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Aqueous altered silicates at the surface of two Plutinos?*

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Abstract. In April 2001 we obtained visible and near-infrared spectra, as well as photometric data, for two Trans-Neptunian Objects (TNOs), 2000 GN_{171} (now numbered 47932) and 2000 EB_{173} (now designated 38628 Huya), which belong to the dynamical class of Plutinos. These observations were made with the FORS1 and ISAAC instruments at the European Southern Observatory-Very Large Telescope (ESO-VLT). The detection of weak absorption features in the visible spectra of these two Trans-Neptunians has been reported elsewhere (Lazzarin et al. 2003). In this paper, we discuss the interpretation of the features, which are different for the two objects, and we present some complementary observations in the near-infrared, as well as more recent (May 2002) visible spectra in which the features are absent. Although the visible colors of the two objects are comparable, the near-infrared spectra are different: (47932) 2000 GN_{171} shows a nearly flat spectrum, except in the *H* band where a broad absorption appears, whereas the spectrum of (38628) Huya (2000 EB_{173}) has a red slope in the *J* band and some absorption beyond 2 micron. The features detected in the visible spectra of the two objects are tentatively attributed to the presence of iron oxides or phyllosilicates at the surfaces of the two objects. The differences between the April 2001 and May 2002 visible spectra are attributed to spatial variations at the surfaces of the objects. We briefly discuss possibilities for aqueous alteration in TNOs, after reviewing what we know about the presence of aqueously altered minerals in other small bodies of the solar system. Further studies monitoring the rotation of these two objects are highly desirable.

Key words. minor planets, asteroids

1. Introduction

Due to the faintness of the objects, few spectra of Trans-Neptunians have been obtained, particularly in the near-infrared. Many of the recorded spectra are featureless, although their slopes in the visible spectral region vary widely, revealing colors from nearly neutral to very red (slopes up to 55%/100 nm). As part of a Large Programme carried out at ESO, we have obtained with the FORS1 instrument at the VLT visible spectra of two Plutinos (TNOs with orbits in a 3:2 resonance with Neptune), namely (38628) Huya (2000 EB_{173}) and (47932) 2000 GN_{171}, in which we detect weak absorption features (Lazzarin et al. 2003). Out of the twelve Centaurs and Trans-Neptunians that were observed by Lazzarin et al., these are the only two objects that present such absorption features in their spectra. Following these detections, we have recorded additional spectra of these two objects in the visible with the FORS1 instrument, as well as near infrared spectra using the ISAAC instrument.

The visible region spectra we have recorded at the VLT are the only such data obtained so far for these two objects. Near-infrared spectra of (47932) 2000 GN_{171} have been obtained at the Keck telescope with the NIRC instrument by M. E. Brown, who reported a flat spectrum between 1.4 and 2.4 μm (M. E. Brown, personal communication). (38628) Huya (2000 EB_{173}) has been observed in the near-infrared with the NIRC instrument at Keck (Brown et al. 2000), with the CISCO instrument at Subaru (Jewitt & Luu 2001), and with the NICS instrument at the Telescopio Nazionale Galileo (TNG) in the Canary Islands (Licandro et al. 2001). Jewitt & Luu report a nearly flat spectrum between 1 and 2.5 μm. In the interval 1.4–2.4 μm, the spectrum recorded by Brown et al. with a higher signal-to-noise is also more or less flat up to 1.9 μm, but the flux decreases continuously with increasing wavelength due to absorption, which reaches approximately 10% at 2.2 μm. Licandro et al. obtained instead a spectrum whose intensity

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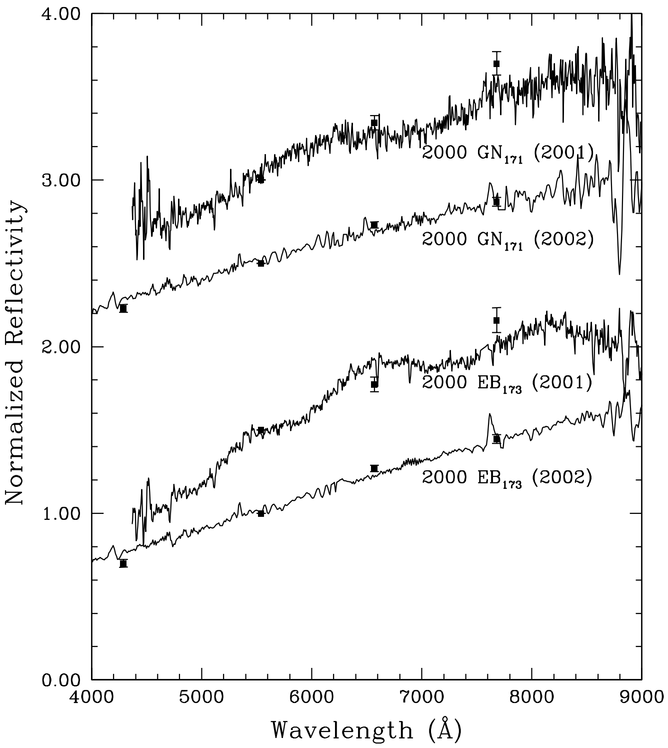

