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# Small Bodies of the Outer Solar System

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**Abstract.** The population of small bodies of the outer Solar System includes objects of different nature: Jupiter Trojans, Centaurs, trans-Neptunian objects, cometary nuclei and satellites of the giant planets. The analysis of these bodies can give us important hints on the composition of the primordial solar nebula at large heliocentric distances, and on the processes which governed the early phases of the planetary formation and the subsequent evolution.
In the last decade a wide programme has been devoted to the study of these small bodies, in order to investigate their surface composition and their thermal and dynamical history. The availability of the new generation large telescopes allowed us to increase our knowledge on the physical properties of these bodies and to investigate analogies and differences among them.

**Key words.** Jupiter Trojans – Centaurs – TNOs – EKB – Cometary Nuclei

## 1. Introduction

The presently known population of small bodies of the outer Solar System includes about 1700 Jupiter Trojans, 60 Centaurs, 900 Trans-Neptunian Objects (TNOs), the small satellites of the giant planets, and a wide number of cometary nuclei. The origin of these bodies is still matter of debate: some of them seem to be pristine and still observable where they formed, while several objects are believed to have moved from the region of accretion and to have suffered a different dynamical evolution. The Edgeworth-Kuiper Belt (EKB), located beyond the orbit of Neptune, is believed to contain remnant material from the formation of the outer planets. In this region, icy planetesimals have formed and grown to larger bodies as TNOs. It has been suggested that the irregular satellites of the giant planets, located on high-inclination eccentric orbits far away from their central planet, could be captured EKB objects. Also Centaurs, orbiting around the Sun between Jupiter and Neptune on unstable planet-crossing orbits, are generally believed to come from the EKB. The most part of Centaurs has been probably injected in the present orbits by gravitational processes and/or collisional events, while some of them could come from the Oort cloud. Jupiter Trojans, located in the jovian Lagrangian points $L_4$ and $L_5$, are believed to be formed through an early trapping of planetesimals during the formation of Jupiter, or through local formation and/or capture of fragments of Jovian satel-

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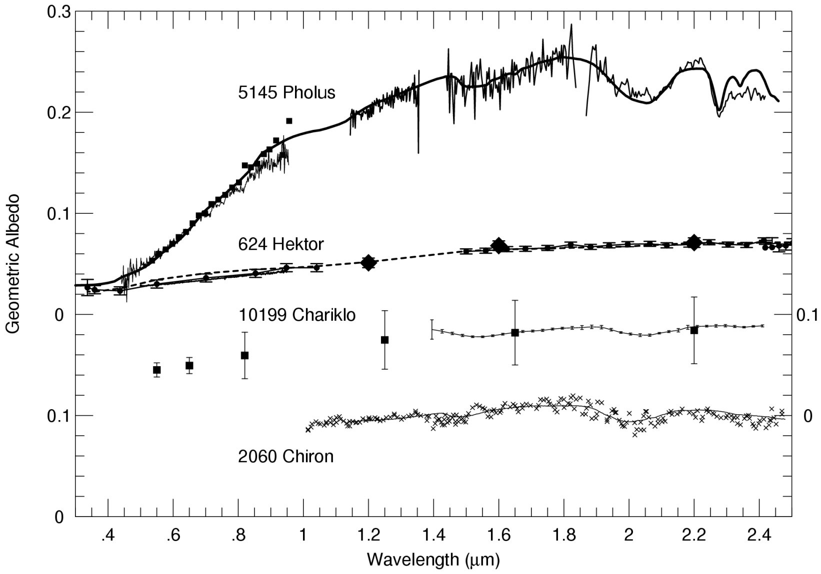


**Fig. 1.** Reflectance spectra, scaled to geometric albedo, of three Centaurs and Trojan asteroid 624 Hektor (from Barucci et al. 2003).

lites and short–period comets (SPC) (Marzari et al. 2003a; 2003b). It has been suggested that Centaurs might be trapped as Trojans during their migration following the escape from the EKB. Conversely, SPC might in part be supplied by Trojans. Recent observations by Jewitt et al. (2000) estimated up to about 10% the possible fraction of Trojans among SPC.

