Chapter 14

Dark Matter in Disk Galaxies

Rotation curves of disk galaxies rise steeply in their inner regions and then remain roughly flat out to the last point measured. To explain these observations within the framework of Newtonian gravity, a considerable amount of unseen mass is required. The idea that unseen matter is needed to account for the rotation velocities of disk galaxies was put forward by Freeman (1970):

> [T]here must be undetected matter beyond the optical extent of NGC 300; its mass must be at least of the same order as the mass of the detected galaxy.

This idea was instantly controversial; many wondered if dark matter on galactic scales is unavoidable. Kalnajis (1983) showed that within the radii accessible to optical spectroscopy, the rotation curves of disk galaxies could be well-fit without any dark matter. Indeed, a truncated exponential disk and a de Vaucouleurs bulge can be combined to yield a rotation curve which is flat to about 10% out to four times the disk's exponential scale length h (van Albada *et al.* 1985). Thus neutral-hydrogen (HI) observations like Freeman's, extending well beyond the optical radii of galaxies, were required to establish the presence of dark matter.

14.1 Rotation Curves

While optical spectroscopy couldn't prove that dark halos exist, rotation curves measured using optical emission lines were important in posing the problem of dark matter in disk galaxies. Results of optical studies are reviewed by Rubin (1983). These show that most disk galaxies have rotation curves which rise at small radii and then level off. For galaxies of a given morphological type (*e.g.* Sc) the shape of the rotation curve shows a systematic trend with luminosity: low-luminosity galaxies show a fairly gradual rise, while in high-luminosity galaxies the rotation curve rises sharply and then levels off or even drops slightly.

14.1.1 NGC 3198

Radio-synthesis velocity maps of neutral hydrogen emission provide the most convincing evidence for dark matter (*e.g.* Carignan & Freeman 1985). In NGC 3198 the rotation curve has been measured to $11h$, or about 31 kpc (van Albada *et al.* 1985). Over such radii most galactic disks are slightly warped, and NGC 3198 is no exception. The warped disk is modeled as a set of concentric circular rings with inclinations varying fairly smoothly from 72° at the center to 76° at the edge. The fitted circular velocity of each ring, plotted against its radius, defines the rotation curve. After rising fairly slowly to a peak value of $157\,\mathrm{km/sec}$ at about $3h$, the rotation curve does not fall significantly below $150\,\mathrm{km/sec}$ out to the last point measured.

The rotation curve of NGC 3198 can be modeled by combining the gravitational forces of

- a thin exponential disk, and
- a dark halo with a core and power-law envelope.

The disk has the usual surface-density profile,

$$\Sigma(R) = \Sigma_0 \exp(-R/h)\,, \tag{14.1}$$

where Σ_0 is the central surface density and h is the disk scale length. For such a mass distribution the circular speed *in the plane of the disk* is

$$v_{\mathrm{d}}^2(R) = 4\pi G \Sigma_0 h y^2 (I_0(y)K_0(y) - I_1(y)K_1(y))\,, \tag{14.2}$$

where $y \equiv R/(2h)$, and $I_n(y)$ and $K_n(y)$ are modified Bessel functions of the first and second kinds (BT87, Ch. 2.6.3(b)).

The halo is assigned the space density profile

$$\rho_{\mathrm{h}}(r) = \frac{\rho_0}{1 + (r/a)^\alpha}\,, \tag{14.3}$$

where r is the spherical radius, a sets the halo length scale, and $-\alpha$ is the asymptotic slope of the profile at large r. The core radius of the halo, defined by $\rho_{\mathrm{h}}(r_{\mathrm{core}}) = \rho_0/2^{3/2}$ (roughly, the 3-D equivalent of the 'half central surface density' definition used observationally) is

$$r_{\mathrm{core}} = a(2^{3/2} - 1)^{(1/\alpha)}\,. \tag{14.4}$$

Since the halo is assumed to be spherical the circular speed is

$$v_{\mathrm{h}}^2(r) = G\frac{M_{\mathrm{h}}(r)}{r} = G\frac{4\pi}{r}\int dr r^2 \rho_{\mathrm{h}}(r)\,. \tag{14.5}$$

The rotation curve in the plane of the disk is found by adding the disk and halo contributions in quadrature:

$$v_{\mathrm{c}}(R) = (v_{\mathrm{d}}^2(R) + v_{\mathrm{h}}^2(R))^{1/2}\,. \tag{14.6}$$

