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LETTER TO THE EDITOR

The water ice rich surface of (145453) 2005 RR$_{43}$: a case for a carbon-depleted population of TNOs?

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ABSTRACT

Context. Recent results suggest that there is a group of trans-Neptunian objects (TNOs) (2003 EL$_{61}$ being the biggest member), with surfaces composed of almost pure water ice and with very similar orbital elements. These objects provide exciting laboratories for the study of the processes that prevent the formation of an evolved mantle of organics on the surfaces of the bodies in the trans-Neptunian belt (TNb).
Aims. We study the surface composition of another TNO that moves in a similar orbit, (145453) 2005 RR$_{43}$, and compare it with the surface composition of the other members of the group.
Methods. We report visible and near-infrared spectra in the 0.53−2.4 μm spectral range, obtained with the 4.2 m William Herschel Telescope and the 3.58 m Telescopio Nazionale Galileo at the "Roque de los Muchachos" Observatory (La Palma, Spain). Scattering models are used to derive information about its surface composition. We also measure the depth D of the water ice absorption bands and compare with those of the other members of the group.
Results. The spectrum of 2005 RR$_{43}$ is neutral in color in the visible and dominated by very deep water ice absorption bands in the near infrared ($D = 70.3 \pm 2.1\%$ and $82.8 \pm 4.9\%$ at 1.5 μm and 2.0 μm respectively). It is very similar to the spectrum of the group of TNOs already mentioned. All of them present much deeper water ice absorption bands ($D > 40\%$) than any other TNO except Charon. Scattering models show that its surface is covered by water ice, a significant fraction in crystalline state with no trace (5% upper limit) of complex organics. Possible scenarios to explain the existence of this population of TNOs are discussed: a giant collision, an originally carbon depleted composition, or a common process of continuous resurfacing.
Conclusions. 2005 RR$_{43}$ is member of a group, may be a population, of TNOs clustered in the space of orbital parameters that show abundant water ice and no signs of complex organics and which origin needs to be further investigated. The lack of complex organics in their surfaces suggests a significant smaller fraction of carbonaceous volatiles like CH$_4$ in this population than in "normal" TNOs. A carbon depleted population of TNOs could be the origin of the population of carbon depleted Jupiter family comets already noticed by A'Hearn et al. (1995).

Key words. Kuiper Belt – solar system: formation

1. Introduction

Spectroscopic and spectrophotometric studies show that about 70% of TNOs present a mantle of complex organics on their surfaces (Brunetto et al. 2006). Long term processing by high energy particles and solar radiation on icy bodies, induces the formation of organic species in their outer layers, resulting in a mantle that covers the unprocessed original ices (Moore et al. 1983; Johnson et al. 1984; Strazzulla & Johnson 1991). Until recently, the only case of a TNO with a surface covered basically by a thick layer of water ice was Charon (Buie et al. 1987; Marcialis et al. 1987), and it has been considered an intringuing case because of the need of a resurfacing mechanism like cryovolcanism or collisons with micro-meteorites (Brown 2002; Cruikshank 1998). Recently, it has been showed that (55636) 2002 TX$_{300}$ (Licandro et al. 2006) and (13308) 1996 TO$_{66}$ (Brown et al. 1999) also have surface composition similar to Charon. During last year the spectra of five other objects were published, revealing that their surfaces are also covered by fresh water ice: (136108) 2003 EL$_{61}$ (Trujillo et al. 2007), its biggest satellite S/2005 (136108) 1 (Barkume et al. 2006) and during the review process of this paper 2003 OP$_{32}$, 1995 SM$_{55}$ and 2005 RR$_{43}$ (Brown et al. 2007). The spectra of these TNOs show all the same characteristics, they are neutral and featureless in the visible and show strong water ice absorption bands in the near infrared. All these TNOs, except Charon, are located in a narrow region of the orbital parameters space ($41.6 < a < 43.6$ AU, $25.8 < i < 28.2$ deg, $0.10 < e < 0.19$). The existence of a population of TNOs with Charon-like surfaces and similiar orbital parameters needs to be explained as it can have a strong impact in the knowledge of the trans-neptunian belt formation theories and/or resurfacing mechanisms.

