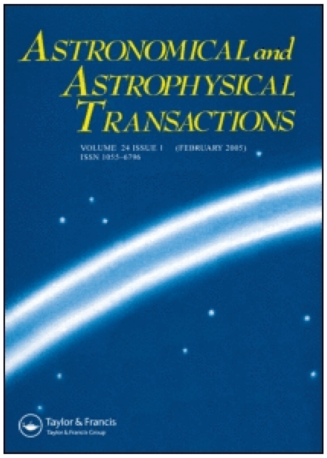

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

The spiral structure and rotation of the neutral hydrogen subsystem in the galaxy

Yu. N. Malahova [a]; I. V. Petrovskaya [b]
[a] Astronomical Observatory Pulkovo, Pulkovskoe shosse, Leningrad, USSR
[b] Astronomical Observatory, Leningrad University, Leningrad, USSR

Online Publication Date: 01 February 1992
To cite this Article: Malahova, Yu. N. and Petrovskaya, I. V. (1992) 'The spiral structure and rotation of the neutral hydrogen subsystem in the galaxy', Astronomical & Astrophysical Transactions, 1:3, 221 - 229
To link to this article: DOI: 10.1080/10556799208260469
URL: http://dx.doi.org/10.1080/10556799208260469

Astronomical and Astrophysical Transactions, 1992,
Vol. 1, pp. 221–229
Reprints available directly from the publisher.
Photocopying permitted by license only

THE SPIRAL STRUCTURE AND ROTATION OF THE NEUTRAL HYDROGEN SUBSYSTEM IN THE GALAXY

Yu. N. MALAHOVA

Astronomical Observatory Pulkovo, Pulkovskoe shosse, Leningrad, USSR, 196140

I. V. PETROVSKAYA

Astronomical Observatory Leningrad University, Bibliotechnaya pl. 2, Leningrad, USSR, 198904

(28 March 1991)

The rotation curve of the Galaxy is found using the whole 21-cm line profile of neutral hydrogen. The distribution of the neutral hydrogen has a ring structure for the region $0.4R_0 \leqslant R < 0.66R_0$, the four-armed logarithmic spiral is found in the region $0.66R_0 \leqslant R < R_0$. The pitch angle of the spiral is found to be 18°, the Sun laying between the arms.

KEY WORDS Galaxy, spiral structure, rotation curve

1. INTRODUCTION

The determination of the rotation curve of our Galaxy is the important problem. The rotation curve is used for the determination of kinematical distances to objects with known radial velocities, and for the construction of models of mass distribution of the Galaxy. The main materials for these investigations are the ratio data of 21-cm neutral hydrogen observations.

The initially developed method (Kwee *et al.*, 1954, van de Hulst *et al.*, 1954) used only the cut-off point of each 21-cm line profile identified with the tangential point of the line of sight where $R = R_0 \sin l$ (R and R_0 are the distances from the galactic center of the observed point and the Sun correspondently, l—the galactic lattitude of the observed point) (Figure 1). Later a method was proposed (Agekyan *et al.*, 1964, Petrovskaya, 1979) that utilized the whole profile, and provided the possibility of determining the rotation curve, not only in the inner region of Solar circle, ($R < R_0$) but also for the outer region ($R > R_0$). Recently, a modification of this method was developed (Petrovskaya, 1987a, 1987b). Because of the nonlinearity of the basic expressions, the maximum likelihood method was used instead of the least square method (Agekyan, *et al.*, 1964, Petrovskaya, 1979), for the determination of the best conformity between the selected values of the distance R and the angular velocity ω. The whole 21-cm line profile was also used by Petrovskaya and Teerikorpi (1986), and Teerikorpi (1989), in the graphic method determining the galactic rotation curve.

