A SIMPLE INTERPRETATION OF THE 'ROLLING MOTIONS'

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Abstract. The rolling motion phenomenon is interpreted as an apparent motion in the observations. It is caused by (i) the combined effect of the differential rotation and the bending of the galactic plane for the spiral arms beyond the solar circle, or (ii) the displacement of the spiral arms from the central galactic plane for those within the solar circle.

I. Introduction

In their study of the galactic central regions, Oort and Rougoor first noticed that the motion of the 3 kpc arm "appears also to vary slightly with latitude: Relative to the center of the arm the part at average distance of 70 pc north of the plane is coming toward us with a velocity of 2.5 km s^{-1}, while the southern half of the arm is moving away with a similar velocity" (Oort, 1962, p. 15). Later, this phenomenon was interpretated explicitly by Rougoor (1964) as the gas motion rolling about the axis of the spiral arm. After this discovery, the 'rolling motions' have been found subsequently in almost all the major spiral arms in the Galaxy (Henderson, 1967; Burton, 1970; Shane, 1971; Harten, 1972). And Rougoor's interpretation was also tacitly accepted in general.

The first theoretical work in support of the concept of the actual rolling motions in spiral arms appeared accidentally in a paper by Fujimoto and Miyamoto (1969) which dealt only with the helical magnetic field in the Galaxy. After recognizing the implications of that paper, Fujimoto and Tanahashi (1971a) examined the observations of the rolling motions in the Perseus arm and found that they are compatible with their results. Furthermore, they proposed that the rolling motions in spiral arms are caused by the free precession of the Galaxy, a mechanism suggested by Lynden-Bell (1965) to account for the bending of the galactic plane (Fujimoto and Tanahashi, 1971b). Other suggestions on the cause of the rolling motions were given in Harten's thesis, but he did not develop a theoretical study to support his ideas.

All of these studies share one common view, namely, the spiral arms are actually rolling. We have taken an entirely different approach to this problem. The rolling motion phenomenon is interpreted as an apparent motion in the observations which is caused by the combined effect of the differential rotation and the bending of the galactic plane for the spiral arms beyond the solar circle or the displacement of the spiral arms from the central galactic plane for those within the solar circle. In this report, only a synoptic description of the observations, the method, and the results will be presented. A detailed exposition is published elsewhere (Yuan and Wallace, 1973).

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II. Summary of the Observations

Almost all the published data of the 21 cm line surveys of the Galaxy contain information on the rolling motions of spiral arms. In his thesis, Harten has completed a very extensive review of the observations of the rolling motion phenomenon. Since the measurement of the rolling motions in the latitude-velocity diagram is very subjective, we also made independent measurements for all the major arms, directly from the observations of Kerr (1969), Hindman and Kerr (1970) and Henderson (1972). Most of Harten's general results are confirmed.

The observations may be summarized as follows:

(i) Despite a drastic change of distance to the Sun from the far branch to the near branch along any given inner arm (those within the solar circle), the gradient dv/db measured from the latitude-velocity diagrams undergoes no appreciable change. This, of course, immediately implies that the actual velocity gradient dv/dz is several factors greater in the near branch than in the far branch of the same spiral arm. For illustration, Harten's results on the Northern Sagittarius Arm are reproduced in Table I.

TABLE I

Rolling motions in the Northern Sagittarius Arm by Harten[a]

l	dv/db (km s^{-1} deg^{-1})		Distance (kpc)		dv/dz (km s^{-1} kpc^{-1})	
	Near	Far	Near	Far	Near	Far
50°	−0.3	−0.2	5.6		−3	
49.5	−0.2	+0.2	4.7	6.5	−2	+2
49	−0.8	+0.4	4.4	6.9	−10	+3
48.5	−1.5	−1.0	4.2	7.3	−20	−8
48	−2.4	−1.3	4.1	7.6	−33	−10
47.5	−2.1	−1.9	4.0	7.8	−29	−14
47	−1.8	−2.5	3.8	8.1	−26	−18
46.5	−2.4	−1.9	3.7	8.3	−36	−13
46	−3.3	−2.5	3.6	8.5	−51	−17
45.5	−3.5	−2.0	3.5	8.7	−56	−13
45	−3.9	−3.0	3.4	8.9	−64	−19
44.5	−3.5	−2.1	3.3	9.1	−59	−13
44	−2.3	−1.6	3.3	9.3	−39	−10
43.5	−2.7	−1.7	3.2	9.5	−47	−10
43	−2.7	−1.7	3.2	9.7	−47	−10
42.3	−1.4	−0.5	3.1	9.8	−25	−3
41.3	−1.5	−0.5	3.0	10.2	−28	−3
40.3	−0.5	0.8	2.9	10.5	−10	−4
39.3	−0.4		2.8	10.8	−8	
38.3	−0.1	−0.2	2.8	11.1	−2	−1
37.3	−0.6	−0.1	2.7	11.4	−12	−5
36.3	−0.9	−0.8	2.6	11.7	−19	−4
35.3	−1.4	−0.8	2.6	11.9	−29	−4

