

Giant Low Surface Brightness Galaxies: Evolution in Isolation

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Abstract. Giant Low Surface Brightness (GLSB) galaxies are amongst the most massive spiral galaxies that we know of in our Universe. Although they fall in the class of late type spiral galaxies, their properties are far more extreme. They have very faint stellar disks that are extremely rich in neutral hydrogen gas but low in star formation and hence low in surface brightness. They often have bright bulges that are similar to those found in early type galaxies. The bulges can host low luminosity Active Galactic Nuclei (AGN) that have relatively low mass black holes. GLSB galaxies are usually isolated systems and are rarely found to be interacting with other galaxies. In fact many GLSB galaxies are found under dense regions close to the edges of voids. These galaxies have very massive dark matter halos that also contribute to their stability and lack of evolution. In this paper we briefly review the properties of this unique class of galaxies and conclude that both their isolation and their massive dark matter halos have led to the low star formation rates and the slower rate of evolution in these galaxies.

Key words. Galaxies: evolution—galaxies: nuclei—galaxies: active—galaxies: ISM—galaxies: spiral—cosmology: dark matter.

1. Introduction

Giant Low Surface Brightness (GLSB) galaxies are some of the largest spiral galaxies in our nearby universe. However, for decades these galaxies remained undetected in galaxy surveys. This is because their optically dim stellar disks have a brightness that lies close to or below the brightness of the night sky. Early photometric studies of galaxies determined that the central surface brightness of galaxies always lies above the brightness limit of $\mu_B(0) \sim 21.65 \text{ mag arcsec}^{-1}$; this is called the Freeman's law (Freeman 1970). However, Disney (1976) predicted that there may be a population of galaxies that lie below this brightness limit. His study indicated that the brightness of the night sky biased observations against detecting low luminosity galaxies such as Low Surface Brightness (LSB) galaxies. Decades later with better telescopes, it became possible to detect sources well below the Freeman limit. Recent surveys have revealed that LSB galaxies contribute a very significant fraction

of the total galaxy number density in the local ($z < 0.1$) universe (Trachternach *et al.* 2006). The first large LSB or GLSB galaxy to be detected was Malin 1. It was accidentally discovered in a survey of low luminosity galaxies (Bothun *et al.* 1987). In the following years several GLSB galaxies were discovered (Bothun *et al.* 1990; Schombert *et al.* 1992; Sprayberry *et al.* 1993).

Although morphologically LSB galaxies span a very wide range from dwarfs and irregulars to very large disk galaxies (McGaugh *et al.* 1995), they are broadly of two types: (1) LSB dwarf and irregular galaxies and (2) disk LSB galaxies of which the larger ones are called GLSB galaxies. Regardless of their size or morphology, all LSB galaxies share the following common characteristics; poor star formation rates, low metallicities, diffuse stellar disks and extended HI gas disks (Impey & Bothun 1997). The LSB dwarfs and irregulars form the larger fraction of LSB galaxies. Studies indicate that they are the most dominant component of the faint end of the luminosity function in our local Universe (Geller *et al.* 2012). Although optically they are often difficult to detect, they are easily detected in HI surveys. Unlike the more isolated larger LSB galaxies, dwarf LSB galaxies can be found in relatively densely populated parts of the Universe such as galaxy groups (Sabatini *et al.* 2003). The fainter ones are generally found in underdense environments such as nearby voids (e.g. Pustilnik *et al.* 2011).

Disk LSB galaxies are not as common as LSB dwarf galaxies. Studies show that they can span a range of sizes (e.g. Beijersbergen *et al.* 1999) but their Hubble morphological type is well-defined as late type spirals – Sc or Sd. In some cases, where there is a very prominent bulge (e.g. UGC 6614, (R)SA(r)) the galaxies are classified as early type spirals (see Figure 1a). But their low surface brightness disks and other