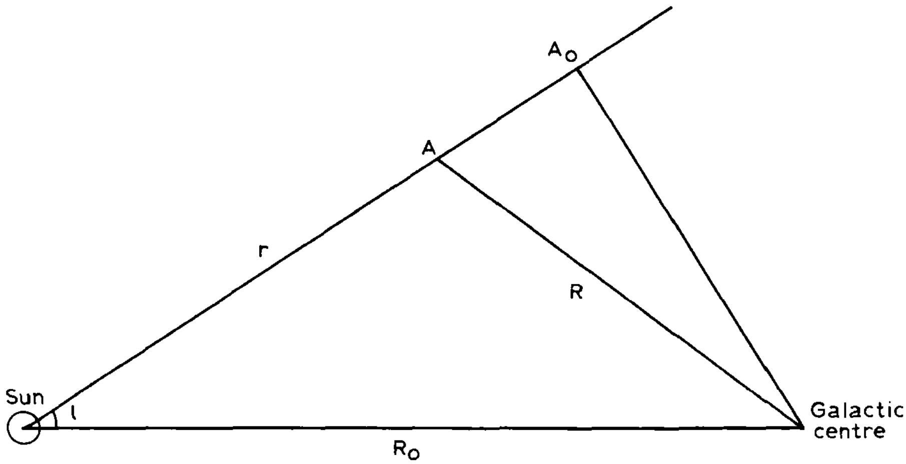

Figure 1 The observed point A has the longitude l and the distances from the Sun and the galactic center r and R correspondingly. R_0 is the distance from the galactic center to the Sun, A_0 is the tangential point.

One of the main propositions in the works by Agekyan (1964) and Petrovskaya (1979, 1987a) was the ring-like distribution of neutral hydrogen density in the galactic plane, $N = N(R)$. The expression for the optical depth is:

$$\tau = \kappa N \bigg/ \left|\frac{dv}{dr}\right| \tag{1}$$

where κ is the coefficient of proportionality, and v is the radial velocity at the point A at a distance r from the observer (Figure 1). This relation can be rewritten as:

$$\begin{aligned}\tau &= \kappa N \bigg/ \left(\left|\frac{d\Omega}{dx}\right| \cdot |\sin l| \sqrt{1 - x^{-2}\sin^2 l}\right) \\ &= y/(|\sin l| \sqrt{1 - x^{-2}\sin^2 l})\end{aligned} \tag{2}$$

where $\Omega = R_0(\omega - \omega_0)$, $x = R/R_0$ is the nondimensional distance of the point A from the galactic center, and

$$y = \kappa N \bigg/ \left|\frac{d\Omega}{dx}\right|.$$

The latter is a function only of x.

We suppose that the deviation law of the observed value τ_i from the true value τ is gaussian:

$$f(\tau_i) = \frac{1}{\sigma_0\sqrt{2\pi}} \exp[-(\tau_i - \tau)^2/(2\sigma_0^2)]. \tag{3}$$

Then the probability function is:

$$L = \frac{1}{(2\pi)^{n/2}\sigma_0^n} \exp\left[-\frac{1}{2\sigma_0^2} \sum_{i=1}^{N} (\tau_i - \tau)^2\right]$$

