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Gaia Data Release 3: Distribution of Spectral Groups of Near-Earth Asteroids

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Abstract—Based on the data from the third edition of the Gaia catalog, containing the reflectance spectra of asteroids, studies of near-Earth asteroids (NEAs) were carried out. The reflectance spectra of about 100 representatives of the Aten, Apollo and Amor groups were used to determine their spectral class. For 47 asteroids such an assessment was made for the first time. For convenience, the classes were grouped into broader spectral groups (according to Tholen). The distribution by spectral groups (average 60% S-group, 20% C-group, 20% others) was consistent with results obtained previously using other data from a larger sample of objects. This distribution remains similar to what is known for NEAs of different sizes. Despite the numerical predominance of group S asteroids in the NEA data sample, asteroids of primitive types (group C) are also found at very small perihelion distances, which can indirectly confirm the widespread occurrence of the phenomenon of sublimation activity of asteroids.

Keywords: asteroids, spectrophotometry, chemical and mineral composition of matter, Gaia, Gaia Data Release 3, NEAs

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INTRODUCTION

Near-Earth asteroids (NEAs) are a crucial class of objects, the study of which is important for refining (clarifying) the picture of the dynamic and chemical evolution of small bodies in the Solar System. In addition, NEAs may pose a potential threat to humanity, which makes their study not only scientifically significant, but also practically important. On the other hand, in some distant future such objects can be considered as potential sources of extraterrestrial natural resources, which increases interest in them (National Research Council, 2010; Hein et al., 2018).

Over the past three decades, direct in situ exploration of asteroids using spacecraft, including the delivery of samples to Earth (see, for example, McMahon et al., 2018; Fujiwara et al., 2006), made it possible to obtain detailed data about some of them. Of course, the initial selection of these objects for space missions was based on data obtained using remote sensing, which underscores the significant contribution of such research to the success of space programs. Thanks to the accumulated large amount of asteroid observation data obtained by remote methods, on the one hand, we are able to estimate the main parameters of particular asteroids in a short time and at minimal cost, and on the other hand, we can apply statistical methods. Considering the large number of discovered and/or newly observed asteroids using spacecraft (such as *WISE*, *Gaia*), it can be noted that space missions provide a significant contribution that allows the use of statistical research methods. It is natural to compare the results of such studies conducted by ground-based and space-based means. The data obtained by the *WISE* spacecraft made it possible to significantly refine the distribution of physical characteristics of asteroids (see Masiero et al., 2014; Mainzer et al., 2012), including NEAs (Grav et al., 2013).

The Gaia project, in which significant attention was paid to asteroids, also raised certain hopes. Particular interest is presented by the observational data published in the recent Gaia Data Release 3 on the spectra of observed asteroids, including NEAs.

For more than ten years, INASAN, the Institute of Astronomy of the Russian Academy of Sciences, together with the Sternberg Astronomical Institute, Moscow State University, have been working on spectrophotometric studies of asteroids, including those approaching the Earth, with the aim of assessing the spectral class, and therefore determining the main type of mineralogy of the surface material. Observations are carried out at the Terskol Peak Observatory using a 2-meter Zeiss telescope on a low-resolution

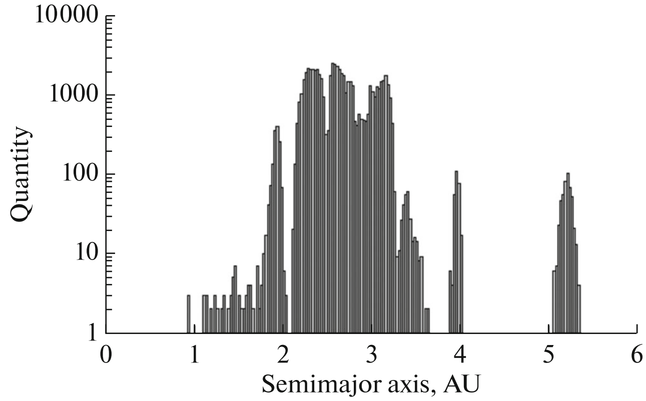

Fig. 1. Orbital distribution of asteroids for which spectrophotometric reflectance spectra were obtained from Gaia DR3 (figure taken from gea.esac.esa.int, full access indicated in the text above).