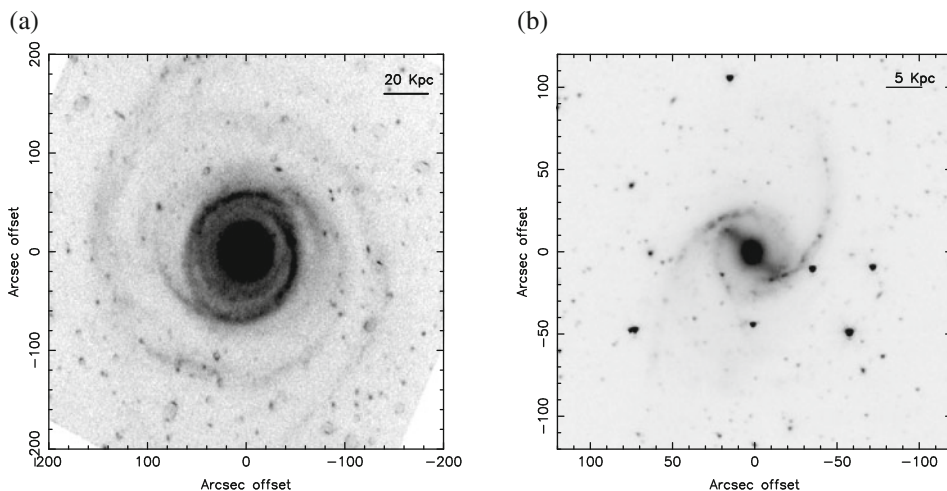


Figure 1. (a) The R band image of the GLSB galaxy UGC 6614. The bar on the top right corner gives the length scale in Kpc. The galaxy has a very prominent bulge and tightly wound spiral arms that form a ring-like structure outside the bulge. The LSB disk extends well beyond the plot boundaries. (b) The 3.6-micron IRAC mid-infrared image of the GLSB galaxy NGC 5905. This is one of the few GLSB galaxies that is also interacting with a nearby companion galaxy (NGC 5908). The interaction has probably induced the formation of the bar and spiral arms.

Table 1. Examples of GLSB galaxies.

Galaxy	Distance (Mpc)	μ_0^a and waveband	Bulge/disk lum. ratio	$M(\text{HI})$ $10^{10} M_\odot$	References
Malin 1	366	26.0, R band	0.40	6.8	Pickering <i>et al.</i> 1997
Malin 2 (F568-6)	201	23.4, B band	0.84	3.6	Pickering <i>et al.</i> 1997
UGC 6614	93.2	24.3, B band	1.35	2.5	Pickering <i>et al.</i> 1997
NGC 7589	120	23.3, R band	1.78	0.9	Pickering <i>et al.</i> 1997
UGC 2936	51.2	24.0, B band	0.83	0.3	Sprayberry <i>et al.</i> 1993
1226+0105	349	23.3, B band	0.51	1.8	Sprayberry <i>et al.</i> 1993
2327–0244 (UM 163)	136	23.2, B band	0.59	0.1	Burkholder <i>et al.</i> 2001

^aExtrapolated disk surface brightness.

properties such as extended HI disks, confirm that they are extreme late type spirals. The really large LSB galaxies are usually referred to as Giant LSB (GLSB) galaxies and are generally isolated systems (Bothun *et al.* 1993). They are found to lie closer to the walls of voids (Rosenbaum *et al.* 2009). This review will focus only on GLSB galaxies; their nuclear and disk properties are very distinct from the LSB dwarf galaxies or smaller LSB disk galaxies.

Apart from their rather exotic and rare nature, GLSB galaxies provide an interesting sample to study how massive dark matter halos can affect star formation and even nuclear activity in galaxies. They also provide an opportunity to understand how galaxies evolve in relative isolation. In this paper, we will review the overall properties of GLSB galaxies and then discuss how their dark matter content and isolation shape their evolution (Table 1).

2. Structural Properties : Disks and Bulges

GLSB galaxies, like High Surface Brightness (HSB) spiral galaxies, have radial surface brightness profiles that follows an exponential form i.e. $\Sigma(r) = \Sigma_0 e^{-r/\alpha}$ where r is the disk radius and α is the disk scale length (de Blok *et al.* 1995). The main difference is that the extrapolated disk central brightness μ_{B0} lies between 22 to 23 mag/arcsec², which is much lower than that observed in regular galaxies and lower than the Freeman limit. Some GLSB galaxies have prominent bulges (e.g. UGC 6614 and UGC 9024, McGaugh and Bothun 1994). In such cases the surface brightness profile can be fitted with two exponential profiles. The stellar disks are usually very large and greater than $\alpha \sim 10$ Kpc (McGaugh and Bothun 1994); but the smaller LSB disk galaxies have stellar disks with $\alpha \sim 4-5$ Kpc.