[a] This table is reproduced for the purpose of demonstrating the great difference between dv/db and dv/dz. Harten's measurements in dv/db are somewhat larger than ours.

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(ii) The gradients dv/db in the outer arms (those beyond the solar circle) and the '3 kpc arm' are predominantly negative for both the northern and the southern skies with an average of -2 km s^{-1} deg^{-1}. Most of the rolling motions can be followed continuously along a given spiral arm.

(iii) The values of the gradient dv/db in the inner arms (except the '3 kpc arm') are decisively smaller in magnitude and more evenly distributed in sign than those in the outer arms. Rapid variations are always found in the directions where the line-of-sight is tangent to a spiral arm.

III. A Simple Interpretation

If, for some unknown region, the gas in spiral arms were rolling in the way that Rougoor described, these rolling motions would likely be uniform along a spiral arm. In other words, the velocity gradient dv/dz must assume a fairly constant value for that arm. It is simply inconceivable that a portion of the spiral arm is turning at a speed two or three times faster than the other directly connected portion. Even more inconceivable is that the near portion of the spiral arm is always the faster turning one. Clearly, the first observational fact in the previous section constitutes strong evidence against the interpretation that the rolling motions in spiral arms actually exist.

As the second and the third observational facts indicate, the systematic and prominent 'rolling motions' are found mainly in the regions exterior to the position of the Sun. (Due to the presence of the Lindblad resonance, the '3 kpc arm' is not treated here.) This seems to suggest that the 'rolling motion' might have something to do with the bending of the galactic plane, which thus far stands as the most distinctive characteristic for the outer regions of the Galaxy. In fact, we shall show that the very fact of the bending of the galactic plane together with the differential rotation will be sufficient to cause the apparent 'rolling motions' in the observations.

The situation may be best illustrated in Figure 1, where an integral sign cross section of the Galaxy is shown schematically. The flattened oval shapes on the distorted portions of the galactic plane represent equal-density (gas) contours of two outer spiral arms. When these oval contours are mapped onto the latitude-velocity diagram, the corresponding contours for equal brightness temperature will appear tilted in the negative sense as shown in the lower part of Figure 1. Because of the bending of the galactic plane, the upper tangent point T_1 is situated farther from us than the lower tangent point T_2 on the same density contour: hence T_1 is more negative in velocity in the latitude velocity diagram. Similar results are obtained in the southern sky. It is remarkable that the negative sense of tilt is simultaneously achieved on both sides of the sky.

As pointed out by Henderson (1967) and Westerhout (1968), the inner spiral arms are not centered on the galactic plane. They are displaced up or down in a random manner, usually 10–30 pc from the central plane. If we take this into consideration, then we find that the same argument may be applied to the interpretation of the

