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Asteroid activity: spectral features and probable physical reasons

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Abstract. Spectral signs of sublimation-driven dust activity of main-belt asteroids with primitive mineralogy (of C, B, F, G, and X types) are considered. The reflectance spectra of active asteroids of primitive types are compared with model ones of a conditionally active C-type asteroid surrounded by a dust exosphere consisting of submicron aggregate particles of different composition. This phenomenon in primitive asteroids may be impact-induced and become subsequently periodic near perihelion if connected with considerable water ice deposits of the asteroids. Significant additional factors influencing the primitive-type active asteroids, although secondary by random nature, are flares and eruptive events on the Sun, and electrostatic field of photoemission nature on the sunlit side of the bodies. We argue that the formation of aggregate dust particles in a dust exosphere of active asteroids may be one of the fundamental processes.

Keywords: asteroids: general; comets: general; methods: observational, radiative transfer, scattering

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1 Introduction

To date, 60 objects of approximately one kilometer in size have been discovered moving in asteroid orbits in the Main Asteroid Belt (MAB) that have shown various signs of dust activity. To systematize the data from different sources as well as mechanisms proposed to explain activity of the bodies, considerable efforts have been undertaken (e.g., Jewitt 2021; Hsieh et al. 2023; Chandler et al. 2024, and references therein). The authors formulated basic criteria, by which a predominant mechanism of each body's activity was proposed. The most common is the sublimation-driven dust activity (SDA) of primitive asteroids.

2 Activity of primitive asteroids and possibilities of its detection by spectral methods

The frequent SDA events in the MAB can be explained by assuming that primitive-type asteroids (C, B, G, F and partly X), which have low-temperature mineralogy, initially contained water ice. Considering the very low thermal conductivity of the surface destroyed layer (regolith) of asteroids, numerical modeling (Schorghofer 2008) has proven the possibility of preserving water ice in their depths for several billion years. As for CO_2 ice (close in thermophysical parameters to water ice), its volatility is almost seven orders of magnitude higher than that of H_2O ice (e.g., Chandler et al. 2020). That makes unlikely presence of CO_2 ice in main-belt asteroids for a long time. Since the content of bound water in carbonaceous chondrites (as probable fragments of primitive asteroids) reaches 20 wt. (e.g., Jarosewich 1990; Alexander et al. 2018), the initial content of unbound H_2O in primitive-type asteroids, as their parent bodies, should not be less. So, the bodies may be considered as first candidates for active asteroids (AAs).

We proceed from the possibility of SDA and related dust exosphere (DE) formation around primitive asteroids whose subsurface matter includes water ice sublimating at high subsolar temperatures near perihelion. The first reflectance spectra of primitive AAs, 145 Adeona, 704 Interamnia, 779 Nina, and 1474 Baira, have been detected in September 2012, close to their perihelia. These spectra are shown in Fig. 1(a–d) in comparison with their canonic reflectance spectra from the SMASSII database obtained when the asteroids were inactive (Busarev et al. 2016). We assumed that the maxima discovered near $0.4 - 0.5\,\mu m$ and/or $0.6 - 0.7\,\mu m$, which are atypical for the surface matter of asteroids, are characteristic of a DE around bodies. Importantly, the reflectance spectra of 145 Adeona, 704 Interamnia, 779 Nina, and 1474 Baira in September 2012 were obtained in the period of solar activity maximum, when frequent solar flares and eruptive coronal mass ejection (CMEs) took place. Hence, the asteroid DEs were exposed to impacts of the shock waves from the CMEs, radiation pressure and solar wind. As a result, the concentration of dust particles affecting the optical thickness of the DEs of these AAs was high.