The low luminosity of LSB galaxy disks indicates a low surface density of stars. The maximum disk hypothesis can be applied to these stellar disks to determine upper limits to mass-to-luminosity (M/L) ratios and stellar disk masses. These upper mass limits show that LSB galaxies have lower stellar surface mass densities than normal spiral galaxies (de Blok *et al.* 2001). Mass modeling of LSB galaxy rotation curves using stellar population synthesis models also indicate a high M/L ratio and low stellar disk surface densities (Swaters *et al.* 2000). The diffuse disks of GLSB galaxies contrasts sharply with their bright bulges (Pickering *et al.* 1999). A good example is UGC 6614 (Fig. 1a), its LSB stellar disk is barely visible except for the tightly wound spiral arms. GLSB galaxy disks often have spiral arms that can be

followed well into their disks (e.g. NGC 5905, Fig. 1b). But the arms are notably ‘thin’ indicating that they are not associated with very massive star forming regions as seen in HSB galaxies. In some galaxies the arms are practically absent (e.g. UGC 1922, O’Neil & Schinnerer 2003). Bars are not common in GLSB galaxies and only 10–15% of LSB disk galaxies have bars in the centers of their disks. Bars and evidence for tidal interactions are weak in LSB galaxies (Mihos *et al.* 1997). The overall lack of strong disk instabilities suggests that the dark halo must be strong in all LSB galaxies and especially for the more massive GLSB galaxies (Mayer & Wadsley 2004).

Although most LSB disk galaxies appear to be late type systems with relatively small bulges, their near-infrared images clearly show that a large fraction of them have significant bulges (Galaz *et al.* 2002; Beijersbergen *et al.* 1999). These bulges are very prominent in the GLSB galaxies (e.g. UGC 6614, Malin 1, Malin 2) and are usually classical bulges. In some GLSB galaxies such as UGC 2936, the bulge is boxy and is possibly a pseudobulge. UGC 2936 also has significant star formation in its disk; both features indicate that there maybe ongoing secular evolution in this galaxy resulting in a more oval than spherical bulge (Kormendy & Kennicutt 2004). GLSB galaxy bulges are notably bright and studies suggest that they are similar to the bulges of HSB galaxies both in stellar population and metallicities (Morelli *et al.* 2012). Thus their bulges are suprisingly very different from their low luminosity disks (McGaugh *et al.* 1995) both in structure and composition. This suggests that the disks and bulges have different evolutionary histories and do not co-evolve.

3. Gas content: HI and molecular gas

One of the main features of all LSB galaxies (dwarf, irregulars and disks) is that they have large amounts of HI gas (O’Neil *et al.* 2004). The HI masses are so large in GLSB galaxies (10^9 – 10^{10}) that they are comparable to the typical stellar masses of late type galaxies (Matthews *et al.* 2001) and make up a considerable fraction of their baryonic mass (McGaugh *et al.* 2000). The HI profiles and maps show that the gas is far more extended than the stellar disks (Pickering *et al.* 1997; de Blok *et al.* 1995). But although the HI masses are large, the HI gas surface densities Σ in $M_{\odot} \text{pc}^{-2}$ are much lower than that of normal late type spirals (de Blok *et al.* 1996). The thinness of the HI distribution has important implications for the star formation properties of GLSB and LSB galaxies in general (see next section). The HI disks are often flared or warped (Matthews & Wood 2003; Pickering *et al.* 1999) or lopsided (Das *et al.* 2007). Such features are more commonly found at larger radii where the stellar disk surface density decreases and the HI disk begins to be more dominant. Thus they appear more prominent in the outer disks of spirals where the effect of the halo becomes more prominent (Reichard *et al.* 2008). The HI rotation curves of GLSB galaxies are usually slowly rising but flatten at relatively high velocities or in some cases continue rising well into their disks. This is a clear indication of their large dark matter content which is also seen in their relatively high mass to luminosity (M/L) ratios.

