Rotation Curves and Dark Matter Properties of Dwarf Galaxies

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Abstract

Optical and H I imaging have been obtained for 73 late-type dwarf galaxies. For a 35 of these reliable rotation curves could be derived. The rotation curves for these dwarf galaxies have shapes that are similar to those of late-type spiral galaxies, but with a larger scatter. Their rotation curves rise to about two disk scale lengths, and start to reach a flat part at larger radii. Mass modeling based on these rotation curves indicates that a wide range in mass models is consistent with the data, ranging from maximum or minimum disk fits with pseudo-isothermal halos to the cuspy halos derived from CDM simulations.

1 Introduction

The most solid evidence for the existence of dark matter in galaxies is the discrepancy between the amount of mass inferred from rotation curves and the amount of mass that is visible in the form of gas and stars. In particular mass models based on the extended H I rotation curves indicated that large amounts of dark matter are required to explain the outer parts of observed rotation curves (van Albada et al. 1985, Begeman 1987). The dark matter properties of galaxies are usually derived by scaling the contributions of the stellar disk and bulge, the H I disk, and the dark matter to fit the observed rotation curve. However, there is a large degree of degeneracy in this fitting procedure, and the observerved rotation curves of spiral galaxies can be fitted with a wide range of halo properties (e.g. van Albada et al. 1985).

The first mass models for late-type dwarf galaxies indicated that the dark matter properties of these galaxies were similar to those of spiral galaxies (Carignan 1985, Carignan, Sancisi & van Albada 1988). A rotation curve study of the dwarf galaxy DDO 154 indicated, however, that this galaxy is dominated by dark matter at all radii (Carignan & Beaulieu 1989). Subsequent studies of dark matter properties of dwarf galaxies show a spread in dark matter properties, ranging from dominated by dark matter to possibly dominated by the stellar disk (Broeils 1992, Côté 1995, Swaters 1999). A questions that has received particular attention recently is whether or not the rotation curves of dwarf galaxies are consistent with the predictions made by cosmological simulations, especially by simulations based on cold dark matter (CDM). Here also a large spread in the results is found. Some studies conclude the rotation curves of these galaxies are not consistent with CDM (Dalcanton & Bernstein 1999, Côté, Carignan & Freeman 2000, de Blok et al. 2001, Blais-Ouellette, Amram & Carignan 2001), and other studies find that they are consistent (van den Bosch et al.2000, van den Bosch & Swaters 2001, Swaters 2001, Swaters et al. in preparation).

These studies suggest that there is a large spread among the dark matter properties of dwarf galaxies. The cause for this large spread is not clear, perhaps it is the result of a intrinsic spread in their dark matter properties, or perhaps it is the result of observational uncertainties.

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2 Uncertainties in rotation curves

There are several effects that may contribute to systematic errors in the observed rotation curves. These may be introduced by the observations, the analysis of the data, or the intrinsic properties of the galaxies themselves.

An important possible source of systematic errors on the rotation curve is beam smearing. If a galaxy is not well-resolved by the beam, this may lead to a smearing out of the inner slope of the true rotation curve, resulting in an underestimate of the slope. However, the effects of beam smearing can be modeled and corrected for (see e.g., Swaters (1999), van den Bosch et al. 2000, van den Bosch & Swaters 2001). Hα long-slit observations have a much better spatial resolution than H I observations, but they may still be affected by seeing, slit width and errors in positioning of the slit (see e.g., Swaters et al. 2002, in preparation).

Systematic effects may also be introduced by the analysis. Corrections for beam smearing may introduce uncertainties (Blais-Ouellette et al., in preparation). For H I observations, systematic effects may be introduced if the rotation curve is derived from a velocity field that is constructed by taking the intensity weighted mean (IWM) of the line profiles. Often, a rotation curve derived from an IWM velocity field underestimates the inner slope (see e.g. Bosma 1978, Swaters 1999). The systematic effects are particularly strong for higher inclinations.

