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Trans-neptunian object (55636) 2002 TX_{300}, a fresh icy surface in the outer solar system

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ABSTRACT

Context. The knowledge of the physical properties of the population of known large trans-Neptunian objects (TNOs) is a key issue in understanding the origin and evolution of the Solar System. In particular, the knowledge of their surface composition helps to understand the original composition of the TNOs and the processes that affect their surfaces during their life.
Aims. We studied the surface composition of bright TNO 2002 TX_{300}, an object with a few hundred kilometer diameter (900–400 km if visual albedo is $0.08 < p_V < 0.4$).
Methods. We report visible and near infrared spectra covering the 0.5–2.2 μm spectral range, obtained with the Italian 3.58 m Telescopio Nazionale Galileo at "El Roque de los Muchachos" Observatory (La Palma, Spain), and derive mineralogical information using multiple scattering models.
Results. The spectrum of this large TNO is dominated by strong water ice absorption bands in the near-infrared and also presents a neutral to blue slope in the whole observed range. Models suggest that the surface of 2002 TX_{300} is fresh, composed of a large fraction of large water ice particles and dark materials (may be carbon and/or silicates) and a very low fraction of highly processed organic materials (tholins). The spectrum of 2002 TX_{300} is very similar to that of Pluto's satellite Charon. This can indicate that there is an ubiquitous mechanism that keeps water ice as the principal component of the outher layer of the surface of some large TNOs.
Conclusions.

Key words. Kuiper Belt – minor planets, asteroids – comets: general

1. Introduction

Identified as the source of the short period comets by Fernández (1980), the trans-Neptunian belt (TNb) is populated by icy bodies (TNOs), remnant planetesimals from the early solar system formation stages (Edgeworth 1949; Kuiper 1951), and which are probably the most pristine objects in the Solar System. The study of their surface properties can provide key information on the composition and early conditions in the pre-solar nebula. Different resurfacing processes, such as formation of an irradiation mantle, collisions and cometary activity, modify their outer layers. Also internal activity (e.g. cryovulcanism) has been suggested as a mechanism that can replenish the surface of large TNOs with ices from the interior (e.g. Stevenson 2004).

Long term processing by high energy particles and solar radiation induces the formation of organic particles in the outer layers, resulting in a mantle that covers the unprocessed original ices. Some of these organic materials have been transported to the inner Solar System by the short period comets since the early stages of the Earth's formation. On the other hand, mutual collisions, very frequent in the TNb, erode the irradiation mantle at different depths. A sufficiently energetic collision can bring fresh unprocessed ices to the surface.

Very few TNOs are known to have a large fraction of water ice on their surface. The best known case is Pluto's satellite Charon (Buie et al. 1987; Marcialis et al. 1987).

The knowledge of an object with a surface composed of such pristine material represents a unique opportunity to study the primitive composition of the pre-solar nebula in the TNb region and the resurfacing processes that produced the present surface of the TNOs.

Spectroscopy, in particular in the near-infrared region, is a powerful method for remote determination of the composition of volatile surface components of the outer solar system objects (Brown & Cruikshank 1997). Due to the small size and large distance of these objects, this technique is limited to the largest members of the TNb. Although the number of published spectra of TNOs is still limited, many different surface properties have been inferred among them. Strong photometric colour variations, from neutral to very red objects, have also been reported by several authors (Jewitt & Luu 2001; Gil-Hutton & Licandro 2001; Davies et al. 2000; Barucci et al. 2000; Boehnhardt et al. 2002; Hainaut & Delsanti 2002; Doressoundiram et al. 2005; Peixinho et al. 2004; McBride et al. 2003). But spectroscopy allows us to better study the mineralogy of these bodies. Some absorption bands, possibly due to hydrocarbons and/or water ice, have been observed in the infrared spectrum of some TNOs, e.g. 1996 TO66 (Brown et al. 1999), (20000) Varuna (Licandro et al. 2001) and (50000) Quaoar (Jewitt & Luu 2004; Pinilla et al. 2004), (90482) Orcus (Fornasier et al. 2004b; de Bergh et al. 2005), 2003 EL_{61} (Trujillo et al. 2006), 2003 UB_{313} (Brown et al. 2005), and 2005 FY_9 (Licandro et al. 2006).

