The ISM of Low Surface Brightness Galaxies

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Abstract. Using Monte Carlo radiative transfer techniques, we model the dust content of the edge-on low surface brightness (LSB) galaxy UGC 7321 and explore the effects of dust on its disk color gradients. Dust alone cannot explain the large radial disk color gradients observed in this galaxy and we find that a significant fraction (∼50%) of the dust in UGC 7321 appears to be contained in a clumped medium, indicating that at least some LSB galaxies can support a modest multi-phase ISM structure. In addition, we report some of the first direct detections of molecular gas (CO) in LSB galaxies.

1. Introduction

Low surface brightness (LSB) disk galaxies can be defined as rotationally-supported galaxies with extrapolated central surface brightnesses ≥1 magnitude fainter than the canonical Freeman value of $\mu_{B,0} = 21.65$ mag arcsec$^{-2}$. Although LSB galaxies are found spanning the full range of Hubble classes, our present work emphasizes the very latest spiral types (Scd-Sdm). LSB disk galaxies are now known to be a common product of galaxy formation, and have received considerable attention during the past decade (see Impey & Bothun 1997 for a review). Nonetheless, our knowledge of the composition and conditions of their interstellar media (ISM) is still highly incomplete. Such information is vital for understanding the evolutionary histories of these galaxies and how star formation progresses in low-density galaxian environments.

LSB galaxies are typically rich in neutral hydrogen, having $M_{HI} \sim 10^8 - 5 \times 10^9 M_\odot$ and $M_{HI}/L_B \sim$ 0.5-1.0 (in solar units). A key difference between high surface brightness (HSB) and LSB galaxies is that in LSBs the bulk of the H I often has a surface density below that needed for efficient star formation (e.g., van der Hulst et al. 1993). Nonetheless, the blue colors and modest amounts of Hα emission seen in the majority of LSB galaxies show that they are still managing to form some new stars.

In spite of the evidence for modest amounts of ongoing star formation, LSB galaxies are often presumed to be devoid of significant amounts of dust and molecular gas. Lines of evidence include: low metallicities ($\lesssim 1/3 Z_\odot$; e.g., Rönnback...
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Figure 1. *Hubble Space Telescope* WFPC2 $R + I$ composite image of the innermost $55'' \times 19''$ section of the disk of UGC 7321. Resolution is $\sim 0.1'' \approx 4.8$ pc.

& Bergvall 1995); low statistically-inferred internal extinctions (e.g., Tully et al. 1998); highly transparent disks (e.g., O’Neil et al. 1998); and past failures to detect CO emission (see below). It has also been argued based on theoretical models that it should be difficult for molecules to form in LSB galaxies owing to their low densities and the lack of cooling from metals (Mihos et al. 1999; Gerritsen & de Blok 1999).

Unfortunately, directly searching for dust and molecular gas in LSB galaxies can be challenging. For example, these galaxies tend to be weak far-infrared and submillimeter sources (e.g., Hoeppe et al. 1994), and the presence of dust or dark clouds is difficult to infer in absorption against the diffuse and patchy background light from their disks. For these purposes, edge-on examples of LSB galaxies thus become particularly valuable.

2. UGC 7321: An Edge-On LSB Galaxy

Matthews et al. (1999) have shown that UGC 7321 is an example of a nearby ($D \sim 10$ Mpc) LSB galaxy viewed near edge-on ($i = 88^\circ$). UGC 7321 has $L_B = 1.0 \times 10^9 L_\odot$, $M_{HI}/L_B = 1.1(M_\odot/L_\odot)$, and a deprojected central surface brightness $\mu_{B,i}(0) \sim 23.6$ mag arcsec$^{-2}$. A comprehensive description of the global properties of this galaxy can be found in Matthews et al. (1999).

Fig. 1 shows a 2.6 kpc-long portion of the central disk region of UGC 7321 as imaged by the WFPC2 on *HST*. It is clear from this image that although UGC 7321 lacks a true dust lane, it is by no means dust-free. Moreover, the dust is seen to exhibit a clumped structure, with the size of the individual clumps ($\sim$30-60 pc) reminiscent of Giant Molecular Clouds in the Milky Way.

