et al. 1995), and the error bars the dispersion around the mean. The mean colors of the sample indicates that the galaxies are probably older than 7 Gyr.

![Figure 3](image3.png)  
**FIG. 3.—** Time trajectory of the model in the ($B - V$, $B - R$) diagram. The diamonds are the observed luminosity weighted colors of LSB disks, from de Block et al. (1995). The trajectory are from 3 Gyr (left) to 12 Gyr (right). The dashed lines mark the 7 Gyr age. Most galaxies are apparently older than 7 Gyr.
corresponding age lower than 7 Gyr, from the region with age higher than 7 Gyr. This plot shows that the model reproduces well the colors of each galaxies (not only their mean value) and that most galaxies are probably older than 7 Gyr, as was concluded from the values of the mean colors of the sample (Fig. 2).

Such old ages may seem difficult to reconcile with those of the relatively young stellar populations in normal late-type galaxies, which have $U - B$ and $B - V$ colors comparable to those of LSBs, and $B - R$ and $V - I$ even redder. However, the very blue colors in LSBs are apparently very well explained by the very low metallicities, rather than by the young stellar ages.

4. TOTAL MAGNITUDE AND OXYGEN ABUNDANCE

In Figure 4 we have plotted the $B - V$ color of our model versus its absolute $B$ magnitude, at different times. The continuous line is for a star formation efficiency (SFE) of 0.3, the dashed line for a SFE = 0.6 (therefore more luminous). The diamonds are the observed galaxies. The vertical error bar is the approximate photometric uncertainty (0.1 mag), while the value of the $B$ magnitude has been rescaled to the total mass of our model, assuming that the stellar mass is proportional to $h^2$, where $h$ is the disk photometric length scale. The tick marks correspond to the age of the different models in Gyr.

The authors are grateful to the referee for motivating improvements in the paper.

This work has been supported by the Danish National Research Foundation through its establishment of the Theoretical Astrophysics Center. R. J. and V. A. D. thank the Theoretical Astrophysics Center for the kind hospitality and support.

The authors are grateful to the referee for motivating improvements in the paper.
REFERENCES

Dalcanton, J. J., Spergel, D. N., & Summers, F. J. 1996, preprint
de Blok, W. J. G., McGaugh, S. S., & van der Hulst, J. M. 1996, MNRAS, 283, 18
de Blok, W. J. G., van der Hulst, J. M., & Bothun, G. D. 1995, MNRAS, 274, 235
Jimenez, R., Jørgensen, U. G., Thejll P., & MacDonald, J. 1995, MNRAS, 275, 1245
Jimenez, R., & MacDonald, J. 1996, MNRAS, 283, 721
———. 1997, in preparation
Jimenez, R., Thejll, P., Jørgensen, U. G., MacDonald, J., & Pagel, B. 1996, MNRAS, 282, 926
Jimenez, et al. 1997, in preparation
Kennicutt, R. C. 1980, ApJ, 344, 685
Kurucz, R. 1992, ATLAS9 Stellar Atmosphere Programs and 2km/s Grid
CDROM Vol. 13

Larson, R. B., & Tinsley, B. M. 1978, ApJ, 219, L46
McGaugh, S. S. 1994, ApJ, 426, 135
McGaugh, S. S., & Bothun, G. D. 1996, preprint
Miller, G. E., & Scalo, J. M. 1979, ApJS, 41, 413
Mo, H. J., McGaugh, S. S., & Bothun, G. D. 1994, MNRAS, 267, 129
Nordlund, Å., & Padoan, P. 1997, in preparation
Padoan, P., Jones, B. J. T., & Nordlund, Å. 1997, ApJ, 474, 730
Padoan, P., Nordlund, Å., & Jones, B. J. T. 1997, MNRAS, submitted
Padoan, P., & Nordlund, Å. 1997, in preparation
Romanishin, W., Strom, K. M., & Strom, S. E. 1983, ApJS, 53, 105
Schombert, J. M., Bothun, G. D., Impey, C. D., & Mundy, L. G. 1990, AJ, 100, 1523
van der Hulst, J. M., Skillman, E. D., Smith, T. R., Bothun, G. D., McGaugh, S. S., & de Blok, W. J. G. 1993, AJ, 106, 548