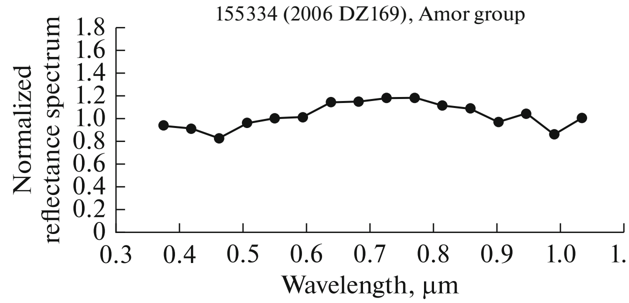

Fig. 2. Reflectance spectrum of asteroid 155334 (2006 DZ169) of the Amor group from the GDR3 catalog.

spectrometer (with a resolving power $R \approx 100$) and at the Caucasus Mountain Observatory of the Sternberg Astronomical Institute, Moscow State University, using photometric methods using a 2.5-meter telescope. For some of the objects included in this observational program, the spectral class was determined for the first time (see, for example, Shcherbina et al., 2017, 2019). Having experience working with spectrophotometric data obtained by ground-based means, we decided to determine the spectral classes of asteroids, which reflectance spectra are presented in the Gaia Data Release 3 database, specifically for NEAs.

This paper, in the section “Spectral data from NEA observations,” provides a brief description of the set of spectral data on asteroids (NEAs) given in Gaia Data Release 3 supplemented by our results obtained in previous works. The Results section presents the results of a brief statistical analysis of this set.

SPECTRAL DATA FROM NEA OBSERVATIONS

The ESA Gaia project, based on observations from the spacecraft launched in 2013, is now at the stage of its third data release, Gaia Data Release 3 (Gaia DR3) (Gaia Collaboration, 2023).

The GDR 3 catalog includes photometric observations of Solar System Objects (SSOs) collected during *Gaia*’s operation from August 5, 2014, to May 28, 2017. The catalog presents reflectance spectra for 60518 objects—numbered asteroids: most of which are in the Main Belt, and also near-Earth asteroids, Trojans and asteroid families of Hungaria, Hilda (https://gea.esac.esa.int/archive/documentation/GDR3/Data_analysis/chap_cu4sso/sec_cu4sso_processingsteps/ssec_cu4sso_spectrophotometryprocessing.html). Figure 1 shows the orbital distribution of asteroids whose reflectance spectra were obtained during the operation of the *Gaia* spacecraft.

Calculation of Reflectance Spectra in GDR 3: Solar Analogs

Using the method described by Bus and Binzel (2002), we determined the spectral reflectance of asteroids by dividing the intensity of the reflected radiation from the asteroid at each wavelength by the average intensity of the spectra of a group of stars similar to the Sun. Such analog stars have physical properties similar to those of the Sun (mass, metallicity, temperature, age), and their spectra resemble those of the Sun. To avoid uncertainties associated with inaccurate knowledge of the magnitude of reddening, stars with reddened spectra are not used as analogs of the Sun. The corresponding normalization gives the reflectivity of the asteroid at a given wavelength. During ground-based observations, one solar analog star, located in close proximity to the asteroid on the celestial sphere, is usually selected. Due to the temporal stability of the equipment of the *Gaia* spacecraft and the fact that observations are carried out outside the Earth’s atmosphere, it was decided to use a method based on dividing the spectrum of each asteroid by the average spectrum of a group of reliable solar analogs. This should, in principle, reduce noise caused by small differences between individual solar analog stars.

The resulting reflectance spectra were normalized to reflectivity at a wavelength of 0.55 μm. They were then resolved into 16 separate spectral bands ranging from 374 to 1034 nm (λ = 374, 418, 462, 506, 550, 594, 638, 682, 726, 770, 814, 858, 902, 946, 990, and 1034 nm).

An example of an asteroid’s reflectance spectrum is shown in Fig. 2 (reflection spectrum of asteroid 155334).

