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EJECTION OF STARS WITH RELATIVISTIC VELOCITIES

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Abstract. We present the results of numerical simulations performed in terms of modified Hills' scenario involving two supermassive black holes (SMBHs). In contrast to the classic Hills scenario (Hills 1988), here one component of the ordinary stellar binary system is replaced with a SMBH that provides a kinetic resource for ejecting a star (the secondary component of the binary) with relativistic velocity (RVS). We examine the conditions that favor relativistic ejections of stars, depending on the pericentric approach, the mass ratio of two SMBHs, and the orbital configuration of the binary system. Applying the simple criteria helped us to sort out the results of numerical simulations by the outcome: conservation of the orbital configuration of the binary system, dynamic recapture of the star by the central SMBH, emission of hypervelocity stars (HVSs), and RVS ejection. In the framework of N-body simulations we estimate the probability for a star to survive in the cross-field of two SMBHs during the ejection with relativistic velocity, and discuss the probability of the detection of RVSs in our Galaxy in the cases where such stars are generated in distant interacting galaxies undergoing a merger of their central parts occupied by SMBHs.

Key words: relativistic velocity stars – stars: supermassive black holes – probability assessment – three body and N-body simulations

1. CLASSIFICATION OF STARS WITH ANOMALOUS KINEMATICS

Since Edmond Halley in 1817 “broke” the thesis of the fixity of stars, ingrained from the era of “primitive” astronomy, his discovery gave way to several generations of kinematic models of our Galaxy. This revolutionary discovery was made by comparing positions of Sirius, Arcturus and Aldebaran, listed in the stellar catalogs compiled by his contemporaries and indicated in Ptolemy's Almagest. Such a large shift in positions cannot be explained by accounting for precession, and Halley concluded that stars have their proper motions.

However, mass measurements of proper motions of stars began only half a century later. Almost immediately stars with large proper motions were found, which were called “flying”. The most famous of the rapidly moving stars, such as Lacaille 9352, 61 Cygnis, Groombridge 1831, Kapteyn's and Barnard's stars, formed the basis for the future classification of stars with anomalous kinematics, which now has the following scheme:

(1) High-velocity stars ($v \leq 300$ km s^{-1});

(2) Runaway stars ($v \leq 300$ km s^{-1});

(3) Hyper-runaway stars ($v \sim 500$ km s^{-1});

(4) Hypervelocity stars, or HVSs ($v \sim 1000$ km s^{-1}).

Stars of these classes belong to different subsystems of the Galaxy: stars of the first class fall from the halo, stars of the second and third classes are ejected from the disk, and those of the fourth class are generated in the center of the Galaxy.

The first three classes were first discovered and then theoretically interpreted in terms of two basic scenarios: collisional activity of stars in rich clusters (Poveda et al. 1967) and the disintegration of close binary systems (CBS) as a result of the explosion of one of the components as an SNIb/c type supernova (Zwicky 1957).

The difference in the velocities of stars of the second and third classes can be explained by the fact that in the case of the third class one of the components at the pre-supernova stage is a Wolf-Rayet star embedded in a common envelope together with its companion, which actually provides more momentum for the star ejection.

As for the fourth class, these stars were first predicted and then discovered. The scenario of their formation suggested by Hills in 1988 again reduces to the disintegration of CBS, caused not by a supernova explosion but by the tidal effect of a supermassive black hole (SMBH).

The first simulation by Hills (1988) of the dynamic capture of a CBS ($1M_\odot + 1M_\odot$) with a semi-major axis of 0.01–0.1 a.u. at pericentric distance 1–10 a.u. from the SMBH with mass $10^6\,M_\odot$ included 250 calculations accounting for arbitrary orbital configurations of the binary system. Based on this statistics Hills estimated the geometric probability of HVS-generation in our Galaxy of about 10^{-3}–10^{-4} per year.

Such a high rate of HVS production could guarantee their easy detection, and hence confirmation of the existence of SMBH at the center of our Galaxy.

By the year 2000, images of several such stars were acquired in the framework of two independent projects carried out on the ESO VLT-8m in La Sillia and Keck 10-m in Hawaii and aimed to finding stars within one arcsec centered on the position of Sgr A* (the so-called S-stars). An analysis of the trajectories of these stars provided information about the gravitational potential at the Galactic center, produced by the central point-like body interpreted as a SMBH. Observations performed on different telescopes yielded similar SMBH mass estimates: $(4.29 \pm 0.07) \times 10^6\ M_\odot$ (Gillessen et al. 2009a) and $(4.5 \pm 0.4) \times 10^6\ M_\odot$ (Ghez et al. 2008).

