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Search for surface variations on TNO 47171 and Centaur 32532

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ABSTRACT

We present photometric and spectroscopic observations of one Trans-Neptunian Object (TNO 47171 1999 TC_{36}) and one Centaur (Thereus also named 32532 2001 PT_{13}). Near-infrared data were acquired with the ISAAC instrument at one of the 8 m telecopes of the Very Large Telescope (VLT, ESO-Cerro Paranal, Chile), while visible data were obtained with the EFOSC2 instrument on the 3.6 m telescope of La Silla (ESO, Chile). These observations were performed to search for rotational variations for both targets. Water ice has been confirmed on both objects. The surface composition models of the targets are presented and discussed, and are also compared to previous observations available in the literature.

Key words. Kuiper Belt – radiative transfer – techniques: spectroscopic

1. Introduction

Trans-Neptunian objects (TNOs), also called Edgeworth-Kuiper Objects, are located beyond the orbit of Neptune. Long-term orbital integrations (Levison & Duncan 1997; Durda & Stern 2000) of TNOs indicate that gravitational instabilities and collisions can scatter their orbits to those of Centaurs. Centaurs, which are located between the orbits of Jupiter and Neptune, may have therefore formed in the Edgeworth-Kuiper Belt. Both of these populations may contain the most pristine and least altered material still observable in the solar system and can provide important information to understand what happened in the protoplanetary nebula at large heliocentric distances. Postulated for the first time by Edgeworth (in 1943), the existence of a disc beyond the orbit of Neptune has been confirmed observationally since 1992 (Jewitt & Luu 1993).

TNOs have orbits with varying eccentricities and inclinations, but they are generally classified in four groups: resonant, classical, scattered and extended disk objects. The first group includes objects trapped in orbital resonances with Neptune. The majority of these are called Plutinos since they have orbital characteristics similar to those of Pluto, being trapped in the mean-motion 2:3 resonance with Neptune. Classical TNOs have semi-major axes confined between 40 and 48 AU. The third group contains TNOs having orbits with larger eccentricity and semi-major axis values. The last group is composed of the furthest objects in the solar system, like Sedna which has a semi-major axis larger than 500 AU. All four of these populations can be described by dynamical models of solar system formation (e.g. Malhotra 1995; Morbidelli 2004).

The physical properties of TNOs and Centaurs are still poorly known. The most relevant characteristic of these populations is the wide variety of colors: these populations include both spectrally red and neutral objects. It has been suggested that this difference in color may be due to the combined effects of different degrees of collisional evolution, which reworked the surfaces revealing fresh interior material, and space weathering alteration due to cosmic ray bombardment on surfaces of ages ranging from freshly excavated material to old crusts (Luu & Jewitt 1996; Jewitt & Luu 2001). Due to the faintness of TNOs and Centaurs and the difficulty of acquiring high quality spectroscopic data, the present knowledge of their surface composition is still very limited and the reason for the wide color diversity is far from understood. In the same way, knowledge on rotational variability is still limited due to the lack of repeated data in photometry or spectroscopy (see Barucci et al. 2004).

In this paper we present new visible and near-infrared spectroscopic and photometric data on two objects: the Plutino 47171 (1999 TC_{36}) and the Centaur 32532 Thereus (2001 PT_{13}). The observations were carried out at the ESO-VLT (Very Large Telescope) with the instrument ISAAC at Unit 1 *Antu* and at the 3.6 m of La Silla (ESO) with the instrument EFOSC2. The results obtained from these observations are presented and discussed in the framework of a comparison with previous observations available in the literature.

Table 1. Spectroscopic observations of the objects.