TNO 2002 TX_{300} was discovered in October 2002 and its brightness suggests that it is one of the largest known TNOs, offering an excellent opportunity for a detailed physical study that would help to increase our knowledge of the TNb. The orbital elements of 2002 TX_{300} classify this object as a Classical TNO.

Sheppard & Jewitt (2003), based on photometric observations of 2002 TX_{300}, report a single-peaked period of 8.12 ± 0.08 h. Ortiz et al. (2003), from simultaneous visible and thermal observations, reported: (a) a possible rotation period of 7.89 ± 0.03 h (or 15.78 h if the light-curve is double-peaked); (b) a surface colour very similar to that of the Sun in the visible region; (c) a lower limit for the visible geometric albedo, $p_V \geq 0.08$, implying that the albedo is higher than that of cometary nuclei and other known albedos of TNOs; (d) an upper limit for the diameter $D < 907$ km. Based on Ortiz et al. data, Grundy et al. (2005) derived a higher lower limit for the albedo $p_R \geq 0.19$.

In this paper we present visible and near-infrared spectroscopy of 2002 TX_{300} and derive mineralogical information from its surface.

2. Observations

We obtained visible and near-infrared spectra of 2002 TX_{300} with the 3.58 m Telescopio Nazionale Galileo (TNG, El Roque de los Muchachos Observatory, Canary Islands, Spain). The near-infrared low resolution spectrum was obtained on 2003 Aug. 22.1 UT, using NICS, the Near-Infrared Camera and Spectrometer (see Baffa et al. 2001). The visible spectrum was obtained on 2003 Sep. 23.1 UT with DOLORES, a camera and spectrometer for the visible. Both instruments are permanently mounted in the Nasmyth foci of the TNG. Both nights were photometric.

The near-infrared spectrum was obtained using the unique, high throughput, low resolution spectroscopic mode of NICS, with an Amici prism disperser (Oliva 2001), which yields a complete 0.8–2.4 μm spectrum. The identification of the TNO was made by taking series of images through the J_s filter separated by one hour, and by comparing them. The object was identified as a moving object at the predicted position and with the predicted proper motion. The slit was oriented in the parallactic angle, and the tracking was at the TNO proper motion. A 1.5″ slit width corresponding to a spectral resolving power $R \simeq 34$ quasi-constant along the spectrum was used. The observing and reduction procedures were as described in Licandro et al. (2002). The acquisition consisted of a series of 3 images of 90 s exposure time in one position of the slit (position A) and then offsetting the telescope by 10″ in the direction of the slit (position B). This process was repeated and a number of $ABBA$ cycles were acquired. The total exposure time was 3240 s. The two-dimensional spectra were extracted and collapsed to one dimension. The wavelength calibration was performed using a look-up table which is based on the theoretical dispersion predicted by ray-tracing and adjusted to best fit the observed spectra of calibration sources and telluric absorptions. To correct for telluric absorption and to obtain the relative reflectance, the G2 stars Landolt 112-1333 and Landolt 115-271 (Landolt 1992) were observed during the same night at a similar airmass. These Landolt stars were observed also on previous nights together with the solar analogue star P330E (Colina & Bohlin 1997) and present similar spectra in the infrared region, so we used them as solar analogues.

By dividing the spectrum of Landolt 112-1333 by that of Landolt 115-271 and then normalizing to unity around 1.6 μm we observed that the resulting spectrum was very flat, the atmosphere was very stable during the observations, and the uncertainty in the slope was smaless than 0.6%/1000 Å. Finally, the spectrum of 2002 TX_{300} was divided by the spectra of the solar analogue stars, thus obtaining the relative reflectance spectrum. Sub-pixel offsetting was applied when dividing the two spectra to correct for errors in the wavelength calibrations due to instrumental flexures.