By 2009, the number of known S-stars increased to 30 (Gillessen et al. 2009b), and currently more than one hundred of such stars are monitored. It follows from observations that there are tens of thousands of stars in the central region with a radius of 1 pc, hundreds of stars in the region with a radius of 0.1 pc, 30 stars within 0.01 pc, and only one star within “the eye of a needle” size of 0.001 pc (Gillessen et al. 2013). At closer distance the zoom scaling is still unknown.

Spectroscopic study of S-stars raised a new problem, which was formulated in 2005 as the problem of the youth of the Galactic center. Where did B-type stars observed in the center of the Galaxy come from? At the same time, a group headed by Warren Brown discovered the first HVS – SDSS J090745.0+024507 – a

B9-type star at a distance of 71 kpc from the Galactic center and moving relative to it at a speed of 709 $\mathrm{km\,s^{-1}}$ (Brown et al. 2005).

Over the next ten years, 20 other such objects were discovered and included in the first catalog of hypervelocity stars. The catalog is based on the MMT survey of northern hemisphere of our Galaxy compiled by Brown and coauthors (Brown et al. 2014) and presents a complete list of properties and physical characteristics of each HVS.

Therefore, objects whose very existence was once believed to be impossible – HVSs, today are used extensively as markers of the dark halo of our Galaxy. At the same time, HVSs, if they were produced via Hills' scenario, should carry information about our Galactic center, which is still poorly observed. Oddly enough, the problem with HVSs is not the abnormally high speed of their spatial movement, but the determination of the direction of their movement: it is impossible to accurately measure their proper motions.

This difficulty led scientists to look for other alternative scenarios that could explain the hypervelocity nature of the stars, and soon it became clear that the inclusion of HVSs is not enough to make the classification of anomalous kinematics complete. Here we talk of stars moving with velocities comparable to the light speed, whose existence is consistent with the laws of Nature.

Before proceeding to theoretical and computational justification of the existence of such stars, we finalize the classification of anomalous kinematics by introducing the fifth class of stars yet undiscovered:

(5) Stars with relativistic velocities, RVSs (velocities of the order of c/2).

2. THEORETICAL JUSTIFICATION OF THE EXISTENCE OF RVS

Numerous simulations of the classic scenario by Hills (1988), carried out independently by different teams (Bromley et al. 2006; Sesana et al. 2007; Sherwin et al. 2008; Dryomova et al. 2014) taking into account the SMBH mass, semimajor axis and component mass ratio of CBSs, as well as the tidal radius, showed that there is a limit on the maximum possible ejection velocity of hypervelocity stars. This constraint is due to the SMBH size, i.e., Schwarzschild radius, $r_{\rm sch} = 2GM_{\rm SMBH}/c^2$: twice its value must not exceed the tidal radius for the star, $r_{\rm t} = 2^{1/3}R \times (M_{\rm SMBH}/M)^{1/3}$, where M and R are the mass and radius of the star, respectively.

The increase of the ejection velocity with increasing SMBH mass, what one would expect at first sight, is justified only for the SMBHs with masses below the limiting value, $M_{\rm lim}$. This value is determined by the condition of innermost bound circular orbit in a non-spinning black hole, i.e. $2r_{\rm sch} = r_{\rm t}$ (Bardeen et al. 1972):

$$M_{\rm lim} = \frac{c^3}{4}\sqrt{\frac{R^3}{2MG^3}}\,. \qquad (1)$$

For example, the limit mass of SMBH, required for ejecting a star of mass $1M_\odot$ and radius $1R_\odot$ at maximum possible velocity, is 57 million solar masses, and the corresponding limit mass for ejecting a star of mass $4.5M_\odot$ and radius $4R_\odot$ is equal to 220 million solar masses.

The limit mass means the maximum energy that the SMBH can transfer to the ejected component. We estimate the velocity of ejection based on the following simple considerations. Let the CBS components move towards each other along a parabolic orbit and approach at a distance equal to the sum of their radii. After momentum exchange they make a 180-degree turn. Thus, the velocity of each component changes by $2v$, and the momentum – by $2mv$, correspondingly.

