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The Interstellar Medium in LSB Galaxies

W.J.G. de Blok

School of Physics, University of Melbourne, Parkville VIC 3052, Australia

Abstract. I describe the properties of the interstellar medium in LSB galaxies, and conclude that apart from low density the other important factor determining the slow evolution of LSB galaxies is the metallicity, and (due to inefficient cooling) the corresponding lack of large amounts of molecular gas.

1. Introduction

Deep surveys of the night-sky have uncovered a large population of disk galaxies with properties quite different from those of the extensively studied "normal" high surface brightness (HSB) galaxies. These so-called Low Surface Brightness (LSB) galaxies, which I will be discussing here, are generally dominated by an exponential disk, with scale lengths of a few kpc. Morphologically they form an extension of the Hubble sequence towards very late-type galaxies.

As the evolutionary rate of a galaxy may in fact be reflected in its surface brightness, LSB galaxies are interesting in that they may be a local example of unevolved galaxies. For example, the gas fraction ($M_{\rm gas}/M_{\rm gas+stars}$) increases systematically with decreasing surface brightness, from a few percent for early type spirals to values approaching unity for late type LSB galaxies (McGaugh & de Blok 1996). In many LSB galaxies the gas mass exceeds the stellar mass.

It is still unclear what the physical driver is for the difference between HSB and LSB galaxies. Investigations of their dynamics, using H I observations (de Blok et al. 1996), suggest that LSB galaxies are low-density galaxies. This is one of the favoured explanations for the low evolution rate of LSB galaxies (see e.g. van der Hulst et al. 1987), as this implies a large dynamical time-scale.

In this paper I will briefly discuss what is known about the interstellar medium (ISM) in LSB galaxies, and show that apart from density, metallicity is one of the main causes for the HSB/LSB difference. A fuller treatment can be found in Gerritsen & de Blok (1998) and de Blok & van der Hulst (1998b).

2. Properties of "normal" LSB galaxies

Measurements of the colours of LSB galaxies by McGaugh (1992), van der Hulst et al. (1993), McGaugh & Bothun (1994), de Blok et al. (1995) all showed that the colours of LSB galaxies are among the bluest known for non-interacting disc galaxies. Two possible causes for these blue colours are low metallicity and recent star formation. Both are found in LSB galaxies. Hα imaging (McGaugh

1992) shows that a few regions of star formation are usually present in LSB galaxies. The low surface brightness of the underlying disc ensures that only a small amount of star formation is needed to significantly influence the colours (de Blok et al. 1995). Measurements of the oxygen abundances in HII regions in LSB galaxies (McGaugh 1994, de Blok & van der Hulst 1998) show that the metallicity is on average 0.2-0.5 solar.

In summary, LSB galaxies are extended, low density galaxies, that are still in an early stage of galaxy evolution. But is it just density (that is gravity) that causes these long time-scales, or does the state of the ISM itself also play a role. This was investigated using N-body simulations. These will be discussed in the next section.

3. N-body simulations

A first attempt was made at modelling the ISM in LSB galaxies to test the density hypothesis by using a hybrid N-body/hydrodynamics code (TREESPH; Hernquist & Katz 1989). An extensive description is of the model, as well as the recipe for transforming gas into stars and the method for supplying feedback onto the gas given in Gerritsen & Icke (1997, 1998). The recipe works well for normal HSB galaxies, with the energy budget of the ISM as prime driver for the star formation. The simulations allow for a multi-phase ISM with temperature between $10 < T < 10^7$ K. One can therefore consider cold $T < 10^3$ K regions as places for star formation (Giant Molecular Clouds in real life).

There are many ways to construct model galaxies. Here a galaxy model is built after an existing galaxy with well-determined properties. LSB galaxy F563-1 is a late-type LSB galaxy, representative of the field LSB galaxies. The optical properties of this galaxy are described in de Blok et al. (1995); measurements of metallicities in H II regions are described in de Blok & van der Hulst (1998a); a neutral hydrogen map and rotation curve are given in de Blok et al. (1996). Parameters such as stellar velocity dispersion, which cannot be measured directly, are set in comparison with values measured locally in the Galaxy. The current star formation rate was deduced from Hα imaging. For convenience these data are summarised in Table 1.

