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Spectrophotometry of (32) Pomona, (145) Adeona, (704) Interamnia, (779) Nina, (330825) 2008 XE3, and 2012 QG42 and laboratory study of possible analog samples

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Six asteroids including two NEAs, one of which is PHA, accessible for observation in September 2012 were investigated using a low-resolution ($R \approx 100$) spectrophotometry in the range 0.35–0.90 μm with the aim to study features of their reflectance spectra. A high-altitude position of our Terskol Observatory (3150 m above sea level) favorable for the near-UV and visible-range observations of celestial objects allowed us to probably detect some new spectral features of the asteroids. Two subtle absorption bands centered at 0.53 and 0.74 μm were found in the reflectance spectra of S-type (32) Pomona and interpreted as signs of presence of pyroxenes in the asteroid surface matter and its different oxidation. Very similar absorption bands centered at 0.38, 0.44 and 0.67–0.71 μm have been registered in the reflectance spectra of (145) Adeona, (704) Interamnia, and (779) Nina of primitive types. We performed laboratory investigations of ground samples of known carbonaceous chondrites, Orguel (CI), Mighei (CM2), Murchison (CM2), Boriskino (CM2), and seven samples of low-iron Mg serpentines as possible analogs of the primitive asteroids. In the course of this work, we discovered an intense absorption band (up to ~25%) centered at 0.44 μm in reflectance spectra of the low-Fe serpentine samples. As it turned out, the equivalent width of the band has a high correlation with content of Fe^{3+} (octahedral and tetrahedral) in the samples. It may be considered as a confirmation of the previously proposed mechanism of the absorption due to electronic transitions in exchange-coupled pairs (ECP) of Fe^{3+} neighboring cations. It means that the absorption feature can be used as an indicator of ferric iron in oxidized and hydrated low-Fe compounds on the surface of asteroids and other atmosphereless celestial bodies. Moreover, our measurements showed that the mechanism of light absorption is partially or completely blocked in the case of intermediate to high iron contents. Therefore, the method cannot probably be used for quantitative estimation of Fe^{3+} content on the bodies. Based on laboratory study of the analog samples, we conclude that spectral characteristics of Adeona, Interamnia, and Nina correspond to a mixture of CI–CM-chondrites and hydrated silicates, oxides and/or hydroxides. Spectral signs of sublimation activity on Adeona, Interamnia, and Nina at minimal heliocentric distances are likely discovered in the short-wavelength range (~0.4–0.6 μm). It is suggested that such cometary-like activity at the highest surface temperatures is a frequent phenomenon for C and close type asteroids including considerable amounts of ices beneath the surface. A usual way of origin of a temporal coma of ice particles around a primitive asteroid is excavated fresh ice at recent impact event (s).

The obtained reflectance spectra of two NEAs, (330825) 2008 XE3 and 2012 QG42, are predominantly featureless and could be attributed to S(C) and S(B)-type bodies, respectively. We discuss reasons why weak spectral features seen in reflectance spectra of the main-belt asteroids are not observed in those of NEAs.

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1. Introduction

Spectrophotometry/spectroscopy is a traditional method of remote study of asteroids and other atmosphereless celestial bodies (e.g., McCord et al., 1970; Adams, 1974). When ground-based telescopes used, the range preliminary from ~0.38 to 1.1 μm is extended up to 2.5 μm (e.g., Vernazza et al., 2008; DeMeo et al., 2009; Hardersen et al., 2014; Fieber-Beyer et al., 2015). It is defined by the boundaries of the most transparent spectral "window" of the Earth's atmosphere, through which the bulk of observational information on asteroids was obtained. It allowed us to enrich our knowledge about these objects, in particular on their taxonomy (e.g., Tholen, 1989; Bus and Binzel, 2002a, 2002b; DeMeo et al., 2009). Further progress in ground-based studies of asteroids are naturally related with increasing both the number (and therefore the sample size) of studied bodies and the accuracy of spectral measurements. High-quality reflectance spectra of asteroids potentially contain not only valuable mineralogical information on the material of which the asteroids are made but also that on the valency state of iron (as well as of other transition metals). As is known, the latter depends on physico-chemical parameters (Platonov, 1976; Burns, 1993) of asteroid matter connected with the formation conditions of the bodies and their subsequent evolution. Unfortunately, various distorting factors, such as observational faults and space weathering, make it difficult to reconstruct reliably the previous conditions. Thus, the final goal of such kind of study is to accurately extract the observational information and to try to correctly interpret it. For most asteroids, except for some bodies investigated by space methods, there is a lack of data about whether or not chemico-mineralogical and other properties vary along their surface. The reason of that is mainly due to (nearly) point-like appearance of asteroids at ground-based observations, which makes it difficult to obtain spectral information of different parts of the asteroids' surface. Indeed, the angular size of (1) Ceres, the largest asteroid with a diameter of ~1000 km, varies in the range 0.″8–0.″3, which is comparable to the limiting angular resolution of ground-based telescopes at the excellent atmospheric seeing. The most important is to minimize the impact of the Earth's atmosphere on reflectance spectra of asteroids and on the reliability of final results and conclusions. To achieve this goal it is useful to compare spectral data obtained with the same facility on asteroids of the same and/or close taxonomic types which are expected to have similar spectral features. Such approach is used in the work to study several of C-B-type asteroids. As before, a laboratory study of spectral characteristics of both meteoritic and terrestrial analog samples is very helpful and used also in our work. In addition, we consider and discuss the reflectance spectra obtained by other authors for the objects of our sample to the date.

