Refined proper motions of some high-velocity stars

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Abstract

We improve the Gaia DR2 proper motions of nine high-velocity stars with the highest proper-motion errors. We reduce the transversal-velocity errors for our stars from to 1.5–746 km/s. We combine our refined proper motions with published radial-velocity and distance data to compute the orbits of these stars in terms of the axisymmetric potential model. Most of the stars considered move in rosette-shaped orbits. J154556.10+243708.9 to move in a highly-elongated loop-shaped orbit, and HVS22 star escapes from the Galaxy.

Key words: hypervelocity stars.

1 Introduction

The first hypervelocity star was discovered by Warren Brown in 2005 by analyzing the results of a spectroscopic survey performed with the MMT telescope. Brown et al. (2005) found a $3M_\odot$-mass main-sequence B-type

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star moving at a Galactocentric velocity of 700 km/s, which is equal to twice the escape velocity at a Galactocentric distance of 100 kpc. The existence of such stars was predicted by Jack Hills (Hills, 1988). The discovery of the first hypervelocity star triggered a great interest in the Hills concept, which had been lying idle for about two decades. When asked about the discovery, Hills responded that it was high time someone found it (Perlman, 2005). There are a lot of mechanisms for accelerating stars to high velocities, e.g., those suggested by Tutukov & Fedorova (2009), however, the Hills mechanism is unique in its capability to accelerate large numbers of main-sequence stars. Hence main-sequence stars are among the hypervelocity star candidates. They can be accelerated and ejected from any galaxy hosting a supermassive black hole at its center. There are several definitions of hypervelocity stars (Brown, 2015). According to Browns definition, main-sequence stars originating from the Galactic center are referred to as hypervelocity stars, and those that escape from the Galactic disk are referred to as hyper-runaway stars.

The Milky Way hosts more than 2×10^{11} gravitationally bound stars and a certain number of gravitationally unbound stars with positive energy in the Galactic gravitational field. These stars emerge from the Galactic center, move into the dark halo along straight-line trajectories, and escape from the Galaxy. Hereafter we denote then as HVS. To kinematically test the hypothesis that they originate in the Galactic center we have to determine their current space velocities. Unfortunately, the angular displacements of these stars in the sky are negligible and determining space trajectories of HVSs with the most advanced ground-based telescopes would require several decades. However, the publication of the second release of the Gaia catalog (Gaia Collaboration et al. 2018) provided proper-motion measurements of unprecedented accuracy to complement the radial velocities measured with the 6.5- and 8.1-m telescopes. The Gaia satellite produced the most complete and accurate catalog of Milky-Way stars with astrometric parameters for more than 1 billion objects. However, the mass and distance range spanned by the Gaia sample differ from those of non-Gaia stars - represented by (2.5-4)$M_\odot$-mass stars in the dark halo (Irrgang et al., 2018). An analysis of combined data will help determine the origin of HVSs, confirm or disprove their hypervelocity status, and make it possible to refine the Galactic potential model (Gnedin et al., 2005; Kenyon, 2008; Kenyon, 2014; Contigiani et al., 2018).

Table 1: Comparison of HVS properties.

Mass of HVSs:	2.5–3.0$M_\odot$
Spectral type:	B9
Travel time:	t_{trvl} ~60–200 Myr
Probability of HVS formation:	(2–8)$\times 10^{--5}$ yr^{--1}
Mass of S-stars:	M $\geq$ 5 M$\odot$
Main-sequence lifetime of S-stars:	$t_{MS} \sim$ 100 Myr
Probability of S-stars formation:	(1–4)$\times 10^{--5}$ yr^{--1}
Runaway stars (RAS):	50–100 km/s
Hyper-runaway stars (HRS):	100–400 km/s
Hypervelocity stars (HVSs):	400–1200 km/s
Relativistic-velocity stars (RVS):	$>$ 30000 km/s

