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GALACTIC SUBSYSTEMS ON THE BASIS OF CUMULATIVE DISTRIBUTION OF SPACE VELOCITIES

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SUMMARY: A sample containing 4 614 stars with available space velocities and high-quality kinematical data from the Arihip Catalogue is formed. For the purpose of distinguishing galactic subsystems the cumulative distribution of space velocities is studied. The fractions of the three subsystems are found to be: thin disc 92%, thick disc 6% and halo 2%. These results are verified by analysing the elements of velocity ellipsoids and the shape and size of the galactocentric orbits of the sample stars, i.e. the planar and vertical eccentricities of the orbits.

Key words. Galaxy: kinematics and dynamics – structure – solar neighbourhood

1. INTRODUCTION

Our Galaxy, the Milky Way (MW), is known to have a composite structure; in other words it consists of several components or subsystems (Binney and Merrifield 1998 - Ch. 10). One of those subsystems, the thick disc, was proposed in 1983 as a result of stellar counts (e.g. Binney and Merrifield 1998 - p. 651). However, it may be noticed that as early as in the fourties Kukarkin concluded that an intermediate subsystem (between disc and halo) should exist (e.g. Zonn and Rudnitskij 1959 - p. 231). The mere names of these subsystems reflect their spatial distribution which is a consequence of the kinematics. Since any study limited to the solar neighbourhood, i.e. to a very small volume surrounding the Sun, cannot take into account the spatial distribution, the emphasis is put on the kinematics because the volume of the velocity subspace is large enough.

Udoubtedly, it is important to establish the regions of the velocity subspace corresponding to each subsystem as well as their fractions. The results obtained up to now (e.g. Alcobé and Cubarsí 2004, Dehnen and Binney 1998, Nordström et al. 2004) show that majority of stars from the solar neighbourhood have low moduli of their space velocities and that they belong to the thin disc. The intention of the present authors is to find a new criterion for separation of the subsystems and, consequently, to establish their fractions in the solar neighbourhood.

For this purpose we use the moduli of the heliocentric velocities, usually referred to as space velocities. As the Sun is known to move around the galactic centre along an almost circular orbit (sense of galactic rotation), and also the stars of the galactic disc participate in the rotation of MW and the corresponding velocity dispersion is not large (in case of thin disc even rather small), the probability that a star having a very high space velocity belongs to either thin disc or thick one becomes very low. On the other hand, in the case of the halo even an almost circular orbit with the same sense as that of galactic rotation can be expected, because the halo is characterised by a small (if any) participation in the galactic rotation and a very high velocity dispersion. Therefore, when a star is assigned to the galactic halo, this is most frequently due to the very low probability that it belongs to either of the two discs. This is the case, for instance, with the stars from the solar neighbourhood for which the component of the galactocentric velocity along $l = 90°, b = 0°$ is negative (opposite to galactic rotation). If one assigns only such stars to the halo, this can result in a bias leading to the final conclusion that the halo, nevertheless, rotates, but opposite to the disc. For this reason some authors use additional data, like metallicity (e.g. Nissen and Schuster 1991), because the halo stars are known to be metal-poor. However, the subsystems, as defined above, are due to kinematical differences and the question concerning any correlation with the chemical composition belongs to an after-study. Therefore, to examine kinematical differences by using space velocities may be advantageous since the space velocities reflect differences in the motion from that of the Sun also in the other two components, where of special importance is the vertical velocity component (perpendicular to the galactic plane) because its modulus is not expected to be high for stars of the two discs.

2. DATA SOURCE

As the data source we use astrometrical catalogue Arihip, constructed by Wielen et al. (2001c) - hereafter referred to as the Catalogue - from several catalogues: FK6 (Wielen et al. 1999, 2000), GC+HIP (Wielen et al. 2001a), TYC2+HIP (Wielen et al. 2001b) and original Hipparcos (HIP) Catalogue (ESA 1997).

