The Mass Distribution in Low Surface Brightness Galaxies

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Abstract. The distribution of the stellar and gaseous components in low surface brightness galaxies has been determined directly from optical and HI imaging. The distribution of what might be the dominant mass component, the dark matter, which is inferred from rotation curves, is far harder to determine. Although the rotation curves themselves can be determined fairly accurately from HI synthesis observations, and in particular from Hα spectroscopy, the uncertainty in the mass modeling leaves room for a wide range of possible dark matter distributions, ranging from maximum stellar disks with shallow dark halos to cuspy dark halos with little mass in stars.

1. Introduction

Low surface brightness (LSB) galaxies have been receiving an increasing amount of attention since their discovery, in part because their properties substantially increase the range in galaxy properties over which theories of galaxy structure, formation and evolution can be tested. In particular, the rotation curves of these galaxies provide important clues to the distribution of dark matter.

2. The visible mass distribution

The visible mass distribution in LSB galaxies can easily be measured directly by optical and HI imaging. Optical surface photometry (e.g., McGaugh & Bothun 1994, de Blok et al. 1995) has shown that the surface brightness of LSB galaxies is well below the average value of 21.65 $B$-mag arcsec$^{-2}$ for high surface brightness (HSB) galaxies (Freeman 1970). The shape of the light distribution is remarkably similar between LSB and HSB galaxies. Both types of galaxies are dominated by exponential disks, and both may have significant bulges (Beijersbergen et al. 1999). The disk scale lengths found in LSB galaxies are in the same range as those for HSB galaxies, indicating that LSB galaxies are not dwarf galaxies. At a fixed luminosity, however, LSB galaxies have larger scale lengths than HSB galaxies.

The HI distribution for a sample of LSB galaxies has been mapped by de Blok et al. (1996). In HI, as in the optical, the shapes of the HI distribution seen in LSB galaxies is similar to those seen in HSB galaxies, ranging from filled HI disks, to disks with central holes in HI or ring-like HI distributions. A key difference between HI in LSB and HSB galaxies is that LSB galaxies...
on average have HI densities that are about a factor of two lower than their HSB counterparts. The HI column densities thus appear related to the surface brightness (see also Swaters et al. 2000a).

3. The total mass distribution

A first estimate of the total mass density has been obtained from the Tully-Fisher relationship for LSB galaxies. Zwaan et al. (1995) found that LSB galaxies follow the same Tully-Fisher relationship as HSB galaxies, and concluded from this that LSB galaxies must have lower total mass densities than HSB galaxies.

This result was placed on firmer footing when rotation curves for LSB galaxies became available. De Blok et al. (1996) and de Blok & McGaugh (1996), on the basis of HI observations, found that the rotation curves of LSB galaxies rise more slowly that those of HSB galaxies if the radii are expressed in units of kpc, confirming the Zwaan et al. (1995) result. LSB galaxies therefore appear to be true low density galaxies.

4. The dark mass distribution

Although it is clear that LSB galaxies have lower surface brightnesses, lower HI densities and lower total densities than HSB galaxies, this does not automatically imply that these galaxies also have lower dark matter densities. Detailed mass modelling is required to obtain limits on the dark matter distribution.

De Blok & McGaugh (1997) derived mass models for LSB galaxies from HI rotation curves, and found that LSB galaxies have to be dominated by dark matter, both because the HI rotation curve shapes ruled out maximum disks, and because the inferred stellar mass-to-light ratios ($\Upsilon$) seem inconsistent with other indicators of $\Upsilon$ in these galaxies.

More recent high resolution observations of the rotation curves of LSB galaxies (Swaters et al. 2000b) and a reanalysis of the original HI observations (van den Bosch et al. 2000) have indicated that the HI rotation curves were affected by beam smearing. Even though the Hα rotation curves presented in Swaters et al. (2000) rise somewhat more steeply than the HI rotation curves of the same galaxies, they do confirm the main conclusion by de Blok et al. (1996) that LSB galaxies have low total mass densities. However, the new Hα rotation curves do change the conclusions derived from the mass modelling.