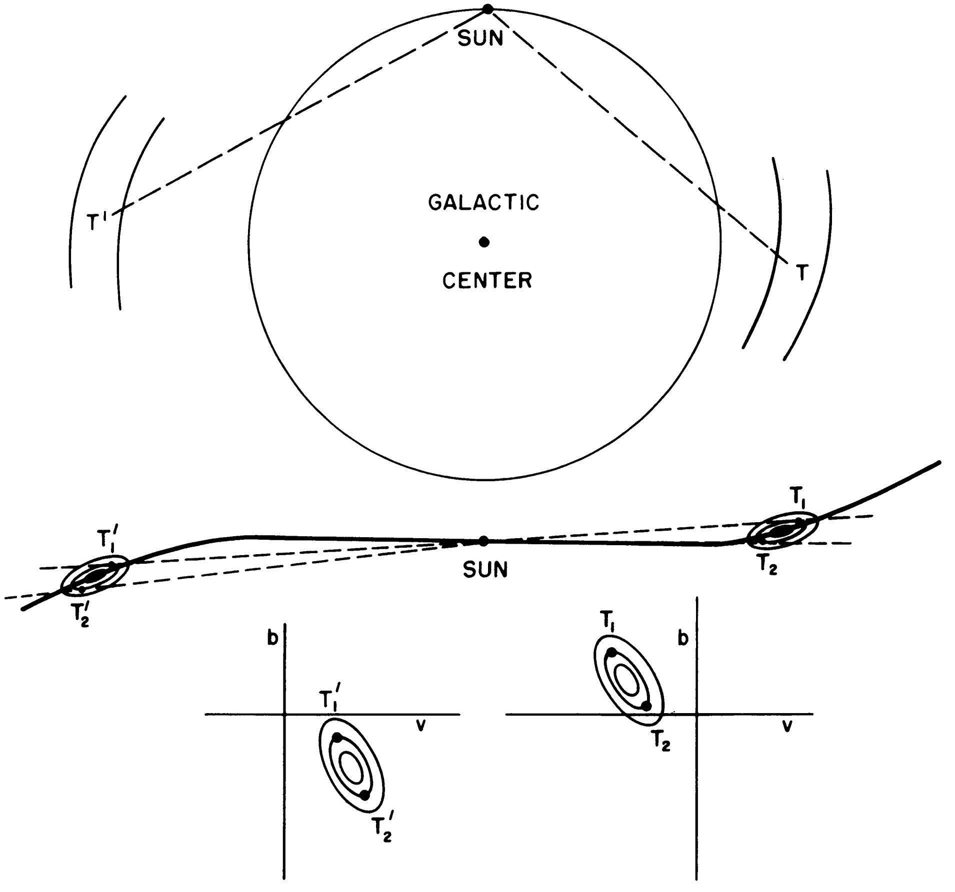

Fig. 1. Geometric explanation of 'rolling motion' for the outer arms. (Top) Plan view showing outer arms. (Middle) Cross-section of the Galaxy showing the bending of the plane and the equal density contours of the two spiral arms. Points T_1 and T_2 are the two tangent points to the lines of sight on a given density contour. (Bottom) The corresponding contours mapped onto the $b-v$ diagram. Note that dv/db is negative in both cases.

'rolling motions' of the inner arms as apparent motions also. The situation, however, is more complicated, because it will depend on whether the arm is above or below the plane and whether the arm is the far branch or the near branch. The signs of the gradients, therefore, are expected to be more mixed, and the degree of the tilt, corresponding to displacements 10–20 pc, is expected to be less pronounced. It might be noted here that the rapid variation of the gradients near the tangent direction can be explained by the velocity crowding. Gas clouds distributed along a considerably lengthy interval centered on the tangent point are clustered into a small region of the velocity scale, hence producing rather impressive magnitudes of dv/db with mixed signs.