Assuming that the components of CBS are at the tidal radius of SMBH, the maximum possible speed that can be acquired by one of the CBS components is $v_\mathrm{p} + 2v$, where $v_\mathrm{p} = \sqrt{(2GM_\mathrm{SMBH})/r_\mathrm{t}}$ is velocity at the pericenter and $v = \sqrt{(GM)/(2R)}$ if we assume that $M_1{=}M_2{=}M$ and $R_1{=}R_2{=}R$. We now estimate the increase in energy due to the exchange of maximum possible momentum between the components in the vicinity of the SMBH pericenter to obtain

$$E_\mathrm{eject} = \frac{M}{2}(v_\mathrm{p} + 2v)^2 - \frac{Mv_\mathrm{p}^2}{2}. \tag{2}$$

Here, E_eject may be interpreted as a kinetic resource for ejecting the star. E_eject allows us to estimate the maximum possible ejection velocity:

$$v_\mathrm{eject} = \sqrt{\frac{2}{M}E_\mathrm{eject}} \sim 2\sqrt{v_\mathrm{p} v}\,. \tag{3}$$

This scheme illustrating the maximum possible exchange of momentum between the CBS components is formulated in the framework of two-body dynamics, which is justified because of very large mass of the third body, SMBH.

According to formula (3), the maximum ejection velocity of a ($1M_\odot$, $1R_\odot$) star at the distance of the tidal radius $485R_\odot$ from the SMBH with a mass of $57 \times 10^6\ M_\odot$ does not exceed 16 000 km s^{-1}. For a star with the parameters ($4.5\,M_\odot$, $4\,R_\odot$) and SMBH mass of 220 million solar mass, the maximum possible velocity of star ejection is $\sim 23\,000$ km s^{-1}.

In the numerical calculations of the dynamical capture of CBS by the central SMBH with a mass of $4.5 \times 10^6\ M_\odot$ (appropriate for our Galaxy) the ejection velocity of the star does not exceed 10 000 km s^{-1}. Hence the kinetic resource of the classic scenario by Hills is about 10 000–20 000 km s^{-1} depending on the mass of the ejected star.

It would be interesting to repeat the above procedure with one component in the CBS replaced with another SMBH of smaller mass compared to the central SMBH. Let us call it the modified Hills scenario. We must take into account the following changes. The maximum possible exchange of momentum between the secondary SMBH and the star occurs not at the distance of the sum of their radii but at the tidal radius $r_{\mathrm{t},2} = 2^{1/3}R \times (M_{\mathrm{SMBH},2}/M)^{1/3}$.

We can therefore use formula (3), where $v = \sqrt{(2GM_{\mathrm{SMBH},2})/r_{\mathrm{t},2}}$, to again estimate the maximum possible velocity of ejection of the star from the CBS. For example, v_eject proved to be 80 000 km s^{-1} for a $(4.5\,M_\odot, 4\,R_\odot)$ star ejected from the CBS with a $4.5{\times}10^5\ M_\odot$ secondary SMBH in the gravitation field of the central SMBH of mass $4.5 \times 10^6\ M_\odot$ at the distance of the tidal radius ($r_\mathrm{t} = 512\,R_\odot$).

In the case of equal masses of the central and secondary SMBHs, v_eject increases up to 115 000 km s^{-1}. The maximum ejection velocity tends to $c/2$ with the SMBH mass increasing to $2.2 \times 10^8\ M_\odot$ while keeping the CBS parameters at ($4.5\,M_\odot$, $4.5 \times 10^5\ M_\odot$).

Hence the modified Hills scenario, unlike the classic one, has enough kinetic resource for ejecting the star component at a relativistic velocity. The idea of existence of stars with relativistic velocities was first suggested by Tutukov &

Fedorova (2009) in the review devoted to the fastest stars in the Universe. Today this idea is confirmed by the simulations described hereafter that were carried out in the framework of three- and N-body concepts.

3. NUMERICAL EVIDENCE FOR THE EXISTENCE OF RVS

The first numerical simulations of the modified Hills scenario were carried out by Guillochon and Loeb in 2015. They obtained the velocity spectrum for ejected stars based on the statistics of 114 688 arbitrary initial orbital configurations of three bodies: the central and secondary SMBHs and the star.

The analysis of the velocity spectrum showed that star ejections with velocities of about one third the speed of light occurred in less than one percent of the cases. In their paper Guillochon & Loeb (2015) discussed in detail the whole set of criteria that they had used in the calculations to distinguish the outcomes of scattering: swallowing a star by the central SMBH ($r_{\rm p} < r_{\rm sch,1}$), swallowing of the star by the secondary SMBH ($r_{\rm p} < r_{\rm sch,2}$), tidal disruption of the star in the field of the secondary SMBH ($r_{\rm p} < r_{\rm t,2}$), dynamic recapture of stars into an orbit around the central SMBH, and, of course, the ejection events.

These criteria, which are based on the results of numerical experiments by Sari et al. (2010), are semi-empirical and not rigorous. However, the main problem is neglecting the finite sizes of approaching bodies. This makes it difficult to answer the question of the survival of stars in the strong tidal cross-field generated by two SMBHs.

