The Mass and Extent of the Galactic Halo

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ABSTRACT

We review the various techniques used to constrain the Galactic halo mass profile for radii $\gtrsim 20$ kpc with particular emphasis on identifying a self-consistent halo model and resolving the apparent discrepancies present in the literature on this subject. We collate published results and demonstrate that they are all consistent with a Galactic halo that is nearly isothermal with a characteristic velocity of 180 to 220 km sec$^{-1}$ and an extent $\gtrsim 200$ kpc.

Subject headings: Galaxy: halo, kinematics and dynamics; Cosmology: dark matter

1. Introduction

Two fundamental parameters that characterize the Galactic halo are its mass and extent. Our understanding of these two quantities frames our subsequent investigations of the halo and provides basic constraints on models of Galactic formation and evolution. For example, if the halo is unequivocally vastly larger and more massive than the luminous component of the Galaxy, then the search for dark matter at large radius becomes a key research endeavor. This review describes the current understanding of the mass distribution of our Galaxy at large ($> 20$ kpc) radii with particular emphasis at reconciling a single model with all of the available data.

2. Preliminaries

What is the Galactic halo? Some investigators use the term halo when describing material just outside of the disk (e.g. 1 to 2 kpc above the disk), while others use it only when describing the material well beyond radii of several tens of kpc. For some investigators, the halo is the spherical stellar component of the galaxy, for others it is only the dark matter component. No particular definition is superior, but it is essential in any discussion to describe one’s adopted definition. Here, we use the term halo to describe the mass distribution external to $\sim 20$ kpc.
The concept of “the mass of the Galactic halo” is ill-defined. If models (cf. Navarro, Frenk & White 1996) of galactic halos are even remotely correct, then halos do not have sharp boundaries and galaxies are sufficiently close to each other that their halos should overlap. Because halos are not discrete, finite objects, “total” quantities (such as total mass or extent) are unmeasurable. Galaxy masses are commonly quoted in the literature, but generally the authors implicitly define that mass to be the mass within the radius that they probed. Again, great care must be taken to explicitly state one’s definition and to be consistent when comparing results from various studies.

Is there an acceptable practical, working definition of a halo? One potential definition is that the halo is the volume enclosing all of the mass that has already decoupled from the Hubble expansion. Although this definition is well-defined theoretically, it is difficult to implement in practice because the current turnaround radius is unobserved and because galaxies are not isolated. For example, although M 31 has decoupled from Hubble flow and is falling toward the Milky Way, we would not consider M 31 to be part of the Galactic halo. Other theoretical definitions such as the mass enclosed within the virial radius, the mass that is gravitationally bound, or the mass within a fixed density contrast relative to the universal mean density, are equally problematic — especially when applied to real galaxies. The only viable solution to this problem is to avoid defining the halo as a discrete entity. Instead, we must focus our discussion on the mass profile or on the mass within a selected, fixed radius.

The emphasis on the mass profile or the enclosed mass within radius, \( R \), raises a second issue. The test particles utilized to measure the mass (e.g. HI atoms, globular clusters, satellite galaxies, or nearby galaxies) must span the radial range over which the enclosed mass is being quoted. For example, one should never rely on the Galactic disk rotation curve, which at best extends to \( \sim 20 \) kpc (Fich & Tremaine 1991), to infer an enclosed mass at \( R > 20 \) kpc. Such an extrapolation requires that one assume a halo profile and extent beyond 20 kpc — assumptions that turn the analysis into a self-fulfilling prophecy. Such studies (cf. Honma & Ken-ya 1998) typically note a slight decrease or increase in the outermost rotation curve that, when extrapolated, leads to large apparent discrepancies with, for example, the halo mass inferred from Galactic satellite dynamics. Most of the apparent discrepancies between different studies are the result of comparing masses derived for different effective enclosed radii or from the extrapolation of results beyond the radii that were directly probed. For illustration, Figure 1 shows the relative sizes (in projection) for the most common regimes discussed in the literature (disk, interior to the LMC, interior to the outermost satellites, and theoretical halo). Notice that the disk and even the LMC at its current position, probe a relatively small fraction of the what can be considered to be the Galactic halo.

