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On the low rate of star formation in LSB galaxies

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Abstract. It is well-known that the low surface brightness (LSB) galaxies are gas-rich and yet have a very low star formation rate. The particular case of UGC 7321 will be discussed where high gas dispersion, as deduced from our dynamical study, is argued to be responsible for the low star formation rate. This article highlights some of the dynamical issues including the low star formation seen in the LSB galaxies, and points out the open problems in this topic.

Keywords : galaxies: halos – galaxies: individual – UGC 7321 – galaxies: kinematics and dynamics – stars : formation

1. Introduction

The low surface brightness (LSB) galaxies are faint, diffuse galaxies with a central brightness of ~ 23 mag arc sec-2 in the *B*-band, that is, about 30 times fainter as compared to the standard or high surface brightness (HSB) galaxies. The LSB galaxies are fascinating objects: these are gas-rich but surprisingly have not had significant star formation in their entire lifetime, and hence are unevolved. The LSBs are difficult to study since even the centre is fainter than the sky background. Despite this, it is important to study these since these could be more numerous than the HSB galaxies, and this has implications for completeness of the mass spectrum of galaxies. Second, a study of LSBs could tell us how gas-rich galaxies evolved early-on. The term LSB has now come to denote different types of galaxies including the giant LSB galaxies. The first LSB to be detected was *Malin 1*, a giant LSB, these are now known to be rare. *Malin 1* is a massive, extended galaxy with a disk scale length of ~ 70 kpc and a total HI gas mass of 5×10^{10} $M_{\odot}$. Most LSBs, however, are low-mass, disk-dominated, gas-rich yet featureless galaxies with weak spiral features and no bright star-forming regions. This article will focus on this more numerous class of LSBs.

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A brief review of the salient features of LSB galaxies with a particular focus on the dynamical aspects including star formation will be given in this section (Section 1). Next, our dynamical study of UGC 7321, a superthin LSB galaxy will be discussed. This gives a high gas velocity dispersion, which we argue would result in low star formation in this galaxy (Section 2). Section 3 describes an ongoing work about measurement of non-axisymmetry in these galaxies. The results and open questions will be summarised in Section 4.

1.1 Puzzling properties of LSB galaxies

1. The LSB galaxies are gas-rich, with a typical HI gas mass of $\sim 10^9$ $M_\odot$, distributed in an extended reservoir typically extending far beyond the stellar disk. The gas mass fraction is high and is often larger than the mass fraction in stars (McGaugh & de Blok 1997). This is strikingly different from the normal or HSB galaxies where even the most gas-rich galaxies like the late-type Sd galaxies have gas fraction of $\sim$ 0.25. Thus, gas is the main dynamical disk component over the major part of a LSB galaxy.

2. Despite being gas-rich, these show very little star formation. This has been the earliest puzzle about these galaxies. The star formation rate (SFR) per unit gas surface density in LSBs is 10 times smaller than in the HSBs; also these show very few massive stars and supernovae. The observed star formation rate in the HSBs is given by the Schmidt-Kennicutt relation, with the star formation rate per unit area being proportional to the 1.4 power of the surface density of gas (Kennicutt 1998). In contrast, the observed rate is much lower for galaxies including the LSBs with lower gas densities in the range of 1- 10 $M_\odot$ pc^{-2} (e.g., Wyder et al. 2009). The reason for this is not well-understood but it could indicate an inefficient star formation or that the gas density is below the threshold value.

3. There are various physical arguments that have been proposed as to why star formation is not triggered in LSBs.

First, the gas surface density is below the threshold surface density as given by the Toomre Q criterion (Toomre 1964); where $Q = [\kappa \, C \, / \, \pi \, G \, \mu] < 1$ denotes that the system is unstable to the growth of local, axisymmetric perturbations in a thin disk. Here κ is the epicyclic frequency in the disk, μ is the surface density and C is the sound speed in the disk. It should be cautioned that using this criterion to indicate onset of star formation is not strictly correct since no account is taken of the detailed gas physics. Despite this, however, the Toomre Q criterion seems to be a surprisingly good indicator of star formation threshold. That is, the galaxies with densities lower than the Toomre value are seen to lie below the Schmidt-Kennicutt relation. We show (in Section 2) that in addition to the low surface density, a high observed gas velocity dispersion C, could be responsible for the low SFR observed in the LSBs.

