Icarus 208 (2010) 945–954

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Surface composition and physical properties of several trans-neptunian objects from the Hapke scattering theory and Shkuratov model ☆

F. Merlin [a,b,*], M.A. Barucci [a], C. de Bergh [a], S. Fornasier [a], A. Doressoundiram [a], D. Perna [a,c], S. Protopapa [d]

[a] *LESIA/Observatoire de Paris, 5 Place Jules Janssen, 92195 Meudon Cedex, France*
[b] *Department of Astronomy, University of Maryland, College Park, MD 20742, USA*
[c] *INAF, Osservatorio Astronomico di Roma, via Frascati 33, 00040 Monteporzio Catone (Roma), Italy*
[d] *Max-Planck Institute for Solar System Research, Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany*

ARTICLE INFO

Article history:
Received 19 March 2009
Revised 3 March 2010
Accepted 7 March 2010
Available online 16 March 2010

Keywords:
Kuiper Belt
Ices
Spectroscopy
Trans-neptunian objects
Centaurs

ABSTRACT

Several different trans-neptunian objects have been studied in order to investigate their physical and chemical properties. New observations in the 1.1–1.4 μm range, obtained with the ISAAC instrument, are presented in order to complete previous observations carried out with FORS1 in the visible and SINFONI in the near infrared. All of the observations have been performed at the ESO/Very Large Telescope. We analyze the spectra of six different objects (2003 AZ$_{83}$, Echeclus, Ixion, 2002 AW$_{197}$, 1999 DE$_9$ and 2003 FY$_{128}$) in the 0.45–2.3 μm range with the model of Hapke (Hapke, B. [1981]. J. Geophys. Res. 86, 4571–4586) and the method of Shkuratov et al. (Shkuratov, Y., Starukhina, L., Hoffmann, H., Arnold, G. [1999]. Icarus 137, 235–246). Water ice is found on two objects, and in particular it is confirmed in its amorphous and crystalline states on 2003 AZ$_{84}$ surface. Upper limits on the water ice content are given for the other four TNOs investigated, confirming previous results (Barkume, K.M., Brown, M.E., Schaller, E.L. [2008]. Astron. J. 135, 55–67; Guilbert, A., Alvarez-Candal, A., Merlin, F., Barucci, M.A., Dumas, C., de Bergh, C., Delsanti, A. [2009]. Icarus 201, 272–283). Whatever the absorption features in the near infrared, all objects but one exhibit a moderate red slope in the visible, as most TNOs and Centaurs. We discuss the implications of the presence of water ice and the probable sources of the red slope.

1. Introduction

Trans-neptunian objects (TNOs) are known as primordial and remnant bodies of the Solar System. Located beyond Neptune, they are separated into four dynamical classes, that are the Scattering Disk Objects (SDOs), the classical Kuiper Belt Objects (KBOs), the Detached Objects (DO) and the Resonant Objects with Neptune (ROs). Centaurs, which orbit completely inside the orbit of Neptune are considered as SDOs; see Davies et al. (2008) and Gladman et al. (2008) for a complete review on the dynamical classes. Although TNOs and Centaurs seem to have a common origin, the observation of TNOs has revealed a high diversity of colors (in the visible and near infrared: Doressoundiram et al., 2008; Tegler et al., 2008, etc.), of absorption features (e.g.: Barucci et al., 2008a; Guilbert et al., 2009) and multiple surface roughnesses (from polarimetry and photometry; e.g., Belskaya et al., 2008) that imply a variety of surface composition. A few trends are drawn from these recent observations. Objects with a diameter close or greater than 1000 km show clear absorption bands in the near infrared (Barucci et al., 2008a), neutral or moderate red slope from visible spectroscopy or photometry (e.g.: Eris, Pluto or Haumea observed by Dumas et al. (2007), Merlin et al. (2009, 2007), Licandro et al. (2006), Brown et al. (2005), Trujillo et al. (2007), Pinilla-Alonso et al. (2009) for instance). The spectra of smaller objects are mainly featureless in the near infrared and exhibit different slopes in the visible (for a sample see, e.g.: Dotto et al., 2003a). It is possible to identify the physical state or/and dilution state of the different ices present on the surface of the biggest and brightest objects, but our knowledge on the surface of the smallest and darkest ones is still limited due to low signal-to-noise level. However, it is very important to compare the chemical composition of the smallest ones with that of the biggest ones to confirm or refute recent theories on the physical processes that govern their surface evolution.

