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THE ROTATION CURVE AND MASS DISTRIBUTION IN M31

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SUMMARY

The existing evidence is reviewed, and new 21-cm H I data presented, concerning the shape of the rotation curve both in the inner and the outer parts of M31. It is concluded that a substantially constant value for the mass-to-luminosity ratio as a function of radius both for the spheroidal and the exponential disk components of the distribution of luminosity is in good agreement with the observations.

The currently accepted rotation curve of M31 has two surprising features:

(i) A sharp minimum at a radius R of $\sim 10'$ (Rubin & Ford 1970) implying a mean mass to light ratio $M/L \sim 1$ within $R = 15'$, and

(ii) A very constant value of rotational velocity in the outer parts of the galaxy (Gottesman & Davies 1970a; Roberts 1972, unpublished) implying an increase of M/L with R beyond 80′.

If confirmed, these features would provide extremely important information on the stellar populations in M31, but a re-assessment of the evidence and a consideration of new 21-cm data lead us to the conclusion that the rotation curve should be modified substantially.

(i) *The minimum at $R \sim 10'$ arc*

The data obtained by Rubin & Ford (1970) comprise radial velocities of H II regions for $R > 16'$, and of regions giving [N II] lines for $R < 8'$. The H II velocities have a large intrinsic spread, as may be seen from the range of more than 100 km s^{-1} covered by the radial velocities of the regions Arp 519, 521 and 521a, all of which lie within 1′ of each other. The derived circular velocities are 433, 240 and 96 km s^{-1} respectively. The only measured values at smaller radii give circular velocities of 66 km s^{-1} at $R = 16'{\cdot}2$, and of 121 and 185 km s^{-1} at $R = 18'{\cdot}6$. In the light of the large scatter at 22′ radius, these three points provide only weak evidence for a fall in the rotation curve at $R < 20'$.

The circular velocities obtained from the [N II] lines show a rapid rise with radius to 200 km s^{-1} at $R = 4'$ and a dramatic fall to < 100 km s^{-1} at $R = 8'$ As Rubin & Ford point out, this fall is steeper than is physically realizable for material in circular orbits. Furthermore, observations on the minor axis of M31 show anomalous radial velocities of up to 100 km s^{-1} within 2′ of the nucleus, corresponding to radii in the plane of less than 8′. In the presence of these large non-circular motions it is impossible to be sure of the reality of the dip in the rotation curve.

Within $R = 20'$, H I observations are difficult because of the very low projected

H I density and the high inclination angle (78°). In the past, measurements of radial velocities at points on the major axis within $R = 20'$ have been contaminated by H I emission from the dense ring at $R = 50'$, but in an extensive series of observations with the Half Mile Telescope at Cambridge (Emerson, in preparation), H I has been clearly detected in this region. For $R < 5'$ the H I has anomalous velocities which cannot represent uniform circular motion in the plane of the disk, while for larger radii the velocities appear to be consistent with true rotation. In Fig. 1, maps with an angular resolution of $6' \times 9'$ show the H I at radial velocities relative to the Sun of -137, -111, -85 and -59 km s^{-1}. The peak brightness temperatures are only ~ 4 K. The regions of highest brightness at these radial velocities lie 50′ NE of the nucleus and were much reduced by the directivity of the paraboloids in this survey, thus allowing the emission near the nucleus to be seen more easily.

