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Review

Achievements of Space Astrometry

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Abstract—Astrometry is the basis for astronomical observations and measurements of coordinates and time. Its main task is to implement a reference frame—the one mentioned in Newton's first law. Since ancient times, astronomers have created star catalogs for this purpose. Work on them led to the discovery of the precession and nutation of the Earth's axis, proper motions and parallaxes of stars, and the orbital motion of binary stars. The modern International Celestial Reference Frame (ICRF) is based on observations in the radio and optical range of very distant objects—quasars. It is to them that the GPS or GLONASS system is tied in the navigation device. The 21st century, with its computational capabilities, has led to the creation of star catalogs of unprecedented power, containing over a billion objects. However, the main breakthrough, even a revolution in astrometry, has happened in space observations. Two spacecraft have already created star catalogs of fantastic accuracy, which makes it possible to approach the solution of problems even the setting of which was unthinkable a few years ago. This article is dedicated to an overview of the achievements of astrometry over the past two millennia, massive star catalogs, and space astrometric projects.

Keywords*:* astrometry; radio astrometry; Hipparcos; NOMAD, UCAC4, PPMXL, and XPM catalogs; GAIA space mission.

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If stars are cataloged, it is something that somebody needs!

BACKGROUND

Astrometry is the oldest part of astronomy. Its main method is positional measurements, i.e., measuring the exact directions to objects, which primarily include stars. Since ancient times, the results of such observations have been documented in the form of star catalogs. The most famous among them, which has not survived to this day, is the catalog of the ancient Greek astronomer Hipparchus (2nd century BC), dated 129 BC. In 2005, researchers assumed that one can see it on the Roman statue of Farnese Atlas (Fig. 1) [1]. It must be admitted that this catalog was far from the first. As is known, Hipparchus, comparing the positions of the stars in his catalog with earlier catalog data, discovered the phenomenon of astronomical precession, the nature of which was explained in 1686 by Isaac Newton.

Astronomical catalogs are different: those of nebulae, galaxies, variable stars, etc. They are called astrophysical. However, we are interested in astrometric catalogs. The data that are usually contained in them are shown in Table 1.

The positions and proper motions of the stars—the exact coordinates and the rates of their change—are needed to build a reference frame on the celestial sphere. There is an abstract concept of *Reference System*, implying a theoretical construction, and a concrete *Reference Frame*, meaning the implementation of a reference frame in practice [2]. Star catalogs serve as the most accurate embodiment of an abstract inertial reference system. It is to them that the coordinates of various objects in the celestial sphere and, ultimately, on the Earth are tied. The well-known GPS/GLONASS system is attached through spacecraft to the catalog of quasars—ultradistant objects, the proper motions of which can be neglected [3].

The proper motions of stars are the rate at which stellar coordinates change. Knowing them, it is possible to translate the coordinates of the stars to another epoch both forward and backward. The analysis of the proper motions themselves makes it possible to study the kinematics of stars in the circumsolar space and the Galaxy as a whole. The discovery of proper motions belongs to the famous English astronomer Edmond Halley, who discovered in 1718 that some bright stars from the Hipparchus–Ptolemy catalog had noticeably changed their positions among other luminaries [4].

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Fig. 1. Hellenistic sculpture of Farnese Atlas. 2nd century AD. National Archaeological Museum, Naples.

It was extremely difficult and dramatic to answer the question about distances to stars. Attempts to detect their parallax displacements caused by the Earth's revolution around the Sun were undertaken back in antiquity. Their absence (of course, caused by the extremely small effect) served as one of the arguments against the heliocentric system of the world. Prominent scientists such as Tycho Brahe, Galileo Galilei, and Robert Hooke were engaged in the search for parallaxes in the modern era. During that work, James Bradley discovered the aberration of light and the nutation of the Earth's axis in 1728, and William Herschel, the orbital motion of binary stars in 1804 [5].

As late as 1837, V.Ya. Struve at the Dorpat Observatory and in 1838 F. Bessel at the Königsberg Observatory and T. Henderson at the Cape of Good Hope Observatory obtained the first reliable estimates of the parallaxes of the nearest stars, which were only fractions of an arc second [6]. Thus, Struve's Altair parallax was found to be $0.181'' \pm 0.094''$. A more visual representation of the smallness of the measured angles is shown in Table 2.

Determination of trigonometric parallaxes, i.e., the distances to stars obtained by the geometric method, through ground-based observations is an extremely time-consuming task. The Earth's atmosphere sets limits for observing small angles. The maximum attainable statistical accuracy of ground-based observations is mostly limited to $0.05''$, which gives an error of 100% in determining the parallax already at a distance of 20 pc. All this led to the fact that from 1838 to 1991, the parallaxes of only 8000 stars were measured—and with high uncertainty [7]. The trigonometric stellar parallax should not be confused with so-called photometric and spectral ones. The latter mean indirect estimates of distances to stars using their astrophysical characteristics. However, to do this, it is necessary to determine, in a true trigonometric way, the distance to stars of one type or another. In the future, this information can be used to calculate the

Table 1. Astrometric catalog data

Data	Commentary
Positions (coordinates)	Always present, can be in the equatorial and/or galactic coordinate system; are given for a specific observation epoch
Proper motions	Changes in coordinates with time; are almost always present in modern star catalogs
Parallaxes	Distances to the stars; are present in special catalogs and catalogs of space astrometry
Magnitudes	The brightness of stars in one or several generally accepted scales; although this value is astrophysical, it is almost always present
Information about multiplicity	Often cited to indicate features in astrometric data
Star numbers in other catalogs	Useful information to combine and compare data from different catalogs
Additional information	Various data, usually of an astrophysical nature, obtained, as a rule, from other catalogs, for example, radial velocities—the velocities of a star along the line of sight, established from spectral measurements

Table 2. Distances and angles at which a ruble coin with a diameter of 2 cm will be visible

Distance	Angle
4 km	1″
40 km	0.1″, parallaxes of the nearest stars
4000 km (Moscow–Lisbon)	0.001″, or 1 mas is the accuracy of Hipparcos
400000 (Earth–Moon)	0.01 mas is the accuracy of GAIA

distance to stars the trigonometric parallax of which is inaccessible for measurements.

