Part 11

Dwarf Galaxies

Dark Matter in Galaxies
IAU Symposium, Vol. 220, 2004
S.D. Ryder, D.J. Pisano, M.A. Walker, and K.C. Freeman, eds.

Kinematics of Extremely Faint Dwarf Galaxies

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Abstract. We present the results of deep, high velocity resolution ($\sim$1.6 km s^{-1}) Giant Meterwave Radio Telescope (GMRT) HI 21 cm observations of extremely faint ($M_B > -12.5$) dwarf irregular galaxies. We find that all of our sample galaxies show systematic large scale velocity gradients, unlike earlier studies which found chaotic velocity fields for such faint galaxies. For some of the sample galaxies the velocity fields are completely consistent with ordered rotation, though the peak circular velocities are comparable to the observed random motions. These are the faintest known galaxies with such regular kinematics. We present ("asymmetric drift" corrected) rotation curves and mass models (including fits for Isothermal and NFW halos) for some of these galaxies and discuss the implications for hierarchical models of galaxy formation.

1. Introduction

Dwarf irregular galaxies are typically dark matter dominated throughout, unlike brighter spirals, where both stars and gas make a significant contribution to the dynamical mass in the inner regions. Sensitive studies of the kinematics of the faintest dwarf systems thus provide direct information on the density profiles of their dark matter halos and can hence be used to place constraints on models of structure formation. However, a major stumbling block in such programs is that it is still unclear whether very faint dwarf irregular galaxies are rotationally supported or not. From a systematic study of the kinematics of a sample of dwarfs, Côté, Carignan & Freeman (2000) found that normal rotation is seen only in galaxies brighter than -14 mag, while fainter dwarfs have disturbed kinematics. This result is consistent with the earlier findings of Lo, Sargent & Young (1993), who from a study of a sample of dwarfs (with $M_B \sim -9$ to $M_B \sim -15$) found that very faint dwarf irregulars have chaotic velocity fields. However, most of these earlier studies were done with modest velocity resolutions ($\sim 6-7$ km s^{-1}) and modest sensitivities which makes it difficult to discern systematic patterns (which typically have amplitudes < 10 km s^{-1}), if any, in the velocity fields of such faint systems. We present here high velocity resolution ($\sim$1.65 km s^{-1}), GMRT HI 21 cm observations of a sample of extremely faint dwarf galaxies.

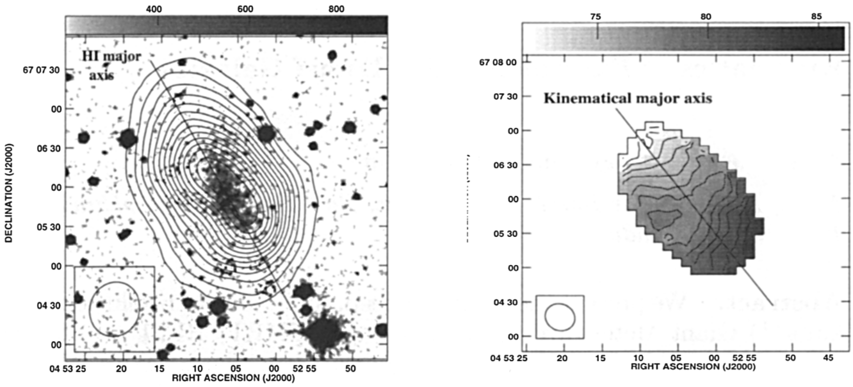

Figure 1. **(Left)** Integrated HI emission map of Cam B at $40'' \times 38''$ resolution overlaid on the Digitised Sky Survey image. The contour levels are 0.05, 0.12, 0.19, 0.26, 0.33 0.41, 0.50, 0.55, 0.62, 0.69, 0.76, 0.83, 0.89 Jy/Beam km s^{-1}. **(Right)** The HI velocity field of Cam B at $24'' \times 22''$ resolution. The contours are in steps of 1 km s^{-1} and range from 70 km s^{-1} (the extreme North West contour) to 84 km s^{-1} (the extreme South East contour). Note that the kinematical major axis of the galaxy is well aligned with the HI and optical major axis.