Fig. 1. Visible spectra of the two Plutinos (47932) 2000 GN_{171} and (38628) Huya (2000 EB_{173}) recorded on April 27, 2001, and May 10, 2002. The 2001 spectra are the same as in Lazzarin et al. 2003, but they are shown here on a more expanded scale. Results of broad-band photometry made the same nights are shown as black squares with error bars. The reflectivities are normalized to 1 at 0.55 μm. The spectra have been offset by +0.5 (for 2000 EB_{173} - 2001), +1.5 (for 2000 GN_{171} - 2002) and +2 (for 2000 GN_{171} - 2001) units for clarity.

rises steeply (slope: 70%/100 nm, but confirmation is required, according to Licandro, private communication) between 0.9 and 1.7 μm , and detected a broad absorption in the *K* band (depth of about 14% at 2.2 μm).

In this paper we present new observations obtained in the framework of the ESO Large Programme, as well as some attempts at interpreting the spectra.

2. Observations in the visible

The visible spectra of the two Plutinos discussed here were obtained on April 27, 2001 (Lazzarin et al. 2003) and May 10, 2002. They were recorded with the FORS1 instrument on the VLT (First Unit Telescope UT1 in 2001 and Third Unit Telescope UT3 in 2002). The observing conditions for April 27, 2001 are summarized in Table 1. Photometric observations in *B*, *V*, *R*, *I* were made the same night, just before the spectroscopic observations. Results of these photometric observations have been published in Boehnhardt et al. (2002). The spectra observed in April 2001 are shown in Fig. 1, along with results from the photometric measurements. As reported in Lazzarin et al. (2003), absorption features are clearly detected in the spectra. Following the detection of these absorption features, we decided to try and confirm them with new observations. We got additional data in May 2002. The observing conditions for this date are also listed in Table 1. We observed two solar-type stars for calibration. An average of the two stellar spectra was used. The data acquisition and data reduction are the same as for the April 2001 spectra (Lazzarin et al. 2003). The May 2002 spectra are shown in Fig. 1 as well. Photometric measurements in *B*, *V*, *R* and *I* were made just before the acquisition of the spectra. The measured magnitudes are: *B*: 21.9 ± 0.02, *V*: 20.89 ± 0.01, *R*: 20.30 ± 0.016, *I*: 19.86 ± 0.024 for (47932) 2000 GN_{171} and *B*: 20.89 ± 0.02, *V*: 19.83 ± 0.01, *R*: 19.21 ± 0.016 and *I*: 18.74 ± 0.024 for (38628) Huya (2000 EB_{173}). To compute the reflectivities, we used as solar color indices: $B - V = 0.67$, $V - R = 0.36$, $V - I = 0.69$ (Hardorp 1980). The resulting reflectivities are shown in Fig. 1.

3. Observations in the near-infrared

The near-infrared spectra reported here were recorded with the ISAAC instrument on UT1 on April 13 and 14, 2001. ISAAC was used in its low resolution spectroscopic mode. The slit was 1″ wide, which corresponds to a spectral resolution of about 500. Spectra in the *J*, *H* and *K* band were recorded separately. The observations were made in the nodding mode in which the object is placed along the slit at two different positions A and B separated by 10 arcsec named A and B. This technique allows a good elimination of the OH sky lines through an adequate combination of A-B and B-A image pairs. We also obtained spectra of solar analogs and AOV stars (observed just before and after the objects and at similar airmasses) for atmospheric correction and solar contribution removal. Table 2 shows the observing conditions during the acquisition of infrared spectra.

In order to connect the spectra in the three different spectral ranges, we recorded series of images in *J*, *H* and *K* before and after the spectroscopic observations. For each target, a set of images following a dither pattern was recorded, as is common in infrared photometric acquisition. Since only the April 14 night was photometric, we have not used the data recorded on April 13. We observed several infrared photometric standard stars (P565-C, S064-F, S279-F and S705-D; Persson et al. 1998) for calibration. The observing conditions for the near-infrared photometry are given in Table 3.

Data reduction for both imaging and spectroscopy was performed using the ECLIPSE package. The infrared spectra were reduced as described in Barucci et al. (2002). Telluric and solar contribution removal was performed by dividing the object spectrum by that of a solar analog or, if not available, by the spectrum of an A0V star, combined with blackbody functions in order to obtain a solar behaviour. In order to increase the signal-to-noise ratio, we degraded the spectral resolution by a factor 2.5. The resulting spectra are shown in Fig. 2.

The photometric reduction was performed using the "jitter" routine and MIDAS-ESO software, following the data processing steps described in Romon et al. (2001) for image combination and sky substraction. The magnitudes of stars and objects were finally derived using classical aperture photometry for each filter. The results of our photometric measurements are listed in Table 3.

Table 1. Observing conditions for visible spectroscopy.