Object	Night	UT*	Spectral band	Ex. time (min)	Airmass	Instrument	Solar analogs
47171 (1999 TC_{36})	15/Oct./2003	5:00	*J*	24	1.12–1.18	ISAAC	HD 209847
47171 (1999 TC_{36})	15/Oct./2003	5:31	*H*	42	1.18–1.38	ISAAC	HD 209847
47171 (1999 TC_{36})	15/Oct./2003	6:34	*K*	60	1.38–2.13	ISAAC	Landolt 93-101
47171 (1999 TC_{36})	15/Oct./2003	5:28	*V*	20	1.21–1.27	EFOSC 2	Hyades 64
32532 (2001 PT_{13})	15/Oct./2003	0:53	*J*	24	1.28–1.37	ISAAC	HD 209847
32532 (2001 PT_{13})	15/Oct./2003	2:58	*H*	42	1.19–1.24	ISAAC	HD 209847
32532 (2001 PT_{13})	15/Oct./2003	1:25	*K*	64	1.19–1.28	ISAAC	HD 209847
32532 (2001 PT_{13})	16/Oct./2003	0:06	*J*	24	1.46–1.56	ISAAC	HD 209847
32532 (2001 PT_{13})	16/Oct./2003	1:57	*H*	42	1.19–1.22	ISAAC	Landolt 115-271
32532 (2001 PT_{13})	16/Oct./2003	0:41	*K*	60	1.24–1.38	ISAAC	Landolt 93-101
							HD 209847

*UT time at start exposure.

2. Observations

We performed our observations in both the visible and near-infrared wavelength ranges. Near-infrared photometry and spectroscopy were carried out during an observing run on October 15th and 16th, 2003 at the VLT with the Infrared-Cooled grating spectrometer ISAAC (`http://www.eso.org/instruments/isaac`). On October 15th we also carried out simultaneous visible spectroscopy of 47171 at the 3.6 m of La Silla equipped with EFOSC2 (ESO Faint Object Spectrograph and Camera, `http://www.ls.eso.org/lasilla/sciops/3p6/efosc/`), a Loral/Lesser CCD with 2048 × 2048 pixels. At the time of the observations, the TNO and the Centaur had heliocentric distances of 31.1 and 9.51 AU, geocentric distances of 30.23 and 8.6 AU, and phase angles of 0.59 and approximately 2.5 degrees, respectively. Table 1 lists the details of the observations.

2.1. Photometry

The near-infrared observations were carried out under good photometric conditions in visitor mode. Photometric *J*, *H* and *K* measurements (centered at 1.25, 1.65 and 2.16 μm) were made before the spectroscopic measurements of each object. We used the jitter imaging technique, generating a combined image with the jitter routine from the ECLIPSE package (see Romon et al. 2001). The calibration was performed by observing several faint infrared standards stars from Hunt et al. (1998) and Persson et al. (1998). The data reduction was carried out using the MIDAS package, and the data processing method that was followed is described in Romon et al. (2001). The photometric values were transformed into reflectivity using solar color indices (Hartmann et al. 1982).

2.2. Spectroscopy

Visible spectroscopy of the TNO 47171 was performed in service mode with a low resolution grism and a 1″ slit (covering the 5000−9000 Angstrom wavelength range with a spectral resolution of about 550). The visible spectrum was reduced using the software package MIDAS with the standard method (Barucci et al. 2000).

Near-infrared spectroscopy was carried out in visitor mode. We used ISAAC in its SW mode (1−2.5 μm spectral range and equipped with a CCD of 1024 × 1024 pixel), with a 1″ slit and with grating at three different central wavelengths corresponding to the *J*, *H* and *K* bands. The spectral resolution in the three bands was about 500. The observations were done by nodding the object along the slit by 10″ between 2 positions A and B. The A and B images were combined using MIDAS and following the procedure already described by Romon et al. (2002) and Barucci et al. (2002a). Several solar analogs were observed during the nights and each spectrum of the targets was divided by the solar analog spectrum observed at similar airmass (see Table 1).

3. Discussion

The newly obtained spectra are presented in Fig. 1 for 47171 and Fig. 2 for 32532. The resolution in the *V* range is on average 550 and around 500 in the *J*, *H* and *K* ranges. To improve the S/N ratio, the spectra in the visible and near-infrared were smoothed by Gaussian filtering of σ = 5 pixels, providing a final spectral resolution of about 250 in the *V*, *J*, *H* and *K* ranges.

