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Mock observations of simulated star cluster on solar orbit

With the advent of the Gaia DR2 catalog, which contains astrometric and photometric parameters for a large number of stars, measured with a high degree of accuracy, data about the cosmos and the Universe, including Star clusters in our Galaxy, are growing. However, when observed, the cluster stars are lost against the background of stars in the dense Galactic field. In addition, observational data alone is not sufficient to study real clusters from birth to destruction. In this regard, a number of numerical simulations of star clusters have been running to explain the processes and to determine the membership of cluster stars. And for this, we need to conduct a mock observation of model clusters. In this paper, we performed analyses on the output data from numerical simulations and developed a method for conducting mock observations of model clusters.

We took one model of a star cluster with an age of 350 Myr, with a mass of 6000 $M_\odot$, and with a star formation efficiency SFE=0.25, and put it in different galactic longitudes and at different distances from the Sun. In conclusion, using this method, we can put a cluster at any point on the celestial sphere, and this in turn allows you to compare with the real observed clusters and evaluate the possibility of detecting physical parameters in them.

Key words: star cluster, galactic coordinates system, equatorial coordinates system, numerical simulations.

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Күн орбитасындағы сандық модельденген жұлдызды шоғырларды бақылау

Жоғары дәлдікпен өлшенетін, жұлдыздардың үлкен санына арналған астрометриялық және фотометриялық параметрлері бар Gaia DR2 каталогының пайда болуының арқасында, ғарыш пен Ғалам және соның ішінде, біздің Галактикадағы жұлдыз шоғырлар туралы деректер артып келеді. Дегенмен Галактиканың тығыз өрісіндегі жұлдыздар фонының әсерінен бақылау кезінде жұлдыз шоғырлары жоғалып кетеді. Сонымен қатар нақты кластерлерді туғаннан ыдырағанға дейін зерттеу үшін тек бақылау деректері жеткіліксіз. Осыған байланысты процестерді түсіндіру және жұлдыздардың шоғырға мүшелігін анықтау үшін жұлдыз шоғырларының бірқатар сандық модельдеулері жүргізіледі. Ал ол үшін жасалған кластерлерді ойша бақылау жүргізу керек. Бұл мақалада біз сандық модельдеу нәтижелерін талдадық және модельдік кластерлердің аспан сферасында ойша бақылау әдісін әзірледік.

Жасы 350 миллион жыл, массасы 6000 $M_{\odot}$ және жұлдыз түзілу тиімділігі SFE=0.25 болатын бір жұлдыз шоғырының үлгісін алып, оны әртүрлі галактикалық бойлықта және Күннен әртүрлі қашықтықта орналастырдық. Қорытындылай келе, осы әдісті қолдана отырып, біз кластерді аспан сферасының кез келген нүктесіне орналастыра аламыз және бұл өз кезегінде нақты бақыланатын кластерлермен салыстыруға және олардағы физикалық параметрлерді бағалауға мүмкіндік береді.

Түйін сөздер: жұлдызды шоғырлар, галактикалық координаттар жүйесі, экваторлық координаттар жүйесі, сандық модельдеу.

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Мнимые наблюдения моделируемых звездных скоплении на солнечной орбите

С появлением каталога Gaia DR2, содержащего астрометрические и фотометрические параметры для большого числа звезд, измеренные с высокой степенью точности, данные о космосе и Вселенной растут, в том числе данные о звездных скоплениях в нашей Галактике. Однако при наблюдении звезды скопления теряются на фоне звезд в плотном поле Галактики. Кроме того, одних наблюдательных данных недостаточно для изучения реальных скоплений от рождения до распада. В связи с этим проводится ряд численных симуляций звездных скоплений для объяснения процессов и определения принадлежности звезд скопления. А для этого нам нужно провести мнимое наблюдение за модельными кластерами. В этой статье мы провели анализ выходных данных численного моделирования и разработали метод проведения мнимых наблюдений модельных скоплений.