2. The GMRT Sample

Our GMRT sample consist of dwarf irregular galaxies with $M_B > -12.5$ mag and have typical HI masses of $\sim 10^{6-7} M_\odot$. The typical integration time on each source is $\sim 16-18$ hrs, which gives a typical rms of $\sim$1.0 Jy/Beam per channel.

3. Results

Unlike earlier studies, our high velocity resolution and high sensitivity GMRT observations detect large scale systematic patterns in the velocity fields of our sample galaxies (see e.g. Figs. 1, 3). For some of the galaxies, the large scale gradients can be modeled as systematic rotation, allowing us to derive the rotation curves and hence determine the structure of their dark matter halos from mass modeling. The rest of this paper discusses the results obtained from the detailed kinematical study of two of our sample galaxies, Camelopardalis B (Cam B) and DDO210.

3.1. Camelopardalis B

Cam B is a very faint ($M_B \sim -10.9$) dwarf irregular galaxy at a distance of 2.2 Mpc. Fig. 1 shows the integrated HI emission from the galaxy at $40'' \times 38''$ resolution overlaid on the Digitized Sky Survey image. The HI emission extends out to a galactocentric distance > 4 times the optical scale length. We have estimated an HI mass of $(5.3 \pm 0.5) \times 10^6 M_\odot$ (taking the distance to the galaxy to be 2.2 Mpc) from the integrated global HI emission profile of the galaxy.

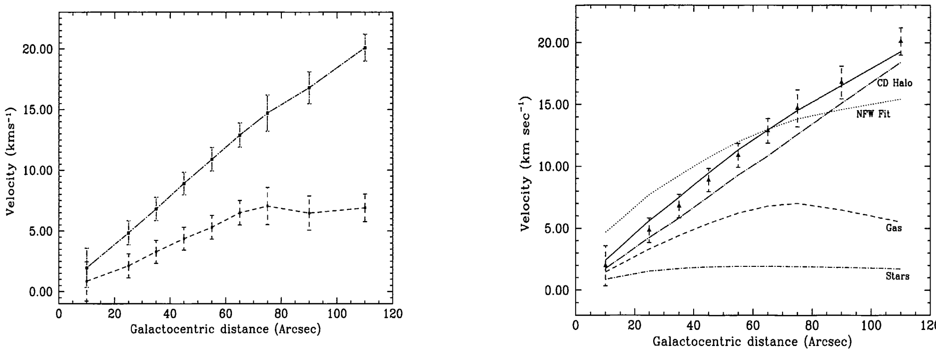

Figure 2. **(Left)** The derived rotation curve for Cam B (dashes) and the rotation curve after applying the asymmetric drift correction (dash dots). **(Right)** Mass models for Cam B using the corrected rotation curve. The points are the observed data. The total mass of the gaseous disk (dashed line) is $6.6 \times 10^6 M_\odot$. The stellar disk (short dash-dot line) has $\Upsilon_V = 0.2$, giving a stellar mass of $0.7 \times 10^6 M_\odot$. The best fit total rotation curve for the constant density halo model is shown as a solid line, while the contribution of the halo itself is shown as a long dash-dot line (the halo density is $\rho_0 = 13.7 \times 10^{-3} M_\odot$ pc^{-3}). The best fit total rotation curve for an NFW type halo (for $c = 1.0$ and $\Upsilon_V = 0.0$) is shown as a dotted line.

The velocity field of Cam B derived from the moment analysis of $24'' \times 22''$ resolution data is shown in Fig. 1. As can be seen in spite of being very faint, Cam B shows very regular kinematics. The isovelocity contours are approximately parallel, which is a signature of rigid body rotation. Also, the kinematic major axis of the galaxy is well aligned with the major axis of both the HI distribution and the optical image. Cam B is the faintest known dwarf irregular galaxy to show such regular kinematics.

