THE GALACTIC ROTATION CURVE TO R = 18 kpc

Leo Blitz and Michel Fich
Radio Astronomy Laboratory
University of California, Berkeley
and
Antony A. Stark
Princeton University Observatory

The major stumbling block in the determination of a rotation curve beyond the solar circle has been the lack of a suitable set of objects with well defined and independently measured distances and velocities which can be observed to large galactocentric radii. Two things have changed this situation. The first was the realization that essentially all local HII regions have associated molecular material. The second was the acquisition of reliable distances to the stars exciting a sizable number of HII regions at large galactocentric radii (Moffat, FitzGerald, and Jackson 1979). Because the velocity of the associated molecular gas can be measured very accurately by means of radio observations of CO, we have been able to overcome the past difficulties and have measured the rotation curve of the Galaxy to a galactocentric distance of 18 kpc.

We have obtained the velocity of the CO related to 184 HII regions. Most of these are new detections, but we have made extensive use of the published literature and have checked the published values to the degree that it was feasible. The results presented here were obtained with the 5 m telescope at the Millimeter Wave Observatory, the 7 m telescope at Bell Laboratories, and the 11 m telescope at Kitt Peak. We have relied heavily on the distances determined by Moffat, FitzGerald and Jackson (1979) who have obtained spectrophotometric distances to 40 of the most distant HII regions. We have also made use of the distances published by Georgelin, Georgelin and Roux (1973), Georgelin and Georgelin (1976), Crampton, Georgelin and Georgelin (1978) and Humphreys (1979) among others to obtain distances to 92 molecular complexes. These complexes are plotted in Figure 1 which shows their locations projected onto the Galactic plane. It is evident from Figure 1 that there should be no systematic errors due to limited longitude coverage.

We have determined the rotation curve under the assumption that the complexes are in circular rotation about the Galactic center, that R_o (the solar distance to the Galactic center) is 10 kpc and Θ_o (the circular velocity of the sun) is 250 km sec^{-1}. HII regions within $\pm$ 15° of the Galactic center and anticenter were omitted from the de-

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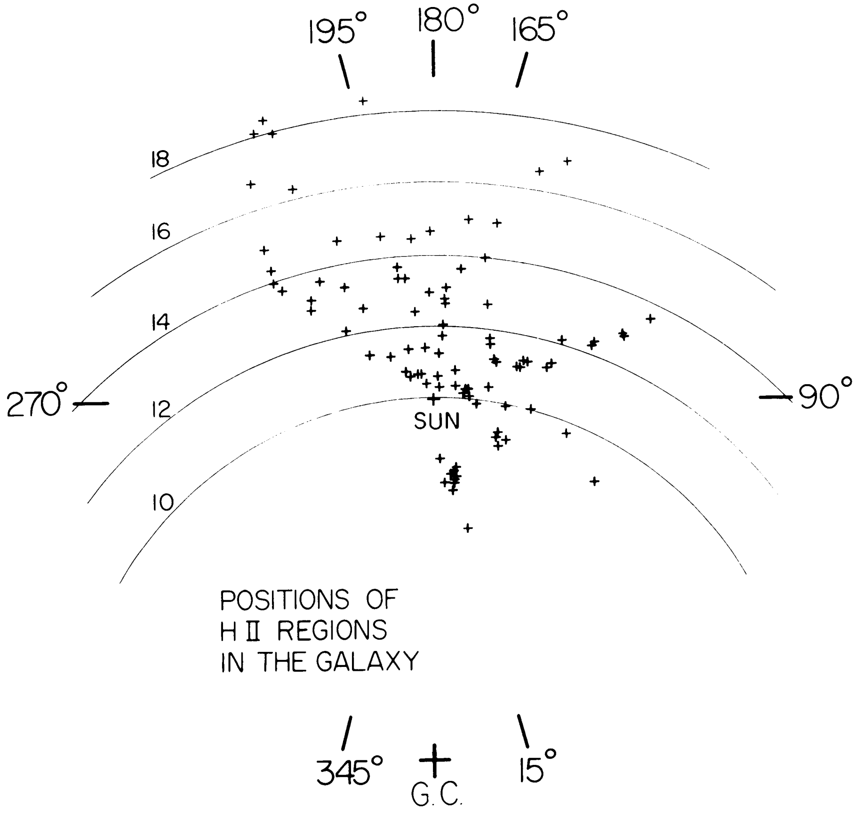

Fig. 1 - The distribution of HII regions used in this investigation projected onto the Galactic plane. Where several HII regions appear to be related to a single molecular complex, such as the S254-S258 complex, they are considered as one object. All of the objects plotted have known distances and CO velocities.

termination of the rotation curve because the radial projection of the circular velocity in these regions is comparable to the random velocities of the complexes. We have used the omitted HII regions to determine the velocity dispersion of the giant molecular complexes.

