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Stellar comet spear

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Abstract. One of the consequences of the evolutionary process of the planetary system is the appearance of comets, asteroids, and even planets (ACP) unbound to their parent star. These small bodies are scattered into interstellar space, orbit the Galactic Center and expand along the star orbit with time. The formed structure resembles a spear in its shape. Similar ACP spears have all stars with planetary systems in the Galaxy. Since such stars are part of the open clusters population, they scatter and form the ACPS spears. In this paper, we performed numerical modeling of the ACP and ASPC spears and estimated their parameters, such as length, width, and time of formation.

Key words: Solar System – comets – open star cluster – Galaxy – kinematics

1. Introduction

Until the 18th century, the interplanetary space of the Newtonian universe was considered empty. This meant that the planets of the Solar system did not exchange matter. One of the consequences of this paradigm was the separation of the phenomena of comets, meteors, and meteorites, attributing them to various natural disasters. It was possible to unite these phenomena only at the turn of the 18–19th century. Ernst Chladni, thus initiated a new, revolutionary change of the astronomical picture of the world (Eremeeva, 2006). With the change of paradigm, it became clear that objects in the Solar system are actively exchanging matter (Martian meteorites, tons of dust falling on the Earth every day). Currently, this statement is not in doubt, and it is difficult to imagine that it was once different.

Nevertheless, the sighting of the first interstellar comet became a real sensation (Meech et al., 2017), and led to a paradigm shift taking place right now, in front of our eyes. We are beginning to understand that not only bodies inside the Solar system exchange matter, but also larger objects - stars, star clusters, and even galaxies. Moreover, ACP objects (asteroids, comets, planets) move freely in the universe, eventually forming clouds, spears and rings along the orbits of their parent bodies. And when approaching, they leave the parent systems and become small interstellar bodies.

This motivates us to take a fresh look at the problems of studying stars and open star clusters, since all stars are born in clusters, and all comets are born in the process of the formation of planetary systems of stars.

Our model assumes the appearance of comets leaving their parent stars due to the gravitational effect from the giant planets. Comets leaving the parent star at the velocities of several kilometers per second end up, prevailingly, in the interstellar space of the Galaxy (Dones et al. (2004) in: Comets II, Univ. Arizona Press, Tucson, pp. 153-174).

Comets leaving the parent star at a velocities of several kilometers per second end up in the interstellar space of the Galaxy. Thus, a cloud resembling a spear is formed (Tutukov & Smirnov, 2004). This process also takes place in the vicinity of all stars with planetary systems. The formation of stars is often accompanied by the appearence of the circumstellar gas-dust disks, the evolution of which leads over time to the formation of planetary systems (Safronov, 1969).

The spear includes not only cometary nuclei but asteroids and planets. The spears of the Sun, stars, and open star clusters formed by the ACP (asteroid – comet – planet) expand the region, in which the objects originating in the given planetary system are situated, to tens of kpc over time. Stars with planetary systems soon begin to be accompanied by ACP spears in the form of spears or even rings, depending on the age of the star. These objects are quite common in the Galaxy since about a third of the stars have planets (Masevich & Tutukov, 1988; Tutukov & Smirnov, 2004).

The work is devoted to the numerical study of the evolution of the free ACP orbits in the Galaxy, leading to their transformation into cometary spears of the Sun, stars, star clusters. Gradually, they form a well-populated ACP component of the Galaxy, composed of filaments of evolved ACP clouds. In particular, for the Solar system, this means that its external boundary expands to several kpc. Interstellar comets are located in ACP spears. ACP spears are generated by distant giants like Jupiter and as a result of the interaction of the planetary Oort cloud with background stars (Faintich, 1971), (Correa-Otto & Calandra, 2019), (Tutukov et al., 2020). Recently discovered interstellar objects 2I/Borisov and 1/I Oumuamua represent this component of the Galaxy (Borisov et al., 2013), (Hallatt & Wiegert, 2020). Note that interstellar meteors with a mass of $\sim 10^4$ g were found by Froncisz et al. (2020), which also represent a significant part of the ACP of the Galactic component. Note also that microlensing facilitates and makes real the process of registering free planets of the Galaxy, lost by parent stars (Mróz et al., 2020).