3.1. 47171 (1999 TC_{36})

This object was observed in September 2003 by Ortiz et al. (2003) with the aim to determine its rotational period. They found a periodic variation of 6.21 ± 0.02 h, but they were not able to confirm the rotation period obtained from other data

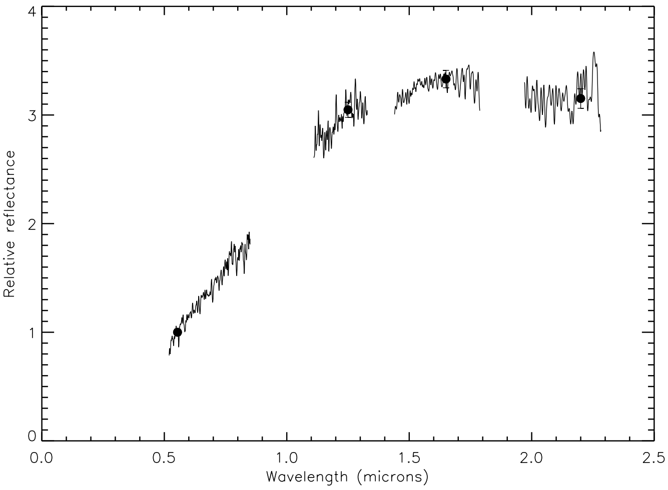

Fig. 1. Spectral reflectance of 47171 obtained in V, J, H and K ranges have been adjusted using the photometric V, J, H and K colors and have been normalized to 1 at 0.55 μm. The $V - J$ color was provided by Dotto et al. (2003a).

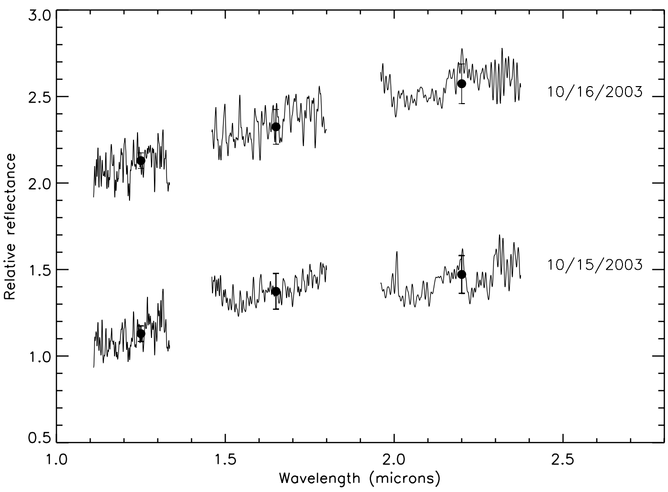

Fig. 2. Spectral reflectances of Thereus measured on October 15th and 16th, 2003. J, H and K spectra have been adjusted using the photometric J, H and K colors of this work. All the spectra are normalized to 1 at 0.55 μm. The J, H and K spectra on the top and bottom have been shifted by +0.5 and −0.5 unit in reflectance, respectively.

taken one month earlier. 47171 was observed also by Peixinho et al. (2002) over 8.362 h, but no apparent periodic variation was present within this time span, which may indicate that the object has a longer rotation period. Since 47171 1999 TC_{36} was recognized as a binary by Trujillo & Brown (2002), it seems that its lightcurve may be complex. A derived V-albedo of 0.05 (assumed to be identical for the two components), obtained from flux measurements in the millimeter range by Altenhoff et al. (2004), gives diameters of about 570 and 225 km for the two bodies. From repeated HST observations of this binary object, Margot et al.(2004) determined their masses and the ratio of their radii, even if more astrometric data are required to improve knowledge about the orbital parameters of this system. Margot et al. (2004) and Grundy et al. (2005) used these results and other assumptions about the objects' densities to estimate that the bodies' diameters are about 300 and 110 km and that the R-albedo is about 0.22±0.1. The object has already been observed spectroscopically in the visible by Lazzarin et al. (2003) and in the NIR by Dotto et al. (2003a) who also provided a model of the surface composition.