THE AGE OF GROUND ASTROMETRIC MEASUREMENTS

The last catalog of the pretelescopic era is that created in 1570–1600 by one of the best observers Tycho Brahe [8]. The accuracy of its positions is about 1′. It was this catalog that allowed Johannes Kepler to derive his famous laws, which, in turn, allowed Newton to discover his law of universal gravitation.

The 18th and 19th centuries were characterized by a gradual increase in the accuracy of observations, which by the mid-20th century reached approximately 0.1″. The latest catalog of the famous FK series (The Catalogs of Fundamental Stars), FK5 Basic [9], contained only 1535 stars the positions and proper motions of which were already at the limit of the accuracy of ground-based observations, and the history of their tracking had lasted more than a century. The catalogs of this series (FK3, FK4, FK5) specified the fundamental coordinate system for many decades. The observation technique was designed in such a way that the coordinates of each star in them were determined individually, independently of each other. This is why the fundamental catalogs contain such a small number of stars.

To extend the systems to a larger number of stars, photographic catalogs were used, for example, PPM (Position and Proper Motions) [10], which contains about 400000 stars, but with much lower accuracy. Such catalogs were called relative. Errors in defining the fundamental system entered distributor catalogs.

Rapidly developing astrophysics demanded from astrometry, above all, high-precision distances (Fig. 2). Astrophysics knows a photometric method to determine distances that uses the period–luminosity relation for variable Cepheid stars. However, to calibrate this scale, it is necessary to measure the distance to several Cepheids using the direct trigonometric method. According to space astrometry data, the distance to the nearest Cepheid, Polar Star, is 137 pc. Measuring the trigonometric parallax from the Earth's surface is almost impossible for the Polar Star. Other Cepheids are even farther away. Determination of distances to the nearest galaxies is based on the Cepheid scale. Further indirect methods make it possible to determine the distances to remote galaxy clusters and the value of the Hubble constant and the age of the Universe. However, to determine them reliably, the period–luminosity relation should be calibrated by a direct method. Ground astrometry was unable to do this [11].

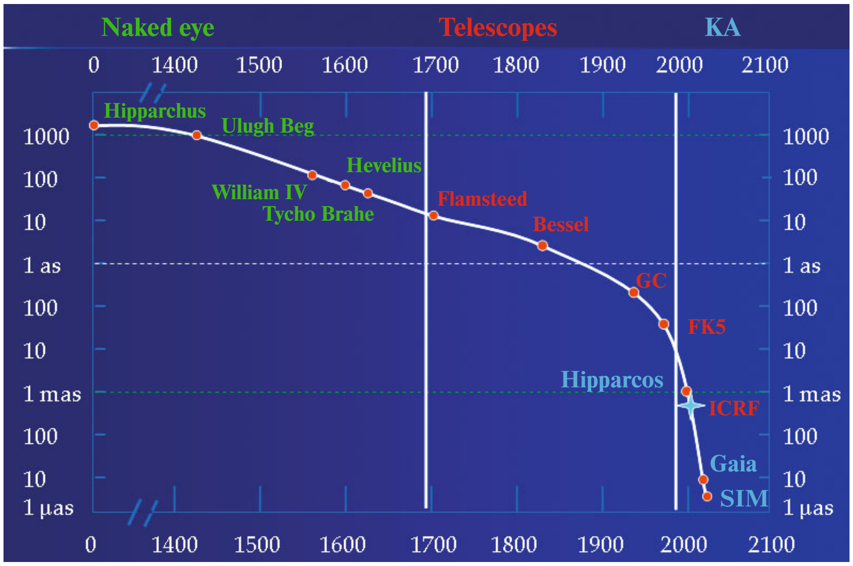

Fig. 2. Dynamics of the accuracy of astronomical observations.

RADIO ASTROMETRY

In parallel with optical observations, radio astronomy was developing, which, with the advent of very long baseline radio interferometers (VLBI), led to a sharp increase in the observation accuracy up to 0.001″ [12].

In the simplest case, a radio interferometer is a system of two radio telescopes that conduct synchronous observations of the same point radio source. This instrument measures the time delay of the arrival of a radio wave front at one telescope compared to the other. For small bases, radio telescopes can be connected directly by communication lines. However, if they are located at distances of several thousand kilometers from one another, and sometimes on different continents, then it is necessary to use the exact time standards set by the atomic clock. Analysis of the measurement of time delays allows one to obtain the geographic coordinates of radio telescopes, the celestial coordinates of the observed radio sources, and subtle effects in the rotation of the Earth—the movement of the poles in its body and the irregularity of rotation. The accuracy of these measurements is determined by the length of the interferometer base, that is, the distance between the telescopes and the wavelength of the received radio emission. In the period 1970–1990, all over the world, work was done to create radio interferometric networks, with the help of which it was possible to achieve an accuracy of positional observations of quasars of about 0.001″–0.0005″ [13]. In our country, such work is being carried out within the framework of the Quasar project, for which the RAS Institute of Applied Astronomy was established in St. Petersburg [14]. The operating network includes the Svetloye, Zelenchukskaya, and Badary radio astronomy observatories and the Center for Data Collection and Processing. All this made it possible to create a reference frame of a fundamentally new type—using instead of stars quasars, the coordinates of which were obtained at the millisecond level of accuracy.

As is known, quasars are cosmological objects that are remote from us at maximum distances. Even if we assume unrealistically high speeds of their lateral motion, comparable to the speed of light, it is difficult to notice their proper motions in this case too. Thus, quasars form a “sphere of fixed stars,” which can be used as a reference frame. However, not all quasars are suitable for such a construction. Some have a variable structure, caused by physical processes within them, which leads to a shift in the center of the radio image. Hence, to construct the reference frame, 667 quiet radio sources were selected, 212 of which had a position determination error of only 0.0004″. The new radio astrometric reference system made it possible to study at a higher level phenomena occurring on the Earth: features of its rotation, the movement of continents, and plate tectonics. However, the radio system has a significant drawback, inaccessibility in optics. While for GPS/GLONASS this is practically unimportant, for optical observations it creates significant problems. This drawback was overcome only by methods of space astrometry, i.e., by carrying out astrometric measurements in the optical range in space.

THE FIRST SPACE ASTROMETRIC PROJECT HIPPARCOS

In 1989, the European Space Agency (ESA) launched Hipparcos (High Precision Parallax Collecting Satellite) to obtain the positions, proper

Fig. 3. Quasar Network radio telescope in Badary.

motions, and parallaxes of stars at millisecond precision levels. The spacecraft worked in orbit for 37 months, during which time it carried out astrometric and photometric measurements of stars according to the program specified in [15].