Assuming that the observed disk has a constant M/L ratio, surface photometry gives a disk scale length of $h = 2.68\,\mathrm{kpc}$. Good fits to the observed rotation curve can be obtained for a wide range of model parameters; even more so than in fitting luminosity profiles, the problem of modeling galactic rotation curves is *severely* underconstrained. The model with the maximum disk mass has a disk mass-to-light ratio of $M/L_{\mathrm{B}} = 3.6$, consistent with a disk-type stellar population. But even this choice does not "nail down" the halo model; the slope and scale parameters may be varied in a correlated fashion over the range $1.9 < \alpha < 2.9$ and $7 < a < 12\,\mathrm{kpc}$. The halo core radius is somewhat better determined, with "subjective" 1-sigma limits of $r_{\mathrm{core}} = (12.5 \pm 1.5)\,\mathrm{kpc}$. Within the last point measured at $30\,\mathrm{kpc}$ the total disk mass is $3 \times 10^{10}\,\mathrm{M}_\odot$ and the total halo mass is about 4 times greater. The detected neutral hydrogen amounts to $5 \times 10^{9}\,\mathrm{M}_\odot$, or about 15% of the maximum disk mass (van Albada *et al.* 1985).

14.1.2 DDO 154 & other dwarf disk galaxies

Uncertainties in mass-to-light ratios make luminous disk galaxies problematic for detailed studies of halo structure. In dwarf disk galaxies, however, the mass in stars is relatively small, and more definitive results can be obtained.

The dwarf irregular galaxy DDO 154 is a striking example of a gas-rich dwarf. While its optical morphology is somewhat irregular, HI observations reveal a regular disk extending to $\sim 15h$. At an adopted distance of 4 Mpc, DDO 154 has absolute magnitude $M_{\rm B} = -13.8$, typical of a dwarf galaxy. The HI flux implies a total mass in neutral hydrogen of $M_{\rm HI} \simeq 2.7 \times 10^8\,{\rm M}_\odot$. This completely overshadows the mass in stars, estimated at $M_* \simeq 5 \times 10^7\,{\rm M}_\odot$ for a mass-to-light ratio of $M/L_{\rm B} \simeq 1$. Neither component comes close to explaining the inclination-corrected rotation curve, which rises to a gentle maximum of 45 km/s at a radius of 5.5 kpc; the total mass of $M_{\rm tot} \simeq 3.8 \times 10^9\,{\rm M}_\odot$ within a radius of 7.6 kpc must be almost entirely dark.

The rather well-determined dark matter distribution in galaxies like DDO 154 allows a comparison with the predicted halo profiles in a Cold Dark Matter (CDM) cosmology (Blumenthal et al. 1984). High-resolution simulations of gravitational clustering by CDM predict that halos should have cuspy central density profiles; a standard fitting function has the form

$$\rho(r) = \frac{\rho_0}{(r/r_{\rm s})^\gamma (1 + r/r_{\rm s})^{(3-\gamma)}} \tag{14.7}$$

where $r_{\rm s}$ is a scale radius and the inner slope $\gamma = 1$ (Navarro, Frenk, & White 1996; hereafter NFW); this profile *completely* fails to fit the rotation curve of DDO 154 (e.g. Burkert & Silk 1997). Indeed, early studies consistently indicated that rotation curves of dwarf and low-surface-brightness galaxies are better fit by halo models with constant-density cores than by models with central cusps (e.g. Moore 1994; Burkert 1995, ...).

More recent studies have modified but not entirely reversed this conclusion. To accuratly probe the central density profiles requires velocity observations with high spatial resolution (van den Bosch et al. 2000), since smearing due to finite beam size would obliterate the kinematic signature of a steep central cusp. Both $\rm H_\alpha$ and CO observations are now being used to obtain higher spatial and spectral resolution (e.g. Simon et al. 2005). The result is that no single profile fits all dwarf galaxies; a minority do indeed fit the standard NFW profile with $\gamma \simeq 1$, but other fits favor much shallower cusps or even constant-density cores.

14.2 Halo Shapes

Rotation curves imply the presence of significant amounts of dark matter but provide little constraint on the *shape* of the dark matter distribution. A highly flattened and dynamically cold dark matter distribution would run afoul of the same stability problem afflicting “bare” disk galaxies, but few other *a priori* constraints are available.

Gas orbits in the disk plane provide some information about halo shapes. The gas settles onto closed, non-intersecting orbits. In an axisymmetric potential such orbits will be circular, but a non-axisymmetric halo will force the gas onto non-circular orbits. Non-axisymmetric halos may cause oval distortions in some disk galaxies (Kormendy 1982) and kinematic asymmetries in HI maps (e.g. MB87, Fig. 8-31). Asymmetries in the Milky Way’s HI kinematics have been attributed to a rotating triaxial halo (Blitz & Spergel 1991). But non-axisymmetric halos will also increase the scatter in the Tully & Fisher (1977) relationship between luminosity and circular velocity; by comparing the observed and predicted scatter, Franx & de Zeeuw (1992) conclude that the potentials of typical disk galaxies can be no flatter than about 0.9 : 1 in the disk plane. Stronger limits are available in special cases; for example, the potential of the E/S0 galaxy IC 2006 is axisymmetric to better than 0.98 : 1 (Franx, van Gorkom, & de Zeeuw 1994).

