What Will Lead the Astrometry Data Accuracy Breakthrough in the Study of Star Clusters?

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Abstract. Star clusters are the most important objects of the Galaxy, allowing to study many questions of its structure and evolution. The combination of gigantic growth of information and breakthrough growth in the accuracy of astrometric measurements allow us to talk about new aspects related to the concept of data intensive domains (DID). It is shown how the accuracy of the data and the increase in the volume of measurements accompany each other and lead to the need for intensification of processing. The latter in its turn will lead to the appearance of new important results for both star clusters and the Galaxy as a whole.

Keywords: star catalogs, open star clusters, proper motions, velocity dispersion.

1 Introduction

The accuracy of measuring astrometric data (proper motions and parallaxes) is a significant aspect for the study of open clusters. The stellar clusters belonging to the disk of the Galaxy are traditionally named as open clusters (OC). The stars of the OC, as a rule, are identified by their proper motions diagrams. A cluster is a system of genetically connected stars that have a common motion in space. The accuracy of measurements plays a decisive role in constructing spatial models and studying the physics of stellar systems. The microsecond accuracy of the angular measurements achieved at the present time in Gaia (Global Astrometric Interferometer for Astrophysics) project [3, 4] will allow us to consider the physics of processes inside stellar systems, to make reliable estimates of the parameters characterizing the OC, will allow to consider experimentally the dissipation of stars, obtain the parameters of the speed ellipsoids, and much more.

The discovery of the proper motions of the stars belongs to the famous English astronomer Edmond Halley, who in 1718 finds out that some bright stars from the catalog of Hipparchus-Ptolemy markedly changed their positions relative to other stars. For example, Sirius is shifted to the south by almost half the diameter of the Moon, [7]. It is curious that it took almost 2,000 years to recognize the motion of stars that were considered immovable, and to estimate at least the order of the value of their motion. This revolution in astronomy occurred not only due to the emergence of the laws of Newtonian mechanics, but also the use of measurements of the star positions in different epochs.

We put an emphasis on the study of star clusters because they are space laboratories and they are located on a region of the sky with a size that accessible for full-scale observation in a telescope. Clusters are areas of high concentration of stars of different masses and types in a small area of the sky. This is effective for making observations, since they fall into one or a small number of observation frames. Group image allow to observe simultaneously so many different stars, as well as to open effectively new objects. Clusters are also convenient for the searching of exoplanets. Over 5000 exoplanet candidates have been discovered orbiting around isolated stars. Many of these stars are once formed or existed in open star clusters.

2 About Data from the Gaia project

What are the characteristics of modern data for their belonging to the category of Big Data and the possibility of their intensive using? Modern astronomers were lucky to work in the period when specialized satellites (space observatories) are launched, aimed at measuring the parameters of distant objects. The Gaia space project [3] is unprecedented both in the accuracy of measurements of position and motion of the stars and in the covering of the sky with stars. These factors, among other things, allow categorize this information both the Big Data, if we take into account the volume, and the data of intensive use, if we talk about the methods of processing.

Gaia is the space telescope of ESA (European Space Agency). It was launched in December 2013. The main goal of the Gaia project is to compile a detailed map of the distribution of Galactic stars. The program of observations with this instrument is designed for five years and will end in 2019. Then, it takes time for the final processing of all data. The data of the first 22 months of observations are presented to this time. Potentially Gaia catalog will allow many times to increase the number of known OC (approximately from 4,500 to 100,000, see [12]). In the second edition of this catalog [4], (second release) or Gaia DR2, coordinates, parallaxes, radial velocities, proper motions, variability data and some other parameters for stars brighter than 21 mag are collected. Different data is available for a different number of objects. Position and photometry - for 1,692,919,135 stars. For 1,331,909,727 of them,

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parallaxes and their proper motions are also available. Radial velocities are given for more than 7 million stars. The star variability data are given for more than half million stars. Also, there are data on 14,099 bodies of the Solar System (mainly on the asteroid of the Main Belt). Table 1 lists some useful characteristics of the catalog in question.