Table 1. Parameters for F563-1 ($H_0 = 75$ km s^{-1} Mpc^{-1}).

L_B	$1.35 \times 10^9\ L_\odot$	
h_*	2.8 kpc	center ($R < 5$ kpc)
h_*	5.0 kpc	outside ($R > 5$ kpc)
SFR	$0.05\ M_\odot$/yr	
$M_{\rm HI}$	$2.75 \times 10^9\ M_\odot$	
$v_{\rm max}$	113 km/s	
$\rho_0^{\rm halo}$	$0.0751\ M_\odot/{\rm pc}^3$	
$R_c^{\rm halo}$	1.776 kpc	

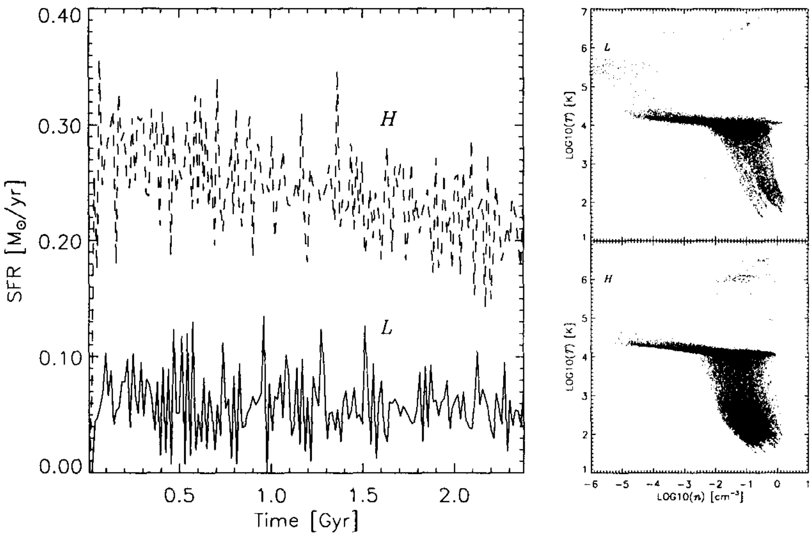

Figure 1. **Left:** The evolution of the SFR versus time. The lower line shows the SFR from simulation L, the upper line represents simulation H. **Right:** Phase diagrams (temperature versus number density) for the simulations. Top panel shows simulation L, bottom panel shows simulation H; each dot represents an SPH particle. The individual particles at the top of each diagram are hot SN particles. Simulation H clearly shows a two-phase structure, while in simulation L almost all gas is in the warm ($T \approx 10^4$ K) phase (85%)

The most difficult problem faced in constructing a model is converting the measured luminosity to a stellar disk mass. This is one of the most persistent problems in analysing the dynamics of galaxies, and, unfortunately, the present observations do not provide a unique answer for this stellar disk mass-to-light ratio $(M/L)_*$. Rather than using the so-called "maximum disk" value $(M/L)_* = 9$, which is an upper limit to the possible values of $(M/L)_*$, a value was adopted based on colours and velocity dispersions of $(M/L)_* = 1.75$. An extensive motivation for this choice is given by de Blok & McGaugh (1997).

An isothermal halo is included in the calculations as a rigid potential. This is justified since the galaxy model evolves in isolation. Any contraction of the halo under the influence of the disk potential will thus be ignored. This is not expected to be important anyway as the mass of the disk (assuming $(M/L)_* = 1.75$) is only 4 per cent of the measured halo mass. For the simulations 40,000 SPH particles and 80,000 star particles are used initially. This corresponds to an SPH particle mass of $9.6 \times 10^4\ M_\odot$ and a star particle mass of $3.0 \times 10^4\ M_\odot$. The low density as found in LSB galaxies, by itself is not sufficient to reproduce the low observed SFRs of LSB galaxies. *Low metallicity gas is required to explain the properties of LSB galaxies.*