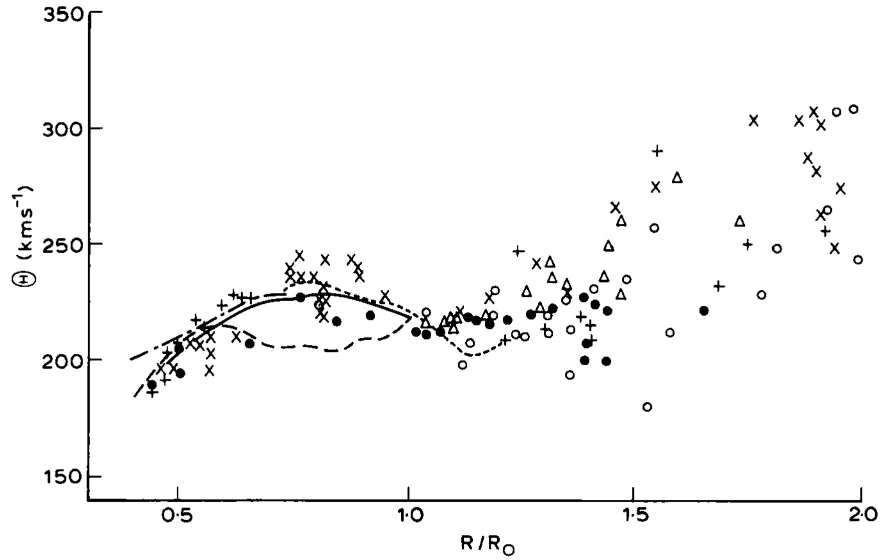

Figure 2 The rotation curve of the Galaxy for the ring HI distribution (----), and under the account of spiral structure: the individual points for the first (+) and the fourth (×) galactic quadrants ($R < R_0$) and the smoothed curve (—). For comparison, we present the results by Burton and Gordon (1978) (—·—) from CO HI data, Georgeline and Goergeline (1976) (......) for HII regions and graphical HI data by Teerikorpi (1989) (●), For $R > R_0$ the results from HI data for the north (+) and the south (×) parts of the Galaxy by Gerasimov and Petrovskaya (1990), the data by Chini from HII (O) and the data by Blitz from CO (Δ) are also presented.

and the estimations of parameters x and y could be found from the condition that L is at maximum:

$$\frac{\partial \ln L}{\partial x} = 0, \qquad \frac{\partial \ln L}{\partial y} = 0. \tag{4}$$

The results of the observations of Weaver and Williams (1974) were used for the northern part of the galactic plane ($20° < l < 160°$) and those of Kerr *et al.* (1986) for the southern part ($200° < l < 340°$).

In the regions of the galactic center and anticenter, the line of sight projection of the rotational velocity is smaller than the effect of nonrotational motions. Therefore, the observations in these regions were not considered. The rotation curve calculated by the maximum likelihood method, was found by Petrovskaya (1987a, 1987b) and shown in Figure 2.

2. THE LARGE SCALE STRUCTURE OF THE NEUTRAL HYDROGEN SUBSYSTEM IN THE GALAXY

The supposition on the ring-like symmetry of HI density is a simplification. The large scale hydrogen distribution deviates from the law $N = N(R)$ both for $R < R_0$ and $R > R_0$. At large distances from the galactic center ($R > R_0$), the main distortion is due to the deviation of the hydrogen layer. We have considered this effect earlier (Gerasimov and Petrovskaya, 1990) and found the corrected rotation curve. The rotational velocity increases as $R^{0,3}$ up to 16 kpc (Figure 2).

In the inner region of the solar orbit ($R < R_0$), the spiral character of neutral hydrogen density distribution must be taken into account.

Previously (Petrovskaya, 1986) we described the density distribution by an m-arm logarithmic spiral:

$$x(\lambda, k) = \exp\{[m(\lambda - c) + 2\pi(k - 1)]/(ma)\}. \tag{5}$$

The density varied as:

$$N(x, \lambda) = N_*(x)\left\{1 + B(x) \sum_{k=1}^{m} \exp[(x - x_k)^2/(2\sigma^2)]\right\} \tag{6}$$

when the distance from the k-th arm $x - x_k$ increased. λ is the azimuthal galactocentric angle, σ the effective width of the arm and a is connected to the pitch angle by the relation $a = \text{arc ctg}\, i$. Petrovskaya (1986) studied a two-arm spiral ($m = 2$) and obtained several sets of the parameters a, c, σ which were equally suitable for describing the observations. However, for a fourth-arm spiral, only one such set was found (Petrovskaya, 1987c). In all cases $B(x) < 0$, which indicated that (5) is the line of minimum density and σ is the effective interarm distance. The sets of the parameters that gave negative values of density were excluded.