Molecular hydrogen gas (H_2) is rare in LSB galaxies (de Blok & van der Hulst 1998; Braine *et al.* 2000) but this is not suprising considering their low star formation rates and low metallicities (Schombert *et al.* 1992). H_2 has been detected in only

a handful of GLSB galaxies and so far never detected in LSB dwarf galaxies (O’Neil *et al.* 2000, Matthews & Gao 2001; O’Neil *et al.* 2003; Matthews *et al.* 2005; Das *et al.* 2006). The masses detected are in the range 10^8 – $10^9 M_{\odot}$ which though significant, are low compared to the galaxy HI gas masses and also low compared to the $M(\text{H}_2)/M(\text{HI})$ fractions observed in normal galaxies. The molecular gas distribution has been studied in very few galaxies (Malin 2, Das *et al.* 2010; UGC 1922, O’Neil & Schinnerer 2003). In UGC 1922 it was mainly concentrated within the inner disk but in Malin 2 it is more extended and supports star formation (Pickering *et al.* 1997). In all these studies CO(1–0) or CO(2–1) was used as a tracer for molecular hydrogen. It is possible that H_2 exists as a cold molecular gas or ‘dark gas’ and resides within photodissociation regions, where the CO molecule has been dissociated by ionizing stellar radiation but H_2 molecule still exists (Planck Collaboration 2011; Grenier *et al.* 2005). In such cases the cold molecular hydrogen gas may exist as diffuse, dark gas but will go undetected in millimeter CO observations. But this is unlikely to be the case in LSB disk or dwarf galaxies as these galaxies are so poor in dust and low in metallicities that the neutral gas will not be able to cool low enough or fast enough to form H_2 molecules via dust particles adsorption. Thus the lack of H_2 gas in these galaxies is probably real (Gerritsen & de Blok 1999).

4. Star formation properties

In general LSB galaxies are low in star formation (O’Neil *et al.* 2007) especially when measured per unit stellar mass (Schombert *et al.* 2011). This is especially true for LSB dwarf galaxies which are some of the most dark matter-dominated systems in our Universe. $\text{H}\alpha$ observations of the larger LSB disk galaxies and especially GLSB galaxies reveal that they have patches of localized star formation (e.g. Auld *et al.* 2006) associated with faint spiral arms or distributed sporadically over their disks. Surprisingly, in spite of their low Star Formation Rates (SFR) many studies clearly show that their colors i.e. (B–V) or (B–R), are usually blue and comparable to normal galaxies (van der Hulst *et al.* 1993). This is partly due to the larger number of localized pockets of star formation in GLSB disks, which are generally large. But it may also be due to the fact that the V or R magnitude of these galaxies are low since their stellar disks are diffuse. So the color (i.e. (B–V) or (B–R)) is high even though the star formation rates are low. A significant population of red LSB galaxies have also been observed. But these are generally smaller galaxies and do not have GLSB disks (O’Neil *et al.* 2000).

The star formation in GLSB galaxies is predominantly associated with their bulges and inner disks. In contrast to the LSB disks, the bulges have a younger population of stars and show ongoing star formation (Morelli *et al.* 2012). The metal content is often solar and similar to HSB galaxies. Evidence for bulge star formation is also seen in the X-ray observations of GLSB galaxies as the diffuse emission associated with star formation is mainly confined to their bulges (Das *et al.* 2009a, b). Thus in general GLSB bulges are similar to the bulges of HSB galaxies in terms of star formation properties. In some galaxies, such as the very massive and distant GLSB galaxy Malin 1, there is both a bright bulge and inner disk that appear to be similar to normal galaxies in surface brightness and structure (Barth 2007). Galex UV observations of the disks indicate that GLSB galaxies have UV emission that extend well

beyond their optical disks (Wyder & Treyer 2011). The extended morphology and UV colors indicate that star formation occurred in bursts and had an efficiency far lower than that found in normal galaxies (Boissier *et al.* 2008). Thus the bright bulges and LSB disks of GLSB galaxies appear to have had very different star formation histories.