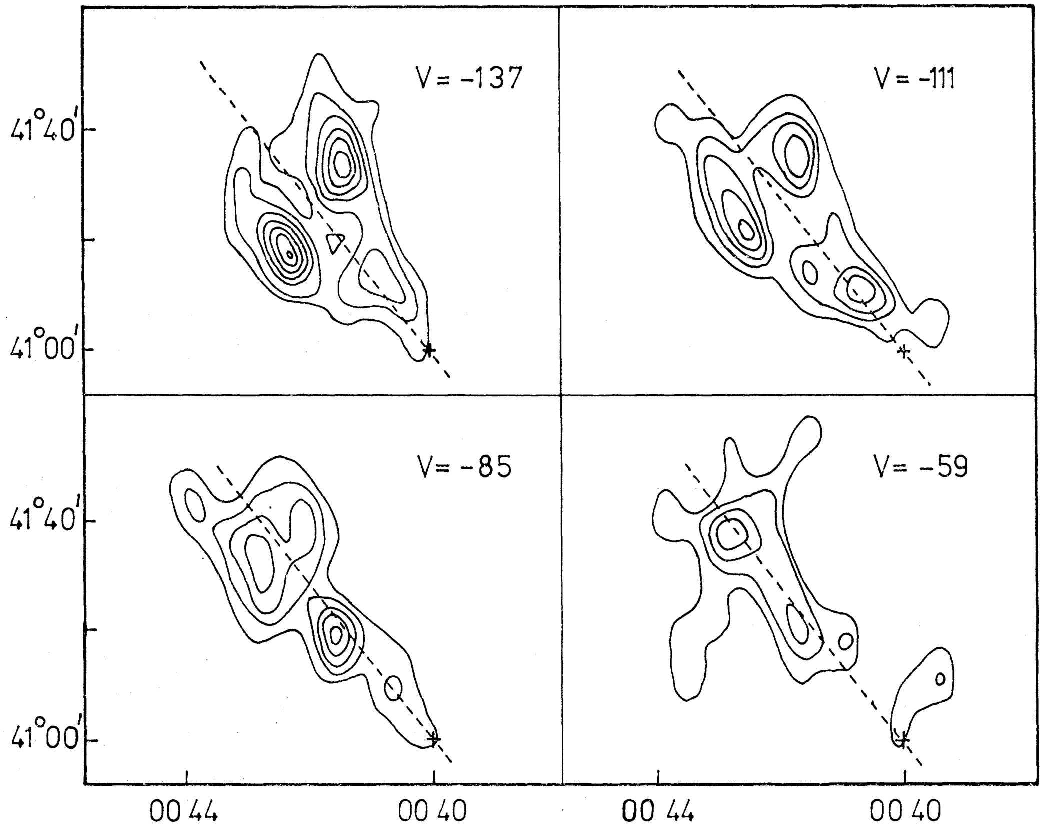

FIG. 1. *H I emission at radial velocities V relative to the Sun, observed with a resolution of* $6' \times 9'$ *and a bandwidth of* 39 *km* s^{-1}. *The contour interval of* 0·45 *K corresponds to twice the rms noise level. The maps are uncorrected for the primary beam of the telescopes which were centred at* $00^h\ 38^m$, $+40°\ 30'$, *and had a relative response* 0·6 *at the nucleus (marked by +) and* 0·3 *at* 25′ *along the NE major axis.*

For the following reasons we believe the H I in Fig. 1 to have velocities close to the circular velocity:

(a) The emission is distributed symmetrically about the major axis.

(b) At any particular radial velocity the regions of emission nearest to the nucleus lie on the major axis. This is consistent with a rotation curve which is rising with increasing radius, an interpretation also consistent with the progressive shifts in the position of maximum intensity from map to map.

(c) Forbidden velocities such as would be implied by extension of the emission beyond the nucleus, are not found.

The emission on the major axis shown in Fig. 1 has not been reported previously. There is, however, some evidence for it in the maps by Gottesman & Davies (1970b) which, for a very wide range of radial velocities, show weak H I extending to within 10–15 arcmin of the nucleus. The agreement with our measurements on the NE major axis is satisfactory and their results suggest that similar emission may be detectable SW of the nucleus. H I with a very wide dispersion of velocities near the nucleus of M31 reported by Whitehurst & Roberts (1972) may also have the same origin.

On the assumption that the systemic velocity of M31 is 300 ± 6 km s^{-1} with respect to the Sun, values of the circular velocity of this H I could be determined to an accuracy of ± 12 km s^{-1} and are plotted at radii of 8′, 12′ and 25′ on the rotation curve of Fig. 2. They are clearly in conflict with a dip in the curve at $R = 10'$.

