"Curiously, one giant elliptical rotates as expected, and that is NGC 3557."

A. Toomre in Discussion I.1

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ROTATION CURVES IN THE OUTER PARTS OF GALAXIES FROM HI OBSERVATIONS

Edwin E. Salpeter
Cornell University, Ithaca, New York

Abstract: 21cm observations at the Arecibo Observatory for 9 edge-on spiral galaxies are described. Flat rotation curves are found in most cases.

INTRODUCTION

I mainly report on 21cm observations carried out at Arecibo of the outermost parts of spiral galaxies in order to derive rotation curves. The data is most clearcut for late-type spirals since the neutral hydrogen tends to extend out further in these cases. The optical emission is then dominated by the disk component and the surface brightness (Freeman 1970) decreases approximately exponentially, $\sigma_L(r) \propto \exp(-\alpha r)$, with r the distance from the center in the galactic plane. The most dramatic question is whether the ratio of the surface density $\sigma_M(r)$ of total gravitational mass to surface brightness $\sigma_L(r)$ is typically independent of r (and of order 5 in solar units) as suggested by Baldwin (1975). Our data corroborates the suggestion by Roberts (1975, 1976) that the ratio σ_M/σ_L in fact increases markedly with r in the outer regions of many spiral galaxies.

If $\sigma_M(r)/\sigma_L(r)$ were constant, the circular rotation velocity $V_{rot}(r)$ of hydrogen in the disk (if velocity dispersion is neglected) would be a unique function of αr. This function (Monnet and Simien 1977) has a rather flat maximum but already decreases quite rapidly for αr between about 5 and 7. With optical radius R_{opt} defined as 0.5 D_o, taken from de Vaucouleur et al (1976), Freeman (1970) gives $\alpha R_{opt} \sim 3$ to 3.5 and the rotation velocity should have dropped below the maximum by $r \sim 1.5R_{opt}$ and even more by $r \sim 2R_{opt}$. There is one clearcut case where the rotation curve is of just that form, the Sab (or Sb) galaxy M81 (Gottesman and Weliachew 1975, Rots 1975). However, there were (even before Arecibo) a few equally clearcut cases where the rotation velocity is flat in the vicinity of $r \sim 1.5R_{opt}$, especially the Sb galaxy M31 (Roberts et al 1975, 1978) and the Scd galaxy NGC2403, which indicate σ_M/σ_L increasing with radial distance r. The outer regions of galactic disks can be warped by $\gtrsim 20°$ (Sancisi 1976) and the interpretation of rotation curves is clearcut only when a galaxy is viewed almost

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edge-on (cos20° is close to unity, but cos80°/cos60° is not). Furthermore, to obtain a rotation-velocity accurately one requires good signal to noise ratios to measure the outer edge of the spectral profile (and not merely its peak). For this reason we surveyed at Arecibo a number of large, nearby, late-type galaxies which are seen almost edge-on.

THE ARECIBO OBSERVATIONS

We selected 14 spiral galaxies of type Sb to Sm accessible to the 21cm beam of the upgraded 1000-foot dish at the Arecibo Observatory, with $R_{opt} > 2\overset{'}{.}7$ and disk inclination less than 40° away from edge-on (four of these 14 galaxies are two galaxy-pairs). IC1727 is too perturbed by its larger partner (NGC672) and four of the single galaxies showed too little hydrogen emission to be useful. Of the 9 remaining galaxies, NGC4517, 4527 and 7331 showed approximately flat rotation curves, but the emission extended only to $r \sim 6'$. The remaining six galaxies were detected out to $r > 10'$, but the radii reported by Krumm and Salpeter (1977) were too large because of sidelobes and beam-smearing (see also Sancisi 1978).