Figure 2 shows the rotation curve of the Galaxy from 7 to 18 kpc determined from the CO velocity data. The curve is a fourth order polynomial fit which excludes the HII regions in the Perseus arm. These are the nine HII regions near R = 11 kpc with Θ < 240 km sec^{-1}. Inclusion of these points lowers the polynomial fit by 5 km sec^{-1} near 11 kpc, but the overall fit is not substantially changed. In the portion of the Galaxy we have sampled, no region shows as large a systematic deviation from the mean rotation curve as the Perseus arm does.

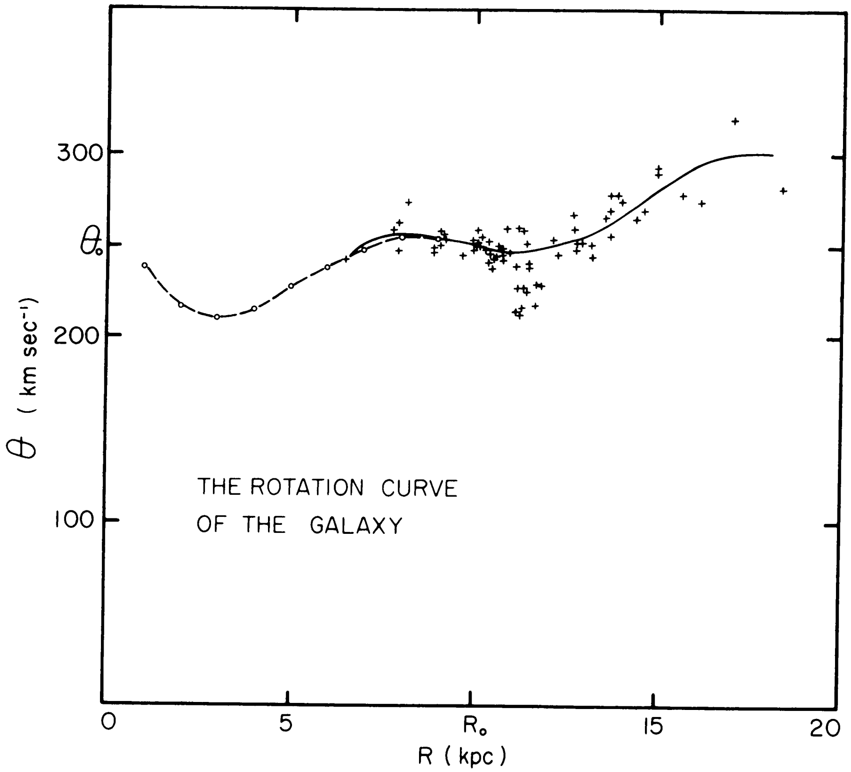

Fig. 2 - The rotation curve of the Galaxy. Dashed line connecting the circles are from atomic hydrogen data. The solid curve is a fourth order least squares fit to the data, which omits the Perseus arm anomolous velocity observations.

The primary result of our observations is that there is no decrease (turnover) in the circular velocity to the last measured point. The Galaxy is therefore typical of the spiral galaxies whose rotation curves were measured by Rubin, Ford and Thonnard (1978). The rotation curve rises from about 12 kpc to 18 kpc and attains a circular velocity of $\sim$ 300 km sec^{-1} at the last measured points. This rise appears to be real because to make the rotation curve flat requires a change in the distance scale by a factor of two. Such a change would affect the points internal to the solar circle causing a marked deviation from the HI rotation curve, shown by the dotted line connecting the circles in Figure 2. Our data show the agreement between the HI and CO rotation curves to be quite good.