In this paper we present visible and near-infrared spectroscopy of a member of this group, (145453) 2005 RR$_{43}$ (a, e, i = 43.06 AU, 0.14, 28.54 deg) and derive compositional information using scattering models. Finally we describe different scenarios that can explain the existence of this population of TNOs.

2. Observations and analysis of the spectrum

We obtained the visible spectrum of 2005 RR$_{43}$ with the 4.2 m William Herschel telescope (WHT) and the near-infrared spectrum with the 3.58 m "Telescopio Nazionale Galileo" (TNG) both at the "Roque de los Muchachos" Observatory (Canary Islands, Spain).

The visible spectrum (0.35–0.95 μm) was obtained on 2006 Sep. 23.18 UT using the low resolution grating (R158R, with a dispersion of 1.63 Å/pixel) of the double-armed spectrograph ISIS at WHT, and a 4″ slit width oriented at the parallactic angle. The tracking was at the TNO proper motion.

Three 900 s exposure time spectra were obtained by shifting the object by 10″ in the slit to better correct the fringing. Calibration and extraction of the spectra were done using IRAF and following standard procedures (Massey et al. 1992). TNO spectra were averaged and the reflectance spectrum was obtained by dividing the spectrum of the TNO by the spectrum of the solar analogue star Hyades 64 obtained the same night just before and after the observation of the TNO at a similar airmass. Final spectrum presented in Fig. 1 was smoothed using a smoothing box-car of 15 pixels to improve the S/N.

The near-infrared spectrum was obtained on 2006 Sep. 29.15 UT, using the low resolution spectroscopic mode of NICS (Near-Infrared Camera and Spectrometer) at the TNG based on an Amici prism disperser. This mode yields a complete 0.8–2.4 μm spectrum. 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 total "on object" exposure time was 11 160 s.

To correct for telluric absorption and to obtain the relative reflectance, solar analogue star Hyades 64 and two G-2 Landolt stars (115–271 and 98–978, Landolt 1992) were observed at different airmasses during the night. The reflectance spectrum of the TNO was obtained using all the SA stars, averaged and then normalized to fit the visible one using the overlapping spectral region between 0.85–0.95 μm. The combined visible and near-infrared (VNIR) spectrum is presented in Fig. 1 together with the spectra of the other members of the group.

The VNIR spectrum reveals three important characteristics: (a) the visible is featureless within the S/N. There is no clear evidence of any absorption reported for other TNOs (e.g. Lazzarin et al. 2004; Fornasier et al. 2004a); (b) it is neutral (the spectral slope, computed between 0.53 and 1.00 μm, is $S' = 0.4 \pm 1\%/1000$ Å), far from the more characteristical red slopes in the TNb (Fornasier et al. 2004b); (c) it presents two deep absorption bands centered at 1.5 and 2.0 μm, indicative of water ice.

The flat visible spectrum is indicative of the lack (or very low abundance) of complex organic and/or silicates in the surface of this TNO.

The depth of the water ice bands is a good indicator of its abundance on the surface of icy objects, it is also a reasonably good marker of the size of the icy particles and of the contamination by non-ice components (Clark et al. 1984). We computed the depth of the bands, D, with respect to the continuum of the spectrum as $D = 1 - R_b/R_c$, where R_b is the reflectance in the center of the band and R_c is the reflectance of the continuum at 1.2 μm. For 2005 RR$_{43}$, D is 70.3 ± 2.1% and 82.8 ± 4.9% at 1.5 μm and 2.0 μm respectively, beeing the deepest water ice absorption bands ever observed in a TNO.