Since practically all stars are formed in star clusters, about one-third clusters membership stars may have planetary systems (Tutukov, 1978). Thus, ACP spears are inherent for clusters as well. It was shown, that evaporation of stars from clusters leads to the appearance of stellar spears clusters along clusters galactic orbits (Tutukov et al., 2020). The presence of massive and distant enough planets in planet systems leads to the loss of asteroids, comets and Earth–like planets from their parent systems with velocities several kilometers per second. This process was demonstrated by numerical model in (Tutukov et al., 2020). Lost ACP objects of stars with planet systems will form wide ACP spears in parent clusters which leads to a quick appearance of a rather dense ACP component of star clusters.It is of interest to point here that velocities of a part ACP objects lost by planet systems exceed second space speed for clusters. As a result stellar clusters are forming ACP spears overlapping with its stellar spears. Resulting ACPS spears have to be rather dense, since a significant concentration of stars in their cluster. It is quite possible that the ACPS spears of several close clusters like Pleiades are now identified by Gagné et al. (2021).To determine the potential trajectory of ACPS objects, it is necessary to study the orbits of open clusters and calculate their motion in past epochs.

The structure of the work is based on the similarity of the evolution of stellar and cometary clouds, turning into spears and, over time, into circular streams around the Galactic Center. Section 2 provides an analytical estimate of the parameters of cometary spears formed by the former stellar population of open clusters. These stars have left their parent cluster and formed spear – like structures stretched along galactic orbits. Section 3 contains a description of the Galaxy model. It was used to calculate the evolution of stellar – cometary clouds, the results of which are presented in Section 4 and Section 5. Section 6 contains a brief discussion and Conclusions.

2. Analytical estimates

A lifetime of open clusters is limited by dissipation of stellar component (Chandrasekhar, 1943). Cluster stars, leaving a cluster with a velocity of about 1 km s^{-1}, enrich the stellar component of the ACP open cluster spear. Thereby, these stars replenish the population of the open cluster ACP component. Including the stars, we call it the ACPS spear. An additional way for enrichment of the stellar component of ACPS cluster spear provides for close binary and unstable multiple stars of the cluster. Dissociation of unstable multiple stars leaving parent cluster for ACPS spears. Supernovae explosions in massive close binaries lead to the appearance of fast stars leaving parent clusters again for cluster ACPS spear.

Let us present here some numerical estimates related to stellar cluster, grounded in assumption that their masses M and radii R are connected by the relation $M = 0.2R^2$ (Tutukov, 2019). Roche lobed Oort cloud radius R_R for a cluster star with mass m will be

$$R_R = 2 \times 10^3 (M/M_\odot)^{1/6} (m/M_\odot)^{1/3} AU \quad (1)$$

The distance of the closest encounter between stars in cluster during time t will be

$$\frac{r_{min}}{AU} = 40 (M/M_\odot)^{1/8} (m/M_\odot)^{1/2} (year/t_{10})^{1/2} \quad (2)$$

where t_{10} is the time in units 10^{10} years. It is evident that during the lifetime of open cluster 10^8 years, planet systems with sizes below ~ 40 AU (Tutukov, 1978) remain untouched by cluster stars. But Roche lobe with filling the latter stellar Oort cloud will be intersected by cluster stars about N times:

$$N = 0.16\ t/\tau_k (M/m)^{1/3} \tag{3}$$

where $\tau_k = \frac{R^{3/2}}{G^{1/2}M^{1/2}}$ is Keplerian time of cluster $\tau_k = 10^5 (M/M_\odot)^{1/4}$ years. For $M \approx M_\odot$ we will have $N \cong 1.6 \times 10^4 (M/M_\odot)^{1/12}\ t/10^{10}$ years times. For an open cluster with $M \approx 10^3 M_\odot$ and lifetime $\sim 10^8$ years cluster stars about 200 times intersect Oort clouds of stars with planets. Let us point here that for Solar Oort cloud this member is about 10^5. The intersection of cloud stars Oort clouds leads to a strong dissipation of their ACP member and to the enrichment of ACP component of clusters themselves and cluster ACP spears. Interaction of stars with Oort clouds can be an efficient source of ACP objects of the ACP cluster spears.