An example of the raw Arecibo data is illustrated in Fig. 1 (for the large, almost completely edge-on Sb galaxy NGC4565) which shows clearly a feature probably present in other galaxies as well: The hydrogen intensity fluctuates and decreases slowly at first and then drops suddenly. For NGC4565 the drop (on the N side) occurs near $11\overset{'}{.}6$ (the profile at $14\overset{'}{.}5$ is mainly the ∿10% sidelobe of the emission at $8\overset{'}{.}7$) and the hydrogen extends at least to $10' = 1.8\ R_{opt}$. For (one side of) NGC 925, 4559 and 4631 the minimum extent is about $7' = 1.5\ R_{opt}$, $8' = 1.8\ R_{opt}$ and $11' = 2.0\ R_{opt}$. The outer edge of each spectral profile for NGC4565 in Fig. 1 is close to 1460 km s^{-1} and the flat rotation-curve (Fig. 2) gives a minimum total mass of about $6\times10^{11}\ M_\odot$ (assuming a distance of 20 Mpc). NGC925, 4559 and the W side of 4631 also show flat rotation-curves and $\sigma_M(r)/\sigma_L(r)$ must increase appreciably for $r \gtrsim 1.5\ R_{opt}$ (the data is poorer for NGC672 and 4656 which are disturbed by their companions). On the E side of NGC4631 (closest to NGC4656) the emission for $r > 15'$ appears at much lower rotation velocities, but this may come from a disturbed extended halo.

A recent extensive survey, carried out at Arecibo on early-type galaxies for a different purpose (Krumm and Salpeter, 1978, in preparation), is also of some relevance. Of about 80 galaxies surveyed, 5 showed sufficiently extended hydrogen emission (to $r \sim 3'$ to 6') to give rudimentary rotation curves: NGC3626 ($S0^+$), 4324 ($S0^+$) and 4698 (Sab) suggest flat rotation curves (but only the last with any reliability), whereas NGC3623 (Sa) shows a slightly decreasing rotation curve. Only one galaxy, NGC3593 (S0a) which is ∿1° away from NGC3623, displays a sudden decrease in rotation velocity on one side--rather similar to NGC4631.

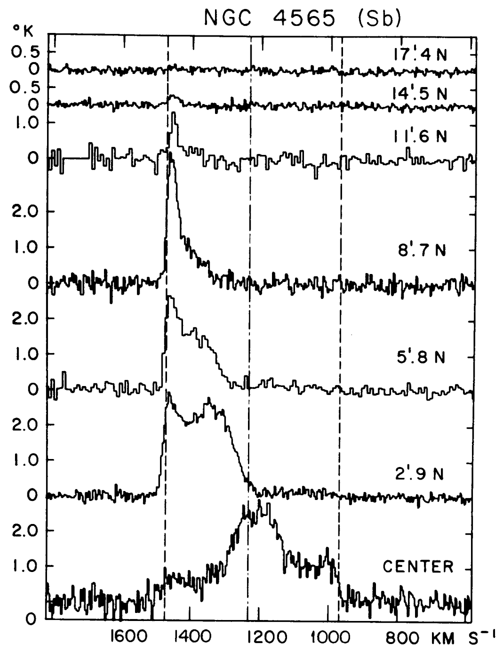

Fig. 1: Spectral profiles at various distances from the center along a semi-major axis.

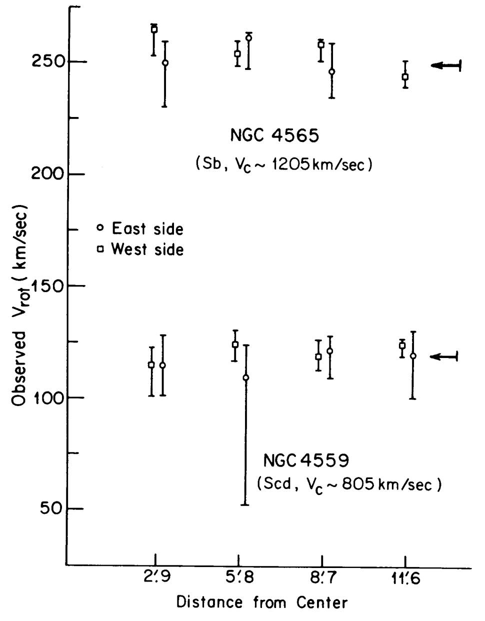

Fig. 2: Rotation curves for two spiral galaxies.