The rotation curve for Cam B was derived from the HI velocity field, assuming it to be an axisymmetric disk (details can be found in Begum, Chengalur & Hopp 2003). The dashed curve in Fig. 2 shows the derived rotation curve. The peak (inclination corrected) rotation velocity for Cam B is ~ 7 km s^{-1}, comparable to the observed dispersion of ~ 7 km s^{-1} in the HI gas. This implies that random motions provide significant dynamical support to Cam B. Equivalently, the observed circular velocity underestimates the dynamical mass of the galaxy. Hence, before constructing mass models, the observed rotational velocity was corrected for the pressure support using the usual "asymmetric drift correction" [see Begum et al. (2003) for more details]. The dot-dashed curve in Fig. 2 shows the "asymmetric drift" corrected rotation curve.

Using this corrected curve, mass models for Cam B were derived. Fig. 2 shows the best fit mass model using a modified isothermal halo. Also shown in the figure is the best fit total rotation curve for an NFW type halo. As can be seen, the kinematics of Cam B is well fit with a modified isothermal halo while an NFW halo provides a poor fit to the data.

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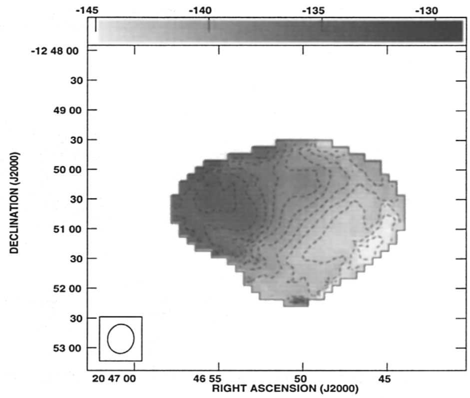

Figure 3. The HI velocity field of DDO210 at $29'' \times 23''$ resolution. The contours are in steps of 1 km s^{-1} and range from -145 km s^{-1} to -133 km s^{-1}.

The "asymmetric drift" corrected rotation curve for Cam B is rising till the last measured point (Fig. 2), hence the core radius of the isothermal halo could not be constrained from the data. The best fit model for a constant density halo gives central halo density (ρ_0) of 12.0×10^{-3} $M_\odot$ pc^{-3}. The derived ρ_0 is relatively insensitive to the assumed mass-to-light ratio of the stellar disk (Υ_V). We found that by changing Υ_V from a value of 0 (minimum disk fit) to a value of 2.0 (maximum disk fit), ρ_0 changes by <20%, hence is well determined. From the last measured point of the observed rotation curve, a total dynamical mass of $1.1\times10^8 M_\odot$ is derived, i.e. at the last measured point more than 90% of the mass of Cam B is dark. Futher, the dominance of the dark matter halo together with the linear shape of the rotation curve (after correction for "asymmetric drift") means that one cannot obtain a good fit to the rotation curve using an NFW halo regardless of the assumed Υ_V.

3.2. DDO210

DDO210 is the faintest ($M_B \sim -10.6$) known dwarf irregular galaxy in the Local Group. From recent HST observations Karachentsev et al. (2002) have estimated the distance to the galaxy to be 950±50 kpc. The HI mass of DDO210, determined from the global HI emission profile from our observations is $(2.8 \pm 0.3) \times 10^6 M_\odot$ (taking the distance to the galaxy to be 1 Mpc).

Fig. 3 shows the velocity field of DDO210 derived from a $29'' \times 23''$ resolution data cube. The velocity field is regular and a systematic velocity gradient is seen across the galaxy. This galaxy was also a part of the sample of Lo et al. (1993). However, our velocity field differs significantly from the velocity field derived by Lo et al. (1993). The systematic pattern seen in our velocity field is, to zeroth order, consistent with that expected from rotation. On the other hand, the velocity field derived by Lo et al. (1993) (based on a coarser velocity resolution of $\sim$ 6 km s^{-1}) is chaotic. This difference in the observed kinematics suggests

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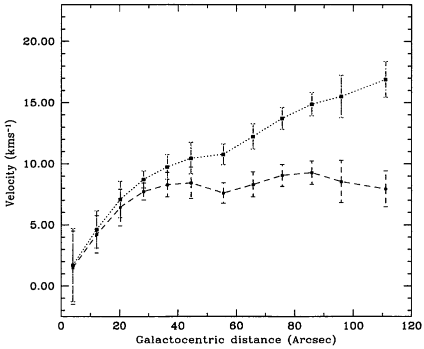


