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Hypervelocity and S-type stars as possible paired components of the parent binary star in the past

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Abstract. It is proposed to consider the problem of the evolutionary connectivity of central near-nuclear S-stars and Hypervelocity Stars (HVS) which might have belonged to a common parent binary star in the past, torn apart by the tidal field of a Super Massive Black Hole (SMBH). Observational data from two independent catalogs made by Gillessen et al., 2017 and by Brown et al., 2018 are used for quantitative estimates. The justification of duality of the stars in the past is based on the analysis of reconstructed trajectories of ejection of HVSs with the use of time-inverse integration method in the Galactic potential and checking the distance from the SMBH at the moment of ejection to argue the scenario by Hills. The dynamic stability of S-stars is also investigated due to the possibility of identifying the pairing of HVS and S-stars in the past. The chaotization timescale of stars in the S-cloud is evaluated to understand the limits of applicability of the criterion of the coplanarity of S-star and HVS orbits.

Keywords: hypervelocity stars; central S-stars; super massive black hole

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1 Introduction

The components of binaries and multiple stars may experience breaks of gravitational bonds during their evolution. Among the various scenarios leading up to the break, the scenario by Hills (1988), considering the tidal destruction of a binary in the SMBH gravitational field, deserves attention. Its gravitational potential, millions of times greater than the stellar one, imprints “traces” in the kinematics of both components: abnormally high spatial velocities. One of the components gets released and becomes a HVS, and the other one, captured in an orbit around the SMBH, meets rapid orbital rotation, typical for S-stars. High velocities are quite acceptable as a result of the redistribution of angular momentum in the classical problem of three bodies.

In 1988, Hills was looking for indirect evidence in favor of the existence of SMBH, for example, the phenomenon of hypervelocity stars accidentally discovered in the early XXI century by Brown et al. (2005). This fascinating SMBH search story culminated in the 2020 when Andrea Ghez and Reinhard Genzel won the Nobel Prize for a long-term monitoring of S-stars (Eckart & Genzel, 1996; Schödel et al. 2003) and non-trivial analysis of their motion, indicating the presence of a SMBH.

Today S-stars and HVS are no longer hypothetical objects. They are systematized in the catalogs by Gillessen et al. (2017) and Brown et al. (2018), respectively. But the argumentation of their possible duality in the past has yet to be found.

In Dryomova et al. (2023) the cross-analysis of observational data from Gillessen et al. (2017); Brown et al. (2018) was used for reconstruction of populations of S-stars and HVS within the framework of the classical scenario by Hills (1988). From the balance of kinetic energy of an ejected component and gravitational binding energy of its companion remaining in SMBH field, the ejection velocity of a potential companion of a really observable S-star (Gillessen et al. 2017) was estimated. On the other hand, the large semi-axis of the orbit of the hypothetically captured companion of the actually observed HVS (Brown et al. 2018) was evaluated. Their model-reconstructed distributions obtained in Dryomova et al. (2023) are in good agreement with the observed ones and somehow confirm the plausibility of their origin from a once common binary star. This was encouraging and prompted us to research further.

2 Reconstruction of the ejection trajectory of the HVS

One of the indirect evidence of the origin of HVS and S-stars from a common parent binary could be the fact of the HVS “central ejection” This can be determined by the value of the pericenter from calculation of HVS trajectory “returned” to the SMBH. So we need to integrate backwards in time the HVS ejection based on its current position and spatial velocity, as well as the Galaxy potential, the precise determination of which is a great challenge itself.

In the HVS catalog by Brown et al. (2018) for each star, the galactocentric distance r_{rf} and its right ascension α and declination δ are known. At first, (α, δ) were converted to spherical galactic (b, l) ones centered at the Sun's position:

$$\begin{aligned} b &= \arcsin(\sin\delta\cdot\sin\delta_{\mathrm{NP}}+\cos\delta\cdot\cos\delta_{\mathrm{NP}}\cdot\cos(\alpha-\alpha_{\mathrm{NP}})); \\ l &= l_{\mathrm{Neq}}-\mathit{\Delta} l; \\ \sin\mathit{\Delta} l &= \cos\delta\cdot\sin(\alpha-\alpha_{\mathrm{NP}})/\cos b; \\ \cos\mathit{\Delta} l &= (\cos\delta_{\mathrm{NP}}\cdot\sin\delta-\sin\delta_{\mathrm{NP}}\cdot\cos\delta\cdot\cos(\alpha-\alpha_{\mathrm{NP}}))/\cos b, \end{aligned} \tag{1}$$

and then converted to Cartesian galactocentric coordinates. The equatorial coordinates of the galactic pole (NP) for the epoch J2000, $\alpha_{\mathrm{NP}} = 192^{\circ}.767$ and $\delta_{\mathrm{NP}} = 27^{\circ}.13$, as well as the longitude of the northern equatorial pole $l_{\mathrm{Neq}} = 122^{\circ}.933$, are used here. R denotes the heliocentric distance of HVS in kpc, and R_0— distance from the galactic center to the Sun ∼8.32 kpc according to Gillessen et al. (2017).

