M/L RATIOS IN GALACTIC DISKS

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Abstract. Models of galactic disks based on optical photometry and uniform M/L ratios have rotation curves which are indistinguishable from those derived from 21 cm hydrogen line observations.

What is the distribution of mass in spiral galaxies? On current evidence there are many answers to this question. So it is of interest to consider the much more limited question "Are the present observational data consistent with the view that the mass-to-light ratios in the disks of spiral galaxies are constant throughout any particular galaxy?" I believe that the published data indicate that the answer is yes. Morton Roberts has already explained that we are in disagreement about this conclusion. Our differences are mainly ones of interpretation rather than of observation and it is appropriate to examine first the basis of many reports in recent years of mass-to-light ratios which increase with radius in the outer part of spiral galaxies. These reports fall into three categories:

(a) A rotation curve has been used to derive a model of the mass distribution which, combined with the results of photometry, leads to an M/L ratio increasing with radius. Examples are M33 (Brandt, 1965; Boulesteix and Monnet, 1970), M81 (Brandt *et al.*, 1972), and M31 (Gottesman and Davies, 1970).

(b) The observed rotation curve shows no turnover point. There are many examples in the published literature.

(c) The outer parts of the rotation curve are flat, even though there may be a peak in the curve at a smaller radius. Roberts and Rots (1973) stressed this point for both M31 and M81. The flat rotation curve implies a total mass diverging as r whereas the total luminosity of spiral galaxies converges rapidly with r.

In contrast to these claims, Freeman (1970) found that in disk galaxies with essentially no spheroidal component, the rotation curves are consistent with exponential disks having uniform M/L. Nordsieck (1973) confirmed this result for galaxies for which there are good optical rotation curves. Our radio data from Cambridge on M33 (Warner *et al.*, 1973) and M31 (Emerson and Baldwin, 1973) indicated the same conclusion.

The cases which fall in category (a) arise mainly from fitting model rotation curves of the Brandt type to the observations. For the curve fitting procedure used in the analysis, this type of curve may be as good as any other (although this is discussed at some length by Nordsieck) but it is well known both that the exact curve fitted depends critically on the position of the outermost measured points in the rotation curve and that the fitted curve is often used at radii beyond the last observed point. This has frequently led to very dramatic increases of M/L with radius in the outer parts of galaxies. This is apparent, for instance, in Brandt's work (1965) on M33.

Hayli (ed.), Dynamics of Stellar Systems, 341–348.

There is no evidence for it being a real effect and I shall not discuss claims of class (a) any further.

In discussing (b) and (c) we shall consider mainly those galaxies for which there is good photometry and good observations of radial velocities which extend to large radial distances. In all cases these depend on the 21 cm hydrogen line results and for reasons of angular resolution they are all very nearby. The galaxies are M33, NGC 6946, IC 342, M31 and M81.

We now examine claims of type (b), that some rotation curves do not show turn-over points, with the implied consequence that there must be large amounts of matter in the outer parts of galaxies for which there is no visible counterpart. Without some idea of where the turn-over point is expected to be, this claim is not a strong one. Take a specific model in which M/L is uniform throughout the disk. Freeman (1970) has shown that a thin exponential disk (a very good description of the luminosity distribution in all disks) having a surface mass density σ of the form $\sigma = \mu_0 e^{-\alpha r}$ has a rotational velocity V_{max} at the turn-over point in its rotation curve at radius $r = 2.15\ \alpha^{-1}$. At $r = 4.0\ \alpha^{-1}$ the rotational velocity has dropped only to 0.9 V_{max}. In fact the disks of spiral galaxies are not infinitesimally thin and have axial ratios which are typically 0.2. The rotation curve for a disk of this type, retaining the exponential fall off in projected surface density, is of very nearly the same shape but with different scale factors in r and V_{max}. Analysing such a disk into homogeneous spheroidal shells