The processing of these observations led to the creation of two catalogs: Hipparcos, containing information on 118 218 stars with an accuracy of the determining positions, annual proper motions, and parallaxes at a level of 1 mas, and the Tycho Catalog (over 1 mln stars) with an accuracy of measuring the positions and proper motions of stars up to 25 mas [16, 17]. This catalog does not contain parallax data.

The positions and proper motions of stars in the Hipparcos and Tycho catalogs are given in the fundamental International Celestial Reference System (ICRS), which has been implemented using the International Celestial Reference Frame catalog (ICRF) of extragalactic radio sources [18]. Since extragalactic sources (quasars) were not available for direct observation on the Hipparcos spacecraft (except for 3C 273), several direct and indirect methods were used to link the preliminary system of the Hipparcos Catalog with ICRF.

The emergence of Hipparcos sparked a boom in articles of all kinds. Let us briefly list some of the main results presented in them (for further details, see the materials of the Hipparcos Venice'97 symposium [19]):

- developing the technology of space astrometric observations, linking the space reference system with the terrestrial one, creating software products using Hipparcos and Tycho data, and providing the astronomical community with access to the results of the space mission;
- calibration of the Hertzsprung–Russell diagram of the luminosity of variable stars of different types (Cepheid, Mira), determination of the absolute magnitudes, and measurement of the masses of components of binary stars;
- studying the kinematics of stars in the circumsolar space, studying the structure of stellar associations, and searching for moving clusters distributing dark matter in the Galaxy;
- calibrating the scale of intergalactic distances and determining the absolute ages of globular clusters.

Note that the success of the Hipparcos mission is primarily associated with the determination of the trigonometric distances of 100 000 stars at the level of 1 mas, which gives an accuracy of 20% up to distances of 200 pc and 50% up to distances of 400 pc. However, for objects located at a distance of 1 kpc and beyond, the accuracy of Hipparcos is insufficient.

The proper motions of the stars obtained with the apparatus, as it turned out, have their own peculiarities, which are not manifested in ground-based observations. When determining the proper motion of a star by traditional methods, the difference in epochs is usually at least 30 years, or even more. The relatively low accuracy of ground-based observations is compensated by the large difference in epochs. In Hipparcos, this difference is only three years. We can say that the proper motions of stars obtained within such a short time are instantaneous. Quite often, a star has an invisible (or not registered by the apparatus) satellite. Due to the rotation of the components around the common center of gravity, there may be differences in the proper motion of the star, determined by the ground-based method (blue arrow in Fig. 4) compared with the cosmic one (red arrow).[1] Comparison of the proper motions of stars from ground-based catalogs with data from space-based catalogs can help in the search for stars with dark satellites.

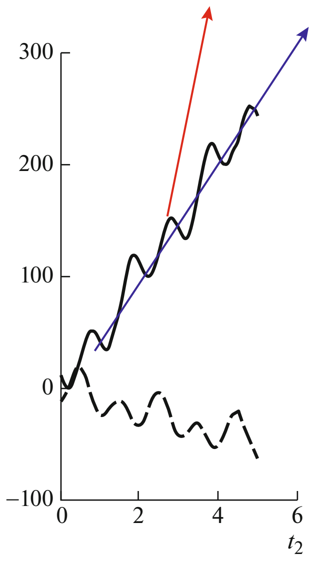

Fig. 4. "Instantaneous" proper motions of stars.

The Hipparcos spacecraft observed about 1 mln stars a few times (two to three observations over the entire period). This information formed the basis of the Tycho catalog. However, the reliability of the data from the first Tycho catalog immediately drew criticism. At one time, the Hipparcos apparatus observed about 3 mln objects. This circumstance made astrometrists create Tycho-2, a new generation catalog [20]. Its novelty consisted in the fact that extensive series of ground-based astrometric observations were used as the first epochs to deduce the proper motions of stars and, for the second epochs, for the entire data array collected by the Hipparcos spacecraft. As a result, the Tycho-2 astrometric catalog appeared, containing the positions and proper motions of stars with an accuracy of about 2.5 mas/yr, as well as two-band photometry

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[1] The figures are in color format in the electronic version of the article on the website of the Publishing and Bookselling Center Akademkniga.

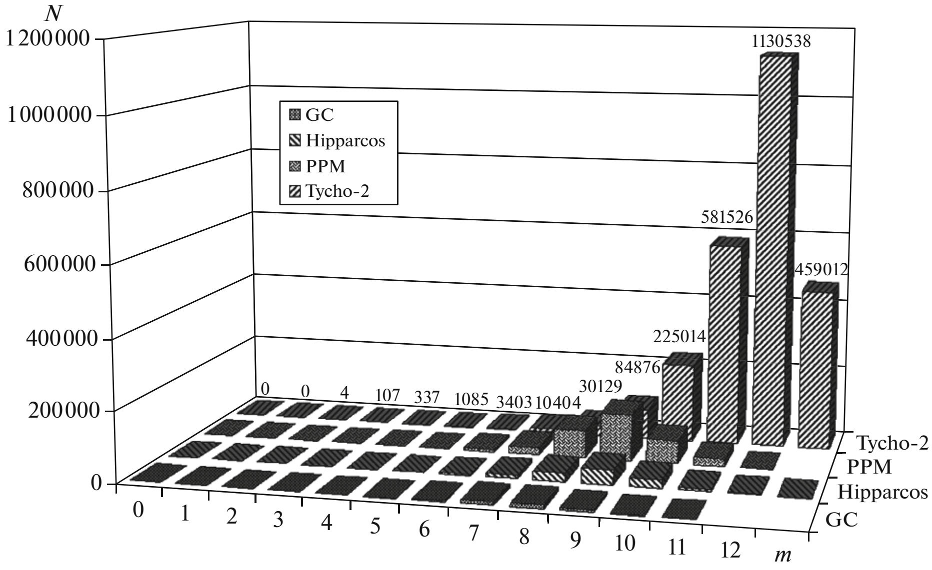

Fig. 5. Comparison of the number of stars in the GC, Hipparcos, PPM, and Tycho-2 catalogs.

of 2.5 mln stars (Fig. 5). The catalog includes objects up to a magnitude of 11.5^{m} [17]. It played an important role in various kinematic studies and, before the GAIA catalog releases, was considered the best in terms of the accuracy of the proper motions of stars.