The use of Arihip has some advantages compared to Hipparcos. Firstly, the proper motions contained in Arihip are more accurate than the original ones from Hipparcos because the ground observations made it possible a majority of the Hipparcos proper motions to be corrected. The errors in proper motions in Hipparcos are on the average 1.3 times higher than those in Arihip. Secondly, in Arihip one can find additional informations on possible duplicity for Hipparcos stars which affects the accuracy of both proper motion and position.

Among all stars given in the Catalogue (total of 90,842) there are 73,023 designated as "astrometrically excellent". In an ideal case all these stars should be single since such stars enable us to reach the highest astrometric accuracy.

However, as said in Introduction, we use the space velocities and for this purpose we also need line-of-sight velocities. This is the main limiting factor in selecting our sample because for only 17.5% of the stars in the Catalogue line-of-sight velocities are available. Among these stars there are those suspected to be multiple or variable. For obvious reasons both kinds are not taken into account. Stars with the lowest rank of (astrometric) excellency are also excluded. Finally, wanting to have parallaxes as reliable as possible we take into account only stars not more distant than 200 pc (parallax ≤ 5 mas). In this way we obtain a sample containing 4614 stars only, mostly stars belonging to the Main Sequence (MS).

Each sample star is characterised with six elements (phase space): two angular coordinates, parallax (distance), components of proper motion and line-of-sight velocity. Using these data one can calculate the phase coordinates (coordinates and corresponding velocity components) in a cartesian reference frame. Clearly, there are two possibilities: to use the equatorial system, or the galactic one. In the latter case, the x axis is positive towards $l = 0, b = 0$, the y one towards $l = 90°, b = 0$ and the z one towards the north galactic pole. The coordinate transformation is carried out by matrix calculation. This procedure also includes the determination of errors. Following the tradition, the velocity components in the galactic frame will be denoted as U, V and W along the axes x, y, z, respectively.

3. ANALYSIS OF SPACE VELOCITIES

The distribution of sample stars in the terms of the space velocity is analysed by dividing the sample into eight intervals. The step is equal to 20 km s^{-1} for stars with space velocity less than 120 km s^{-1}. Since within the interval between 120 km s^{-1} and 140 km s^{-1} there are only 34 stars, the next group includes the space-velocity interval between 120 km s^{-1} and 160 km s^{-1}. The rest of the sample stars (space velocity over 160 km s^{-1}) forms the eighth interval. The corresponding values are presented in Table 1.

Table 1. Grouping of sample stars according to space velocity.

Group	v [km s^{-1}]	Cum. number	n
1	$0 \leq v < 20$	831	831
2	$0 \leq v < 40$	2 504	1 673
3	$0 \leq v < 60$	3 463	959
4	$0 \leq v < 80$	3 935	472
5	$0 \leq v < 100$	4 227	292
6	$0 \leq v < 120$	4 388	161
7	$0 \leq v < 160$	4 485	97
8	$0 \leq v \leq v_{\max}$	4 614	129

The cumulative number (third column) is the total number of stars for which the space velocity is less than the upper limit of the corresponding interval. The fourth column (n) of the table gives the increment of the cumulative number.

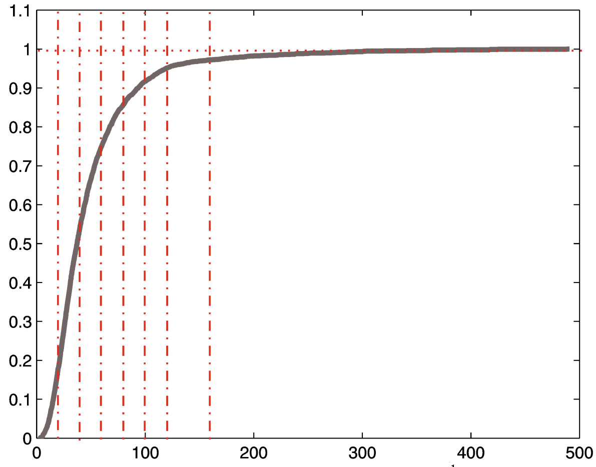

Fig. 1. *Cumulative number (normed to total number of stars) versus heliocentric space velocity.*

The dependence of the cumulative number on the corresponding value of the space velocity is presented in Fig. 1. It is easily seen that up to the space velocity of about 80 - 100 km s^{-1}, the cumulative number increases rather fast. At higher velocities this increase is slowed down to become practically negligible after 180 km s^{-1}. This asymptotic behaviour of the cumulative number will be thoroughly examined.

