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EVIDENCE FOR DARK MATTER FROM ROTATION CURVES: TEN YEARS LATER

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ABSTRACT

During the past decade, observations have confirmed that rotation curves are generally flat or rising across the optical galaxies out to the limits of the neutral hydrogen. Regrettably, parameters of the dark halos can be evaluated only in terms of assumed mass distributions. However, it seems well established that dark matter forms an increasingly dominant component with decreasing galaxy luminosity. A major advance of the decade has been the observation that in some gas rich dwarf irregulars the mass in dark matter exceeds that in luminous matter at virtually all radii. Interior to the final measured point in DDO 154, 90% of the mass is dark, and integral $M/L \geq 75$.

INTRODUCTION

It is now over ten years since astronomers started asking questions about dark matter: Is it necessary?, Where is it?, How much is there?, What is it? In this talk, I shall emphasize recent attempts to answer the first three questions, based on observational evidence principally from rotation curves. With very few exceptions, rotation velocities within spirals are constant or rising to the limits of the observations. Hence only a lower limit to the mass of a galaxy is obtained from internal velocity measures. It is still correct, as Bosma (1978) stated, that the best rotation curves are composite: optical observations at small radial distances, and radio observations for HI gas extending beyond the optical image.

The usual assumptions in deducing a mass distribution from a velocity distribution are that Newtonian gravitational theory is valid, that a self gravitating disk of constant M/L dominates at small radial distances, that an isothermal halo dominates at large radial distances, and that the internal extinction is not a function of radius. An isothermal halo distribution is adopted, not because of its reality, but because it produces a flat rotation curve. Extinction surely decreases away from the center; a more realistic treatment will only enhance the observed increase of M/L with radius, a primary evidence for dark matter. Many arguments can be given to contradict recent statements (Valentijn 1990) that galaxies are opaque (although optical depths of unity may exist). Background galaxies detected through foreground galaxies (Hodge 1974; Gurwell & Hodge 1990) show that, for example, extinction reaches only 1.3 V-magnitudes at the center of the Small Magellanic Cloud. Evidence supports the following: spiral galaxy masses increase approximately linearly to the limits of the observations, while luminosities asymptotically reach a limiting luminosity. Hence cumulative M/L values increase with radius with a gradient that is in excess of any value which might be attributed to population variations. A dark halo is the major contributor to the mass.

With $H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1}$, a value of M/L (mass to blue luminosity ratio in solar units) of about 800 is necessary to close the universe. However, individual field spirals exhibit velocities and luminosities which predict M/L values generally less than 10 within the final measured point. Thus, internal dynamics of spirals require only a small percentage of the closure mass.

ESCAPE VELOCITIES

If the kinetic energy of a star at galaxy radius r exceeds the negative of its potential energy Φ at that r , the star will escape from the galaxy. For a point mass, $v_{esc} = (2GM/r)^{1/2} = 2^{1/2}v_{circ}$, where M is the galaxy mass interior to r . Because galaxies do not consist of central point masses, it is not possible to infer a total mass for a galaxy unless the complete rotation curve or the gravitational potential or the form of the mass distribution beyond r is known. For our own Galaxy, knowledge of the escape velocity at the position of the sun will not determine the total mass uniquely, due to the uncertainty in the exterior mass distribution. For rotation velocities assumed constant to $r = 41$ kpc, with $v_{circ} = 220$ km/s and $v_{esc} = 500$ km/s, the mass interior to $M(r = 41 \text{ kpc}) = 5 \times 10^{11} M_{\odot}$ (Binney and Tremaine 1987; see also Leonard and Tremaine 1990), with an uncertainty at least a factor of two.

Historically, Oort (1921) noted that the distribution of high velocity stars in the solar neighborhood showed an asymmetry in direction. In the direction of galactic rotation few stars had velocities greatly in excess of the solar rotation; Oort identified the observed velocity limit with the escape velocity from the Galaxy. A recent analysis of high velocity stars in the vicinity of the sun (Carney et al. 1988) shows a few stars with velocities approaching 500 km/s. This represents a lower limit to the escape velocity at the solar circle only if these stars are bound to the Galaxy, not bound to the Local Group, and are not the product of disruption of globular cluster binaries. Given difficulties in determining both the escape velocity and the uncertainty in mass distribution beyond the solar circle, it is unlikely that a mass for the Galaxy can be determined by this method independent of an assumed model.