The Set of NEAs in Question

The present study mainly focuses on near-Earth asteroids (NEAs). These objects have perihelion distances equal to or less than 1.3 AU. Recall that NEAs

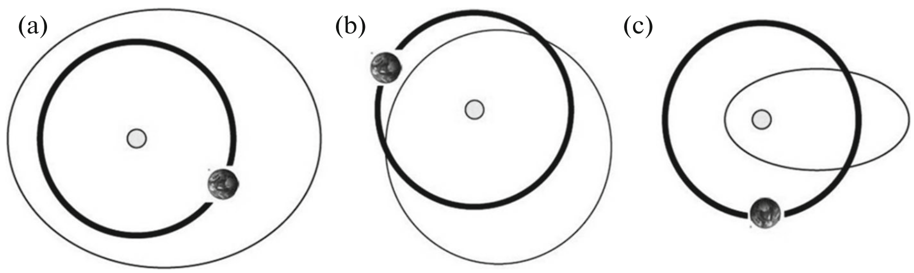

Fig. 3. Approximate orbits of asteroids: (a) (1221) Amor; (b) (1862) Apollo; (c) (2062) Aten. The Earth's orbit is indicated by a thick line.

are divided into groups. NEAs are grouped according to the names of typical representatives: (1221) Amor, (1862) Apollo, (2062) Aten; orbits are shown schematically in Fig. 3.

• Amor type. They do not enter inside the Earth's orbit, since the perihelion distances of representatives of this type are greater than the aphelion distance of the Earth.

• Apollo type. Can penetrate inside the Earth's orbit. The semimajor axes of the orbits are greater than those of the Earth, and the perihelion distances are less than the aphelion distance of the Earth.

• Aten type. They are located mainly inside the Earth's orbit, only going beyond its limits near their aphelion. The aphelion distances of such asteroids are greater than the perihelion distance of the Earth, and the semi-major axes are smaller than those of the Earth.

NEAs, whose trajectories allow them to approach the Earth's orbit to within 0.05 A.U. or less at the present time and having an absolute magnitude of no more than 22.0, are classified as potentially hazardous asteroids (PHAs). This size limit corresponds to the size of objects of 140 m or more, since it was assumed that smaller bodies do not pose a serious threat to the Earth. However, in recent years, after the Chelyabinsk event (asteroid fall on February 15, 2023), asteroids of decameter size and larger are considered dangerous (see Shustov, 2019).

The Gaia Data Release 3 catalog presents reflectance spectra of NEAs for the following groups: 4 objects belong to the Aten group, 49 to the Apollo group, 37 to the Amor group, for a total number of 90 asteroids. To ensure the statistical significance of the sample, we included data on the spectral types of NEAs obtained as a result of spectrophotometry carried out at the Terskol Peak Observatory since 2013. Thus, additional objects were added to the analysis: 3 from the Aten group, 8 from the Apollo group and 6 from Amor group, for a total number of 107 asteroids.

In the considered data array, supplemented by information obtained at the Terskol Peak Observatory, it was possible to confirm, clarify, or for the first time determine the spectral types of 24 PHAs, including 4 asteroids from the Aten group, 19 from the Apollo group and one from the Amor group.

Determination of the Spectral Class of Asteroids

As part of this study, additional parameters were collected for each asteroid, including geometric albedo, orbital period and diameter, which are of auxiliary importance in determining the spectral type. Spectral classification was carried out in accordance with the Tholen or Bas–Binzel taxonomies (SMASSII) applied to data from the NASA database (https://ssd.jpl.nasa.gov/horizons/), if available. The results were compared with previous studies carried out using the low-resolution spectrophotometry method of INASAN in collaboration with the SAI MSU at the Terskol Peak Observatory since 2013; most of the class estimates were confirmed.

Let us describe the procedure for determining (assigning) the spectral class for each given asteroid. This procedure, proposed in the work (Savelova et al., 2022), is called "construction of a spectrophotometric corridor." Briefly, it is as follows. Using the work (Bus and Binzel, 2002), the reflectance spectra of asteroids up to approximately 2000 were extracted from the SMASS II database for distribution by spectral class. The maximum and minimum reflectance values for each wavelength were determined, thereby creating a "range" of possible values for each class. The number of asteroid spectra used to construct this "range" is presented in Table 1.