For this purpose the following steps are undertaken:

- the values of the cumulative number, normed to the total number of stars, for each of 4 614 stars (thus we have 4 614 points) are smoothed out by applying the method of moving average with five points;

- the values smoothed out in this way are approximated using the following function

$$f(x) = a\,\exp(bx) + c\,\exp(dx), \qquad (1)$$

the values of the coefficients are: $a = 1216.0$, $b = -0.000662$, $c = -6498.0$, $d = -0.02864$;

- the gradient of the cumulative number is calculated at each point;

- the coefficient and the curvature radius are calculated at each point.

The gradient of the cumulative number is expressed through the inclination (with respect to the axis of abscissae) of the tangent to the curve representing the dependence of the cumulative number. This inclination, being almost equal to 90° at very low velocities, is decreased by less than 10° up to the value of 100 km s^{-1} where it abruptly changes to become very low at higher velocities. The fraction of stars for which the heliocentric space velocity is less than 100 km s^{-1} is 91.6%. This could be the fraction of stars of the thin disc in our sample.

The lowest value of the curvature radius ($R_{\rm min} = 39.7$), i.e. the highest value of the curvature coefficient, occurs at the space velocity of 181.16 km s^{-1}. At velocity values above this one, the increment of the cumulative number is very low. Such a behaviour is expected for stars of the galactic halo. The present sample contains 103 stars with space velocity exceeding the value of 181.16 km s^{-1}. Their fraction is 2.2%.

If these two fractions are accepted for the thin disc and halo, then the remaining stars should belong to the thick disc. Their fraction is 6.2%.

The next step is to calculate the mean solar motion, velocity dispersions and vertex deviation (velocity ellipsoid) for each group from Table 1. In the groups containing stars with higher heliocentric velocities, those belonging to the thick disc and halo will be more numerous than in the ones with stars of lower velocities. This circumstance will be reflected in the values of the velocity dispersions. This is the reason why the elements of the velocity ellipsoid are calculated. The description of the procedure can be found in Trumpler and Weaver (1962). The errors are calculated by applying the Monte Carlo method.

Table 2. Elements of solar motion for groups 1–8. Velocities $U_\odot$, $V_\odot$, $W_\odot$ and $v_\odot$ are given in [km s^{-1}].