HALO PARAMETERS

The rotation curve of the Sc galaxy NGC 3198 is everyone's favorite, extending flat to 11 disk optical scale lengths (van Albada et al. 1985). To evaluate parameters of the halo and their contribution to the observed velocities, we must first subtract in quadrature the contribution of the constant M/L disk. Limiting cases for so doing are shown in Figure 1 (Kormendy 1988). The upper figure illustrates the maximum possible disk ($M/L=4.4$); the lower shows the minimum disk ($M/L=0$). During the mid-1980's, it was customary to analyze rotation curves by adopting the maximum disk consistent with the inner rise of the rotation curve and with the disk surface brightness profile (Kent 1984, 1986, 1988). From these models, galaxies with a range of 100 in luminosity ($-21 < M_B < -16$) show a variation of only a few in central density ($\rho_o=10^{-3} M_{\odot} pc^{-3}$), and a ratio of dark matter to luminous matter $M_{dark}/M_{lum} \sim 1$ at the Holmberg radius (Carignan 1987). The halo mass so determined is a lower limit.

A major conceptual advance came when Athanassoula and her colleagues (1987) pointed out that a low mass halo would permit $m=1$ spiral modes to dominate, producing lopsided one-armed spirals. Adding mass to a halo inhibits $m=1$ modes until $m=2$ modes dominate, and so on. By requiring dominant $m=2$ modes, these authors showed that disk masses \sim one-half that of the maximum disk are required on the basis of present theories of spiral structure.

By combining the "no $m=1$ modes" condition for the disk with a modified isothermal mass distribution for the halo, Athanassoula et al. (1987) and Kormendy (1988, 1990) have deduced core radii, central densities, and velocity dispersions for dark halos and correlated these with Hubble types, optical luminosities, and maximum rotation velocities. It seems well established that dark

