SUBLIMATION ACTIVITY OF (145) ADEONA, (704) INTERAMNIA, (779) NINA, AND (1474) BEIRA AND SOME CONFIRMATIONS

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Introduction: Discovering spectral signs of sublimation activity in September 2012 on four main-belt asteroids (MBAs) of primitive types (145) Adeona, (704) Interamnia, (779) Nina, and (1474) Beira at their perihelion distances [1, 2] raised questions about the probable mass nature of this phenomenon among MBAs that could contain free water ice. As is known, the mineralogy of solid rock bodies is sensitive to conditions of their origin. The same is true for distant rock-ice small planets which cannot be studied directly. However, the ellipticity of orbit of such a planet (if available) makes it possible to test the volatility of its material depending on heliocentric distance and accompanying surface temperature changes.

Based on observations on the same observatory and with the same facilities, we are able to confirm this periodic sublimation process on Nina as it approached perihelion in September 2016.

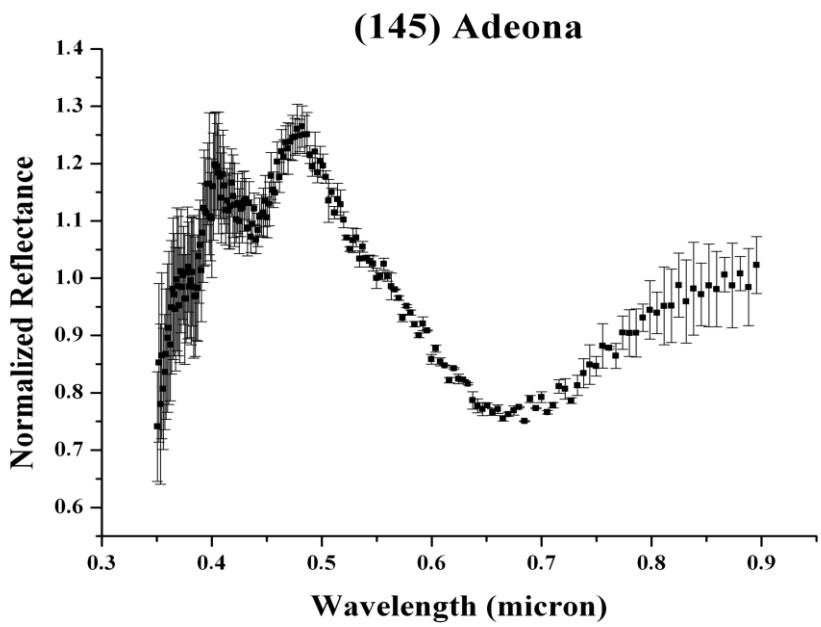

Fig. 1. Averaged and normalized (R = 1 at 0.55 μm) reflectance spectrum of (145) Adeona on 19 September 2012. The spectrum is calculated as an average of two spectra (error bars represent the standard deviation).

Observational Data and Discussion: Spectra of several MBAs, (145) Adeona, (704) Interamnia, (779) Nina, and (1474) Beira, were obtained in September 2012 using a 2-m telescope with a low-resolution (R ≈ 100) CCD spectrophotometer in the 0.35-0.90 μm wavelength range at Terskol Observatory (Mt. Terskol, 3150 m above sea level, Russia) operated by IA RAS. To calculate reflectance spectra of the asteroids, a standard reduction procedure was employed, and HD9986, HD10307, and HD 173071 were used as solar analog stars. The corresponding averaged and normalized reflectance spectra of the asteroids obtained in September 2012 are shown in Figs 1-4.