Table 1 Characteristics of Gaia DR2 catalog [3]

Catalogue completeness	0.77×10^6 to G = 10 mag; 47×10^6 to G = 15 mag; 360×10^6 to G = 18 mag; 1192×10^6 to G = 20 mag.
Sky density	mean density ~25000 stars deg−2; maximum density ~750000 stars deg−2
Parallax accuracies	7 μas at G = 10 mag; 26 μas at G = 15 mag; 600 μas at G = 20 mag.
Radial velocity accuracies	1–15 km s−1 to GRVS ≈ 16 mag, depending on spectral type
Tangential velocity accuracies	5 million stars better than 0.5 km s−1; 10 million better than 1 km s^{-1}; 25 million better than 3 km s^{-1}; 40 million better than 5 km s^{-1}; 60 million better than 10 km s^{-1}
Distance accuracies from Galaxy model	10 million better than 1 percent; 20 million better than 2 percent; 50 million better than 5 percent; 100 million better than 10 percent

Also Gaia DR2 provide astrophysical information, such as interstellar reddening, atmospheric parameters, and rotational velocities, for stars brighter than G ≈ 12 mag (~5 million stars) [3].

3 Astrometry measurement accuracy

3.1 Accuracy of measurements at different observation epochs

With what astrometric measurements began the astronomers? Ancient Greek astronomers began work on the definition of stellar coordinates in the first half of the III century BC. The first in Europe star catalog was created by Hipparchus. This catalog included precise coordinates for 850 stars. Then the data were supplemented by Ptolemy himself and other Alexandrian astronomers, increasing the number of stars in the catalog to 1022. The size of Ptolemy's measuring instruments did not exceed 10 minutes. Classic work of Claudius Ptolemy "Almagest" appeared in 140 AD and included a full complex of astronomical knowledge of that time. Ptolemy's catalog, included in the Almagest, is the only ancient astronomical catalog that has come down to us. For each object Ptolemy gives a description of the position in the constellation, indicates the celestial coordinates and magnitudes. The value of this catalog, like the entire "Almagest", can not be overemphasized. "Almagest" for 13 centuries remained the basis of astronomical research. Only in the 15th century did another star catalog appear (Ulugbek), based on original observations, although the accuracy of the measurements did not exceed one in the Ptolemy's catalog. The first European high-precision catalog was published by Tycho Brahe at the end of the 16th century.

English astronomer Edmund Halley in 1718 found that some bright stars from the catalog of Hipparchus-Ptolemy markedly changed their positions among other stars. Among others were Sirius, shifted to the south by almost half the diameter of the Moon (the apparent angular diameter of the Moon at an average distance from the Earth is 31'05"), Arcturus moved on two diameters to the south and Aldebaran, displaced 1/4 of the diameter of the Moon to the east. The changes could not be attributed to the errors of the Ptolemy catalog, which, as a rule, did not exceed 6' (1/5 of the diameter of the Moon), [7].

The first international project - the "Carte du Ciel" catalog was adopted on the initiative of the astronomers of the Paris Observatory in 1887. This project involved photographing with a double overlap of the entire sky with the help of the Henry brothers astrographs (D = 230 mm, F = 3460 mm, field 2° x 2°). It was carried out only in 1938. Photographic plates (about 20,000) were measured and stored at 23 observatories in different countries. The measured coordinates of about three million stars to the 12-th mag are published. The "Sky Map" catalog has now acquired a special value as a document showing the relative positions of stars up to the 12-th magnitude throughout the sky in an epoch close to 1900. This catalog is widely used to determine the photographic proper motions of stars with a high accuracy - up to ± (0.003-0.006) "/yr with the difference of epochs of the order of 100 years.

As a result of the Hipparcos (HIgh Precision PARarallax COllecting Satellite) [10], which performed millions of star measurements in the time period of 37 months, two star catalogs were obtained. The HIPPARCOS catalog contains the coordinates, proper motions and parallaxes measured with error about one thousandth of a second, for 118,218 stars. This accuracy for stars is achieved in astrometry for the first time. In the second catalog - TYCHO, was given a slightly less accurate information for 1,058,332 stars. The creation of these two catalogs marked the birth of a new direction - space astrometry.

In 2013, the European satellite Gaia was launched. The goal of this project is to measure coordinates, proper motions and parallaxes for 50 million stars with accuracy better than 10 microseconds of arcsec (1 millisecond = 1/1000 seconds, denoted by mas, 1 microsecond = 1×10^6 seconds denoted by μas).

The effect of increasing accuracy and an increase in the number of measurements of stellar motions with time and that gave the above accuracy of Gaia DR2 astrometry is shown in Figure 1. The main data are collected in Table 2. The measurement accuracy of this section will be discussed in the next section. The accuracy is extremely useful and needed to be able to talk about the physics of different phenomena in the OC.