2 Refining the proper motions

For most of the known high-velocity stars Gaia DR2 (Gaia Collaboration 2018) provides proper motions of unprecended accuracy, which can hardly be improved by any significant amount. However, the proper-motion errors increase rapidly at the faint end of the Gaia DR2 magnitude distribution ($G_{mag} \geq 19.0^m$), reaching 1 mas/yr or more for the faintest stars. The Gaia DR2 proper motions of these stars can potentially be improved by taking into account positional data from other surveys with sufficient positional accuracy and appreciable epoch difference from 2015.5. An analysis of the currently publicly available large-scale sky catalogs showed that the most promising survey candidates are SDSS (Paris et al. 2018) (observing epochs about 2001, implying an epoch difference with Gaia DR2 of $\sim$ 15 years), PanStarrs (Chambers wt al. 2016) (observing epochs about 2011, implying an epoch difference with Gaia DR2 of $\sim$ 4 years), and UKIDSS (Lawrence et al. 2007) (observing epochs about 2008, implying an epoch difference with Gaia DR2 of $\sim$ 7 years). Here we try to refine the Gaia DR2 proper motions for nine hypervelocity stars from the Open Fast Star Catalog (Boubert et al. 2018) with the Gaia DR2 total proper-motion errors $(\sigma(\mu_\alpha)^2 + \sigma(\mu_\delta)^2)^{1/2} \geq 1.5$ mas/yr. We start by cross-matching stars in Gaia DR2, SDSS, PanStarrs, and UKIDSS surveys within 5 arcmin from the target star with a cross-match radius of 2 arcsec. We then use Gaia DR2 as the reference catalog to define the frame to which we reduce the star positions from the other three catalogs via standard linear (6-constant) procedure (we ignore higher-order terms be-

Table 2: Parameters of HVSs.

Name	RA	DEC	V_r km/s	Distance, kpc	PM_{RA} mas/yr	PM_{DEC} mas/yr	V_r/dist references*
HVS22	175.443518	4.704796	597.8	84.36	2.440 ± 1.356	0.911 ± 1.283	1/4
LMST-HVS26	103.649037	17.054187	307.0	0.2	6.141 ± 0.861	-13.616 ± 1.272	2/2
SDSSJ074256.45+275946.9	115.735261	27.996373	28.6	11.44	0.569 ± 1.140	0.075 ± 0.809	3/5
SDSSJ085508.03+031505.4	133.783462	3.251498	54.7	13.56	-0.116 ± 1.206	-0.895 ± 0.697	3/5
J154556.10+243708.9	236.483739	24.619116	193.0	85.05	0.153 ± 0.964	-0.328 ± 1.087	1/9
SDSSJ053553.15+004051.6	83.971484	0.680988	-5.9	2.41	0.826 ± 1.003	0.494 ± 1.176	3/5
SDSSJ072331.00+374628.2	110.879210	37.774511	-26.1	10.94	0.554 ± 0.969	1.167 ± 0.624	3/5
SDSSJ023849.85+281023.6	39.707734	28.173200	-71.6	8.98	-1.032 ± 0.536	0.860 ± 1.064	3/5
SDSSJ092613.29+201253.0	141.555401	20.214739	76.8	5.31	-0.027 ± 0.493	-0.264 ± 0.863	3/5

* V_r and distance references: 1. Smith et al. (2010); 2. Zhong et al. (2014); 3. Boubert et al. (2018) 4. Brown et al. (2014); 5. Alam et al. (2015); 6. Brown et al. (2009)

cause of the small size of the 5-arcmin-radius area) along the lines described in Klinichev et al. (2018). We then infer the proper-motion components via least squares method and, finally, compute the weighted average of the proper-motion value so inferred and the Gaia DR2 proper motion and adopt this estimate as our refined proper motion.

The results are listed in Table2. Its columns give: column (1), the name of the star; columns 2 and 3, the Gaia DR2 equatorial coordinates (epoch 2015.5); column 4, the radial velocity in km/s; column 5, the heliocentric distance in kpc; columns 6 and 7, the refined PM_{RA} and PM_{DEC} proper-motion components in mas/yr, and column 8, the radial-velocity/distance references. Figs. 1 and 2 illustrate this procedure in the case of the star SDSSJ085508.03+031505.4. Figs. 1 and 2 show the quantities $\Delta\alpha \times cos\delta = (\alpha - \alpha_{Gaia}) \times cos\delta$ and $\Delta\delta = (\delta - \delta_{Gaia})$ (both in arcsec) plotted as a function of time. The slopes of the corresponding linear least-squares fits (the dashed lines) give the estimates μ_α and μ_δ of the components of the proper motion of the star. The final estimates $\mu_\alpha(Final)$ and $\mu_\delta(Final)$ listed in Table 2 are computed as the weighed averages of these μ_α and μ_δ values and the corresponding values provided in Gaia DR2, $\mu_\alpha(GaiaDR2)$ and $\mu_\delta(GaiaDR2)$.