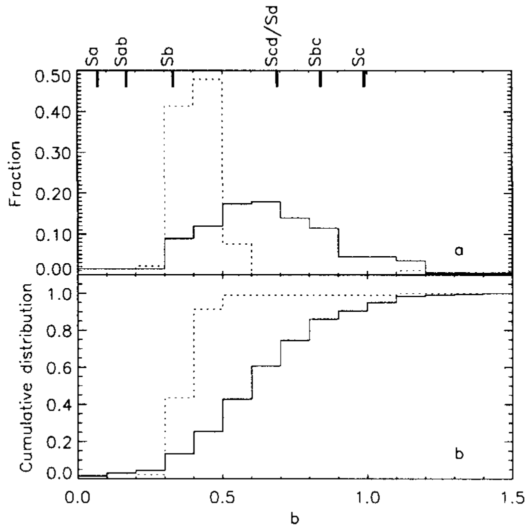

Figure 2. (*a*) Distribution of the birthrate parameter b, the ratio of the current SFR to the average past SFR. Solid line shows the b values derived for simulation L, dotted line shows the b distribution for a simulation of an Sc galaxy (Gerritsen & Icke 1998). On the top are average b values for different types of galaxies (Kennicutt et al. 1994). The bottom panel shows the cumulative distribution for the two simulations. Less than 20% of the b values for the LSB galaxy are below $b = 0.4$, hence one expects at most 20% of LSB galaxies to be "red"

To show this two model galaxies were constructed using the structural parameters of F563-1. Model H represents an LSB galaxy with a solar metallicity gas. Although the structural parameters relevant for F563-1 were used, the model is in effect a model HSB galaxy, which is "stretched out" to give the low (surface) densities found in LSB galaxies. This model therefore tests the low-density hypothesis. The other model, L, has the same structural parameters as H, but in addition the cooling efficiency of the gas below 10^4 K was lowered by a factor of seven. Cooling below 10^4 K is dominated by metals, so lowering the efficiency is equivalent to lowering the metallicity by an equal amount. Model L thus most closely approximates what is currently known observationally about LSB galaxies. Direct observational support for a low metallicity ISM in LSB galaxies comes from oxygen abundance measurements of H II regions in LSB galaxies. Those studies yield metallicities of approximately 0.5 times solar metallicity (McGaugh 1994). Measurements of the oxygen abundance in F563-1 (de Blok & van der Hulst 1998a) give an average oxygen abundance of 0.15 $Z_{\odot}$ (compare with the difference in metallicity between models H and L).

For both simulations the SFR varies on time scales of a few tens of Myr and the amplitude of these variations can exceed 0.1 $M_{\odot}$/yr. However, only simulation L yields a simulated average SFR that comes close to the observed value. The SFR of model H is a factor of ~ 5 too high. The rapid variability in the SFR is due to the discrete nature of star formation in the simulation. New star particles have a mass of approximately $5 \times 10^4\ M_\odot$ and thus represent (large) stellar clusters. A small number of clusters will give the impression of a rapidly varying SFR (as in LSB galaxies). When the SFR increases, the large numbers of fluctuations going on at the same time will give the impression of a smoothly varying SFR. It is therefore not so much the absolute value of the average SFR which determines the colours, but the contrast of any SF fluctuation with respect to the average SFR. For LSB galaxies the large contrast leads to blue colours.

Figure 1 shows the temperature versus density for all gas particles in both simulations. The top panel shows simulation L; the bottom panel shows the phase diagram for simulation H. Most particles have a temperature of 10^4 K. In simulation H a large fraction of the particles has a temperature of about 100 K. This simulation shows a two-phase structure, and resembles the ISM in simulations of HSB galaxies (Gerritsen & Icke 1998). Quantitatively, the cold gas fraction ($T < 1000$ K) makes up 37% of the total gas mass in simulation H and only 4% in simulation L. This reflects the cooling properties of the gas: in simulation L seven times less heat input is required to keep the gas at 10^4 K as in simulation H. In practice simulation L only contains a warm, one-phase ISM. The simulated absence of metals prevents the ISM from cooling efficiently. The essential information to retain from this phase diagram is that we need a different ISM for LSB galaxies, where the bulk of the gas is not directly available for star formation, as it is too warm (of order 10^4 K). The simulations do not include phase transitions from neutral to molecular gas, but as an estimate for the H_2 mass one can consider all star forming gas ($T \lesssim 300$ K) to be molecular. This gas represents less than 2% of the total gas mass. One thus expects the disks of LSB galaxies to contain only negligible amounts of (cold) molecular gas. This is consistent with observations by Schombert et al. (1990) and de Blok & van der Hulst (1998b) which will be discussed below.