A third source of systematic effects is the galaxy itself. If a galaxy has a strong bar, or if it is lopsided or interacting, the derived rotation curve may not reflect the underlying potential. More trivially, if a galaxy lacks emission line gas at certain radii the rotation curve cannot be derived. Although this is obviously not a problem for galaxies that are viewed sufficiently face-on, it is a real problem for edge-on galaxies.

In order to be able to derive an accurate rotation curve, one needs to observe galaxies that are symmetric and well-resolved, with inclinations between about 40 and 80 degrees, with well-sampled velocity fields. We have selected a sample of dwarf galaxies taking these criteria into account, making this sample well-suited to investigate the relations between the luminous and dark properties in the dwarf galaxies regime, and the relation between rotation curve shape and the distribution of light.

3 Optical and H I properties

For all the dwarf galaxies in the sample, optical R-band surface photometry has been obtained. These observations were used to derive magnitudes, surface brightnesses and disk scale lengths, and especially radial surface brightness profiles from which the contribution of the stellar disk to the rotation curve was derived. Despite the sometimes irregular optical appearance of late-type dwarf galaxies, most of them have surface brightness profiles that are well represented by an exponential decline.

H I observations have been obtained as part of the Westerbork H I Survey of Spiral and Irregular Galaxies (WHISP), a project which is being carried out at the Kapteyn Institute (see also Swaters et al. 2001).

The ratio of the H I extent to the optical diameter, defined as 6.4 disk scale lengths, is on average 1.8 ± 0.8, similar to the range observed in spiral galaxies. Most of the dwarf galaxies in this sample are rich in HI, with typical M_{HI}/L_B of 1.5. The relative H I content M_{HI}/L_B increases towards fainter absolute magnitudes and towards fainter surface brightnesses. Dwarf galaxies with lower average H I column densities also have lower average optical surface brightnesses. More details on the HI properties of these galaxies are given in Swaters (1999) and Swaters et al. (2001).

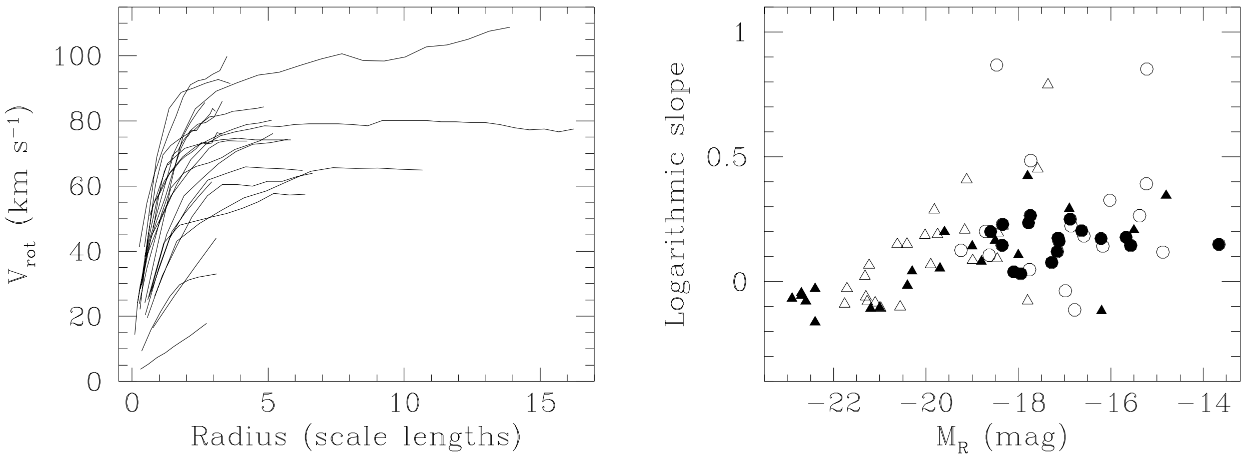

Figure 1: On the left, a compilation of the 20 high quality dwarf galaxy rotation curve. On the right, the logarithmic slope between two disk scale lengths and the last measured points. Filled circles correspond to late-type galaxies in the high quality rotation curve sample, open circles represent dwarfs in the low quality rotation curve sample, open triangles are galaxies in Verheijen's (1997) Ursa Major sample, filled triangles represent the galaxies from various sources presented in Broeils (1992).