## 2. Physical Properties

The investigation of the physical properties of the small bodies in the outer Solar System is an important step to constrain the composition of the primordial nebula at large solar distances and the mechanisms which governed the planetary formation and the subsequent thermal history. The most exploited technique to investigate the nature of atmosphereless bodies is the analysis of their spectral characteristics. In particular visible and near-IR wavelength ranges are the most diagnostic spectral intervals, since they contain signatures of mineralogical compounds (like olivines, pyroxenes, feldspar, and phyllosilicates) and the most important features of organic compounds and hydrocarbon ices. Asteroids in the outer part of the main belt or sharing Jupiter's orbit (the jovian Trojans) have generally low albedo and featureless spectra, and are classified as P- and D-type. Many of them have quite red surfaces but never as red as the reddest TNOs or Centaurs. As an example Fig. 1 reports the spectra of three Centaurs (Pholus, Chariklo and Chiron) and the Trojan asteroid Hektor, classified as D-type asteroid. Based on their spectral shapes, the reddest P- and D-type asteroids are generally assumed to contain organic compounds on their surface, by analogy with material found in carbonaceous chondrites. The comparison between the spectral behaviour of Jupiter Trojans and nuclei of SPC reveals that these two different populations might have a quite similar surface composition (Barucci et al. 2003; Fornasier et al. 2004a; Dotto et al. 2004). The early temperatures in the region of the protoplanetary nebula where these objects

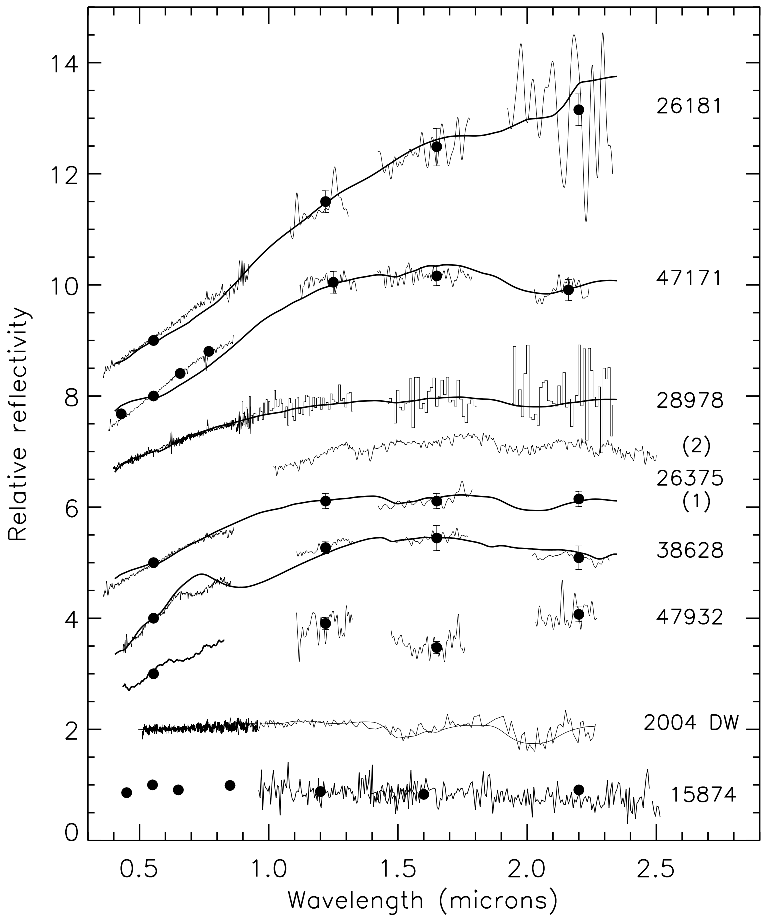


**Fig. 2.** Spectra of TNOs up to 2.5 $\mu$m, normalised at 0.55 $\mu$m and shifted.

formed, were probably low enough to allow water ice condensation during the formation of both Trojans and comets. As a consequence, Trojans might have water ice in their interiors similar to cometary nuclei.

The spectra of Centaurs and TNOs, on the contrary, show a huge variety of characteristics. In Fig. 2 all the visible and near-IR spectra of TNOs at present available in literature are reported (Dotto et al. 2003a and references therein), including the largest TNO so far known 2004 DW (Fornasier et al. 2004b). Several objects show signatures diagnostic of water and hydrocarbon ices, and/or minerals that can be present on their surfaces, while some others show almost flat and featureless spectra. This is surprising, though that Centaurs and TNOs formed at large solar distances, beyond the snow line, and must be composed by water and/or hydrocarbon ices. Although the majority of TNOs and Centaurs seem to have homogeneous surface compositions, some of them show spectral differences in observations carried out at different dates and at different viewing geometry, and consequently are candidates to have heterogeneous surface compositions (Dotto et al. 2003a). No correlations have been found among the ob-

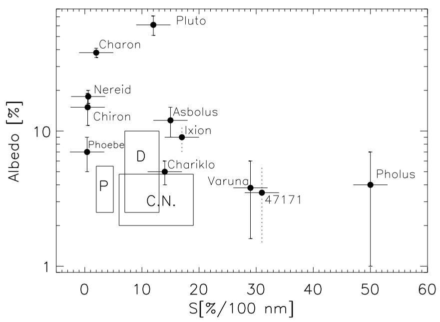


**Fig. 3.** Albedo vs. spectral slope of Centaurs, TNOs, P- and D-type asteroids, cometary nuclei (CN) and satellites Phoebe and Nereid (from Dotto et al. 2003a).

