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SIMULATION OF THE MOTION OF STARS ESCAPING FROM THE GALACTIC CENTER

K. S. Shirokova[1,2]

[1] *Department of Celestial Mechanics, Saint Petersburg State University, Universitetsky prospekt 28, Peterhof, Saint Petersburg 198504, Russia; xebusk@mail.ru*

[2] *The Central Astronomical Observatory of the Russian Academy of Sciences at Pulkovo, Saint Petersburg 196140, Russia*

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Abstract. Motions of stars escaping from the Galactic center are simulated. It is shown that the Galactic bar reduces the initial velocity needed to escape from the Galaxy.

Key words: methods: numerical – stars: kinematics and dynamics

1. INTRODUCTION

Hypervelocity stars represent a new class of fast moving stars. Their speeds exceed the escape velocity at the point of observation. The first such object was discovered a decade ago (Brown et al. 2005), yet their existence was predicted by Hills (1988), who suggested that a close interaction between a tight binary system and a supermassive black hole may result in one of these stars to be kicked out at a very high speed of up to 4000 $\mathrm{km\,s^{-1}}$. Many other mechanisms have been proposed since then, but the Hills scenario still remains the most realistic.

The formation of a hypervelocity star consists of several stages: (1) a tight binary approaches a black hole, (2) one of the components gains sufficient velocity, (3) survives, and (4) flies through the galaxy. Dremova et al. (2015) estimated the probabilities of the second, third, and fourth stages in the axisymmetric Galactic potential model by Fellhauer et al. (2006).

To study the effect of non-axisymmetric Galactic center potential, we performed simulations adding a bar to the above model.

2. CALCULATIONS AND RESULTS

The potential of the Fellhauer et al. (2006) model consists of three components representing the disk, the bulge, and the halo,

$$\Phi = \Phi_{\mathrm{d}} + \Phi_{\mathrm{b}} + \Phi_{\mathrm{h}}, \tag{1}$$

where

$$\Phi_{\mathrm{d}} = -\frac{G \cdot M_{\mathrm{d}}}{\sqrt{x^2 + y^2 + (b + \sqrt{z^2 + c^2})^2}}, \tag{2}$$

$$\Phi_{\rm b} = -\frac{G \cdot M_{\rm b}}{\sqrt{x^2 + y^2 + z^2 + a}}, \tag{3}$$

$$\Phi_{\rm h} = \frac{v_0^2}{2} \cdot \ln(x^2 + y^2 + \frac{z^2}{q_\phi^2} + d^2). \tag{4}$$

The parameters of this model are: $M_{\rm d} = 10^{11}\ M_\odot$, $b = 6.5$ kpc, $c = 0.26$ kpc, $M_{\rm b} = 3.4 \times 10^{10}\ M_\odot$, $a = 0.7$ kpc, $v_0 = 186$ km s^{-1}, $q_\phi = 1$, and $d = 12$ kpc. To preserve the total mass of the Galaxy we reduced the bulge mass by the mass of the bar and hence $M_{\rm b} = 1.4 \times 10^{10}\ M_\odot$.

To facilitate the calculations, we modeled the bar by a homogeneous triaxial ellipsoid (Kondratyev 2007). Here, x_1, x_2, x_3 are the projections of the radius-vector on the x, y, z-axes in the rotating bar coordinate system.

The external bar potential is:

$$\Phi_{\rm bar} = \pi G \rho\, a_1 a_2 a_3 \int_\lambda^\infty \Big(1 - \sum_1^3 \frac{x_i^2}{a_i^2 + \nu}\Big) \cdot \frac{d\nu}{\sqrt{(a_1^2 + \nu)(a_2^2 + \nu)(a_3^2 + \nu)}}, \tag{5}$$

where λ is ellipsoidal coordinate of x and obtained from

$$\frac{x_1^2}{a_1^2 + \lambda} + \frac{x_2^2}{a_2^2 + \lambda} + \frac{x_3^2}{a_3^2 + \lambda} = 1. \tag{6}$$

The internal bar potential is:

$$\Phi_{\rm bar} = \pi G \rho\, a_1 a_2 a_3 \int_0^\infty \Big(1 - \sum_1^3 \frac{x_i^2}{a_i^2 + \nu}\Big) \cdot \frac{d\nu}{\sqrt{(a_1^2 + \nu)(a_2^2 + \nu)(a_3^2 + \nu)}}. \tag{7}$$

The general set of equations thus acquires the following form:

$$\Phi = \Phi_{\rm d} + \Phi_{\rm b} + \Phi_{\rm h} + \Phi_{\rm bar}. \tag{8}$$

The parameters of the bar are:

$$a_1 = 3 \text{ kpc}, \quad a_2 = a_3 = 1 \text{ kpc}, \quad \rho = \frac{M_{\rm bar}}{\frac{4}{3}\pi a_1 a_2 a_3}, \quad M_{\rm bar} = 2 \times 10^{10}\ M_\odot.$$

Our initial velocities are based on the calculations of Dremova et al. (2015), where the prototype of the binary system was the real binary star MR Cyg with $m_1 = 4.5\ M_\odot$, $m_2 = 2.5\ M_\odot$, $r_1 = 4.07\ R_\odot$, and $r_2 = 3.17\ R_\odot$. We performed the calculations with the semimajor axis equal to that of this binary system, $a = 11.314\ R_\odot$, and with the semimajor axis set equal to several times that value.