(ii) *The rotational velocity in the outer parts of M*31

At larger radii it is possible to define the radial velocity of H I on the major axis with greater accuracy, and corresponding values of rotational velocity are plotted (assuming an inclination for M31 of 78°) in Fig. 2 for points on both the NE and SW major axis. For both the NE and the SW points there are irregularities in the curve on a scale of 20′–30′ and there are also differences between the two curves which are typically 10 km s^{-1} but rise to 30 km s^{-1} at $R = 45'$. These differences show that non-circular motions are present in M31. The true rotation can best be approximated by taking the mean of these curves, which also has the advantage of being insensitive to the exact value of the systemic velocity. It has a peak value of ~ 250 km s^{-1} at $R = 60'$–$70'$, falling to about 200 km s^{-1} at $R = 150'$. Because of the high inclination of M31 it is not clear that a significantly better rotation curve will be obtained by making use of radial velocities at additional points off the major axis. The deviations from the mean rotation curve will be discussed elsewhere (Emerson, in preparation) in relation to the overall H I structure.

Because of the strong dependence of the deduced mass distribution in a galaxy on the exact form of the rotation curve, we have chosen not to analyse the mean curve obtained here by one of the standard methods (e.g. that of Burbidge, Burbidge & Prendergast 1959) but to compare the observations directly with a simple model of the mass distribution comprising two populations, associated respectively with the spheroidal and exponential disk components of the luminosity distribution analysed by de Vaucouleurs (1958) from his B photometry. Each component was assumed to have a constant M/L ratio throughout and a range of values was tested to see if a reasonable fit to the observed points could be obtained. It is worth mentioning that for a wide range of M/L values the spheroidal population dominates the rotation curve for $R < 15'$, and the disk population for $R > 30'$. The three lines in Fig. 2 show the best-fitting model, together with two others not so well fitting to provide an indication of the accuracy of the procedure. We think that the fit of the best curve to the data in the outer parts is sufficiently good that no increase of M/L with radius is indicated.

The best-fitting curve has apparent M/L ratios of 25 ± 5 for the spheroidal component and $12{\cdot}5 \pm 2{\cdot}5$ for the disk component. The corrections necessary to