Group	v [km s^{-1}]	$U_\odot$	$V_\odot$	$W_\odot$	$v_\odot$	$L_\odot$ [°]	$B_\odot$ [°]
1	$0 \le v < 20$	$0.55^{+0.05}_{-0.05}$	$1.50^{+0.05}_{-0.05}$	$4.04^{+0.05}_{-0.05}$	$4.34^{+0.05}_{-0.05}$	$69.8^{+1.87}_{-1.82}$	$68.4^{+0.67}_{-0.65}$
2	$0 \le v < 40$	$5.24^{+0.04}_{-0.04}$	$8.72^{+0.04}_{-0.04}$	$5.89^{+0.03}_{-0.03}$	$11.75^{+0.04}_{-0.04}$	$58.98^{+0.22}_{-0.21}$	$30.02^{+0.17}_{-0.16}$
3	$0 \le v < 60$	$7.68^{+0.04}_{-0.04}$	$12.25^{+0.04}_{-0.04}$	$6.29^{+0.03}_{-0.03}$	$15.77^{+0.04}_{-0.04}$	$57.93^{+0.15}_{-0.14}$	$23.50^{+0.12}_{-0.11}$
4	$0 \le v < 80$	$8.62^{+0.04}_{-0.04}$	$14.67^{+0.04}_{-0.04}$	$6.95^{+0.03}_{-0.03}$	$18.38^{+0.04}_{-0.04}$	$59.56^{+0.13}_{-0.13}$	$22.22^{+0.10}_{-0.10}$
5	$0 \le v < 100$	$9.58^{+0.04}_{-0.04}$	$16.49^{+0.04}_{-0.04}$	$7.34^{+0.03}_{-0.03}$	$20.44^{+0.04}_{-0.04}$	$59.84^{+0.13}_{-0.12}$	$21.06^{+0.10}_{-0.10}$
6	$0 \le v < 120$	$10.73^{+0.04}_{-0.04}$	$18.06^{+0.04}_{-0.04}$	$7.48^{+0.03}_{-0.03}$	$22.30^{+0.04}_{-0.04}$	$59.28^{+0.12}_{-0.12}$	$19.61^{+0.08}_{-0.08}$
7	$0 \le v < 160$	$11.49^{+0.04}_{-0.04}$	$19.37^{+0.05}_{-0.05}$	$7.52^{+0.04}_{-0.04}$	$23.75^{+0.05}_{-0.05}$	$59.31^{+0.12}_{-0.12}$	$18.46^{+0.09}_{-0.09}$
8	$0 \le v \le v_{max}$	$11.50^{+0.09}_{-0.09}$	$23.91^{+0.12}_{-0.12}$	$7.54^{+0.07}_{-0.06}$	$27.58^{+0.11}_{-0.11}$	$64.32^{+0.21}_{-0.20}$	$15.86^{+0.15}_{-0.14}$

Table 3. Elements of velocity ellipsoids for groups 1–8.

Group	$v\,[\mathrm{km\,s^{-1}}]$	$\sigma_U\ [\mathrm{km\,s^{-1}}]$	σ_U/σ_V	σ_U/σ_W	l_ν [°]
1	$0 \le v < 20$	$9.52^{+0.06}_{-0.05}$	$1.28^{+0.01}_{-0.01}$	$1.34^{+0.01}_{-0.01}$	$24.7^{+1.1}_{-1.1}$
2	$0 \le v < 40$	$17.14^{+0.05}_{-0.04}$	$1.44^{+0.01}_{-0.01}$	$1.69^{+0.01}_{-0.01}$	$16.7^{+0.3}_{-0.3}$
3	$0 \le v < 60$	$23.00^{+0.05}_{-0.05}$	$1.54^{+0.01}_{-0.01}$	$1.84^{+0.01}_{-0.01}$	$10.0^{+0.3}_{-0.2}$
4	$0 \le v < 80$	$27.48^{+0.06}_{-0.06}$	$1.56^{+0.01}_{-0.01}$	$1.93^{+0.01}_{-0.01}$	$9.1^{+0.2}_{-0.2}$
5	$0 \le v < 100$	$31.05^{+0.06}_{-0.06}$	$1.57^{+0.01}_{-0.01}$	$1.99^{+0.01}_{-0.01}$	$8.2^{+0.2}_{-0.2}$
6	$0 \le v < 120$	$33.64^{+0.07}_{-0.07}$	$1.55^{+0.01}_{-0.01}$	$2.00^{+0.01}_{-0.01}$	$9.3^{+0.2}_{-0.2}$
7	$0 \le v < 160$	$35.86^{+0.08}_{-0.08}$	$1.51^{+0.01}_{-0.01}$	$2.01^{+0.01}_{-0.01}$	$10.5^{+0.2}_{-0.2}$
8	$0 \le v \le v_{max}$	$43.54^{+0.39}_{-0.38}$	$1.14^{+0.02}_{-0.02}$	$2.01^{+0.03}_{-0.03}$	$11.1^{+3.8}_{-3.7}$

The solar motion is presented in Table 2. For each group the components in the galactic cartesian system $(U_\odot, V_\odot, W_\odot)$, as well as the modulus $(v_\odot)$ and the direction (longitude, latitude) are given. Each quantity is given with its error. Table 3 gives the velocity ellipsoid: the velocity dispersion in the U component σ_U, the ratios of the velocity dispersions in the V and W components to that in the U component, σ_U/σ_V and σ_U/σ_W, respectively, as well as the vertex deviation l_ν.