Object	Night (UT)	UT-start (hh:mn)	T_{exp} (min)	Airmass	seeing (arcsec)	Calib. stars
2000 EB_{173}	27/04/01	02:13	60	1.21	0.88	HD 144585
2000 GN_{171}	27/04/01	03:51	60	1.09	0.77	HD 144585
2000 EB_{173}	10/05/02	02:12	53	1.11	0.88	Landolt 98-978
						Landolt 102-1081
2000 GN_{171}	10/05/02	00:37	53	1.13	0.69	Landolt 98-978
						Landolt 102-1081

Table 2. Observing conditions for infrared spectroscopy.

Object	Night (UT)	UT-start (hh:mn)	UT-end (hh:mn)	Filter	Airmass (object)	seeing (arcsec)	T_{exp} (min)	star for spectra div.	Airmass (star)
2000 EB_{173}	14/04/01	06:19	7:49	*J*	1.37	0.88	52	HD 120445	1.49
2000 EB_{173}	14/04/01	04:08	5:09	*H*	1.11	0.97	56	HD 79752	1.05
2000 EB_{173}	14/04/01	05:16	6:16	*K*	1.13	0.57	56	HD 79752	1.05
2000 GN_{171}	13/04/01	01:36	2:30	*J*	1.42	0.90	48	HD 44594	1.39
2000 GN_{171}	13/04/01	06:14	7:13	*J*	1.22	0.46	40	HD 44594	1.39
2000 GN_{171}	14/04/01	02:23	3:23	*H*	1.21	0.64	56	HD 79752	1.05
2000 GN_{171}	13/04/01	02:41	6:11	*K*	1.18	0.63	172	HD 87344	1.09

Table 3. Observing conditions for infrared photometry and results.

Object	Night (UT)	UT-start (hh:mn)	Filter	Airmass	seeing (arcsec)	T_{exp} (s)	m_{filter}	Absolute[1] Magnitude	Colors
2000 EB_{173}	14/04/01	03:30	*J*	1.15	0.55	360	18.09 ± 0.06	3.39 ± 0.06	
2000 EB_{173}	14/04/01	03:38	*H*	1.15	0.55	360	17.64 ± 0.08	2.94 ± 0.08	$J - H = 0.45 \pm 0.1$
2000 EB_{173}	14/04/01	03:46	*K*s	1.15	0.55	360	17.87 ± 0.07	3.17 ± 0.07	$H - K = -0.23 \pm 0.11$
2000 EB_{173}	14/04/01	07:52	*J*	1.66	0.80	360	17.86 ± 0.06	3.16 ± 0.06	
2000 EB_{173}	14/04/01	08:00	*H*	1.66	0.80	360	17.58 ± 0.08	2.88 ± 0.08	$J - H = 0.28 \pm 0.1$
2000 EB_{173}	14/04/01	08:08	*K*s	1.64	0.80	360	17.57 ± 0.08	2.87 ± 0.08	$H - K = 0.01 \pm 0.11$
2000 GN_{171}	14/04/01	01:49	*J*	1.28	0.72	360	19.55 ± 0.06	5.0 ± 0.06	
2000 GN_{171}	14/04/01	01:57	*H*	1.28	0.72	360	19.54 ± 0.07	4.99 ± 0.07	$J - H = 0.01 \pm 0.09$
2000 GN_{171}	14/04/01	02:05	*K*s	1.28	0.72	360	19.11 ± 0.07	4.56 ± 0.07	$H - K = 0.43 \pm 0.1$

[1] Absolute magnitudes were computed using a phase coefficient $\beta = 0.14$ mag/deg (Belskaya et al. 2003).

4. The results

In the visible spectrum of (47932) 2000 GN_{171} recorded on April 2001 (Fig. 1), there is some absorption between about 6200 Å and about 8200 Å (the long wavelength wing of this feature is not very well defined), with a minimum at about 7100 Å (depth of about 8 per cent). In the case of (38628) Huya (2000 EB_{173}), two weak features are detected in the spectrum recorded on April 2001 (Fig. 1), one between 5400–5500 Å and 6600 Å (with a minimum at about 5900 Å and a maximum depth of about 7 per cent), and another one, a little deeper (depth 8.6 per cent), between about 6600–6800 Å and 8200–8300 Å (minimum around 7400–7500 Å). In addition, we see the beginning of an absorption beyond 8200–8300 Å at the edge of the spectral range.

As explained in Lazzarin et al. (2003), we have checked that these features cannot be due to an imperfect elimination of telluric absorptions, to differential refraction effects or to overlapping of orders. Instrumental effects are also excluded since the features only appear in the spectra of two of the five TNOs and Centaurs observed during the same night, and since these features are different for the two objects. It should be noted that the same solar analog was used for all five objects, and that the features were still present after a synthetic solar spectrum was used instead of the solar analog (see Lazzarin et al. 2003). In addition, for each Plutino, the spectrum is an average of two spectra recorded subsequently, and the features appear in the two individual spectra.