DISCUSSION

M31 and the best few Arecibo cases show that at least some spiral galaxies have an increasing ratio $\sigma_M(r)/\sigma_L(r)$ of mass-density to surface brightness. Although M81 provides a counter-example, I want to argue that this is the rule rather than the exception: Huchtmeier (1975) gives a compilation of rotation curves for 17 galaxies and about half of these show flat or increasing rotation curves. The other half show a decreasing rotation velocity after reaching a maximum some distance r_{max} from the center, but the numerical value of r_{max} is crucial: If $\sigma_M(r)$ were indeed proportional to $\sigma_L(r)$, then r_{max} would have to be $\sim 0.6\ R_{opt}$. In reality, except for M81 and one or two other cases, r_{max} is much larger; for NGC3109, for instance, $r_{max} \approx 19'$, $R_{opt} \approx 6'$ and V_{rot} at $r \sim 40'$ is still larger than at $r \sim R_{opt}$.

It is not clear whether the constancy of σ_M/σ_L for M81 is connected with it being of early type or with having close companions. For the galaxies with increasing $\sigma_M(r)/\sigma_L(r)$, it is also not known how much further the "invisible halo" (Ostriker and Peebles 1973) extends than the hydrogen boundary at $\sim 2\ R_{opt}$. The physical form of the "invisible" mass need not be particularly exotic: White dwarfs and low mass stars ($M < 0.08\ M_\odot$) which cannot burn hydrogen cool to quite low light-to-mass ratios in 10^{10} years. An "early stellar population III" which formed mainly into stars with $M < 0.08\ M_\odot$ and/or $M > 1.5\ M_\odot$ (which end up as black holes, neutron stars or white dwarfs) would be effectively invisible. An initial mass function in the outer disk weighted more towards $M \sim 0.2\ M_\odot$ probably also gives sufficiently large σ_M/σ_L.

If V_{rot} were exactly constant, the (volume) mass density $\rho_M(r)$ would be proportional to r^{-2} and the mass M(r) contained inside radius r would be proportional to r. This law must break down at very small and very large r, but for a number of galaxies V_{rot} is remarkably constant over quite a dynamic range of distances r. This is illustrated not only by the Arecibo data but by more accurate recent HI data on M31 (Roberts and Whitehurst 1978, this volume) and by some recent optical rotation curves (V. Rubin, unpublished). The precision of the constancy of V_{rot} is probably not an accident of the formation history of a galaxy, but some servomechanism was at work. One such possibility comes from an instability (Lovelace and Hohlfeld 1977), which is related to the derivative of $V_{rot}(r)$.

As mentioned, the outer radius R of the "invisible stellar population III" is not known, but for galaxies in clusters tidal breakup must limit R since $M \propto R$ and tidal effects depend strongly on M and R. "Population III" debris, stripped from the outermost layers of many galaxies, may accumulate towards the center of a cluster. Similar stripping may occur from individual galaxies in double or triple systems, such as M81.

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REFERENCES

Baldwin, J. E.:1975, in "Dynamics of Stellar Systems", IAU Symposium No. 69, A. Hayli (ed.), Reidel, Dordrecht.
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G.: 1976, Second Ref. Cat. of Bright Galaxies, Univ. of Texas Press, Austin, Texas.
Freeman, K. C.: 1970, Astrophys. J. 160, 811.
Gottesman, S. T. and Weliachew, L.: 1975, Astrophys. J. 195, 23.
Hutchtmeier, W. K.: 1975, Astron. Astrophys. 45, 259.
Krumm, N. and Salpeter, E. E.: 1977, Astron. Astrophys. 56, 465.
Lovelace, R. V. and Hohlfeld, R. G.: 1977, Cornell Univ. CRSR Report 661.
Monnet, G. and Simien, F.: 1977, Astron. Astrophys. 56, 173.
Ostriker, J. P. and Peebles, P. J.: 1973, Astrophys. J. 186, 467.
Roberts, M. S.: 1975, in "Dynamics of Stellar Systems", IAU Symposium No. 69, A. Hayli (ed.), Reidel, Dordrecht.
Roberts, M. S. and Whitehurst, R. N.: 1975, Astrophys. J. 201, 327.
Rots, A. H.: 1975, Astron. Astrophys. 45, 43.
Sancisi, R.: 1976, Astron. Astrophys. 53, 159.
Sancisi, R.: 1978, this volume.

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DISCUSSION FOLLOWING PAPER I.3 GIVEN BY E.E. SALPETER

BALDWIN: On the assumption of constant mass-to-light ratio in an exponential disk the circular velocity at one Holmberg radius is about 0.85 of that at the peak of the rotation curve. Do you agree then that for data at up to one Holmberg radius we are talking about an expected drop of only 30 km/s from the peak?

