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Statistical analysis of Fe abundances gradients in the Galaxy

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Abstract Using the high precision data of the proper motions and parallaxes from Hipparcos catalogue, we obtained the orbital parameters of 1302 stars in the Galaxy based on the mass distribution model provided by Allen and Santillán. Fe abundances of 1295 stars among our samples were analyzed. With the correlation analyses between [Fe/H] and orbital parameters, we obtained that the Fe gradient is -0.057 ± 0.007 dex/kpc along the direction of the maximum galactocentric distance (hereafter $DG_{\max}$) in the range of 8.5 kpc $< DG_{\max} < 17$ kpc. We also got the result that the vertical gradient is steeper than the radial gradient. Furthermore, we divided the samples into two subgroups: giants and dwarfs; F, G and K stars; and then analyzed them respectively. Our results show that the gradient becomes flatter and flatter from giants to dwarfs, from F type to G and K type stars. We also divided the samples into disk and halo stars using maximum vertical distance $Z_{\max} = 1$ kpc as the criterion and got the result that the abundances of the disk stars are much higher than that of the halo stars. Our work suggests the existence of the galactic gradient and supports those chemical evolution medels which show that the halo was formed before the disk at the early stage of the Galaxy.

Keywords: **stars, abundances-Galaxy, evolution.**

The study of the abundances gradient within the Galaxy is of great importance for our understanding of the chemical evolution of the Galaxy. Analyses of element abundances using the observational data have become the research field of many astronomers. Many related papers have been published up to now. Most of these papers suggest the existence of the abundance gradient. However, there are many uncertainties about the value of the gradient and its variations in space and time scale.

Up to now, five types of objects have been used in the abundances gradient study. They are H Ⅱ regions[1], planetary nebulae (PN)[2—5], early type stars especially B-type stars[6—11], supernova remnants[12] and global clusters[13]. Element characteristics of the interstellar medium (ISM) are records of abundances enhancement process caused by stellar nucleosynthesis. Most astronomers select these objects to study because the chemical composition of these objects is similar to that of the present ISM or the historical ISM. We can summarize these researches as follows:

1) The existence of the abundances gradient in the Galaxy is gradually accepted by astronomers. In the research of H Ⅱ regions and planetary nebulae, a good linear correlation between abundances and galactocentric distance has been obtained, while the analysis of B-type stars obtains different results.

2) Different elements have different gradients. Using different sample data and data process methods, different gradients are obtained from 0 to -0.1 dex/kpc. The abundances gradients of some elements have some correlations while others do not.

3) Different types of objects show different gradients. From researches of PN, there are small differences in the measured gradients among different types of Ⅰ, Ⅱ and Ⅲ. According to these results, the gradients become steeper with time. Therefore, types Ⅰ and Ⅱ objects of PN have gradients similar to those of H Ⅱ regions[4].

Our research in this paper has some different features compared with other investigations:

First, the samples we selected are the main sequence (MS) stars. The energy of MS star is provided by the core H burning. Production of nuclear reactions hardly has effect on the chemical composition of its outer atmosphere. Thus, its outer atmosphere should have composition similar to that of the ISM where star formed.

Second, stellar orbital parameters are used in our statistical analysis. Supposed that the potential field of the Galaxy has not changed greatly during its evolution lasting billions of years, kinematic characteristics of the stellar orbits must be good indicators of the galactic formation and evolution. We calculated the stellar orbital parameters in the Galaxy using galactic mass distribution model and used these kinematic parameters to analyze the abundances gradient. This can reflect the process of galactic evolution factually. Previous researches are mainly carried out in the radial direction of the galactic disk. Multi-parameter analysis can give us a comprehensive understanding of the galactic abundances gradient.

Third, a large number of samples are used in our analysis. The number of samples used by other researchers is less than 300, while our samples reach up to 1 302. The large number of samples generally provide more reasonable statistical results.

1 Data selection

In order to do the orbit numerical integration and abundances analysis, we have to know the metallicity [Fe/H], right ascension (RA), declination (DE), proper motion (PM), parallax (Plx) and radial velocity (RV) for each sample. It is very difficult to find all these data in a single catalogue, so we used several catalogues.

