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Beyond Neptune, the new frontier of the Solar System

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Abstract. Trans–Neptunian Objects (TNOs) and Centaurs are thought to be the least thermally processed bodies in the Solar System. The study of their physical and dynamical properties represents an unique opportunity to analyse primordial material and to investigate the processes which governed planetary formation. An ESO Large Programme was carried out at VLT and NTT in order to improve our knowledge on the physical characteristics and the surface composition of these objects. A summary of the obtained results is here presented and discussed.

Key words. TNOs – EKB – Centaurs – vis. nir spectroscopy – surface composition

1. Introduction

The first astronomer who hypotised the presence of planetary material beyond the orbit of Neptune was Edgeworth (1943). He argued that comet–like debris from the formation of the Solar System could orbit beyond Neptune, since a lack of such a continuum of particles would imply an "edge" on the protoplanetary nebula. This idea was then reconsidered by Edgeworth himself (Edgeworth 1949) and by Kuiper (1951). Only 40 years after, the advent of new technologies allowed the discovery of the first Trans-Neptunian Object (TNO), called 1992 QB1 (Jewitt & Luu 1993).
In the last decade the number of known TNOs is widely increased. So far we know more than 760 TNOs. The whole population is expected to count more than 38000 bodies larger than 100 km in diameter (Trujillo et al. 2001). The region where these objects orbit around the Sun is called Edgeworth-Kuiper Belt (EKB).
On the basis of the present knowledge of their dynamical characteristics, TNOs have been grouped into three different dynamical classes: 1) classical objects (also called Cubewanos from 1992 QB1) with low eccentric orbits and semi–major axes typically between about 35 and 47 AU; 2) resonants objects, also called Plutinos, with Pluto–like orbits located in the 3:2 mean motion resonance with Neptune; 3) scattered objects, at very large heliocentric distances and high inclinations.
A population which is supposed to be

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strictly linked to TNOs is that of Centaurs, located between Jupiter and Neptune. The orbits of Centaurs cross those of outer giant planets and are unstable, with dynamical lifetime of $10^6 - 10^7$ years (Asher & Steel 1993; Hahn & Bailey 1990). So far we know 45 Centaurs but the whole population has been estimated to include more than 10^7 bodies with diameter larger than 1 km (Sheppard et al. 2000). Since Centaurs are widely believed to come from the EKB and to have been scattered in the present orbits by gravitational instabilities or mutual collisions, they might constitute a transition population from TNOs to short-period comets.
Due to their distance from the Sun, TNOs and Centaurs did not suffered strong thermal processes. Consequently, their study represents an unique opportunity to analyse almost unprocessed material, coming from the frontiers of the Solar System, and to investigate the composition of the protoplanetary nebula at these solar distances.

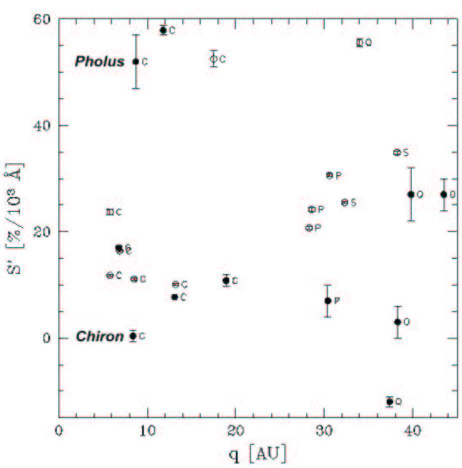

Fig. 1. Visible spectral slopes of Centaurs (C), Cubewanos (Q), Plutinos (P), and Scattered objects (S) vs. the perihelion distances (from Lazzarin et al. 2003).

2. Surface composition

Visible and near–infrared spectroscopy is the most important tool to investigate the surface composition of atmosphereless bodies. Due to the intrinsic faintness of TNOs and Centaurs, their photometric and spectroscopic observation is a very difficult task and large telescopes are necessary.
In April 2001 we started an ESO Large Programme at VLT and NTT aimed at the physical properties and the surface composition of Centaurs and TNOs. Considering the results obtained in the framework of our ESO Large Programme and the few others in the literature we can rely on visible spectra of 23 objects, among Centaurs and TNOs, and complete spectra between 0.4 and 2.5 micron of 9 Centaurs and 10 TNOs.

2.1. Visible spectra

Fig.1 shows the visible spectral slopes (S') of Centaurs (C), Cubewanos (Q), Scattered objects (S) and Plutinos (P) as a function of the perihelion distances (from Lazzarin et al. 2003). The most evident characteristic is the huge variety of S' values: TNO and Centaur populations include objects with both flat and very red visible spectra.
For TNOs some correlations have been suggested among visible spectral slopes, orbital inclinations and solar distances (e.g. Boehnhardt et al. 2002), but they still need to be confirmed. The huge spectral diversity can be explained in terms of balance between ageing (space weathering) and rejuvenating (collisions) processes. In fact, laboratory experiments simulating the so-called “space weathering” on initially ice-rich surfaces, showed that a darkening of the surface and a reddening of the spectral slope can be due to the action of solar wind and microimpacts. The bombardment by high-energy radiation of mixtures of rocks and water and hydrocarbon ices produces an irradiation mantle which is hydrogen–poor, carbon rich, and dark (Strazzulla 1997; Strazzulla 1998), and is characterised by a red spectrum. Subsequent collisions,

revealing "fresh" material excavated from layers below the surface, or re-condensation of gas and dust after temporary cometary–like activity, or further exposition to space weathering processes, can flatten again the spectra. The presently observed distribution of the visible slopes of TNOs should be the result of all these mechanisms.