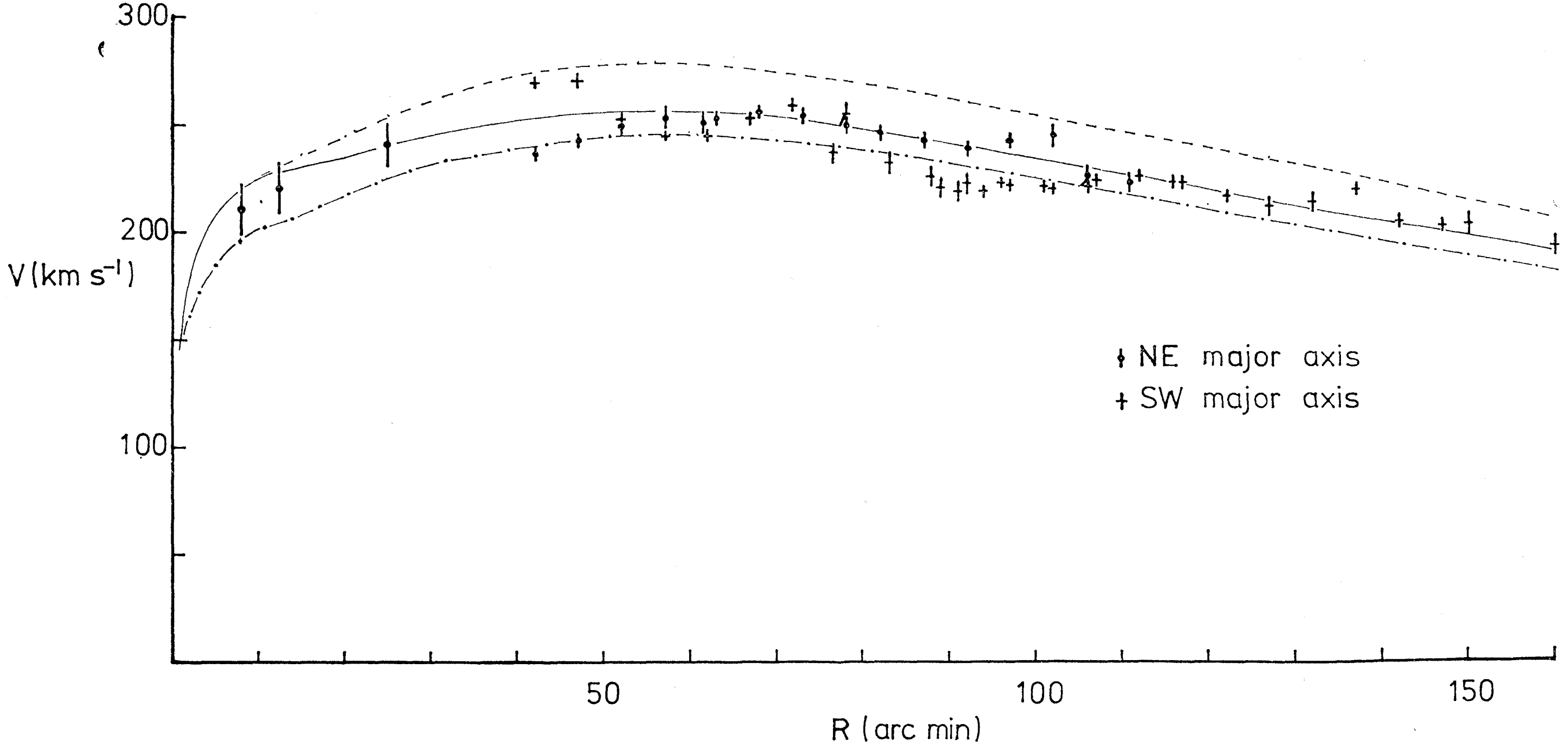

FIG. 2. *The rotation curve of M31 derived from H I measurements on the major axis compared with three model curves.* ———, $(M/L)_{sph} = 25$, $(M/L)_{disk} = 12{\cdot}5$; – – – –, $(M/L)_{sph} = 25$, $(M/L)_{disk} = 16$; —·—·—·—, $(M/L)_{sph} = 19$, $(M/L)_{disk} = 12{\cdot}5$.

reduce these values to unabsorbed M/L ratios are uncertain. Van Genderen (1972) reports a gradient in the internal absorption of M31 from $\sim 0^{m}\cdot 9$ at 15′ to $\sim 0^{m}\cdot 3$ at 96′, with a mean value of $\sim 0^{m}\cdot 6$; the measurements did not extend to the spheroidal population within $R = 15'$. We have in fact used the overall values of Heidmann, Heidmann & de Vaucouleurs (1971) of $0^{m}\cdot 44$ for absorption in the Galaxy and $0^{m}\cdot 6$ for internal absorption in M31. The M/L_{B} values corrected for absorption are then 10 for the spheroidal and 5 for the disk populations. The latter may be compared with the apparent M/L_{B} ratio of 4·9 independent of radius in the disk of M33 (Warner, Wright & Baldwin 1973) which, when corrected for absorption using the data of Heidmann *et al.* (1971) gives an absorption-free M/L ratio of 3·0.

We conclude that the observations of M31 and M33, the two galaxies for which the most detailed data exist, do not indicate values of M/L increasing with radius in the outer parts of these galaxies. The values of M/L now have sufficient accuracy for useful comparisons to be made with those of model stellar populations. An urgent need which emerges is for methods of determining the true absorption corrections to be applied to the photometry of nearby galaxies.

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