4 Rotation curves

The rotation curves were determined in two steps. First, an initial estimate of the rotation curve was obtained by fitting a rotation curve by eye to the data cube at 30″ resolution (at the full resolution of 15″, the signal-to-noise ratio was too low to derive a rotation curve). Next, this rotation curve was refined by constructing detailed models of the data cubes, based on the rotation curve, the observed H I distribution (at the full resolution) and a constant velocity dispersion, assumed to be 8 km s^{-1}. This model was then convolved to a resolution of 30″, and compared with the observations. The best fit was determined by finding the lowest value of χ^2, but the adjustments to the rotation curves were determined by eye.

The main advantage of this procedure is that it takes into account the detailed effects of beam smearing. The distribution of HI, the inclination, the velocity gradients and of course the size of the beam are all taken into account. As a result, the derived rotation curves are to a large extent free of the effects of beam smearing. Comparison of the rotation curves derived in this way with those derived from Hα observations, which have been obtained for a small subsample, indicate that the procedure works well. Rotation curves have been derived for 35 dwarf galaxies. These have been subdivided in a high-quality category, containing 20 galaxies, and a low-quality category with 15 galaxies.

In the left panel of Fig. 1 the rotation curves of the galaxies in the high-quality sample are shown, with the radius expressed in units of optical disk scale lengths. The most striking feature in this figure is that the rotation curves look much like those of spiral galaxies. Most of the rotation curves rise steeply in the inner parts and start to flatten after about two disk scale lengths. There are several galaxies that have fairly flat rotation curves, with amplitudes as low as 60 km s^{-1}. Whether the flat part in the rotation curve is reached seems to depend more on the radial extent of the rotation curve than on its amplitude. There are no galaxies with solid body rotation curves that extend beyond three disk scale lengths. Note that some galaxies have rotation curves that do not extend much beyond two or three disk scale lengths, and thus we cannot rule out that these galaxies might have rotation curves that keep rising. The main difference between rotation curves of dwarf galaxies and those of spiral galaxies is that there are no declining rotation curves among