The parameters of the fourth-arm spiral found by Petrovskaya (1987c) are given in the first line of Table 1. These were obtained from analysis of the observational data of Weaver and Williams (1974) and Kerr *et al.* (1986). The region of the galactic plane $0.4 \leqslant x < 1$ was studied. It follows from (Petrovskaya, 1987c) that the density distribution is close to axisymmetric in the region $0.4 \leqslant x \leqslant 0.65$. This is in agreement with the location of the well known molecular ring.

In order to avoid the alteration of the spiral parameters by the ring structure, we recalculated these parameters beyond the ring region ($x > 0.65$) (Malahova *et al.*, 1990). The set of derived parameters is presented in the second line of Table 1.

The rotational curve found in the articles by Petrovskaya (1987a, b) is under the supposition of the axisymmetric density distribution was used by Petrovskaya

Table 1 The parameters of the spiral structure of the Galaxy. For each of the four approximations, the values of pitch angle i, $a = \text{arc ctg}\, i$, the effective interarm distance σ, the position angle of minimum density line, c, and of maximum density line, $\theta = c + 45°$, are presented. In the last column, the region of the Galaxy is calculated for which the parameters are determined.

Approximation number	*a*	*i*	σ	*c*	θ	*The region described*
1	4	14°	0.060	20°	65°	$0.4 \leqslant x < 1$
2	4	14°	0.11	85°	40°	$0.7 < x < 1$
3	4	14°	0.14	80°	35°	$0.65 < x < 1$
4	3	18°	0.11	10°	55°	$0.65 < x < 1$

(1986, 1987c) and Malahova *et al.* (1990). The above method may be strictly applied only for the region $x \leq 0.65$ and this curve should be considered as a first approximation when $x > 0.65$.

It is possible that the spiral deviations in the region $0.65 < x < 1$ are the cause of the deviation of the rotation curve from the results that were found earlier using the tangential points of the HI and CO line profile (Burton and Gordon, 1978) and HII region (Georgeline and Georgeline, 1976) (Figure 2). Therefore, the rotation on the curve in this region was recalculated. The spiral structure was taken into account.

3. THE DETERMINATION OF THE ROTATION CURVE UNDER THE ASSUMPTION OF SPIRAL DENSITY DISTRIBUTION OF NEUTRAL HYDROGEN

In order to obtain the function $\Omega = \Omega(x)$ in the second approximation for the region $0.65 < x < 1$ we assumed that the density distribution has the form (6), that is, a concentration of a neutral hydrogen along a four-arm logarithmic spiral, with parameters which were calculated by the above method beyond the ring region (second line of Table 1) and with a value of the coefficient given in Table 2. Then,

Table 2 The values of $y = N/d\Omega/dx$ and $-B(x)$ for the calculation of hydrogen density distribution obtained as the fourth approximation.

x	y	$-B(x)$
0.66	16.3	0.598
0.68	11.1	0.625
0.70	4.07	0.619
0.72	2.38	0.605
0.74	1.98	0.607
0.76	2.32	0.628
0.78	2.68	0.645
0.80	2.45	0.634
0.82	3.03	0.645
0.84	5.45	0.673
0.86	10.01	0.681
0.88	7.96	0.653
0.90	10.40	0.644
0.92	9.87	0.629
0.94	34.2	0.649
0.96	35.8	0.655
0.98	22.3	0.666

from (4) and the expression for the optical depth (2) one obtains:

$$y = \frac{\sum_{i=1}^{n} \frac{\tau_i \{1 + B(x) \sum_{k=1}^{m} \exp[(x - x_k)^2/(2\sigma^2)]\}}{|\sin l_i| \sqrt{1 - x^{-2} \sin^2 l_i}}}{\sum_{i=1}^{n} \frac{\{1 + B(x) \sum_{k=1}^{m} \exp[(x - x_k)^2/(2\sigma^2)]\}^2}{\sin^2 l_i (1 - x^{-2} \sin^2 l_i)}} \tag{7}$$