The spectra recorded in May 2002 look very different from the April 2001 spectra. We see no obvious features (Fig. 1). Another Trans-Neptunian (28973 Ixion, formerly 2001 KX76) was observed the same night and no absorption feature is detected in its spectrum either. The same solar analog (average of two stellar spectra; see Table 1) was used for the three objects. In the spectrum of (47932) 2000 GN_{171}, we only notice a slight change of slope at 6200 Å, the wavelength at which the

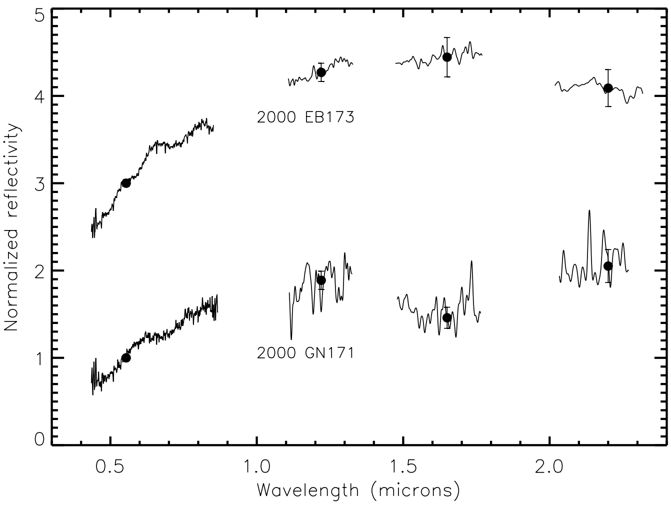

Fig. 2. Visible (April 2001 data) and infrared spectra of (47932) 2000 GN_{171} (bottom) and (38628) Huya (2000 EB_{173}) (top). The visible spectra are normalized at 0.55 μm and the infrared J, H, K spectra placed using our photometric results (a mean of two photometric datasets for (38628) Huya (2000 EB_{173})) and $V-J$ colors from McBride et al. (2003). The spectrum of (38628) Huya (2000 EB_{173}) is shifted by 2 units for clarity.

absorption detected in April 2001 occurs. Furthermore, there are differences in the spectral slopes between the 2001 and 2002 spectra, particularly for (38628) Huya (2000 EB_{173}). This could be due to time variations or to spatial variations. Although time variations are possible, we consider it more probable that the material responsible for the absorption does not uniformly cover the surface of these objects, and that we observed different parts of the objects in April 2001 and May 2002. Such heterogeneities have already been observed at the surface of several TNOs and Centaurs (Brown et al. 1999; Barucci et al. 2002; Bauer et al. 2002). Furthermore, variations in our 2001 observations of (38628) Huya (2000 EB_{173}) are revealed in the data on timescales of 4 and 0.5 h for the near-infrared and visible, respectively. Indeed, our near-infrared photometric measurements made 4 h apart show lower magnitudes in both J and Ks for the second set as compared to the first set (Table 3), while our two individual visible spectra of the same object recorded half-an-hour apart show a difference (of about 50%) in the depth of the 7400–7500 Å band. Such variations, if real, must be due to surface heterogeneities on this object which rotates in a few hours (see below). Yet another possible indication of surface heterogeneities on (38628) Huya (2000 EB_{173}) is the difference between the near-infrared spectra recorded by Brown et al. (2000) and Jewitt & Luu (2001).

A rotation period of 8.329 ± 0.05 h has been recently determined for (47932) 2000 GN_{171} (Sheppard & Jewitt 2002). As Sheppard & Jewitt observed that object on April 25, 2001, we can place our 2001 observations on their lightcurve very precisely. However, given the current uncertainty on the rotation period of (47932) 2000 GN_{171}, we cannot conclude with certainty that we were indeed looking at different parts of the object in April 2001 and in May 2002.

Concerning (38268) Huya (2000 EB_{173}), the rotation period which has been very recently determined (6.75 h if the lightcurve is single-peaked; Ortiz et al. 2003) is also too uncertain to be sure that different parts of the object were observed during our two runs. New observations are required to resolve these issues.

To connect the J, H and K spectra of (47932) 2000 GN_{171}, we used our single set of photometric measurements. In the case of (38628) Huya (2000 EB_{173}), an average of two sets of photometric measurements was used. The visible and near infrared spectra shown in Fig. 2 have been combined using the $V-J$ color indices of McBride et al. (2003), as they were derived from simultaneous V and J magnitude measurements ($V-J = 1.97 \pm 0.05$ for (47932) 2000 GN_{171}, and $V-J = 1.77 \pm 0.06$ for (38628) Huya (2000 EB_{173})). To compute reflectivities, we used as solar color indices, $V-J = 1.08$, $J-H = 0.29$ and $H-K = 0.06$, as in Barucci et al. (2001).

For (38268) Huya (2000 EB_{173}), we find a "red" slope in the J band, as found by Licandro et al., although our slope is much less steep. Furthermore, we have an indication of an absorption in the K-band region, as found also by Licandro et al. (and, although less clearly, by Brown et al.). However, if instead of using average values for our infrared colors (Fig. 2), we use the $J-H$ and $H-K$ color indices we measured on April 2001 around 8 UT (Table 3), we get nearly identical reflectivities in J, H and K, and therefore no more absorption is present in the K band.