Therefore in our simulations of the modified Hills scenario we used the N-body approach to describe the star's structure. We set 4000 elementary cells (Fig. 1, the bottom row) uniformly filling the volume of a sphere of radius $4.07R_\odot$. These elementary cells all have the same size and the same mass of $4.5M_\odot/N$. All elementary cells interact with each other and with both SMBHs via gravity exclusively, and the gas pressure in the star is taken into account by not allowing the elementary cells to approach each other at a distance less than the sum of their radii.

We performed a series of calculations to evaluate the survival probability of a star in the field of a single SMBH, and found that if the mass loss of the star is less than 25%, it remains in bound state (Dryomova et al. 2014). The dependence of the star's mass-loss rate on pericentric distance inferred in terms of our model proved to agree well (Dryomova et al. 2015a,b) with the results of hydrodynamic simulations (Guillochon & Ramirez-Ruiz 2013) and with the results obtained in terms of the semi-analytical affine stellar model (Ivanov & Novikov 2001). Thus our "purely" gravitational model of the star proved to be efficient and convenient for the large number of simulations of those orbital configurations that were promising for relativistic ejections according to preliminary computations performed in terms of the three body problem.

We considered the model of a CBS consisting of a ($1M_\odot$, $1R_\odot$) star and a ($4.5\times10^5M_\odot$, $1.9R_\odot$) SMBH, starting on a parabolic trajectory from the apocenter of $10^5R_\odot$ and approaching the central SMBH ($4.5\times10^6M_\odot$, $19.07R_\odot$). The semi-major axis of the CBS is $125R_\odot$ and the pericentric distances ranged from 100 $R_\odot$ (the tidal radius of the star in the field of the central SMBH) to 500 $R_\odot$ (the tidal radius of the CBS in the field of the central SMBH). Initially, we ran the calculations for an ensemble of 50 000 orbital configurations in terms of the three-body problem, from which we selected a few dozen configurations favorable for the relativistic ejection.

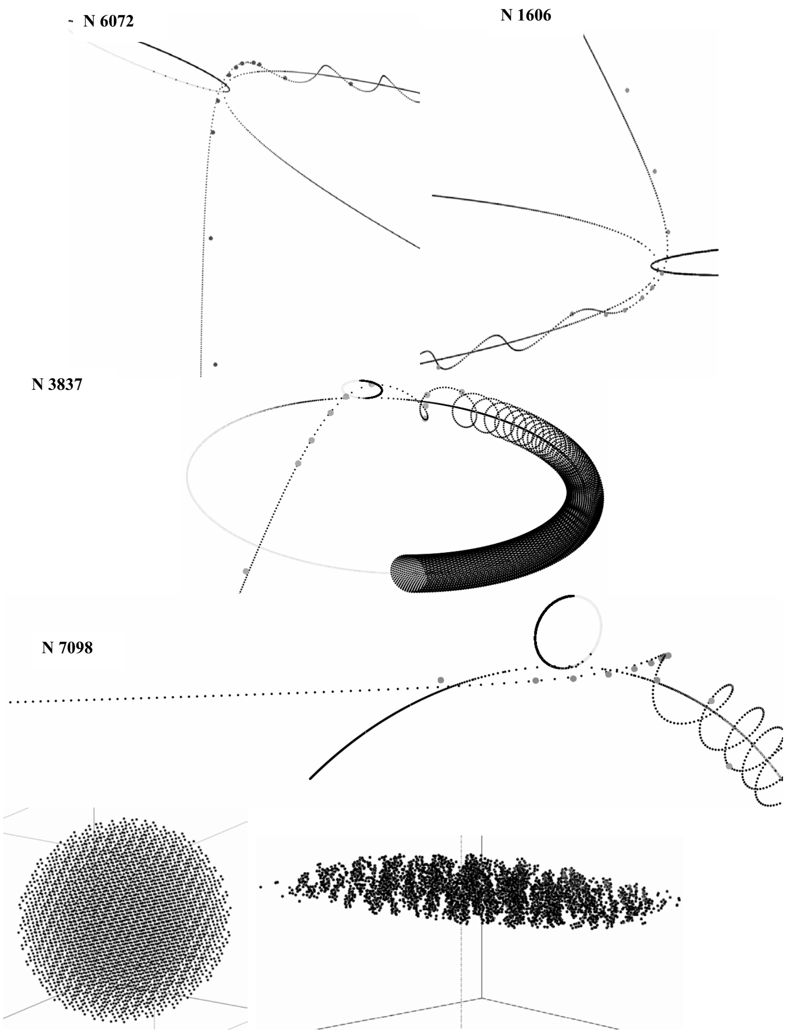

Fig. 1. Fragments of trajectories of ejected stars simulated in terms of the modified Hills scenario. The solid lines show the orbits calculated in terms of the three-body problem and the circles indicate the trajectory of the star, calculated in terms of the N-body problem. Each circle is made up of 4000 elementary cells describing the structure of the star. The numbers near each fragment indicate the orbital configuration of the CBS. The bottom row illustrates variants of different behavior of N structural elements of the star in the tidal field of two SMBHs.