Fluctuations in the SFR as shown in Fig. 3, may very well explain why most of the LSB galaxies detected in surveys are blue. As McGaugh (1996) argues, the selection effects against finding red ($B - V > 1$) LSB galaxies on the blue sensitive plates on which surveys have been carried out are quite severe. Assuming that blue LSB galaxies are currently undergoing a period of enhanced star formation, implies that there exists a population of *red, non-bursting, quiescent* LSB galaxies. The fraction of red LSB galaxies can be estimated by calculating the distribution of the birthrate parameter b for simulation L. The b parameter is the ratio of the present SFR over the average past SFR. Birthrate parameters have been determined for a large sample of spiral galaxies by Kennicutt et al. (1994). The trend is that early type galaxies have small values for b, while late type and irregular galaxies have large values for b, often exceeding 1, indicating that those galaxy are still actively forming stars. Here this analysis is applied to simulation L in order to estimate the fractions of blue and red LSB galaxies.

In Fig. 2a I plot the distribution of b values for simulation L (solid line), where I have followed the value of b over the duration of the simulation in steps of 15 Myr. Thus if the SFR peaks in a particular time interval, the corresponding value of b will be high. If the SFR is low in this time interval b is also low. In total there are 200 b values. Also shown in Fig. 2a are the b distribution for a simulation of an HSB Sc galaxy (Gerritsen & Icke 1998, dotted line) and the mean values for different galaxy types (from Kennicutt et al. 1994). Due to the low average SFR the distribution for the LSB simulation is much broader than the distribution for the HSB simulation, and the average b value is larger. The LSB galaxy has b values larger than the average for early type galaxies for most of the time. "Classical" LSB galaxies are blue compared to HSB galaxies, they thus have an excess of recent star formation or equivalently a higher b value. I now define a LSB galaxy to be "blue" if its birthrate parameter b exceeds the average value of b for a HSB late-type galaxy (see Kennicutt et al. 1994 for relations between birthrate parameter and colour). Fig. 2a shows that this requires that $b_{LSB} > \langle b_{HSB} \rangle \approx 0.4$.

LSB galaxies that do not meet this requirement are "red": non-bursting, but nevertheless still gas-rich. From Fig. 2b (which shows the cumulative b distribution) once can see that over 80 percent of the fluctuations result in blue LSB galaxies. Less than 20 percent of the fluctuations therefore results in red LSB galaxies. Using population synthesis models and the burst strengths found in simulation L one can derive that the red LBS galaxies must have $B - V \sim 1$, $R - I \sim 0.6$ and $\mu_0(B) = 24.5$ for the red population.

A recent CCD survey (O'Neill et al. 1997) has picked up a class of LSB galaxies which have $\mu_0(B) \simeq 24$ and $B - V \simeq 0.8$. If some of these galaxies are indeed the non-bursting counterparts of the blue LSB galaxies, they should be metal-poor and gas-rich, and share many of the properties of the modelled galaxies.

In summary, if the blue colours found in LSB galaxies are the result of fluctuations in the star formation rate, then this implies that the red gas-rich LSB galaxies constitute less than 20% of the gas-rich LSB disk galaxies. This does not rule out the existence of a population of red, gas-poor LSB galaxies. These must however have had an evolutionary history quite different from those discussed here and possibly have consumed or expelled all their gas quite early in their life.