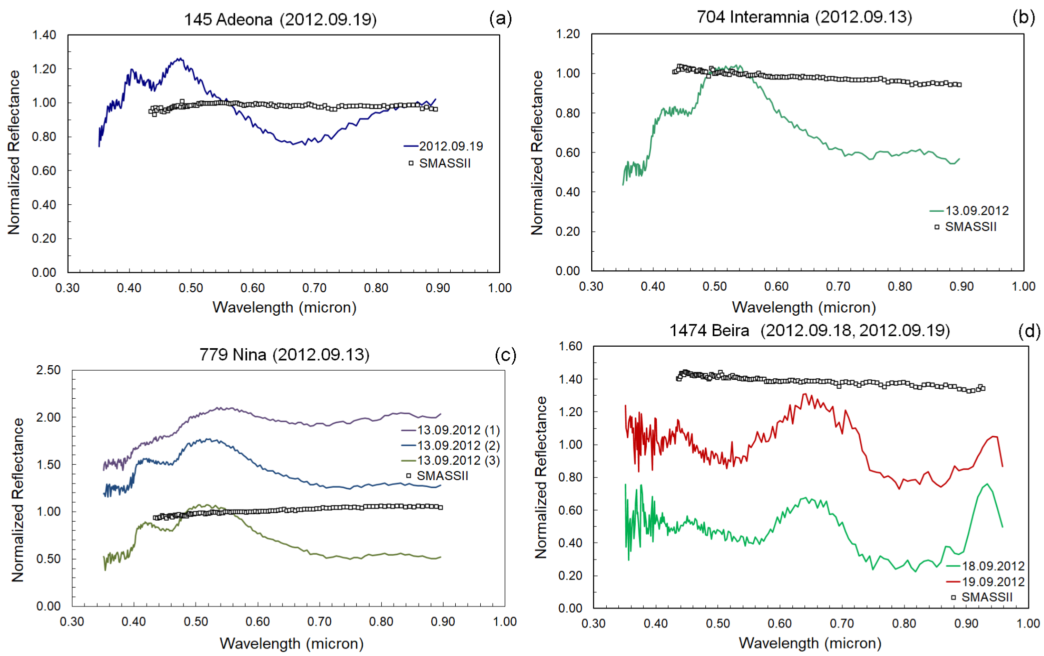

Fig. 1. Reflectance spectra of primitive AAs 145 Adeona (a), 704 Interamnia (b), 779 Nina (c), and 1474 Beira (d) obtained in September 2012 compared with their reflectance spectra from the SMASSII database registered in inactive states of the bodies (Busarev et al. 2016).

To substantiate our assumptions about the features of the observed reflectance spectra of AAs, numerical model spectra of a conditional AA of C-type were calculated (Busarev et al. 2021 and references therein). Examples of the model spectra for dust aggregate particles of different compositions (water ice, tholins, and olivine) and two structures of dust aggregates (dense and fluffy) in the DE above the asteroid surface are shown in Fig. 2(a–f). The optical thickness of the exosphere was $\tau = 0.5$, and the material of aggregates, the radii (r) of smaller constituents in the aggregates are specified in the diagrams.

Thus, a good coincidence of observational reflectance spectra of primitive AAs 145 Adeona, 704 Interamnia, 779 Nina, and 1474 Beira with numerically modeled ones of a conditional active C-type asteroid surrounded by an optically thin DE is

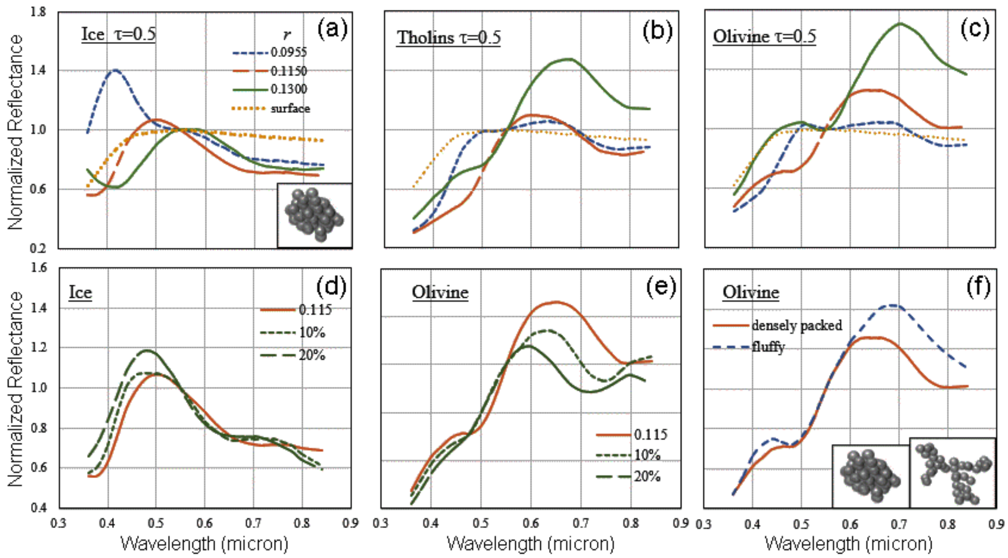

Fig. 2. Normalized model reflectance spectrum of a conditional AA of C-type (reflectance spectrum of its surface is shown by the dotted line) surrounded by a DE with optical thinness $\tau = 0.5$ from dust aggregates of various compositions (water ice, tholins and olivine). The sizes of smaller components in aggregates are given in microns in (a) and (b). The structures of dense and fluffy dust aggregates are shown in the insets (Busarev et al. 2021).