An intriguing property of UGC 7321 noted by Matthews et al. (1999) is that this galaxy exhibits strong radial $B - R$ color gradients: $\Delta(B - R) \sim 1.0$ from the disk center to its outermost observed edge. These gradients suggest that the disk of UGC 7321 was built up slowly in time, from the inside out, and that viscous evolution has been inefficient. Large radial color gradients have also been seen in other LSB galaxies (e.g., de Blok et al. 1995; Bell et al. 2000; Matthews et al. 2000). This offers an important clue to the formation histories of these galaxies. However, properly interpreting this phenomenon requires accurately correcting for the reddening effects of dust.
3. Monte Carlo Models of the Dust in UGC 7321

In order to further examine the role of dust in UGC 7321, we have computed 3-D Monte Carlo radiative transfer models of UGC 7321 at optical and NIR wavelengths over a range of optical depths. Our models were computed on a $200^3$ element grid (resolution $\sim 53$ pc) and included both absorption and multiple scattering of photons. We employed “forced first scattering” and a “peeling-off” procedure in order to allow us to efficiently treat the very low optical depth regimes encountered in LSB galaxies. Our models assume exponential stellar and dust distributions and Galactic dust grain properties. These simulations are described in detail in Matthews & Wood (2000). Here we highlight a few key results.

One output from our Monte Carlo models is scattered light images. From these we find that models containing only a smoothly distributed dust component are unable to reproduce the observed morphology of UGC 7321. Purely smooth models, even with very low optical depths, exhibit a dust lane, a pronounced central concentration of light, and a clear asymmetry about the disk midplane not seen in the real galaxy. We instead find the best-fitting models are those with a significant fraction (50%) of the dust in a clumpy medium. This implies that interstellar pressures are sufficient to sustain at least a modest multi-phase ISM in some LSB galaxies. Our best 2-phase ISM model for UGC 7321 has a mean edge-on $B$-band optical depth toward the galaxy center $\bar{\tau}_{B,e} \approx 4.0$, equivalent to a total dust mass $M_d \sim 8.8 \times 10^5 M_\odot$ and an extinction toward the galaxy center $A_B \sim 0.65$ magnitudes. Within the central regions of the stellar disk, the gas-to-dust ratio appears to be at least several times the Galactic value, while the global gas-to-dust ratio for UGC 7321 is $\sim 1600$.

From our Monte Carlo models we are able to rule out that the large radial color gradient observed in UGC 7321 can be explained fully by dust. In fact, our models show that for $\tau_{B,e} \geq 4.0$, the dust-induced $B - R$ radial color gradient saturates at $\Delta(B - R) \sim 0.31$—i.e. no additional amount of dust can further increase this gradient (Fig. 2). This establishes that the large radial color gradients observed in UGC 7321 and other similar late-type LSB galaxies must instead arise from significant stellar population and/or metallicity gradients.

4. Deep CO Observations of LSB Galaxies

Since LSB galaxies are actively star-forming systems that can harbor dust and dark nebulae, it seems likely that molecular gas should be present in these galaxies. However, it is unclear how well the CO molecule might be expected to trace $H_2$ in the diffuse, low-metallicity environments of LSB galaxies, and past searches have failed to detect CO emission from such objects (Schombert et al. 1990; Knezek 1993; de Blok & van der Hulst 1998). Nonetheless, late-type spirals are in general not strong CO emitters (cf. Young & Knezek 1989), and past CO searches in LSB galaxies have employed only modest integration times.

Using the NRAO 12-m telescope we have obtained very deep, high-quality CO(1-0) observations of a sample of 6 edge-on LSB galaxies, with total integration times $\geq 15$ hours per object toward their optical centers. Weather conditions were excellent, and typically $T_{\text{sys}} \sim 300$ K. The details of this study will be described further in Matthews & Gao (in prep.).
As a result of our deep observations, we have detected 3 of the 6 LSB galaxies at a > 4σ level, and one additional source was marginally detected (∼ 3σ). Our CO(1-0) spectrum of the edge-on LSB UGC 7321 is shown in Fig. 3. In all cases, the detected CO lines are relatively broad (W20 ∼200 km s\(^{-1}\)) and similar to the global H I linewidths, suggesting the CO in our targets is spread over a regions a few kpc across, as is commonly seen in normal very late-type spirals.

Assuming a standard Galactic conversion factor, the H\(_2\) masses inferred for the detected galaxies are ∼ 1 – 5 × 10\(^7\) M\(_\odot\), with M\(_{H2}\)/M\(_{HI}\) ∼0.02-0.03. In comparison, typical M\(_{H2}\)/M\(_{HI}\) ratios for HSB Sd galaxies are 0.19±0.10 (Young & Knezek 1989), implying that LSB galaxies are comparatively molecular gas-deficient. However, we caution that the the validity of the Galactic CO-to-H\(_2\) factor for LSB systems is still a matter of debate, and will require further investigation.

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