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Gaia Data Release 3: analysis of reflectance spectra of near-Earth asteroids and Mars-crossers

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Abstract. Since July 2014, the European Space Agency (ESA) Gaia mission has been observing objects in the Solar System as part of its various scientific missions. The third data release (DR3) includes observations of more than 150,000 objects, including asteroids. Analysis of Gaia asteroid reflectance spectra has allowed for the first time to determine spectral types for many objects and to confirm or refine previously determined classes. The distribution of spectral groups coincides with the analysis of ground-based observations performed by other authors, with a sample overlap of less than 20%. The main groups include the S-group (∼60%) and the C-group (∼20–25%). Mars-crossing objects are slightly more likely to have mixed mineralogy. This distribution remains constant over different ranges of object diameters. Analysis of the distribution of spectral groups by semi-major axis and perihelion distance may serve as indirect evidence for the prevalence of sublimation-dust activity in primitive asteroids.

Keywords: astronomical databases: Gaia Data Release 3; asteroids: Near-Earth Asteroids, Mars-crossers

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1 The Gaia Space Mission

Gaia, an ESA mission, was launched on December 19, 2013, from Kourou, French Guiana, and began operations on July 25, 2014. The mission's primary goal is to create a highly accurate three-dimensional map of the positions and velocities of stars in the Milky Way. The satellite is equipped with two telescopes and an astrometric instrument with 106 CCD detectors, enabling precise astrometric and photometric measurements. Gaia also has two spectrophotometers – the Blue Photometer (BP) and the Red Photometer (RP), operating in the wavelength ranges of 330–680 nm and 640–1050 nm, respectively. The large volume of data obtained from repeated scans of the celestial sphere by Gaia provides results for Solar System objects as well. DR3 includes information on more than 150,000 Solar System objects, making it the largest space-based survey of asteroid reflectance spectrophotometry in the visible range to date.

Reflectance spectra are calculated by dividing the flux of each spectrum by the spectrum of a solar analog and normalizing it at a wavelength of 550 nm. The calibration process removes instrumental and astrophysical effects, resulting in arrays of 60 internal flux values and their uncertainties. The spectra have been verified for internal consistency and have a signal-to-noise ratio $(S/N) > 13$. Gaia's reflectance spectra were compared with ground-based telescope data and other space missions, showing good agreement for bright objects. For each Solar System object, a reflectance spectrum is calculated at 16 points representing integral reflectance values (Gaia Collaboration 2023). An example of such a reflectance spectrum is presented in Fig.1.

2 Near-Earth Asteroids and Mars-Crossers

This study analyzes Gaia data for near-Earth asteroids (NEAs) and Mars-crossers. NEAs are divided into groups such as Atens, Apollos, and Amors based on orbital parameters, due to their proximity to Earth and potential collision threat. Mars-crossers are asteroids whose orbits intersect Mars, allowing the study of dynamic processes and migration of small bodies in the Solar System.

The investigation provides valuable data on the composition, structure, and dynamics of small bodies, crucial for developing strategies to protect Earth from possible collisions.

3 Evaluation of Asteroid Spectral Groups

This study is a continuation of the work by Shcherbina et al. (2024), which analyzed the spectral group distribution among near-Earth asteroids. Key steps in spec-