[Fe/H]. [Fe/H] data are selected from two catalogues. Most of them are selected from a catalogue given by Marsakov et al.[14]. In the catalogue, they gave the absolute magnitude, metallicity, effective temperature, surface gravity, distance and tangential velocity of 5 489 F stars which are located within 80 pc from the Sun. Rest of them come from the fifth edition of "[Fe/H] determination"[15]. There are 5 946 [Fe/H] values of 3 247 stars in the catalogue including 4 716 [Fe/H] values of 2 497 field stars.

Radial velocity. Radial velocity data adopted in the paper come from several catalogues. Some data are derived from the fifth edition of Bright Star Catalogue compiled by Hoffleit et al.1). The catalogue and its previous editions have been widely used as a basic data source for stars brighter than 6.5 magnitude. Some RVs are selected from radial velocities catalogue by Barbier-Brossat et al.[16]. In this catalogue, radial velocities, obtained from 1970 to 1985, of 24 200 stars are collected. Others are taken from two radial velocity catalogues for bright southern stars obtained by Andersen and Nordström[17, 18]. They obtained RVs of 697 stars using the observa-

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1) Hoffleit, D., Warren Jr., W. H., Preliminary Version of the Bright Star Catalog, 5th Revised Edition.

tional data taken by a 1.5 m telescope at ESO.

Other kinematic data. In order to obtain the orbit of a star in the Galaxy, we have to know its proper motion and parallax. These data are obtained from Hipparcos Catalogue published by ESA in 1997[19]. Hipparcos satellite is a bigh precision astrometric space observatory launched in August 1989 by ESA. During its three-year observation, high-precision positions, proper motions, parallaxes and other data of 118 218 stars were obtained. These data compose a large high precision astronomical database.

In order to get the orbit parameters and analyze Fe abundances, only a small part of the data in these catalogues were used. First, we take [Fe/H] data from Fe catalogues. If there are more than one record for a star, only the updated one is used. Second, we take RA, DE, PM and Plx of these samples from Hipparcos Catalogue. Finally we get the radial velocities from radial velocity catalogues. After these crossed selections, there are 1 302 samples for the analysis.

2 Stellar orbit calculation

Allen and Santillán[20] presented an improved model of the galactic mass distribution in 1991 (hereafter AS1991) based on Allen and Martos[21] 1986 model (hereafter AM1986). The AM1986 model has been used widely. In the AS1991 model, they replaced the central mass distribution in the AM1986 model with a spherically symmetric potential. Some improvements were also made in other parts. Thus the improved AS1991 model is more reasonable. The model consists of a spherical central bulge, a disk and a massive spherical halo. The total mass of the model is 9×10^{11} $M_\odot$. It is extremely simple, fully analytical, continuous, and with continuous derivatives everywhere. Results from the model are in good agreement with the observational rotation curve and perpendicular force F_z at the Sun location.

Given the original kinematic data (X, Y, Z, U, V, W. X, Y and Z are position coordinates in the galactocentric right-angle coordinate system; U, V and W are velocities along the directions of X, Y and Z respectively) of a star, we can calculate its orbit in the galactic potential field. In this paper, we used the Runge-Kutta-Fehlberg algorithm[22] with automatic steplength control. The orbits of stars were numerically integrated backward 1.6×10^{10} a with the maximum energy variation $\delta(E)/E < 10^{-6}$ and the maximum momentum variation $\delta(H)/H < 10^{-6}$ at the end of the integration.

Given position coordinates X, Y and Z, the galactocentric distance (hereafter DG), and the projection of DG on the disk, R, can be obtained easily from the following relations:

$$DG = \sqrt{X^2 + Y^2 + Z^2},$$

$$R = \sqrt{X^2 + Y^2}.$$

From Hipparcos Catalogue, we can only obtain stellar right ascensions, declinations, proper motions and parallaxes, but no kinematic parameters. We have to calculate the stellar initial position parameters from these data. We used an algorithm provided by Johnson et al.[23] with which we could calculate the galactocetric space-velocity components U, V and W for a star if its proper motion, parallax and radial velocity were given.

AS1991 model is a symmetrical, static Galaxy model. Since the factual condition of the Galaxy is very complex, there may be some differences between the calculated orbital parameters and the factual ones.

