THE CIRCULAR VELOCITY AT THE SUN

G. R. Knapp
Owens Valley Radio Observatory, Caltech

The galactic rotation velocity at the Sun, Θ_0, can be derived several ways, none of them direct and unambiguous - (1) the solar velocity can be found relative to the halo population (the RR Lyrae stars, globular clusters etc.), but may contain an unknown contribution from possible systematic rotation of the halo system (2) the product $R_0\ \omega(R_0) = R_0\ (A-B)$ can be calculated but is uncertain because of large uncertainties in each of these three quantities (3) the motion of the Sun with respect to the center of the Local Group can be found but includes the motion of the galactic center of mass and (4) the velocity-longitude dependence of the outer HI boundary can be examined to deduce the most likely value of Θ_0. The incorporation of new data into analyses using methods (1) and (3) gives essentially the same answers as older studies. Examination of the accumulated current evidence suggests that the best values for the solar rotation velocity Θ_0 and the galactocentric distance R_0 are 220 km s^{-1} and 8.5 kpc respectively.

The value of the velocity of the LSR about the galactic center, Θ_0, is of fundamental importance for any studies of objects at more than a few kiloparsecs from the Sun, both those of galactic structure and of the motions of external galaxies. Unfortunately, there is no simple and direct way to measure this quantity. Its value must therefore be deduced in the context of the other galactic motions and scales, viz. the distance R_0 to the galactic center, the Oort constants A and B which describe the differential galactic rotation in the solar vicinity, the galactic dynamics and rotation curve, the motions of the halo population, and the peculiar motions of our nearest neighbors in extragalactic space, the members of the Local Group. All of the lines of evidence must be examined to find a self-consistent set of values for the galactic parameters, including Θ_0.

There are the following ways, more or less indirect, to estimate the value of Θ_0.

(1) Measure the peculiar motion of the LSR with respect to the halo population, viz. the globular clusters. This method gives $\Theta_0 \sim 200$ km s^{-1}.

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 225–230.

https://doi.org/10.1017/S0074180900014510 Published online by Cambridge University Press

(2) Measure the peculiar motion of the LSR with respect to the members of the Local Group. This method gives $\Theta_0 \sim 300$ km s^{-1}.
(3) Analyse the motions of the high-velocity stars. There are no stars traveling in the $\ell=90^o$ direction at velocities greater than ~ 65 km s^{-1} with respect to the LSR, which must measure the local escape velocity. This method suggests $\Theta_0 \sim 300$ km s^{-1}.
(4) Find Θ_0 by measuring both ω_o (R) and R_o, where ω_o is the local angular velocity. R_o is measured by the distance to the center of mass of the globular cluster or RR Lyrae systems, or by heliocentric distances to stars at galactocentric distances R_o. Such stars are characterized by having radial velocities relative to the LSR of 0 km s^{-1}, and a value of R_o follows from simple geometry. The angular velocity ω is measured via the Oort A and B constants:

$$A = -\frac{1}{2}R_o \left\{\frac{d\omega}{dR}\right\}_{R_o} \quad \text{km s}^{-1}\ \text{kpc}^{-1} \tag{1}$$

$$B = -\omega_o - \frac{1}{2} R_o \left\{\frac{d\omega}{dR}\right\}_{R_o} \quad \text{km s}^{-1}\ \text{kpc}^{-1} \tag{2}$$

so that $\Theta_0 = R_o$ (A-B)
The constants A and B are measured by observations of stellar radial velocities, distances and proper motions [see the descriptions by Schmidt (1965) and Mihalas (1968)]. The values of these constants must further be in agreement with the value of $2AR_o$ found from 21-cm observations of the HI disk. A careful discussion of all the evidence by Schmidt (1965) led to: A=15 km s^{-1} kpc^{-1}; B=-10 km s^{-1} kpc^{-1}; R_o=10 kpc; Θ_0 = 250 km s^{-1}. The resulting dynamical model for the Galaxy produces a rotation curve which rises approximately linearly from ~ 200 km s^{-1} at R $\sim$ 1 kpc to 250 km s^{-1} at 10 kpc then falls slowly ($\sim R^{-0.2}$) beyond R_o. This model for the Galaxy was adopted by the I.A.U. in 1963, and these values used in galactic studies ever since.

There has been a lot of activity of late using each of the above methods; for the first three methods the numerical values found agree well with older values.

(1) <u>The Motions of the Halo Population</u>

The LSR motion may be measured by a 'solar motion solution' relative to the halo population. The disadvantage of this method is that there may be an (unknown) net rotation of the halo objects <u>as a system</u> which adds to the calculated value of Θ_0.

Woltjer (1975) from an analysis of globular cluster motions, finds Θ_0 = 200 to 225 km s^{-1}. Hartwick and Sargent (1978) have measured the velocities of members of the distant halo population (the dwarf spheroidal galaxies and the 'Palomar' interloper globular clusters) and find Θ_0 = 220 km s^{-1}. It has been suggested (Lynden-Bell 1976) that these latter objects do belong to a system, i.e. the Magellanic Stream, but the radial velocities measured by Hartwick and Sargent do not bear this out. Thus, except for the unlikely eventuality that both subsets of the halo objects belong to the same systematically rotating system, this straightforward observation leads to a lower value of Θ_0 ($\sim$215±20 km s^{-1}) than the standard value.