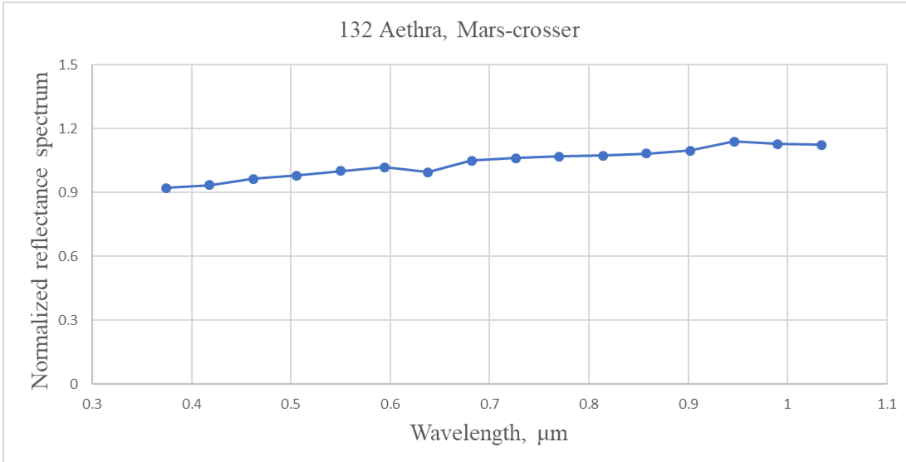

Fig. 1. Normalized reflectance spectrum of asteroid 132 Aethra (Mars-crosser) from the GDR3 catalog.

tral classification included the collection of parameters such as geometric albedo, orbital period, and diameter. The classification was performed according to the Tholen or Bus–Binzel (SMASS II) taxonomies, using data from the NASA database (https://ssd.jpl.nasa.gov/horizons/) and compared with previous studies conducted by INASAN in collaboration with SAI MSU.

The procedure, known as "spectrophotometric corridor construction", involved:

1. Extracting reflectance spectra of asteroids from the SMASS II database (Bus & Binzel 2002).
2. Determining maximum and minimum reflectance values for each wavelength, creating spectral class ranges.
3. Classifying asteroids based on albedo, spectral gradient, the presence of absorption bands, and matching with template spectra.

In cases of ambiguity, asteroids could be assigned to multiple classes. The spectral classes were divided into major groups (C, S, X) and minor groups (rare classes like Ld, T, D, V, O), considering similar mineral compositions. Some asteroids were classified as mixed due to characteristics of both high and low-temperature classes. Among the 731 reflectance spectra of Mars-crossers, 92 could not be definitively classified and were excluded from further analysis. The remaining 556 had their spectral class determined for the first time. Table1 shows the distribution of Mars-crossers and NEAs.

This study and the previous work by Shcherbina et al. (2024) were inspired by the research of Binzel et al. (2019), which presented a sample of approximately 1000

Table 1. Distribution of spectral groups of near-Earth asteroids and Mars-crossers based on GDR3 Data with supplementary spectrophotometric observations from the Terskol observatory (Bus & Binzel 2002).

Asteroids	Total Number	C-group	S-group	X-group	Minor group	Mixed
Mars-crossers	639	154	359	25	27	74
Atens	7	3	1	1	1	1
Apollos	57	12	36	1	3	5
Amors	43	8	28	0	6	1
Total number	746	177	424	27	37	81

near-Earth asteroids, including Mars-crossers. It is important to emphasize that the originality of the current sample compared to the sample used in Binzel's paper exceeds 80%. Specifically, there is an overlap of only 126 objects, while the remaining ones are new.

4 Distribution of asteroids by spectral groups

The spectral group affiliations of near-Earth asteroids and Mars-crossers were determined, and the results are presented in Fig.2. As shown, the percentage content of the main spectral groups is very similar (S-group, approximately 60%, C-group, approximately 20-25%). There is a slightly higher number of objects exhibiting signs of mixed mineralogy among the Mars-crossers, possibly due to more active impact evolution.

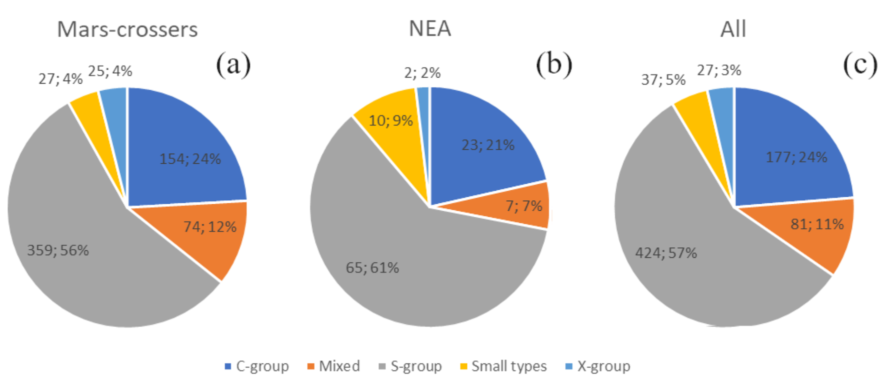

Fig. 2. Distribution by spectral groups (a) Mars-crossers; (b) near-Earth asteroids; (c) complete sample from Gaia DR3 + observations of individual near-Earth asteroids at the Terskol observatory.