Мы взяли одну модель звездного скопления с возрастом 350 млн лет, массой 6000 $M_{\odot}$ и эффективностью звездообразования SFE=0.25 и разместили ее на разных галактических долготах и на разных расстояниях от Солнца. В заключение сделан вывод: с помощью этого метода мы можем поставить скопление в любую точку небесной сферы, а это в свою очередь позволяет сравнить с реально наблюдаемыми скоплениями и оценить возможность обнаружения в них физических параметров.

Ключевые слова: звездное скопление, галактическая система координат, экваториальная система координат, численное моделирование.

Introduction

There are a lot of rarefied gas and dust in space, the so-called molecular clouds. Stars appear in such Molecular clouds. And the volume of such gas is very large, and this leads to the formation of stars in groups [1, 2]. The number of such stars in groups reaches from 103 to 107 stars, and they can be considered peers, since they appear almost at the same time on a relatively galactic time scale. During the formation of stars, there is a response coming from massive stars in the form of ionizing radiation, stellar winds and light pressure can easily destroy an entire molecular cloud [3, 4]. The size and dynamic state of the cluster play an important role, since stars can live in the parent cluster for up to several billion years depending on it [5]. Also, The secular evolution of star clusters, especially the time of their decay, can vary greatly depending on the cluster mass, density profile and the impact of the galactic tidal field [6, 7, 8, 9].

Along with the development of technology, new methods of exploring the cosmos and the Universe are growing. Analyzing this data, we will get a detailed understanding of star clusters, and this in turn gives a new understanding of the Galaxy and the Universe as a whole. Studying star formation in our Galaxy and in other galaxies leads to knowledge about the evolution of galaxies [10, 11].

Also, when conducting observations, the study of groups of stars is relatively easier than single stars. And in extra galactics it is impossible to observe single stars at all. Due to the fact that the stars in the groups are almost the same age, we are given privileges when determining the ages of the stars of the group. Therefore, the study of the population of star clusters and their age distribution allows us to learn the history of star formation in the vicinity of the Sun and in galaxies [12]. It is very important for us to know the processes in clusters for a correct understanding of observational data, and a wrong understanding can distort information about the universe as a whole.

However, despite the improvement of telescopes, there remain difficulties in observing star clusters, separating stars belonging and not belonging to the cluster, and, consequently, difficulties in studying the structure and determining various parameters of the cluster. To understand the evolution of star clusters, we perform numerical simulations. This significantly reduces the study time from birth to the collapse of one cluster than the study through observation. To do this, we will need to develop a method for observing numerical models of clusters.

In addition, conducting imaginary observations of model clusters makes it possible to evaluate the possibility of detecting so-called tidal structures in actually observed star clusters, which, according to numerical modeling, should be observed in middle-aged clusters evolving in the tidal gravitational field of the Galaxy. Difficulties in detecting these structures are associated with a small number of stars in them, which is why they were lost against the background of stars of a dense galactic field. With the advent of the GAIA DR2 catalog, which provides astrometric and photometric parameters for an unprecedented large number of stars, measured with a high degree of accuracy and homogeneity, the search for tidal tails became possible. The main Gaia DR2 catalog [13] contains five-parameter astrometric solutions (coordinates, proper motions and parallaxes) for 1,330 million stars, visible stellar magnitudes in the Gaia G photometric band, as well as in the red GRP and blue bands GBP, for 1.380 million stars. Gaia's array of astrometric and, in a number of respects, photometric data is unprecedented in volume and accuracy. In the last 2-3 years, using these data, structures that are presumably tidal tails have been detected in several clusters [14, 15, 16, 17], but this is clearly not enough to confidently confirm the results of numerical modeling and to further study the dynamic evolution of star clusters.

In this paper, methods are discussed and the results of imaginary observations of model clusters are presented. The initial data for numerical simulations are done in the same way as in [18, 19, 20] works, using the Phi-GRAPE code.

Development of instruments for mock observations of star clusters

Our simulation of the dynamics of a stellar cluster is carried out in a Cartesian galactocentric coordinate system. To make a comparison with real star clusters that are located in our Galaxy, the first step is to translate the positions and velocities of the cluster star into spherical galactic and equatorial coordinate systems, while placing the cluster at different points of view and different distances from the Sun.