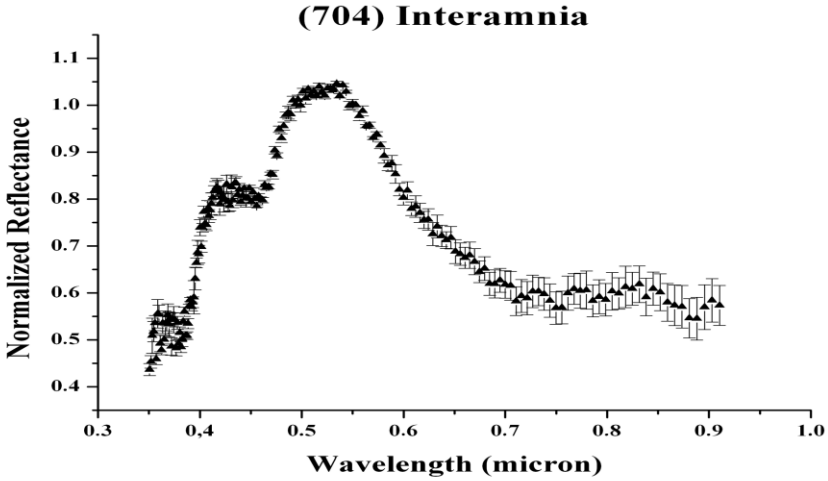

Fig. 2. Averaged and normalized reflectance spectrum of (704) Interamnia on 13 September 2012. The spectrum is calculated as an average of five spectra.

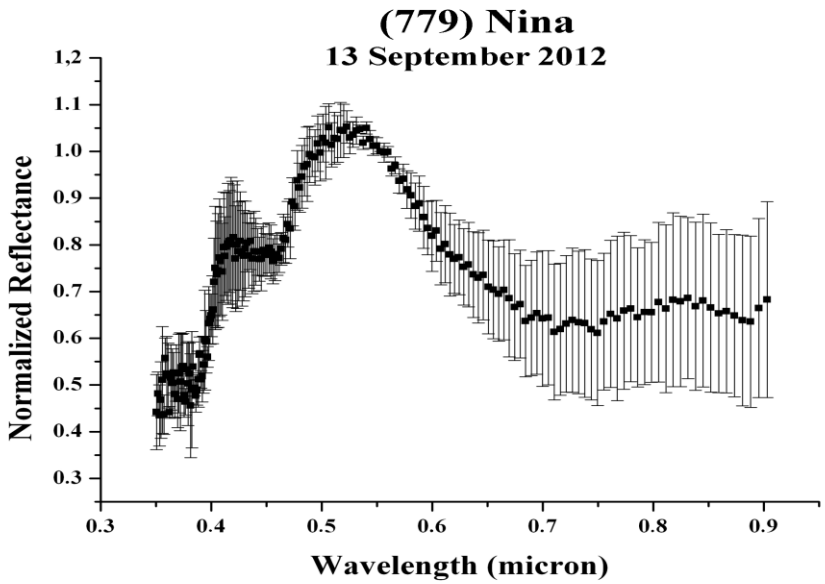

Fig. 3. Averaged and normalized reflectance spectrum of (779) Nina on 13 September 2012. The spectrum is calculated as an average of twelve spectra.