3 Orbits

3.1 Galactic potential model

We use an axisymmetric model gravitational potential of the Galaxy represented by three components: the Miyamoto and Nagai (1975) disk , Hernquist spheroid (Hernquist 1990), and modified isothermal dark-matter halo.

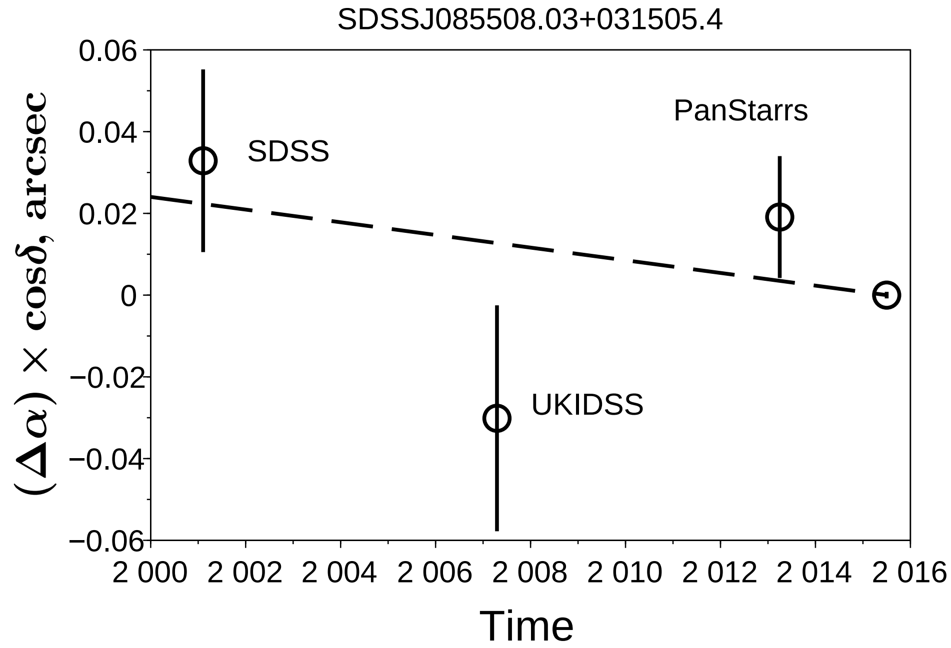

Figure 1: The offset of the SDSS, UKIDSS, and PanStarrs catalog positions of the star SDSSJ085508.03+031505.4 along the right ascension direction reduced to Gaia DR2 frame with respect to its Gaia DR2 2015.0 position, $\Delta\alpha \times cos\delta = (\alpha - \alpha_{GaiaDR2}) \times cos\delta$, plotted as a function of time. The dashed line shows the least-squares fit used to estimate the proper motion component μ_α. The final estimate $\mu_\alpha(Final)$ is computed as the weighed average of this μ_α value and the value provided in Gaia DR2