SALPETER: Assuming a pure exponential disk for NGC 4565, one has to guess its scale length from Freeman's measurements on other galaxies. I use correlations with de Vaucouleurs "corrected" radii (rather than Holmberg radii) and find a drop to less than 0.85 times the maximum velocity at a 10' distance. However, if your guess of the scale length is more correct than mine you would have to add a nuclear mass component to avoid too low a velocity at small distances (2', say), and this in turn would enhance the velocity drop at 10'. The velocity drop should be even more apparent for the W side of NGC 4631, for M31 and for Huchtmeier's best cases.

STROM: Is there any evidence for or against the presence of a "halo" of neutral hydrogen surrounding NGC 4565 or is the gas restricted to the disk?

SALPETER: The Arecibo beam cannot resolve the disk thickness and we have not looked far from the disk. The Westerbork data shows a warped disk but, as far as I know, no halo.

SANCISI: HI SIZES AND ROTATION CURVES OF SOME EDGE-ON GALAXIES

Two of the galaxies studied by Krumm and Salpeter (1977, A.A. 56, 465) at Arecibo, NGC 4565 and 4631, have also been investigated with the Synthesis Radio Telescope at Westerbork (WSRT). The WSRT data do not show the large extent of the HI disks and the flat rotation curves reported by these authors.

NGC 4565. The HI layer of this galaxy shows a large bending in the outer parts (Sancisi: 1976, A.A. 53, 159). On the western side the HI emission extends out to 11!5 radius, not to 14!5 as reported by Krumm and Salpeter. Beyond 11!5 the WSRT maps, even when convolved to the Arecibo resolution, do not show any signal: the 3σ upper limit is about 12 mJy, or $N_H = 7 \times 10^{19}$ cm^{-2} for a 27 km/s wide channel and the 0!8 × 1!9 WSRT beam, or correspondingly 16 mJy and 1.5×10^{19} cm^{-2} for the 3!2 × 3!2 Arecibo beam. At these positions the WSRT and Arecibo data have similar sensitivities.

The rotation curve is flat out to about 8' ($\approx$ 50 kpc if H = 55 km/s/Mpc). Between 8' and 11!5 it is not well defined because of the bending, but may drop off by 10 or 20 km/s. The maximum rotational velocity is 250 ± 10 km/s. For comparison the Holmberg radius is 10', and the de Vaucouleurs radius is 8'.

NGC 4631. This system is in close interaction with NGC 4656. The distribution of HI around NGC 4631 and between the two galaxies is quite complex (Weliachew et al.: 1977, A.A., in press). The HI disk of NGC 4631 on the western side extends to about 10' (= 15 kpc) from the center, not 20' as reported by Krumm and Salpeter. At 14!5 the Arecibo data show a peak intensity of about 100 mJy, whereas the WSRT 3σ upper limit at the same resolution is 20 mJy. At this position the WSRT observations have a factor 2 better sensitivity. The corresponding 3σ limits on the column density are 6×10^{19} cm^{-2} for a 27 km/s wide channel and a 48" × 89" beam, or 1.5×10^{19} cm^{-2} for the 3!2 × 3!2 Arecibo beam. At distances of 20' the WSRT data are not adequate for a comparison.

The rotation curve is approximately flat out to 9!5 (∿ 14 kpc) on the west side, i.e. out to the Holmberg radius. Beyond this distance no HI emission is detected. On the east side the rotation curve is flat out to about 6'. Beyond this limit the radial velocity drops off in rough agreement with Krumm and Salpeter's results. However this gas does not seem to be part of the NGC 4631 disk (Weliachew et al. 1977). The maximum rotational velocity is 150 ± 10 km/s.

Some spurious signal due to side lobes is clearly present in the Arecibo observations of these two galaxies, and may explain all or most of the discrepancy with the WSRT results. The possibility of sufficiently bright and extended emission (angular size > 15'), which could have escaped detection in the WSRT observations, seems to be ruled out by the agreement of the WSRT values of flux density with single dish measurements.

To sum up: (1) The extent of the HI disks at the detection limit of the present Arecibo and Westerbork observations ($1\text{-}5 \times 10^{19}$ cm^{-2}) is significantly less (25 to 50 percent) than reported by Krumm and Salpeter. The HI does not extend much farther than the Holmberg radius. It is possible, of course, that these objects have significantly larger HI sizes at lower densities. (2) The rotation curves are flat out to the edge of the bright optical disk well inside the Holmberg radius. At larger distances from the center they are poorly defined or not determined at all because no HI is detected.