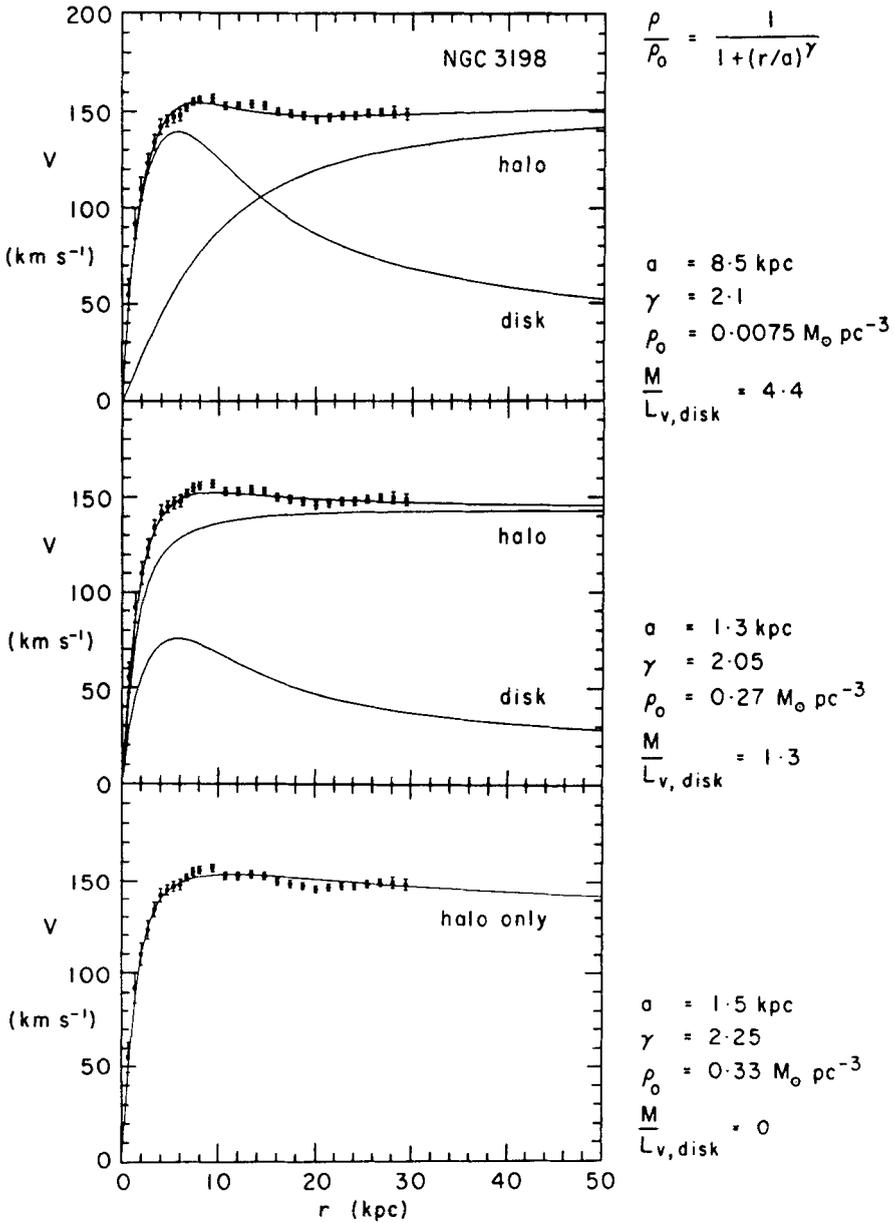


Fig. 1. Alternative decompositions of the rotation curve of NGC 3198 from Kormendy (1988). The observations (van Albada et al., 1985) are shown as points, along with the model disk and halo rotation curves and their sum in quadrature (curves). For the assumed form of the halo density distribution ρ , model parameters are given at right. Note the large variations in core radii a , central densities ρ_0 , and M/L ratios among the three models.

matter becomes an increasing fraction of the total mass with decreasing galaxy luminosity. Smaller core radii, higher central densities, and higher central are less well established for low luminosity galaxies. Because the parameters are model dependent, the resulting correlations may be to some extent artifacts of the models. A valuable analysis by Lake and Feinswog (1989) shows how little the rotation velocities constrain the halo parameters. It is probably correct to conclude that values for parameters of the dark halos are imprecisely known.

THE INNER RISE OF THE ROTATION CURVE

For various reasons, both physical and observational, it may be unwise to use the inner rise of rotation curves to constrain the disk mass, as is done in maximum disk models. Photographic spectra were generally overexposed in the central regions, so as to detect the weak outer emission; innermost velocities from these spectra are poor. Even CCD spectra at low spatial resolution may not spatially resolve inner velocities. Echelle CCD spectra (Rubin and Graham 1987) reveal that some nearby galaxies have velocities which remain high at the innermost measured velocity; the entire velocity gradient occurs in the inner central pixel. Steep rises and sharp elbows in the rotation curves are unobservable at low ($30''$) resolution 21-cm HI observations. A comparison of optical and 21-cm velocities for Virgo galaxies (Rubin et al. 1989) reveals that 21-cm velocities are consistently lower than optical velocities at small radial distances; optical and 21-cm velocities match only at large radial distances.

Inner gas disks may not be in equilibrium and the predominant motions may not be circular. Gas disks can be tilted, warped, or twisted with respect to the plane defined by the disk; the $H\alpha$ disk in M31 is twisted and appears much more face-on than the disk (Ciardullo et al. 1988). An even greater complexity arises if nuclear bulges are triaxial, with nuclear gas moving on elliptical orbits, as observed for NGC 4845 (Bertola et al. 1988). Hence velocities at small r deduced on the basis of assumed circular orbits and geometries of the outer disk may be incorrect.

NGC 2683 is a nearby large Sb galaxy which exhibits many interesting dynamical properties. It has a patchy dusty disk, seen projected against a nuclear bulge (Fig. 2). Measured optical velocities fall slightly from 220 to 200 km/s over the inner $2'$. Virtually the entire 440 km/s nuclear velocity gradient occurs over the innermost pixel (30 pc). Velocities are double valued within the innermost arc minute, with some gas velocities negative with respect to the sense of rotation. We may be viewing the inner region through foreground disk material warped out of the plane.

VLA observations (Fig. 3; Casertano and van Gorkom 1991) detect HI gas to $700''$, and show that velocities decrease beyond about $50''$. Interior to this, velocities are distorted by the lower resolution. Even though the rotation curve falls, dark matter is required, for even a disk with $M/L=8$ predicts velocities lower than observed (Fig. 3). However, a falling rotation curve puts an *upper* limit to the halo mass, for too much halo produces too flat a rotation curve. For all of these reasons, NGC 2683 is an interesting galaxy which illustrates the need for high spatial resolution at small r , and the need for dark matter even with a falling rotation curve. We must learn why the dynamics of NGC 2683 are different from so many other field spirals.