Several studies have tried to understand the lack of star formation in LSB galaxies. In general the presence of copious amounts of neutral hydrogen gas in galaxies indicates that they have the capacity to form stars through cloud collapse and star formation. But although LSB galaxies are gas-rich, they are very poor in star formation. Both their Star Formation Rates (SFRs) and metallicities are low. Also, as mentioned in the previous section molecular gas, which is always found associated with star formation, is rarely detected in these galaxies. One of the reasons for the low SFR is the lack of strong global as well as local disk instabilities. Both types of instabilities induce cloud collisions and shocks that result in gas compression and gas cooling; these processes can trigger star formation. The global disk instability criterion X_m depends on Σ (see Mihos *et al.* 1997). If Σ is low, global nonaxisymmetric disk instabilities such as spiral arms and bars cannot form. In LSB galaxies, the low surface densities of both the stellar and HI disks results in the formation of only small bars and weak spiral features. Such weak nonaxisymmetric instabilities cannot drive the large-scale massive star formation that is commonly observed in HSB galaxies. Alternatively, localized star formation can be produced by local disk instabilities. The latter is measured by Toomres Q parameter, which also depends on the Σ of the HI gas disk. But again since Σ is low in GLSB galaxies, local instabilities are also difficult to form (van der Hulst *et al.* 1993; Das *et al.* 2010). Localized star is observed in some GLSB disks; it may be due to distant tidal interactions (e.g. NGC 5905, van Moorsel 1982) or small accretion events (e.g. Malin 2, Pickering *et al.* 1997). The other two factors responsible for low SFRs in LSB galaxies are their low metal content and low dust masses (Gerritsen & de Blok 1999). Metals are important for gas cooling and the presence of dust is important for the formation of H₂ molecules. The lack of both, which is intimately related to the low SFRs in GLSB galaxies, contributes to the slow evolution of these galaxies.

5. Nuclear properties

LSB dwarfs, irregulars and smaller disk galaxies show very little nuclear activity. But the larger LSB disk galaxies often show nuclear star formation and some have Active Galactic Nuclei (AGN). A large fraction of GLSB galaxies are relatively bulgeless (McGaugh & Bothun 1994) but there is often a bright core due to nuclear star formation. In most bulgeless galaxies, the nuclear activity appears as a luminous point in an often featureless low luminosity disk (Matthews *et al.* 1999). Strong H α and [OI] emission lines in their spectra indicate ongoing nuclear star formation. High resolution ground-based imaging indicates that the star formation is often in the form of Kpc scale rings, as seen in the GLSB galaxy NGC 5905 (Comer n *et al.* 2010). Hubble Space Telescope (HST) observations have shown that nuclear star formation can lead to the formation of compact nuclear star clusters that may sometimes co-exist with AGN activity (Seth *et al.* 2008). This activity can contribute to the formation of a central massive object (CMO) and lead to the build-up of a bulge in an otherwise bulgeless galaxy (Davies *et al.* 2011).

A significant fraction of bulge-dominated GLSB galaxies show AGN activity (Sprayberry *et al.* 1995; Galaz *et al.* 2011). This is not surprising as studies indicate that the growth of nuclear black holes in galaxies is intimately linked to the growth of their bulges (e.g. Silk & Rees 1998; Heckman *et al.* 2004). The strong correlation of black hole mass (M) with bulge mass or bulge luminosities in galaxies ($M - \sigma$) is due to this SuperMassive Black Hole (SMBH) – bulge co-evolution (e.g. Gültekin *et al.* 2009). Early studies by Schombert (1998) suggested that half of GLSB galaxies have AGN but later studies of larger samples showed that only about 15% had AGN (Burkholder *et al.* 2001). AGN activity will give rise to relatively broad H α and H β emission lines that can be detected in the optical spectra of the galaxies, whereas star formation will result in narrower lines emission (Schombert 1998). Depending on whether the lines have a broad component or not, the nuclei are either Seyfert 1 (Sy 1) or Seyfert 2 (Sy 2) type AGN. We examined at the SDSS spectra of a large sample of LSB disk galaxies collected from the literature and concluded that the fraction of GLSB galaxies hosting AGN activity is not more than 10% (Subramaniam *et al.* 2013). The presence of an AGN can also be confirmed from X-ray observations. Compact X-ray emission associated with the nucleus of a galaxy is a signature of AGN activity and has been detected in a few GLSB galaxies such as UGC 6614 (Naik *et al.* 2010), UGC 2936 (Das *et al.* 2009a) and UGC 1455 (Das *et al.* 2009a). Radio emission associated with AGN activity has also been detected in several GLSB galaxies (Das *et al.* 2007; Mishra *et al.* 2013) (Fig. 2). For example, in UGC 6614 the nuclear emission has a compact core at millimeter wavelengths (110 GHz, Das *et al.* 2006) as well as longer wavelengths (1.4 GHz, Das *et al.* 2009b, see also Fig. 1a). The spectral index α between these frequencies is close to 0 (i.e. a flat core) suggesting that the source is definitely an AGN. At lower frequency of