The orbital parameters for 1 302 stars are obtained using our calculation program. In these parameters, the maximum $DG_{\max}$ is 17.04 kpc and the maximum $Z_{\max}$ is 3.86 kpc. Due to the limitation of the AS1991 model, if an orbit has a minimum galatocentric distance (hereafter $DG_{\min}$), $DG_{\min} < 1$ kpc, its error will be very large. So we excluded those samples with $DG_{\min} < 1$ kpc.

3 Results of statistic analyses

Using the method described above, we obtained the orbital parameters of 1 302 stars. Considering that if an orbit has $DG_{\min} < 1$ kpc, its error will be very large because of the limitation of AS1991 model. We excluded 7 samples with $DG_{\min} < 1$ kpc. Finally, the number of our samples used to analyze is 1 295. In these samples, $DG_{\max}$ values are between 8.5 and 17.04 kpc, $Z_{\max}$ values between 0 and 3.86 kpc.

Fig. 1 shows the results of [Fe/H] as the functions of $DG_{\max}$, $R_{\max}$, $Z_{\max}$ and the orbital eccentricity. The lines are fitting results for [Fe/H] and kinematic parameters using a linear relationship: $[\mathrm{Fe/H}] = A + B^{*} X$, where X represents orbital parameter, B is gradient and A is fitting constant. In table 1, we listed out fitting parameters and statistic results of linear regression analyses for these samples. For most samples, because $Z_{\max}$ is very small compared with $R_{\max}$, $DG_{\max}$ is determined by $R_{\max}$ to a great extent. Thus fig. 1(a) and (b) are very similar.

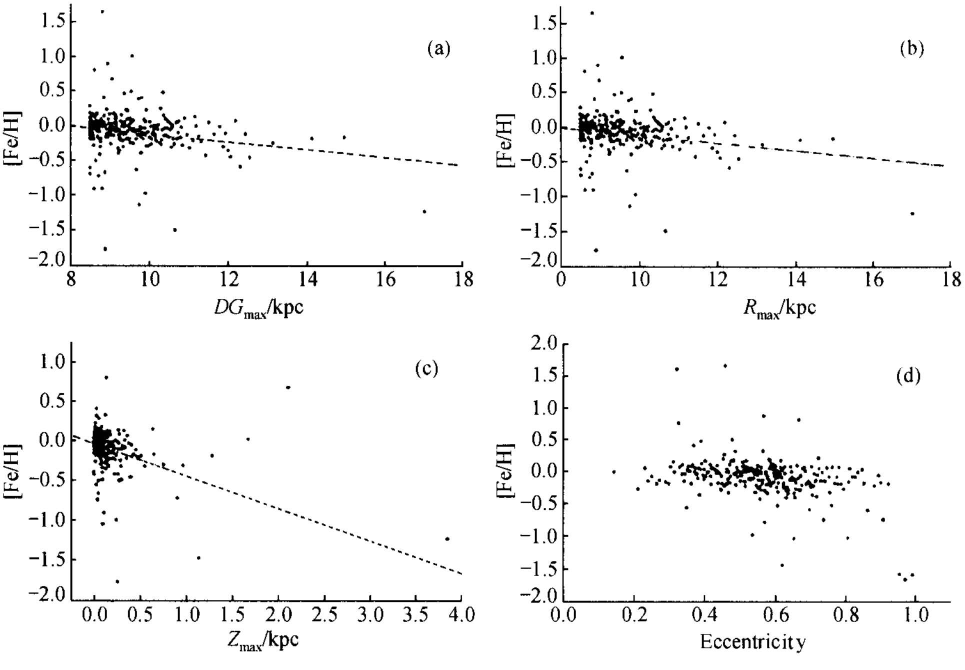

Fig. 1. Fe gradients for different kinematic parameters. (a) $DG_{\max}$; (b) $R_{\max}$; (c) $Z_{\max}$; (d) eccentricity.

Table 1 Statistic results for Fe gradients

Parameters	A	B	R	SD	n
$DG_{\max}$	0.447(0.066)	-0.057(0.007)	-0.229	0.264	1295
$R_{\max}$	0.440(0.066)	-0.057(0.007)	-0.226	0.264	1295
$Z_{\max}$	-0.037(0.008)	-0.411(0.023)	-0.451	0.242	1295

A and B, linear regression factors; R, correlation coefficient; SD, standard deviation; n, sample number.