Similarly, decomposition of the vector of the total spatial velocity of HVS into Cartesian components in the galactocentric coordinate system was performed, taking into account the movement of the Sun according to Schönrich et al. (2010). The components of the Sun's velocity ($U = +11.1$ km/s; $V = +245$ km/s; $W = +7.25$ km/s) correspond to the following orientation of the axes: **X** is directed from SMBH in the direction opposite to the direction of the Sun, **Y** increases along the way of the rotation of the disk of the Galaxy, **Z** is directed to the NP of the Galaxy. To calculate the total spatial velocity of HVS one needs information about the radial velocity V_{r} and proper motion components, μ_α and μ_δ, from Brown et al. (2018).

Integration was carried out using four-component Galactic potential from Kenyon et al. (2008), including the central field of point mass SMBH, a spherically symmetric bulge in the model by Hernquist (1990), an axisymmetric disk by Miyamoto & Nagai (1975), and dark matter halo in the model by Navarro et al. (1997):

$$\mathit{\Phi}_{\mathrm{Galaxy}}(r) = -\frac{G\cdot M_{\mathrm{SMBH}}}{r}-\frac{G\cdot M_{\mathrm{bulge}}}{r+a}-\frac{G\cdot M_{\mathrm{disk}}}{r_{\mathrm{d}}-\frac{G\cdot M_{\mathrm{galo}}}{r}\cdot\ln\left(1+\frac{r}{r_{\mathrm{s}}}\right)} \tag{2}$$

Here a— bulge radius, $r_{\mathrm{d}=\sqrt{\mathrm{R}_{\mathrm{xy}}^2+(\mathrm{b}+\sqrt{\mathrm{c}^2+\mathrm{z}^2})^2}}$, R and z — radius and thickness of the disk, b and c — the characteristic scales of the disc length and thickness, respectively, r_{s} — normalizing multiplier of the order of the characteristic scale of the halo. A set of parameters from Fragione et al. (2017) was used in the calculations: $a = 0.1$ kpc, $b = 2.75$ kpc, $c = 0.3$ kpc, $M_{\mathrm{SMBH}} = 4.28\cdot 10^6\ M_\odot$, $M_{\mathrm{bulge}} = 3.76\cdot 10^9\ M_\odot$,

$M_{\text{disk}} = 5.36 \cdot 10^{10}\ M_{\odot}$, $r_{\text{s=}}$ 20 kpc, $M_{\text{halo}} = 10^{12}\ M_{\odot}$. For integration we used the velocity formulation of the numerical algorithm by Verlet & Weis (1972), which is an explicit numerical scheme of the second order of accuracy with the conservation of all motion integrals (Tutukov et al. 2007). The integration step is calculated as a millionth of the ratio of the spatial velocity HVS to the instant acceleration in the Galactic potential.

Analysis of the "returned" trajectories reconstructed for 21 Galaxy-unbound HVSs from the catalog by Brown et al. (2018) showed that the ejected HVS-tracks are rather far away from the SMBH, as can be seen from their pericentric distances r_{app} in Fig. 1. Several stars appear to be in relative proximity to the SMBH: the Koposov's star HVS-S5 ($r_{\text{app}} = 1.66$ kpc), HVS15 ($r_{\text{app}} = 1.4$ kpc); HVS54 ($r_{\text{app}} = 5.7$ kpc), HVS6 ($r_{\text{app}} = 5.5$ kpc), and HVS3 ($r_{\text{app}} = 8.9$ kpc). It should be mentioned that there is a problem of large uncertainties Δ_{μ_α} and Δ_{μ_δ} in the measurement of proper motion, often comparable to or even greater than the obtained values. For this reason four additional calculations of the returned trajectories were performed for each of the 21 HVSs $(\mu_\alpha^+, \mu_\delta)$; $(\mu_\alpha^-, \mu_\delta)$; $(\mu_\alpha, \mu_\delta^+)$; $(\mu_\alpha, \mu_\delta^-)$, where $\mu_\alpha^+ = \mu_\alpha + \Delta_{\mu_\alpha}$, $\mu_\alpha^- = \mu_\alpha - \Delta_{\mu_\alpha}$, $\mu_\delta^+ = \mu_\delta + \Delta_{\mu_\delta}$, $\mu_\delta^- = \mu_\delta - \Delta_{\mu_\delta}$. This allowed us to estimate the "error ellipses" with semi-major axes $\mu_\alpha^+ - \mu_\alpha^-$ and $\mu_\delta^+ - \mu_\delta^-$. As it can be seen from Fig. 2 the central trajectories of the ejection are possible for 8 HVS.

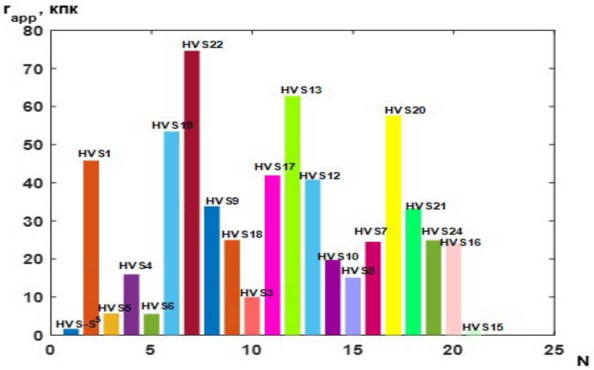

Fig. 1. Pericentric distances r_{app} of reconstructed tracks for HVSs from Brown et al. (2018).