The assessment of belonging to spectral classes was carried out on the basis of albedo, spectral gradient, the presence of pronounced absorption bands and the correspondence of the asteroid spectrum to the created patterns of reflectance spectra. For example, as shown in Fig. 4, asteroid 155334 fits perfectly within the reflectivity "range" of S-class asteroids, and its geometric albedo also fits S-class. Note that similar classes and subclasses (or intermediate classes, designated by two letters, for example, Cb is an intermediate option between class C and B) have similar bound-

Table 1. The number of reflectance spectra used to construct "spectrophotometric corridors" from the SMASS II database, the spectral class was taken from the article (Bus and Binzel, 2002)

Class	Number of spectra	Class	Number of spectra	Class	Number of spectra
A	16	K	23	Sr	4
B	30	L	19	T	6
C	80	R	2	V	8
Cb	13	S	176	X	79
Cg	6	Sa	10	Xc	35
Cgh	8	Sk	8	Xe	19
Ch	95	Sl	22	Xk	29
D	2	Sq	17		

aries of the "spectrophotometric corridor," sometimes intersecting, and similar albedo values, sometimes differing only in absorption bands. Therefore, in case of ambiguity in the assessment of belonging to one or another class, the asteroid was assigned the value of several classes (for example, C, Cb, B), especially in cases where the absorption bands characteristic of the classes were not unambiguously determined.

The use of a similar technique for creating a "spectrophotometric corridor" is described in detail in the work (Savelova et al., 2022).

Due to some convention in defining subclasses and the possibility of an asteroid corresponding to several classes with a similar mineral composition at once (which is quite understandable, given the features of the data, on a rather sparse set of values at 16 points), spectral classes are traditionally divided into large groups according to their characteristics:

• The C-group covers classes B, C, Cb, Cg, Ch, Cgh, which also correlates with classes B and F in Tholen's taxonomy and reflectance spectra similar to those of the carbonaceous chondrites CI and CM.

• The S-group includes classes S, A, Q, R, K, L and intermediate classes Sa, Sq, Sr, Sk, Sl, representing spectra close to stony-iron meteorites, ordinary chondrites and achondrites.

• The X-group consists of classes X, M, E, P according to Tholen's classification and intermediate classes Xe, Xc, Xk.

• Small groups include rare classes Ld, T, D, V, O.

Individual asteroids may exhibit features characteristic of both high- and low-temperature classes (S and C, respectively), which may indicate a complex impact history for these asteroids.

Division into larger groups allows us to speak in general terms about the predominant mineralogy of the surface material of the asteroid, without going into details (low-temperature mineralogy of representatives of the C-group; high-temperature mineralogy of the S-group; predominance of X-group metals; rather exclusive composition of the substance, but represented by a small number asteroids in principle – the so-called small groups; as well as special asteroids of mixed mineralogy). Such division into larger groups is traditional in spectrophotometric studies of asteroids, especially when using low-resolution reflectance spectra, and is often used for a general assessment of the distribution of chemical and mineralogical properties of asteroids, while circumventing some inaccuracies or doubts in the determination of close classes.

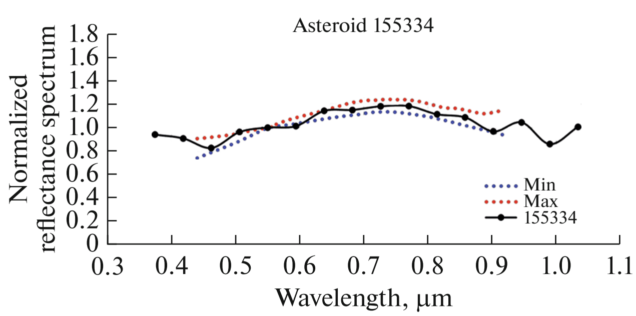

Fig. 4. Reflection spectrum of asteroid 155334 (2006 DZ169) of the Amor group from the GDR3 catalog.

RESULTS

Note that for almost half of the objects we gave an assessment of the spectral type for the first time. Membership of a specific spectral class was determined for 22 asteroids of the Apollo group, 23 asteroids of the Amor group and 5 of the Aten group, for a total number of 47 asteroids.

The results are presented in Table 2 and diagrams in Fig. 5.

The statistics presented, unfortunately, are based on a small data set. We still attempted to establish

Table 2. Distribution of spectral groups of near-Earth asteroids, according to the GDR3 database + addition of the results of spectrophotometric observations obtained at the Terskol Peak Observatory

NEAs asteroid group	Total	C-group	S-group	X-group	Small groups	Mixed mineralogy
	assessed as PHAs	assessed as PHAs	assessed as PHAs	assessed as PHAs	assessed as PHAs	assessed as PHAs
Aten	7	3	1	1	1	1
	4	*2*	*0*	*0*	*1*	*1*
Apollo	57	12	36	1	3	5
	19	*4*	*12*	*0*	*0*	*3*
Amor	43	8	28	0	6	1
	1	*0*	*1*	*0*	*0*	*0*
Total	**107**	**23**	**65**	**2**	**10**	**7**
	24	***6***	***13***	***0***	***1***	***4***