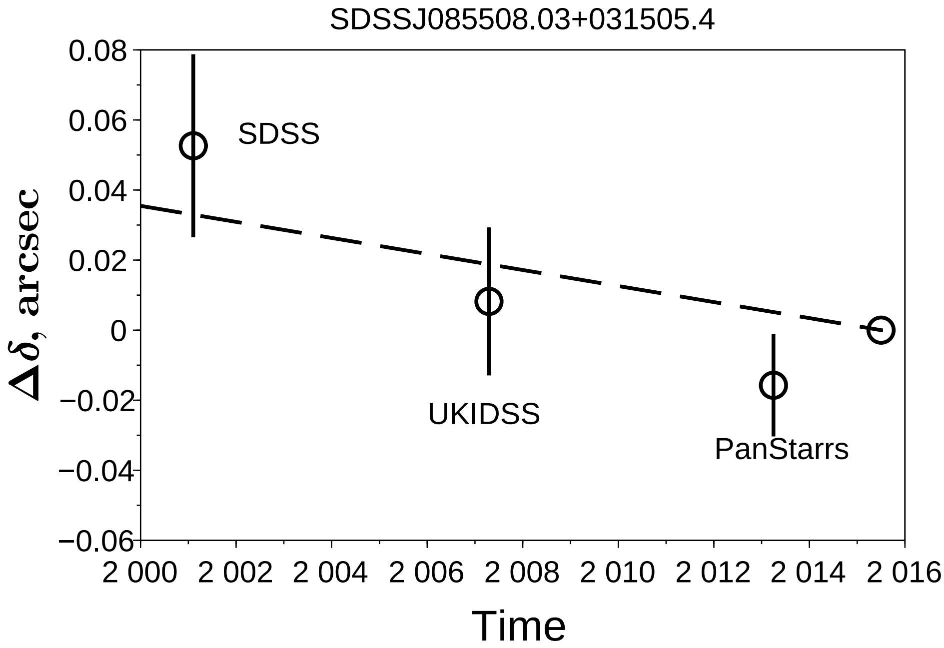

Figure 2: The offset of the SDSS, UKIDSS, and PanStarrs catalog positions of the star SDSSJ085508.03+031505.4 along the declination direction reduced to Gaia DR2 frame with respect to its Gaia DR2 2015.0 position, $\Delta\delta = (\delta - \delta_{GaiaDR2})$, plotted as a function of time. The dashed line shows the least-squares fit used to estimate the proper motion component μ_δ. The final estimate $\mu_\delta(Final)$ is computed as the weighed average of this μ_δ value and the value provided in Gaia DR2

The formulas for the potentials of these three components have the following form:

$$\phi_{disk} = -\frac{GM_{disk}}{\sqrt{R^2 + \left(a + \sqrt{z^2 + b^2}\right)^2}} \tag{1}$$

$$\phi_{spher} = -\frac{GM_{spher}}{\sqrt{R^2 + z^2} + c} \tag{2}$$

$$\phi_{halo} = V_{halo}^2 \ln\left(R^2 + z^2 + d^2\right) \tag{3}$$

Fig. 3 shows the Galactic rotation curve corresponding to this potential.

3.2 HVS orbits

We integrated the orbits of nine HVS objects from Table 2 for 5 Gyr forward. We show the computed orbits in Figs. 4 and 5 (the Galactic-plane projection and meridional section of the orbit of SDSSJ085508.03+031505.4, respectively) and Figs. 6 and 7 (the Galactic-plane projection and meridional section of the orbit of J154556.10+243708.9, respectively). Most of the stars move in rossette-shaped orbits (see Fig. 4 as an example) with the important exceptions of J154556.10+243708.9, which moves in a highly elongated loop-like orbit reaching a maximum Galacticentric distance of 543 kpc (see Fig. 6), and HVS22, which appears to be escaping the Galaxy at a high velocity of 910 km/s.

4 Conclusions

We refined the Gaia DR2 proper motions of nine high-velocity stars with Gaia DR2 total proper-motion errors $\sigma\mu \geq 1.5$ mas/yr and computed the Galactic orbits of these objects. The total errors of our refined proper motions range from 1 to 1.9 mas/yr compared to 1.4 to 2.5 mas/yr for the initial Gaia DR2 proper motions. Our proper-motion errors translate into transversal velocity errors ranging from 1.4 to 760 km/s compared to 2.0 to 992 km/s for the original Gaia DR2 proper motions. We computed the orbits of the stars considered in terms of the adopted axisymmetric potential model and found