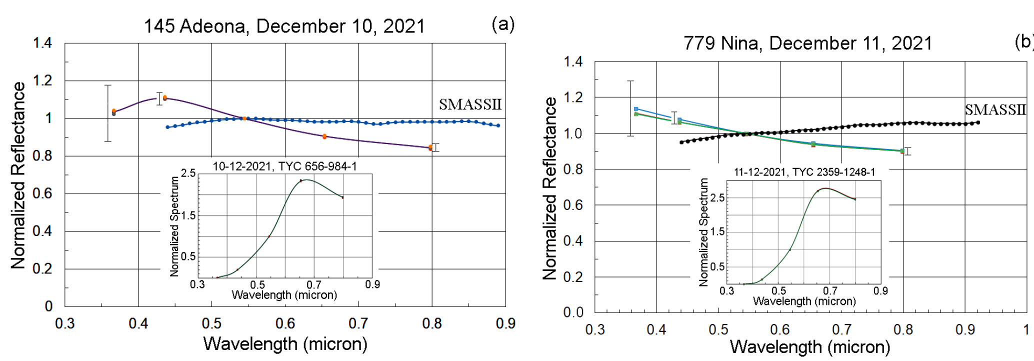

Fig. 3. Normalized reflectance spectra of AAs 145 Adeona (a) and 779 Nina (b) obtained in December 2021 and approximated by the UBVRI-data in comparison with their reflectance spectra from SMASSII database. Normalized approximated spectra of the corresponding non-variable reference stars are given in the insets (Busarev et al. 2023).

a confirmation of SDA and the presence of a related DE around these and similar asteroids.

Moreover, we confirmed activity of two from mentioned AAs, 145 Adeona and 779 Nina, by their UBVRI-photometry in December 2021 at the Caucasian Mountain Observatory (CMO) of the SAI MSU. The normalized approximated reflectance spectra of the asteroids are shown in Fig. 3(a, b) in comparison with their spectra from the SMASSII database obtained when the asteroids were inactive. To check the stability of the photometric conditions, we used non-variable reference stars observed simultaneously with the asteroids. The normalized approximated spectra of these stars are given in the insets of the figures for comparison with those of the asteroids.

As seen from Fig. 3, the later reflectance spectra of AAs 145 Adeona and 779 Nina are more smoothed than those of the asteroids in Fig. 1, obtained in September 2012. Modeled reflectance spectra of a conditional active C-type asteroid show (Busarev et al. 2023, 2024; Criswell 1972) that smoothed spectra of AAs correspond to a lower optical thinness (up to ~ 0.1) of the DE.

3 On the possibility of the formation of dust aggregates in the plasma sheath of primitive AAs

As is known from the results of the first space studies of the lunar surface (e.g., Criswell 1972; Rennilson & Criswell et al. 1974), the force of electrostatic field of photoemission nature can exceed the force of gravity and is capable to tear charged dust particles of submicron and micron sizes from the surface and to bring them into a state of levitation. Such particles, together with electrons and protons, form a plasma-dust shell (plasma sheath), with a thickness from centimeters near the subsolar point to about a kilometer near the terminator, “sliding” above the sunlit surface of a rotating airless body. Theoretical calculations and model simulations show (e.g., Nitter & Havnes et al. 1992; Lee 1996; Colwell et al. 2005; Poppe et al. 2015) that the smallest charged dust particles ($\sim 10^{-2}$ microns and less), once inside this plasma sheath, are accelerated by the increasing electrostatic gradient (up to $\sim 300\,V/m$) so that they are ejected from the gravitational field of the body. At the same time, particles of a slightly larger size, from 10^{-2} to $1\,\mu m$, in the same conditions balance between the forces of the electrostatic and gravitational fields, but can be ejected at any moment under the influence of fluctuations in the solar wind or radiation pressure.

Thus, we assume that: a temporal DE formed on a primitive AA due to SPA could partly coincide with the plasma sheath above the sunlit surface of the body and replenish the plasma sheath with new submicron dust particles during the rotation of the asteroid; it leads to an increase in the optical thickness of the DE to ~ 0.5

We assume that the growth of submicron aggregate dust particles in the plasma sheath of AAs may be analogous to dust coagulation in protoplanetary disks (e.g., Matthews et al. 2018).

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