Interestingly, the Astronomical Calculation Institute of Heidelberg University released the next catalog of the FK series, FK6, which is a combination of the FK5 and Hipparcos data [21, 22].

MASSIVE ASTROMETRIC CATALOGS OF THE EARLY 21st CENTURY

Initially, in 1991, the accuracy of the positions of stars in Hipparcos was about 1 mas, but over the past 30 years, because of errors in the proper motions of approximately 1 mas/yr, it has degraded to 30 mas. As a result, the need arose for new observations and catalogs. In the early 21st century, the widespread introduction of computer processing methods and comparison of different observational catalogs led to the emergence of massive stellar catalogs of previously unthinkable volumes, containing about 1 bln records.

The first massive catalog was probably the Naval Observatory Merged Astrometric Dataset (NOMAD), including over 1 bln objects, which became available to the astronomical community in 2004 [23]. At the same time, certain technical difficulties appeared with storing data of such a volume in an ordinary laboratory or at home. There are 1800 separate files in the catalog; the format of each of its values (coordinates, proper motions, stellar characteristics) is a binary integer, which ensures a high reading speed. Nevertheless, even the simplest processing of the NOMAD on a modern personal computer takes over an hour. If it is necessary to solve such problems on a one-shot basis, this is acceptable, while with constant work with an array of data, one should think about a distributed computing system. The superhigh density of stars in such catalogs makes it possible to put forward and solve problems that were previously impossible to formulate. For example, one can study the structure of the entire Galaxy over vast areas rather than in the solar space. Figure 6 shows the distribution of stars in the NOMAD catalog over the celestial sphere in the Aitoff projection [24]. The color of the stars was selected artificially by comparing the color components of the RGB model with the infrared magnitudes H, J, and Ks. The image in Fig. 6 creates the illusion that we are looking at our Galaxy from outside. In reality, this is an infrared image of the Milky Way in the celestial sphere. Note that this is not a photograph but a computer image, where each point corresponds to an entry in the catalog.

The high density of stars makes it possible to study the distribution of dusty matter. Let us put on the map not the stars themselves but only the average color index of all the stars that fall into a specific pixel of the image; these are tens of thousands of stars or more (Fig. 7). The resulting image clearly shows the “reddening” of the color, caused mainly by the distribution of dusty matter.

Finally, with catalogs of this capacity, it is possible to explore small areas, but in detail. Figure 8 shows the neighborhoods of globular star cluster M13 according to the NOMAD catalog. Once again, I draw attention to the fact that this is not a photograph but a computer-generated image.

With all the advantages of the catalog, only 340 mln stars (!) have data on proper motions, and their accu-

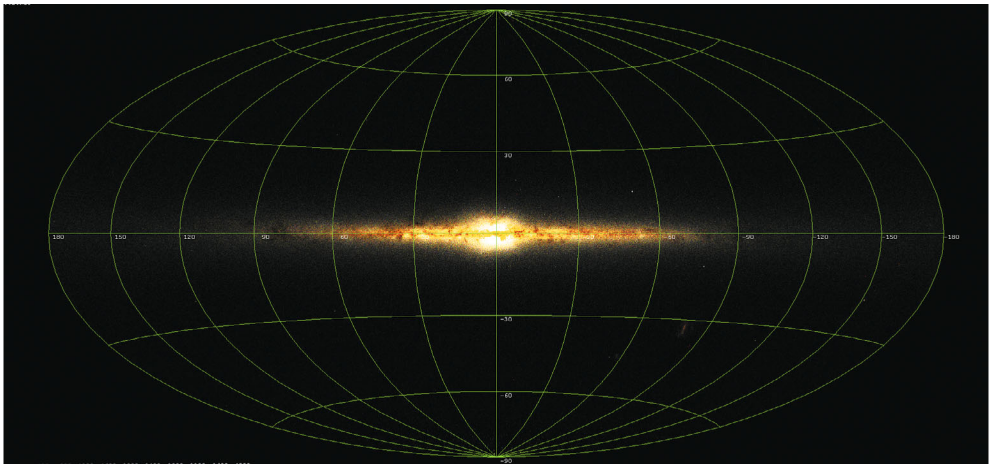

Fig. 6. NOMAD stars in the Hammer–Aitoff projection, visualization of infrared magnitudes into the visible range.

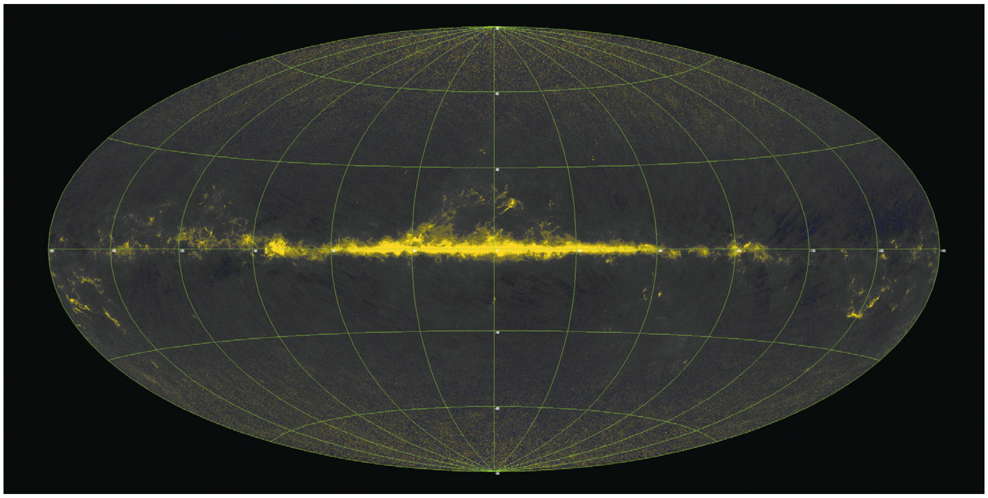

Fig. 7. Average color index (J–K) of a star in the NOMAD catalog. Yellow corresponds to a higher value; blue, to a lower value.

racy is inhomogeneous. Therefore, massive catalogs of the next generation are now used (Fig. 9). They are smaller than NOMAD but much more accurate.