The near-infrared spectra of (47932) 2000 GN_{171}, a fainter object than (38628) Huya (2000 EB_{173}), are a lot noiser, especially that in the K band. A broad absorption is present in the H band.

5. Interpretation of the spectra

Little is known about the composition of TNOs and Centaurs. By analogy with asteroids in the outer belt, and from cosmochemical arguments, it is believed that they contain abundant ices, carbonaceous compounds and some silicates. The spectroscopic studies carried out so far in the near-infrared have revealed the signatures of water ice for several objects (Centaurs 5145 Pholus and 2060 Chiron, TNO 1996 TO_{66}, now numbered 19308), possibly that of a light hydrocarbon (5145 Pholus) and that of a silicate, maybe olivine, for 5145 Pholus (see, e.g., Cruikshank et al. 1998; Luu et al. 2000; Brown et al. 1999).

The red slopes in the visible have been interpreted as due to Titan tholins (for 5145 Pholus) or to kerogen-type material (for the Centaurs 1998 SG_{35} and 2000 QC_{243}; Dotto et al. 2003). Dark silicates can also produce a red slope (see the paper on the Trojan asteroid Hektor by Cruikshank et al. 2001). However, the two TNOs have much redder spectra than Hektor, and have also redder spectra than D-type asteroids.

In order to interpret the absorption features detected in the visible, we have first explored the possibility that they are due to ices. The ices that have already been detected in the solar system are, in addition to water ice, CH_4, NH_3, CO, CO_2, N_2 and SO_2 ices. None of these ices can explain the observed features. Water ice does not produce significant absorption at these wavelengths (the only absorptions below 1 μm are absorptions at 0.9 and 0.81 μm, which are extremely weak, and do not match the observed positions and shapes). Methane ice, which is detected at the surface of Pluto (and Triton), has very weak and narrow absorptions below 8000 Å that do not resemble the observed features (Grundy & Fink 1996).

These features cannot be due to solid hydrocarbons either, as far as we can tell. Indeed, in the visible, only a broad absorption centered in the UV has been identified in the laboratory for hydrocarbons (aromatic absorption). It should be noted however that porphyrins, a class of organic molecules present on Earth and possibly in some meteorites (see Gaffey et al. 1989 for a review), show three features near 0.4 and 0.5–0.6 μm (Holden et al., 1991), but these features do not match the ones we observed.

Some anhydrous silicates have very weak absorptions beyond 0.6 μm. This is the case, for instance, of a magnesium-poor olivine that has an absorption around 0.65 μm (Sunshine & Pieters 1998). A feature detected in a main-belt A-type asteroid, 289 Nenetta, has been associated with this type of silicate (Sunshine et al. 1998). However, in addition to a very steep slope in the visible, olivine has strong and broad absorptions centered around 1 μm (due to Fe^{2+}) that are not seen in our spectra of the two TNOs.

The weak feature detected at 0.6 μm on (38628) Huya (2000 EB_{173}) presents some analogy with a weak feature detected at the surface of a few S-type asteroids, which is generally coupled with another weak feature around 6700 Å (the center can vary from 6500 to 6800 Å) (Hiroi et al. 1996). These features have been tentatively assigned to spinel-group minerals. Such minerals have been detected in meteorites – but only in inclusions – and also in Interplanetary Dust Particles (see Mackinnon & Rietmeijer et al. 1987), but in very small amounts. However, even if they were present, spinel minerals, which are formed at high pressure and high temperature, are very unlikely to be abundant enough in TNOs to be spectroscopically detectable at these wavelengths.

The features we detect also present some analogy with features detected in spectra of dark asteroids that have been attributed to the presence of minerals produced by the aqueous alteration of anhydrous silicates (Vilas & Gaffey 1989; Vilas et al. 1994). Based on all the studies carried out so far for asteroids (see review by Bus et al. 2003), this is the only remaining possibility. Therefore, we will discuss it in some detail here.

The attribution of visible features detected in spectra of dark asteroids to the presence of aqueous altered minerals on their surfaces is based on laboratory studies of various minerals and on comparisons with meteorites. Hydrated silicates are the dominant component of carbonaceous chondrite matrix (a fine-grained opaque mineral) material. Aqueous alteration products found in carbonaceous chondrites include phyllosilicates, sulfates, carbonates and other oxides like magnetite, with phyllosilicates being the most abundant ones. It is generally believed that the abundant evidence of aqueous alteration seen in meteorites is the result of aqueous alteration in their parent bodies, the asteroids, although other opinions exist (see below).

The presence of hydrous altered silicates in asteroids initially found strong support in the detection of a strong feature at 3 μm indicative of phyllosilicates. This feature has been detected in a number of low-albedo (mainly C-type) asteroids (see, e.g., Jones et al. 1990).

The relatively recent detection of weak absorptions in the visible reinforced the idea of aqueous alteration as an important process for asteroids (Vilas and Gaffey 1989; Vilas et al. 1994). The C-type asteroids (and asteroids belonging to the subclasses B, F and G) that have weak absorption features in their visible spectra are essentially asteroids in the outer part of the main belt and beyond the main belt (Hildas, Cybeles). They are low-albedo (p_V of about 0.05) asteroids, considered to be primitive.