Repeating the calculations for these configurations in terms of the N-body model confirmed only four events of RVS ejection whose fragments we show in Fig. 1 (the upper and the middle rows). In all the other events the stars were destroyed, although according to the criteria used by Gillochon & Loeb (2015) in their three-body model, these events had to be classified as successful for the star ejection at a relativistic speed. One of the reasons for such a high statistics of star destruction is due to unfavorable relative positions of the three bodies (the star and two SMBHs) at the pericenter of the orbit by analogy with the lunisolar tides, where all three bodies are aligned, resulting in maximal effect of both SMBHs known as the syzygial tide.

For a number of configurations (N3837, N1606, N6072, N7098) the positions of three bodies at the pericenter produced neap tide, when the combined gravitational effect of the two SMBHs is minimal and, as a consequence, the stars survived. Another reason allowing the star to avoid destruction in the strong gravitational cross-field is very rapid passage of the pericenter region. We obtained maximal star ejection velocity of about 112 000 km s^{-1} (Dryomova et al. 2016).

4. CONCLUSION

We have a complete, albeit still inconclusive, classification of stars with anomalous kinematics. Today we know that the scenario involving two SMBHs is capable to generate stars with relativistic velocities (RVSs). The results of long-term monitoring revealed that the center of our Galaxy hosts only one SMBH. Therefore, any ejections of stars with relativistic velocities have to be of extragalactic origin.

The first successful detection of gravitational waves in the GW150914 event gives us confidence that it will be eventually possible to map the events of SMBH merging throughout the observable Universe and thus to evaluate the population of RVSs. Twelve years ago, hypervelocity stars have not yet been observed, and nobody knows when the first RVS will be discovered, but now we have strong theoretical evidence for the existence of RVSs.

REFERENCES

Bardeen J. M., Press W. H., Teukolsky S. A. 1972, ApJ., 178 347

Bromley B. C., Kenyon S. J., Geller M. J. et al. 2006, ApJ, 653, 1194

Brown W. R., Geller M. J., Kenyon S. J., Kurtz M. J. 2005, ApJ, 622, 33

Brown W. R., Geller M. J., Kenyon S. J. 2014, ApJ, 787, 89

Dryomova G. N., Dryomov V. V., Tutukov A. V. 2014, Astronomy Reports, 58, No. 5, 291

Dryomova G. N., Dryomov V. V., Tutukov A. V. 2015a, Baltic Astronomy, 24, 1

Dryomova G. N., Dryomov V. V., Orlov V. V., Tutukov A. V., Shirokova K. S., 2015b, Astronomy Reports, 59, No. 11, 1018

Dryomova G. N., Dryomov V. V., Tutukov A. V. 2016, submitted to Astronomy Reports

Ghez A. M., Salim S., Weinberg N. N. et al. 2008, ApJ, 689, 1044

Gillessen S. 2013, in *Star Clusters across Cosmic Time* (International workshop Modest-13), Almaty, 23

Gillessen S., Eisenhauer F., Trippe S. et al. 2009a, ApJ, 692, 1075

Gillessen S., Eisenhauer F., Fritz T. K. et al. 2009b, ApJ, 707, 114

Guillochon J., Loeb A. 2015, ApJ, 806, 124

Guillochon J., Ramirez-Ruiz E. 2013, ApJ, 767, 25
Hills J. G. 1988, Nature, 331, 687
Ivanov P., Novikov I. 2001, ApJ, 549, 467
Poveda A., Ruiz J. , Allen C. 1967, Bol. Obs. Tonantzintla y Tacubaya, 4, 86
Sari R., Kobayashi S., Rossi E. M. 2010, ApJ, 708, 605
Sesana A., Haardt F., Madau P. 2007, ApJ, 660, 546
Sherwin B. D., Loeb A., O'Leary M., 2008, MNRAS, 386, 1179
Tutukov A. V., Fedorova A. V. 2009, Astronomy Reports, 53, No. 9, 839
Zwicky F. 1957, *Morphological Astronomy*, Springer, Berlin, 258