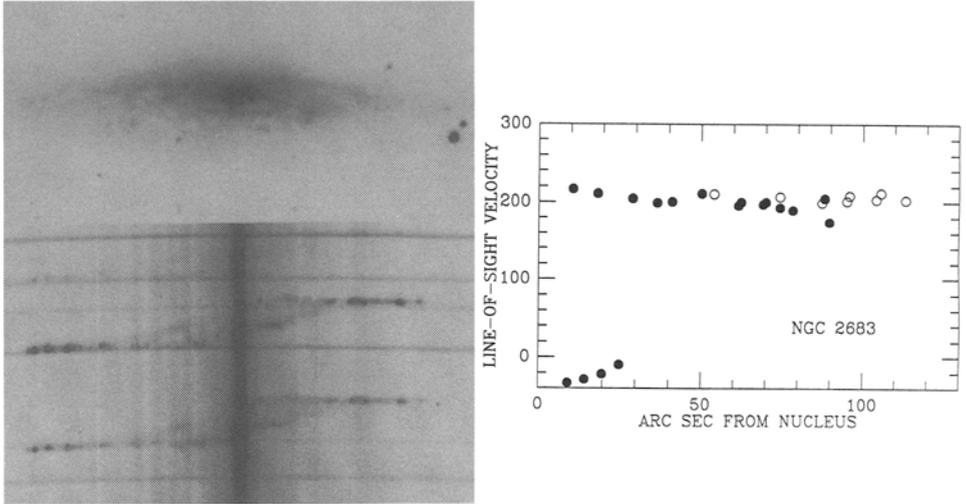


Fig. 2. (Left: image) NGC 2683 from a Kitt Peak 36", Mould R filter + TI CCD frame; original scale 0.86"/pixel, 600 sec. (Left: spectrum) H α and [NII] emission from major axis spectrum, inner 120" only. KP 4-m; dispersion=0.33Å/pixel, scale=0.91"/pixel, 6000 sec. Note double valued velocities within 60" of nucleus. (Right) Measured velocities; different symbols refer to different sides of major axis. Note that velocities remain nearly constant to within 10" of nucleus.

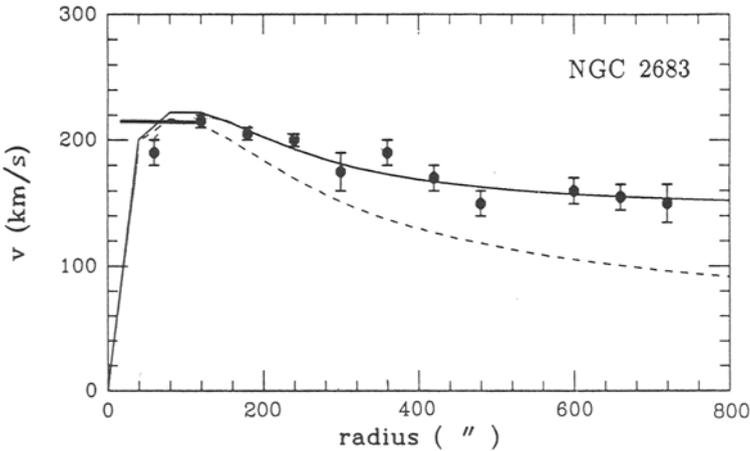


Fig. 3. HI velocities (Casertano and van Gorkom 1991) showing declining rotation curve in NGC 2683. The dashed line represents velocities for a disk with $M/L=8$; the solid line shows velocities predicted for disk+dark halo model. Horizontal line at small r indicates optical velocities. At large r , the rotation curve declines, but dark matter is still required.

DARK MATTER IN DWARF IRREGULARS

Very early in the study of the systematic properties of galaxy dynamics it was recognized that the galaxies of lowest luminosity might offer important clues concerning the distribution of dark matter. "Does the common form for the Sc rotation curves mean that all Sc galaxies, small or large, sit in generally similar potential wells, in which the optical galaxy defines only that region in which matter happens to be luminous? If we could observe beyond the optical image, especially for the smaller galaxies, would the velocities continue to rise?... Is the luminous matter only a minor component of the total galaxy mass?" (Rubin et al. 1980a).