We may use the data to find the Oort A constant by plotting Ω vs. R and performing a least squares polynomial fit to the data, which is

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shown in Figure 3. A is given by $-\frac{1}{2} R_o \left(\frac{d\Omega}{dR}\right)_{R_o}$ and has the value 12.9 km sec^{-1} kpc^{-1} if we exclude the Perseus arm and 13.3 km sec^{-1} kpc^{-1} if we include it. These values are considerably lower than the generally accepted value of 15 km sec^{-1} kpc^{-1} (Schmidt 1965), and are reminiscent of the values first suggested by Weaver (1955, 1958). We may also determine the curvature parameter α given by $-\frac{1}{4} R_o \left(\frac{d^2\Omega}{dR^2}\right)_{R_o}$ in the same manner. We find that $\alpha = -1.8$ km sec^{-1} kpc^{-2} and is relatively insensitive to the inclusion or omission of the Perseus arm observations.

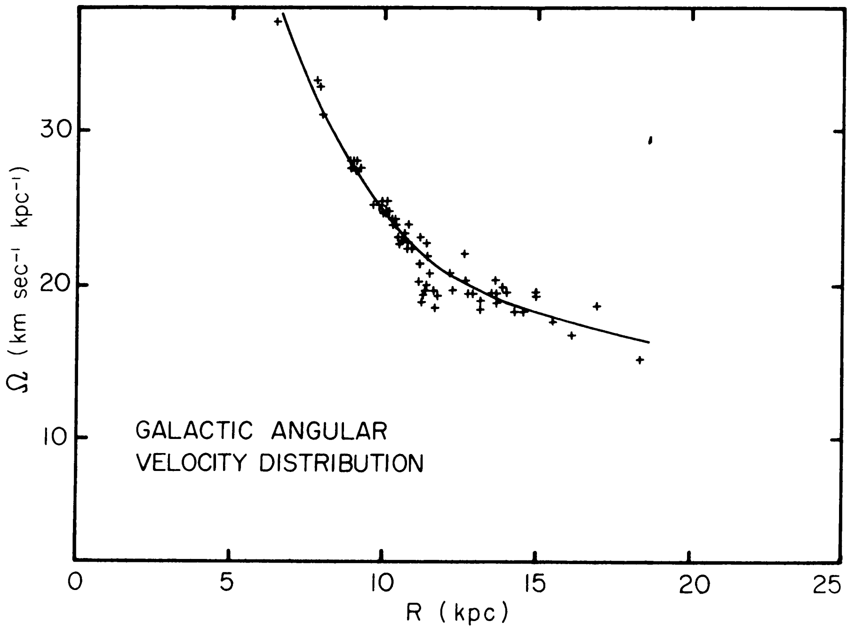

Fig. 3 - Plot of angular velocity Ω vs. R. The solid line is a third order polynomial fit to the data which omits the Perseus arm data. The circle gives the solar values.

The complexes within $\pm$ 15° of ℓ = 180° can be used to determine the velocity dispersion of the giant molecular complexes. We use the spectrophotometric distance and the rotation curve in Figure 2 to obtain a circular velocity for the anticenter complexes and subtract the projection of the circular velocity from the observed radial velocity. The result is just the radial component of the random velocity of each complex. The velocity dispersion of 17 giant complexes in the anticenter is 7 km sec^{-1} which should be contrasted with a dispersion of 8 km sec^{-1} obtained by Stark (1979) for <u>all</u> of the gas toward the galactic anticenter. Stark's observations sample low intensity, low mass molecular clouds. We therefore conclude that the velocity dispersion of high and low mass molecular material is very nearly the same.

The mean velocity of the anticenter complexes is -7 km sec^{-1}. Toward the Galactic center, the mean of four complexes with known distances is $+7$ km sec^{-1}. If we assume that the molecular complexes with unknown distances are at R = 8 kpc, the mean velocity of ten complexes within $\pm 15^{o}$ of $\ell = 0^{o}$ is $+5$ km sec^{-1}. These values are consistent with a net radial outward motion of the Local Standard of Rest (LSR) of $\sim$6 km sec^{-1}, a suggestion first proposed by Kerr (1961). This conclusion is reinforced by our observations of four high latitude clouds. These objects are probably within $\sim$100 pc of the sun and their motions are presumably tied to the LSR. The radial velocity of each of these clouds is nearly zero. This implies that the observed mean velocities toward the Galactic center and anticenter are due more likely to an outward motion of the entire LSR rather than an error in the measurement of the solar motion relative to the LSR.

Finally, we use the rotation curve to determine the mass of the Galaxy interior to 18 kpc. Using the simplest of mass models, we assume that the mass is distributed in a uniform sphere to the last measured point, and find that the mass of the Galaxy is 3.4×10^{11} $M_{\odot}$. Using different models produces only inconsequential changes to the mass estimates. This mass is considerably larger than has been previously thought and is $\sim$50% larger than the value derived for M31 under the same set of assumptions. Our observations indicate, therefore, that the Galaxy is the most massive member of the local group.