Second, in the normal galaxies molecular hydrogen gas (H_2) forms the site of star formation, which is generally lacking in the LSBs. In fact, the molecular gas has only been detected in a few giant LSBs such as Malin 2 (Das et al. 2010). The LSBs have very low metallicities, and low dust content as indicated by negligible dust extinction. Thus dust grains which are the usual sites of formation of H_2 gas are lacking here, hence it is not surprising that the LSBs should have low molecular gas content, and hence low star formation.

Third, the normal triggers for star formation - either secular ones such as gas inflow due to bars, or external ones say due to tidal interactions with galaxies- are weak in the LSBs. In particular the LSBs are found in regions of low galaxy density (Rosenbaum et al. 2009). Our planned work (Section 3) will measure strength of bars in LSBs which will have a bearing on the triggering of star formation.

4. The LSB galaxies are unevolved objects. This is indicated by their bluer colours and lower metallicities which imply that these are slowly evolving via sporadic star formation. The stellar disk has very low surface density with the central values being ~ 10 times smaller than those in the normal or HSB galaxies (de Blok 2006). This is a very important point regarding their dynamical origin and evolution. The low mass disk and the resultant low star formation rate need to be studied further theoretically.

5. The LSBs are dark-matter dominated in terms of the mass fraction from the inner regions (de Blok, McGaugh & Rubin 2001). Within the optical disk, the mass fraction in the dark matter is about 90 % and 10% in baryons, whereas within the same radius the two are comparable in the HSBs. It has been suggested that the dark matter dominance could help prevent star formation but the detailed physical mechanism for this is not yet understood. The dark matter dominance and the weak stellar disk together point to a different formation and evolution of LSB galaxies. Their location in a region of low number density of galaxies could play an important role in the determination of their properties including the formation and stability of low surface density disks. This needs to be investigated by future theoretical studies.

It has been suggested by de Blok (2006) that the LSBs may form an alternate track to the Hubble sequence. While the Hubble sequence is shaped by secular instabilities and galaxy interactions, these are not significant in the evolution of the LSBs.

The most interesting, open question, in a way which defines the LSBs, is, why is there so little star formation in these galaxies? An answer to this question will also shed light on why star formation is allowed to proceed in other galaxies.

2. Dynamical study of UGC 7321, a superthin LSB galaxy

We have an ongoing programme aimed to determine the properties of dark matter halos in galaxies that involves a dynamical study of the vertical scale heights of the interstellar atomic hydrogen (HI) gas. The HI gas typically extends to 2-3 times the stellar disk size and hence is an excellent tracer of the dynamics in the outer regions. The disk is supported in the plane by rotation. Using this the mass within a given radius can be calculated for a given radius. The rotation velocity is observed to be nearly constant to the farthest radius which indicates the existence of a dark matter halo. We note that the vertical structure of the disk gives additional information on the dark matter halo distribution, especially its shape. This information has been underutilized so far.

We use the observed rotation curves and the HI vertical scale height data as simultaneous constraints to obtain the radial density profile and the shape of the dark matter halos in galaxies. A galaxy is modeled as a gravitationally coupled star-gas system in the field of the dark matter halo. The stellar and gas distribution is assumed to be axisymmetric, and is concentric and coplanar. The galactic disk is supported vertically by pressure so that the self gravity of the disk components and the halo is balanced by the vertical pressure in the disk. Due to its lower dispersion, the gas is concentrated closer to the mid-plane than the stars. Hence, despite its low mass fraction, the gas contributes significantly to the gravitational force near the mid-plane. The Poisson equation and the equation for hydrostatic equilibrium along the vertical direction for the stars and gas are solved together so as to obtain their vertical scale height and radial variation (see Narayan & Jog 2002 for details). By comparing the results with the observed data on rotation and the HI gas scale heights, the dark matter halo properties are constrained.

There are only a handful of galaxies which have the measured HI scale height data. We have applied this approach to study the dark matter halo in three galaxies. The somewhat surprising result is that the dark matter halo profile in spiral galaxies does not appear to be universal.