4. Molecular gas

Three galaxies from the sample of LSB galaxies in de Blok et al. (1996) were observed with the 15-m James Clerk Maxwell Telescope at Mauna Kea, Hawaii, in the ^{12}CO (J= 2 – 1) line at 230 GHz rest-frequency (see de Blok & van der Hulst 1998b). No CO emission was detected at any of the positions after on-source integration times of $\sim$ 1.5 hours per position. Typical RMS-noises at 500-kHz-resolution were $T_A^* \sim 6$ mK.

The non-detections of CO can be taken at face-value to suggest that LSB galaxies are poor in H_2, thus confirming the models. There are, however, several factors which complicate this naive interpretation. The most important of these is the conversion factor X which is used to convert the measured CO brightness temperature into an H_2 mass. The value of X is uncertain and is inferred to have a large range.

Wilson (1995) demonstrated that Maloney & Black's (1988) ideas concerning a variation in X with metallicity is borne out in observations of galaxies in the

Local Group. Based on measurements of the CO luminosity and determination of the virial masses of individual clouds, Wilson finds that the conversion factor increases as the metallicity decreases. Israel (1997) investigated the metallicity dependence of X in a different way using the FIR surface brightness and HI column density to estimate the column density of H_2 and found an even steeper relationship.

The average oxygen abundance for the observed LSB galaxies is $12 + \log(O/H) \sim 8.4$. Using the above results this would lead to conversion factor values X of 2 to 6 times the Galactic value.

The star formation rates and HI column densities in the galaxies used to derive the dependence of X on metallicity are appreciably higher than those commonly found in LSB galaxies. The lower star formation rate implies a lower energy density of the radiation field and consequently lower dissociation of the CO and H_2. The result will be that X probably is not as large as in the extreme case of the SMC, so some care should be exercised in using these results for estimating the H_2 mass limits for LSB galaxies. One effect of the low metallicities is a less efficient cooling of the ISM, which leads to *higher* cloud temperatures, making it difficult for a cold molecular phase to exist. Bearing these effects in mind I estimate that X will be ~ 4 times the Galactic value in LSB galaxies. In other words, LSB galaxies should contain 4 times more H_2 than the Galactic value suggests. The upper limits then imply that LSB galaxies roughly have (less than) 25% of their gas mass in the form of H_2. This is still lower than is found in HSB galaxies.

The conclusion then is that there are no large amounts of H_2 hidden in LSB galaxies. The low star formation rates measured in LSB galaxies can thus be explained by the lessened importance of a molecular component. A detailed comparison between the properties of star forming regions in LSB and HSB galaxies may be a good way to put more constraints on the way stars form in environments that lack a cold component.

5. Conclusions

What then causes the low evolution rate for LSB galaxies? The low density has often been invoked to explain this, since the dynamical time scales with $1/\sqrt{\rho}$. This scenario is exactly what is tested in simulation H. The result is striking: adopting "standard" values for the star formation process results in a SFR identical to the rates of HSB galaxies.

Thus the low density in itself seems not capable of doing the job, and we have to rely on a scarcity of heavy elements to reproduce a true LSB galaxy. This fits in logically with the notion that stars are the producers of these elements; the low star formation activity prevents metal enrichment of the ISM. It implies that the SFR has been low throughout the evolution of LSB galaxies, and that these galaxies are "trapped" in their current evolutionary state: low density prevents rapid star formation, which prevents enrichment of the ISM, which prevents cooling, resulting in a warm one-phase ISM. So although the lack of metals is directly responsible for the low SFR, the low density may ultimately determine the fate of LSB galaxies.

Due to the fluctuations in the SFR in LSB galaxies and their large contrast with the average SFR, the spread in colours among LSB galaxies will be larger than among HSB galaxies. From the distribution of birthrate parameters in the simulations one deduces that, if the currently known blue *gas-rich* LSB galaxies are the most actively star forming LSB galaxies, they constitute over 80 percent of the total population of *gas-rich* field LSB disk galaxies. This implies that there is at most an additional 20 percent of quiescent, gas-rich LSB disk galaxies. This does not preclude the existence of an additional red, gas-poor population. However this population must have an evolutionary history quite different from that described in this work.

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