Kinematics of Giant Low Surface Brightness Galaxies

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Abstract. High sensitivity H I observations now exist for six giant low surface brightness (LSB) disk galaxies including the two prototypes, Malin 1 (Bothun *et al.* 1987; Impey & Bothun 1989) and F568-6 (also known as Malin 2; Bothun *et al.* 1990). Their H I surface brightnesses are generally low, but proportionally not as low as their optical surface brightnesses. Their total H I masses and radial extents are quite large, however, with $M_{\rm HI} \sim 10^{10} M_\odot h_{75}^{-2}$ and with detectable H I out to 100 kpc h_{75}^{-1} or more in a couple of cases. The rotation curves of these systems rise slowly and are consistent with negligible disk contribution, similar to many previously observed dwarf galaxies. However, the peak rotation velocities of these galaxies are high (>200 km s^{-1}) and infer high dynamical masses. These galaxies provide the some of the first examples of galaxies that are both massive and dark matter dominated.

1. Introduction

The serendipitous discovery of Malin 1, whose remarkable properties are described by Bothun *et al.* (1987) and Impey & Bothun (1989), demonstrated the existence of very large, very luminous, but very diffuse, galaxies. As an example of an L^* galaxy that is extremely hard to detect, Malin 1 helped confirm the idea, first clearly articulated by Disney (1976), that the brightness of the night sky can and does bias our understanding of galaxies and of the range of galaxy properties. It also helped to spur subsequent deliberate searches for low surface brightness (LSB) galaxies such as those of Schombert & Bothun (1988) and Impey *et al.* (1996). While these surveys didn't find any objects with properties as extreme as Malin 1 (indeed, none of these surveys was deep enough to detect Malin 1 itself), they did turn up several giant LSB galaxies whose properties approach those of Malin 1. F568-6 (Bothun *et al.* 1990), 1226+0105 (Sprayberry *et al.* 1993), UGC 6614 (van der Hulst *et al.* 1993), and two other galaxies from Sprayberry *et al.* (1995a) are the closest "cousins" to Malin 1 and have physically large disks with scale lengths greater than 10 kpc h_{75}^{-1}, total luminosities of L^* or greater, central surface brightnesses in B fainter than 23 mag arcsec^{-2}, and total H I masses of greater than $10^{10} M_\odot h_{75}^{-2}$.

These giant LSB galaxies probe a previously unexplored region of parameter space for galactic disks. Knezek (1993) and Sprayberry *et al.* (1995b) have tabulated optical and single-dish H I properties, while previous H I synthesis studies of LSBs by McGaugh (1992), van der Hulst *et al.* (1993), de Blok *et al.* (1996), and de Blok & McGaugh (1997) concentrated largely on smaller, less

luminous LSB galaxies. Rotation curve studies so far have shown that the shape of a rotation curve is closely related to the rotation velocity of the galaxy. Slow rotators (i.e., the dwarfs mentioned above) have slowly rising rotation curves. Galaxies with rotation speeds in excess of 100 km s^{-1} tend to have flat rotation curves while the fastest rotators (> 200 km s^{-1}) have slightly declining rotation curves (Casertano & van Gorkom 1991; Broeils 1992). These results for the faster rotators are entirely based on HSB galaxies, however.

In the inner parts of HSB galaxies the rotation curves are often dominated by the luminous mass, i.e., the rotation curve can be fit by scaling the luminous component by a constant mass-to-light ratio (the "maximal disk" hypothesis). Only at large radii does the dark matter component become important. However, within the massive HSB galaxies a slight trend was found with surface brightness: less bright, less compact galaxies tend to be more dark matter dominated (Casertano & van Gorkom 1991). At a given total mass and mass-to-light ratio, a disk with a larger scale length will reach it's peak rotation velocity at a larger radius and will have a lower peak rotation velocity than the disk with the smaller scale length. If the galaxies have comparable halo properties, the halo should contribute proportionally more to the kinematics in the large scale length case. With their much larger and thus more diffuse disks giant LSB galaxies provide an important contrast to massive HSB galaxies and an important probe into the structure of galactic halos.