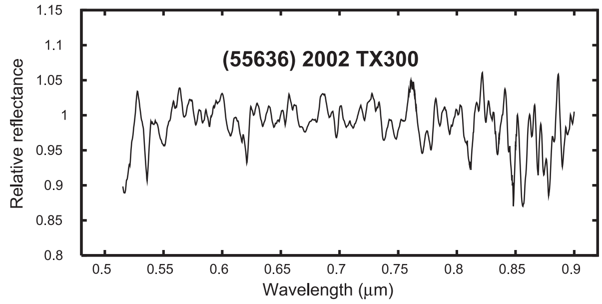

Fig. 1. Visible reflectance spectra of 2002 TX_{300} normalized at 0.55 μm. The spectrum is featureless and with a slightly blue slope.

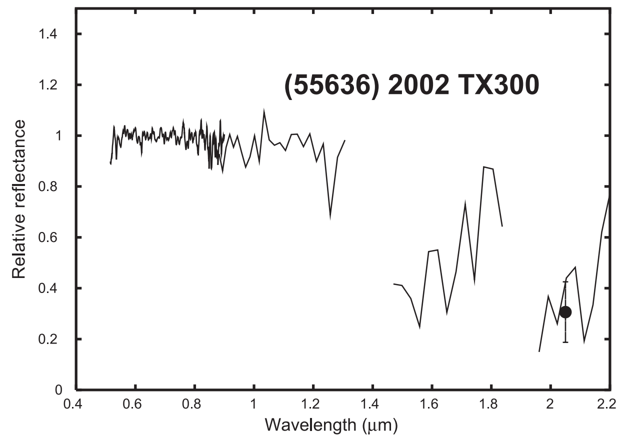

Fig. 2. Visible and near-infrared reflectance spectra of 2002 TX_{300} (red line), normalized at 0.55 μm. Note the slightly blue slope and the deep absorptions bands at 1.5 and 2.0 μm, typical of water ice. Regions corresponding to the strong telluric water ice absorption bands are not plotted. The large dot corresponds to the mean value and the standard deviation of the reflectance spectrum between 1.95 and 2.15 μm.

The visible spectrum was obtained with DOLORES using the LR-R grism and the 1.0″ slit width. Three 900s spectra were obtained by shifting the object 5″ in the slit direction to better correct the fringing. Images were over-scan and bias corrected, and flat-field corrected using lamp flats. The two-dimensional spectra were extracted, sky background subtracted, and collapsed to one dimension. The wavelength calibration was done using the Neon and Argon lamps. The three spectra of the TNO, obtained at different positions of the slit were averaged. The reflectance spectrum was obtained by dividing the spectrum of the TNO by the spectrum of the G2 star Landolt 115-271 obtained the same night at a similar airmass. The visible spectrum was normalized at 0.55 μm and smoothed using a smoothing box-car of 15 pixels (see Fig. 1).

The near-infrared spectrum was re-binned to the resolution of the prism (at least 3 pixels per resolution element) to improve the S/N without losing spectral resolution, and normalized to join the visible spectrum at 0.9 μm (see Fig. 2). The normalization factor was computed to match the linear fit of the near-infrared spectrum in the 0.8–1.2 μm range with that of the visible spectrum at 0.9 μm. We used this wide range in the near-infrared because, as the spectrum is featureless and the S/N of NICS spectrum is lower around 0.9 μm due to the sensitivity of the detector, the fit gives a more reliable result at 0.9 μm than using the 0.8–1.0 μm region.

3. Results and discussion

3.1. Analysis of the spectrum

The visible spectrum presented in Fig. 1 is featureless within the *S/N* and slightly blue. No signatures of any absorption band centered at 0.7 μm typical of that observed in low albedo main belt asteroids and attributed to silicate aqueous alteration are found. This very weak absorption has been reported for other TNOs (e.g. Lazzarin et al. 2004; Fornasier et al. 2004a).