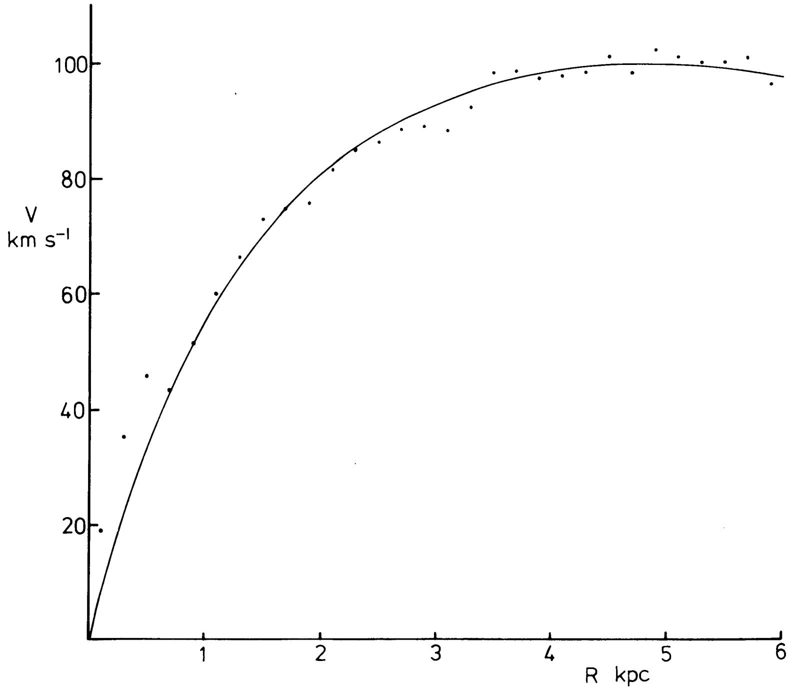

Fig. 1. The rotation curve of M33, uncorrected for inclination. Solid points are the radio observations of Warner *et al.* (1973). The full line is a model of uniform M/L based on de Vaucouleurs' (1959) photometry.

of axial ratio 0.2 one may calculate its rotation curve numerically. The turn-over radius is 2.42 α^{-1} and the rotational velocity drops to 0.9 V_{max} at 4.5 α^{-1} i.e. the radial scale is about 12% greater than for the thin disk. Freeman (1970) found that the central surface brightness of most disks show a remarkably small scatter about $21^m.6$ (arcsec)$^{-2}$. If M/L is constant in the disk, the surface brightness at the radius where $V = 0.9\ V_{max}$ will be $4^m.9$ ($e^{-4.5}$) fainter at $26^m.5$ (arcsec)$^{-2}$. This value is close to that of the faintest features detectable on all but the most recent long exposure plates. So it is no surprise that, in galaxies where the H I detected so far extends only to the Holmberg radius ($26^m.5$ (arcsec)$^{-2}$) there should be little sign of any turn-over in the rotation curve. Two of the examples given by Roberts (this volume, p. 331) illustrate this point exactly.

This result forces us to make a more quantitative comparison of observations with model predictions and restricts the discussion to the galaxies listed earlier. As Dr King reminded us yesterday, it is best to make comparisons in the observational plane rather than using derived quantities. The data for M33 is presented in Figure 1 which compares the rotation curve of a thick exponential disk of uniform M/L, whose