The results from Binzel et al. (2019) show very similar distributions: about 60% of the population consists of S-type asteroids, 20% C-type, and 20% other classes. This distribution indicates the diversity of NEA sources, reflecting their origins from various regions of the Main Asteroid Belt.

As noted by the authors of the mentioned paper, this distribution remains constant among asteroids of different diameters (Fig. 3). Of course, the diameter values for Mars-crossers and NEAs are determined for only a small number of asteroids (311 in total, including 234 Mars-crossers and 77 NEAs). Additionally, it should be noted that diameter data may be inaccurate due to the difficulties in determining this parameter.

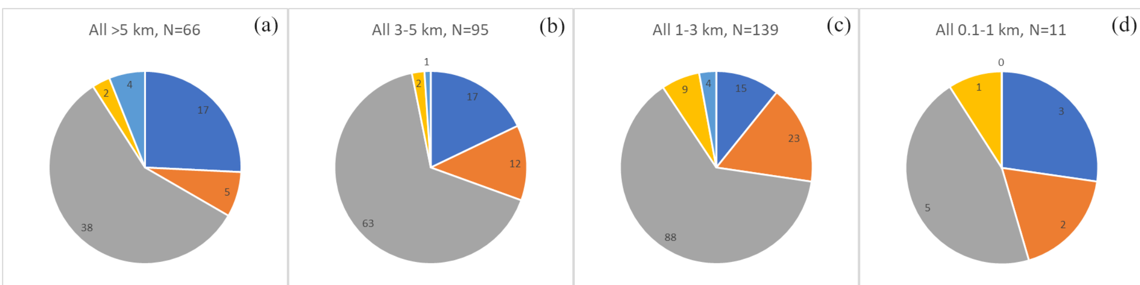

Fig. 3. Distribution of NEAs and Mars-crossers by spectral classes of asteroids of various sizes (Diameter values are taken from the NASA database). The number of asteroids included in each distribution is indicated within each sector.(a) Distribution by spectral groups for asteroids with a diameter greater than 5 km. (b) Distribution for asteroids with a diameter from 3 to 5 km. (c) Distribution for asteroids with a diameter from 1 to 3 km. (d) Distribution for asteroids with a diameter less than 1 km.

The analysis of the distribution of various spectral groups of asteroids by semi-major axis and perihelion distance of orbits shows that C-type asteroids cover almost the entire range of semi-major axis values. S-type asteroids are concentrated closer to the inner edge of the Main Belt, which is associated with their high-temperature mineralogy. Notably, despite the numerical predominance of the S-group, primitive-type asteroids (C-group) are also found at small perihelion distances. The presence of such asteroids in this zone may explain the phenomenon of sublimation activity of primitive asteroids, which is supported by the correlation of their activity with the passage of the perihelion zone, noted in several studies (e.g., Busarev et al. (2023)).

5 Conclusions

1. The analysis of reflectance spectra of asteroids from the Gaia spacecraft allowed for the first-time determination of spectral classes for many objects. For asteroids with previously determined classes recorded in the JPL NASA database, their affiliations were confirmed or refined.
2. The distribution of spectral groups in the sample matches the results of ground-based observations (Binzel et al. 2019) with a sample overlap of about 20%. The percentage content of the main spectral groups is similar: the S-group is about 60%, and the C-group is about 20–25%. Among the Mars-crossers, more objects with mixed mineralogy are observed, associated with active impact evolution.
3. This statistic is also maintained for asteroids of various diameters, as noted in the work of Binzel et al. (2019).
4. Representatives of the C-group cover a wide range of semi-major axis values and small perihelion distances, confirming the hypothesis of sublimation-dust activity of primitive-type asteroids through a comet-like mechanism.

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