The visible features detected in the spectra of (38628) Huya (2000 EB_{173}) and (47932) 2000 GN_{171} are a little different from those generally seen in spectra of dark asteroids. In particular, the feature detected at 0.7 μm in the spectrum of (47932) 2000 GN_{171}, which occurs at about the same position as the shallow feature detected in spectra of some C-type asteroids (and attributed to an Fe^{2+} to Fe^{3+} charge transfer transition in oxidized iron in phyllosilicates), is much narrower. Indeed, the 0.7 μm feature detected in spectra of asteroids generally spreads from 0.57 to 0.83 μm (see, e.g., Vilas et al. 1993). In addition, the features in the spectrum of (38628) Huya (2000 EB_{173}) are closer in wavelength than those usually seen for asteroids.

In addition, some phyllosilicates have absorption bands in the near-infrared around 1.4. 1.9 and 2.2-2.3 μm (Hunt 1977). It is interesting to note that Jewitt & Luu (2001) have tentatively detected such features in spectra of the Centaur 1999 DE_9. They attribute absorption features at 1.4 and 2.25 μm to the presence of either Al or Mg in minerals that incorporate OH within their structure. Higher signal-to-noise spectra of 1999 DE_9 are needed to confirm the reality of these features, particularly the one at 2.25 μm. We looked for such features in our near-IR spectra of (38628) Huya (2000 EB_{173}) and (47932) 2000 GN_{171}. The 1.4 μm absorption falls in a region of strong telluric absorption, and our spectra in the *K*-band are quite noisy. We detect however an absorption at 2.28 μm in the spectrum of (38628) Huya (2000 EB_{173}) (Fig. 2) that would be very interesting to confirm with higher signal-to-noise data.

We have attempted to model combined visible and near-infrared spectra of the two Plutinos. For (38628) Huya (2000 EB_{173}), we first looked for a mixture that would reproduce satisfactorily a combined spectrum that includes the 2002 visible spectrum. Our best model corresponds to a geographical (or spatial) mixture of Ice tholins (McDonald et al. 1996), Titan tholins (Khare et al. 1984), and some water ice (Fig. 3, upper part). In Fig. 3, lower part, we see that such a model does not fit the 2001 visible spectrum which has a very different slope and absorption features. We have tried to add some hydrated minerals to account for the absorptions. The lack of laboratory data for aqueous altered minerals is a major difficulty. We find that a geographical (spatial) mixture that includes some jarosite (a secondary product of the aqueous alteration of iron sulfide minerals), in addition to Titan tholins, water ice and amorphous carbon could improve the fit with the spectra at very short wavelengths in the visible and beyond 2 μm. However, jarosite, which is one of the few hydrated minerals for which laboratory data are available, cannot account for the band around 0.74 μm. And we have not found any dark asteroid or carbonaceous meteorite that presents in its spectrum a band as narrow and deep as the one we detect around 0.74 μm. Concerning (47932) 2000 GN_{171}, the band at 0.7 μm, although somewhat wider, is still narrower and deeper than bands detected at the same wavelength in dark asteroid or meteorite spectra. Furthermore, we cannot explain the absorption in the *H* band (in particular, there is no accompanying feature at 2 μm that would be typical of water ice); this is why no model is presented in this paper.

By analogy with observations of C-type asteroids that have revealed weak absorptions in their visible spectra in the same wavelength range, and since we do not see any strong and broad absorption in the near infrared typical of the most common anhydrous silicates, we consider the possibility that the absorptions detected in the visible spectra of the two Plutinos are due to hydrous minerals at the surface of the objects. Nevertheless, more laboratory studies of the effect of irradiation and weathering on other types of material (in particular carbonaceous material) are required before we exclude them entirely. Our hypothesis concerning hydrous minerals is further supported by the detection of weak features in the near-infrared spectrum of a Centaur by Jewitt & Luu (2001) that could be due to phyllosilicates (see also Lederer et al. 2001, 2002). In what follows, we therefore examine the possibility that aqueous altered material could be present at the surface of TNOs, given our knowledge of aqueous alteration in other cold small bodies of the solar system,