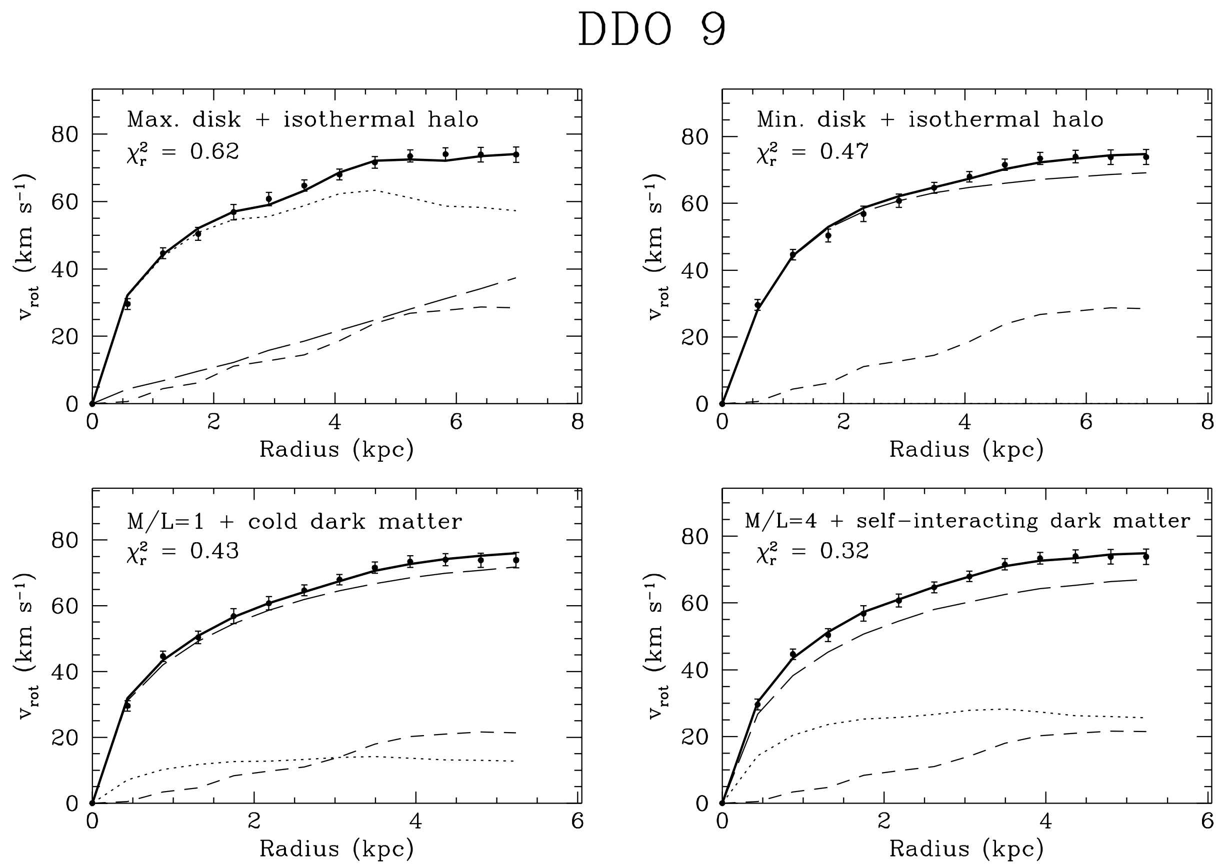

Figure 2: Mass models for DDO 9. The dotted line represent the contribution of the stellar disk, the short dashed line that of the gas, the long dashed line the dark matter, and the full line gives the best fit mass model.

the dwarf galaxies in our sample.

In the right panel of Fig. 1, the rotation curve shape, defined here as the logarithmic slope between two disk scale length and the last measured point, is plotted against the absolute magnitude, both for the dwarf galaxies in this sample (circles) and two comparison samples of spiral galaxies (triangles). From this figure, it is seems that the rotation curve shape depends only slightly on the absolute magnitude: spiral and dwarf galaxies with $-20 < M_R < -14$, which all have little or no bulge, appear to have similar rotation curve shapes. At the bright end, near $M_R = -22$, there are several galaxies with declining rotation curves, but these galaxies also have strong bulges. Towards fainter absolute magnitudes the spread in shapes increases. The cause of this spread is unclear. The fact that the spread is larger among the data derived from the lower quality rotation curves suggests it may in part be due to observational uncertainties.

The similarity in rotation curve shape for spiral and dwarf galaxies suggests that the rotation curve shapes do not depend strongly on luminosity. On the other hand, the fact that the presence of a bulge does affect the shape of the rotation curve, suggests that the rotation curve shape is closely coupled to the distribution of light (see also Sancisi & van Albada 1987). Indeed, Swaters (1999) found a correlation between the central concentration of light and the inner rotation curve shape, both for spiral and dwarf galaxies.

5 Dark matter properties

Generally, the rotation curves of the dwarfs in this sample rise steeply, and begin to reach a flat part after about two disk scale lengths. This has important consequences for the dark matter properties derived by fitting mass models to the rotation curves. For one example galaxy, sets of mass models are shown in Fig. 2. Below, the general results from Swaters (1999) and Swaters (2001a) are discussed.