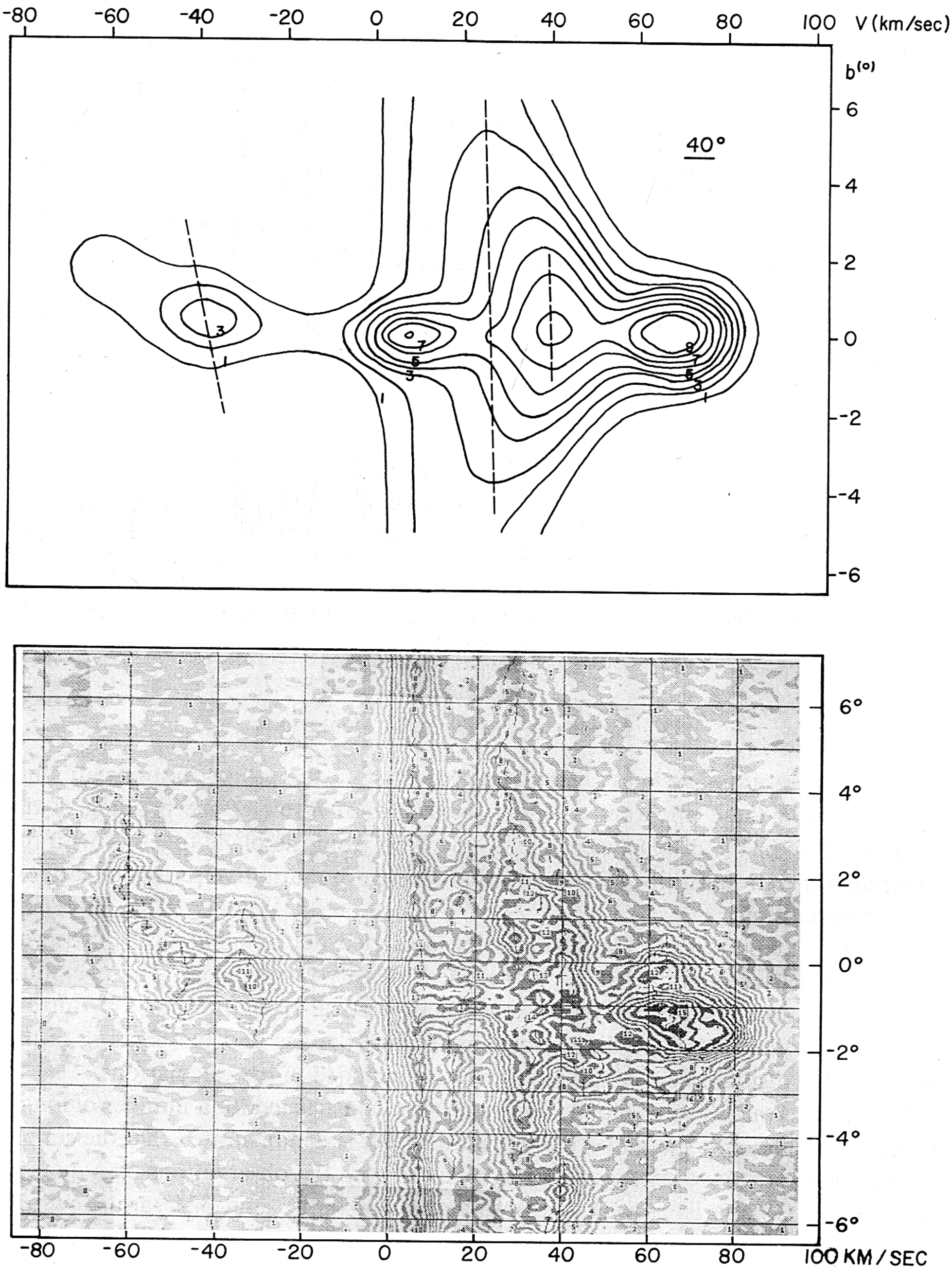

Fig. 2. Theoretical latitude-velocity diagram at $l = 40°$ compared with observations by Henderson at the same longitude.

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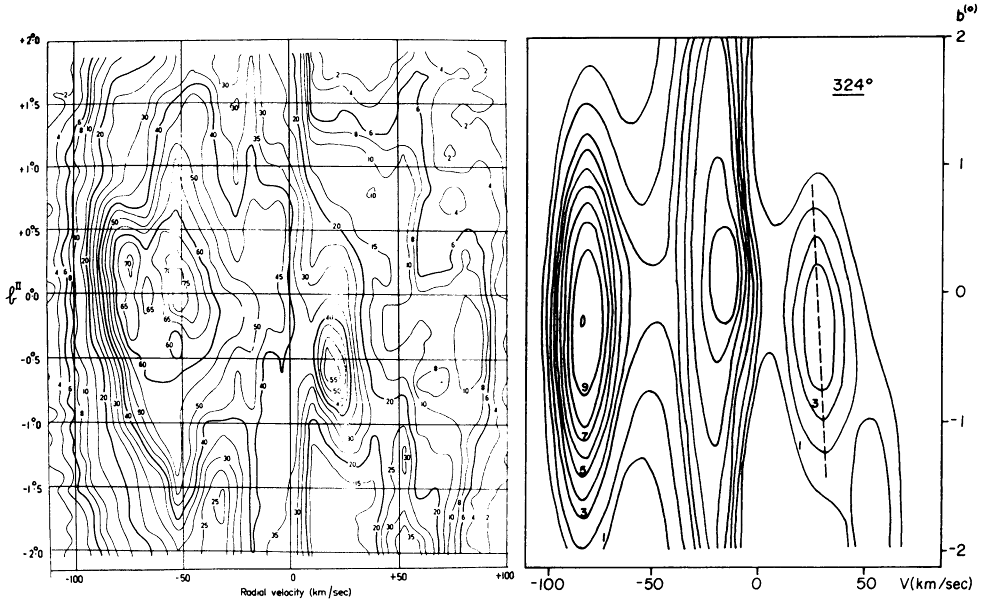

Fig. 3. Theoretical latitude-velocity diagram at $l=324°$ compared with observations by Kerr at the same longitude.