The UCAC4 catalog contains 113 mln stars from 8 to 16 magnitudes [25]. The errors of their proper motions range from 1 to 10 mas/yr. The UCAC4 contains photometric data from the 2MASS project—an infrared ground-based catalog with 437 mln objects, containing positions and magnitudes in three bands H, J, and Ks but no data on the proper motions of stars [26].

The PPMXL catalog—the most massive—contains about 900 mln stars and, apparently, is the most complete up to magnitude 20 [27]. The accuracy of proper motions is estimated on the interval from 4 to 10 mas/yr. However, practice has shown that the real accuracy of coordinates and proper motions is several times worse. The PPMXL contains photometric data in six bands—two visible and four infrared—but not for all stars.

Both catalogs are based primarily on observations by the United States Naval Observatory (USNO). In addition, they use information from more than 140 other star catalogs.

The XPM catalog was compiled by combining the data from the 2MASS and the USNO-A2.0 observational catalog, which made it possible to obtain the positions and proper motions of 314 mln stars in the range of magnitudes from 10^m to 20^m [28]. The algorithm for calculating proper motions is such that they are absolutized relative to galaxies located at distances at which, at the current level of accuracy, their own motions are invisible. This made it possible to compile the above-mentioned 2MASS catalog, which, in addition to the coordinates of point sources (stars), contains information about the position of about 1 mln extended objects, most of which are galaxies.

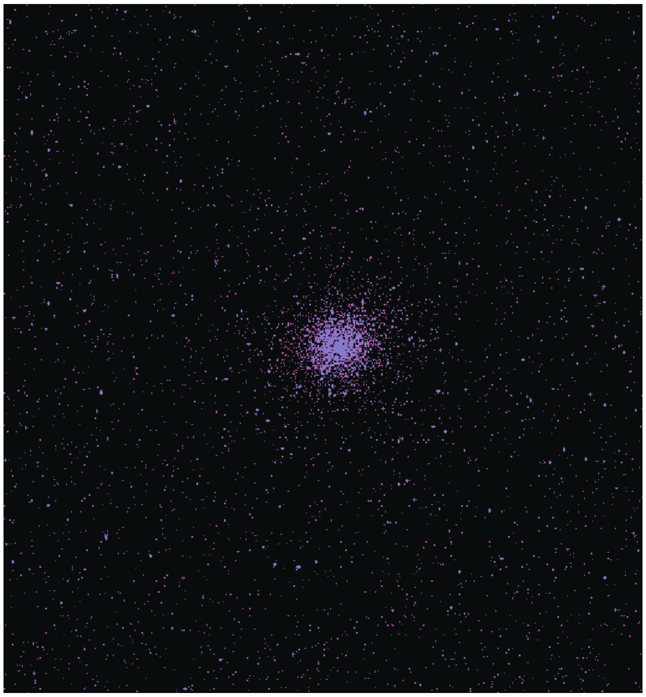

Fig. 8. Neighborhoods of star cluster M13 obtained from NOMAD data.

The UCAC4, PPMXL, and XPM are the most massive and accurate astrometric catalogs of ground-based astrometry. The comparison shows some systematic differences between them [29]. Generally speaking, comparing data from different catalogs is a classic astrometric problem, making it possible to assess their accuracy and the level of errors in the data, both random and systematic. While the influence of the former can be reduced by massiveness, the latter are more dangerous. Systematic errors, i.e., those having the form of a functional dependence on the coordinates and the brightness of the star, can be incorrectly interpreted as real kinematic effects. Revealing systematic errors is one of the most important tasks of observational astrometry [30].

GAIA SPACE MISSION

Spacecraft. After the completion of the Hipparcos project, the idea of a new mission appeared immediately. Several options were planned, but the Global Astrometric Interferometer for Astrophysics (GAIA) project received financial support [31]. The spacecraft, launched on December 19, 2013, is still in orbit. The cost of the entire project, including data processing, is approaching €1 bln.

In principle, the apparatus is like the Hipparcos. GAIA, like Hipparcos, measures arcs (angular distances) between objects. The optical scheme of the telescope consists of two mirror telescopes with the main mirrors (M1, M1) 1.5 × 0.5 m in size (Fig. 10). Using auxiliary mirrors, both telescopes project the image into one focal plane, and the separation of the images is assigned to digital processing. Unlike Hipparcos, the GAIA space telescope does not use a so-called input catalog preliminary list of stars the astrometric parameters of which are specified by observations [32]. In GAIA, objects are identified and classified directly on board. Perhaps the world's largest CCD matrix (more precisely, a mosaic of matrices) is located in the focal plane (Fig. 11) [33].

The spacecraft moves around Lagrange point L2 of the Earth—Sun system so as not to fall into the shadow of the Earth; note that it does not move away from L2 by more than 1 km (Fig. 12). To increase the reliability of the primary data, as well as the results of their analysis, the satellite orientation should be known with an accuracy of about 150 m and the speed, up to 1 mm/s (Fig. 13). Over 6.5 years, the spacecraft, slowly rotat-

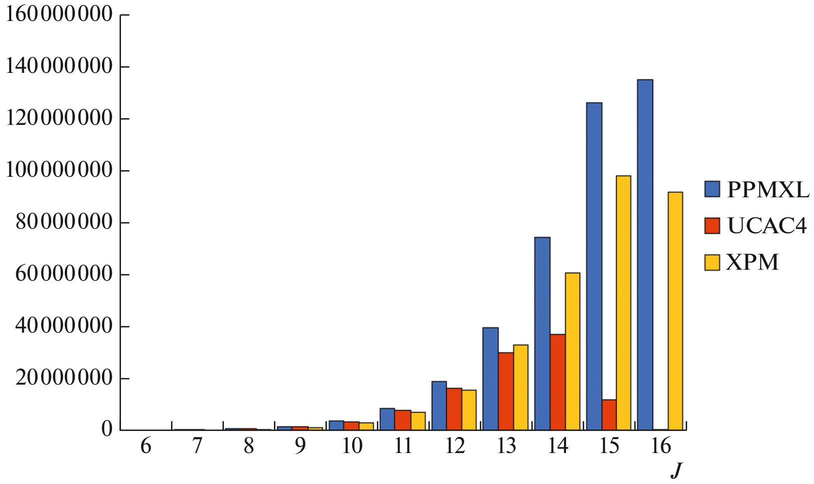

Fig. 9. Distribution of stars in massive star catalogs by magnitude (only those stars that have these photometric data).