(2) Motion with respect to the Local Group of Galaxies.

This method suffers from several disadvantages, the most serious being that the resulting solar motion is compounded of the galactic rotation and of the peculiar motion of the Galactic Center with respect to the barycenter of the Local Group, and there is no way intrinsic to the method to disentangle the two. Other disadvantages, which are not so intractable since they can be dealt with reasonably by careful analysis, are the non-uniform distribution of local group members about the Galaxy, the concentration of most of the mass in the Galaxy and M31, the fact that several of the members are satellites of one or the other of the big galaxies, and the question of membership. Two such analyses, those of Lynden-Bell and Lin (1977) and Yahil, Tammann and Sandage (1977) confirm the value of the solar motion of $\sim$ 300 km s^{-1} (towards $\sim$ $\ell=105^{\circ}$, $b=-8^{\circ}$). From an accompanying analysis of the Magellanic Cloud motions (Lin and Lynden-Bell 1977), Lynden-Bell and Lin suggest that essentially all of this motion is galactocentric rotation of the LSR. The value of $\sim$ 300 km s^{-1} is also found by de Vaucouleurs (1972) from observations of nearby galaxies outside the local group, when a distance-dependent K-term (Hubble expansion) is included.

(3) The orbits of the high-velocity stars.

Recent analyses of the motions of the high-velocity stars have been made by Isobe (1974), who finds $\Theta_0 \sim 275$ km s^{-1}, and by Greenstein and Toomre (1978) who suggest $\Theta_0 \sim 300$ km s^{-1}. However, this method contains a hidden assumption; that essentially all of the mass of the Galaxy is inside the solar orbit. This is certainly true of the visible mass, but there is increasing evidence (e.g. Hartwick and Sargent 1978; Jackson 1978 this conference) for a large component of the galactic mass at distances $R > R_0$. The high-velocity stars may thus be affected by a much larger potential than previously assumed.

(4) Value of $\Theta_0 = (A-B)\ R_0$

This determination is probably on the shakiest ground at the moment because of uncertainties in the quantities A,B and R_0. Recent measurements of R_0 all give values less than 10 kpc. R_0 has been measured using globular clusters by Harris (1976), RR Lyrae stars by Oort and Plaut (1975) and using OB stars on the solar circle by Crampton et al. (1976). These measurements give values of R_0 between 8 and 9 kpc.

Many recent measurements of A and B have likewise been made, amongst them those by Fricke and Tsioumis (1974), Dieckvoss (1978), Balona and Feast (1974), and Crampton and Georgelin (1975). Values of A from $\sim$ 11 to 17 km s^{-1} kpc^{-1} and B from -7 to -15 km s^{-1} kpc^{-1} have been found; no attempt will be made in the present paper to suggest "correct" values of A and B from these numbers. Finally, the quantity $2AR_o$ has recently been re-evaluated from 21-cm data by Gunn et al. (1978); we find AR_o = 110±2 km s^{-1}, suggesting that both R_o and A are smaller then their "standard" values. All of this suggests that the value of Θ_o found from equation (3) is significantly smaller then 250 km s^{-1}.

In the above work, we have also investigated the galactic rotation curve and its interaction with the value of Θ_o. It is already known that the rotation curve flattens outside R_o (Jackson 1978, this symposium), and further, it has been known for a long time that if $\Theta_o \sim 220$ km s^{-1}, the galactic rotation curve is flat inside R_o also, to $R/R_o \sim 0.5$ (see Kwee, Muller and Westerhout 1954). This rotation curve shape agrees with those determined both optically and by 21 cm observations for almost all other galaxies (Rubin 1978, this symposium). If this is the case, then the rotation curve itself gives the value of Θ_o, since the tangent point velocity is

$$V_M = \Theta_o \, (1-\sin\ell) \qquad (4)$$

so long as $\Theta_R = \Theta_o$. Thus we find a formal value of Θ_o = 220±3 km s^{-1}.

Thus I think the best determination of the velocity of the LSR about the galactic center, Θ_o, is that given by the globular motions, i.e. 220 km s^{-1}. This value also provides a good fit to 21 cm observations both at distances $R > R_o$, and at $R < R_o$. With this value, the 21 cm observations lead to a flat rotation curve for the Galaxy, consistent with those of every other large galaxy observed.

The implied flatness of the rotation curve and the large extent of the (invisible) Galaxy requires a high total mass for the Galaxy ($\sim 10^{12} M_o$). This value is consistent with the derived using distant halo objects by Hartwick and Sargent (1978), with the large mass implied by the relative approach velocities of the Galaxy and M31 ($\sim$ 100 km s^{-1}), and with the large mass required by the orbits of the high-velocity stars.