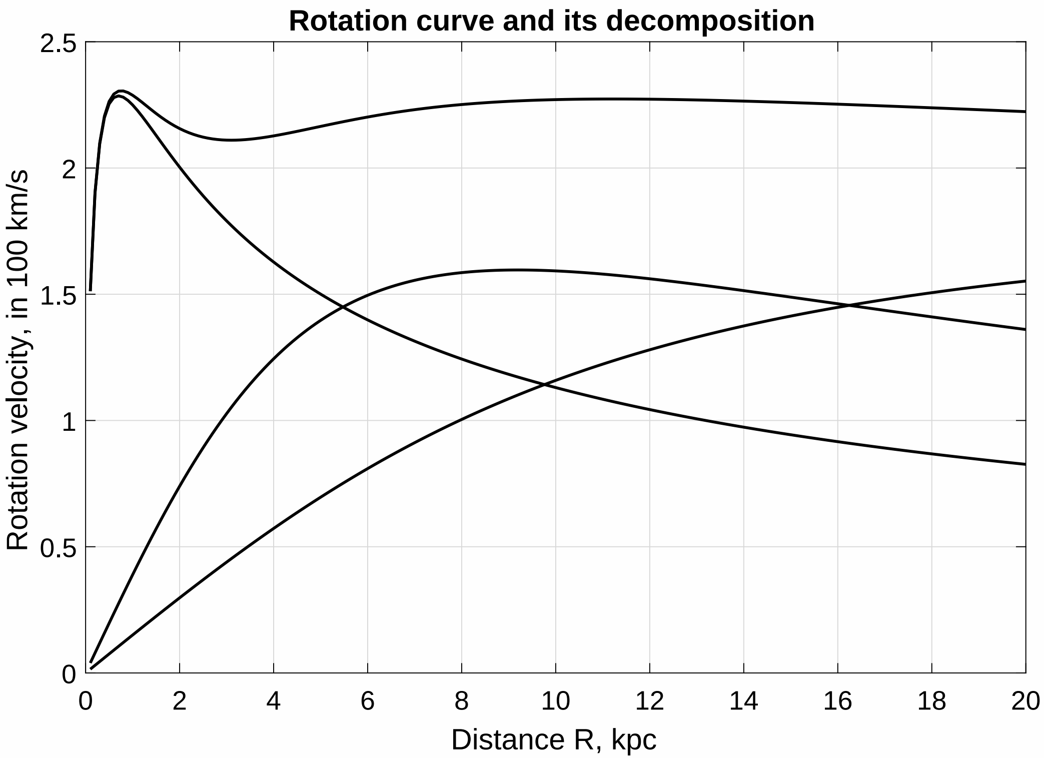

Figure 3: Decomposition of the rotation curve based on the adopted Galactic gravitational potential (see text)