Table 2. Colors of the objects.

Object	Night	$J - H$	$J - K$
47171	10/Oct./2001[a]	0.36 ± 0.06	0.33 ± 0.06
47171	15/Oct./2003	0.42 ± 0.05	0.39 ± 0.05
32532	10/Oct./2001[b]	0.51 ± 0.06	0.62 ± 0.06
32532	15/Oct./2003	0.45 ± 0.04	0.57 ± 0.05
32532	16/Oct./2003	0.41 ± 0.04	0.61 ± 0.05

[a] Dotto et al. (2003a).
[b] Barucci et al. (2002a).

We obtained new visible and near–infrared spectra in the J, H and K bands in October 2003 (Fig. 1). The spectra are combined considering the measured colour indices $J - H = 0.42 \pm 0.05$ and $J - K = 0.39 \pm 0.05$ (see Table 2) and the $V - J = 2.29 \pm 0.07$ given by Dotto et al. (2003a). The general behaviour is very similar to the previous observations of this object. We compute a spectral gradient of the visible spectrum between 520 and 850 nm of 29%/100 nm, which is slightly less than the value of 31.5%/100 nm we derive from the visible spectrum of Lazzarin et al. (2003). To investigate the possible composition of the surface of this object, we ran a radiative transfer model, based on the Hapke theory, considering simple geographical mixtures of different materials. We used several minerals, ices and different organics complexes (e.g. tholins and kerogens), and for each mixture we produced a synthetic spectrum and compared it to our observations.

The mixture that best reproduces the observed spectral behaviour between 0.4 and 2.3 μm is composed of 57% Titan tholin (particles of 7 μm size), 25% ice tholin (10 μm), 10% amorphous carbon (10 μm) and 8% water ice (10 μm). This mixture has an albedo of about 0.13 at 0.55 μm. Tholins are hard, red-brownish substances made of complex organics compounds and they are the best candidates for reproducing the red slope up to 1.2 μm (Khare et al. 1984, 1993). Earth's present oxidizing atmosphere does not allow tholin synthesis, but it is possible to make them in the laboratory from mixtures of methane, ammonia and water vapor subjected to lightning discharges.

The surface composition model presented here is the same as that already suggested by Dotto et al. (2003a) to model observations carried out in 2001 (Fig. 3). Our model agrees better in the visible range with the 2003 spectrum which, however, is more limited in spatial coverage. These spectroscopic observations reveal a relatively homogeneous surface for this Plutino and they correlate well with the weak luminosity variation obtained in photometry.

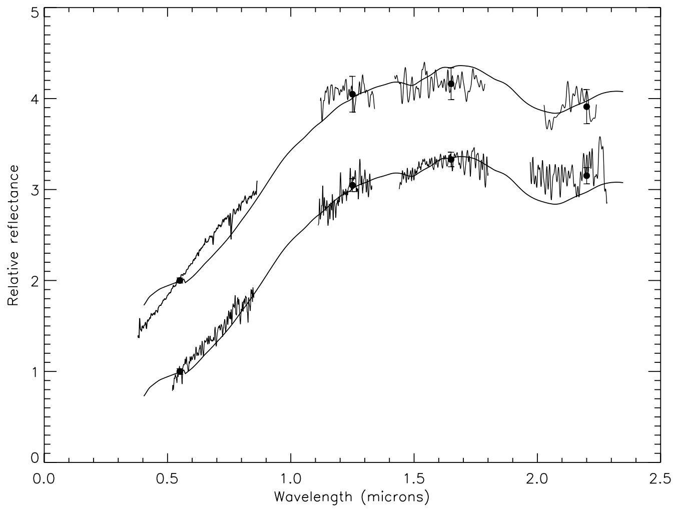

Fig. 3. Spectral reflectance of 47171 during 2003 (*bottom*: this work) and 2001 (*top*: Dotto et al. 2003a shifted by 1 unit in reflectance). The two continuous lines represent the model composed of 57% Titan tholin, 25% ice tholin, 10% amorphous carbon and 8% water ice with an albedo of 0.13 at 0.55 μm. All the spectra are normalized to 1 at 0.55 μm.