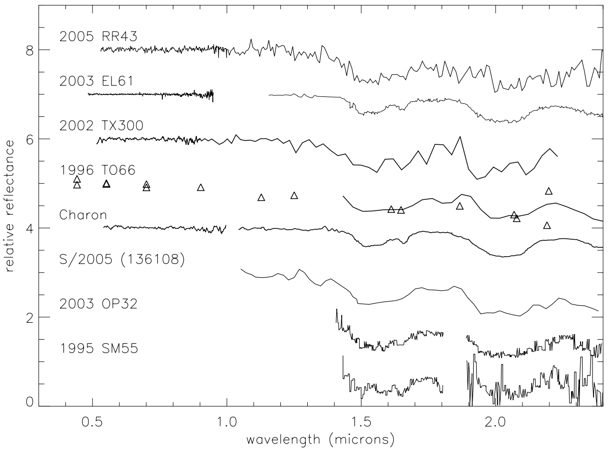

Fig. 1. Spectrum of 2005 RR$_{43}$, normalized at 0.55 μm, together with the spectra of the other members of the group shifted in the vertical axis for clarity. References in Table 1.

Thus, we conclude that the surface of 2005 RR$_{43}$ is composed by a large fraction of large sized (or a thick layer of) water ice particles, and none or a very small fraction of complex organics or silicates.

This is confirmed by scattering models. We use the simple one-dimensional geometrical-optics formulation by Shkuratov et al. (1999), to obtain information about the surface composition.

It is important to determine if water ice is in amorphous or crystalline state as it can be indicative of resurfacing processes. Crystalline water ice can be easily identified by an absorption band at 1.65 μm. This band has been detected in the spectrum of TNOs Charon (Brown & Calvin 2000) and 2003 EL$_{61}$ (Trujillo et al. 2007), the only TNOs that have spectra similar to 2005 RR$_{43}$ and sufficiently high signal-to-noise to see this band. Unfortunately, the relatively poor S/N of our spectrum does not allow us to clearly detect this feature.

So we first tried to model 2005 RR$_{43}$ spectrum with pure amorphous water ice, but all the tests we made produced a band at 1.5 μm narrower than that seen in the spectrum (see Fig. 2). We then tried with pure crystalline water ice obtaining a better fit. Finally we used an intimate mixture of crystalline and amorphous water ices obtaining even better results and improving the fit above 2 μm, although this part of the spectrum is too noisy to be a significant constraint. We thus conclude that water ice in the surface of 2005 RR$_{43}$ is, at least in a significant fraction, crystalline.

On the other hand, all these models allow a small percentage of minor components such as amorphous carbons or silicates (e.g. Olivine), up to 5%. We notice that the S/N of the spectrum and the model itself do not allow us to make a detailed study of the surface mineralogy. An important parameter to include, that could help to better constraint the models and, in particular, determine the abundance of minor dark constituents, is the albedo of the TNO, as even a small amount of them can darken the surface significantly.

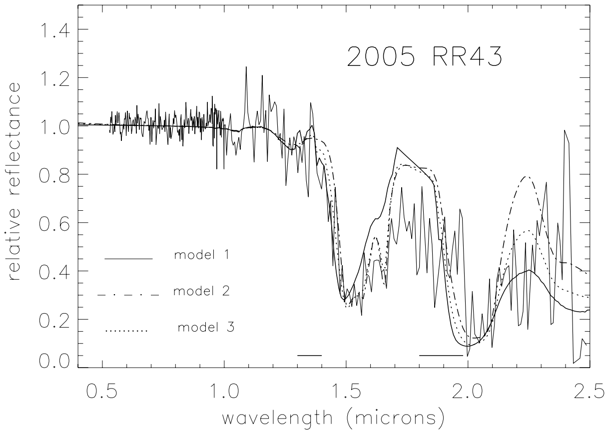

Fig. 2. Best fits of the spectrum with the Shkuratov approximation (intimate mixtures of amorphous water ice (AWI), crystalline water ice (CWI) and olivine (O)). Model 1: 95% AWI (70 μm)5% O (30 μm); model 2: 95% CWI (50 μm) + 5% O (30 μm); model 3: 55% AWI (60 μm) + 40% CWI (70 μm) + 5% O (30 μm). The width of 1.5 μm band is best fitted with crystalline water ice.