From fig. 1 and table 1, we can see that [Fe/H] has some relations with these orbital parameters. The correlation with $Z_{\max}$ is stronger than that with $DG_{\max}$ and $R_{\max}$. Gradient to $DG_{\max}$ is -0.057 ± 0.007 dex/kpc and -0.411 ± 0.023 dex/kpc to $Z_{\max}$. We should notice that the gradient in direction Z is steeper than that in direction R.

[Fe/H] has correlation with the eccentricity (e). To a great extent it is because that eccentricity and $DG_{\max}$ have a relation as follows:

$$e = \frac{\sqrt{DG_{\max}^2 - DG_{\min}^2}}{DG_{\max}}.$$

It is a nonlinear relationship. Thus [Fe/H] has a nonlinear relationship with the eccentricity. Here we do not make statistical analysis for them.

In order to understand the gradients among different luminous types and spectral types in detail, we subdivided the samples into two subgroups. One has 320 giants and 757 dwarfs, the other has 813 F-type stars, 228 G-type stars and 152 K-type stars. Statistical results for these subgroups are listed in table 2.

Table 2 Statistic results for subgrouped samples

(a)

Parameters	A	B	R	SD	n
$DG_{\max}$	0.801(0.166)	−0.092(0.017)	−0.285	0.289	320
$R_{\max}$	0.781(0.167)	−0.090(0.017)	−0.278	0.290	320
$Z_{\max}$	−0.023(0.017)	−0.333(0.044)	−0.390	0.278	320

(b)

Parameters	A	B	R	SD	n
$DG_{\max}$	0.367(0.084)	−0.052(0.009)	−0.211	0.278	757
$R_{\max}$	0.363(0.084)	−0.051(0.009)	−0.210	0.278	757
$Z_{\max}$	−0.048(0.010)	−0.459(0.029)	−0.498	0.246	757

(c)

Parameters	A	B	R	SD	n
$DG_{\max}$	0.411(0.064)	−0.053(0.007)	−0.268	0.208	813
$R_{\max}$	0.410(0.064)	−0.052(0.007)	−0.267	0.208	813
$Z_{\max}$	−0.034(0.008)	−0.408(0.029)	−0.449	0.193	813

(d)

Parameters	A	B	R	SD	n
$DG_{\max}$	0.414(0.197)	−0.059(0.020)	−0.191	0.324	228
$R_{\max}$	0.381(0.198)	−0.056(0.020)	−0.180	0.325	228
$Z_{\max}$	−0.047(0.019)	−0.437(0.035)	−0.640	0.254	228

(e)

Parameters	A	B	R	SD	N
$DG_{\max}$	0.248(0.107)	−0.039(0.011)	−0.275	0.152	152
$R_{\max}$	0.248(0.107)	−0.039(0.011)	−0.247	0.152	152
$Z_{\max}$	−0.091(0.016)	−0.186(0.061)	−0.234	0.153	152

(a) Giants; (b) dwarfs; (c) F-type stars; (d) G-type stars; (e) K-type stars.

From above, we can see that the relationship between abundances of giants and $DG_{\max}$ is similar to that between abundances of dwarfs and $DG_{\max}$, while the gradient value of the former is steeper than the latter. For $DG_{\max}$, the gradient of giants is -0.092 ± 0.017 dex/kpc, and that of the dwarfs is -0.052 ± 0.009 dex/kpc. In direction Z, dwarfs show steeper gradient and better correlation. The gradient of dwarfs is -0.459 ± 0.029 dex/kpc, and that of the giants is

-0.333 ± 0.044 dex/kpc.

Taking the large dispersion of G-type star result into account, we can conclude from table 2 that the gradients to $DG_{\max}$ become flatter and flatter with -0.053 ± 0.007, -0.059 ± 0.020, -0.039 ± 0.011 dex/kpc for F, G and K stars respectively. However, this tendency is not manifested for $Z_{\max}$. Their gradients to $Z_{\max}$ are -0.408 ± 0.029, -0.437 ± 0.035 and -0.186 ± 0.061 dex/kpc respectively.

If all samples are divided into two groups: disk stars and halo stars, using $Z_{\max} = 1$ kpc as the criterion, then we can get 1 272 disk stars and only 23 halo stars. Their abundance distributions are shown in fig. 2. It is very apparent that metallicity of disk stars is higher than that of halo stars.