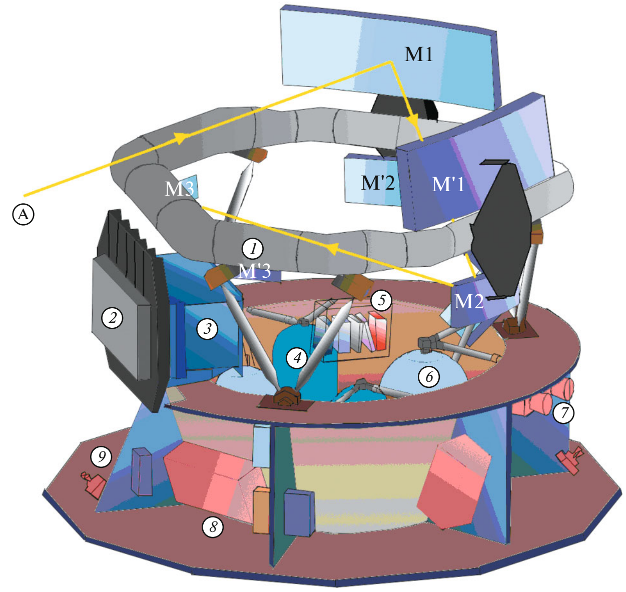

Fig. 10. GAIA telescope layout: M1, M2, M3 are mirrors of the first telescope; M'1, M'2, M'3 are mirrors of the second telescope; (*1*) mirror mounting system; (*2*) sensor cooling system; (*3*) assemblage in the focal plane; (*4*) nitrogen cylinder; (*5*) diffraction gratings of the spectroscope; (*6*) fuel tank; (*7*) star sensor; (*8*) electronics and batteries; (*9*) main power plant.

ing and processing, has been scanning the celestial sphere in such a way that, on average, each object has been observed at least 70 times over the entire life of the satellite (Fig. 14). This makes it possible to determine the coordinates of an object with an accuracy of 10 microseconds of arc (μas) and the proper motions of stars with an accuracy of 10 μas/yr. Recall that GAIA is a scanning device; therefore, it cannot be pointed at a specific object and the observation plan cannot be changed.

In addition to astrometric data, GAIA immediately performs a rough spectral classification using a two-band photometer in the 330–680 and 640–1050 nm ranges, as well as finer spectral analysis to determine the radial velocities and parameters of stellar atmospheres, which, in principle, was not implemented with Hipparcos [34]. Photometers also allow plotting light curves of variable stars.

After calculations for each star, its trajectory in the celestial sphere will be obtained. An example of such a trajectory is shown in Fig. 15, where a parallax ellipse is clearly visible, and its displacement over several years makes it possible to estimate the proper motion of the star.

GAIA project in numbers. The final version of the catalog will contain approximately 1.6 bln objects. For 10^6 stars brighter than 12^m, the position determination accuracy will be about 4 μas (0.004 mas); for 30 × 10^6 stars brighter than 15^m, 10 μas; and for all fainter stars, brighter than 20^m, no less than 150 μas. The coverage density will range from 25000 to 3 mln stars per square degree near the galactic equator.

The GAIA will determine the radial velocities of 200 mln stars (today, they are known for only 7 mln). The accuracy of the radial velocities of bright stars ($V < 15^m$) is expected to be at the level of 1–2 km/s, and that of fainter ones, 5–10 km/s [35].

The GAIA will analyze the variability of 100 mln stars, determine the masses of about 10000 stars, and search for exoplanets at distances of up to 200 pc. About 500000 minor planets of the solar system will be observable. At cosmological distances, the discovery of 500000 (!) new quasars is expected.

The GAIA project is a computational challenge. For complete data processing, it is necessary to perform up to 10^{21} floating point instructions. For comparison, we can say that in the year when GAIA was

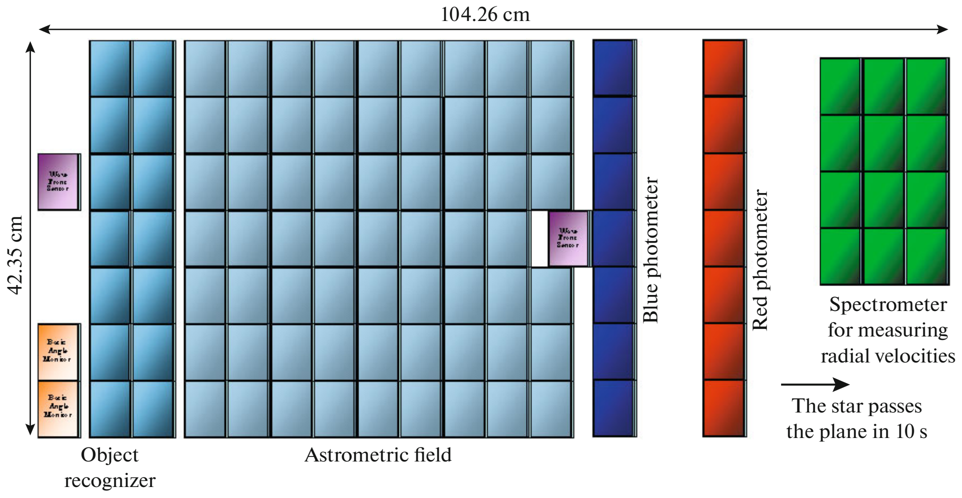

Fig. 11. CCD mosaic in the focal plane of the telescope.

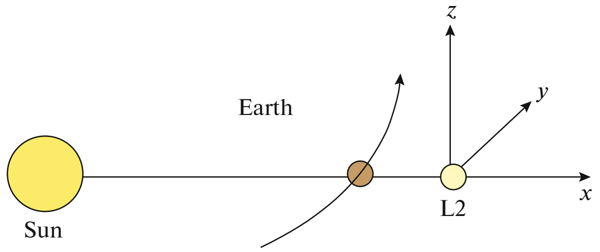

Fig. 12. Location of the spacecraft is point L2.