The final issue to be discussed involves the rather unsavory, but widespread practice of selective citation. A proper halo model must be in accordance with all of the available data (to within the associated uncertainties) — although one does not need to accept all of the available conclusions! For example, it is inappropriate to cite only the measures of the Galactic mass inside of 50 kpc (e.g. rotation curve and the kinematics of the inner globular clusters) as a measure
Fig. 1.— A comparison of the range over which various probes sample the Galactic halo. The plotted areas are scaled relative to the projected area of the halo enclosed by the probe — a plot of the relative volumes probed would show an even larger difference between the inner and outer regions.
of the mass of the Galactic halo. Not only do they not probe beyond 50 kpc (and are therefore almost entirely insensitive to whatever mass might be present beyond 50 kpc), but if the Galaxy had such a small total mass, one would not be able to account for the dynamics of the outer satellite systems and the dynamics of the Local Group. Therefore, the omission of the probes at larger radii does not simply lead to “a conservative mass estimate” but instead leads to a result that is inconsistent with existing data. Every data set and analysis approach includes some assumption(s) that if violated by nature would result in a serious under or overestimate of the Galactic mass. Because the uncertainties are dominated by systematic errors, the use of all of the data strengthens the conclusions by more than the standard $1/\sqrt{N}$ intuitive understanding.

With these caveats in mind, we proceed to briefly discuss the principal methods for the determination of the mass profile of our Galaxy for $R > 20$ kpc.

3. The Methods

3.1. The Rotation Curve

As mentioned previously, the rotation curve of our Galaxy does not provide strong leverage on the mass profile for $R > 20$ kpc, but it does provide a key anchor for the mass profile at small radius. Models used to explain the dynamics of the outer halo cannot predict velocities at small radii that are inconsistent with the precise measures of the disk rotation. For example, although it is plausible that the outer halo systems might be well fit by an isothermal halo with $v_c = 300 \text{ km sec}^{-1}$, such a model can be rejected because it predicts that the rotation curve of the galaxy at all $R$ is $300 \text{ km sec}^{-1}$.

The measurement of the outer rotation curve of our galaxy is complicated by our position within the disk. The exact values of $v_c(15 \text{ kpc})$ has oscillated mostly between $180 \text{ km sec}^{-1}$ and $220 \text{ km sec}^{-1}$ (Fich & Tremaine 1991) and the uncertainties are large as $R \to 20$ kpc. Our final model should include the full range of these possibilities, but should not over interpret a rise or decline in the rotation curve at large radii. For an isothermal sphere model, the implied mass ratio between the two extremes is only $(180/220)^2 = 0.67$, which in this endeavor is not considered to be a serious discrepancy.

A strikingly different conclusion is reached if one interprets the decrease in the rotation curve from $220 \text{ km sec}^{-1}$ at $8$ kpc to $180 \text{ km sec}^{-1}$ at $15$ kpc as due to a centrally concentrated mass distribution. This velocity drop is nearly consistent with a Keplerian fall-off and would imply a central mass of about $1.1 \times 10^{11} M_\odot$. The rotation speed values recently derived by Merrifield and Olling (1998) of $166 \text{ km sec}^{-1}$ at $R = 20$ imply, for an assumed Keplerian rotation curve, a Galactic mass of $1.2 \times 10^{11} M_\odot$. These values for the Galactic mass are a factor of ten smaller than
the mass inferred at 200 kpc from the dynamics of satellite galaxies. However, this discrepancy is completely fictitious and entirely produced by the extrapolation of the Keplerian rotation curve to large radii (for which the rotation curve provides no evidence). If instead we ask what rotation velocity is implied at 15 or 20 kpc for an isothermal halo normalized to have an enclosed mass of $1.2 \times 10^{12} M_\odot$ at $R = 200$ (a value shown later to be implied by the distant Galactic satellite galaxies), the characteristic velocity is $v_c = 165 \, \text{km sec}^{-1}$ — actually lower than that measured by the rotation curve at $R = 15$ kpc and in agreement with Merrifield and Olling’s value at $R = 20$ kpc! Therefore, the observed rotation curve places no significant constraints on models of the Galactic halo that include a massive isothermal-like component that is consistent with the dynamics of the outer halo (obviously, the rotation curve is also consistent with a halo that truncates shortly outside $R = 20$ kpc). This exercise demonstrates why the extrapolation of data from one regime to larger radii is perilous.