3. Discussion and conclusions

To date, about 40 TNOs have been observed spectroscopically in the near-infrared. Among them only seven exhibit a spectrum similar to that of 2005 RR$_{43}$. Table 1 summarizes their 1.5 μm band depth (D) and spectral slope S' computed as in Sect. 3 for 2005 RR$_{43}$. Notice that all of these TNOs have very deep water ice absorptions, $D > 40\%$ and $S' \sim 0$.

Brown et al. (2007) noticed that, excluding Charon, these objects present very similar spectral properties and orbital parameters (see Fig. 2 of Brown's paper). On the other hand, the spectra and colors of other TNOs in the neighbourhood of the cluster, e.g. (20000) Varuna (Licandro et al. 2001) or (50000) Quaoar (Jewitt & Luu 2004), are different from the spectrum of 2005 RR$_{43}$ and present the variety of colors and composition observed in other regions of the TNb. Thus, we also conclude that objects in Table 1 (except Charon) are part of a population clustered in the space of parameters and with similar surface properties different from those of the objects in the neighbourhood.

There are other smaller TNOs, with no photometric or spectroscopic data published, that according to their orbital parameters, could be also members of this population like 1995 GJ, 1999 OK$_4$, 1999 RA$_{215}$, 2003 FB$_{130}$, 2005 PM$_{21}$. Photometric and/or spectroscopic observations are needed.

Water ice surfaces with no traces of organics should not be common in the TNb assuming that the original chemical composition of all TNOs is very similar: objects composed of abundant water ice, some molecular ices like CO, CO$_2$, CH$_4$,N$_2$ and silicates. Long term processing by high energy particles and solar radiation induces the formation of complex organic species in the outer layers of the TNOs resulting in a dark and usually red mantle that covers the unprocessed original ices. Thus, the existence of a population of TNOs with no signs of organics, in a very narrow region of the space of orbital parameters is an intriguing fact that needs to be explained. We discuss three different scenarios that need to be further studied:

1) **Collisional family**: the destruction of the irradiation mantle by an energetic collision has been proposed by Licandro et al. (2006) to explain the fresh surface of one of the member of this population, 2002 TX$_{300}$. Such an impact breaks the irradiation mantle and produces enough energy to sublimate a certain amount of ices on the upper layers of the body (Gil-Hutton 2002). The material sublimated by the collision can be globally redeposited over the TNO on a timescale of tens of hours (Stern 2002) and the low vertical diffusion velocity of the ice ensures that large particles can be formed with a high efficiency while being downward transported and deposited on the surface. Brown et al. (2007) proposed that the TNOs listed in Table 1 (but Charon) are fragments produced by a catastrophic collision suffered by 2003 EL$_{61}$. This would explain the rapid rotation of this large object, the existence of two satellites orbiting it, and the clustering of objects in a small region of the TNb with similar surface properties.

Table 1. H: absolute magnitud; S': spectral gradient; D: absorption at 1.5 μm. References: 1. Brown & Calvin (2000), 2. Fink & DiSanti (1988), 3. The online updated database from Hainaut & Delsanti (2002), 4. Brown et al. (2007), 5. Brown et al. (1999), 6. Noll et al. (2000), 7. Licandro et al. (2006), 8. Tegler et al. (2007), 9. Trujillo et al. (2007), 10. Barkume et al. (2006), 11. This work.