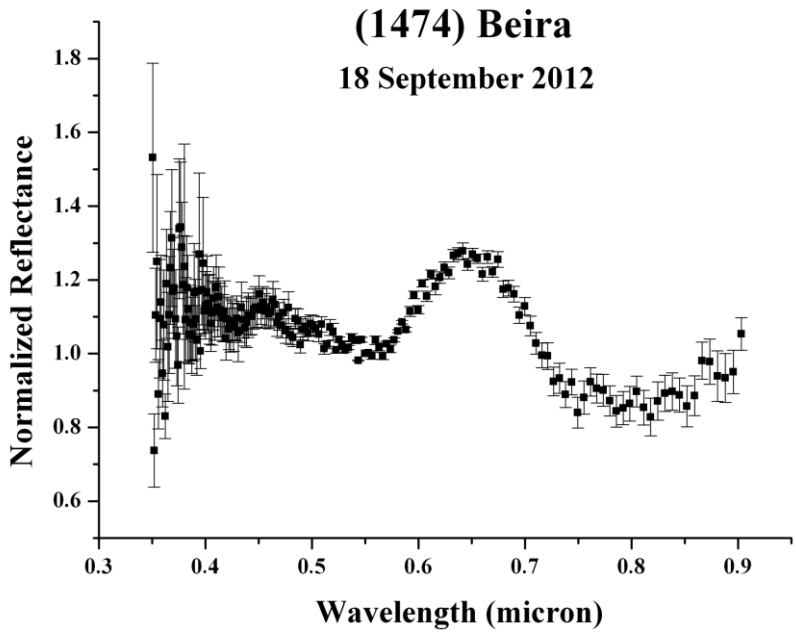

Fig. 4a. Averaged and normalized reflectance spectrum of (1474) Beira on 18 September 2012. The spectrum is obtained as an average of five spectra.

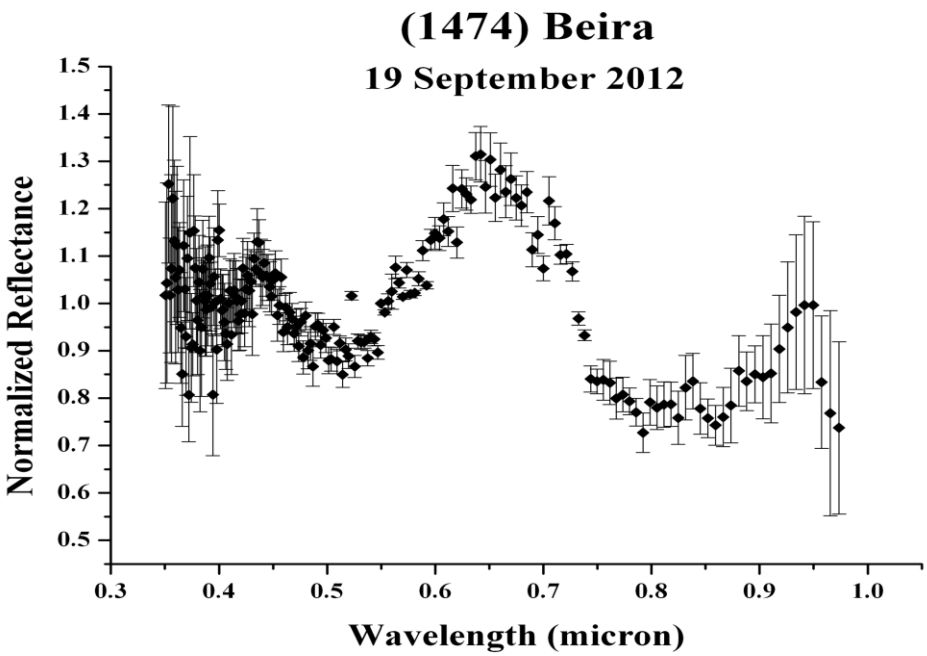

Fig. 4b. Averaged and normalized reflectance spectrum of (1474) Beira on 19 September 2012. The spectrum is obtained as an average of nine spectra.

We found [1, 2] unusual overall shapes of the reflectance spectra of Adeona, Interamnia, Nina (in the range ~0.4-0.6 μm), and Beira (in the range

~0.55-0.75 μm) at the times of these observations, appearing as a considerable growth of reflectivity in the short-wavelength range (up to ~30-40%) (Figs 1-4). Such maxima were absent in reflectance spectra of other asteroids observed by us at the Terskol observatory with the same facilities and nearly concurrently. At the time of our observations, Interamnia, Nina, and Beira were near their perihelion distances, when temperature on the surface reached a maximum near the subsolar point. At the same time, Adeona approaching to the Sun was close to its middle heliocentric distance. We suggested that the unusual visible-range increase in asteroid reflectivity could be a result of sublimation activity of the surface matter including water ice [1, 2].