Conversely, the available data sample of visible spectra of Centaurs suggests the presence of two distinct groups: one redder (Pholus-like) and one with neutral colors, more similar to Chiron (Luu et al. 2000; Doressoundiram et al. 2001). In this scenario objects recently injected from the Edgeworth-Kuiper belt should have an older surface covered by a red irradiation mantle (like Pholus), while the objects belonging to the group of Chiron should have younger surfaces rejuvenated by collisions and/or cometary-like activity. To confirm such a dichotomy more observational data are needed.

2.2. Near infrared spectra and modeling

Fig.2 shows the available visible and near–infrared spectra of Centaurs and a sample of the spectra obtained for TNOs in the framework of our ESO Large Programme (by Bauer et al. 2002; Barucci et al. 2002; Cruikshank et al. 1998; de Bergh et al. 2003; Doressoundiram et al. 2003; Dotto et al. 2003a; Dotto et al. 2003b; Luu et al. 2000; Romon–Martin et al. 2002).

Several attempts have been performed so far to interpret the obtained spectra by modeling the surface composition of Centaurs and TNOs with appropriate mixtures of minerals and ices. As an example, the red slopes of many of these visible spectra are modeled with the presence on the surface of tholins or kerogens. Low albedo can be due to a consistent percentage of amorphous carbon, while spectral features at 1.5 and 2 micron are related to the presence of water ice. The feature observed at about 2.3 micron on the spectrum of Pholus has been interpreted as possibly due to the presence on the surface of this Centaur of methanol ice (Cruikshank et al. 1998). The continuous solid lines superimposed to the spectra in Fig.2 are the compositional models so far suggested for each object.

3. Conclusion

On the basis of the available data sample, we can summarize our knowledge of the visible and near-infrared spectral features of TNOs and Centaurs, as follows:

- A huge diversity is evident among the spectral characteristics at visible wavelengths: TNO and Centaur populations include both objects with flat and very red visible spectra. For Centaurs this could be related to the presence of two different population: one composed by Pholus–like objects, and the other one composed by Chiron–like bodies. Conversely, TNOs show a continuous trend of variation of visible spectral slopes, probably due to the balance of ageing and rejuvenating processes which altered their surfaces.
- Water ice, even in small percentages, has been detected on the surface of 7 Centaurs and 6 TNOs. The spectra of the other objects do not show the presence of water ice. This might represent a paradox, since TNOs and Centaurs have accreted at large heliocentric distances and must to contain water and/or hydrocarbon ices. Laboratory experiments are currently in progress to investigate the processes which may alter water ice on the surface of these bodies and/or make undetectable its spectral features.
- Chariklo, Asbolus, and 2001 PT13 show different spectra during different observational runs. This has been interpreted as an indication of compositional heterogeneity of their surfaces.
- Chiron shows temporary cometary-like activity, combined with flat and featureless spectra. Data acquired during periods of high activity do not show spectral features at 1.5 and 2 micron, typical of water ice, while spectra obtained when the object was not active reveal water ice features.

The study of physical properties and surface composition of TNOs and Centaurs

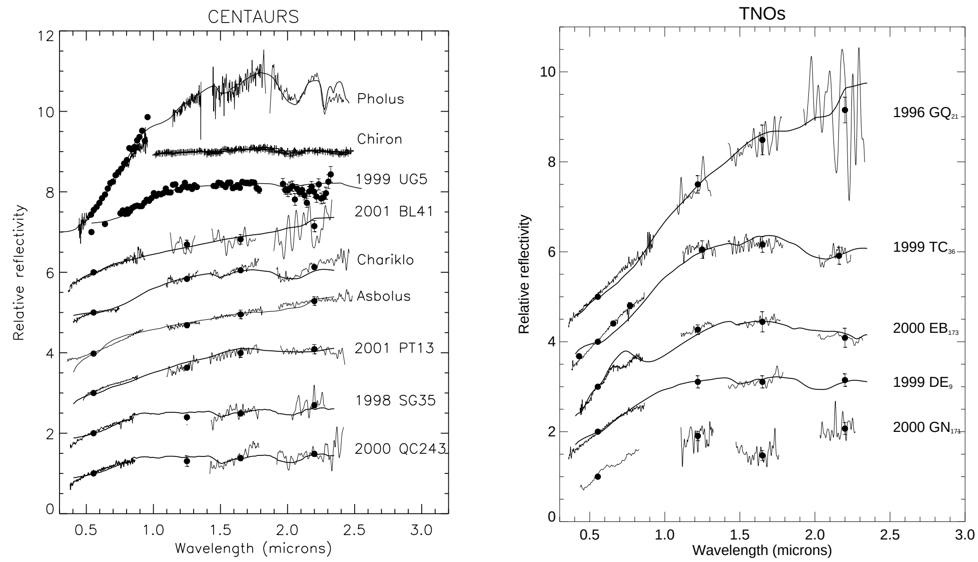

Fig. 2. Visible and near–infrared spectra of Centaurs (left panel) and TNOs (right panel). Spectra are normalised at 0.55 micron, except the spectrum of Chiron wich is normalised at 1.25 micron. Spectra are shifted by one unit for clarity.

is still at the beginning, and several questions are still without answer. Further observations and laboratory experiments are needed to investigate the origin and evolution of these populations and to understand their possible link with all the other small bodies in the outer Solar System (e.g. the system Pluto-Charon and the population of short period comets).

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