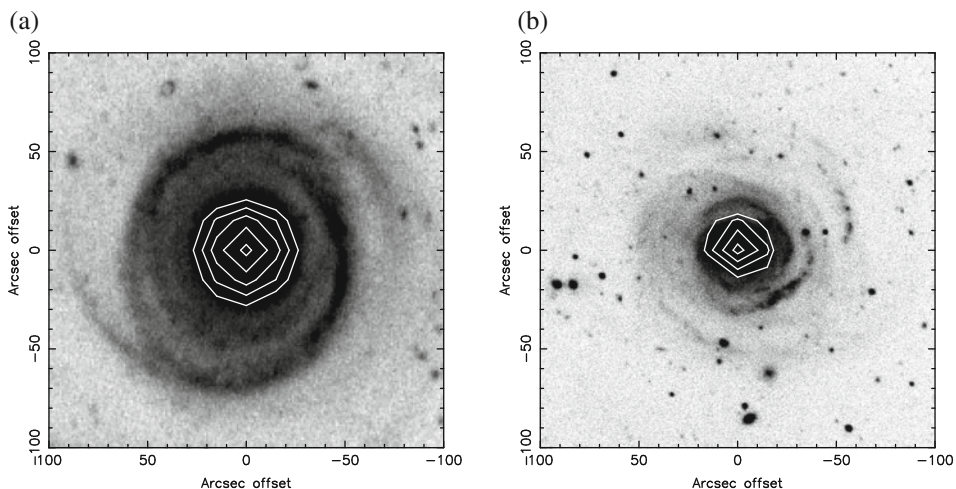


Figure 2. (a) The contours of VLA 1.4 GHz continuum emission from UGC 6614 overlaid on the R band image of the galaxy. The figure shows some extended features which could be due to outflows associated with the AGN. This is clearer in the 610 GHz observations (Mishra *et al.* 2013). (b) The contours of VLA 1.4 GHz continuum emission from Malin 2 overlaid on the 2MASS K band image of the galaxy. The compact emission is centered on the galaxy nucleus and does not show extended features at 610 GHz (Mishra *et al.* 2013).

Table 2. List of galaxies, types and black holes masses.

Galaxy	Red-shift	Hubble class and nuclear type	Black hole mass (10^6 solar mass)	References
Malin 2 (F568-6)	0.046	Sd/p, Sy 1	0.3	Ramya <i>et al.</i> 2011
UGC 6614	0.021	(R)SA(r)a, Sy 1	3.9	Ramya <i>et al.</i> 2011
UGC 6968	0.028	S, Sy 1	0.5	Ramya <i>et al.</i> 2011
UGC 1922	0.036	S, Sy 1	0.4	Ramya <i>et al.</i> 2011
1226+0105	0.079	Sc, Sy 1	12.7	Subramanium <i>et al.</i> 2013
2315-0000	0.030	SAB(rs)a, Sy 1	3.8	Subramanium <i>et al.</i> 2013
Malin 1	0.083	S, Sy 1	0.5	Subramanium <i>et al.</i> 2013
2MASX J09593953 +0035117	0.066	Irr, Sy 1	1.0	Subramanium <i>et al.</i> 2013
SDSS J135943.13 -003424.4	0.164	Sc, NLSy1	19.9	Subramanium <i>et al.</i> 2013

610 MHz, the emission is extended beyond the core (Das *et al.* 2009b) and resembles jets or outflows associated with the AGN activity (Mishra *et al.* 2013). Extended emission is also seen in 2327-0244 (or UM 163) and resembles a one-sided jet (Das *et al.* 2009b). Another example of compact radio emission associated with an AGN is Malin 2 (see Fig. 1b).