In Fig. 1 three mass models are shown for the five galaxies for which Swaters et al. (2000) presented Hα rotation curves. Interestingly, in all galaxies except F568-3, the contribution of the stellar disk can be scaled to explain the inner parts of the rotation curve. The derived values for $\Upsilon$ may be high: up to 17 in the $R$-band. Most of these are outside the range of what current population synthesis models predict. If these high values of $\Upsilon$ are to be explained solely by a stellar population, the stellar content and the processes of star formation in LSB galaxies need to be very different from those in HSB galaxies. Alternatively, these high mass-to-light ratios might indicate the presence of an additional baryonic component associated with the disk, suggested to be in the form of cold molecular gas (e.g., Pfenniger et al. 1994) or white dwarfs (e.g., Ibata et al. 1999). On the other hand, the fact that the stellar disk can be scaled to explain
Figure 1. Mass models for 5 LSB galaxies. From top to bottom the maximum disk and minimum disk mass models with isothermal halos, and a mass model with an NFW halo and \( \Upsilon = 1.0 \). The dotted line represents the contribution of the stellar disk, the short dashed line that of the gas, the long dashed line the dark matter, and the full line gives the best fit mass model.

The observed rotation curve may simply reflect the possibility that the luminous and dark mass have a similar distribution within the optical galaxy.

The other extreme for the contribution of the stellar disk to the rotation curve is to assume that its contribution is negligible. From Fig. 1 it is clear that the minimum disk mass models fit the rotation curves equally well as the maximum disk models. In fact, good fits can be obtained with any mass-to-light ratio lower than the maximum disk one, demonstrating that the degeneracy that exists in the mass modeling for HSB galaxies also exists for LSB galaxies.

If the contribution of the stellar disk is close to maximum, then the derived core radii for the dark halos are large, and the central densities low. In the minimum disk case, on the other hand, high central dark matter densities, similar to those found in HSB galaxies, and small core radii are required to explain the observed rotation curves. Because of this large degeneracy it is not possible to determine the distribution of dark matter from rotation curves alone, nor is it possible to determine whether the dark matter density in LSB galaxies scales with luminous or total mass density. If the fractional contribution of the stellar disk to the rotation curve is similar in all galaxies, then the central dark matter density does scale with surface brightness. If, on the other hand, HSB galaxies are close to maximum disk, and LSB close to minimum disk, which is consistent with the values for \( \Upsilon \) expected from current stellar population synthesis models, then LSB and HSB galaxies may well have identical halos, and hence the dark matter density is not correlated with surface brightness.
Another possible model for the dark matter distribution is shown in the bottom row of Fig. 1. Here, mass models are displayed that are based on halo profiles with a radial distribution as suggested by Navarro et al. (1997), which have a steep slope of $r^{-1}$ in the inner parts. This profile has been derived from CDM simulations, and it has been successful in explaining the rotation curves of HSB galaxies. The HI data indicated that these NFW halos are inconsistent with the observed rotation curves (e.g., McGaugh & de Blok 1998), which has been one of the reasons for the recent surge in finding alternatives for CDM.

The NFW mass models in Fig. 1 have been derived for $\Upsilon = 1$, and have been corrected for adiabatic contraction. These NFW mass models fit the observed rotation curves nearly as well as those based on isothermal halos, except for F568-3. The derived concentration parameters $c$ for the NFW fits are consistent with a $\Lambda$CDM cosmology ($9 < c < 16$). This demonstrates that LSB galaxies may have cuspy halos, despite the fact that they appear to be low density objects. There is still controversy on this point. De Blok et al. (this conference) find that a substantial fraction of their new H$\alpha$ observations are inconsistent with an NFW halo. Pickering et al. (this conference) on the other hand, find that most of the H$\alpha$ rotation curves for their sample of about 70 LSB galaxies can be fitted with a cosmologically meaningful NFW profile. At this point it is unclear whether this apparent dichotomy is the result of observational uncertainties or non-circular motions in the inner parts of the galaxies, or whether the rotation curves of LSB galaxies are in fact inconsistent with cuspy halos.

The fact that the three mass models discussed above, as well as many others, can provide good fits to the observed rotation curves of LSB galaxies, reflects the large degree of freedom that exists in the mass modeling. Based on rotation curves alone, even with the high spatial resolution of H$\alpha$ observations, it is difficult to get useful constraints on the dark matter properties. Independent estimates of the mass in the stellar disks, obtained for example from stellar velocity dispersions, are essential.

References