After running the simulation of the star clusters, we will get the output data (file.dat), which contains information about each star given in Table 1. In addition, the first three lines of each file (snapshot) show the snapshot number, the number of particles (stars) in the cluster and the age of the cluster in NB-units.

We introduce Cartesian galactocentric coordinates of the so-called Local Standard of Rest (LSR) - a point in space that defines the origin of the coordinate system in stellar astronomy.

$$X_{LSR}=8178 \text{ pc } (+-13\text{pc}),\ Y_{LSR}=0.0 \text{ pc},\ Z_{LSR}=0.0\text{pc},$$

$$VX_{LSR}=0.0 \text{ km/s},\ VY_{LSR}=224.737 \text{ km/s},\ VZ_{LSR}=0.0 \text{ km/s}. \quad (1)$$

Coordinates of the Sun relative to LSR:

$$X_{\odot}=0.0 \text{ pc},\ Y_{\odot}=0.0 \text{ pc},\ Z_{\odot}=20.8\text{pc } (+-\ 0.3 \text{ pc}),$$

$$VX_{\odot}=11.10 \text{ km/s},\ VY_{\odot}=12.24 \text{ km/s},\ VZ_{\odot}=7.25 \text{ km/s}. \quad (2)$$

Table 1

Designation in the code	Denoted value	Unit of measurement
ind	Name (numbering) of stars	
m	Mass at the moment of a given age	NB
x,y,z	Cartesian coordinates (from the center of the Galaxy)	NB
vx,vy,vz	Cartesian velocities (from the center of the Galaxy)	NB
m0	Initial mass	NB
ZZZ	Metallicity of the star	
t0	The time of the appearance of a star	NB
event	Type of star	
SSE MAss	Star mass	M_{SUN}
SSE Spin	Rotation of the star on its axis	
SSE Rad	Star radius	R_{SUN}
SSE Lum	Star luminosity	L_{SUN}
SSE Temp	Star temperature	Kelvin K
SSE MV	Absolute magnitude	
SSE BV	Color indicator	

To rotate the coordinate system around the Z axis by the required angle (ϕ), we will perform the following operations:

$$X_G = x \cdot \cos\phi + y \cdot \sin\phi, \quad Y_G = -x \cdot \sin\phi + y \cdot \cos\phi, \quad Z_G = z, \qquad (3)$$

$$VX_G = vx \cdot \cos\phi + vy \cdot \sin\phi, \quad VY_G = -vx \cdot \sin\phi + vy \cdot \cos\phi, \quad VZ_G = vz. \qquad (4)$$

After we can transfer from a galactocentric system to a heliocentric one:

$$X_\star = X_G - X_\odot - X_{LSR}, \quad Y_\star = Y_G - Y_\odot - Y_{LSR}, \quad Z_\star = Z_G - Z_\odot - Z_{LSR}, \qquad (5)$$

$$VX_\star = VX_G - VX_\odot - VX_{LSR}, \quad VY_\star = VY_G - VY_\odot - VY_{LSR}, \quad VZ_\star = VZ_G - VZ_\odot - VZ_{LSR}.$$

Next, we find the galactic spherical coordinate system, there are distance d, galactic longitude l and galactic latitude b, also the radial velocity Vr, proper motions in l and b – pml and pmb.

$$d = \sqrt{(X_\star^2 + Y_\star^2 + Z_\star^2)},$$

$$l = \mathrm{atan2}(Y_\star, X_\star),$$

$$b = \mathrm{asin}(Z_\star/d), \qquad (6)$$

$$V_r = \cos l \cdot \cos b \cdot VX_\star + \cos b \cdot \sin l \cdot VY_\star + \sin b \cdot VZ_\star.$$

$$pm_l = (-\sin l \cdot VX_\star + \cos l \cdot VY_\star)/d, \qquad (7)$$

$$pm_b = (-\sin b \cdot \cos l \cdot VX_\star - \sin l \cdot \sin b \cdot VY_\star + \cos b \cdot VZ_\star)/d.$$

Thus, we rotate our cluster relative to us by the required angle and find its spherical galactic coordinates. Then, using the Python package [21], we switch to the equatorial coordinate system.