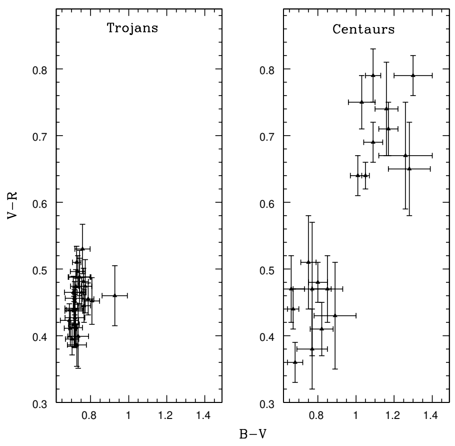


**Fig. 4.** Plot of V-R versus B-V colours for Trojans and Centaurs (from Fornasier et al. 2004a).

ject dimensions, spectral characteristics and dynamical properties.

Fig. 3 reports, as a function of the visible spectral slope, the albedos so far known for P- and D-type asteroids, cometary nuclei, two satellites of giant planets (Phoebe and Nereid), Centaurs, and TNOs, including the Pluto-Charon system. The most evident characteristic is that cometary nuclei, and P- and D-type asteroids are clustered around low albedo values, while the positions of Centaurs and TNOs, even including the system Pluto-Charon, are spread-out. For TNOs, Centaurs and irregular satellites at each value of the visible spectral slope can correspond several values of albedo, implying the relation between albedo and "colours" is not linear. This seems to be due to different processes which alternatively age and rejuvenate the surfaces of atmosphereless bodies. In the outer solar system, surface materials of small bodies are exposed to a flux of energetic ions throughout their evolution. When ices are irradiated by ions, chemical modifications are induced including formation of more and less volatile species. If ices contain simple hydrocarbons, irradiation often forms a complex, refractory dark residue having a red-sloped spectrum (Strazzulla 1998). The spectral slope can become neutral again due to collisions revealing material coming from subsurface layers (Luu & Jewitt 1996), or re-condensation of gas and dust after temporary cometary activity (Luu et al. 2000), or long-term irradiation (Moroz et al. 2004). These mechanisms are believed to be able to produce the variety in colours and albedos today observable among TNOs.

Fig. 4 (right panel) shows the color–color plot of Centaurs. It is evident a dichotomy between red (Pholus-like) and neutral (Chiron-like) objects (Dotto et al. 2003b; Peixinho et al. 2003). This might be associated with either an intrinsic heterogeneous composition or with a different degree of surface alteration. In this last scenario, spectrally red Centaurs would have been recently injected from the EKB and should have older surfaces, while the objects belonging to the Chiron group might have surfaces rejuvenated by collisions and/or cometary–like activity. As shown in Fig. 4, the spectral slopes of Trojans are very similar to those of the less red Centaurs. The lack of red objects in the Trojan population compared to Centaurs and TNOs might reflect either an intrinsic different planetesimal composition with increasing heliocentric distances, or a diverse degree of surface alteration and/or a different collisional history. Collisions, which are supposed to have played an important role in shaping the present Trojan swarms, might have destroyed ultra–red material. In any case, further observations, laboratory experiments, and dynamical studies are needed to investigate the effects of collisions, dynamical capture and space weathering processes on the evolution of all these objects.

## 3. Conclusions

The available sample of data on small bodies in the outer Solar System is rather limited, but the most evident property is the huge variety of the detected physical and dynamical characteristics. All the Trojan asteroids have similar spectral slopes, comparable to those of SPC nuclei and less red Centaurs. The populations of Centaurs and TNOs include objects with very red and neutral spectra. Some of them have featureless spectra, while some others show several spectral features diagnostic of minerals and/or ices. The population of irregular satellites of giant planets is still poorly known. A huge improvement to our knowledge of these bodies will be done by the Cassini mission that in these days is starting its tour around Saturn and its moons.
Ground–based and space observations are strongly needed to better define the physical and mineralogical characteristics of all these populations of bodies. In particular, mid- and far- infrared observations are fundamental to know the albedo and the surface composition of these objects and to have more information about their nature and history.

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