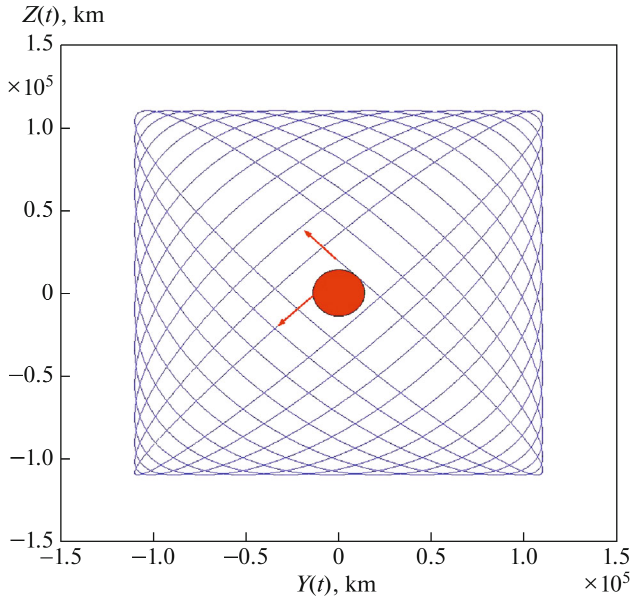

Fig. 13. Orbit of the vehicle relative to Lagrange point L2.

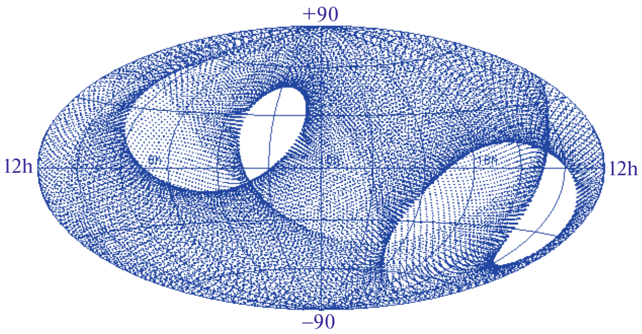

Fig. 14. Scanning the celestial sphere in 100 days.

launched, all computers in the world performed 10^{25} such operations a year! By the way, one of the largest computational projects in the world—the search for extraterrestrial artificial signals in radio observations using distributed computing (SETI program)—is also astronomical [36]. If it had taken only a second to process one object, one would have waited 30 years before the final release of the catalog. Forward Fourier analysis of all variable stars would take 100 years if performed on a single PC.

To solve these complex computational problems, the apparatus is equipped with a computer that compresses the "raw" data and transmits them to the Earth at a speed of 3–8 Mbit/s, which, in turn, are processed in a computer center specially built for this in Madrid. The total volume of raw data transferred from the spacecraft is estimated at 250 Tbit; unpacked data will take 150 TB; and working copies, archives, and tests, 1 PB [37].

General relativity with GAIA. To achieve accuracy at the level of fractions of mas, relativistic celestial mechanical models and models of light propagation must be used [38]. Using the Newtonian model will lead to errors in astrometric data.

The relativistic observation model includes the following:

- modeling of relativistic aberrations [39];
- consideration of relativistic effects in satellite motion up to corrections of the level of 0.6 mm/s;
- relativistic effects in the propagation of light, taking into account the monopole gravitational field of all major planets and some of their satellites, the quadrupole field of giant planets, i.e., taking into account the nonsphericity of gravitational fields, and the influence of the motion of bodies [40];
- relativistic effects in the motion of small bodies of the solar system;
- relativistic effects in the motion of stars (Rømer effect, microlensing).

For a long time, general relativity largely remained a theoretical discipline and was used to describe extreme objects (neutron stars, black holes). However, high-precision observations have made it a practical discipline. Without considering relativistic effects, microsecond accuracies are unattainable. Note that the relativistic model of light propagation in the solar system was used back in the processing of Hipparcos data [41].

Scientific objectives for GAIA. During the GAIA mission, it is planned to solve a wide range of scientific problems. Even a short enumeration of them makes an impressive list:

- mapping of the Galaxy;
- physics of stars (classification, luminosity, effective temperatures, metallicity index);
- kinematics and dynamics of the Galaxy;
- calibration of the scale of cosmic distances;
- clarification of the age of the Universe;
- distribution of dark matter in the Galaxy (microlensing, observations of "brown" dwarfs);

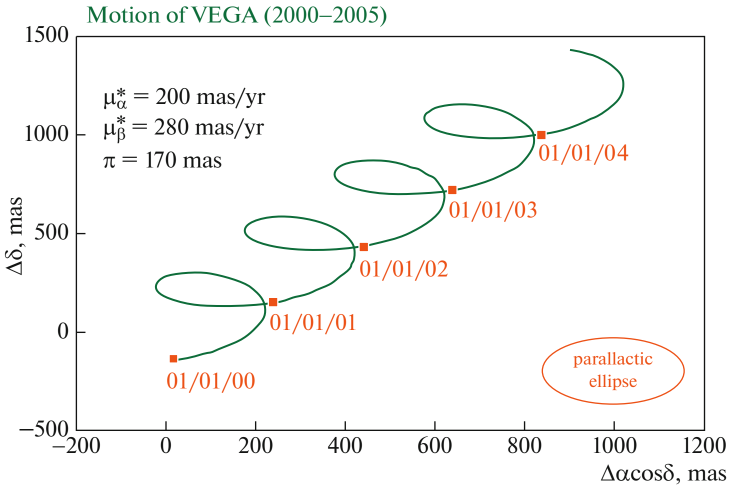

Fig. 15. Star trajectory example.

- construction of a fundamental frame of reference, communication of radio and optical systems through direct observation of quasars;
- verification of the general theory of relativity;
- refinement of the solar system model.

Special attention should be paid to the problem of calibration of the distance scale [42]. As was mentioned at the beginning of this article, distance is the most difficult parameter to observe. The method for estimating the distances to galaxies and, ultimately, the scale of the entire Universe is determined by the accuracy of the distance to the Cepheids and the reliability of obtaining the period–luminosity relation. To calibrate the distance scale, the GAIA needs to measure the following:

- parallaxes to Cepheids located closer than 3 kpc with an accuracy of better than 1% and distances to all Cepheids in the Galaxy, with an accuracy of no worse than 4%;
- parallaxes for RRLyr-type variables that are closer than 3 kpc with an accuracy of 1%; for other stars of this type, the parallax error should not exceed 10%;
- parallaxes of Mira in the Galaxy (relative error should not exceed 6%);