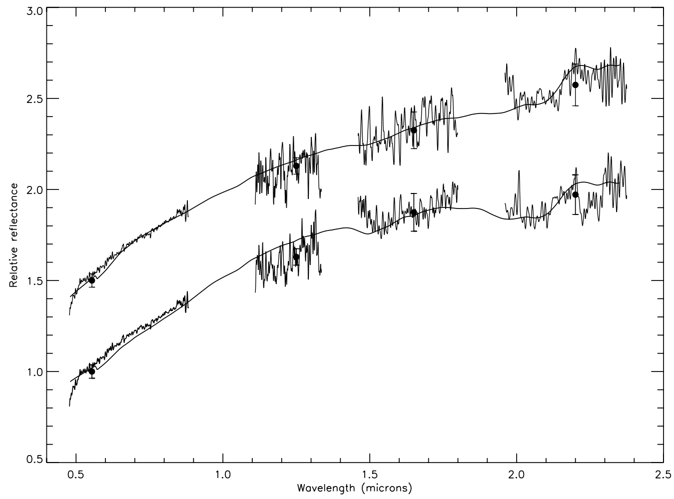

Fig. 4. Spectral reflectance of 32532. The lower and the upper spectra in the near-infrared (this work) were obtained October 15 and October 16, 2003, respectively. The visible part of the spectrum was recorded in October 10, 2001 by Barucci et al. (2002a). Each spectrum has been normalized to 1 at 0.55 μm and the upper spectra has been shifted by 0.5 unit in reflectance.

3.2. 32532 Thereus (2001 PT$_{13}$)

Ortiz et al. (2002) observed Thereus and initially determined a periodic signal of 4.15±0.05 h. They obtained data in two separate photometric runs, acquiring lightcurves with an amplitude of about 0.16 mag. Nevertheless, since the object would be near the critical rotation breakup limit, a rotation period of 8.3±0.1 h seemed more likely. Farnham et al. (2003) found a rotation period of 8.3378 ± 0.0012 h and, using a multi-wavelength lightcurve, determined the absolute magnitudes: $H_R = 8.80$ and $H_V = 9.30$. On the basis of this result, a diameter ranging from 40 to 90 km for a geometric albedo of 0.2−0.04 can be assumed. Ortiz et al. (2003) re-analysed their two main data sets and found a refined period of 8.3091 ± 0.0001 h.

The observations we carried out in October 2003 are shown in Fig. 2. To combine the *J*, *H*, and *K* parts, we used the colour indices reported in Table 2. The general behaviour of the spectra obtained on the 15th and the 16th of October 2003 are similar: featureless in *J* and some weak, broad bands in the *H* and *K* regions, in particular around 1.5 for the night of October 15th, 2003, and 2 μm for both nights. These spectral features give us confirmation of the presence of water ice on the surface of this object, which was already detected by Barucci et al. (2002a). The albedo of Thereus is still unknown, so it does not constrain our modeling attempts. However, since most of the Centaurs and TNOs for which the albedo has been measured are dark objects (albedo ≈ 0.04−0.12, Barucci et al. 2002b), except for a few cases (see e.g. Cruikshank et al. 2005; and Grundy et al. 2005), we assumed that Thereus has a relatively low albedo.