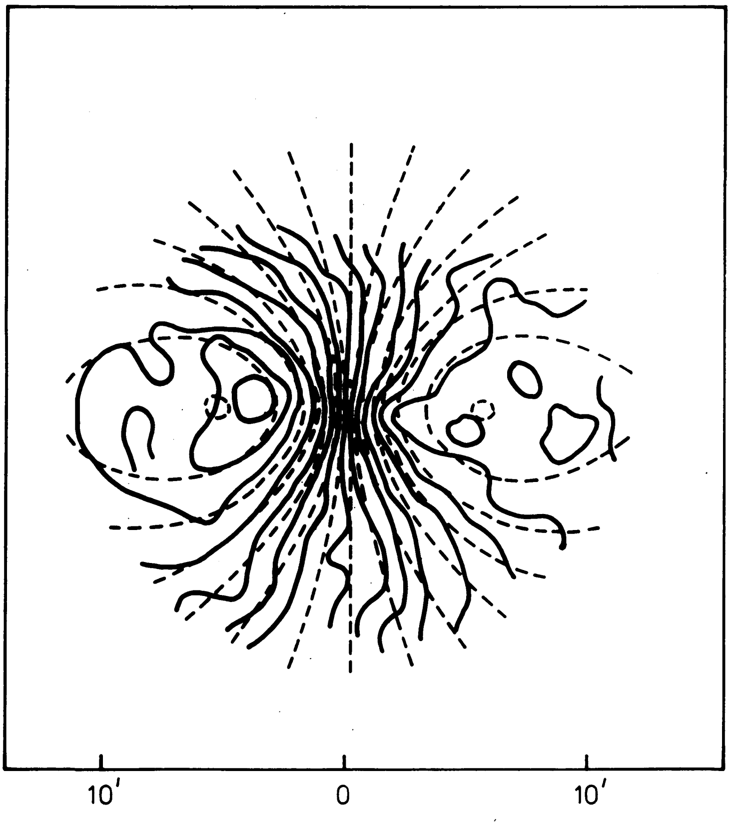

Fig. 2. The radial velocity field in NGC 6946. Full lines are the observations of Rogstad *et al.* (1973). Dotted lines are for a uniform M/L model based on Ables' (1971) photometry.

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scale length α fits de Vaucouleurs (1959) photometry, with our radio rotation curve data (Warner *et al.*, 1973). The agreement is very good. H I measurements have been made at radii larger than 6 kpc but the radial velocities show deviations from uniform circular motion. Within 6 kpc the deviations are everywhere less than 10 km s^{-1} and for this reason the mean rotation curve provides the best comparison for model predictions.

For NGC 6946 and IC 342, whose luminosity profiles are also nearly pure exponential disks with only very small central spheroidal components, it is better to make comparisons of models with the measured radial velocity fields since non-circular motions are evidently more important. Figures 2 and 3 show the radio radial

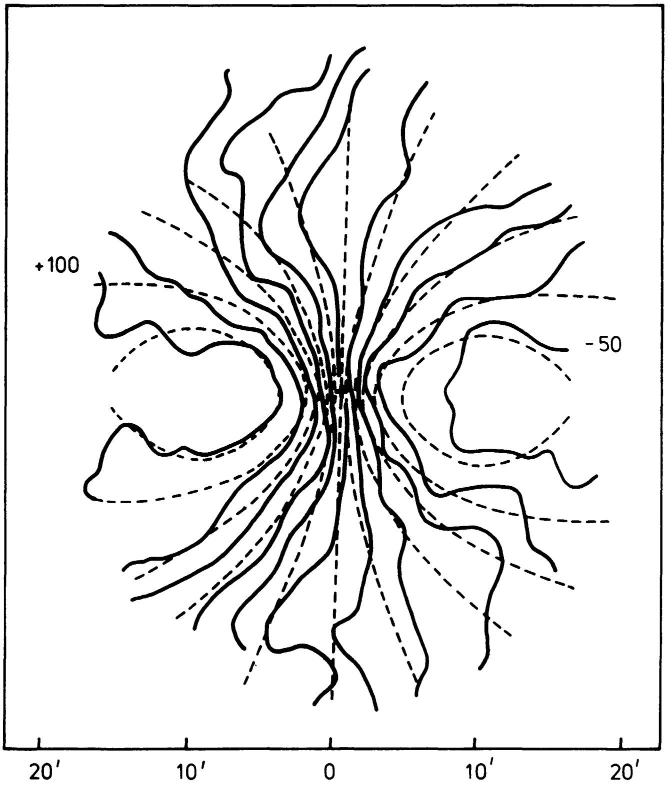

Fig. 3. The radial velocity field in IC 342. Full lines are the observations of Rogstad *et al.* (1973). Dotted lines are for a uniform M/L model based on Ables' (1971) photometry.

velocity data from Rogstad *et al.* (1973) as full lines compared with exponential disk models (dotted) having scale lengths obtained from Ables' (1972) photometry. Axial ratios of the disks were taken to be 0.2 and the inclinations used for NGC 6946 and IC 342 were 37° and 30° respectively. One criterion for judging the fit to be good or not is whether any large scale differences between the observations and the model are masked by the departures from circular motion shown in the observations. On this basis it seems that the fit is good in both cases. IC 342 suffers from observational limitations in the lack of some data at short interferometer baselines, giving rise to the apparently greater extension of the H I along the minor axis than along the major axis. It is difficult to assess how this may affect the velocity field in the outermost parts on the major axis.