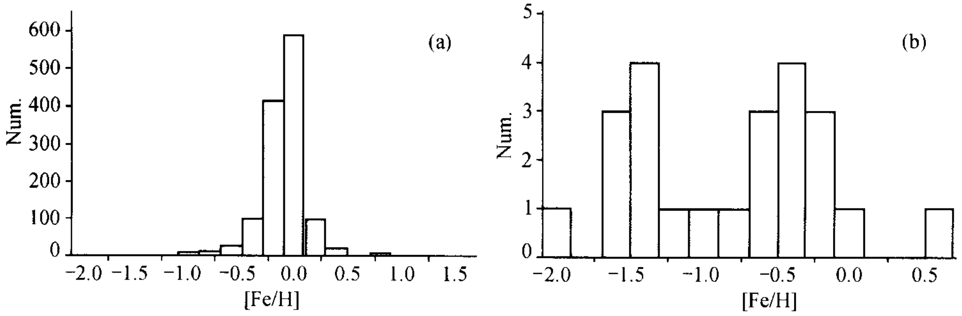

Fig. 2. [Fe/H] distribution for disk stars and halo stars. (a) Disk stars; (b) halo stars.

Among all the samples, there are 21 stars with [Fe/H] less than -1. 9 of them have $Z_{\max}$ larger than 1 kpc. While the whole samples with $Z_{\max} > 1$ kpc are only 23. That means quite a part of halo stars have very low metallicities. The close relationship between halo stars and low metallicity is an important criterion for galactic evolution theory.

Because most of our samples (excluding 23) are disk stars, very few data of halo stars became important source of the statistical dispersion. If we exclude samples with $Z_{\max} > 1$ kpc, the gradient of disk stars can be obtained as shown in fig. 3. The standard deviation of [Fe/H] to $R_{\max}$ is 0.236. Compared with the results in table 1, the dispersion is much smaller.

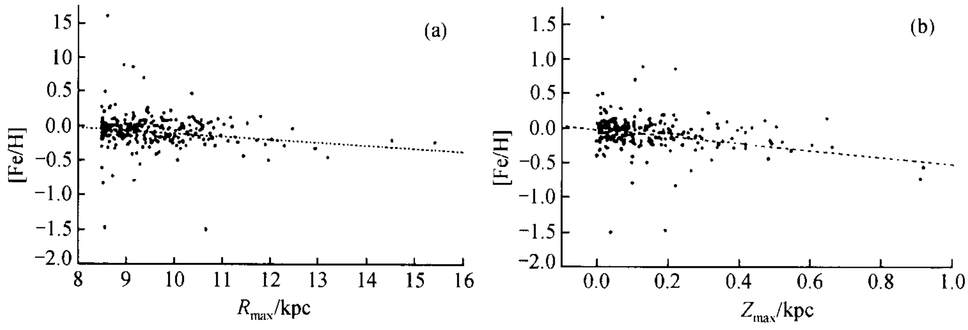

Fig. 3. Fe gradient for disk stars. (a) $R_{\max}$ direction; (b) $Z_{\max}$ direction.

On the other hand, there are 7 B-type stars in the 10 samples with highest [Fe/H]. B-type stars are young stars compared with other spectral types. It suggests that the metallicity increases with the Galaxy evolution.

4 Conclusion

We obtained the orbital parameters of 1 302 stars in the Galaxy. Excluding the samples with $DG_{\min} < 1$ kpc, [Fe/H] of 1 295 stars are statistically analyzed. Our results show the existence of abundances gradients in the Galaxy once again. Gradients to $DG_{\max}$, $R_{\max}$ and $Z_{\max}$ are given as follows:

$$[\mathrm{Fe/H}] = -(0.057 \pm 0.007) DG_{\max} + (0.447 \pm 0.066),$$
$$[\mathrm{Fe/H}] = -(0.057 \pm 0.007) R_{\max} + (0.440 \pm 0.066),$$
$$[\mathrm{Fe/H}] = -(0.411 \pm 0.023) Z_{\max} - (0.037 \pm 0.008).$$

Among these results, gradient to $R_{\max}$ has a middle value compared with the results from other researchers. In addition, we noticed that the vertical gradient is much steeper than the radial gradient.

From the analysis of 1 295 samples, we learned that the existence of the abundances gradient is true and the gradient in vertical direction is steeper than that in radial direction. Variation tendencies among different types of samples exist. Different objects, such as disk and halo stars, young and old stars, have different metallicities.