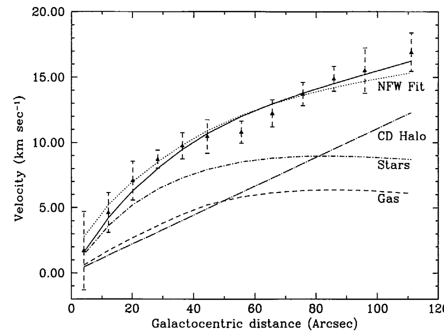


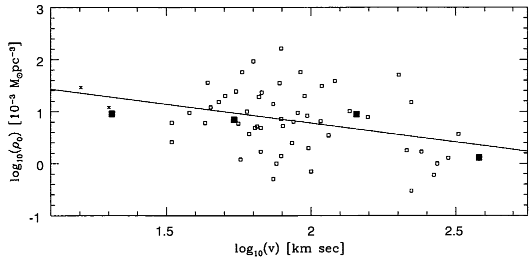
Figure 4. **(Left)** The hybrid rotation curve (dashes) and the rotation curve after applying the asymmetric drift correction (dots). **(Right)** Mass models for DDO210 using the corrected rotation curve. The points are the observed data. The total mass of the gaseous disk (dashed line) is $3.6 \times 10^6 M_\odot$. The stellar disk (short dash-dot line) has $\Upsilon_B = 3.4$, giving a stellar mass of $9.2 \times 10^6 M_\odot$. The best fit total rotation curve for the constant density halo model is shown as a solid line, while the contribution of the halo itself is shown as a long dash-dot line (the halo density is $\rho_0 = 29 \times 10^{-3} M_\odot$ pc^{-3}). The best fit total rotation curve for an NFW type halo, using $\Upsilon_B = 0.5$, c=5.0 and v_{200}=38.0 km s^{-1} is shown as a dotted line. See text for more details.

that high velocity resolution and high sensitivity is crucial in determining the systematic gradients in the velocity fields of faint galaxies like DDO210.

Fig. 4 shows the derived rotation curve for DDO210 and the "asymmetric drift" corrected rotation curve. We find that the "asymmetric drift" corrected rotation curve of DDO210 can be well fit with either a modified isothermal halo (with a central density $\rho_0 \sim 29 \times 10^{-3}$ $M_\odot$ pc^{-3}) or an NFW halo. In the case of the NFW halo however, a good fit is obtained for a wide range of parameters; the halo parameters could not be uniquely determined from the fit. Fig. 4 shows the best fit mass model for DDO210.

4. Discussion

In Fig. 5 we plot the core density of isothermal halo against circular velocity and absolute blue magnitude for a sample of galaxies, spanning a range of magnitudes from $M_B \sim -10.0$ mag to $M_B \sim -23.0$ mag. Cam B and DDO210 are also shown in the figure, lying at the low luminosity end of the sample. We have used B magnitudes because this is the only band for which data is currently available for both our sample and the other galaxies. As can be seen in the figure, there is a trend of increasing halo density with a decrease in circular velocity and absolute magnitude, shown by a best fit line to the data (solid line), although the correlation is very weak and noisy. Further, as a guide to the eye, we have also binned the data and plotted the median value (solid points). Binned data



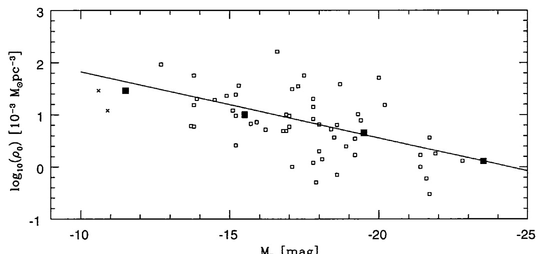


Figure 5. Scatter plots of the central halo density against the circular velocity and the absolute blue magnitude . The data (empty squares) are from Verheijen (1997), Broeils (1992), Côté et al. (2000) and Swaters (1999). The filled squares are the medians of the binned data, and the straight lines are the best fits to the data. Cam B and DDO210 are shown as crosses.

also shows a similar trend. Such a trend is expected in hierarchical structure formation scenarios (e.g. Navarro, Frenk & White 1997).

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