IV. Results of Numerical Calculations

In the above section, we have shown qualitatively that the rolling motions are only apparent. And these apparent motions are a natural result of the bending of the galactic plane or the displacement of an inner arm from the plane together with the differential rotation. In this section, we shall present quantitative results to support our interpretation.

Extensive numerical calculations have been carried out to simulate the observed latitude-velocity diagrams, based on the linear density-wave theory. The computation scheme is the same as that in constructing theoretical 21-cm profiles (e.g., Burton, 1970), except that the three dimensional motion of the gas and the bending of the plane (or the displacement of an inner arm) are included in the calculations.

The theoretical latitude-velocity diagrams were constructed for a number of longitudes for both the northern and the southern sky. It is demonstrated that the simple interpretation we have proposed also agrees well with the observations on a quantitative basis. Comparisons with the observation for $l=40°$ and $324°$ are shown in Figures 2 and 3.

V. Concluding Remarks

(i) Because of the extremely complicated nature of the '3 kpc arm', we have not tried to resolve the rolling motions in the '3 kpc arm' with our analysis.

(ii) With the present interpretation, we have avoided not only the difficulty of the origin of the rolling motions, if they are real, but also the problem of breaking the over-all gas flow in the Galaxy from the symmetry which is strongly established by the even distribution of the mass within the galactic plane.

(iii) The large-scale magnetic field with the strength and the topology observed in the Galaxy is not likely to be capable of introducing or maintaining an actual rolling motion. Fujimoto and Miyamoto's local analysis on the circular arm model is not free from the winding dilemma.

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References

Burton, W. B.: 1970, *Astron. Astrophys. Suppl.* **2**, 291.
Fujimoto, M. and Miyamoto, Y.: 1969, *Publ. Astron. Soc. Japan* **21**, 194.
Fujimoto, M. and Tanahashi, Y.: 1971a, *Publ. Astron. Soc. Japan* **23**, 7.
Fujimoto, M. and Tanahashi, Y.: 1971b, *Publ. Astron. Soc. Japan* **23**, 13.
Harten, R. H.: 1972, Ph.D. Thesis, University of Maryland.
Henderson, A. P.: 1967, Ph.D. Thesis, University of Maryland.
Henderson, A. P.: 1972, *Latitude-Velocity Maps* $l=16°$ to $230°$, $\Delta l=5°$, $b=10°$ to $+10°$, Astronomy Program, University of Maryland.
Hindman, J. V. and Kerr, F. J.: 1970, *Australian J. Phys. Astrophys. Suppl.* No. 18, 43.
Kerr, F. J.: 1969, *Australian J. Phys. Astrophys. Suppl.* No. 9, 1.
Lynden-Bell, D.: 1965, *Monthly Notices Roy. Astron. Soc.* **129**, 299.
Oort, J. H.: 1962, in L. Woltjer (ed.), *Interstellar Matter in Galaxies*, Benjamin, New York, p. 3.
Rougoor, G. W.: 1964, *Bull. Astron. Inst. Neth.* **17**, 384.
Shane, W. W.: 1971, *Astron. Astrophys. Suppl.* **4**, 1 and 135.
Westerhout, G.: 1970, in H.-Y. Chiu and Muriel (ed.), *Galactic Astronomy*, Gordon and Breach, New York, Vol. 1, p. 167.
Yuan, C. and Wallace, L.: 1973, *Astrophys. J.* **185**, 453.

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DISCUSSION

Baldwin: Are there any positions where the slope of $\mathrm{d}V/\mathrm{d}b$ is of the opposite sign, and how large are such regions?

Yuan: The positive slopes are seen rather frequently in the spiral arms interior to the position of the Sun. This is consistent with our mechanism. As for the spiral arms beyond the position of the Sun, positive slopes are rarely found, and in no case can they be followed more than a few subsequent longitudes.