These conclusions are also valid for NGC 5907 and 4244 (Sancisi, in preparation), and for NGC 891 (Sancisi et al.: 1975, in La Dynamique des Galaxies Spirales, p. 295). Other galaxies have been known to have flat rotation curves inside the Holmberg radius. The results from these edge-on galaxies, therefore, do not seem to bring any significantly new evidence on the dynamics and mass distribution in galaxies.

BOSMA: THE KINEMATICS OF A SAMPLE OF ABOUT TWENTY SPIRAL GALAXIES

We briefly describe the results of a study aimed to relate the morphology of spiral galaxies to dynamical parameters as inferred from e.g. rotation curves. 21-cm HI line data with high spatial resolution (ratio Holmberg radius/beamsize larger than ∿ 5) have been collected for about twenty galaxies of various morphological types, either from the literature or from still unpublished recent studies using the Westerbork telescope.

The radial velocity fields of these galaxies have the characteristic pattern expected for an inclined disk in differential rotation, but most of them show in addition specific patterns of noncircular motions, and small-scale irregularities. Often there is a strong resemblance in the type of noncircular motions among different galaxies, although their amplitude varies. These types of noncircular motions constitute not only dynamical problems by themselves, but also restrain the derivation of rotation curves.

We briefly discuss the main types of noncircular motions:

(1) Motions associated with spiral arms. Visser (this volume) has constructed a model to describe these motions in M81 and has corrected the rotation curve for their effects. For other galaxies showing hints of similar effects we have made no correction.

(2) Large-scale symmetric deviations. In many galaxies the kinematical major axis changes its position angle as function of radius, but the velocity field still has a central symmetry.

a. In cases where this major axis change is in the inner parts usually there is a misalignment with the major axis of some of the structures seen on optical photographs. We then suspect an oval or bar-like distortion to be present in the potential field of the disk. The effect on the rotation curve is probably not so large; we did not correct for this effect.

b. In cases where the major axis change is in the outer parts the major axis of the inner parts of the optically visible disk is usually well aligned. In these cases we suspect the plane of the galaxy to be warped. Models have been constructed using concentric tilted rings (cf. Rogstad et al.: 1974, Ap.J. 193, 309), with circular motion in each ring independent of its orientation.

Some ambiguity exists in the proposed split up (the warped barred spiral), and the assumptions concerning the resulting rotation curves are not backed up by an adequate theory.

(3) Large-scale asymmetries. These occur mainly in the outer parts (M81, M101), and can usually be attributed to tidal interaction with a neighbouring galaxy. We have used a rotation curve for the symmetric inner parts only.

Apart from these problems, instrumental limitations hamper the determination of the rotation curves in the inner parts of most galaxies. Sometimes rapid variations in radial velocities occur there on the scale of one beamsize, sometimes no HI gas is detected. These problems can be partly solved using optical data; however, for still $\sim$ 40% of the galaxies in our sample the rotation curve in the central parts is not well determined.