2. The Data

To date we have obtained VLA H I synthesis observations for five giant LSB galaxies. The data for the first four including Malin 1 and F568-6 have been published in Pickering *et al.* (1997) and the fifth, UGC 2936, has been published as part of my thesis work, Pickering (1998). The H I velocity fields overlayed on H I intensity maps for these five galaxies are shown in Figure 1. Australia Telescope Compact Array H I data for another giant, gas-rich LSB galaxy, NGC 289, has been published by Walsh *et al.* (1997).

Figure 2 shows the radially-averaged H I surface density profiles, derived rotation curves, and critical density profiles calculated from the rotation curves for the galaxies from Pickering *et al.* (1997) and Pickering (1998). The critical density profiles are calculated using the method of Kennicutt (1989) assuming a gas velocity dispersion of 6 km s^{-1}.

3. Stability of Giant LSB Disks

In two of the cases shown in Figure 2 the H I surface density lies below the critical density at all radii which is consistent with the low rate of star formation in those disks. However, in the other three cases significant portions of the disks have H I surface densities that exceed the critical density. In the case of UGC 2936 there is a fairly significant amount of star formation occurring. Figure 3 shows the optical rotation curve based on Hα for UGC 2936 plotted with the H I position-velocity map and rotation curve. The last measured points in the optical rotation curve occur at radii of about 14 kpc h_{75}^{-1} which is in excellent agreement with the radii at which the H I surface density shown in Figure 2 falls below the critical
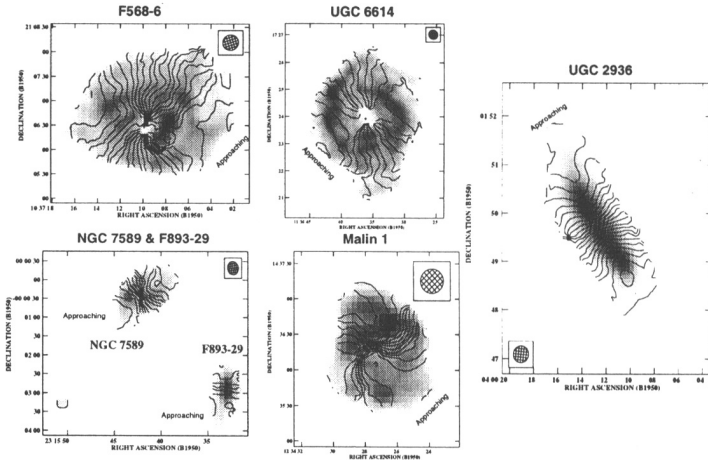
Figure 1.   H I isovelocity contours overlayed on H I intensity greyscale for 5 giant LSB galaxies: Malin 1, F568-6, UGC 6614, NGC 7589, and UGC 2936. The velocity contour spacing is 20 km s^{-1} in all cases.
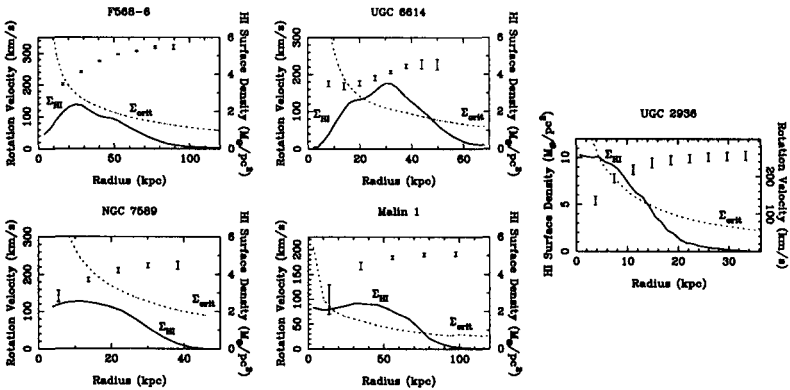