### 3.2. Stellar Escape Speed

Stars observed locally are presumably bound to the Galaxy. Therefore, the fastest moving stars place a lower limit on the local escape velocity (cf. Carney & Latham 1987). An analysis of these stars suggests that the local escape speed is between 450 and 650 km sec$^{-1}$ (Leonard & Tremaine 1990). Converting the observed velocities into an estimate of the escape speed requires a model for the Galactic potential and the stellar velocity distribution. While the fastest observed star provides a well-defined lower mass limit, the derivation of an upper limit is highly model dependent. Applying a Jaffe (1983) model (which provides a flat rotation curve at small radii and a sharp, $\rho \propto r^{-4}$, cutoff at large radii, and an adopted circular velocity of 220 km sec$^{-1}$ at small radii), the lower limit on the escape velocity provides a lower mass limit at 200 kpc of $3.8 \times 10^{11} M_\odot$ (Kochanek 1996). This is an interesting lower mass limit because the inferred scale length, $r_j$, of the Jaffe model is 44 kpc and is roughly equivalent with the current position of the Large Magellanic Cloud (LMC) — thereby suggesting that any dark halo that exists must extend at least to the current position of the LMC. If this minimal halo is characterized as an isothermal sphere, then $v_c \gtrsim 180 \, \text{km sec}^{-1}$.

### 3.3. Distant Satellite Galaxies and Globular Clusters

The most distant probes, that are still plausibly within the Galactic halo, globular clusters and satellite galaxies at $R > 50$ kpc. These objects provide the best opportunity to measure the outer halo mass profile, but suffer from other difficulties. There are few such objects ($\sim 15$ at $R \geq 50$ kpc), typically only their radial velocity is known, their velocity ellipsoid is unknown, the
outermost ones may not be gravitationally bound to the Galaxy, and they have sufficiently large orbits that in a Hubble time they have completed only 1 or 2 orbits. Some of these problems are being addressed, for example proper motions have been measured for the nearest satellites (Majewski & Cudworth 1993).

The properties of the satellite sample can be analyzed to provide constraints on the mass and extent of the halo. The simplest approach is to apply the escape velocity argument to these objects. Assuming a point mass potential (i.e. all of the mass is within the current position of the satellite), the radial velocity of the Leo I satellite (177 km sec$^{-1}$ in the local standard of rest) and the distance to Leo I (230 kpc from the Galactic center), we calculate that $M_{MW} > 8 \times 10^{11} M_\odot$ (for a listing of satellite data and references see Zaritsky 1994). If we exclude Leo I from the sample (one could claim that it is an unbound satellite) the satellite that implies the next largest lower mass limit is Pal 14, $M_{MW} > 4.3 \times 10^{11}$. The difference between this limit and that from Leo I is substantial, which might lead one to conclude that Leo I is indeed likely to be unbound. However, Pal 14 is nearly three times closer to the Galactic center than Leo I, so the two satellites are not sampling the same region of the halo. Because of these ambiguities, and the fact that the data from all of the other satellites are not being exploited, this approach is unsatisfactory.

An improvement over the simple binding mass argument is provided by the projected mass calculation (cf. Bahcall & Tremaine 1981). In this approach one combines the observables (radial velocity, $v_r$, and distance, $r$) into a “mass-like” variable, $v_r^2 r$, and uses either an analytic treatment or simulations to recover the expected value of this variable. From those calculations one can derive the “correction” factor necessary to convert the observed $v_r^2 r$ into an unbiased estimate of the mass. This approach has several advantages. First, it is mathematically stable (unlike a virial mass analysis). Second, the correction factor is easily calculable for various models. Third, it uses all of the data and can provide a confidence interval on the final mass rather than just a lower limit. However, this approach also suffers from some of the same problems as methods discussed previously. For example, it assumes that the test particles are on bound, relaxed orbits. The application of a mathematically sophisticated version of this technique (Little & Tremaine 1989), using the quantity $v_r^2 r$ as the diagnostic variable for a point mass model, and assuming isotropic orbits, results in mass estimates that range from $4.6 \times 10^{11} M_\odot$ to $12.5 \times 10^{11} M_\odot$, with and without the inclusion of Leo I in the sample (Zaritsky et al. 1989). The large difference arising from the inclusion or exclusion of Leo I has led some to suggest that Leo I is unbound and should not be included. However, below we demonstrate that the nature of Leo I has little influence on the final result if a more realistic halo model is adopted.