REFERENCES

Balona, L.A., and Feast, M.W. 1974, M.N.R.A.S. 167, p 621.
Crampton, D., Bernard, D., Harris, B.L., and Thackeray, A.D. 1976, M.N.R.A.S. 176, p 683.
Crampton, D., and Georgelin, Y.P. 1975, Astron. Astrophys. 40, p 317.
de Vaucouleurs, G. 1972, in I.A.U. Symposium 44, ed. D.J. Evans, D. Reidel Publishing Co., Dordrecht, Holland.
Dieckvoss, W. 1978, Astron. Astrophys 62, p 445.
Fricke, W. and Tsioumis, A. 1975, Astron. Astrophys. 42, p 449.
Greenstein, J.L., and Toomre, A.R. 1978, in preparation.
Gunn, J.E., Knapp, G.R., Tremaine, S.D. 1978, (in preparation)

Harris, W.E. 1976, A.J. 81, p 1095.
Hartwick, F.D.A., and Sargent, W.L.W. 1978, Ap. J. (in press)
Isobe, S. 1974, Astron. Astrophys. 36, p 327.
Jackson, P.D. 1978, preceding paper.
Kwee, K.K., Muller, C.A., and Westerhout, G. 1954, B.A.N. 12, p 211.
Lin, D.N.C., and Lynden-Bell, D. 1977, M.N.R.A.S. 181, p 59.
Lynden-Bell, D. 1976, M.N.R.A.S. 174, p 695.
Lynden-Bell, D., and Lin, D.N.C. 1977, M.N.R.A.S. 181, p 37.
Mihalas, D. 1968, 'Galactic Astronomy' W.H. Freeman Co., San Francisco.
Oort, J.H., and Plaut, L. 1975, Astron. Astrophys. 41, p 71.
Rubin, V.C., 1978, preceding paper.
Schmidt, M., 1965, in 'Galactic Structure', ed. A. Blaauw and M. Schmidt, University of Chicago Press.
Woltjer, L. 1975, Astron. Astrophys. 42, p 109.
Yahil, A., Tammann, G., and Sandage, A.R. 1977, Ap. J. 217, p 903.

DISCUSSION

Oort: I feel some hesitation to accept as low a value as 220 km s^{-1} for Θ_o (as you suggest), because it leads to a disturbingly high relative velocity of the Galaxy and the Andromeda nebula. This velocity is already difficult to account for if Θ_o = 250 km s^{-1}. Commenting also to Dr. Jackson, I want to draw attention to the fact that there are apparently quite high radial motions in the outermost arms of the Galaxy. These were first discovered by Miss Kepner from 21-cm observations at Dwingeloo, and were later confirmed by Verschuur from NRAO observations. In particular there is an arm-like feature extending over some 20° around the longitude of the anticenter, where it has a radial velocity of -100 km s^{-1}. The presence of such large radial motions may seriously affect our determination of the rotation velocity for points in the second and third quadrants of longitude.

Knapp: The terminal-velocity vs longitude curve for the outer HI envelope (defined as the velocity of the 1 K contour in the Weaver-Williams and Kerr-Harten-Ball Surveys) appears to reflect circular motion except in the ℓ = 80°-180° region. The negative-velocity field in the anticenter direction is certainly not in circular motion. In any case, the fact that $\Theta_o = 220 + \beta$ from the rotation curve at $R < R_o$ where β is the gradient of Θ_R in km s^{-1} per 8.5 kpc strongly suggests that $\Theta_o < 250$ km s^{-1}, because the largest value of β observed for an external galaxy (NGC 4596) is 30.

Jackson: In fact we see a difference between the rotation curves for the second and third quadrants which is consistent with a radial outward motion of 5 km s^{-1} for the LSR or an inward motion of 5 km s^{-1} for the outer parts of the Galaxy. Nevertheless, because we included both outer quadrants of the Galaxy, our mean rotation curve results are independent of a uniform radial motion.

Schmidt-Kaler: In a joint work with Dr. Maitzen we obtained RV's of more open clusters. We now have spectra of 90 early-type open clusters; in the classical Johnson and Svolopoulos paper there were only 29. What we see is exactly in line with your results: $\omega(R)$ is steeper than Schmidt's model going inside and flatter going outside.

Jackson: Indeed, we are familiar with your extensive cluster work which essentially extends to $R-R_o \simeq 3$ kpc. However, we are going out to $R-R_o \simeq 7$ kpc, where the flattening, or even the increasing, of the rotation curve becomes more evident.

de Vaucouleurs: One well-known difficulty with Θ_o = 200-220 km s^{-1} is the large residual velocity of the Galaxy relative to the Local Group compared with the velocity dispersion of the other members, which is less than 50 km s^{-1}.

Knapp: With Θ_o = 220 km s^{-1}, the center-of-mass velocity of the Galaxy is 115 km s^{-1} towards ℓ = 145°, b = 20°. The direction is only $\sim$ 20° away from M31. It appears that M31 and the Galaxy are currently approaching each other: the timing argument suggests that the mass of the M31/Galaxy system is $\sim 3\times10^{12}$ $M_{\odot}$. The Local Group is perhaps a little unusual in having much of its mass in these two members.

https://doi.org/10.1017/S0074180900014510 Published online by Cambridge University Press