3. Galaxy Model

Bulge, represented by a power-law spherical density potential with an exponential cut–off. With the accepted normalizations $\alpha = 1.8$, $r_c = 1.8/8.178$, $v_c(1,0) = 1$ it is presented:

$$\begin{gathered} \rho(r) = \left(\frac{r_1}{r}\right)^{\alpha} e^{(r/r_c)^2} \\ \rho(R = 8.178, z = 0) = 27.37 \end{gathered} \tag{4}$$

The potential of the Galactic disk, $\Phi(R,\ z)$, is mathematically described by the expressions by Miyamoto & Nagai (1975):

$$\Phi(R,\ z) = -1/\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2} \tag{5}$$

where a is the radius of the disk $a = 1.0$, b is the thickness of the disk $b = 0.1$, R is the radial distance from the galactic center, z is the coordinate in the accepted galactic rectangular coordinate system.

Halo - spherically symmetric spatial density distribution of the dark matter in the halo along the profile of (Navarro et al., 1996), with the accepted normalizations 16/8.178, $v_c(1,0) = 1$ it is presented

$$\begin{gathered} \rho(r) = \frac{1}{4\pi a^3} \frac{1}{(r/a)(1 + r/a)^2} \\ \rho(R = 8.178, z = 0) = -2.69 \end{gathered} \tag{6}$$

where a is the radius.

4. The Sun motion

Figure 1 shows the orbit of the Sun calculated backward 5 billion years by dint of the so-called "classical potential of the Milky Way" by Bovy (2015) – Eqs. 4 - 6. We took the distance of the Sun to the Galactic Center $R_0 = 8.178$ kpc, and the circular velocity of the Sun $V_0 = 232.8$ km s^{-1} (McMillan, 2017), (Gravity Collaboration et al., 2019). Initial values of the Sun rectangular coordinates and spatial velocity components are $(X\ Y\ Z) = (R_0\ 0\ 20.8)$, $(U\ V\ W) = (0\ V_0\ 0)$. Directions of the coordinate axes: the X–axis is directed to the center of the Galaxy, the Y–axis is in the direction of rotation of the galactic disk, and the Z–axis is directed to the North Pole of the Galaxy. The directions of the spatial velocity components are similar.

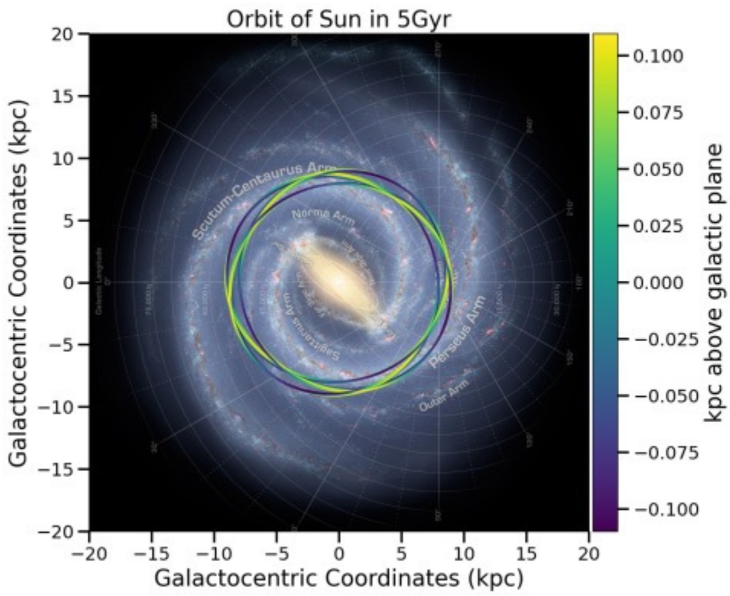

Figure 1. The Sun motion in our Galaxy model. Color bar shows the distance of the Sun to the Galaxy disk plane.

In the XY–plane on Fig. 1, the position of the orbit during the integration time occupies a strip about 1000 pc wide. In this case, along the Z–coordinate, the orbit changes by ± 100 pc.

What the number of the revolutions of the Sun n_{Sun} are shown in Fig. 1? Based on the fact that the Sun speed is $V_0 = 232.8$ km s^{-1} (≈ 233 pc per million year), we found the path length for 5 billion years. It will be $L \approx 1155$ kpc. The orbital length of the the one period is $L_{orb} = 2\pi R_0 \approx 50.5$ kpc. Then

$n_{Sun} \approx 22$. Thus, Fig. 2 shows the orbit of the Sun for one revolution equal to ≈ 250 million years.