The VNIR spectrum in Fig. 2 reveals two important features: (a) the slope, computed between 0.53 and 1.2 μm, $S' = -1\%/1000$ Å, indicates that the colour of this TNO is slightly bluer than the Sun, far from the typical red slope of the TNOs ($S' = 26.5\%/1000$ Å, Hainaut & Delsanti 2002), but not unique as other TNOs also present bluish surfaces (e.g. Charon, 1999 SM_5, 1996 TL_{66}, 2004 AZ_{84}); (b) there are two large absorption bands centered at 1.5 and 2.0 μm. A polynomial fit indicates that the depth of the bands with respect to the underlying continuum are $59 \pm 6\%$ and $67 \pm 10\%$ respectively. These are the deepest water ice absorption bands observed in a TNO. Up to now only two TNOs have a similar spectrum: 1996 TO_{66} (Brown et al. 1999) and Charon (Buie et al. 1987; Marcialis et al. 1987; Cruikshank 1998).

The *S/N* in the near-infrared region, where we claim the detection of water absorption bands, is low, in particular in the *K* band. Because of their faintness, this is the case for most of the already observed TNOs. But even if 2002 TX_{300} is rather bright in the visible, it is very faint in *K*, because of its neutral colour and deep absorption at 2 μm, thus it is even more difficult to attain better results with the current technology. To demonstrate that the *S/N* of our spectrum is sufficient to support a claim detection of water ice, we computed the *S/N* at different wavelengths. Considering that most of the noise is produced by the sky background (that is much higher than the signal from the object in the H and K region), we obtained the dispersion of sky values around the two dimensional reduced spectra, in boxes of a size equivalent to that considered to extract the spectrum of the TNO. The average *S/N* computed in this way in the H band is ~20, thus the detection of a band that absorbs 60% more light than the continuum is sufficiently secure. In the K band (considering the 1.95–2.22 μm region), the *S/N* is ~3–4, consistent with the fact that it is possible to "see by eye" the spectrum in the two-dimensional reduced image. To show that the absorption detected is not an artifact due to the low *S/N*, the average (and standard deviation) of the mean value of the reflectance computed in the 1.95–2.15 μm region is also plotted in Fig. 2 (large dot at 2.05 μm). Considering the error bar, there is a deep absorption of at least 32% (3σ) with respect to the underlying continuum.

We cannot claim that the absorption at 1.2 μm is real as only one spectral resolution element departs significatively from the continuum. More data is needed to confirm it.

3.2. Modeling

The colour of TNOs goes from neutral to very red. The observed very red colour of some TNOs is probably due to an evolved surface which is the result of long term processing by solar radiation, solar wind, and galactic cosmic-rays. This results in the selective loss of hydrogen and the formation of an "irradiation mantle" of carbon residues (Moore et al. 1983; Johnson et al. 1984). This process makes an initially neutral colour and high albedo ice become reddish. Further irradiation

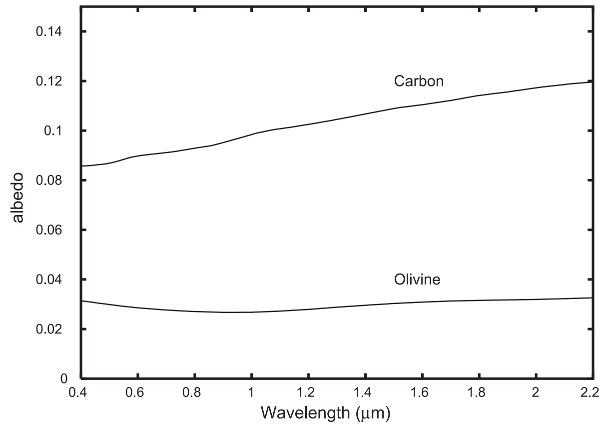

Fig. 3. Reflectance spectra of the carbon and olivine obtained from the optical constants taken from Rouleau & Martin (1991) and Dorschner et al. (1995) respectively. Note that both materials are very dark and do not present deep absorptions.