Galactic chemical evolution models, which show that the halo was formed before the disk at the early stage of the Galaxy, are supported by our results.

It is the beginning of our work to study element abundances gradients using a large number of samples. We are going to analyze the elements which have great importance to the galactic evolution study, such as O, Na, S and Ar, in forthcoming papers. Through these researches we hope that we can have a better understanding about stellar nucleosynthesis and the chemical evolution of the Galaxy.

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References

1. Shaver, P. A., McGee, R. X., Newton, L. M. et al., The galactic abundance gradient, MNRAS, 1983, 204: 53.
2. Amnuel, P. R., The features of chemical abundances in Galactic planetary nebulae, MNRAS, 1993, 261: 263.
3. Maciel, W. J., Köppen, J., Abundance gradents from disk planetary nebulae: O, Ne, S and Ar, A&A, 1994, 282, 436.
4. Maciel, W. J., Abundance gradients from planetary nebulae in the galactic disk, IAU Samp., 1997, 180: 397.
5. Maciel, W. J., Quireza, C., Abundance gradients in the outer galactic disk from planetary nebulae, A&A, 1999, 345: 629.
6. Lennon, D. J., Dufton, P. L., Fitzsimmons, A. et al., Dolidze 25: a metal-deficient galactic open cluster, A&A, 1990, 240: 349.
7. Fitzsimmons, A., Dufton, P. L., Rolleston, W. R. J., A comparison of oxygen and nitrogen abundances in young clusters and associations and in the interstellar gas, MNRAS, 1992, 259: 489.
8. Kilian, J., Montenbruck, O., Nissen, P. E., The galactic distribution of chemical elements as derived from B-stars in open clusters, A&A, 1994, 284: 437.
9. Kaufer, A., Szeifert, T., Krenzin, R. et al., The galactic abundance gradients traced by B-type stars, A&A, 1994, 289: 740.
10. Smartt, S. J., Dufton, P. L., Rolleston, W. R. J., A metal deficient early B-type star near the edge of the galactic disk, A&A, 1996, 305: 164.
11. Smartt, S. J., Dufton, P. L., Rolleston, W. R. J., The chemical composition towards the galactic anti-centre, A&A, 1996, 310: 123.
12. Binette, L., Dopita, M. A., D'Odorico, S. et al., The galactic abundance gradient from supernova remnant observations,

A&A, 1982, 115: 315.

13. Dauphole, B., Geffert, M., Colin, J. et al., The kinematics of globular clusters, apocentric distances and a halo metallicity gradient, A&A, 1996, 313: 119.
14. Marsakov, V. A., Shevelev, Y. G., Catalogue of ages, metallicities, orbital elements and other parameters for nearby F stars, BICDS, 1995, 47: 13.
15. Cayrel de Strobel, G., Soubiran, C., Friel, E. D. et al., A catalogue of [Fe/H] determinations: 1996 edition, A&AS, 1997, 124: 299.
16. Barbier-Brossat, M., Petit, M., Catalogue bibliographique de vitesses radials stellaires, A&AS, 1990, 85: 885.
17. Andersen, J., Nordström, B., Radial velocities of bright southern stars. V. 146 population II F stars and related stars, A&AS, 1985, 62: 355.
18. Nordström, B., Anderson, J., Radal velocities of bright southern stars. IV. 551 A-and F-type HR and FK stars, A&AS, 1985, 61: 53.
19. Perryman, M. A. C., Lindegren, L., Kovalevsky, J. et al., The Hipparcos Catalog, A&A, 1997, 323: L49.
20. Allen, C., Santillán, A., An improved model of the galactic mass distribution for orbit computations, RMAA, 1991, 22: 255.
21. Allen, C., Martos, M. A., A simple realistic model of the galactic mass distribution for orbit computations, RMAA, 1986, 13: 137.
22. Press, W. H., Teukolsky, S. A., Vetterling, W. T., Numrical Recipes in C, The Art of Scientific Computing, 2nd ed., Cambridge: Cambridge University Press, 1993.
23. Johnson, D. R. H., Soderblom, D. R., Calculating galactic space velocities and their uncertainties, with an application to the Ursa Major group, AJ, 1987, 93: 864.