To investigate the possible composition of the objects' surface, we combine our observations with the visible spectrum and the $V - J = 1.61 \pm 0.04$ of Barucci et al. (2002a). We ran a radiative transfer model, based on Hapke theory, taking into account several minerals, ices and organics. The mixture that best reproduces the observed spectral behaviour is composed of 77% amorphous carbon (size of particles of 10 μm), 5% Triton tholin (10 μm), 7% Titan tholin (10 μm), 8% ice tholin (10 μm), 2% water ice (10 μm) and 1% methanol (5 μm) for the first night and by 77% of amorphous carbon (10 μm), 8% Triton tholin (10 μm), 3% Titan tholin (10 μm), 10% ice tholin (10 μm), 1% water ice (10 μm) and 1% methanol (5 μm) on the second night (Fig. 4). These models correspond to albedos of 0.059 and 0.057 at 0.55 μm, respectively. The models that best reproduce the spectra were determined using a chi-square test. As the method uses several parameters (e.g.: optical constants, particles size), the obtained results are not unique.

Barucci et al. (2002a) obtained two spectra of Thereus in the near-infrared region using the same instrument (in 2001). The spectra were obtained during two different runs: the first one in September 2001 and the second one in October 2001. The first spectrum (reported in Fig. 5, bottom) shows absorption features of H_2O ice near 1.5 and 2.0 μm. The second spectrum obtained in October 2001 was featureless (Fig. 5, top), revealing the heterogeneous nature of the surface of Thereus. Moreover, Licandro et al. (2005) obtained eight spectra covering more than half the rotational period and also obtained variations in the 2−2.3 μm range, despite more noisy spectra. In particular, the water ice absorption band at 2.0 μm appears in 3 spectra while the 5 others are featureless.

Analysing the rotational phase at which the different spectra of Thereus have been acquired, we can see that water ice seems to be present on only part of the surface of this body. Table 3 gives the rotational phases for the different near-infrared spectra acquired in 2001 and 2003, based on the determination of the rotational periods of Farnham et al. (2003) and Ortiz et al. (2003), with associated errors. The relation between spectra and rotational phase may be made with a good level of confidence between the data obtained on September 2001 and those acquired on October 2001, and between the data of

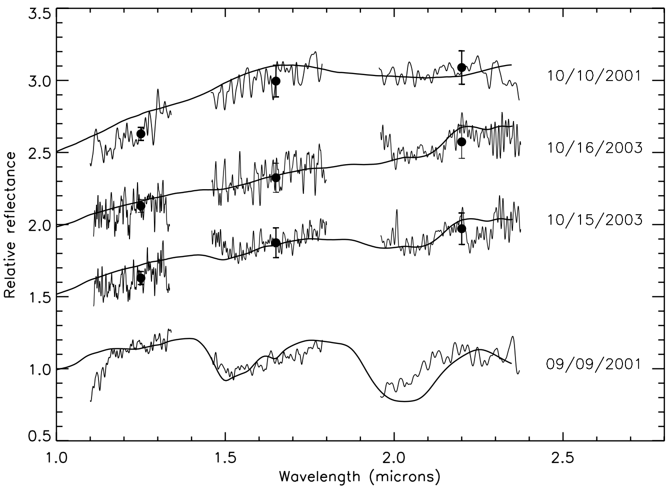

Fig. 5. Spectral reflectance of Thereus obtained on September and October 2001 (Barucci et al. 2002a) and October 2003 (15 and 16, this work). For the lower spectra, photometric data were not available and the spectra in the three spectral ranges have been adjusted to fit the 1.5 and 2.0 μm signatures (see Barucci et al. 2002a). The continous line superimposed on the spectrum obtained on September 2001 represents the synthetic spectrum for a mixture of 90% amorphous carbon, 5% Titan tholin and 5% water ice, while the model for the spectrum obtained on October 2001 consists of a mixture of 70% amorphous carbon, 15% Titan tholin, 12% ice tholin and 3% olivine (Barucci et al. 2002). For the two spectra of 2003, the models of the surface composition (this work) correspond to a mixture of about 77% amorphous carbon, 5% Triton tholin, 7% Titan tholin, 8% ice tholin, 2% water ice and 1% methanol (for the 15th October) and 77% amorphous carbon, 8% Triton tholin, 3% Titan tholin, 10% ice tholin, 1% water ice and 1% methanol (for the 16th of October). The two top spectra and the lower spectra have been shifted by 0.5 unit in reflectance.