2. Observations and data reduction

Spectrophotometry of the Asteroids (32) Pomona, (145) Adeona, (704) Interamnia, (779) Nina, (330825) 2008 XE3, and 2012 QG42 was performed in September 2012 using the 2-m telescope of Terskol Observatory operated by Institute of Astronomy of Russian Academy of Science (IA RAS). The observatory is situated at high altitude of 3150-m above sea level, making especially favorable conditions for observations at shorter wavelengths. The telescope is equipped with a prism CCD-spectrometer (WI CCD 1240 × 1150 pix.) working in the range 0.35–0.97 μm, with $R \approx 100$ resolving power. DECH spectral package (Galazutdinov, 1992) was employed to reduce CCD observations by means of standard reduction procedures (such as flat-field correction and bias and dark subtraction) and to extract asteroid spectra. Wavelength calibration of the spectra was done using the positions of hydrogen Balmer lines in the spectrum of α Peg (B9III) observed in a repeated mode. The total exposure time spent on each target was typically ~1–2^h. The obtained reflectance spectra were corrected for the difference in air mass by applying a conventional method based on using observations of a solar analog star (e.g., McCord et al., 1970). In our work a single solar analog star, HD 10307 (G1.5V) (Hardorp, 1980), was intentionally exploited to avoid possible differences in the calculated reflectance spectra of asteroids as in the case of several solar analogs use. Observations of the same star were performed to determine the running spectral extinction function of the terrestrial atmosphere (Busarev, 2011). The observations of HD 10307 were made nearly in the same range of the air masses at (or close to) which the asteroids of the sample were observed (see Table 1). The values of the signal-to-noise ratio (S/N) of the asteroid spectra were estimated in the range of 0.4–0.8 μm. They are given, along with other data, in Table 1. To reduce high-frequency fluctuations in the reflectance spectra, they were smoothed by the method of "running box average" with a 5-point averaging interval. This allowed us to study considerably wider spectral features of the observed asteroids and to assess their spectral types according to shapes of their reflectance spectra. As a rule, averaging of the asteroid consecutive reflectance spectra was made when they had a close overall shape and observational spectra were obtained at minimal air masses.

Ephemerides (taken from the IAU Minor Planet Center on-line service at http://www.minorplanetcenter.net/iau/MPEph/MPEph.html) and observation parameters of the asteroids are given in Table 1.

3. Analysis and interpretation of asteroid reflectance spectra

3.1. 32 Pomona

Average diameter and geometric albedo of Pomona according to recent WISE-data are of 81.78 km and 0.25 (Masiero et al., 2014). The asteroid rotates with a period of 9.448^h (Harris et al., 2012). In total, eight separate spectra of Pomona were registered on the night 19/20 of September, 2012, together with the spectra of HD10307 used as a solar analog star (Table 1). We used them to calculate an average spectrum of the asteroid and normalized it to 1.0 at 0.55 μm (Fig. 1a). It corresponds to an S-type body having mineralogy dominated by pyroxenes, olivines, and other high-temperature compounds (e.g., Gaffey et al., 1989, 1993). Given the rotational period of the asteroid, the total exposure time spent to obtain the eight spectra (2 h) corresponds to ≈1/5 of its rotational period. In terms of its shape, the spectrum is very similar to that obtained by McCord and Chapman (1975a) but differs to some extent from that by Bus and Binzel (2002a or 2003a) and Xu et al. (1995) (Fig. 1b). We find two relatively weak and broad absorption bands in the obtained spectra of Pomona at 0.49–0.55 μm and 0.73–0.77 μm (Fig. 1a). We suppose that the former one, at 0.49–0.55 μm, has a complex nature. It is probably a superposition of two or even three wide spectral features. It was established earlier that electronic spin-forbidden crystal-field transitions in Fe^{2+} ions in M2 crystallographic positions of clinopyroxenes are responsible for a couple of weak bands near 0.505 μm and 0.550 μm (e.g., Burns et al., 1973; Platonov, 1976; Hazen et al., 1978; Matsyuk et al., 1985; Burns, 1993; Klima et al., 2006). If asteroid surface matter consists of a clinopyroxene and Fe orthopyroxene mixture then an additional weak band can originate at 0.525 μm due to the spin-forbidden crystal-field electronic *d*–*d*-transitions in Fe^{2+} ions in M1 crystallographic sites of Fe orthopyroxenes. Moreover, a common absorption band at 0.49–0.55 μm (as any other one) could be widened because of