For the Milky Way Galaxy, we get a spherical halo with a density falling faster than the isothermal case (Narayan, Saha & Jog 2005), but this gives a low total mass of the Galaxy as compared to other techniques. Alternatively, a progressively prolate halo with a vertical-to-planar axis ratio of 2 at a radius of 24 kpc explains the HI data well, and also gives a correct value of the total mass of the Galaxy (Banerjee & Jog 2011).

For the nearby Andromeda galaxy, our best-fit model gives an isothermal, flattened halo with an axis ratio of 0.4 (Banerjee & Jog 2008). This lies at the most oblate end of the distribution obtained from cosmological simulations.

For the low surface brightness, superthin galaxy UGC 7321, the best-fit halo is spherical with a pseudo-isothermal density profile. It is compact and dense, and hence it dominates the dynamics even at small radii (Banerjee, Matthews & Jog 2010). The calculated vertical scale height versus radius is compared with the data in Fig. 1. The best-fit central halo density is in the range of 0.039-0.057 $M_\odot$ pc^{-2} and the core radius lies in the range 2.5-2.9 kpc. The core radius thus is comparable to the disk

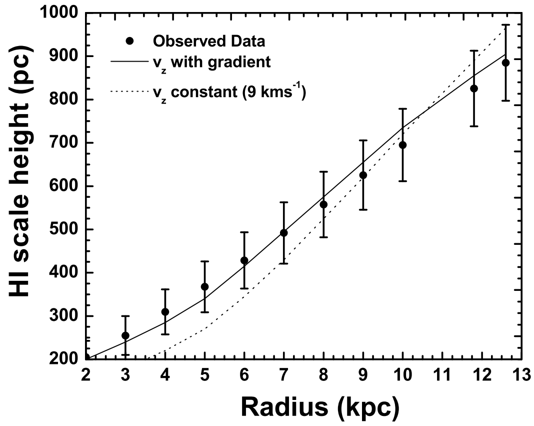

Figure 1. The vertical HI scale height (in pc) vs. galactocentric radius (in kpc) for the best-fit case of a spherical, isothermal halo with a constant velocity dispersion (dotted line), and for the case with the velocity dispersion decreasing slowly with radius (solid line). The latter gives a better fit to the data. This is taken from Banerjee, Matthews, & Jog (2010).

scale length of 2.1 kpc. This is in contrast to the HSB galaxies where the core radius is typically 3-4 times the disk scale length. This plus the high central halo density means that the dark matter halo mass dominates the visible mass from the innermost regions. Thus the dark matter is likely to play a crucial damping or restricting role in the formation of a disk or star formation in this galaxy.

We show that the dark matter is dominant for the determination of the vertical disk structure and dynamics as well. This is illustrated in Fig. 2 which gives a comparative plot of the observed surface density plot of the stars, and the HI gas, and the dark matter halo versus radius. The stellar and the halo surface density were calculated within the total gas scale height. This gives the relative importance of the vertical force near the mid-plane region due to the three components.

2.1 High gas dispersion and its effect on star formation

The HI gas dispersion plays a crucial role in the determination of HI vertical scale height, unfortunately its accurate observational measurement is difficult. The typical value measured for a large sample of about 200 face-on galaxies is 8 km s^{-1} (Lewis 1984). This dispersion is non-thermal in origin while the thermal speed is much lower ($<$ 1 km s^{-1}). For the particular LSB galaxy, UGC 7321, a range of values 7 - 9 km s^{-1} is the observed range, the larger value in this range gives a good fit in our model (see the dotted line, Fig. 1). A better fit requires even higher values of gas dispersion in the inner regions, and a small gradient showing an increase in velocity from 9 to 11 km s^{-1} between 11 to 2 kpc gives the best fit to the data. This high value of gas