Object	H_V	S'	D	Ref
Charon	0.9	–0.6	41.5 ± 3.4%	(1, 2)
1995 SM$_{55}$	4.8	2.4	70.2 ± 5.9%	(3, 4)
1996 TO$_{66}$	4.5	4.5	59.1 ± 1.9%	(3, 5, 6)
2002 TX$_{300}$	3.3	1	64.1 ± 3.9%	(7)
2003 OP$_{32}$	4.1	–1.1	64.2 ± 2.5%	(4, 8)
(136108) 2003 EL$_{61}$	0.2	–0.4	40.7 ± 2.1%	(8, 9)
S/2005 (136108) 1	3.5	NA	69.1 ± 1.0%	(10)
2005 RR$_{43}$	4.0	–0.4	70.3 ± 2.1%	(11)

Although this scenario appears promising, it has several problems: first, the low mean intrinsic collisional probability makes highly improbable a catastrophic collision with a large projectile capable of providing enough kinetic energy to disperse large fragments to their present positions, even in a TNb more massive that the present one. Second, it is difficult to model the collisional process to produce such a family working with so few members and given the large uncertainties in their orbital elements. Third, the current dispersion in orbital elements of the fragments shows orbital elements expected from a too high dispersive velocity of 400 m/s. Brown et al. argued that only 2003 EL$_{61}$ does not fit withing a smaller velocity of 140 m/s and argued that this TNO has large excursions in eccentricity over time owing to chaotic diffusion within the 12:7 mean-motion resonance (MMR) with Neptune. If this is the case, following the analysis by Nesvorny & Roig (2001) of the 12:7 MMR with Neptune, and cited by Brown et al. (2007), the chaotic diffusion enlarge the initial eccentricity of any orbit near its borders in such a way that it becomes Neptune grazing and the body escapes in less than 10^8 yr, dispersing very fast any object in its vicinity. But the collision must have happened in the distant past, when the belt was far more crowded with large objects (Morbidelli 2007). Fourth, if the collision happened in the distant past, the effects of long term processing by high energy particles and solar radiation should be present and are not. Gil-Hutton (2002) shows that the time scale required to form a black irradiation mantle of carbon residues in a TNO is $\sim 6 \times 10^8$ years. The competition of this effect with resurfacing due to high frequency impacts will increase the time scale to 10^9 years while intermediate states would result in red spectra. Moreover the efficiency of this process depends on the presence of organics on the surface so the absence of an irradiation mantle can be explained by the loss of organics or the absence of them in the original composition. Thus, a possible solution of this problem is that the loss of organics was produced by the collision and recondensation process that formed the family.

2) **Originally carbon depleted population**: another possible scenario is a population of objects originally carbon depleted, strongly concentrated in the space of orbital parameters, and in a region that it is dynamically unstable (the hot population). But this has also several problems: why carbon depleted objects were formed in a narrow region of the solar nebula and remained grouped until present time? However, the existence of a population of carbon depleted TNOs is an interesting case, as it could be the origin of the population of carbon depleted Jupiter family comets already noticed by A'Hearn et al. (1995) and whose origin remains unknown.

3) **Continuous resurfacing process**: another possible scenario is that these objects are exposed to a mechanism that replenishes their surfaces permanently with fresh material from their interiors like cryovolcanism. Anyhow, it is difficult to explain why this mechanism affects so efficiently this group of TNOs and only this group.

In conclusion, the spectrum of TNO 2005 RR_{43} in the visible and near-infrared range shows that its surface is covered by large water ice grains. Scattering models reveal that the observed water ice is, at least in a significant fraction, crystalline. 2005 RR_{43} spectrum is very similar to those of TNOs Charon, 1996 TO_{66}, 2002 TX_{300}, 2003 OP_{32}, 1995 SM_{55}, (136108) 2003 EL_{61} and S/2005 (136108). It also has orbital elements very similar to those of these last four TNOs, supporting the existence of a population of TNOs with their surface covered by fresh water ice and almost no complex organics. The lack of complex organics suggests a signficant smaller fraction of carbonaceous volatiles like CH_4 in this population than in "normal" TNOs. Such carbon depleted population of TNOs could be the origin of the population of carbon depleted Jupiter family comets already noticed by A'Hearn et al. (1995). The origin of this population needs to be further investigated.