Both previous mass estimates (with or without Leo I) imply a Galactic halo that extends many tens of kpc. For an isothermal halo with $v_c = 220$ km sec$^{-1}$, the inferred extents are 43 and 112 kpc, respectively. In either case, many of the satellite orbits would penetrate the mass distribution and the assumption of a point mass potential is likely to be violated. If we examine the implications from using an isothermal sphere model, rather than the point mass model, we arrive at a different conclusion regarding the influence of Leo I. In the isothermal sphere model,
one derives $v_c$ and the inclusion or exclusion of Leo I makes only a modest difference (154 vs. 169 km sec$^{-1}$, respectively, for assumed isotropic orbits). The difficulty with this model is that it makes no prediction about the extent of the halo, which formally leads to an infinite halo mass. Nevertheless, from the best fit isothermal sphere model we calculate that the enclosed Galactic mass within 200 kpc is $1.3 \times 10^{12} M_{\odot}$.

One potential difficulty for any of these models is that they do not account for the fact that distant satellites, like Leo I, have only completed 1 or 2 orbits. An assumption that is used in deriving the necessary correction factors is that satellites are distributed randomly in orbital phase. This assumption breaks down when the satellite has only completed a limited number of orbits. The solution to this problem is to construct models that follow the orbits of individual satellites. These models rely on an assumption about the age of the universe.

### 3.4. Timing Arguments

The timing argument was first applied by Kahn and Woltjer (1959) to the Milky Way-M 31 system. Because M 31 is moving toward the Galaxy, one can presume that the gravitational attraction between M 31 and the Galaxy is sufficient to decouple the pair from the Hubble expansion. By adopting an age of the Universe and measuring both the distance to M 31 and its velocity, simple orbital equations provide a firm lower limit the mass of the pair of galaxies. The only potential loopholes in this argument involve invoking random peculiar velocities for the galaxies or interactions with other galaxies.

The application of the simple model (radial orbits, point masses) results in mass estimates of between 3 and $4 \times 10^{12} M_{\odot}$ for the M 31-Milky Way pair. Assuming either that the relative masses of the two galaxies scale with their luminosities or with their circular velocities squared results in a mass ratio of between 1.3 and 1.7 between M 31 and the Galaxy. Adopting 1.5 as the mass ratio, the mass of the Milky Way is then inferred to be $\sim 1.4 \times 10^{12} M_{\odot}$. However, this analysis excludes considerations of angular momentum, the overlap of the two halos at earlier times, and the growth of the halos with age. All of these considerations will increase the total masses.

We can also apply the timing argument to the Leo I-MW system. In contrast to M 31, which is falling toward the Galaxy and so one can assume that the system is seen “shortly” after turnaround, Leo I is moving outward and so one can either assume that it is on its first outward trajectory (although a simple calculation suggests that it would have traveled much farther than its current location in a Hubble time) or on its second outward trajectory. Adopting the second option leads one to infer a mass for the Galaxy of between 1.1 and $1.5 \times 10^{12} M_{\odot}$. Again we have neglected angular momentum, overlapping mass distributions, and the evolution of the Galactic halo.

Finally, more complex models attempt to embed the two body system into the larger
environment (cf. Einasto & Lynden-Bell 1982, Raychaudhury & Lynden-Bell 1989, Peebles 1995, Shaya, Peebles, & Tully 1995). By doing this, one can investigate the origin and expected magnitude of the angular momentum and utilize the dynamics of other Local Group galaxies to constrain the mass. The results are all consistent and, as expected, the derived masses are somewhat larger than those from the simple timing argument. Einasto & Lynden-Bell derive $M_{MW} = 1.9 \times 10^{12} M_\odot$; Raychaudhury and Lynden-Bell derive $M_{MW} = 1.3 \times 10^{12}$; Peebles (1995) derives $M_{MW} \sim 2 \times 10^{12} M_\odot$; and Shaya et al. derive $M/L = 175$, which roughly converts to $2.3 \times 10^{12} M_\odot$. The statistical analysis of the satellite galaxies (following Little & Tremaine 1989), the MW-M31 timing argument, the Leo I-MW timing argument, and the analysis of galaxies out to 3000 km sec$^{-1}$ recessional velocity (Shaya et al.), all imply that the Galactic mass out to $\sim 200$ kpc is $\gtrsim 1.2 \times 10^{12} M_\odot$.