Not much is known about the Black Hole (BH) masses in LSB galaxies. The large bulges of GLSB galaxies suggest that they may harbour SMBH's (i.e. BH's with masses larger than $10^6-10^7 M_\odot$) (Rees 1984). The bulge mass and galaxy sizes suggest that the BH masses may be comparable to the SMBHs in ellipticals. However, studies of the optical spectra of Sy 1 type nuclei in GLSB galaxies suggest that the BH masses lie in the $10^5-10^6 M_\odot$ range instead (see Table 2). Sy 1 AGN usually have a broad component in their $H\alpha$ or $H\beta$ emission lines due to the effect of the Broad Line Region (BLR) clouds on the emission from the AGN. Assuming virial equilibrium in the BLR region, the BH mass can be estimated from the width of the broad component of the $H\alpha$ or $H\beta$ emission lines and the line luminosities (Greene & Ho 2007). This is a virial approximation and hence does not give as accurate a BH mass as reverberation mapping or stellar kinematic techniques. But it does give an estimate of the BH mass range. Studies done so far (Table 2) indicate that the masses lie more in the InterMediate Black Hole (IMBH) mass range rather than the SMBH range (Ramya *et al.* 2011). When the bulge velocity dispersions are plotted against the BH masses to obtain the $M - \sigma$ correlation for these galaxies, most GLSB galaxies are found to lie below the standard $M - \sigma$ correlation (Gultekin *et al.* 2009). The points have a scatter but their distribution suggest that as the BH masses approach $10^7 M_\odot$, they begin to follow the $M - \sigma$ correlation for bright galaxies. Thus only GLSB galaxies that have SMBHs of masses larger than $10^7 M_\odot$ allow the same evolutionary track as normal galaxies on the $M - \sigma$ relation.

6. Dark matter in GLSB galaxies

LSB galaxies are one of the most dark matter-dominated systems in our nearby Universe (de Blok & McGaugh 1997). The only class of galaxies that have comparable baryon-to-dark matter ratios are dwarf spheroidal galaxies, which are the prime

targets for dark matter particle searches (e.g. Abdo *et al.* 2010). Traditionally low luminosity galaxies have been associated with massive dark matter halos (Kormendy 1990; Kormendy & Freeman 2004). In the case of GLSB galaxies the main observational evidence that suggests the presence of massive dark halos in these galaxies is the large M/L ratios derived from rotation curve fitting methods (McGaugh & de Blok 1998). Even when a maximum disk is applied to the galaxies, the dark matter is substantially more than the stellar and gas mass combined. The rotation curves in GLSB galaxies are slowly rising and flatten at velocities of 200–300 km/s, indicating the presence of very massive halos that have large dynamical masses (Pickering *et al.* 1997). Another approach is to derive the M/L ratio from the galaxy colors (Bell *et al.* 2003). This method suggests that like most faint galaxies, LSB galaxies lie at the lower end of the luminosity curve and their masses were underestimated in earlier photometric surveys.

One of the surprising and puzzling aspects of dark matter in LSB galaxies is that the distribution does not follow predictions of Cold Dark Matter (CDM) theories of structure formation. CDM predicts that the dark matter profiles of galaxies should have cuspy cores which follow the NFW profile (Navarro *et al.* 1996). However, rotation curve studies show that in general LSB galaxies have profiles that are closer to isothermal or flat core in shape; there is no evidence for cuspy halos in these galaxies (McGaugh *et al.* 2001). Mass modeling of the hybrid $H\alpha$ and HI rotation curves indicate core sizes of the order of 1 Kpc (de Blok *et al.* 2001). However, beam smearing in rotation curve modeling has always cast some doubts against the isothermal core model, as it can result in inaccuracies in estimating velocities in the very inner regions. But further studies using two-dimensional high resolution optical velocity fields of LSB galaxies confirmed that the the NFW model cannot work for dark matter halos in low luminosity galaxies (Kuzio de Naray *et al.* 2008).

7. Formation of GLSB galaxies

Nothing much is known about the formation of LSB galaxies and why they are so different from HSB galaxies. The early theoretical study by Hoffman *et al.* (1992), which was based on the hierarchical picture of galaxy formation, showed that large LSB galaxies will form in voids due to rare 3σ perturbations in under dense regions of the Universe. The smaller amplitude peaks ($1-2\sigma$) can be associated with the smaller dwarf LSB galaxies (Dekel & Silk 1986). Unlike GLSB galaxies their distribution does not depend so much on the large scale structure and their distribution is more uniform. In this scenario, the GLSB galaxies, that form in under dense regions, will have normal bulges but large unevolved disks. Although observations do indicate that GLSB galaxies are often isolated, they do not always populate the interior of voids (Bothun *et al.* 1986). Instead recent studies using the SDSS show that the larger LSB galaxies are in fact more clustered towards the outer edges of the void walls and filaments (Rosenbaum *et al.* 2009). They reside in relatively isolated environments compared to isolated environments compared to HSB galaxies (Ceccarelli *et al.* 2012) and their relative isolation must have contributed to their slow evolution.