M31 and M81 differ from the other galaxies mentioned in having significant spheroidal components. For galaxies of this type the luminosity distribution can be modelled in most cases by a spheroidal distribution whose surface brightness follows Hubble's Law for elliptical galaxies superposed on an exponential disk of the kind discussed. The division into these two parts is an arbitrary one and may not correspond to a sharp physical distinction. But for purposes of deriving model rotation curves it provides a way of exploring the next most simple mass distribution, in which the disk has one uniform value of *M/L* and the spheroidal population a different value. The rotation curve of M31 has been discussed elsewhere (Emerson and Baldwin, 1973) and it suffices to say that a good fit to the observations was obtained by a model

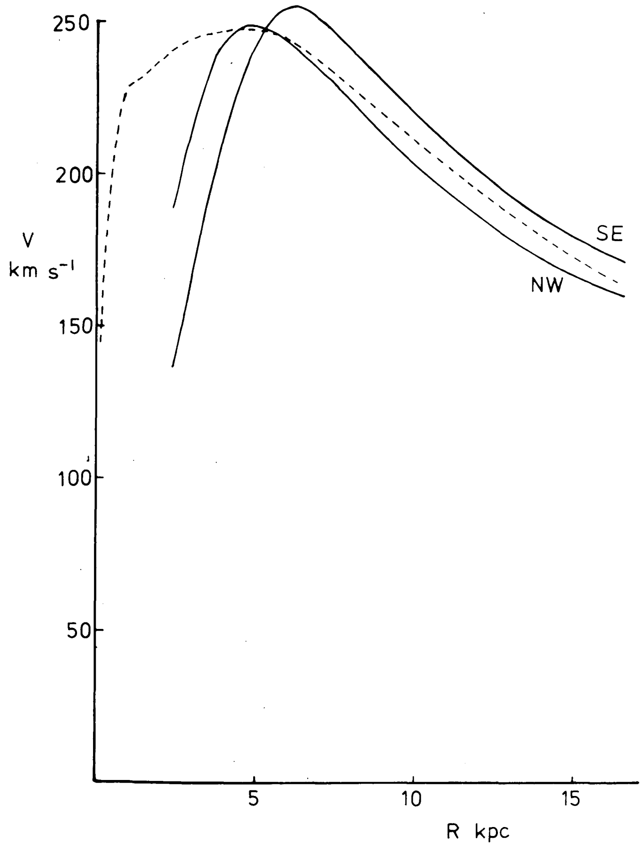

Fig. 4. The rotation curve of M81. Full lines are from the observations of Gottesman and Weliachew (1975) for the two halves of the galaxy. The dotted line is for a model based on the photometry of Brandt *et al.* (1972). See text.

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of this kind in which the values of M/L_B, uncorrected for absorption, were 25 for the spheroidal population and 12.5 for the disk. The differences between the model and the observations were smaller than the difference between the rotation curves derived from the two halves of the major axis of M31. In the outer 20 arcmin of the curve there are observational differences from the values obtained by Roberts which reach 20 km s^{-1}. This is the only point on which our disagreement is an observational one. It needs to be cleared up but, whichever way it is resolved, it will not affect the argument presented here that the magnitude of the non-circular motions is larger than any systematic departure from a curve corresponding to a uniform M/L ratio.

The final case is that of M81 and it is of particular interest since the H I extends to large distances beyond the visible limits of the galaxy. Roberts and Rots (1973) give a rotation curve extending to 30 kpc radius and Gottesman and Weliachew (1975) one extending to 16 kpc radius. Good photometry also has been obtained by Brandt *et al.* (1972). The luminosity distribution closely resembles that of M31, the ratios of