4. ANALYSIS OF ORBITS

The aim of the present paper is to separate stars of different subsystems of MW using as the input data the space velocities in a sample of nearby stars. For this purpose one can use the dependence of the cumulative number on the space velocity (Fig. 1), as well as the values of the kinematical moments obtained for different groups (Tables 2 and 3). We find a good agreement between these two approaches. In the consideration of the cumulative number we obtain that, at the values of space velocities up to 100 km s^{-1}, stars of the thin disc prevail and the values of the ratio of the velocity dispersions σ_U/σ_V appear as typical for samples composed of thin-disc stars, usually about 1.55 (e.g. Dehnen and Binney 1998). This is, obviously, not valid for the first two groups because they are composed of stars kinematically very similar to the Sun and they are biased. As for the halo stars, the value of about 180 km s^{-1}, as their statistical lower limit, cannot be confirmed in the analysis based on the velocity ellipsoid because their fraction is very low so that this effect cannot be noticed in the behaviour of the velocity dispersions.

The question of belonging to any of the three subsystems in our sample is also examined by studying the galactocentric orbits of the sample stars. Such an examination has been used by other authors (e.g. Pauli 2005). For the purpose of calculating the galactocentric orbits for the stars of our sample we use a model of MW proposed earlier by one of us (Ninković 1992). In this model there are three contributors to the galactic potential: bulge, disc and (dark) corona. The potentials of the bulge and disc are described by the Miyamoto–Nagai formula, but with different parameter values (the disc is much more flattened than the bulge) for them the axial symmetry is valid (potential depends on R, the distance to rotation axis, and $|Z|$, distance to galactic plane). The corona potential is spherically symmetric with a cut-off radius equal to 70 kpc. Following the IAU recommendation (Kerr and Lynden-Bell 1986), we assume that the distance of the Sun to the axis of galactic rotation is 8.5 kpc and the corresponding circular velocity is 220 km s^{-1}. In the present paper it is also taken into account that the Sun is not in the galactic plane. A value of +15 pc is assumed for its galactocentric Z coordinate (e.g. Kulikovskij 1985 - p. 13). For the solar motion with respect to the local standard of rest it is assumed $(U, V, W)_{\mathrm{LSR}} = (10.00 \pm 0.36, 5.25 \pm 0.62, 7.17 \pm 0.38)$ km s^{-1}, the values obtained by Dehnen and Binney (1998) by analysing a large sample containing 11 865 stars belonging to the Main Sequence from Hipparcos. With these values, the Cartesian galactocentric spatial coordinates (X, Y, Z) and velocity components $(\dot{X}, \dot{Y}, \dot{Z})$ are calculated for all stars of the sample. The galactocentric spatial coordinates and velocity components are transformed to a cylindrical galactocentric coordinate system, (R, ϑ, Z) and $(\dot{R}, \dot{\vartheta}, \dot{Z})$, respectively. These are the values, including time as the parameter, appearing as the initial conditions for solving the partial differential equations (the Lagrange equations in R and Z with angular–momentum integral included). The initial value for time is shifted from the Catalogue epoch (J2000.0) to zero. The time interval for the integration of an orbit is the same for all orbits - 10 billion years with a step of approximately 3.3 million years, thus we obtain 3 334 points for each star orbit. As the precision control, the energy integral is used.

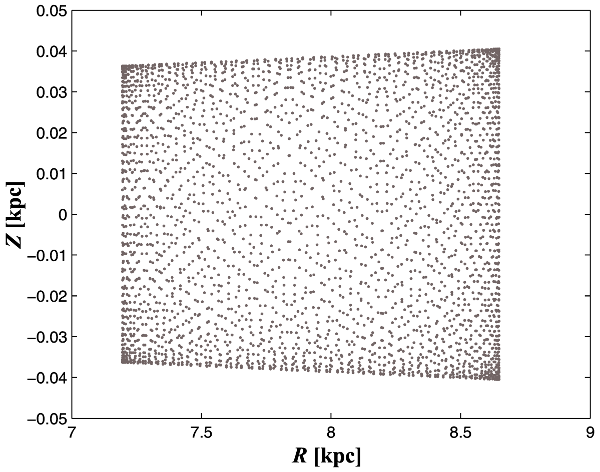

Fig. 2. *Galactocentric orbit of a typical thin-disc star; R is distance to axis of galactic rotation, $|Z|$ is distance to galactic plane.*