Ten years later, a spectacular answer is available. There exist dwarf irregular galaxies which are very gas rich, and in which the dark mass exceeds the luminous mass by an enormous amount. The dwarf DDO 154, discovered by Krumm and Burstein (1984), has a ratio $M_{HI}/L_B \geq 5.4$, making it one of the most gas rich dwarfs known (Carignan and Freeman, 1988; Carignan and Beaulieu 1989). The HI has been detected extending 5 times the Holmberg radius (Fig. 4), and is dynamically more important than the stellar disk. The slow rise of velocity with radius precludes a high mass disk; the luminous disk is only a small fraction of the mass. Interior to the final measured point, 90% of the mass is dark, and integral $M/L \geq 75$. This is about 10 times that of a normal higher luminosity field spiral. Note however, that even with the enormous fraction of dark matter, the absolute amount is less than that for a higher luminosity spiral. The very high fraction of dark matter in low luminosity dwarf galaxies is one of the major discoveries of the past ten years. It leads naturally to the yet unanswered question "Is there a population of galaxies that is totally dark?"

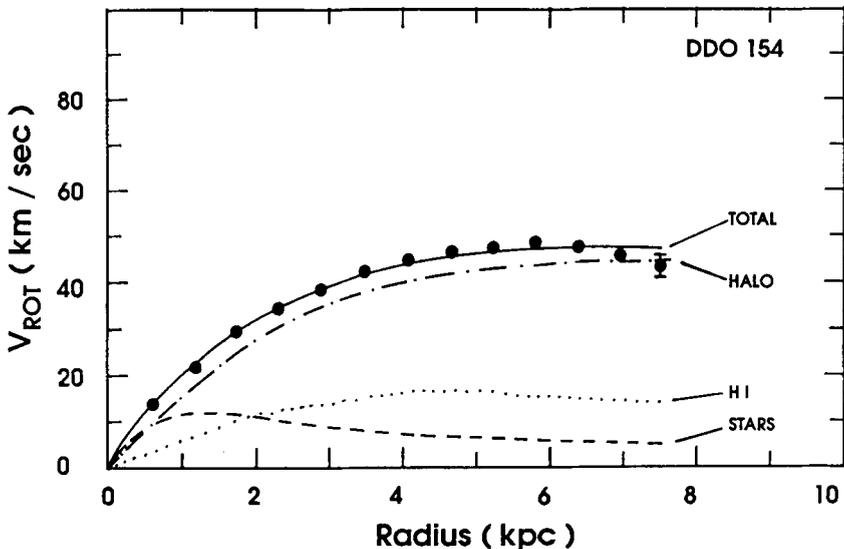


Fig. 4. Mass model for DDO 154 from Carignan and Beaulieu (1989). The stellar disk has $M/L_B = 1$, and a mass of $5.0 \times 10^7 M_\odot$; the HI mass is $2.7 \times 10^8 M_\odot$. The dark plus luminous mass to the last measured point is $3.8 \times 10^9 M_\odot$.

ENVIRONMENTAL EFFECTS ON SPIRAL DYNAMICS

Fifty years ago, Hubble believed that a galaxy evolved in splendid isolation, living out its life constrained to the morphology it acquired at birth. Astronomers now recognize that a galaxy is a continuously evolving structure, which will acquire stars or lose stars through gravitational interactions, will acquire gas or lose gas through infall or galactic winds, and will be actively forming stars or quiescent depending upon its most recent history. Some evidence of this complex evolutionary history must be contained both in the present galaxy morphology and the galaxy dynamics.

Morphological differences between field and cluster spirals are observed. Galaxies in clusters are segregated by morphological type. Spirals in the Virgo cluster core have HI disks which are deficient, asymmetrical, and truncated in the direction of M87, yet the CO gas, denser and more difficult to strip, appears normal. Thus while morphological properties imply a complex evolutionary history for cluster spirals, dynamical history is harder to decipher.