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REFERENCES

Crampton, D., Georgelin, Y.M., and Georgelin, Y.P.: 1978, *Astron. and Ap.* 66, 1.
Georgelin, Y.M., and Georgelin, Y.P.: 1976, *Astron. and Ap.* 49, 57.
Georgelin, Y.M., Georgelin, Y.P., and Roux, S.: 1973, *Astron. and Ap.* 25, 337.
Humphreys, R.M.: 1978, *Ap. J. (Suppl.)*, 38, 309.
Kerr, F.J.: 1961, M.N.R.A.S., 123, 327.
Moffat, A.F.J., FitzGerald, M.P., and Jackson, P.D.: 1979, *Astron. and Ap. (Suppl.)*, 38, 197.
Rubin, V.C., Ford, W.K., and Thonnard, N.: 1978, *Ap. J. (Letters)*, 225, L107.
Schmidt, M.: 1965, in *Galactic Structure*, ed. A. Blaauw and M. Schmidt (Chicago: University of Chicago Press), p. 513.
Stark, A.A.: 1979, Ph.D. Dissertation, Princeton University.
Weaver, H.F.: 1955, *A.J.*, 60, 202.
Weaver, H.F.: 1958, Trans. IAU X, 696.

DISCUSSION FOLLOWING BLITZ

Guelin: There is strong evidence (e.g. W.W. Roberts) that HII, HI gas and stars have large (~15 km/s) non-rotational velocities in the Perseus arm. CO cloud velocities could also be affected in this region (Yuan, 1976). Since your data partly relies on the Perseus arm, your results could be affected.

Blitz: The CO shows the same velocity anomalies as the other Population I tracers, but the Perseus arm represents only ~10% of the data presented here. The shape of the rotation curve changes only slightly, and the value of A goes from 12.85 to 13.30, when the data from the Perseus arm are included.

Thaddeus: What happens when you compare the ordinary rotation curve obtained from the stellar radial-velocities with that derived from CO? How much does the use of CO improve over the standard method? It would be interesting to see the two side by side.

Blitz: It has not been possible to obtain a reliable *quantitative* rotation curve without the CO data. Jackson, FitzGerald and Moffat, on whose optical data we have heavily relied in the outermost portions of the Galaxy, published a rotation curve last year in the form of a plot of $\Omega-\Omega_o$ vs R (Proceedings of IAU Symposium #84). While their data indicate that the rotation curve deviates markedly from the Schmidt model, the uncertainties in the measurements of radial velocity are so large that no reliable quantitative conclusions can be drawn. For example, if my memory is correct, there are many cases where the CO and stellar data differ by as much as 10 km s^{-1}, although the differences do not appear to be systematic.

Lo: As you pointed out yourself, the derived galactic circular velocities depend critically on the adopted distances of the CO sources. How accurate are the distances to the HII regions associated with the CO sources, and how reliable is the assumption that the CO sources are at the same distance as the HII regions?

Blitz: I believe that the assumption that the CO is at the same distance as the HII is very accurate. We mapped some of the most distant sources and found that the HII regions occurred at or near the CO peaks, as always seems to be the case locally. Also, for most sources in the second and third quadrants, only a single line is detected toward any HII region. Although a few points may be in error, they are likely to be a very small proportion of the total. The errors in the distances are the largest source of uncertainty in the determination of the circular velocity. Most of the largest distances are probably good to ~20-25%, and the corresponding uncertainty in θ from all sources of error is $\lesssim$20 km s^{-1} for any one point. Not all of the distances are as accurate, however.

Lo: One further comment. The velocity dispersion of outlying globular clusters measured by Hartwick and Sargent suggests that the total mass of the galaxy is many times $10^{11}M_\odot$.

Blitz: If one extends the rotation curve we have presented to ~50 kpc, one derives a mass which agrees, within the errors, with the mass

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derived by Hartwick and Sargent for an isotropic velocity distribution.

Morris: How does the slope of the rotation curve change if you assume R_O=8.5 kpc and θ_O=220 km s^{-1}, values which are suggested by recent studies?

Blitz: For these values the shape is unaffected because θ_O/R_O is unchanged. The rise in the rotation curve shown here, however, indicates that θ_O=250 km s^{-1}, if one uses the analysis of Knapp, Gunn and Tremaine. We have not yet determined how the shape changes with R_O=8.5, θ_O=250 km s^{-1}.