These theories imply that the surface of any atmosphereless body in the Solar System is directly exposed to cosmic rays, solar wind or high energy particles coming from the Sun or from the interstellar medium. These phenomena are very important in the transformation of the species located in the first layers of the surface, those that are accessible from visible and near-infrared spectroscopy. These physical processes, called space weathering, tend

---

☆ Based on observations made with ESO Telescopes at the Paranal Observatories under programme ID 178.C-0036.

* Corresponding author at: Department of Astronomy, University of Maryland, College Park, MD 20742, USA.

E-mail addresses: merlin@astro.umd.edu, frederic.merlin@obspm.fr (F. Merlin).

0019-1035/$ - see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2010.03.014

to modify the initial rich icy layers into organic or carbon rich materials that are usually dark and red (Strazzulla et al., 2003) with possible physical state changes. Crystalline water ice, for example, requires high temperature (more than 100 K) to be formed and seems to be sensitive to space weathering that transforms it into its amorphous state at low temperature (Mastrapa et al., 2008). A balance can exist between crystalline and amorphous water ice above 40 K, from thermal recrystallization and irradiation processes (Zheng et al., 2009). However, the authors consider only ion irradiation and other irradiation sources need to be investigated too. Crystalline water ice, that displays a clear absorption band at 1.65 μm (see Grundy and Schmitt, 1998; Mastrapa et al., 2008), is usually detected on the surface of big objects which are covered by water ice. Recent studies suggest that big objects are more easily submitted to major rejuvenation events than the small ones, as condensation of volatile species (Schaller and Brown, 2007a) or cryo-volcanism processes (Jewitt and Luu, 2004). These scenarios also explain the presence of large amounts of very volatile species, such as nitrogen or methane, on the surface of the three biggest objects (Pluto, Eris, 2005FY9 or Makemake). Contrary to the big objects, small bodies would be dominated by space weathering (Strazzulla et al., 2003; Brunetto et al., 2006) which explains why the small TNOs are usually the darkest ones (Lykawka and Mukai, 2005; Stansberry et al., 2008). However, cometary like activity, non-disruptive collisions, or disruptive ones, could renew the surface of any object, small or big, with fresh material (see Gil-Hutton (2002) for instance). It seems to be the case, for instance, for the crystalline water ice rich objects of the Haumea family (Brown et al., 2007; Pinilla-Alonso et al., 2007; Barkume et al., 2008). Therefore, it seems that collisional history and size give stronger constraints on the surface evolution of these bodies than the objects' dynamics (no clear trends have been obtained yet from photometry, Doressoundiram et al., 2008). For example, Gil-Hutton et al. (2009) find that the presence of crystalline and amorphous water ice on the surface of the Haumea family members could perhaps be explained as a balance between irradiation and collisions. Observation of small icy bodies and recurrent spectral analyses are required to better constrain these scenarios and better investigate the surface properties of TNOs and Centaurs.

In this paper, the spectra of six objects are presented as well as the results of spectral models (obtained with the models of Hapke (1981, 1993), Shkuratov et al. (1999)). These six objects are representative of most TNOs observed until now, they are relatively dark, have different spectral slopes in the visible, and have diameters between 300 and 850 km (except Echeclus that is smaller, as the other Centaurs, see Table 1 for details on the physical properties). The use of the complete spectrum from 0.4 to 2.35 μm and of the albedo determined in the V band by Stansberry et al. (2008) is very helpful to minimize the errors on the models' free parameters, which are the particle sizes and the relative amounts of the chemical compounds. In fact, the albedo and the absorption features depend on the quantity and the particle size of bright and dark compounds, respectively. The goal of this work is to better constrain the chemical composition, especially the icy species as water ice.

Table 1
Physical properties of the six studied objects. Dynamical class comes from Gladman et al. (2008) whereas visual albedo and diameter come from Stansberry et al. (2008).