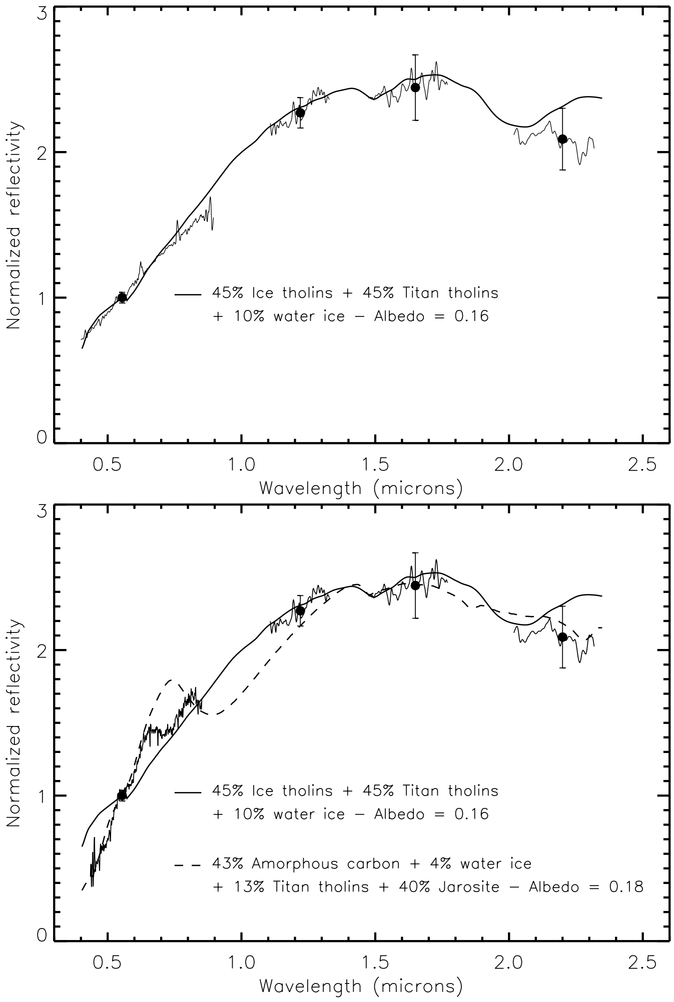

Fig. 3. Models of the combined visible-near infrared spectrum of (38628) Huya (2000 EB_{173}). In the upper part of the figure, the visible portion of the spectrum corresponds to the data obtained in May 2002. In the lower part, the visible portion is instead the April 2001 spectrum (same as in Fig. 2). The albedos correspond to albedos at 0.55 μm.

6. Aqueous alteration in small bodies of the solar system

Minerals that could have been produced by aqueous alteration have been detected not only in carbonaceous meteorites and dark asteroids, but also in interplanetary dust particles and micrometeorites. They may also be present in comets. There is a considerable interest in their search as they could have played a very important role in bringing water to Earth. Different ways to form aqueous altered minerals in these cold, primitive, small solar system bodies have been considered. We will briefly review them and see if they can apply to TNOs.

Two main mechanisms have been invoked: low temperature (273–400 K) alteration by liquid water above the melting point of water ice, and hydrocryogenic alteration (temperatures between about 200 and 273 K) (see, e.g., Rietmeijer & Mackinnon 1987). Hydrocryogenic alteration is a processus that occurs in thin interfacial water layers at dust/ice interfaces in dust/ice mixtures (Rietmeijer 1985). This latter mechanism has been considered for comets, while alteration by liquid water is supposed to be the main mechanism responsible for the formation of hydrous minerals in asteroids.

As mentioned above, the presence of hydrated minerals in carbonaceous meteorites is generally believed to be due to aqueous alteration inside their parent bodies, the asteroids. Aqueous alteration in asteroids is supposed to be connected to some early heating event either due to the decay of ^{26}Al, a now extinct short-lived isotope, or to electrical induction heating due to a strong early solar wind (T-Tauri phase) (Jones et al. 1990). Jones et al. (1990) favor this last mechanism as it is the one that best accounts for the observed decline in hydrated silicate abundance for C-class asteroids from 2.5 to 3.5 AU, and for the variety of hydration states of C-class asteroids. Studies of asteroids with orbits beyond 3.5 AU (D-type and P-type asteroids), that are therefore more ice-rich than C-type asteroids, have shown that none of them contain in their spectra the 3-μm feature typical of water of hydration. The prevalent explanation is that induction heating is much less efficient further away from the Sun (see, e.g., Jones et al. 1990). If this interpretation is correct, by analogy with D-type asteroids and Trojans, aqueous alteration would not be expected for TNOs. One should note, however, that Cruikshank et al. (2001) have suggested that the lack of hydration features in asteroid spectra at large distances from the Sun might be due instead to an increasing amount of spectrally opaque material on their surfaces.

Indications for the presence of hydrated silicates in comets, which are better analogs to TNOs, come from two main sources: 10-μm spectroscopy (Sandford & Walker 1985; Bregman et al. 1987), and in-situ analyses of comet Halley

(Rietmeijer et al. 1989; Fomenkova et al. 1992). However, progress in 10-μm spectroscopy of comets, with the detection of other types of silicates that have features at these wavelengths (Crovisier et al. 1997; Wooden et al. 1999) may lead to a revision of this spectroscopic detection. Furthermore, the strong feature at 100 μm that would be indicative of hydrated silicates (Malfait et al. 1999) has not been detected in spectra of Hale-Bopp (Lellouch et al. 1998). The in-situ analyses of comet Halley dust ejecta made with the PUMA mass spectrometers onboard the VEGA spacecraft by Rietmeijer et al. and Fomenkova et al. seem to imply the presence of hydrated silicates and possibly Mg-carbonates. However, Schulze et al. (1997), who also analyzed data from PUMA, came to the conclusion that, although low temperature aqueous alteration is not excluded, it could not have been intensive and may be limited to the crust.