3 Dynamic stability of the S-cloud

Another indirect evidence of gravitational binding of the S-HVS pair in the past could be the coplanarity of theirs orbits. A star ejected at 1000 km/s, without collisions

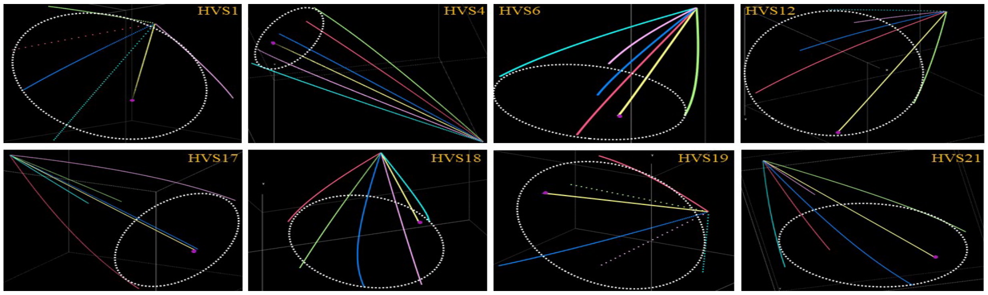

Fig. 2. "Error ellipses" for 8 HVSs from Brown et al. (2018). The purple dot is SMBH. Blue shows the ejection trajectory according to μ_α, μ_δ. Yellow is a possible central ejection trajectory.

or tidal approaches, reaches the neighborhood of the halo in $\sim 10^8$ yrs. During this time, does the original orbital configuration of the captured star in the vicinity of the SMBH, surrounded by a cloud of other previously captured stars, remain the same? The motion of each star in the S-cloud, which is controlled by the SMBH, is perturbed at least by all stars in the cloud. So, what is the time scale this perturbation swings the orbits of the stars?

To estimate the time of chaotization, a model S-cloud of 25 S-stars was "prepared" by Gillessen et al. (2017), which are no farther away from the SMBH than $1''$. In the course of a direct numerical integration in the formulation of the N-body problem (N=26), we tracked the orbital evolution of the S-cloud in the Newtonian potential of SMBH with orbital monitoring of S2 as the most well-studied star due to its short orbital period (~16 years). As can be seen from the Fig. 3, conservation of the initial spatial configuration of the orbit of S2 is possible on the interval of ~1,000 revolutions ($\sim 10^4$ years). After that, the change in the spatial configuration of the orbit S2 becomes noticeable. These results are consistent with the conclusion from Beckers et al. (2024), who obtained an estimate of the Lyapunov time of the order of 420 years. Obviously, the condition of coplanarity of S and HVS orbits cannot serve as a reliable criterion for establishing their possible evolutionary relationship in the past.

4 Conclusion

According to the results of numerical simulations, the central ejection can be considered as a reliable criterion for the potential evolutionary relationship between S-stars and HVS in the past. Within the uncertainties of the orbital parameters of HVSs (Brown et al. 2018), it was shown that 9 out of 20 unbound with Galaxy HVSs could be the binary components of S-stars in the past. "Error ellipse" of these stars admits

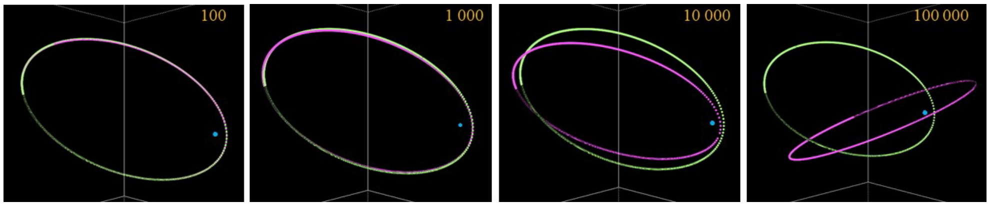

Fig. 3. The positions of the orbit of S2 at the initial moment of time (green color) and at moments after 100, 1,000, 10,000 and 100,000 (from left to right) orbital periods (purple color).

central ejection trajectories. From the bound energy balance, there is quantitative agreement between the velocities of the considered HVSs from Brown et al. (2018) and the gravitation energies of the observed S-stars (Gillessen et al. 2017) in the SMBH field. The perturbing potential of the S-cloud effectively chaoticizes the orbits of stars with a timescale of 10^4 years, changing their spatial configurations. Does this mean that, in principle, it is impossible to establish an evolutionary relationship of the S-HVS pair? In order to determine the further search and identification strategy of S-HVS pairs, we need the knowledge of their chemical composition, metallicity, luminosity, and temperature, on the basis of which we could estimate the age as a criterion of the evolutionary synchronism. The reconstructed chronology of the population of S-stars in the vicinity of the SMBH could provide a constraint on the distance limit of paired to them HVSs.

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