According to taxonomic classification [3], Adeona is of Ch type, Interamnia – of B, Nina – of X, and Beira – of B. Values of geometric V-band albedo of Adeona, Interamnia, and Nina are 0.06, 0.08, and 0.16, respectively [4]. It should be emphasized that such type asteroids are expected to be primitive containing low-temperature compounds (hydrated silicates, oxides and hydro-oxides, organics, etc.) (e. g., [5]). Despite the previously assumed high-temperature mineralogy of Nina, radar observations showed that the asteroid is also primitive but has a heterogeneous composition [6]. This is confirmed by elevated standard deviations on Nina's averaged reflectance spectrum obtained from 12 separate reflectance spectra over about a half of its rotational period (Fig. 3). A comparison of reflectance spectra of the asteroids and their supposed analog samples [2] leads to a conclusion that the silicate component of the asteroids' surface material is a mixture of hydrated and oxidized compounds, including oxides and hydroxides of bivalent and trivalent iron and carbonaceous-chondritic material. At the same time, the sublimation activity of Adeona, Interamnia, Nina, and Beira at high surface temperatures points to a substantial content of water ice in their material. This contradicts the previously existing notions on the C-type and similar asteroids (based on investigations of carbonaceous chondrites) as bodies containing water only in the bound state.

Later, on 26 and 28 September 2016, we acquired spectral confirmation of a regular sublimation activity on (779) Nina just before its perihelion passage (Fig. 5). Nina's reflectance spectra obtained at gradually decreasing heliocentric distances demonstrate a dramatic change of the spectral slope from positive to neutral (nearly at the same rotational phases), produced likely by a growth of coma of sublimed water ice particles scattered reflected from the asteroid light in the short-wavelength range (Fig. 5, curves 2 and 3).

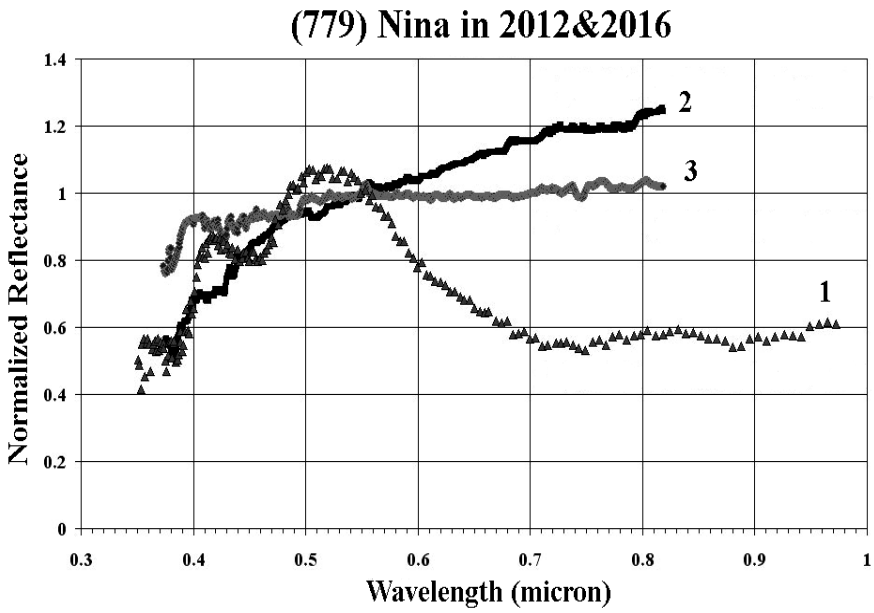

Fig. 5. Comparison of averaged and normalized reflectance spectra of (779) Nina (perihelion distance q = 2.0589 AU) obtained on 13 September 2012 (1, heliocentric distance r = 2.149 AU, after perihelion) and on 26 September 2016 (2, heliocentric distance r = 2.060 AU, before perihelion) and 28 September 2016 (3, r = 2.060 AU, before perihelion). Spectra on 26 and 28 September 2016 were acquired nearly at the same rotational phases of Nina and correspond to its successively decreasing heliocentric distance near perihelion.