Another possibility is that LSB galaxies are formed in halos with large angular momentum (Jimenez *et al.* 1998). However, in this scenario the LSB galaxies form rather late at $z = 0.7$. Other models of protogalaxies with large angular momentum

also form extended galaxy disks that are very similar to GLSB galaxies (Dalcanton *et al.* 1997). These results indicate that there must be some connection between the halos of GLSB galaxies and their properties, as well as evolution. But halo spin alone cannot account for their relative isolation and poor evolution. Instead it is possible that a combination of both isolation and halo spin are important to explain the unique properties of these galaxies and how they fit into the picture of hierarchical structure formation.

8. Evolution of GLSB galaxies

Galaxies evolve by two methods. (i) The first is through external triggers such as interactions with other galaxies and accretion of smaller galaxies. Even distant interactions can cause significant non-axisymmetric disk perturbations that result in cloud collisions and gas in-fall from the disks into the galaxy centers. Both distant interactions and mergers result in an overall increase in star formation. Interactions can lead to the formation of global disk instabilities such as bars and spiral arms. These perturbations further enhance the rate of gas infall to galaxy nuclei, often leading to nuclear starburst (Friedli & Benz 1993). All these processes can result in the build-up of central mass concentrations that often weaken and even destroy bars in the centers of galaxies (Norman *et al.* 1996; Das *et al.* 2003). These processes also contribute to the growth of super massive black holes and AGN in galaxy nuclei. The GLSB galaxy NGC 5905 is a good example (Fig. 1a); the galaxy is interacting with the relatively distant spiral galaxy NGC 5908 and the interaction has resulted in the formation of a strong bar. The bar is associated with a bright bulge that shows star formation and relatively tightly wound spiral arms. (ii) The second mode of galaxy evolution is the slow secular form, that is due to internal processes in galaxies (Kormendy & Kennicutt 2004). In secular evolution, bars play a very prominent role as they exert gravitational torques on gas resulting in the pile-up of gas in inner/outer rings and in the centers of galaxy disks. Bars can become unstable resulting in the formation of disky bulges, called pseudo bulges. The GLSB galaxy UGC 2936 is a good example of secular evolution in an isolated galaxy. It has ongoing disk star formation which are evident in the radio continuum emission maps (Das *et al.* 2009b) and a disky bulge (Pickering *et al.* 1999).

The two most crucial factors that affect the evolution of GLSB galaxies is their isolation and their massive dark matter halos. Since their discovery more than two decades ago, it has been clear that GLSB galaxies are relatively isolated compared to HSB galaxies (Sprayberry *et al.* 1995). More recent studies using the Sloan Digital Sky Survey (SDSS) confirm that GLSB galaxies are generally isolated and often found close to the edges of voids (Galaz *et al.* 2011; Rosenbaum *et al.* 2009). The lack of interactions thus results in less disk instabilities and hence lower star formation rates in GLSB galaxies. This leads to a slower pace of evolution in these galaxies. But perhaps the most important factor influencing GLSB galaxy evolution is the massive dark matter halos found in these systems. It has been known from the early work of Ostriker & Peebles (1973) that galaxies become more stable against the formation of disk instabilities when there is a massive halo component. Later numerical studies have shown that this result is very relevant to the LSB galaxies (Mayer & Wadsley 2004). In fact simulations show that the dark matter halos

stabilize disks even in tidal interactions with other galaxies (Mihos *et al.* 1997). Thus the dark matter halos slow down the formation of global and local non-axisymmetric instabilities and hence lead to a slower rate of galaxy evolution in GLSB galaxies.

9. Conclusions

1. GLSB galaxies are an extreme form of late type spiral galaxies. They are characterized by very faint, extended disks that are low in stellar density but very rich in neutral hydrogen gas. They have low metal content and low star formation rates. Molecular gas, which is associated with star formation, is rarely detected in these galaxies.
2. Their disks are embedded in very massive dark matter halos that make them very stable against disk instabilities such as bars and spiral arms. Hence star formation is low; this leads to very low surface brightness disks that often lie close to or below the brightness of the night sky.
3. Their nuclei sometimes host AGN activity. Indirect estimates of the associated black masses yield values 10^5 – $10^7 M_{\odot}$. The AGN can also be detected in X-ray and radio emission.
4. The distribution, morphology and disk dynamics of GLSB galaxies indicate that both their isolation and dominant dark matter halos contribute to their extremely slow rate of evolution compared to normal galaxies.

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