gradually reduces the albedo at all wavelengths, and the material becomes very dark, neutral in colour, and spectrally featureless as the fresh ices are covered by the created deep irradiation mantle (Andronico et al. 1987; Thompson et al. 1987). The neutral colour of 2002 TX_{300} is indicative that or either its surface has a deep irradiation mantle or it has a low fraction of complex organics. The large water ice absorption bands observed are indicative of a high abundance of water ice, which argues against a deep irradiation mantle, so we conclude that the surface of 2002 TX_{300} is depleted of complex organics. This is also supported by the high albedo reported by Ortiz et al. (2003) and Grundy et al. (2005). Then the surface of 2002 TX_{300} should be composed of a large fraction of water ice and a very low fraction of organic materials like tholins.

Taking this into account, we modeled the spectrum of 2002 TX_{300} using the simple one-dimensional geometrical-optics formulation by Shkuratov et al. (1999) to obtain mineralogical information. We fit the continuum and only the absorption band at 1.5 μm, considering the low *S/N* in the *K* band. All the derived models are also consistent with the data in the *K* band region.

We tried several areal mixtures using water ice and two dark components, olivine and amorphous carbon particles. Note that neither olivine nor amorphous carbon are proposed to be on the surface of the TNO, they are simply convenient materials for which the optical constants are known. The optical constants the olivine are those of olivine with 60% Fe ($y = 0.4$) in Dorschner et al. (1995), and the optical constants of amorphous carbon are those labeled as AC1 in Rouleau & Martin (1991). The optical constants of water ice were taken from Grundy & Smith (1988) in the 1–2.5 μm spectral region, and from Warren (1986) in the visible region. The reflectance spectra of olivine and carbon are shown in Fig. 3 and were computed for 10 μm size particles. In the 0.5–2.0 μm region their modeled spectra for different particle sizes are very similar. The combination of carbon and olivine produces a dark, neutral and almost featureless spectrum.

The data fit well using different combinations of particle sizes and abundances. Two of these models are shown in Fig. 4 and correspond to what we consider limiting cases: Model 1 (dashed line) corresponds to an areal mixture of 90% water ice particles of 60 μm size, 8% olivine particles of 10 μm size and 2% amorphous carbon particles of 10 μm size; Model 2 (dashed-dot-dashed line) corresponds to an areal mixture of 40% water ice particles of 250 μm size, 30% olivine particles of

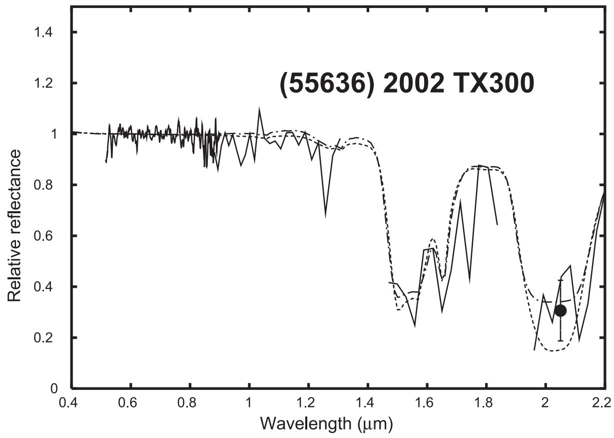

Fig. 4. Spectral models compared to the reflectance spectra of 2002 TX_{300}. Overploted as a dashed line is Model 1 and as a dashed-dot-dashed line is Model 2 (see text).