Results

We took one model of a star cluster with an age of 350 Myr, a mass of 6000M_ ⊙ and a star formation efficiency SFE=0.25. Using our method, we put the cluster models in a certain position relative to the Sun and calculated the spherical coordinates, distances, proper and radial motions of stars in this cluster position. Figure 1-2 show the spatial and velocity distribution of the stars of this cluster in galactocentric Cartesian coordinates. In all N-body simulations that have been launched in the potential of the galaxy, stars appear that refer to tidal tails. It can be seen that the cluster began to collapse, forming at the same time at some distance from the center (220-280 pc) clearly distinguishable tidal structures. Also, the velocities of the tidal tail stars differ from the cluster stars, and thus we can notice them in the velocity distribution too. After that, we put the same model in different places along the galactic longitude and at different heliocentric distances (Table 2).

Table 2

№	Galactic longitude (l) [degree]	Heliocentric distances (d) [pc]	Right ascension (α) [degree]	Declination (δ) [degree]	Color on plots
1	270.7^0	200 pc	131.5^0	-52.7^0	blue
2	86.5^0	1000pc	315.7^0	45.02^0	orange
3	277.02^0	2000pc	145.25^0	-53.7^0	red

Figures 3-5, for example, show the results of such a study of a model cluster located in the plane of the galactic disk at a different heliocentric distance and at a different galactic longitude. As we can see, the tidal tails, which are very clearly visible in Figures 1-2, are no longer quite noticeable. It may depend on the angle of view. And of course, the further away the cluster is, the smaller it becomes (Figure 5).

Figures 6-8 show diagrams of right ascension - declination and proper motion in right ascension – proper motion in declination for stars of this cluster. After putting the model cluster on the celestial sphere, the appearance of our cluster may change. But still, the heliocentric distance plays a big role in observation.

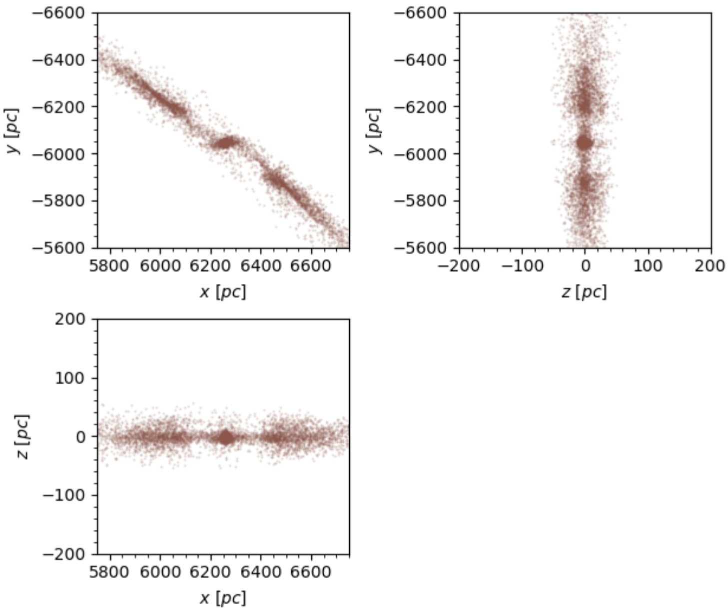

Figure 1 – Spatial distribution of the stars of the model cluster in galactocentric Cartesian coordinates