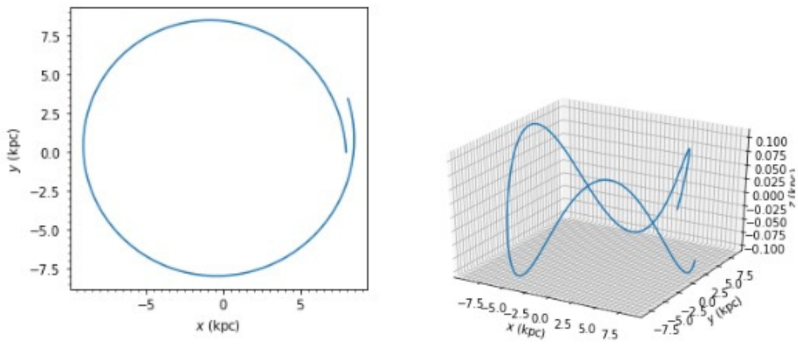

Figure 2. Full revolution of the Sun around the Galaxy Center. Left panel shows the orbit of the Sun in the XY–plane, right panel – in the 3D space.

What causes the orbital oscillations in Z–coordinate (clearly visible on Fig. 1 and Fig. 2)? There are two reasons: 1) the position of the Sun is not exactly in the plane of the Galaxy (Z = 20.8 pc) and 2) the asymmetry of the potential due to the spatial shape of the bulge.

Thus, if the comet is lost by the Solar cometary spear, it is unlikely to meet the Sun again. Indeed, the size of the area or the dimensions of the target is 1000×100 pc.

5. The results of the simulation of the evolution of the Solar and star cluster comet spears

5.1. Comet Clouds Representation

Our model is consisting of decaying objects. We represent the objects themselves as gravitationally unbound points n=1000, point-centered at the time $t = 0$ and then scattering in all directions with particular velocity. The velocity module is different for each type of objects - comets, stars, and star clusters. The cloud lost by the Solar system includes $n = 1000$ points with velocities uniformly distributed over the sphere with radius $v_{ACP} = \sqrt{u^2 + v^2 + w^2}$.

In our study, we considered both clouds of comets leaving the planetary system (for example, the Sun), and clouds of comets lost by all the open cluster member stars. Cometary clouds, leaving the parent star, turn into spatially stretched structures resembling spears in their features. Over time, the spears begin to become cometary streams enclosed in a rings around the Galaxy Center.

5.2. Simulation study of ACPS

We consider two stages of the ACPS clouds formation:

– Comets lost by a star (Sun) with the velocity assumed to be the same for all comets and is 2 km s^{-1} (Tutukov et al., 2020);

– Star clusters disintegrate and loose individual stars at an average speed of 1 km s^{-1}.

As a result of the open cluster evolution, a spear consisting of stars and comets is formed. The calculation results of our model are presented in Fig. 3.