3.5. Putting It All Together

The proper way to constrain the Galactic mass profile is not to divide the data and the methods into a myriad of possibilities, but instead to treat them all in a single, self-consistent manner. This approach is best illustrated in the work of Kochanek (1996) who fit one model to all of the data available at that time. To accomplish this, he selected the Jaffe model and used a Bayesian statistical approach following that of Little and Tremaine (1989) to derive the characteristic scale and circular velocity of the Jaffe model, $r_j$ and $v_j$. Using all of the data discussed previously, he derives that $v_c = 219[188, 251]$ km sec$^{-1}$ and $r_j = 204[116, 359]$ kpc, where the values in brackets indicate the 90% confidence limits. The best fit values imply a mass at 200 kpc of $1.1 \times 10^{12} M_\odot$. Taking the 90% confidence limits on $r_j$ and $v_c$ independently, we calculate limits on the mass at 200 kpc of 0.6 and $17.8 \times 10^{12} M_\odot$. These are almost certainly conservative values for the 90% confidence limit because it is not evident that good fits (acceptable within the 90% confidence limit) are obtained when both $v_c$ and $r_j$ are selected at their individual 90% confidence limits. As previously described for the isothermal sphere model, the exclusion of Leo I makes little difference to the derived parameters. The results without Leo I are $v_c = 221[190, 254]$ km sec$^{-1}$ and $r_j = 168[78, 321]$ kpc, which results in an enclosed mass at 200 kpc of $9.8 \times 10^{11} M_\odot$, a change of $\sim 10\%$ in comparison to the enclosed mass derived if Leo I is included. Kochanek’s treatment also demonstrates that the results are robust (consistent within the uncertainties) to excluding or including various sets of data.

4. Other Galaxies

We can further test the results for the mass and extent of our Galaxy by comparing to the results obtained for other galaxies. The analysis of other galaxies presents its own problems but
circumvents most of those present in the approaches discussed so far. Zaritsky et al. (1993,1998) and Zaritsky & White (1994) compiled and analyzed the dynamics of satellite galaxies for primary galaxies similar to the Milky Way. In general, the primaries are somewhat more luminous than the Milky Way and they are Sb to Sc type spirals. The satellite sample contains 115 satellites around 69 spiral primaries. The projected separations and radial velocity differences are plotted in Figure 2. The philosophy behind the approach is to assume that the primaries are sufficiently similar that the satellites can be treated as orbiting a single, typical galaxy. Therefore, even though there are only one or two satellites per galaxy, the analysis of the entire sample has significantly better statistics than the analysis of the Galactic satellite sample.

The detailed approach utilized to analyze this sample is based on modeling the halo growth over time, from its beginning as a seed perturbation in a uniform background to the current time, and the characterization of the properties of test particles within the final halo. Models that produce a satellite distribution similar to the observed distribution are accepted. This analysis, conducted on the first sample of 69 satellites, led to an estimate of the enclosed mass at 200 kpc of \(1.8[1.5,2.3] \times 10^{12} M_\odot\). The newer sample is qualitatively similar to the original one and samples the large radii better, so the same analysis applied to that sample should produce similar results. The estimated mass is somewhat larger than the results quoted above for the Galactic mass enclosed within 200 kpc, but the primary galaxies in this sample have an average circular velocity of 250 km sec\(^{-1}\). If we presume that halo profiles scale as \(v_c^2\), then the implied enclosed mass for the Milky Way within 200 kpc is \(1.4 \times 10^{12} M_\odot\), which is perfectly consistent with Kochanek’s results.