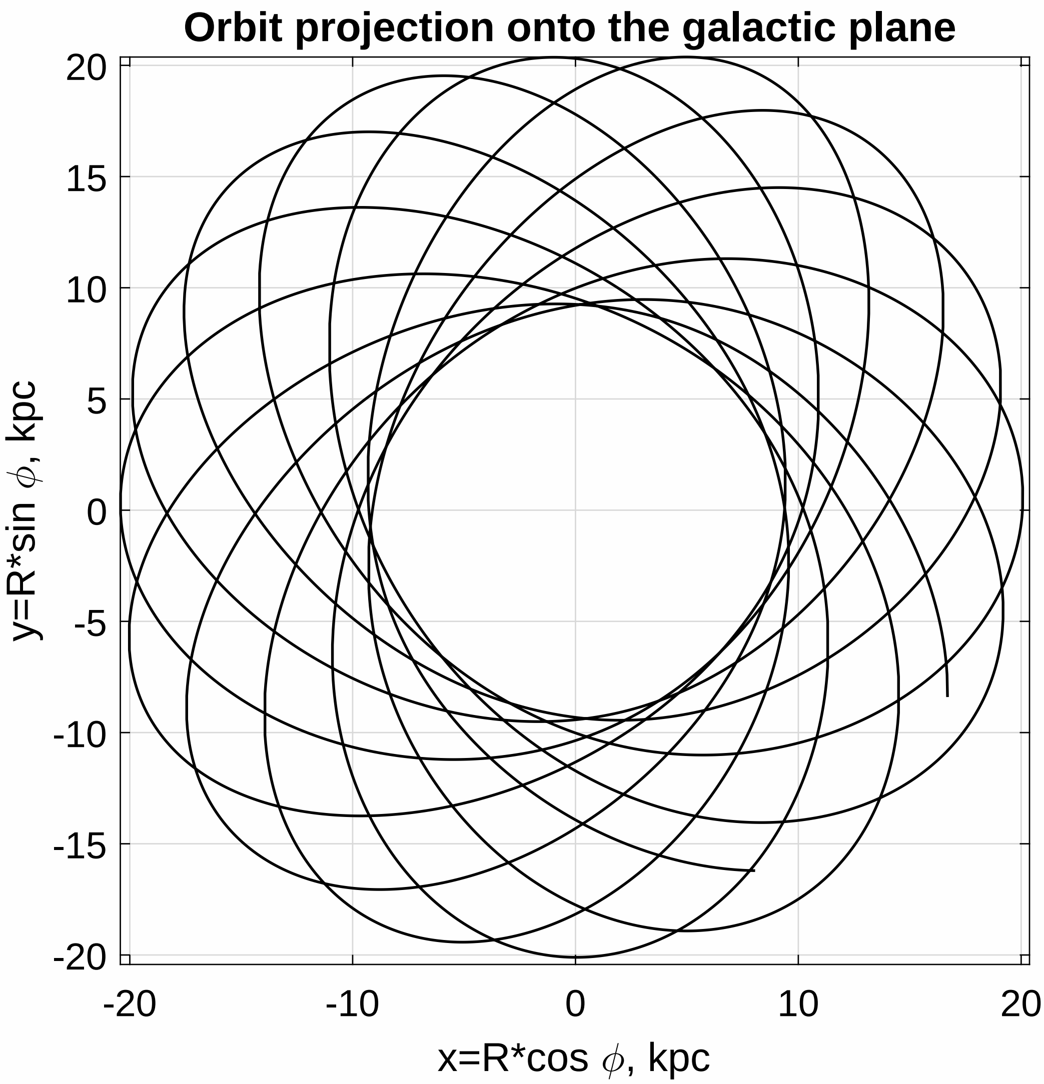

Figure 4: Galactic-plane projection of the rosette-shaped orbit of the star SDSSJ085508.03+031505.4