October 15th, 2003 and those of October 16th, 2003. The rotational periods of Farnharm et al. (2003) and Ortiz et al. (2003) are both derived from measurements carried out during the last four months of 2001. This explains the best agreement in rotational phases for the 2001 runs.

Observations and models of 2003 show few differences. According to Farnham et al. and Ortiz et al., the difference in rotational phases is about 0.25 in H and 0.22 in K (see Table 3). The spectra of September and October 2001 for which significant differences are observed correspond to larger differences in rotational phases. We cannot compare the rotational phases of 2001 with those of 2003 due to a much longer interval between observations. It is evident that the surface of Thereus is heterogenous. According to Luu & Jewitt (1996) and Jewitt & Luu (2001) who simulated the diversity of colours, an inhomogeneous surface may be the product of reddening processes (due to irradiation that increases, with time, the reddening of the mantle) in competition with non disruptive collisions, with projectiles that excavate the irradiation mantle of targets. Cometary activity that could make surfaces heterogeneous is not excluded either for these distant objects, particularly for Centaurs (Delsanti et al. 2004).

Table 3. Rotational phase during spectroscopic observations (of this work (*) and of Barucci et al. 2002a) with zero phase assigned to September 21, 2001 at 5h20 UT.

Night	Filter	Rot-phase[a]	Rot-phase[b]
9/Sep./2001	J	0.2820 ± 0.0016	0.1723 ± 0.0001
9/Sep./2001	H	0.1583 ± 0.0016	0.0481 ± 0.0001
9/Sep./2001	K	0.9683 ± 0.0016	0.8575 ± 0.0001
10/Oct./2001	J	0.7230 ± 0.0024	0.8915 ± 0.0002
10/Oct./2001	H	0.5733 ± 0.0024	0.7413 ± 0.0002
10/Oct./2001	K	0.3546 ± 0.0024	0.5218 ± 0.0002
15/Oct./2003*	J	0.8421 ± 0.1085	0.3473 ± 0.0091
15/Oct./2003*	H	0.1156 ± 0.1085	0.6217 ± 0.0091
15/Oct./2003*	K	0.9573 ± 0.1085	0.4628 ± 0.0091
16/Oct./2003*	J	0.6198 ± 0.1086	0.1329 ± 0.0091
16/Oct./2003*	H	0.8645 ± 0.1086	0.3801 ± 0.0091
16/Oct./2003*	K	0.7321 ± 0.1086	0.2473 ± 0.0091

[a] Based on the rotation period of Farnham et al. (2003) with P = 8.33784 ± 0.0012 h.
[b] Based on the rotation period of Ortiz et al. (2003) with P = 8.3091 ± 0.0001 h.

4. Conclusions

NIR spectral reflectances for the TNO 47171 (1999 TC_{36}) and the Centaur Thereus were obtained with the VLT using ISAAC, and a visible spectrum of the TNO 47171 has been obtained with the 3.6 m telescope of La Silla using EFOSC2. Our observations and modeling confirm the results obtained by Dotto et al. (2003a) for the Plutino 47171 suggesting an homogeneous surface composition. The analysis of our near-infrared reflectance spectra of the Centaur 32532 confirms the presence of water ice on its surface and indicates significant surface variations.

The analysis of the available observations of Centaurs and TNOs shows that several objects – Chariklo (Dotto et al. 2003b), 38628 Huya (de Bergh et al. 2004 and Fornasier et al. 2004), 47932 2000 GN_{171} (de Bergh et al. 2004), 1999 UG_5 (Bauer et al. 2002), 1996 TO_{66} (Brown et al. 1999), Chiron (Groussin et al. 2004) and Thereus (Barucci et al. 2002a and this paper) – present variations of their surface properties. This would indicate that partial resurfacing by non-disruptive collisions and/or cometary activity is quite common. More observations and albedo measurements are strongly needed to better investigate the composition of these bodies and search for surface variations. This information would help improve our understanding of the evolutionary processes of these icy bodies.

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