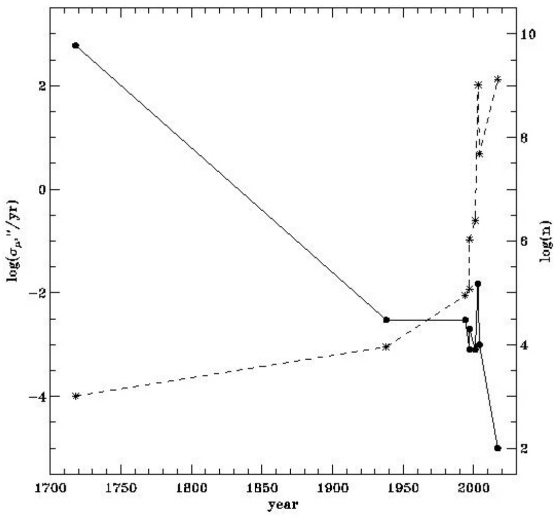

Figure 1 The increase in the accuracy of the proper motions measuring (bold points) and the number of stars (asterisks) with time

Table 2 Increase with time in the accuracy of measuring of the proper motions of stars in different catalogs, [12]

Year	Proper motion accuracy		n	catalog name
	min	max		
1718	600.0	600.0	1022	Ptolemy's catalog is used
1938	0.00300	0.00600	9055	Carte du Ciel, [11]
1994	0.00300	0.00420	89676	PPM, [9]
1997	0.00080	0.00200	118218	Hipparcos, [10]
1997	0.00200	0.00600	1,058,332	Tycho-2, [5]
2001	0.00080	0.00600	2,500,000	ASCC-2.5, [6]
2003	0.01500	0.07000	1,045,175,762	USNO-B1.0, [8]
2004	0.00100	0.02000	48,330,571	UCAC2, [14]
2017	0.00001	0.00001	1,331,909,727	GAIA DR2, [4]

In Figure 1, three periods of development of the considered measurements are presented. From 1700 to 1938 - a huge increase in accuracy, almost 500 times associated with the improvement of mainly measurement techniques. The next period - the plateau from 1930 to the early 2000-th is associated with the commissioning of large mirrors, and the third period of sharp growth in accuracy, the straight line is almost vertical down! It is the development of cosmic astrometry, related to measurements from space instruments.

3.2 On the magnitude and accuracy of peculiar (internal) motions of stars in clusters

For a long time the answer to the question of what real velocities the stars have inside the clusters remains a mystery. Various calculations show that in such stellar systems as the OC, these velocities are extremely small, see Table 3.

Table 3 The predicted in calculations velocity dispersion inside the OC, the cluster radius is 100 pc

Mass, M_{SUN}	dispersion, km/s
100	0.05
400	0.09
1000	0.14
10000	0.46

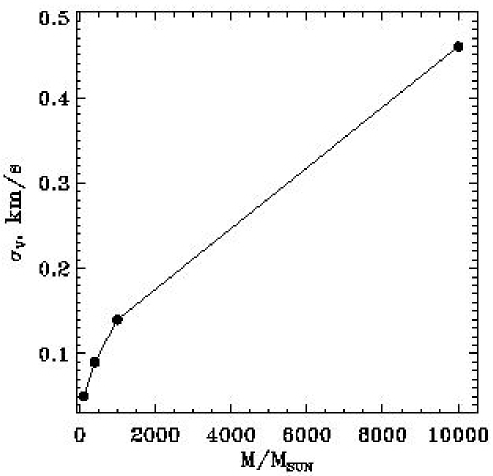

Figure 2 The predicted velocity dispersion of stars inside the OC

The dynamics of an isolated OC is equivalent to the classical problem of n bodies. The magnitude of the average residual motions is presented in Table 3 for several values of mass and cluster radius. The values obtained from the formulas are in excellent agreement with the observed dispersion. Although such observations are extremely small, they are not reliable and are made, of course, only for the nearest clusters. So for the Pleiades, the total mass of stars can be assumed equal to 300 solar masses and a radius of 3.5 pc. In this case, we find the dispersion of 0.43 km/s, which agrees perfectly with the observations of 0.42 km/s, [1].

3.3 OC in Gaia DR2

Data intensive methods should be effective for working with large volumes of clusters data, as well as their processing and extraction from Gaia DR2.