Hydrous silicates are detected in some Interplanetary Dust Particles (IDPs) collected in the Earth's stratosphere (see, e.g., Mackinnon & Rietmeijer 1987) and in micrometeorites collected in Antarctica. Part of the IDPs and micrometeorites may be derived from comets (Sandford & Walker 1985; and Walker 1988), although the layer-lattice silicates IDPs may come predominantly from asteroids (Sandford & Bradley 1989). It is interesting to note that, more recently, it has been suggested that, in fact, IDPs rich in water and in deuterium could come from TNOs (see, e.g., Robert 2001). In this case, it would not be surprising to find aqueous altered material in TNOs.

Hydration in comets could be facilitated by the hydrocryogenic mechanism known to exist in terrestrial permafrost (Rietmeijer & Mackinnon 1987). However, according to Rietmeijer & Mackinnon, because the temperature inside the nucleus needs to be rather high, this mechanism would only occur during a passage through perihelion or after repeated passages. By analogy with what may be happening in comets, we would not expect hydrated silicate formation in TNOs, which are always at large heliocentric distances.

However, the large TNOs may have been subjected to significant radiogenic heating (Jewitt 1996; Luu & Jewitt 2002). It remains to be seen whether this would have been sufficient for aqueous alteration of the anhydrous material inside the TNOs, and if this alteration could extend to the surface (some mechanism capable of transporting enough heat to the surface, maybe through cracks, would be required).

Another way to heat a TNO is by impacts. The low velocity impacts leading to accretion of material or repeated collisions of the TNO with other bodies – which were certainly very abundant in the past when the Kuiper Belt was much more massive (Stern 1996) – could have provided a transient heat source. However, the heat generated and the duration of the heating episode(s) may not have been sufficient for aqueous alteration of minerals (see, e.g., Kerridge & Bunch 1979). Model predictions are very uncertain in this respect (Orosei et al. 2001).

It has also been suggested that the hydrated minerals present in IDPs, meteorites, and possibly in comets, were not formed in-situ but in the early solar nebula where aqueous alteration could have occurred on grains when the nebula started to cool (see, e.g., Grossman & Larimer 1974). Fegley & Prinn (1989) have argued that the time required to hydrate silicate grains exceeds the lifetime of the primordial solar nebula. More recently, however, Rietmeijer & Nuth (2001) have suggested that serpentine could in fact form in the solar nebula by the hydrogenation of very small Fe-rich silicate grains condensing from the gas phase. According to Robert (private communication), this scenario, however, is very unlikely as it is incompatible with the high values of the D/H ratio measured in serpentines in meteorites.

Recent observations at 100 μm with the Infrared Space Observatory (ISO) have shown that clay minerals may be present in some circumstellar disks around young stellar objects (see Malfait et al. 1999), which would favor their formation in the early solar nebula. Another argument in favor of formation of clay minerals in the protosolar nebula is the very large range of D/H ratios measured in deuterium-rich meteorites (Robert 2001). Although a process different from the ones considered above would have to be found, if indeed hydrated minerals could be formed in the early solar nebula, then hydrated minerals could have been present originally in TNOs.

7. Conclusion

During one observing run (in April 2001), we detected absorption features in visible spectra of two Plutinos. New observations made about one year later do not reveal any features. We suggest that this is due to heterogeneities on the surfaces of the objects. In addition, we have obtained infrared spectra of the two objects that look different: a generally flat spectrum is observed for (47932) 2000 GN_{171} (except for a weak band around 1.6 μm), while a steep spectrum in the J band and a weak and broad absorption in the K band are seen for (38628) Huya (2000 EB_{173}).

The only explanation we have found for the weak features detected in the visible part of the spectra and the lack of very strong absorptions in the near-infrared is that aqueously altered minerals are present at the surfaces of the two objects. Furthermore, we argue that, based on what we know about other primitive bodies in the solar system, the presence of aqueously altered minerals in TNOs is not excluded. However, additional observations and progress in modelling, as well as more laboratory studies on possible surface materials and their alteration, are required to resolve this issue.

From an observational point of view, it is obviously essential to repeat observations around 0.6–0.7 μm to confirm the detection of the features. Since the signatures have apparently been seen on only part of the objects, rotationally-resolved spectroscopy is required. We also need good spectroscopic measurements at both longer and shorter wavelengths. This would help in identifying the component(s) or mixture(s) responsible for the detected absorptions. In particular, we need high signal-to-noise spectra near 0.9 μm, especially for (38628) Huya (2000 EB_{173}). Rotationally-resolved 1–2.5 μm spectroscopic observations are also required, not only to search for features typical of hydrated minerals but also to better study the broad 2-μm absorption present in spectra of (38628) Huya (2000 EB_{173}) and the 1.6 μm absorption present in spectra of (47932) 2000 GN_{171}. Three-micron spectroscopic studies are highly desirable, but given the faintness of the objects, they may not be currently feasible. Moreover, one would also need a measurement of the albedo of these two objects (which requires photometric measurements in the far infrared, achievable with the SIRTF satellite), as it would bring some useful constraints on the nature of the material that constitutes the bulk of their surfaces, as well as on their dimensions.

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