As an initial approximation, we calculated the subsolar temperature (T_{ss}) on the surface of an asteroid re-emitting solar electromagnetic energy as a black body (with the thermal conductivity ignored) taking into account only the Stefan–Boltzmann's law, the body's geometric albedo (p_v) and its heliocentric distance (r) according to the formula [1]:

$$T_{ss} = 394\ \mathrm{K} \cdot ((1 - p_v) / r^2)^{1/4} \qquad (1)$$

The calculations yielded the following subsolar temperatures on the surface of the considered asteroids at the moment of observations: $T_{ss,o}$ = 236.5 K (Adeona), 238.6 K (Interamnia), 257.3 K (Nina), 308.3 K (Beira, Fig. 4a), and 308.7 K (Beira, Fig. 4b).

Among the most abundant volatiles near the surface of terrestrial planets only H_2O, CO_2 and their mixtures exhibit the closest position of the triple points to the specified temperatures. In particular, the triple point of crystalline H_2O ice (Ih) is at 273.16 K (that of carbon dioxide is approximately 60 K lower) in terrestrial conditions, and at lower pressures, its sublimation curve covers a temperature range from 130 K to 273.16 K corresponding to entire ice Ih melting curve within 251.165 K to 273.16 K (e. g., [7, 8] and references

therein). Consequently, we may expect that, on primitive MBAs, there is a subsurface layer or reservoir of frozen volatiles, where water ice dominates.

Assuming that a temporal hypothetical coma of an asteroid includes a substantial portion of submicron H_2O ice particles, we use results of Mie theory describing the light scattering by spherical particles [9] and, in particular H_2O ice particles [10]. As was shown in the mentioned studies, for the particles with the refractive index of water ice (n = 1.33), the intensity of scattering is maximum when the size parameter $x = 2\pi\rho/\lambda \approx 6$ or $\rho/\lambda \approx 1$, where ρ is the radius of scattering particles. Consequently, in this case, the mean radius of such particles ρ and the spectral position of the scattering maximum λ approximately coincide. Thus, from the described theoretical results and our analysis of the reflectance spectra of discussed asteroids (Figs. 1–4), we can estimate the average radius of ice (H_2O) particles in the hypothetical coma as ~0.48, ~0.53, ~0.52, and ~0.65 μm for Adeona, Interamnia, Nina, and Beira, respectively.

Conclusions: Previous findings of cometary-like bodies among MBAs were interpreted in most cases as random events connected with "dynamical" contamination of the asteroid family with atypical icy objects (for instance, extinct comet nucleus), which become active only due to sporadic collisions or impacts (e. g., [11, 12]). Another point of view is that free water ice is abundant in the subsurface matter of primitive main-belt asteroids themselves (e. g., [13, 14]).

Our discovery of simultaneous sublimation activity on several primitive MBAs at shortest heliocentric distances supports the last opinion and points likely to the same or similar physical and chemical conditions of origin of the bodies corresponding to the outer edge of the main-belt and beyond.

References: [1] Busarev V. V. et al. (2015) *Icarus 262,* 44–57. [2] Busarev V. V. et al. (2016) *Solar Sys. Res. 50*, 281–293. [3] Bus S. J. and Binzel R. P. (2002). *Icarus 158,* 146–177. [4] Masiero J. R. et al. (2014) *Astrophys. J., 791,* 121–131. [5] Gaffey M. J. et al. (2002). In: Asteroids III (W. F. Bottke et al. eds.), Univ. of Arizona Press, 183–204. [6] Shepard M. K. et al. (2010). *Icarus 208,* 221–237. [7] Longhi, J. (2005) *Geochim. Cosmochim. Acta,* 69, 529–539. [8] Feistel R., Wagner W. (2007) *Geochim. Cosmochim. Acta,* 71, 36–45. [9] Mie G. (1908) *Ann. Phys. (New York) 25*, 377–445. [10] Hansen J. E., Travis L. D. (1974) *Space Sci. Rev. 16*, 527–610. [11] Hsieh H. H., Jewitt D. (2006) *Science 312*, 561–563. [12] Hsieh H. H. et al. (2011) *Aph J. 736*, L18–L23. [13] Schorghofer N. (2008) *Aph J. 682*, 697-705. [14] Rivkin A. S., Emery J. P. (2010) *Nature 464*, 1322–1323.