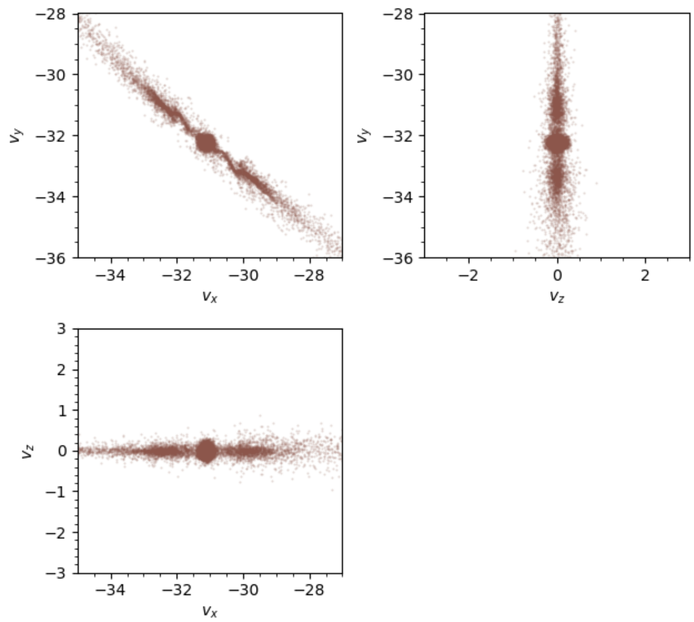

Figure 2 – Velocity distribution of the stars of the model cluster in galactocentric Cartesian coordinates