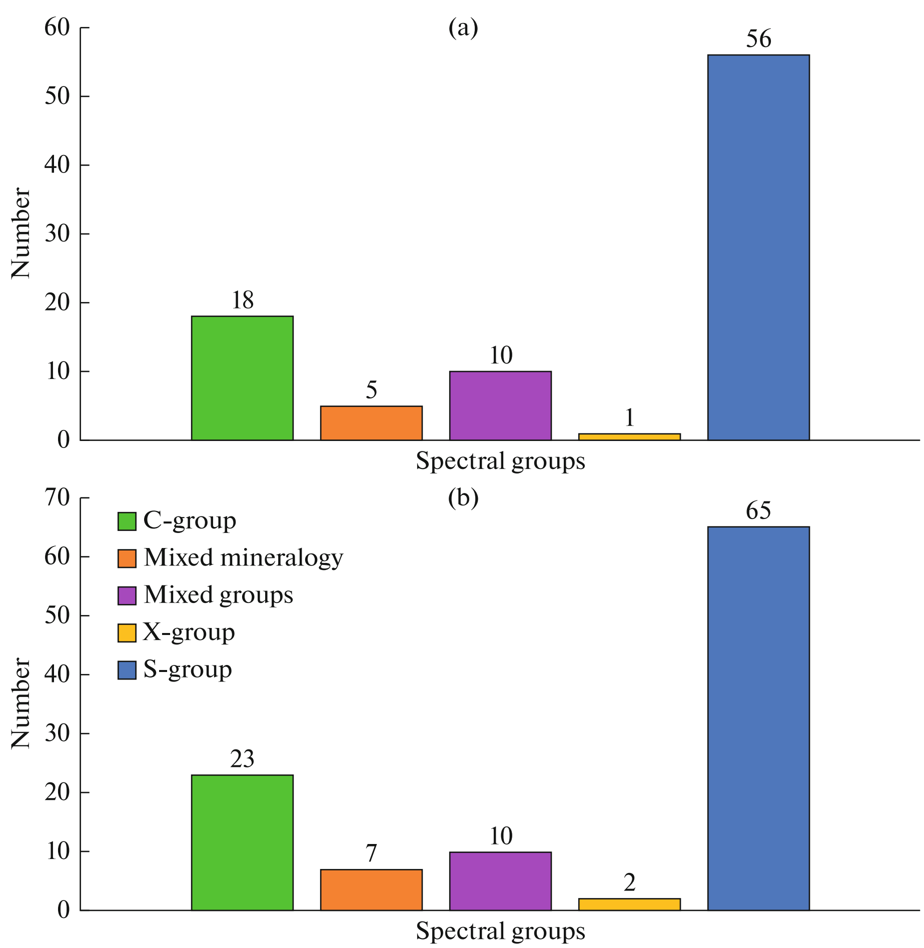

Fig. 5. Distribution of spectral groups Near-Earth asteroids: (a) GDR3 (90 NEAs); (b) GDR3 + addition of the results of spectrophotometric observations obtained at the Terskol Peak Observatory (107 NEAs).