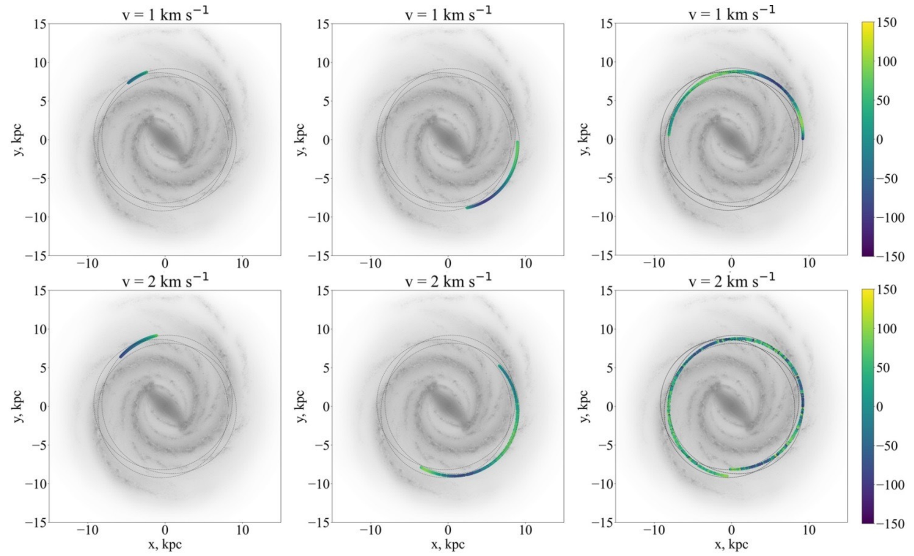

Figure 3. Evolution of stellar and cluster ACPS spears in the time intervals 1, 4.6 and 10 Gyr. Top panels show the evolution of the spear that scatters with velocity v = 1 km s^{-1}, bottom panel with v = 2 km s^{-1}. Color shows pc above the Galactic plane (Z–axis).

Obviously, over time $\approx$ 10 Gyr, the spear consisting of the stars and small bodies will close, revolving around the Galaxy Center and form an annular stream.

Comets and other members of the ACPS family leaving the parent star at speeds of several kilometers per second end up in the interstellar space of the Galaxy. Thus, a cloud resembling a spear is formed. We named the cometary spear of the Sun and other stars the solid-state ACP component lost by the Sun and other stars during the formation of their planetary systems. In a sense, they expand the boundary of the parent star's planetary system, effectively distributing the matter of this planetary system far beyond the star.

Stars with planetary systems soon begin to be accompanied by ACP clouds in the form of spears or even rings, depending on the age of the star. These objects are quite common in the Galaxy since about a third of the stars have planets (Masevich & Tutukov, 1988).

5.3. The width of the ACPS stream

We considering the kinematics of

- a cometary spear of the star (the Sun) – comets leave the Solar system at a velocity v = 2 km s^{-1};
- a cometary spear of the open cluster – comets leave the cluster at a velocity v = 1 km s^{-1}.

Fig. 3 shows the star (the Sun) with a cometary spear, and an open cluster with an aggregated comet spear. These spears make the same number of revolutions around the Galactic Center (22 for 5 billion years). The orbits fill a flattened torus with a cross-section of 100×1000 pc.

However, due to the potential of the Galaxy Eqs. 4 - 6 the comet stream is expanded to about one kpc, see Fig. 4. Fig. 4 demonstrate an increase in the filling density of the torus with orbits in the projection onto the XY plane.

As can be seen in Fig. 4, the comets cross-section density increases with a scattering velocity increasing. This is due to the expansion of the ACPS spear, the width of which depends on the peculiar velocity of the comets and galactic potential by Miyamoto & Nagai (1975) and Navarro et al. (1996).

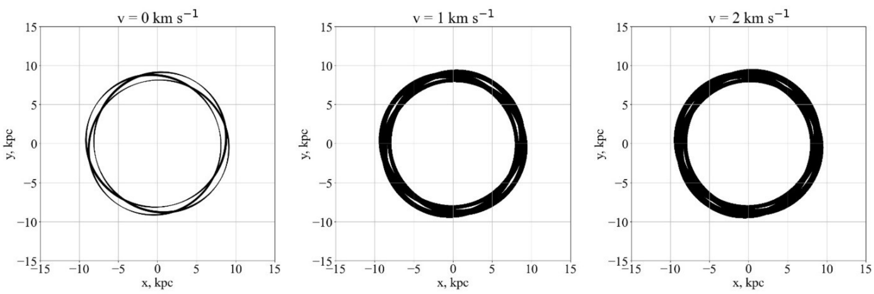

Figure 4. Calculation of the orbits of the Sun (left panel), clouds (spears) of Sun comets (middle panel), spears of cluster comets (right panel). Integration time is 4.6 billion years.

6. Conclusion.

This work is devoted to the numerical study of the evolution of the orbits Free (unbound) ACPS in the Galaxy, leading to their transformation into cometary spears of the Sun, stars, star clusters. Gradually, they form a well–populated ACP component of the Galaxy, composed of filaments of evolved ACP clouds.

The stellar component of the ACPS spears is now discovered for several clusters with ages $\sim 10^8$ years (Li et al., 2021). Their length corresponds to the expansion velocities ~ 0.5 km s^{-1}. Thus, the formation of ACPS spears of open clusters is well supported now by observations.

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