$$F(x) \equiv \sum_{i=1}^{n} \left\{ \left(\tau_i - \frac{y\{1 + B(x) \sum_{k=1}^{m} \exp[(x - x_k)^2/(2\sigma^2)]\}}{|\sin l_i| \sqrt{1 - x^{-2} \sin^2 l_i}} \right) \right.$$

$$\cdot \left[\frac{B^1(x) \sum_{k=1}^{m} \exp\{(x - x_k)^2/(2\sigma^2)\} + \beta(x)(x - x_k)^2 \frac{1}{\sigma^2} \sum_{k=1}^{m} \exp \frac{(x - x_k)^2}{2\sigma^2}}{|\sin l_i| \sqrt{1 - x^{-2} \sin^2 l_i}} \right.$$

$$\left. \left. - \frac{1 + B(x) \sum_{k=1}^{m} \exp[(x - x_k)^2/(2\sigma^2)]}{x^3 (1 - x^{-2} \sin^2 l_i)^{3/2}} |\sin l_i| \right] \right\} = 0. \tag{8}$$

The calculations were carried out as follows. The value of the function $F(x)$ was found for a fixed value of $\Omega = \Omega_*$ and $x = x_1, x_2, \ldots, x_p$. The value $x = x_*$, for which $F(x_*) = 0$ was taken as the true value, corresponding to the adopted value Ω_*. This procedure was repeated for other values of Ω and thus we obtained law $\Omega(x)$.

The intensity was derived from the line profile in the galactic plane ($l = 0^0$), published by Weaver and Williams (1974) and Kerr *et al.* (1986), the interval Δl being equal to 1°.

There is a difficulty in the calculations of $F(x)$. As according to (2), τ increases unlimitedly when $|\sin l| \to x$ a sharp maximum of $F(x)$ can be found for some value x. In order to avoid these sharp changes the directions for which $x - |\sin l_i| < \delta$ were not taken into account. The value of $\delta = 0.002$ was adopted.

The rotation curve in the second approximation is then used for deriving the parameters of the spiral in the region $0.65 < x < 1$ (third line of Table 1). The calculations of the rotation law outside the ring region are repeated using the expressions (7)–(8), and the above mentioned algorithm. The derived curve (third approximation) is shown in Figure 2. The values Ω are given in Table 3 together with the standard errors of the averaged values of x. This curve is in good agreement with the result found by other authors (Burton and Gordon, 1978, Georgeline and Georgeline, 1976), which are shown in Figure 2. The final density distribution outside the ring region, found using this rotation curve (third approximation), is shown in Figure 3. The parameters of the corresponding four arm spiral are given in the fourth line of Table 1. The further approximations do not differ from this result.

The schematic structure of the subsystem of neutral hydrogen is shown in Figure 3. The ring region in the interval $0.4 \leqslant x \leqslant 0.65$ is outlined. The four arms of the logarithmic spiral with pitch angle $i = 18°$ go away from the ring. The width of the arms correspond to the effective interarm distance $\sigma = 0.11$. The four-arm logarithmic spiral with the pitch angle $i = 14°$ obtained by Petrovskaya (1987c) for the region $0.4 \leqslant x < 1$ is also shown in Figure 3 (the dashed line). The

Table 3 The values $\Omega = R_0(\omega - \omega_0)$ and corresponding distances of the galactic centre for the first, I, and the forth, IV, galactic quadrants when $\Omega > 120\,\mathrm{km\,s^{-1}}$. In the last column the standard errors ε of the distances are presented.