Table 3. Comparison of GAIA catalog releases

	DR3	DR2	DR1
Total number of sources	≈ 1800000000	1692919135	1142679769
Number of sources with five parameters	≈ 1500000000	1331909727	2057050
Number of sources with two parameters	≈ 300000000	361009408	1140622719
Sources with an average G value	≈ 1800000000	1692919135	1142679769
Sources with average G_{BP} photometry	≈ 1500000000	1381964755	–
Sources with average G_{RP} photometry	≈ 1500000000	1383551713	–
Sources with radial velocities	Unknown	7224631	–
Variable sources	Unknown	550737	3194
Known asteroids with epoch data	Unknown	14099	–
Effective temperatures (T_{eff})	Unknown	161497595	–
Sources with radius and luminosity	Unknown	76956778	–

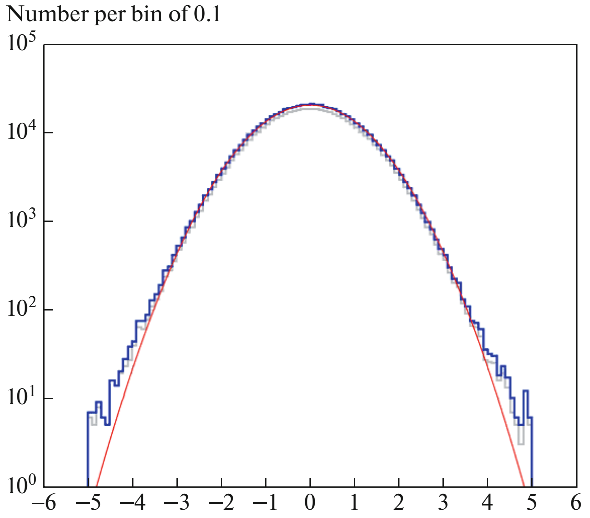

Fig. 16. Parallax distribution of 556 849 quasars according to GAIADR2 data.

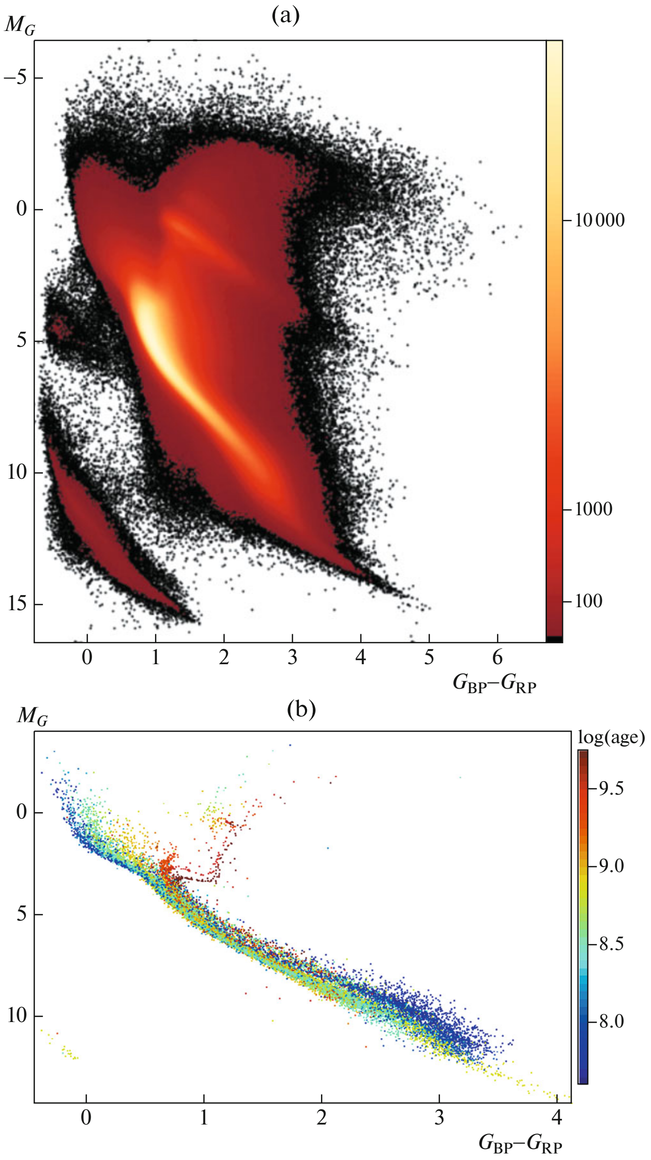

Fig. 17. Hertzsprung–Russell diagrams for all stars and 32 open star clusters according to GAIADR2.

- parallaxes of individual stars in 20 globular clusters with an accuracy of 10% and the average distance to all globular clusters, at a level of 1%;
- parallaxes of Cepheids in Magellanic Clouds with an accuracy of 30%, which will answer the question about the period–luminosity relation for Cepheids in our and other galaxies.

Preliminary results of the mission. In 2016, the so-called first release of the GAIA catalog, GAIADR1 [43], saw the light of day. It contains 1 140 622 719 stars, for which only coordinates are given, and a special TGAS subset (Tycho–Gaia Astrometric Solution, 2 057 050 stars with an accuracy of about 0.3 mas), which became a combination of the Hipparcos and Tycho-2 catalogs and GAIA data. The DR1 set also recorded light curves for about 3000 Cepheids and RR Lyrae stars. Even the first release made it possible to link the catalog system with ICRF [44]. The kinematics of the Galaxy using the TGAS subset was studied in our country as well [45].

On April 25, 2018, GAIA DR2 was released [46]. It contains a significant amount of data obtained exclusively on the spacecraft (Table 3). However, according to the authors of [47], individual parallaxes should be used with caution. Many stars even have negative parallax. Figure 16 shows the distribution of parallaxes for half a million quasars (it should be zero), but, as you can see, the spread of parallax for such objects is ±5 mas. Because of this, the construction of the Hertzsprung–Russell diagram gives a rather blurry picture (Fig. 17a), and if we use the averaged distance data for stars belonging to open clusters, the picture becomes clearer (Fig. 17b). These charts are the first to use the color index $G_{BP}-G_{RP}$ from the difference in magnitudes determined on the spacecraft and not using ground-based sources [48].

In December 2021, the so-called early third release of the catalog was published [49], which will contain information on almost 1.5 bln stars with all five astrometric parameters up to stars 21^m. For the same number of stars, improved two-band photometry will be presented. It is argued that the photometric system of DR3 is different from DR2.

The release of the first final version, in which the declared accuracy is fully realized, is scheduled for 2022.

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