Name	Dynamical class	Albedo	Diameter (km)
2003 AZ_{84}	Resonant	$0.123^{+4.31}_{-2.91}$	$585.8^{-95.5}_{+98.8}$
Echeclus	Centaur	$0.038^{+1.89}_{-1.08}$	$83.6^{-15.2}_{+15.0}$
Ixion	Resonant	$0.156^{+12.0}_{-5.53}$	$573.1^{-141.9}_{+139.7}$
55565 (2002 AW_{197})	Classic	$0.118^{+4.42}_{-3.00}$	$734.6^{-108.3}_{+116.4}$
26375 (1999 DE_9)	Resonant	$0.069^{+1.58}_{-1.19}$	$461^{-45.3}_{+46.1}$
120132 (2003 FY_{128})	Scattered	$0.07^{*+0.}_{-0.}$	$307^{-0.0}_{0.0}$

*Arbitrary value.

2. Observations and data reduction

In this paper, we analyze the spectra of six objects observed in the framework of a ESO Large Program (P.I.: M.A. Barucci). The spectroscopic and photometric data were obtained from almost simultaneous visible and near-infrared observations carried out at UT1, UT2 and UT4 VLT–ESO telescopes (Cerro Paranal, Chile). The visible spectroscopic data were obtained using FORS1 and were already presented in Alvarez-Candal et al. (2008). The near-infrared H and K spectroscopy was obtained with SINFONI and the results are presented in Guilbert et al. (2009). The V, J, H and K photometry, used to calibrate and align the different spectroscopic ranges, is reported and discussed in DeMeo et al. (2009). The near-infrared spectroscopy in J, presented in this paper, was carried out using the ISAAC instrument in its SW mode (1.1–1.4 μm spectral range and equipped with a Rockwell Hawaii 1024 × 1024 pixel Hg:Cd:Te array). The spectral resolution is about 500 with a 1″ slit. The observations (see Table 1) were done by nodding the object along the slit by 10″ between two positions A and B. The A and B images were combined using the ESO software packages Eclipse and MIDAS following the procedure described by Barucci et al. (2000). Several solar analogs were observed during each night at similar airmasses as the objects, and the TNOs reflectivity was obtained by dividing their spectra by that of the solar analog star closest in time and airmass, as reported in Table 2. Each spectrum has been smoothed with a median filter technique (see Merlin et al., 2009) to increase the S/N ratio. The final spectral resolution is 250. The obtained J spectra together with V and H + K spectra, calibrated with the simultaneous photometry, are reported in Fig. 1.

These six complete spectra from 0.4 to 2.3 μm have a spectral resolution between 250 and 1500 (spectral resolution is oversampled in the V band). In order to increase the signal-to-noise level, we reduced the spectral resolution to 250. This spectral resolution is accurate enough to detect the broad absorption bands we are looking for (water ice, methane ice, methanol ice, etc. see, de Bergh et al. (2008) for a review of probable chemical compounds) and get some information on their physical states (for instance, water ice in amorphous or crystalline phase). Fig. 1 shows the results of our "degraded resolution" spectra for all the objects. The signal-to-noise level is improved by a factor 3–10, depending on the wavelength range. Alvarez-Candal et al. (2008) reported the absorption features detected in the visible range, whereas Guilbert et al. (2009) discuss about those observed in the H and K bands. The main absorption features are detected in the near infrared, close to 1.5 and 2.0 μm, which indicates the presence of water ice. Except for 2003 AZ_{84}, the visible spectra appear featureless and show similar mean red slopes (around 20 ± 5%/100 nm, see Alvarez-Candal et al., 2008). With the available 0.4–2.3 μm range spectra, we aim to constrain the surface composition using different models to compare our data with the existing ones, and to derive new information on these objects that have different dynamic properties. Usually, the signal-to-noise level is good in the V band, relatively good in the H band and is lower in the K and J bands, especially in the cases of 1999 DE_9, Echeclus and 2003 FY_{128}.

3. Spectral analyses tools

3.1. The models

In order to investigate the surface properties of these objects, we use the spectral models developed by Hapke (1981, 1993)