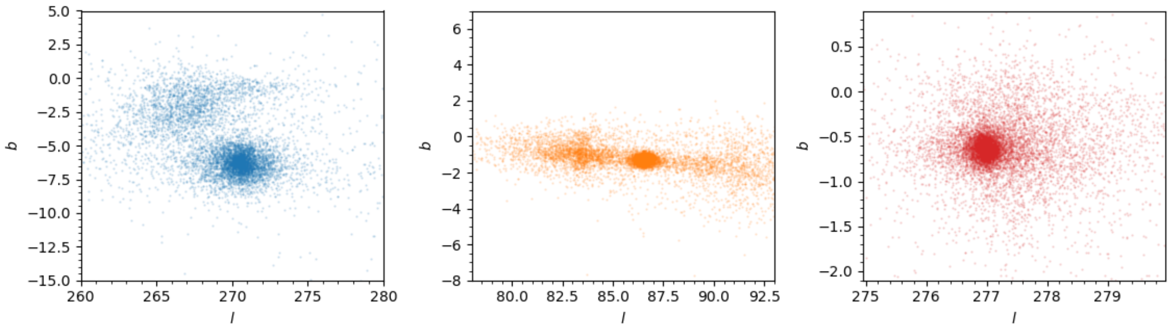

Figure 3 – Galactic latitude l and longitude b diagram of cluster stars

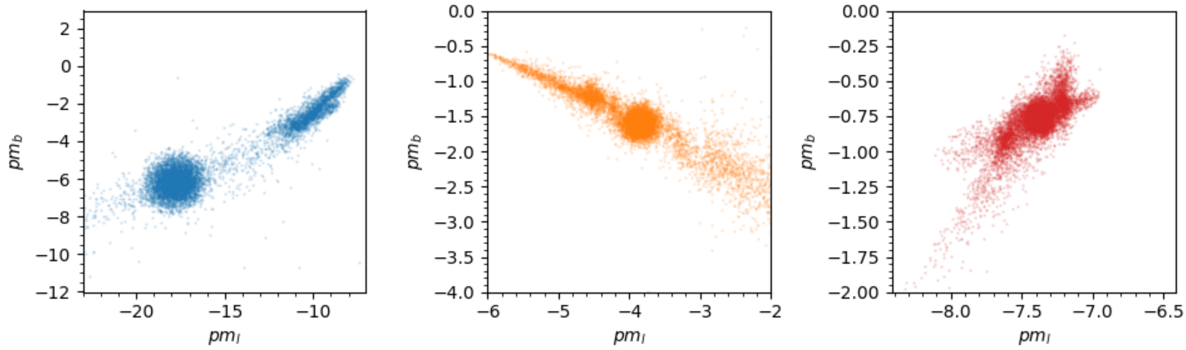

Figure 4 – proper motion by galactic l and longitude b diagram of cluster stars

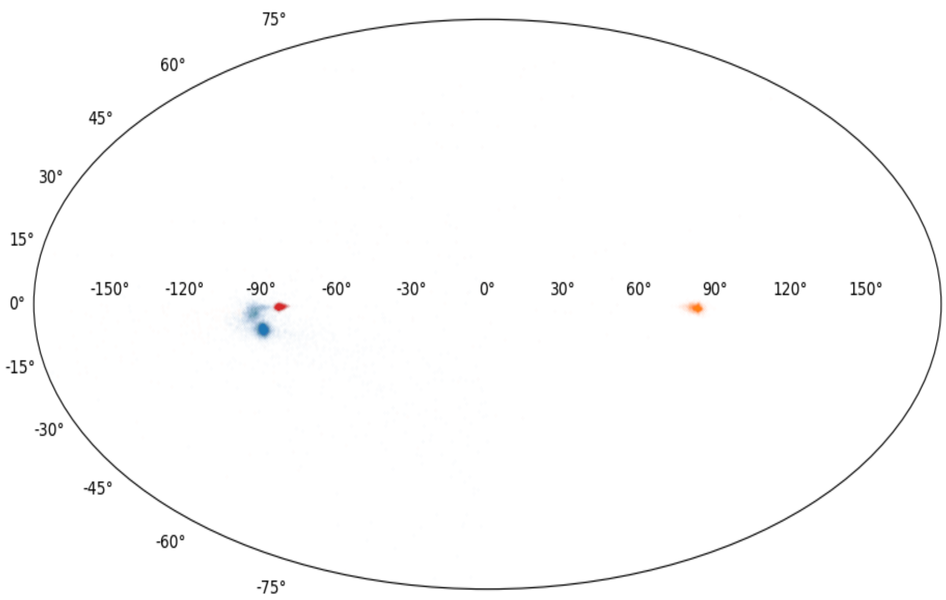

Figure 5 – Galactic latitude l and longitude b diagram of cluster stars

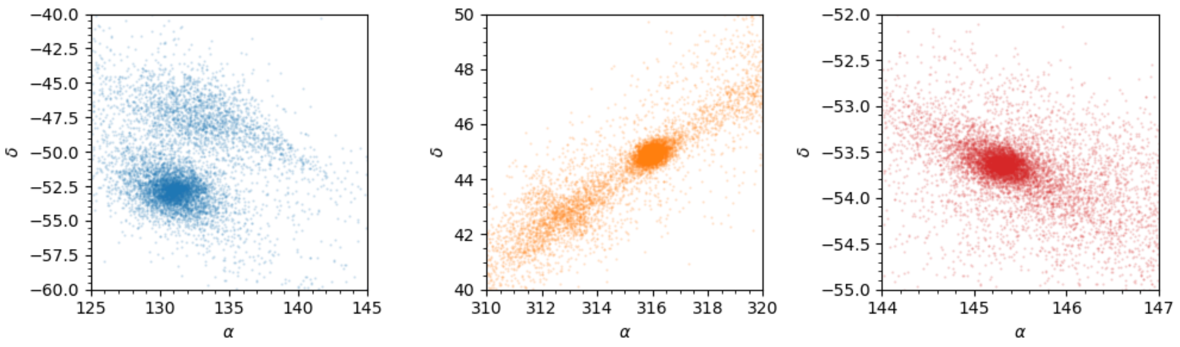

Figure 6 – Right-ascension–declination diagram for the stars

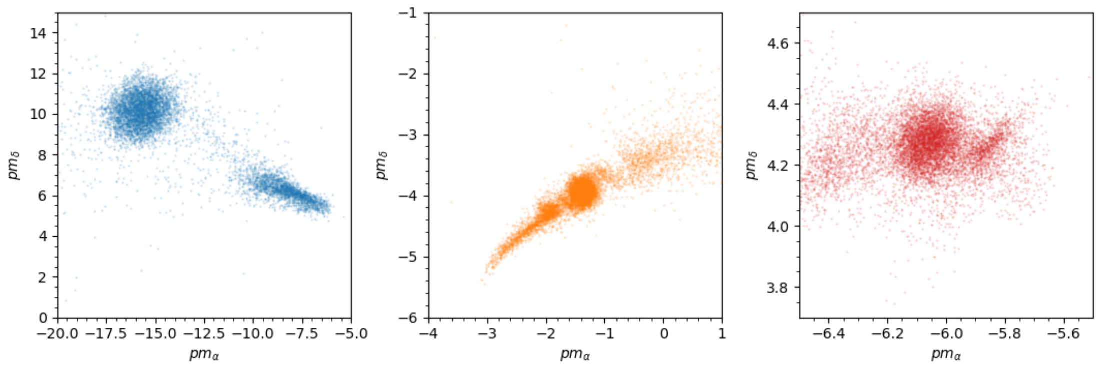

Figure 7 – Diagram of proper motion in right ascension – proper motion in declination for the stars

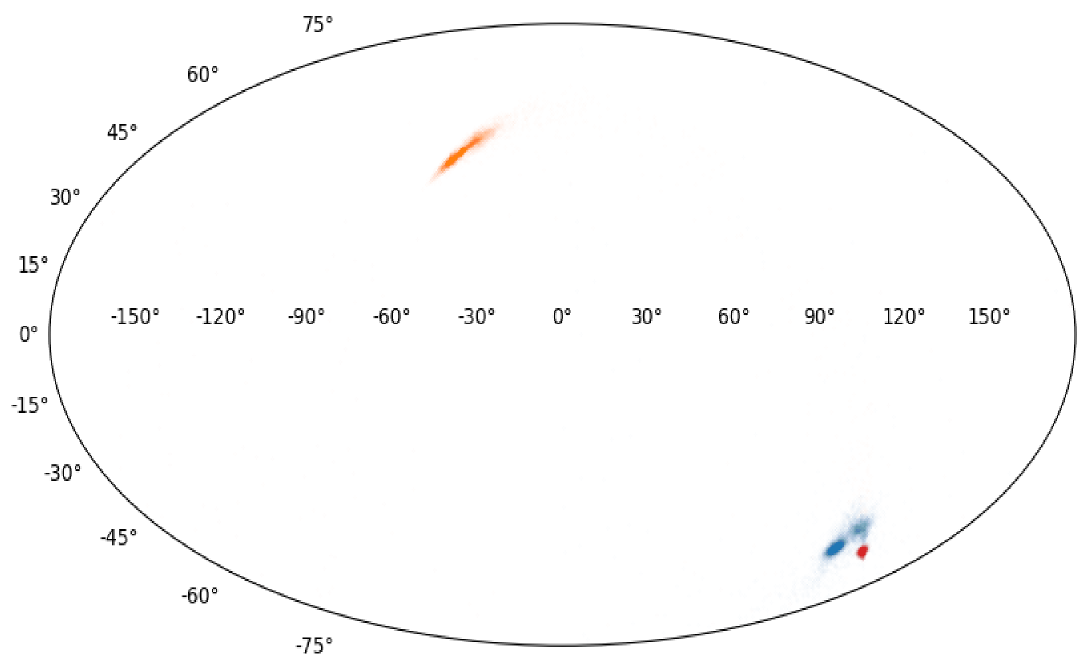

Figure 8 – Right-ascension–declination diagram for the stars

Conclusion

Runs for numerical simulation of star clusters were carried out repeatedly with different initial data. From these runs, one model was chosen with the Age = 350 Myr, mass is 6000M, and star formation efficiency SFE=0.25. Also, the chosen cluster rotates around the center of the Milky Way galaxy at a distance equal to the Solar distance. The simulation clearly shows that clusters have a tidal tail that starts at a distance from the center with 220 pcs. To compare numerical models with real observational data, it is necessary to conduct a mock observation of cluster stars from the simulation. To do this, a code has been developed for putting our cluster on the celestial sphere. The results show that depending on the galactic longitude and distance, a star cluster may have a different shape. Since the same model was placed at different angles and distances from us (but the cluster still remains in its orbit). In addition, particles of one tidal tail are sometimes visible, and the second is not observed, and sometimes it coincides with the angle of vision and is not visible, this confuses observers. However, we can say that by the proper motion of the stars in the right ascension and declination, that the particles of the tails differ from the main cluster.

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