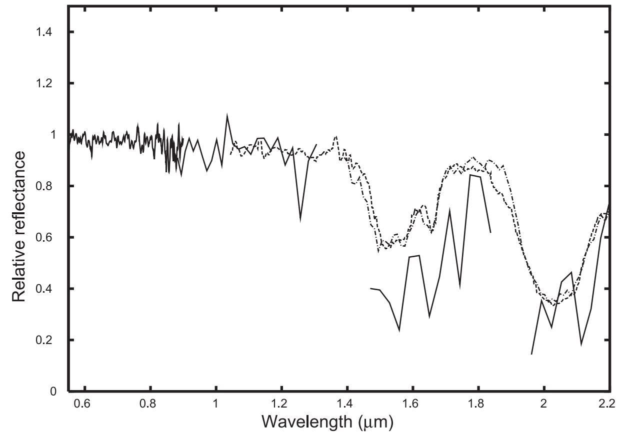

Fig. 5. Reflectance spectrum of 2002 TX_{300} (solid line) compared to two reflectance spectra of Charon from Brown & Calvin (2000) and Buie & Grundy (2000) (dashed and dashed-dot-dashed lines respectively) normalized to fit the 2002 TX_{300} spectrum. Notice that the spectra of both TNOs are very similar, but the water absorption bands observed in the 2002 TX_{300} spectrum are deeper than those in the Charon spectrum.

10 μm size and 30% amorphous carbon particles of 10 μm. Similar results can be obtained by changing relative abundances and size particles, but, the smaller the water ice abundance used, the larger the water ice particle size needed to fit the spectrum. Model 1 is the "water rich" case and gives an albedo value $p_V = 0.44$ at 0.55 μm, while Model 2 is the "water poor" case and gives $p_V = 0.13$. In the first case the albedo seems to be too high but it is similar to that of Charon (e.g. Brown & Calvin 2000), while Model 2 provides an albedo that is close to the lower limit given by Ortiz et al. (2003) and Grundy et al. (2005), but the use of very large (250 μm in diameter) water ice particles is needed to reproduce the observed absorption bands.

The scattering models provide solutions that are model dependent and far from unique (see Poulet et al. 2000). Considering also the *S/N* of our spectrum, we do not claim to provide detailed mineralogical description of the surface of 2002 TX_{300}. But in all possible combinations of surface materials, as illustrated by the two cases presented here, large water ice particle sizes (>40 μm and probably much larger) are needed to reproduce the observed deep absorption bands, in particular that at 1.5 μm. Note also that Roush et al. (1996) and Brown et al. (1999) use large water ice particles to reproduce the observed absorption bands in the spectrum of Charon and 1996 TO_{66} respectively. Thus we can conclude that the surface of 2002 TX_{300} is composed of a large fraction of large water ice particles, a certain fraction of dark materials (maybe carbon and silicates) and a very low fraction of highly processed organic materials.

3.3. 2002 TX_{300} and Charon

The 2002 TX_{300} spectrum is very similar to that of Charon (see Fig. 5), thus providing another example to study similar processes in their surfaces. The water ice absorption bands observed in the 2002 TX_{300} spectrum are even deeper than those in the Charon spectrum, suggesting that the amount of water ice on its surface and/or the size of the water ice particle, are larger in 2002 TX_{300} than in Charon. Unfortunatelly, the *S/N* of our spectrum do not allows to distinguish between amorphous or crystalline water ice on the surface of 2002 TX_{300}. The crystalline nature of the water ice on the surface of Charon, revealed by the absorption feature observed at 1.65 μm, is a very important and intringuing property that still needs to be explained (Brown 2002), as crystalline water ice is turned into the amorphous form with bombardment from solar ultraviolet radiation on short timescales (Kouchi & Koruda 1990). Crystalline water ice was also detected in (50000) Quaoar (Jewitt & Luu 2004) so a higher *S/N* spectrum of 2002 TX_{300} in this region could help to determine if there is a unbiquitous mechanism that causes the ice to be in crystalline form on the surface of TNOs.