Let us consider the dependence of the proper motion on parallax, expressing the angular measurements of the proper motions in the scale of spatial (tangential) velocities in km/s units. Considering the contents of the entire catalog, it is necessary to distinguish the proportion of stars having the values typical for the peculiar velocity of a star in the cluster, Table 3. Having passed this chain in the opposite direction from the value of the tangential velocity to the parallax value, it becomes clear for what volume of the catalog data this boundary is valid. Comparison of the obtained boundary with respect to the parallax with the distribution of the number of Gaia DR2 stars along the parallaxes makes it possible to reveal the expected number of stars for which

DID will give measurements of sufficient accuracy for studying the motions or kinematics of stars inside the OC. Now it is possible to understand what and how many OC can be expected up to a given distance from the Sun (parallax).

Let us take the velocities characteristic of real clusters, see Figure 2. We use the formula $V_t = 4.74\frac{\mu}{\pi}$, km/s. By this formula, we obtain approximately the relationship between proper motion and parallax: π=10μ, where they are expressed in the same units of measurement. A convenient ratio roughly corresponds to measurements with an accuracy of about 0.474 km/s (this value is chosen specifically from real values on Figure 2 to simplify the relationship between π and μ above), which is necessary to understand the kinematics of stars inside clusters.

Table 4 The distances to which Gaia DR2 covers the stars, [3]

Star type	π, mas	π, arcsec	r_{SUN}, pc
up to $V=20^m$			
Bright (B1V)	600	0.0006	1700
Faint (M6V)	130	0.00013	7500
up to $V=15^m$			
Bright (B1V)	26	0.000026	3900
Faint (M6V)	9	0.000009	10000

As can be seen in Figure 1 (and Table 2), the unprecedented high accuracy of Gaia DR2 measurements is approximately 0.00001 angular seconds. This corresponds to the formula above parallax equal to an order of magnitude less than 0.0001 angular sec (which corresponds to a distance from the Sun equal 10 kpc).

Table 4 shows the characteristic limiting distances from the Sun to various stars in Gaia DR2. Thus, this accuracy makes it possible to study almost all the clusters of Gaia DR2 (see Table 4, where we see this limit corresponds to the weakest stars up to $V=15^m$). As already mentioned, in this case the accuracy exceeds the value of the peculiar velocities of membership stars in clusters. Thus, it can be assumed that Gaia's data help one can study the kinematic structure of clusters located in a large part of the Galaxy (up to its center, located about 8 kpc from the Sun). This picture is somewhat overshadowed by the fact that to determine star distances, especially for distant clusters (at distances exceeding only 200 pc!), Gaia parallaxes in pure form are unsuitable and additional procedures are being developed for their use, [2].

4 Conclusion

As estimated [12], according to Gaia's data, up to one hundred thousand previously unknown star clusters can be found. Although it is very difficult to distinguish the cluster stars from field stars. What opportunities for studying the OC give the catalogs. Whether the necessary accuracy limit is reached or when to expect it. To what clusters by the distance from the Sun, the modern measurement technique yields valuable data that can correctly estimate the processes inside the clusters. We tried to answer these and similar questions in this publication.

We see that the increase in the accuracy of astrometric measurements has slowly increased over the course of about two hundred years (from the 10 minutes at the beginning of the 18th century to the 30s at the 19th century). Over the past 20 years, there has been a real breakthrough in accuracy.

The discovery with Gaia's data of new, previously unknown clusters, has already begun, for example [2]. The first dozens of previously unknown clusters have already found. By the way, before this search, a lot of work was done on the intensive search (application of DID technology!) for currently known clusters. Was compiled a list of known clusters from the different sources. Then by Gaia DR2 data to the stars selected within the fields of those clusters a membership rule was apply. As a result, there were discovery of 60 new open clusters, which are not included in the combined list. Thanks to the quality of Gaia DR2 astrometry, the homogeneous high precision parameters derived, [2].

It is very important to mention the problem of determining distances by parallaxes. The distances to the clusters are estimated through a maximum likelihood procedure, maximising the posterior probability density function with taking into account many parameters, such as the measured average parallax for each of the membership stars and the distribution of stars inside the cluster.

The distances to clusters with mean parallaxes smaller than ∼ 0.2 mas would be better constrained by a Bayesian approach using the star density distribution of the Milky Way or the cluster model.

The Gaia DR2 parallaxes are affected by a zero-point offset. To accounted for this bias, add +0.029 mas to all parallaxes before distance estimation.

He led to the fact that for almost all OC in the Gaia project (and in their future will be open about 100 thousand) it will be possible to study previously inaccessible processes inside the clusters. This, in turn, represents the prospect of revolutionary changes in the science of clusters. Undoubtedly, there can be methods of intensive data use.

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