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References

A'Hearn, M. F., Millis, R. L., Schleicher, D. G., et al. 1995, Icarus, 118, 223
Baffa, C., Comoretto, G., Gennari, S., et al. 2001, A&A, 378, 722
Barkume, K. M., Brown, M. E., & Schaller, E. L. 2006, ApJ, 640, L87
Brown, M. 2002, Ann. Rev. Earth. Planet. Sci., 30, 307
Brown, M., & Calvin, W. 2000, Science, 287, 107
Brown, R., Cruikshank, D., & Pendleton, Y. 1999, ApJ, 519, L101
Brown, M. E., Barkume, K. M., Ragozinne, D., et al. 2007, Nature, 446, 294
Brunetto, R., Barucci, M., Dotto, M. E., & Strazzulla, G. 2006, ApJ, 644, 650
Buie, M., Cruikshank, D., Lebofsky, L., et al. 1987, Nature, 329, 522
Clark, R. N., Brown, R. H., Owensby, P. D., et al. 1984, Icarus, 58, 265
Cruikshank, D. 1998, in Solar System Ices, ed. B. Schmitt et al. (Kluwer), 655
Fink, U., & DiSanti, M. A. 1988, AJ, 95, 229
Fornasier, S., Dotto, E., Barucci, A., et al. 2004a, A&A, 422, 43
Fornasier, S., Doressoundiram, A., Tozzi, et al. 2004b, A&A, 421, 353
Gil-Hutton, R. 2002, P&SS, 50, 57
Hainaut O. R., & Delsanti, A. C. 2002, A&A, 389, 641 `http://www.sc.eso.org/ ohainaut/MBOSS/`
Jewitt, D. C., & Luu, J. 2004, Nature, 432, 731
Johnson, R., Lanzerotti, L., & Brown, W. 1984, Adv. Space Res. 4, 41
Landolt, A. 1992, AJ, 104, 340
Lazzarin, M., Barucci, M., Boehnhardt, H., et al. 2003, AJ, 125, 1554
Licandro, J., Oliva, E., & Di Martino, M. 2001, A&A, 373, L29
Licandro, J., Ghinassi, F., & Testi, L. 2002, A&A, 388, L9
Licandro, J., di Fabrizio, L., Pinilla-ALonso, N., et al. 2006, A&A, 457, 323
Marcialis, R., Rieke, G., & Lebofsky, L. 1987, Science, 237, 1349
Massey, P., Valdes, F., & Barnes, J. 1992, in A User's Guide to Reducing Slit Spectra with IRAF, `http://iraf.noao.edu/iraf/ftp/iraf/docs/spect.ps.Z.`
Moore, M., Donn, B., Khanna, R., & A'Hearn, M. 1983, Icarus, 54, 388
Morbidelli, A. 2007, Nature, 446, 273
Nesvorny, D., & Roig, F. 2001, Icarus, 150, 104
Noll, K. S., Luu, J., & Gilmore, D. 2000, AJ, 119, 970
Shkuratov, Y., Starukhina, L., Hoffmann, H., et al. 1999, Icarus, 137, 235
Stern, S. A. 2002, AJ, 124, 2297
Strazzulla, G., & Johnson, R. 1991, in Comets in the Post-Halley era, ed. R. L. Newburn Jr., M. Neugebauer, & J. Rahe (Netherlands: Kluwer Academic Publishers), 243
Tegler, S. C., Grundy, W. M., Romanishin, W., et al. 2007, AJ, 133, 526
Trujillo, C. A., Brown, M., Barkume, K. M., et al. 2007, ApJ, 655, 1172