For 8 Virgo spirals, Chincarini and de Souza (1985) conclude that rotation properties are normal. Yet from 15 spirals in 4 clusters, Whitmore et al. (1988) find that rotation curves for spirals within 1 Mpc of the cluster centers have rotation curves which are flat or falling; galaxies near the periphery or in the field have rotation curves which are flat or rising. NGC 7793, an Sd galaxy in the Sculptor group, also has a declining rotation curve (Carignan & Puche 1990). These tantalizing results need more evidence.

Galaxies in small compact groups live in an even more treacherous environment. Some of the galaxies in the Hickson (1982) compact groups (Rubin et al. 1991) are tidally interacting and distorted; some appear morphologically normal. Observed velocity patterns range from too peculiar to form rotation curves (1/3 of spiral sample), to abnormal (1/3), to normal (1/3); peculiar rotation curves are only loosely coupled with peculiar morphology. There is a surprisingly good correlation of luminosity with (log) maximum rotation velocity, i.e., the Tully-Fisher relation, particularly for galaxies with normal rotation curves.

For individual galaxies, values of integral M/L_B are low (median = 3.5), slightly lower than for field spirals of equivalent Hubble type. Historically, values of M/L_B ratios determined from the application of the virial theorem for compact groups are at least an order of magnitude higher than M/L_B ratios determined for individual group spirals from their rotation velocities. Hence the dark matter that produces the large group M/L_B is not clumped about each spiral, and is likely to be a common intergroup background.

In the dense cluster environment, it is expected that dark halos are modified, or may have not been permitted to form. Computer simulations (White 1978, Barnes 1989) suggest that galaxies or compact groups will merge into a single object within a few ($t \sim 10^8$ years) orbital periods. Hence dynamical records may reveal both evolutionary histories and the dark matter parameters. However, modifications due to the cluster environment appear subtle, so untangling these records has been difficult. That's what the future is for.

SYSTEMATIC PROPERTIES OF ROTATION CURVES

Now that rotation curves of spirals are accumulating at a fairly rapid rate, it will be possible to learn more about their systematic properties. Like the Sc's and Sb's studied earlier, the Sa's too show (Fig. 5; Rubin et al. 1985) an increase in radius and in rotation velocity as a function of absolute magnitude. Moreover, the forms of the rotation curves vary; low luminosity spirals reach their maximum velocities only near their outer radii, while high luminosity spi-

als reach their maximum velocities just beyond their nuclei. For Sc galaxies, Rubin et al. (1980b) suggested that the radius where the velocity reaches 100 km/sec, in units of the optical radius, is an accurate luminosity discriminator. Early discussions of these systematic properties (Rubin 1983) led to a characterization of the mass forms of galaxies (Burstein and Rubin 1985) which has been controversial.

However, recent work by Distefano et al. (1990) has supported the earlier mass characterizations, suggesting that it may be profitable to continue similar analyses. Persic and Salucci have made numerous studies of systematic parameters of spiral dynamics; their recent parameterization (1990) of rotation curves nicely quantifies the systematic variations with luminosity. The most ambitious study is that of Casertano and van Gorkom (1991), which combines extended rotation curves with a luminosity parameter, the disk scale length, for 28 spirals. A plot of rotation curve forms on the V_{\max} , disk scale length plane (Fig. 6) offers a graphic look at the variation of forms of rotation curves as a function of these two parameters. These works are surely just the start of numerous compilations which will teach us more about the interplay of luminous matter and dark matter in spiral galaxies.

CONCLUSIONS

With the assumption that Newtonian gravitational theory is valid, dark matter is necessary to account for the flat or rising, and now even falling, rotation curves observed in spiral galaxies. The distribution and amount of the dark matter are not well constrained, although a few facts have emerged during the last decade. Dark matter becomes more dominant in galaxies of low luminosity, where it exceeds the luminous matter at virtually all radii. It is probable that totally dark galaxies exist. For almost no galaxy can we point to the "edge" of the mass. Thus rotation curves offer only lower limits to the masses and M/L values for spiral galaxies.

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Discussion

Casertano: Your point of the uncertainty of the disk mass derived from the inner rise of the rotation curve is well taken. However, in the case of NGC 2683 (Casertano and van Gorkom 1991), the decline in rotation velocity outside the optical disk offers some leverage on the disk mass. We find that the luminous mass must be at least *half* the maximum mass to explain the velocity decline. Unless, of course, the dark matter in NGC 2683 is truncated, which would make this galaxy truly unusual.