3.4. Possible resurfacing mechanisms

What does this composition tell us about the evolution of 2002 TX_{300}? Gil-Hutton (2002) shows that the total amount of radiation received by classical TNOs during the age of the solar system should produce very dark, neutral surfaces, and suggests that different observed colours are due to collisions that erode the irradiation mantle at different depths depending on the energy of the collision. If the surface of 2002 TX_{300} is not mainly composed of very dark, neutrally coloured materials but by a large amount of water ice, we can conclude the existence of a resurfacing process that either destroyed the irradiation mantle or prevented its formation.

A possible mechanism, also suggested to explain the neutral colour and strong water ice absorption bands observed in the 1.4–2.2 μm spectra of 1996 TO_{66} (Brown et al. 1999), is that the irradiation mantle was destroyed by a collision. Under the collisional resurfacing hypothesis, only an energetic impact can bring fresh ices to the surface of a TNO (Gil-Hutton 2002), as less energetic impacts can only erode the upper layers of the irradiation mantle. Such an impact will produce vaporization of the eroded material that can globally be distributed over the TNO surface on a timescale of tens of hours (Stern 2002). The fact that the radiative cooling timescale of the vapor is hours to days, together with the low vertical diffusion velocity of ice, ensures that large ice particles can be formed with a high efficiency while being downward transported and deposited on the surface. Note that the typical sticking efficiency of condensates is very close to 1, enhanced by the likely electrostatic charge they may have (Pruppacher 1996).

Another possible mechanism is cometary activity. Some comets have been observed to be active at large heliocentric distances, not too far from the TNO region. Hainaut et al. (2000) suggest cometary activity in 1996 TO_{66} based on temporal variations in the rotational lightcurve and absolute magnitude of the

TNO. According to this mechanism, sublimated gases from below the irradiation mantle tend to destroy it. The effect in the spectrum of a TNO-like object is well known in the case of Centaur (2060) Chiron (Luu et al. 2000). Chiron is firmly established as a comet with a weak but persistent coma. Its spectrum has some similarities to that of 2002 TX_{300}: neutrally coloured and with water ice absorption bands in the near-infrared. The depth of the water ice absorption bands in the reflectance spectrum of Chiron is time-variable (Luu et al. 2000), and this variability is attributed to the coma activity: during periods of high-level outgassing, the dust in the coma masks the presence of water ice and the bands are not visible. Unlike 2002 TX_{300} and 1996 TO_{66}, the observed water ice absorption bands in Chiron are not very deep, even when the comet is not active. This can be indicative of a significant amount of dust on the surface, typical of comet nuclei that form dust mantles due to outgassing (Rickman et al. 1990), and/or small water ice grains. If cometary activity is the resurfacing mechanism in the case of 2002 TX_{300}, the large fraction of water ice detected implies that the dust mantle is very thin.

4. Conclusions

We obtained visible and near-infrared spectra of 2002 TX_{300} with the 3.58 m Telescopio Nazionale Galileo. The complete visible and near-infrared spectrum of TNO 2002 TX_{300} covering the 0.5–2.2 μm range is presented. The spectrum reveals two important features: a neutral to blue slope, ($S' = -1\%/1000$ Å, in the 0.5–1.2 μm range) far from the typical red slope of the TNOs ($S' = 26.5\%/1000$ Å, Hainaut & Delsanti 2002) and two large water ice absorptions bands centered at 1.5 and 2.0 μm, with band depth of about 60% with respect to the underlying continuum.

The mineralogical analysis using the formulation by Shkuratov et al. (1999) indicates that the surface of 2002 TX_{300} is composed of a large fraction of large water ice particles, a certain fraction of dark materials (perhaps carbon and silicates) and a very low fraction of highly processed organic materials. It likely corresponds to a fresh icy surface. The spectrum of 2002 TX_{300} is similar to that of Charon and TNO 1996 TO_{66}. The observed fresh icy material may have been produced by a recent energetic collision that deeply eroded the irradiation mantle, and/or comet activity. Further observations of these TNOs are needed to obtain more information on the resurfacing mechanism.

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