Bok: I hope that everyone realizes that an expansion velocity of 6 km s^{-1} implies that the LSR is moving outward in the Galaxy at a rate of 6 kpc in only one billion years, i.e. four or five galactic revolutions. Before we accept such a fantastic rate of expansion, we should see to what extent we can adjust our distance scale - or impose streaming motions - to obtain a smaller rate of expansion or no expansion. Is our Sun really on the way out?

Blitz: It is not clear why one should expect the 6 km s^{-1} outward motion of the LSR to persist for 10^9 years. The stars which define the LSR would probably disperse on this timescale. Furthermore, we know from the random velocities of the giant molecular complexes that coherent radial motions of the same magnitude as we postulate for the LSR are quite common, even for masses as large as 2 x 10^5 $M_\odot$. The observed motion of the LSR might also result from the radial component of an elliptical orbit of the LSR. Finally, the motion could also be cyclical or irregular, depending on the perturbations in the gravitational potential of the disk, brought about, say, by the passage of a density wave every $\sim$2 x 10^8 yr. In this regard, Lin, Yuan and Roberts have recently argued from an analysis of the observational data that according to the density wave theory, the LSR *should* have an outward component of $\sim$6 km s^{-1}.

Radhakrishnan: A recent analysis of the HI absorption spectrum towards Sgr A (Radhakrishnan and Sarma, submitted to Astronomy and Astrophysics) clearly indicates that all of the hydrogen in the direction of the galactic centre - excluding the gas within 3 kpc of the centre - has a mean velocity with respect to the Local Standard of Rest (LSR) of 0±0.25 km s^{-1}. Your conclusion that the LSR has a net radial outward motion of approximately 6 km s^{-1} (as suggested by Kerr (1961)) seems to be untenable unless you are also prepared to conclude that all of the HI gas within 7 kpc of the Sun in the direction of the galactic centre also shares precisely this motion.

Blitz: One cannot use the HI data to refute the hypothesis that the LSR has some radial motion with respect to the molecular gas until one can reconcile the different results implied by your observations and the observations of HI in emission toward the Galactic center. These results (note particularly those already published by Burton and Liszt (1978) and Burton, Gallagher and McGrath (1977)) show unquestionably that the ridge of maximum emission does not occur at a velocity of 0 km sec^{-1} but at about +5 km sec^{-1}, in rough agreement with the CO data. I would be more inclined to trust the emission data since it samples all of the gas along the line of sight and is less likely to be affected by anomalies caused by, say, a single massive cold cloud along the line of sight. Burton has also pointed out in the past that the HI seen in emission toward the anticenter has a net negative velocity, a result which is also in agreement with the CO results. It is important to emphasize that the motion which we claim to exist has an outward component with respect to the *molecular* gas, particularly the giant molecular complexes. If these were to have a preferential inward motion with respect to the center of the Galaxy, as one might expect if they are formed as a result of compression behind a density-wave shock, then the radial motion of the LSR with respect to the Galactic Center could be zero. It would still be necessary to explain, however, the residual motion of the LSR with respect to the HI in emission.

Radhakrishnan: Since when does emission data sample all of the gas along the line of sight and since when is it less likely to be affected by anomalies than absorption data? By definition the optical depth is always added all along the line of sight. On the other hand emission samples all the gas only when it is optically thin. If there is one thing we know and have known for years about the HI gas towards Sgr A, it is its high optical depth at near zero velocities. I have no quarrel with the elegant interpretation of Burton and Liszt of the inner galaxy where high velocities prevail; but for sampling the gas outside the inner galaxy their emission measurements at low velocities and all other such measurements are no match for direct optical depth determinations against Sgr A. The molecular complexes must have a preferential inward motion.

Blitz: It is impossible for me to try to reconcile the HI absorption and emission data without seeing your results in detail. However the depth of the HI absorption profile toward Cas A demonstrates that the absorption toward Sgr A could be dominated by a single cold cloud or a small path length through the Galaxy. Furthermore the mean positive residual of the CO and the peak HI emission appears to be shared by the HI emission which is at low optical depths ($|v| \lesssim 7$ km s^{-1} from the line center; not what one might call high velocity emission) and which thus samples all the gas along the line of sight. The same is true for the HI at high latitudes toward $\ell=0°$. I think more observations or more detailed analyses of existing observations are necessary to decide whether the LSR is moving out or the molecular complexes are moving in.

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