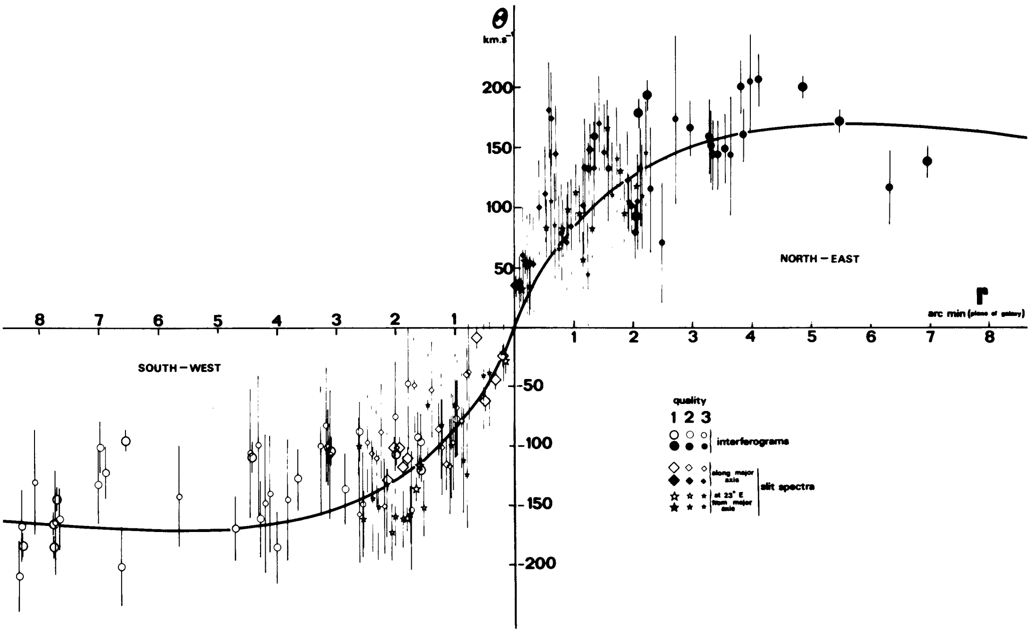
We have collected rotation curves for 23 galaxies, of which 11 are warped, 3-5 have oval distortions or bars, and 4 have large-scale asymmetries. Most rotation curves do not decline very fast, if at all, past the turnover radius, and none of them show the Keplerian drop-off in the outer parts. We have calculated mass models using both the thin-disk method described by Nordsieck (1973, Ap.J. 184, 719), and the spheroid(s)+disk model fitting described by Shu et al. (1971, Ap.J. 166, 465). These methods are perhaps not justified in view of massive haloes, but they are relatively simple.

The distribution of mass surface density, $\sigma_m(r)$, with radius r shows that larger galaxies have a slower decline of $\sigma_m(r)$ with r, and that probably earlier type spirals have a steeper increase of $\sigma_m(r)$ towards the center. No unique correlation with Hubble type has been found, partly because of the difficulties mentioned above. The curves of mass within a cylinder of radius r, M(r), derived using Nordsieck's method, do not converge to a final value at the radius of the last measured point R_O. Comparison with the results from the mass model fits shows that usually 20% - 40% of the mass in the model fit lies beyond R_O.

The "total" mass-to-light ratio ($M(R_O)/L_B$) turns out to be independent of Hubble type, colour and luminosity, with typical values between 5 and 15 (H = 75 km/s/Mpc). For a number of galaxies, most of them not being warped, we have calculated the radial distributions of the mass-to-light ratio and of the total mass-to-HI gas mass ratio. M/L has a tendency to increase with radius, M/HI has a tendency to drop off to a more or less constant, but for each galaxy different, level. Given the uncertainties arising from noncircular motions, beamsmoothing, thin disk approximations etc., these results should be considered as very tentative.

A detailed account of the work summarized here will be presented elsewhere (Bosma, 1978).

COMTE: NEW OPTICAL ROTATION CURVE OF M101



Rotation curve of the galaxy M101 derived from a velocity field obtained by interferometry and spectroscopy of the Hα line, across a 7' radius in the optical disk. The rotation velocities have been computed owing to a systemic velocity of 238 km/s, a major axis position angle of 35° and an inclination of 27°. A mass model, based on the photometric parameters of M101, built for a pure exponential disk in circular rotation with a blue M/L ratio of 4 and a total disk mass of $\sim 10^{11}$ $M_\odot$ at 6 Mpc, fits correctly the data (solid line) with a turnover velocity of 170 km/s at 5!5 from the center. The blue M/L ratio

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of the bulge has been estimated to be $\sim$ 1.5.

FITZGERALD: Work being done by Jackson, Moffat and myself indicates that the rotation curve for the Milky Way is probably also flat out to about $R \simeq 18$ kpc from the galactic center. This work is based on observations made of very small young open clusters and stars in HII regions. Distances are determined by cluster fitting where possible, and spectroscopic parallaxes for cases in which no main sequence of zero age is determined. Radial velocities are taken from the literature for Hα, and measured from various image tube plates for stars. A plot of $|\omega - \omega_o|$ versus $(R - R_o)$ for this new data suggests V(R) increases beyond the sun ($R > 10$ kpc). However, there is sufficient observational error that a flat curve with $V = 250$ km/s beyond $R = 10$ kpc is consistent with the data, whereas the Schmidt model is definitely excluded.

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