The angles between the initial velocity vector and Galactic plane are chosen randomly in accordance with the distribution $f(\alpha) = \cos(\alpha)$. The angles between the initial velocity vector and the semimajor axis of the bar are chosen randomly in two ways using (1) the above distribution and (2) uniform distribution. We use the fourth-order Runge-Kutta integrator to compute the motion of each simulated star until 150 million years or until its Galactocentric distance reaches 50 kpc (hypervelocity stars are observed at such distances).

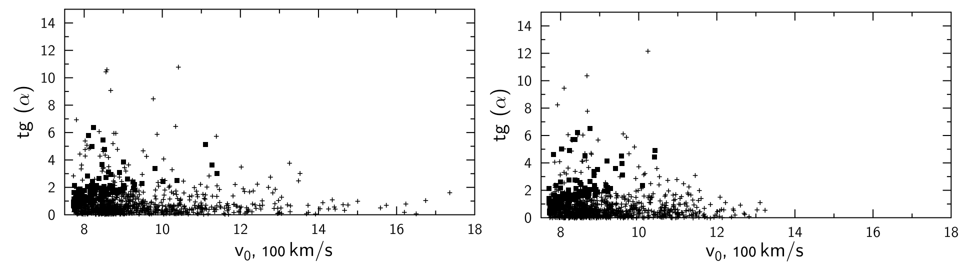

Fig. 1. The distribution of the angle α between the initial velocity vector and the Galactic plane versus the initial velocity v_0 of the star, in the units of 100 $\mathrm{km\,s^{-1}}$, for simulations with the semimajor axis of a binary system equal to 282 $R_\odot$ and the pericentric distances 10 000 $R_\odot$ (the left panel) and 15 000 $R_\odot$ (the right panel). The pluses and squares denote the hypervelocity and non-escaping stars, respectively.

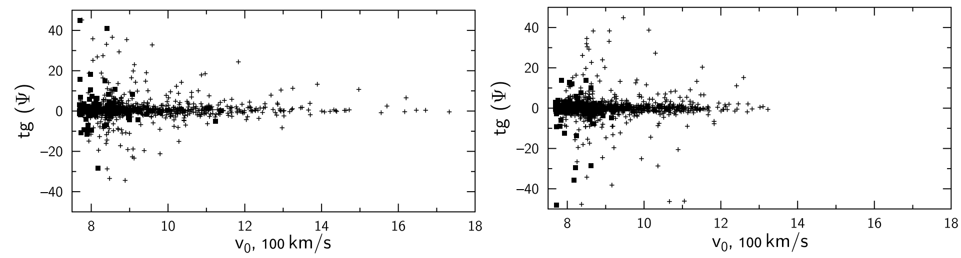

Fig. 2. The angle ψ between the initial velocity vector and the semimajor axis of the bar versus the initial velocity v_0 of the star, in the units of 100 $\mathrm{km\,s^{-1}}$, for simulations with the semimajor axis of a binary system equal to 282 $R_\odot$ and the pericentric distances 10 000 $R_\odot$ (the left panel) and 15 000 $R_\odot$ (the right panel). The pluses and squares denote the hypervelocity and non-escaping stars, respectively.

Fig. 1 shows the distribution of the angle between the initial velocity vector and the Galactic plane, plotted versus the initial velocity. We limit the range of angles α to the $[0;\ \pi/2]$ interval because the model potential is symmetric with respect to the Galactic plane. For non-escaping stars, $\tan(\alpha)$ can be seen to increase with increasing initial velocity. This can be explained by the influence of the Galactic disk.

Fig. 2 shows the distribution of the angle between the initial velocity vector and the semimajor axis of the bar, plotted versus the initial velocity. This angle is distributed uniformly in the $[-\pi;\ \pi]$ interval. Non-escaping stars show no dependence on this angle, and hence ψ does not depend on the formation probability of hypervelocity stars.

Table 1 lists some of the results of our calculations. As is evident from the table, almost all probabilities are close to unity. For closer binaries the probabilities in the model with a bar are higher than in the model without it, for wider binaries the probabilities are about the same in all cases. This may be explained by the decrease of the velocity to reach the boundary distance: initial velocities for closer binaries are higher than those for wider ones and that is why this effect is more conspicuous.

Table 1. Probabilities of hypervelocity star formation: R_p is the semimajor axis of the binary and P is the probability estimated in terms of the Fellhauer et al. (2006) model. Here $P_{\rm bar}$ is the probability estimated in terms of the model with a bar with a cosine distribution of angles between the initial velocity vector and the semimajor axis of the bar (the number in brackets is the probability estimated in the case of the uniform distribution of these angles).

$a = 11\ R_\odot$		
R_p	P	$P_{\rm bar}$
100	0.933	0.995
150	0.939	0.998
215	0.929	0.996
1500	0.905	0.999
1600	0.796	0.996
$a = 282\ R_\odot$		
R_p	P	$P_{\rm bar}$
10 000	0.893	0.897 (0.877)
15 000	0.903	0.892 (0.883)

3. CONCLUSIONS

Simulations of the motions of stars escaping from the Galactic center after the interaction of a binary system with a supermassive black hole show that the Galactic gravitational field has little effect on the formation probability of hypervelocity stars – the crucial factor is the velocity gained by the star after the interaction.

A comparison of the results of our calculations performed using the Fellhauer et al. (2006) model of the Galactic gravitational potential and the same model with a bar added in the central part shows that the bar reduces the initial velocity needed for the star to escape from the Galaxy.

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