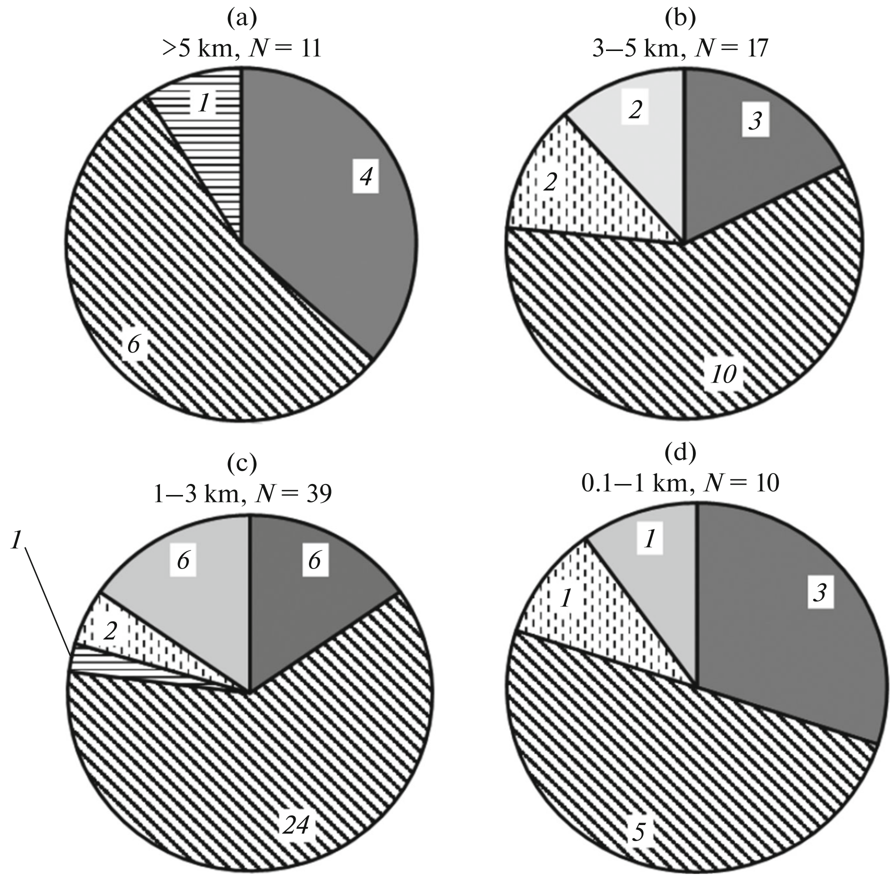

Fig. 6. Distribution of NEAs from the GDR3 database + additions by spectral classes of asteroids of various sizes (diameter values are taken from the NASA database). Diagram legend: oblique shading corresponds to the S-group, horizontal shading to the X-group, vertical intermittent shading to mixed mineralogy; dark fill—C-group, light fill—small groups. Within each sector, the number of asteroids included in the distribution is indicated: (a) distribution by spectral groups of NEAs, whose diameter is more than 5 km; (b) distribution by spectral groups of NEAs, whose diameter is from 3 to 5 km; (c) distribution by spectral groups of NEAs, whose diameter is from 3 to 1 km; (d) distribution by spectral groups of NEAs, whose diameter is less than 1 km.

some statistical dependences on the NEA parameters. Information about the diameter, semi-major axis and perihelion distance was taken from the NASA database (https://ssd.jpl.nasa.gov/horizons/).

Figure 6 shows that the relative proportion of S-types remains throughout the entire size range (50–60% of the sample).

The results are in good agreement with the work of (Binzel et al., 2019), which presents a sample of more than 1000 NEAs, including Mars-crossers. As the authors of the paper noted, the fractional distributions of the main taxonomic classes (60% S, 20% C, 20% other) appear remarkably constant over a size range of the order of magnitude (10 km to 100 m), which is eight orders of magnitude by mass.

Figure 7 shows the distribution of asteroids of different spectral groups along the semi-major axis and perihelion distance of the orbits. The intervals of semi-major axis values of the considered NEA spectral groups overlap, and the distribution of C-type asteroids covers almost the entire interval of semi-major axis values. The maximum number of S-type asteroids is shifted to the inner edge of the Main Belt, which is logical, since this type assumes high-temperature mineralogy of the surface material (see Fig. 7a). Let us note that, despite the numerical predominance of S-group asteroids in the NEA sample, asteroids of primitive types (C-group) are also present at very small perihelion distances (see Fig. 7b). It is possible that the presence of such asteroids in this zone is a factor that helps to explain the phenomenon of sublimation activity of primitive types of asteroids, which is confirmed by a series of works (see, for example, Busarev et al., 2022, 2023), which noted a correlation between the activity of asteroids and the passage of perihelion zones.