14.2.1 NGC 4650A

The three-dimensional shape of a disk galaxy's potential can only be inferred from tracers which travel far from the plane of the disk. Polar-ring galaxies are therefore important for discussions of halo shapes; these are S0 galaxies with rings or disks of gas and stars in *polar* orbits. Such rings probably form via mergers or mass transfers (Schweizer, Whitmore, & Rubin 1983). Early studies established that the central objects resemble S0 galaxies seen roughly edge-on; in particular, these objects exhibit the rapid rotation characteristic of S0 disks. Observed rotation velocities in the disk plane and in the ring plane are comparable. Simple models in which the potential is halo-dominated and both the disk and ring rotate at the local circular velocity then imply that the dark halos of these systems are nearly spherical (Whitmore, McElroy, & Schweizer 1987).

However, more sophisticated models including the gravitational potentials of the central galaxy and polar ring and the effects of random motions in the S0 disk appear to rule out a spherical halo for the polar-ring galaxy NGC 4650A. These models assign the ring a mass significantly greater than the observed HI mass (Sackett & Sparke 1990); presumably the *stellar* component of the ring accounts for the difference, though the blue colors of this population (Whitmore et al. 1987) imply a relatively low mass-to-light ratio. Best-fit halo models have minor axis ratios between 0.3 : 1 and 0.4 : 1 (Sackett et al. 1994). This is comparable to the axial ratio of the central S0; in this case the dark matter appears to be as strongly flattened as the luminosity!

14.3 Is There a "Disk-Halo" Conspiracy?

Besides the apparent coincidence of shapes just mentioned, yet another coincidence demands explanation: Bahcall & Casertano (1985) argue that "at least one parameter of a two-component mass model must be finely tuned in order to reproduce the observed flatness of... rotation curve[s]". At small radii, the rotation velocities of disk galaxies are set by the luminous components, while at large radii they are set by the dark matter. It appears that these two components must "conspire" to produce rotation curves which remain flat to many times the disk scale length, h (van Albada & Scancisi 1986).

Recent studies have somewhat blunted the teeth of this conspiracy. For one thing, rotation curves are not invariably flat; low-luminosity disk galaxies exhibit gently *rising* rotation curves, while high-luminosity disk galaxies have rotation curves which peak at about $2h$ and gently decline further out (Ruben et al. 1985, Casertano & van Gorkom 1991). Moreover, at least part of the proposed conspiracy may be explained by the dynamical response of a pre-existing dark halo as a disk slowly grows inside it (Blumenthal et al. 1986, Barnes 1987, Athanassoula 1988, Ryden 1991).

But the shapes of halos may provide fresh evidence for conspiracy theorists. Numerical simulations of clustering in a universe full of CDM generally yield strongly triaxial halos. Highly flattened yet axisymmetric halos might be easier to explain if dark matter is baryonic and dissipative (e.g. Pfenniger, Combes, & Martinet 1994).

14.4 Conclusions

The evidence indicates that dark halos are many times more massive than visible galaxies, that the dark matter is much more extended than the luminous component, that dark halos often have relatively large core radii, and that halos are somewhat flattened (e.g. Trimble 1987, Ashman 1992).

The dark halo hypothesis for flat rotation curves would be in trouble if the gas was the only tracer providing evidence for massive halos. But there is ample evidence for massive halos from other observations (BT87, Ch. 10). In the Milky Way, maximum stellar velocities in the solar neighborhood imply that our galaxy has a potential well deeper than the visible matter alone can generate; velocities of globular clusters and satellite galaxies do not show the fall-off with radius expected in a Keplerian potential, and the tidal forces required to explain the truncations of these systems and the tearing-off of the Magellanic Stream likewise demand more mass than is seen in stars and gas. The present motion of the Milky Way and M31 toward each other implies a total mass at least ten times the luminous mass of these galaxies, and the orbits of binary galaxies seem to be inconsistent with Keplerian potentials. Finally, not only gas and stars but even *light* seems to respond to the gravitational field of the dark matter in galaxy halos; distortions of background galaxies may be attributed to weak gravitational lensing by halos extending to at least $100 kpc$ (Brainerd, Blandford, & Smail 1996).

More problematic is the relationship between the halos detected in real galaxies and those predicted in a CDM-dominated universe. A general mechanism capable of disrupting the steep central cusps produced in gravitational clustering experiments is needed. Moreover, the scant information on axial ratios of halos does not seem that consistent with the predictions of CDM simulations. Despite the successes of CDM in describing structure on larger scales, an outside possibility remains that a good part of the dark matter associated with individual galaxies is composed of baryons.