Most strikingly, for about 80% of the dwarf galaxies in this sample, the inner rise of the rotation curve can be explained by scaling up the contribution of the stellar disk to the rotation curve, i.e., maximum disk works for dwarf galaxies (see Fig. 2, top left). Galaxies for which maximum disk does not work all have low quality rotation curves or clear non-circular motions. The required maximum disk stellar mass-to-light ratios may be high (up to 20 in the R-band), and it therefore seems unlikely that they can be explained by stars alone. Alternatively, it might indicate the presence of an additional baryonic component associated with the disk, e.g., consisting of white dwarfs or cold molecular gas.

On the other hand, the rotation curves can also be explained by completely ignoring the stellar disk (Fig. 2, top right). In fact, a good fit to the rotation curve can be obtained with any mass-to-light ratio between zero and the maximum disk value. This illustrates well the large degree of freedom that exists in the mass modeling.

Interestingly, the observed rotation curve can also be explained by assuming a maximal contribution of both the stellar and the gaseous disk. Bosma (1981) already noticed that the H I and the total mass density were similar, and recently Hoekstra et al. (2000) found that the observed rotation curves of spiral galaxies can be explained if the H I is scaled up by a factor of around 10. H I scaling produces remarkably good fits for late-type dwarf galaxies, but the scaling factor is found to be lower towards low surface brightness dwarf galaxies. The fact that the H I and the stellar disks can be scaled to obtain a good fit to the rotation curve indicates that the dark and the visible matter are coupled.

The rotation curves of the dwarf galaxies in this sample rise sufficiently steeply to accomodate the cuspy halos that have been found from cosmological simulations (e.g., Navarro et al., 1997, hereafter NFW, see Fig. 2 bottom left). Van den Bosch & Swaters (2000) found that the observed rotation curves are consistent with cold dark matter halos in a ΛCDM universe, but also that there is a large degeneracy in the mass modeling. For most galaxies equally well fitting mass models can be obtained for cuspy halos or halos with constant density cores, and there are no galaxies which can only be explained by a CDM-type halo. Van den Bosch & Swaters (2000) also found that the observed rotation curves of dwarf galaxies were not consistent with the very steep inner slopes predicted by some CDM N-body simulations (Fukushige & Makino 1997, Moore et al. 1998, Klypin et al. 2001). Also, the observed rotation curves are only consistent with NFW halos for low stellar mass-to-light ratios, up to about 2 in the R-band. If the mass-to-light ratios are substantially higher than that, closer to the maximum disk values, the observed rotation curves of dwarf galaxies cannot be reconciled with an NFW halo.

Because of these and other problem that CDM faces various alternatives for CDM have been proposed, such as warm dark matter or self-interacting dark matter. The remaining panel in Fig. 2a shows a mass model in which the disk has a stellar mass-to-light ratio of 4, and the dark halo is a self-interacting dark matter halo (Davé et al. 2001). This mass model also provides a good fit to the data.

A possible concern about these mass models is that the spatial resolution of the H I observations is not sufficient to measure the inner shape of dwarf galaxy rotation curves with accurately. The large degeneracy in the mass modeling may simly be a reflection of this lack of precision. However, this does not appear to be an important effect. The degeneracy is also seen in the closest galaxies with H I observations, for which the linear size of the beam seems small enough to measure the inner slope accurately. Moreover, recent Hα observations also show that a large degeneracy exists in the mass models fitted to these high resolution rotation curves (Swaters et al., in preparation).

It seems that the dark matter properties, the mass distributions, and in particular the inner slopes of the mass distributions of dwarf galaxies are still poorly determined, as is evidenced by the lack of consensus in the literature on this topic, in particular on whether or not dwarf galaxies are consistent with CDM predictions. This lack of consensus may in part be explained by systematic effects that may have affected some observed rotation curves. To resolve this controversy, rotation curves with high spatial resolution are needed to determine the inner shape of the mass distribution unambiguously. To break the large degree of freedom that exists in the mass modeling, independent estimates of the mass in the stellar disk, obtained for example from stellar velocity dispersions, will be essential.

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