Figure 2.   Radially-averaged H I surface density profiles (*solid lines*), rotation curves (*data points*), and critical density profiles (*dotted lines*) for Malin 1, F568-6, UGC 6614, NGC 7589, and UGC 2936. The critical density profiles are calculated assuming a gas velocity dispersion of 6 km s^{-1}.
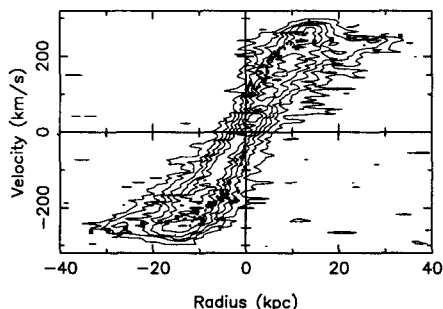
Figure 3.   Optical rotation curve (*filled circles*) for UGC 2936 plotted
with the H I rotation curve (*filled squares*) and major axis position-
velocity map (*contours*). The position-velocity map is corrected for
$i = 61°$ with contour levels of $9.0 \times 10^{-3} \times (1\ 2\ 3\ 4\ 5\ 6\ 7)$ Jy/beam.

density. In the case of Malin 1 the large uncertainty in the inclination, and thus
the absolute scaling of the rotation curve, leads to a large uncertainty in the
determination of the critical density as well as in the line-of-sight corrections to
the surface density. The inclination is much more well-determined in the case of
UGC 6614, though, so it's more clearly a case where the critical density criterion
predicts widespread star formation where none is observed to occur. This is an
indication that the conditions in a giant LSB disk are quite different than in the
HSB galaxies used to calibrate the critical density criterion. One might expect
this to be the case since the dark halo will be more kinematically dominant as
a disk becomes more diffuse resulting in a lower restoring force in the disk. The
lower restoring force results in a thicker and more stable disk at a given velocity
dispersion which might explain the results for UGC 6614.

4.   Mass-to-Light Ratios in Giant LSB Galaxies

If these rotation curves are modeled by a disk component alone, the amplitude of
the rotation curves in these galaxies requires R-band M/L's (assuming $h_{75} = 1$)
of up to 15–20 in the cases of F568-6 and UGC 6614. The shapes of the curves,
however, are not well-produced by the disk-only fits. Quillen & Pickering (1997)
used the strengths of the optical and H I spiral arms along with the strengths of
the velocity perturbations due to the spiral arms to place much better constraints
on the disk M/L's in UGC 6614 and F568-6. They find that in both cases the R-
band M/L's are in the range of about 1 to 5 which clearly rule out the maximal
disk-only results. If the bulge component is included and assumed to have the
same M/L as the disk, the M/L constraints are even tighter: < 1.5 for F568-6
and < 2.5 for UGC 6614. Thus there's no indication that giant LSB galaxies
have disk mass-to-light ratios that differ significantly from more normal HSB
galaxies.

The global M/L's for giant LSB galaxies derived by measuring the mass
enclosed by the last measured points in the rotation curves are similarly not far
out of line with what is found for HSB galaxies. This is rather remarkable since
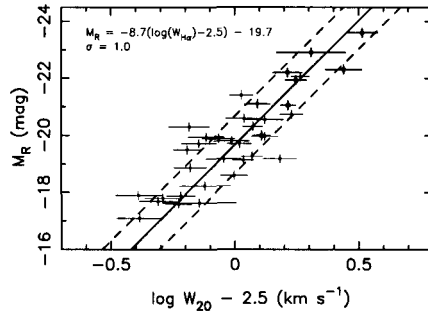their last measured points are at radii approaching 100 kpc h_{75}^{-1} in a couple of

Figure 4.   Absolute R magnitude, M_R, versus H I linewidth, W_{20} for the giant LSB galaxies (*filled circles*) and other LSB galaxies from the samples of Zwaan *et al.* (1995) and Sprayberry *et al.* (1995b) (*filled squares*).

cases and greater than 35 kpc h_{75}^{-1} in all cases. The five galaxies from Pickering *et al.* (1997) and Pickering (1998) all have R-band global M/L's in the range 11–15. A typical HSB galaxy such as NGC 3198 (Begeman 1989), for example, has a total R-band M/L of 10 at a radius of 22 kpc h_{75}^{-1}. Zwaan *et al.* (1995) and Sprayberry *et al.* (1995b) showed that LSB galaxies follow the same Tully-Fisher relation as comparable HSB galaxies which also implies that their global mass-to-light ratios must be at least roughly similar. Figure 4 shows the results for the giant LSBs plotted with results for other LSB galaxies. The giant LSB galaxies are completely consistent within the uncertainties with the Tully-Fisher relation derived from the other LSB galaxies.