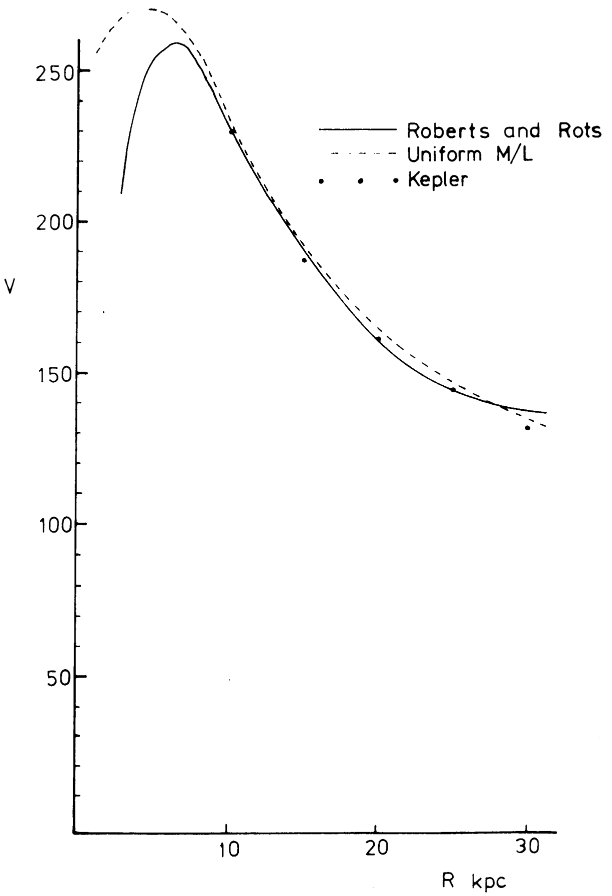

Fig. 5. The rotation curve of M81. The observations of Roberts and Rots (1973) (full line) are compared with model rotation curves described in the text.

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the luminosity of the spheroidal distribution to that of the disk being quite similar and the physical scales of the two components in M81 are each about one half of their value in M31. In modelling M81 the exact value of M/L chosen for the spheroidal distribution is not very important since there are no H I measurements closer than 3.5 kpc to the nucleus or optical values closer than 5 kpc. Figure 4 shows Gottesman and Weliachew's (1975) rotation curve compared with a model having $(M/L)_{sph} = 9$ and $(M/L)_{disk} = 9$. In the range 6 kpc $< r <$ 16 kpc the agreement is better than 10 km s^{-1}. Figure 5 shows Roberts and Rots (1973) curve together with an almost identical model ($M/L = 11$) and also a Keplerian curve. The fit to the model is again satisfactory and the close agreement of that with the Keplerian curve demonstrates that most of its mass (90%) is within 10 kpc radius. The agreement at large r, where Roberts and Rots describe the curve as flat, is excellent but possibly spurious since Weliachew and Gottesman found departures from circular motion as large as 60 km s^{-1} at similar radii in the south following portion of M81. Taken at its face value it suggests that an upper limit to the mass in M81 between 10 kpc and 30 kpc radius is $1.0 \times 10^{10}\ M_{\odot}$.

In conclusion, this discussion of the galaxies for which there are the best data supports the view that no significant variations of mass-to-light ratio with radius in the disks of spiral galaxies have yet been detected. In the case of M81 a useful upper limit can be set to the mass density of any extensive halo at radii near 20 kpc.

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DISCUSSION

Roberts: Your examples of the iso-velocity curves derived at Cal Tech and the deviations from pure circular motion that they imply are not germane to the discussion. A constant $V_c(R)$ and one slowly decreasing will show up in the outer parts of your theoretical iso-velocity curves as surprisingly small differences. Thus, for the comparison you wish to make you should also include the constant $V_c(R)$ case.

Further you can not dismiss the real difference in the observed rotation curve for M31 as derived at Cambridge and at Green Bank. These differences cannot be reconciled. You report signals at velocities where no such signal is seen by the 300-ft telescope. The importance in our difference lies in the fact that your decreasing $V_c(R)$ curve is consistent with the model you chose to describe galaxies. However your model does not at all fit the rotation curve derived from Green Bank data for M31. Thus a difference of

~ 30 km s^{-1} may be 'small' but it is a vital discriminant in the description of the mass distribution within a galaxy.

Finally wide band studies of the luminosity distribution within a galaxy do not describe the mass distribution.

Baldwin: It is true that measurements on the major axis are more likely to give good evidence on the rotation curve than ones near the minor axis. But there can be deviations from circular motion even at points on the major axis, both tangential and in the z direction. The latter is particularly likely in the cases of NGC 6946 and IC 342 while both have very low inclinations.

I agree that the differences in the iso-velocity curves of a constant $V_c(R)$ and that of a constant M/L model are quite small. Indeed that was one of the main points of my talk. If we are to say that $V_c(R)$ is constant then we must be very sure that the measured values denote circular motion. If they are disturbed by large non-circular motions, as I illustrated, then the case for $V_c(R)$ being constant is very weak. The differences between our observations of M31 need to be cleared up but regardless of which way this is settled, we still have differences in the two halves of the rotation curve which are large, implying that what is measured is not the true rotation curve.

Pişmiş: The rotation curve, you showed, of M31 exhibits fluctuations resembling waves. Would you consider them physically significant details?

Baldwin: The peaks in the M31 rotation curve correspond with the H I spiral arms in the sense that faster rotation speeds occur on the outside of the arms. But that, I think, does not commit one to any particular theory of such arms!