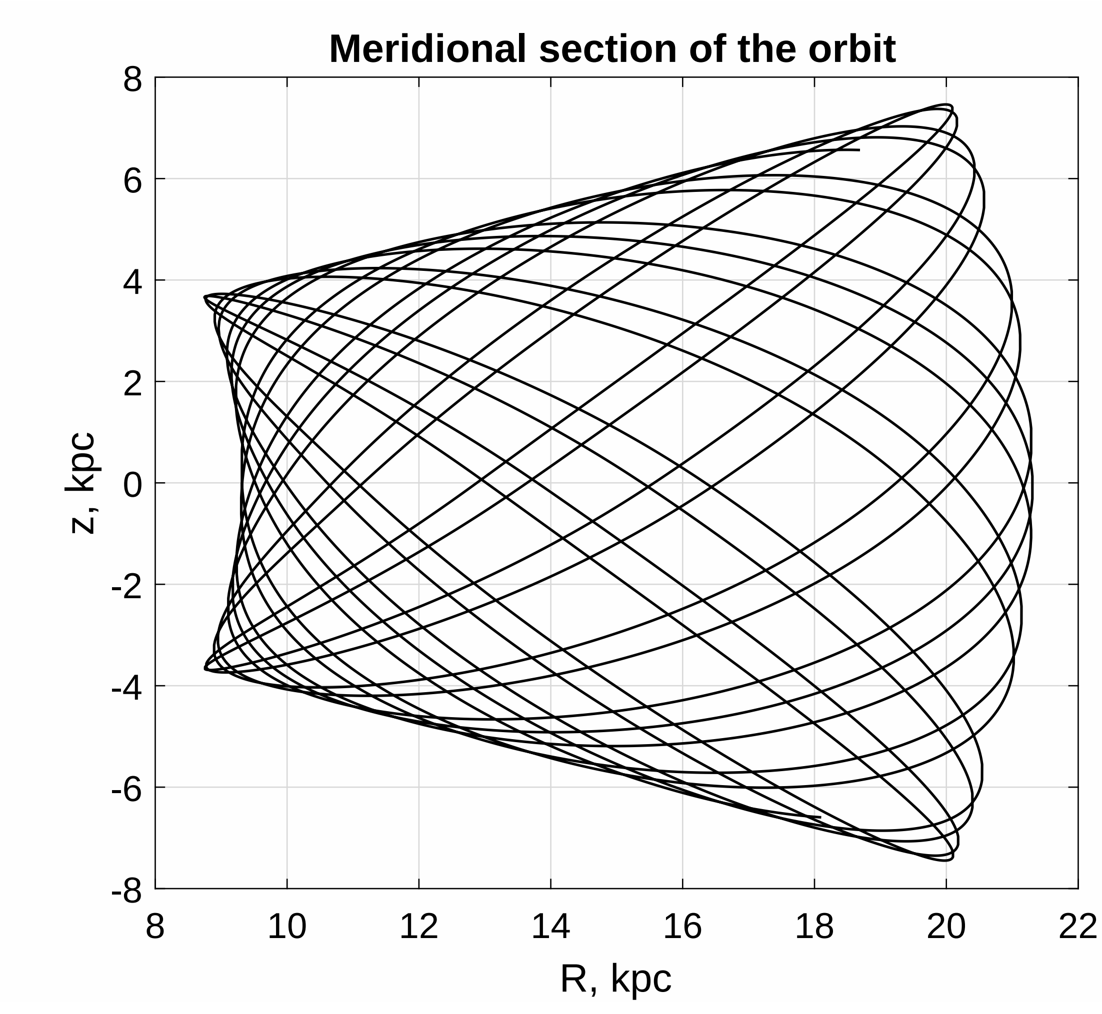

Figure 5: Meridional section of the orbit of the star SDSSJ085508.03+031505.4

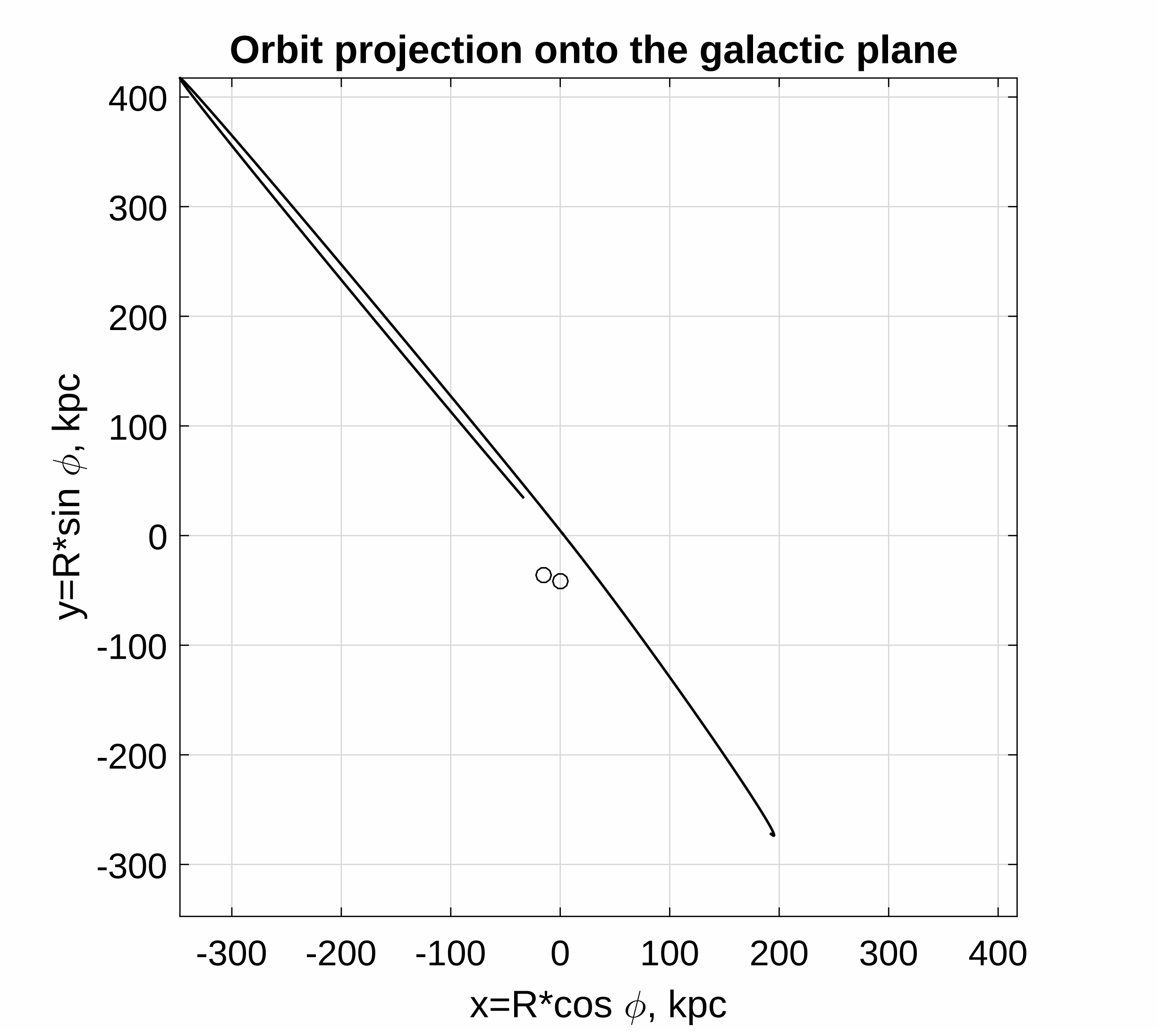

Figure 6: Galactic-plane projection of the rosette-shaped orbit of the star SDSSJ085508.03+031505.4

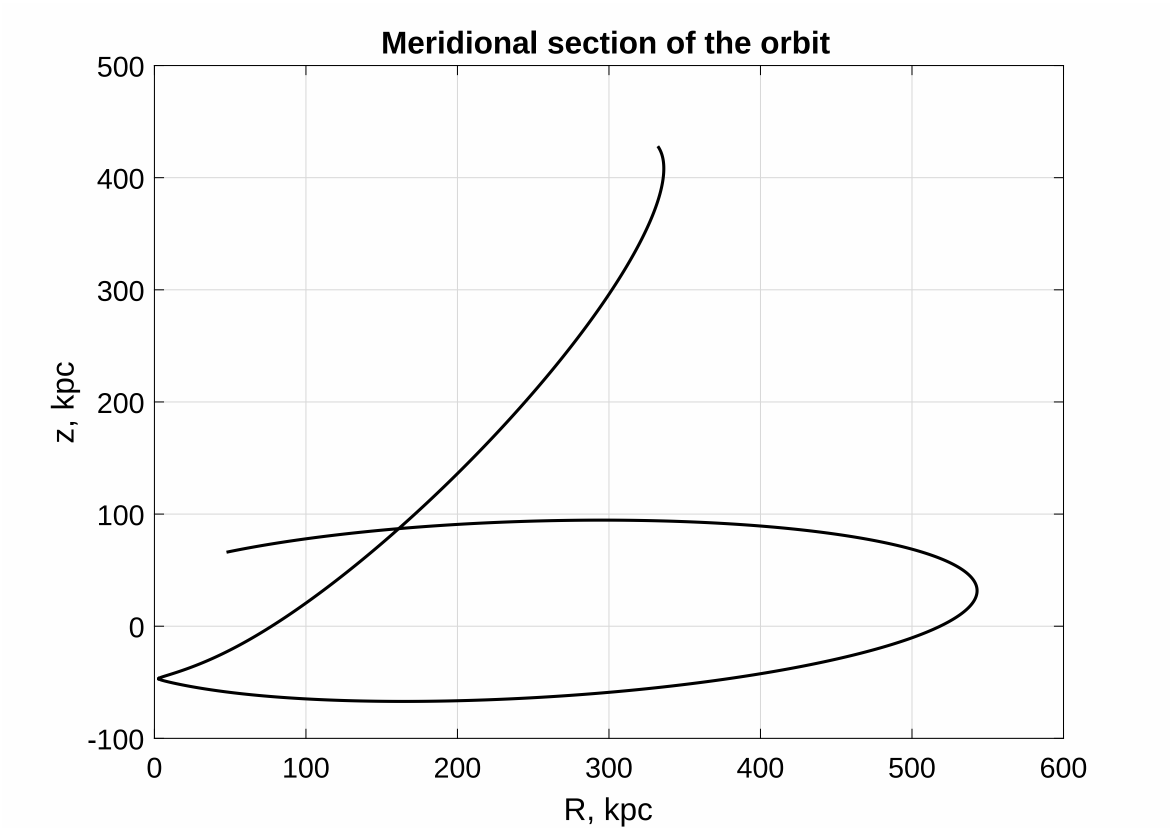

Figure 7: Meridional section of the orbit of the star SDSSJ085508.03+031505.4

most of the stars moving in rosette-shaped orbits, J154556.10+243708.9 to move in a highly-elongated loop-shaped orbit, and HVS22 star to be escaping from the Galaxy.

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