5. Discussion

Individually, each approach that we have described has potentially catastrophic problems. However, these problems and the data are different in each approach; therefore, the consistency between various approaches more than validates any single approach. In Figure 3 we plot the results discussed here for comparison. Each result is plotted at the relevant radius. Error bars generally represent ~ 90% confidence intervals. For the rotation curve datum (Fich and Tremaine) we chose a range of 180 to 240 km sec\(^{-1}\) as representative of the 90% confidence interval at \(R = 16\) kpc. We plot the quoted 90% confidence intervals for Kochanek’s measurement of the mass enclosed at 50 kpc. For his estimate of the mass enclosed at 200 kpc, we have adopted his confidence 90% intervals on the quantities \(v_c\) and \(r_j\). Therefore, the plotted uncertainty is probably overestimated because it is the combination of both variables being at the extreme of their 90% confidence range. For the measurement of the mass enclosed at 100 kpc from the analysis of the orbit of the Large Magellanic Cloud (Lin, Jones, & Klemola) we adopt their error estimate (for which the confidence level is unclear). Two values are overplotted from Zaritsky & White (ZW) for \(H_0 = 75\) km sec\(^{-1}\). The upper one is the value of the mass derived for the average
Fig. 2.— The projected separation and absolute value of the radial velocity differences for the Zaritsky et al. (1998) sample of satellite galaxies.
galaxy in the sample. The lower has been corrected by the square of the disk circular velocity of the average ZW galaxy (250 km sec$^{-1}$) relative to the Milky Way. ZW concluded that halos are not correlated with disk rotation speeds (so it is unknown whether the correction for the circular velocity difference is appropriate). Three values are plotted from the Zaritsky et al. (ZOSPA) study (the one at slightly smaller radius is derived assuming radial orbits, the central one is the lower limit derived by applying the timing argument to Leo I, and the one plotted at the slightly larger radius is derived assuming isotropic orbits). The limits on the Einasto & Lynden-Bell results were taken from their preferred range of solutions with the additional limitation that the age of the universe is between 10 and 15 Gyr. Peebles’s paper did not quote uncertainties. For the Shaya et al. result we adopted the 2σ contour from their model with external mass perturbers and draw an arrow to the right indicating that this value applies to large unspecified enclosed radii.

All of the data in Figure 3 are entirely consistent with an isothermal sphere with $v_c \sim 180$ km sec$^{-1}$. There is no evidence for a significant truncation of the mass profile at large radii.

Our Galaxy has a M/L ratio (for the mass enclosed within 200 kpc) of $\sim 100$ in solar units. Because of the presence of M 31, the Galactic halo cannot extend much beyond 200 kpc and M/L is unlikely to be more than 200. If all galaxies have $M/L \sim 100$, then $\Omega_{galaxies} \sim 0.07$, which is well below the critical value but well above the limit on $\Omega_{baryons}$ of 0.0193 (Burles and Tytler 1998). If we accept the conclusion from the MACHO experiment (Alcock et al. 1997) that 50% of the Galactic dark matter is baryonic, this predicts that $\Omega_{baryon} \sim 0.035$ which is significantly larger than the limit from the deuterium observations. Four possible solutions to this problem are (1) the halo baryonic component is highly concentrated toward the center of the Galactic halo (so that it is $\lesssim 50\%$ of the total dark matter in the halo but $\sim 50\%$ of the dark matter to the radius of the Large Magellanic Cloud), (2) the dark matter is composed of primordial black holes (which are baryonic but which do not participate in big bang nucleosynthesis), (3) the halo dark matter is highly clustered (Widrow & Dubinski 1998) and the line-of-sight to the Large Magellanic Cloud intersects a high density feature (which would again imply that the baryonic matter is $\lesssim 50\%$ of the total halo), or (4) the interpretation of the microlensing events as originating from halo MACHOs is incorrect (Sahu 1994, Zhao 1998, Zaritsky & Lin 1998).

6. Conclusions

All of the measurements of the mass of the Galactic halo are consistent if one accounts for the fact that they reflect results from different radial ranges within the halo. A simple isothermal sphere model fits the data from 10 kpc to 300 kpc. An “isothermal-like” model where the characteristics rotation curve drops slightly ($\sim 20\%$) from the standard disk value 220 km sec$^{-1}$ at radii $\gtrsim 20$ kpc is entirely consistent with all of the data. Barring fundamental problems with our understanding of gravity, the Galactic halo extends at least $\sim 200$ kpc and contains $\gtrsim 10^{12}M_\odot$. 
Fig. 3.— A comparison of various measurements of the mass of the Galactic halo (see text for details). The solid lines illustrate the expected enclosed mass for isothermal spheres with $v_c = 180$ and 220 km sec$^{-1}$. ZW and ZOSPA stand for Zaritsky & White (1994) and Zaritsky et al. (1989), respectively.
Models that extrapolate the declining rotation curve between 10 and 20 kpc outward, and so predict a low halo mass, are incompatible with the orbit of the Magellanic Clouds, with the dynamics of the distant Galactic satellites, with the dynamics of the Local Group, and with the halo properties inferred for other spiral galaxies. Despite the mystery regarding the nature of the dark matter, the measurement of its distribution around spiral galaxies is now secure.

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