Ω ($\mathrm{km\,s^{-1}}$)		x_{I}	x_{IV}	ε
215		0.43	0.45	0.05
210		0.47	0.48	0.01
205		0.49	—	0.01
192		0.53	0.48	0.01
180		0.53	0.52	0.01
170		0.55	0.53	0.01
160		0.59	0.56	0.02
155		0.61	0.56	0.02
142		0.63	0.56	0.02
130		0.65	0.56	0.02
120		—	0.62	0.02
		$x_{\mathrm{I+IV}}$		
110		0.76		0.02
105	0.74		0.76	0.02
100		0.74		0.02
92.5		0.76		0.02
80	0.79		0.82	0.01
65		0.82		0.01
60	0.82		0.88	0.01
55		0.80		0.02
50	0.81		0.89	0.01
45		0.90		0.01
22.5		0.94		0.03

difference between these results is due to different assumptions about the density distribution for $x > 0.4$. For the outer region, $x > 1$, we presented in Figure 3, the four arm logarithmic spiral obtained by Blitz (1983). This spiral has the pitch angle $i = 22°$.

4. DISCUSSION

The smoothed rotation curve which was determined from different suppositions about the density distribution is shown in Figure 2. The dashed line is a simple solution computed on the assumption of the ring distribution of neutral hydrogen, $N = N(x)$. The solid line shows the rotation curve according to the final density distribution in the region $0.65 < x < 1$. The individual points are also present in Figure 2.

This data corresponds to a four-arm logarithmic spiral, with a pitch angle equal to $i = 18°$, which crosses the circle of radius R_0 at the position angle $\theta = 55°$.

According to our result, the Sun is located between the spiral arms.

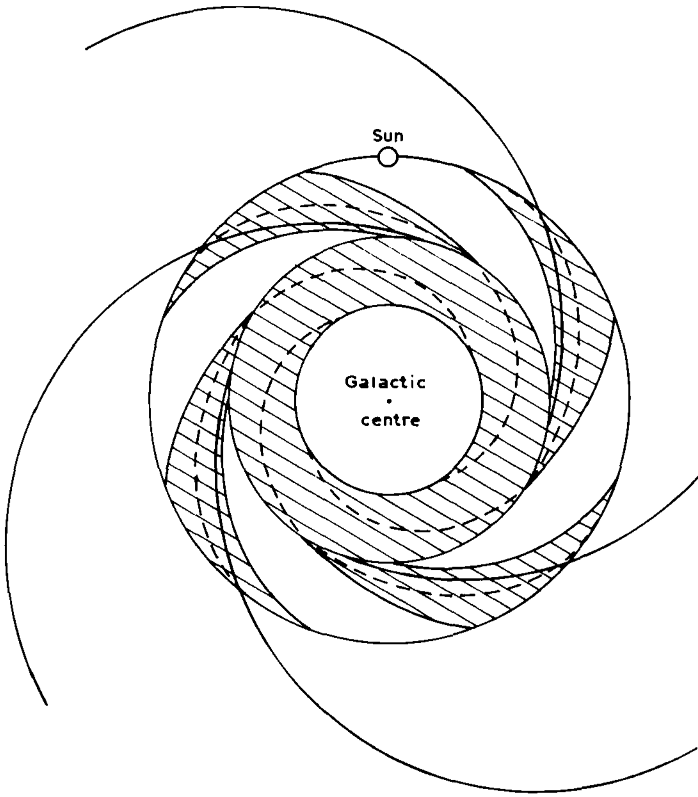

Figure 3 The model of the spiral structure of the Galaxy. The solid line represents the line of maximum density distribution of the neutral hydrogen. The four spiral arms extend from the ring in the region $0.4 \leq R/R_0 \leq 0.65$, the half of interarm distance is equal to $0.11\ R_0$, and a pitch angle is equal to 18°. The arms are crosses at the circle of radius R_0 at position angle 55°. The result by Petrovskaya (1979) for the region $0.4 \leq R/R_0 < 1$ is shown by the dashed line ($i = 14°$). The results of Blitz (1983) for the outer regon ($R > R_0$) are represented.

To follow the behavior of the rotation curve linear R_0 we also presented the data for the outer region of the Galaxy ($x > 1$) (Gerasimov and Petrovskaya, 1990). The final result is in agreement with the curve found by Burton and Gordon (1987). The result obtained by Teerikorpi (1987) using the graphical method, is noted by points. In the latter the spiral structure was not taken into account. Perhaps this is the reason for the deviation of the points obtained "graphically" from our final results. The result of Georgeline and Georgeline (1976) from HII regions are marked by a point curve in Figure 2.