5.   Shapes of Giant LSB Rotation Curves and NFW Halos

The high resolution numerical simulations of galactic halos by Navarro *et al.* (1996) showed that dark matter halos over several orders of magnitude in mass have density profiles that can all be well-described by a single two parameter density profile. This so-called NFW halo profile has a halo circular velocity profile of the form

$$V_{\mathrm{NFW}}(r) = V_{200}\sqrt{\frac{1}{x}\frac{\ln(1+cx) - cx/(1+cx)}{\ln(1+c) - c/(1+c)}} \tag{1}$$

where the two free parameters are V_{200}, the circular velocity of the halo at the virial radius, and c, the concentration of the halo. Navarro *et al.* (1996) compared some observed rotation curve shapes with those predicted by a NFW halo profiles within a Standard Cold Dark Matter (SCDM) universe and found that while HSB galaxies can be made consistent by tweaking M/L, LSB dwarfs cannot be made consistent with SCDM.

Navarro *et al.* (1997) developed this further and showed that the NFW halo profile is a generic result of hierarchical clustering and that different cosmologies result in different relations between V_{200} and c. Using this, one can turn the comparison around and see what cosmologies are consistent with the values of
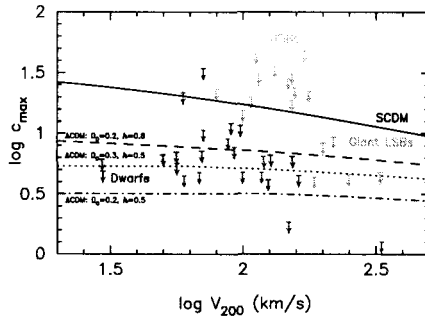
Figure 5.   Results of maximal NFW fits to samples of LSB and HSB rotation curves taken from the literature plotted with the predicted V_{200}—c relations for different cosmologies. The predictions were calculated using the method described by Navarro *et al.* (1997)

V_{200} and c one measures from galactic rotation curves. A quick and dirty way to estimate this and place upper limits on c is to fit galactic rotation curves using only Equation 1, basically a maximal NFW halo fit. The results of some maximal halo fits to the giant LSB galaxies as well as other samples of LSB and HSB rotation curves taken from the literature are shown in Figure 5. As in Navarro *et al.* (1996), the HSB galaxies could be made consistent with SCDM. They could also be made consistent with everything else and hence don't have much predictive power when fitting with a halo only. This is because much of the mass concentration in HSB galaxies is due to the baryonic component rather than the dark halo component. In the LSB cases the baryonic component is much less concentrated and less kinematically important so they offer better constraints on the halo properties. Almost all of those cases fall below and are not consistent with SCDM. Most of them are consistent with lower density models that include a cosmological constant (ΛCDM). However, a few have very low best-fit concentrations when fitted with an NFW halo only. Those are cases where the rotation curve is solid-body-like and linearly rising and thus has a shape that is not well-described by Equation 1.

6.   Conclusions

Giant LSB galaxies are some of the first known examples of massive galaxies whose kinematics are dark halo dominated at almost all radii. Their rotation curve shapes cannot be reproduced by scaling their stellar components by constant mass-to-light ratios. Even the amplitudes of their rotation curves would require higher mass-to-light ratios than are allowed by other constraints such as spiral arm strengths. The shapes of their rotations curves cannot be made consistent with the predictions of SCDM, but are consistent with the predictions of low density ΛCDM models.

While at a given radius a giant LSB galaxy's halo dominates its kinematics to a greater extent than in an HSB, the global mass-to-light ratios are about the same in both cases. The giant LSB galaxies also follow, or are at least consistent with, the same Tully-Fisher relation as other LSB and HSB galaxies.

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