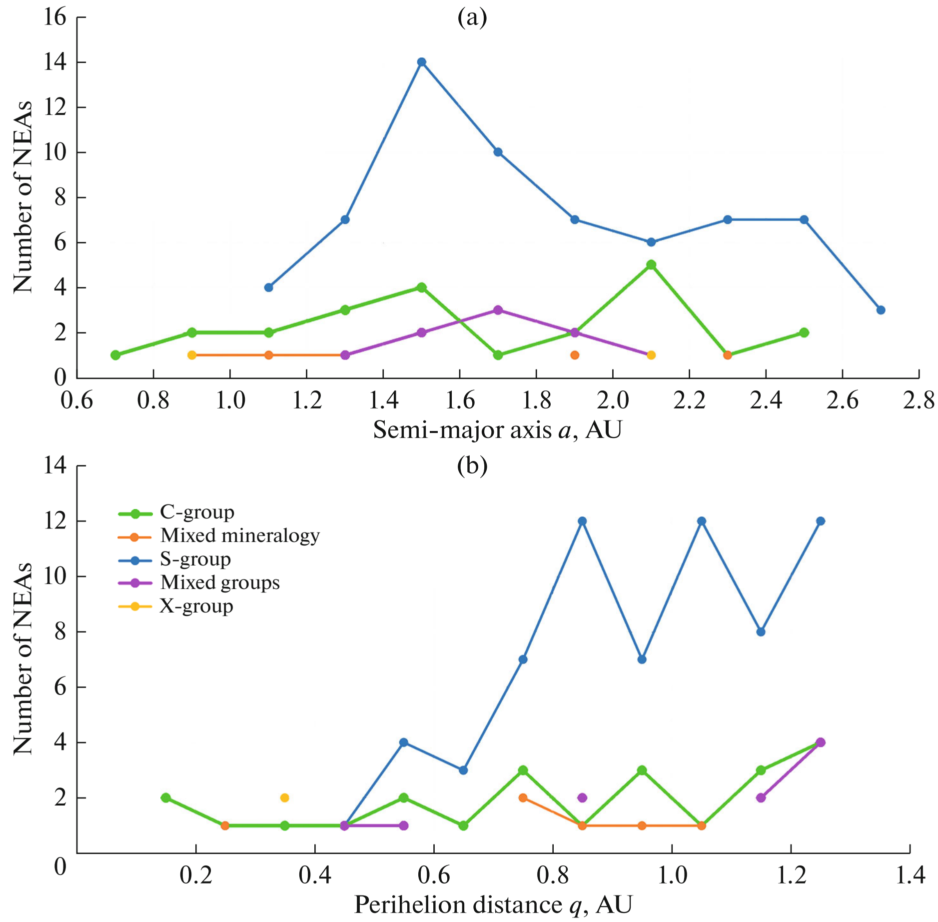

Fig. 7. Distribution of the number of NEAs of a given spectral class: (a) along the semi-major axis; (b) depending on the perihelion distance.

CONCLUSIONS

(1) As a result of the analysis of the reflectance spectra of asteroids obtained from the *Gaia* spacecraft, their spectral types were determined, and about half of them 47 objects—received an estimate of their spectral type for the first time. For asteroids, spectral types which were previously identified by other authors (and entered into the NASA JPL database), confirmation or clarification of belonging to one or another class was obtained.

(2) The assessment of belonging to the spectral class was made by a combined method: using a "spectrophotometric corridor," built according to the minimum and maximum values of the normalized reflectivity at each wavelength, the albedo value, the spectral gradient, and the presence of pronounced absorption bands. Using a "spectrophotometric corridor" as one of the selection filters significantly speeds up the process of estimating the spectral class. In case of an uncertain result (if several classes similar in their chemical and mineralogical composition are suitable), several classes were assigned.

(3) For subsequent analysis, all classes were divided into several traditional groups (C-group, S-group, X-group, small groups and mixed mineralogy group). This division allows for a general analysis of the distribution of the predominant type of mineralogy, in this case, near-Earth asteroids, without focusing on the more subtle differences within each group, and also avoiding controversial issues of belonging to similar classes.

(4) The statistics of the distribution of spectral groups of this sample of asteroids coincides with the results of ground-based observations of a large number of objects (Binzel et al., 2019), namely 60% are representatives of the S-group, 20% are representatives of the C-group, 20% are representatives of other groups.

(5) Similar statistics remain approximately the same when considered within certain diameter intervals. A similar pattern was also noted by the authors of the work (Binzel et al., 2019).

(6) When analyzing the distribution of spectral groups according to semi-major axis values and perihelion distances of asteroid orbits, we noted that rep-

resentatives of the C-group cover a wide range of semi-major axis values and are also present at fairly small perihelion distances. Indirectly, this can serve as confirmation of the hypothesis that explains the sublimation-driven dust activity dust activity of asteroids of primitive types (C-group) by a comet-like mechanism.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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