The location of the spiral arms outside the ring (Figure 3) is in agreement with Blitz's data for the outer region of the Galaxy ($i = 22°$, $\theta = 50°$). It should be noted that the pitch angle i increases with increasing distance from the galactic center R. This is apparently connected with the deviation in the form of the spiral structure from the logarithmic form. The four-arm spiral structure with pitch angle $i = 13°$ was also obtained by Henderson (1977) for the region between the Sun and the galactic center (optical and 21-cm line data). The similar results are obtained by Caswell and Haynes (1987). Both authors also found that the Sun is located between the spiral arms. Therefore our picture of the spiral structure of the Galaxy is in agreement with the other results.

We thank our colleagues A. B. Yermalayeva (Rodchenko) and A. G. Gerasimov for their help in the calculations, and Z. I. Kadla, for useful discussions.

References

Agekyan, T. A., Petrovskaya, I. V. and Fesenko, B. I. (1964). *Astron. Zh.* **41,** 1027.
Blitz, L. (1979). *Astrophys. J.* **231,** L115.
Blitz, L. (1983). In "Surveys of the Southern Galaxy", eds. W. B. Burton and F. P. Israel, Dordrecht, 117.
Burton, W. B. and Gordon, M. A. (1978). Astron. Astrophys. **63,** 7.
Caswell, J. L., Haynes, R. F. (1987). *Astron. Astrophys.* **171,** 262.
Georgeline, Y. M. and Georgeline, Y. P. (1976). *Astron. Astrophys.* **49,** 57.
Chini, R. (1985). In "The Milky Way Galaxy", IAU Symp. **106,** eds. H. van Woerden, R. J. Allen, W. B. Burton, Reidel, Dordrecht, p. 101.
Gerasimov, A. G. and Petrovskaya, I. V. (1990). *Kinematica Fiz. Nebesn. Tel,* **6,** 5, 17.
Henderson, A. P. (1977). *Astron. Astrophys.* **58,** 189.
Kerr, F. G., Bowers, P. F., Jackson, P. D. and Kerr, M. (1986). *Astron. Astrophys. Suppl. Ser.* **66,** 373.
Kwee, K. K., Muller, C. A. and Westerhout, G. (1954). *Bull. Astron. Inst. Netherl.* **12,** 456, 211.
Malahova, Yu. N., Petrovskaya, I. V. and Rodchenko, A. V. (1990). *Voprosy Nebesn. Mech. Zv. Dinamici,* Alma-Ata, Nauka, p. 121.
Petrovskaya, I. V. (1979). *Pis'ma Astron. Zh.* **5,** 632.
Petrovskaya, I. V. (1986). *Vestn. Leningr. Univ., Mat. Mekh. Astron.* **1,** 126.
Petrovskaya, I. V. (1987a), *Kinematica Fiz. Nebesn.* Tel **3,** 4, 19.
Petrovskaya, I. V. (1987b). In "*Evolution of Galaxies*", Proceedings 10-th European Reginal Astronomy Meeting of the IAU, *PUbl. Astron*; *Inst. Czech.* **69,** p. 307.
Petrovskaya, I.V. (1987c). *Pis'ma Astron. Zh.* **13,** 474.
Petrovskaya, I. V. and Teerikorpi, P. (1986). *Astron. Astrophys.* **163,** 39.
Teerikorpi, P. (1989). *Astron. Astrophys.* **209,** 46.
Van de Hulst, H. C., Muller, C. A. and Oort, J. H. (1954). *Bull. Astron. Inst. Netherl.* **12,** 117.
Weaver, H. and Williams, D. B. V. (1974). *Astron. Astrophys. Suppl. Ser.* **17,** 1.