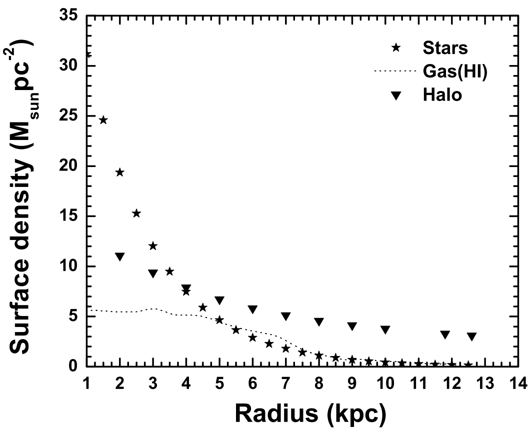

Figure 2. The surface density (in $M_\odot$ pc^{-2}) within the total gas scale height vs. radius (in kpc) for stars, HI gas, and the dark matter halo; this denotes the relative values of the vertical force near the mid-plane. Clearly, the dark matter dominates the vertical dynamics in this galaxy starting from the inner regions ~ 4 kpc or ~ 2 disk scale lengths. This is taken from Banerjee, Matthews, & Jog (2010).

dispersion deduced serendipitously from our model implies a low SFR as discussed below.

This high gas dispersion will increase the value of the Toomre Q parameter and hence could inhibit star formation, as shown next. Recall that $Q = [\kappa \, C \, / \, \pi \, G \, \mu] < 1$ denotes that the system is unstable to the growth of gravitational instabilities while > 1 denotes a stable system. We calculated the values of Q using the observed parameters at a radius of R = 4 kpc (or about two disk scale lengths): for the gas dispersion, C = 7-9 km s^{-1}, the Q values are calculated to be 4 - 5.1, which are already much greater than 1 indicating that the disk is stable. A higher value of C = 11 km s^{-1} (needed to explain the HI scale height data) gives an even higher Q value = 6.3 . Thus, UGC 7321 is highly stable against the growth of gravitational instabilities, and hence star formation. We stress that the high gas dispersion and the low gas surface density both contribute to a high value of the Toomre Q parameter in this case.

Interestingly, Das et al. (2010) find a similar high value of 13 km s^{-1} for gas dispersion in the molecular gas in Malin 2. This gives an independent evidence for high gas dispersion in the LSBs.

The high value of gas dispersion in a LSB is unexpected since the various standard sources for energy input into gas are not applicable here. First, the acceleration of HI clouds via supernova as proposed for the Galaxy by McKee & Ostriker (1977) is not applicable here due to very low supernova rates. Second, the dynamical heating due to bars (Das & Jog 1995; Saha, Tseng, & Taam 2010) is not applicable here since

UGC 7321 has no detected bar (Pohlen, Balcells, & Matthews 2004). Thus the source of kinetic energy for the gas in the LSBs is a puzzle.

3. Measurement of non-axisymmetry in centres of LSBs

We propose to measure the non-axisymmetry in the central regions of LSBs via Fourier analysis of galaxy images using the high resolution HST archival data, in a programme started with A. Maybhate (STScI) and J. Gallagher (Univ. of Wisconsin). Although early theoretical work indicated that bars and spiral structure are weak in these galaxies (Noguchi 1987, Mayer & Wadsley 2004), the observational evidence had already shown (Matthews & Gallagher 1997) that bars are quite common in the LSBs. Thus this topic needs to be looked at again. With this motivation in mind, we plan to measure the strength of bars ($m = 2$) and lopsidedness (m=1) where m denotes the azimuthal Fourier component in a sample of LSB galaxies. These asymmetries could drive the gas towards the central regions (see Jog & Combes 2009), and help in AGN fueling.

4. Summary and open questions

We show that a dynamical study of UGC 7321 indicates that it has a surprisingly high HI gas dispersion. This along with the low gas surface density makes the disk strongly resistant to star formation in this galaxy. Thus the high gas dispersion plays an important role in determining the low star formation rate that is observed.

The high value of the gas dispersion is unexpected given that the typical accelerating mechanisms - secular or external (supernovae, bars or interactions)- do not operate efficiently in this case. Future measurements of bars and lopsidedness in these will tell us what role these non-axisymmetric features play in the dynamics of LSBs. The gas dispersion values and the strength of bars need a further systematic study, both via observations and theory. We hope our work has drawn attention to this important topic.

The low star formation rate in the LSBs can be traced in turn to low disk surface density, so that despite a high gas fraction the actual gas surface density is below the threshold for star formation. The question then is, why do low mass disks form and are stable in these galaxies. The dense, compact dark matter halos and the low galaxy density environment may both play an important role in this process. This needs to be explored by N-body simulations of the formation and early evolution of galaxies.

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