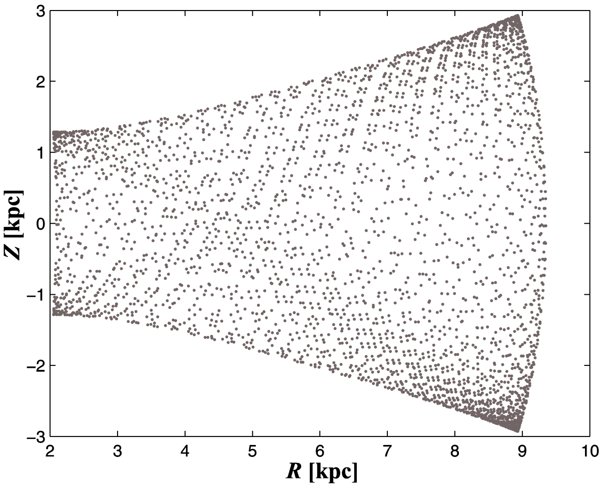

Fig. 3. *Galactocentric orbit of a typical thick-disc star; R is distance to axis of galactic rotation, $|Z|$ is distance to galactic plane.*

The equations are solved numerically by applying the Dormand-Prince (1980) algorithm based on the Runge–Kutta method of the fourth order.

The solutions of the equations are spatial cylindrical coordinates of stars projected onto the meridional plane (R, Z) for the same epoch. In their shapes and sizes they can roughly comprise three cases shown in Figs. 2 – 4. These cases correspond to the thin disc, thick disc and halo, respectively. Though the sample stars are at present rather close to each other, they cannot remain always within a small volume because of the dispersion in the initial conditions.

The orbits of halo stars are not concentrated in the galactic plane. They occupy a large volume of the configuration subspace of the phase space, or they are said to be chaotic (e.g. Pauli 2005), Fig. 4. During the long time interval of the integration they can go very far from the galactic plane so that they can be found at various distances both from the galactic centre and galactic plane.

The orbits of stars belonging to the thin and the thick discs (examples presented in Figs. 2 and 3 respectively) are similar in their shapes (not in sizes). They have well defined minimum and maximum distances from the axis of the galactic rotation ($R_{\rm p}$ and $R_{\rm a}$, respectively) and also the corresponding distances from the galactic plane ($|Z_{\rm p}|$ at $R_{\rm p}$ and $|Z_{\rm a}|$ at $R_{\rm a}$), unlike the case of the halo. Therefore, it is suitable to define the following dimensionless quantities:

$$e_{\rm p} = \frac{R_{\rm a} - R_{\rm p}}{R_{\rm a} + R_{\rm p}}, \qquad e_{\rm v} = \frac{\frac{1}{2}\left(|Z_{\rm a}| + |Z_{\rm p}|\right)}{R_{\rm m}}, \qquad (2)$$

where $R_{\rm m} = \frac{R_{\rm a}+R_{\rm p}}{2}$ is the mean distance from the axis of galactic rotation, whereas $e_{\rm p}$ and $e_{\rm v}$ are the planar and the vertical eccentricities.

For the stars belonging to the thin disc (Fig. 2), by analysing the shapes and sizes of their galactocentric orbits we establish the following upper limits for the planar and vertical eccentricities: $(e_{\rm p} < 0,5)$ and $(e_{\rm v} < 0,08)$. Within these eccentricity limits the shape and size of the projection of a galactocentric orbit onto the meridional plane correspond to a small trapezium with well defined sides. These stars have nearly circular orbits and, therefore, they cannot go far from the initial galactocentric position in either R or $|Z|$. We find 4 258 sample stars (92.3%) corresponding to these eccentricity limits.

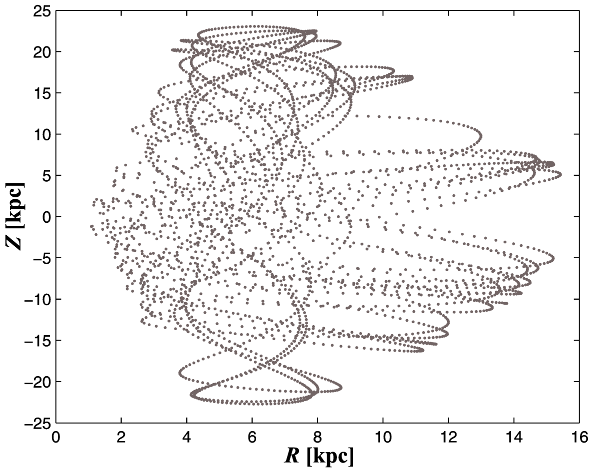

Fig. 4. *Galactocentric orbit of a typical halo star; R is distance to axis of galactic rotation, $|Z|$ is distance to galactic plane.*

A similar analysis is carried out for stars of the thick disc (Fig. 3). The eccentricity limits established by us are $(0,5 < e_{\rm p} < 0,8) \wedge (0,08 < e_{\rm v} < 0,3)$. The projections of their orbits onto the meridional plane have still the trapezium shape, but partly curvilinear in the sides parallel to the galactic rotation axis, whereas the other two sides remain almost straight. These stars remain close to the galactic plane in their motion, but the planar eccentricity can be very high. Therefore, they can reach a distance to the galactic rotation axis very different from the present one. We find 270 sample stars (5.9%) corresponding to these eccentricity limits.

The remaining 86 stars (1.9%) have orbits of the shape as presented in (Fig. 4) and they belong to the halo.

These fraction values obtained through the orbit calculation agree very well with those obtained by using the cumulative number. Thus, the results obtained by the method of the cumulative number are confirmed.

5. CONCLUSION

A sample of 4614 stars from the Arihip Catalogue with high-quality kinematical data is formed and analysed.

(i) It is established that up to a heliocentric space velocity of about $100\,\mathrm{km\,s^{-1}}$ the sample is dominated by stars of the thin disc, between approximately 100 and $180\,\mathrm{km\,s^{-1}}$ stars of the thick disc dominate and stars of the halo for heliocentric space velocity above $\approx 180\,\mathrm{km\,s^{-1}}$.

This result is obtained by analysing the cumulative distribution of space velocities and verified by analysing the velocity ellipsoids and galactocentric orbits of the sample stars. Based on this, the method using the cumulative distribution might be applied in the separating of the galactic subsystems. However, any method based on kinematics only is insufficient for the difficult task of separating subsystems since the physical properties of stars should be taken into account.

(ii) The fractions of the thin disc, thick disc and halo found here are 92%, 6% and 2%, respectively.

These values seem reasonable, but the fraction of the halo might be too high. The number of halo stars in the solar neighbourhood is generally very small so the true halo fraction is still very uncertain. This may be an object of future studies.

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ГАЛАКТИЧКИ ПОДСИСТЕМИ НА ОСНОВУ КУМУЛАТИВНЕ РАСПОДЕЛЕ ПРОСТОРНЕ БРЗИНЕ

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Оригинални научни рад

Из каталога ARIHIP формиран је узорак од 4614 звезда са расположивим просторним брзинама и квалитетним кинематичким подацима. У сврху раздвајања подсистема Галаксије анализирана је кумулативна расподела просторне брзине. Добијено је да танком диску припада 92% од укупног броја звезда, дебелом диску 6% и халоу 2%. Ови резултати су потврђени анализом елемената елипсоида просторних брзина звезда и анализом облика и величине галактоцентричних орбита, тј. планарног и вертикалног ексцентрицитета орбита.