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New frontiers in the Solar System: trans-Neptunian objects/Les nouvelles frontières du système solaire : les objets transneptuniens

Surface composition of TNOs and Centaurs: visible and near-infrared spectroscopy

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Abstract

Visible and near-infrared spectroscopy is the most effective technique to investigate the surface composition of atmosphereless bodies. However, the intrinsic faintness of Trans-Neptunian Objects (TNOs) and Centaurs imposes strong observational limits, and the sample of available information on these objects is still rather limited. Visible and near-infrared spectra, as well as models of the surface compositions, are today available only for about fifteen objects among TNOs and Centaurs. The most evident property is the huge variety of spectral features, physical characteristics, and compositions. This poses still unanswered questions about the origin and the early evolution of these small bodies. ***To cite this article: E. Dotto et al., C. R. Physique 4 (2003).***

Résumé

Composition de surface des Objets Transneptuniens et des Centaures : spectroscopie visible et infrarouge proche. La spectroscopie dans les domaines du visible et de l'infrarouge proche est la méthode la plus couramment utilisée pour explorer la composition de surface de corps sans atmosphère. Cependant, la faible luminosité intrinsèque des Objets Transneptuniens (OTN) et des Centaures induit de fortes contraintes observationnelles, et l'échantillon d'informations disponibles sur ces objets est encore très restreint. Des spectres dans le visible et dans l'infrarouge proche, aussi bien que des modèles de composition de surface, n'existent aujourd'hui que pour environ 15 objets parmi les Objets Transneptuniens et les Centaures. La propriété la plus évidente est la grande diversité de caractéristiques spectrales, physiques et compositionnelles. Ceci pose des questions non encore résolues sur l'origine et les premiers stades de l'évolution de ces petits corps. ***Pour citer cet article : E. Dotto et al., C. R. Physique 4 (2003).***

Keywords: TNO; Centaurs; Visible spectroscopy; Near-infrared spectroscopy

Mots-clés : OTN ; Centaures ; Spectroscopie visible ; Spectroscopie infrarouge proche

1. Introduction

The presently known population of small bodies in the outer Solar System includes about 50 Centaurs and more than 810 Trans-Neptunian Objects (TNOs). The origin of Centaurs is still uncertain. They are generally believed to come from the

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Edgeworth-Kuiper Belt (EKB) and to have been injected into their present orbits by gravitational processes and/or collisional events [1]. However, some Centaurs could come from the Oort cloud [2].

The available data sample of the spectroscopic characteristics of TNOs and Centaurs is so far very limited. Visible spectra are available for 24 objects, while near-infrared spectra up to 2.5 µm have been published only for nine Centaurs and for 12 TNOs. For some of these bodies we have also models of their surface composition. The reason for this lack of information is primarily the intrinsic faintness of these objects which makes observations very difficult and often close to the limit of even very large telescopes. Consequently, discovery and detection of Centaurs and TNOs are very difficult tasks, and physical observations at a good signal-to-noise ratio can be obtained only for the brightest objects, through careful observational and data processing techniques, and sophisticated calibration procedures.

2. Visible and near-infrared spectroscopy: observations and reduction requirements

Spectroscopy covering the wavelength range between 0.4 and 2.5 µm, is an important tool to investigate the surface composition of atmosphereless bodies. Visible and near-infrared reflectance spectroscopy provides the most sensitive technique to investigate minerals and ices present on the surfaces of TNOs and Centaurs. Since these objects formed at large heliocentric distances and low temperature, ices are likely to be the major components of their surfaces. The visible and near-infrared wavelength regions encompass diagnostic spectral features of silicate minerals, like pyroxene, olivine, and sometimes feldspar, carbonaceous assemblages, organics and water-bearing minerals, such as phyllosilicates. At near-infrared wavelengths there are also signatures from NH_3 ice (at 2 and 2.25 µm), water ice (1.5, 1.65, 2.0 µm), hydrocarbon ices (e.g., CH_4 at about 1.7 and 2.3 µm) or CH_3OH at 2.27 µm, and from solid C–N bearing material (at about 2.2 µm). Weakly active comets, Centaurs and potentially TNOs can show fluorescent gaseous emission bands. In addition, the slope of the continuum in the visible wavelengths (0.3–1.0 µm) can give constraints on the composition, particularly for the especially 'red' objects, whose reflectance increases rapidly with wavelength in this region.

The reduction of spectroscopic data follows the standard procedure: bias and flatfield corrections, cosmic ray removal, wavelength calibration, response and flux calibration through standard stars, alignment and co-addition of the jittered spectra (in the infrared). The critical steps concern a potential systematic error due to faint field star contamination which can affect the data reduction of these very faint bodies, the dominant sky background in the infrared and the choice of solar analogs. In order to remove the contribution from the Sun, the spectrum of the target is divided by the spectrum of a solar analog obtained at the same airmass as the object. Such solar analogs have been studied by [3]. The problem is that those stars are too bright for the large aperture telescopes ($V \leqslant 6$) and pose obvious problems of saturation. Alternatively, observers use synthetic analog, C-type asteroids or even A0 type stars, but without completely satisfactory results, or sometimes a personal or privately circulated list of good solar analogs.

The faintness of the objects limits the spectroscopic observations. In fact, even with the larger telescopes of the 8 to 10 meter class, only objects up to magnitude $V = 22$–23 are observable over visible wavelengths and <21 Vmag for near-infrared spectroscopy. Long exposure observations are not very optimal because the rotation rates of TNOs and Centaurs are typically a few hours and the resulting spectra represent the signal from different rotational phases of an object.

3. Spectral characteristics, physical properties and surface alteration

Fig. 1 shows spectra up to $\sim$2.5 µm of several Centaurs and TNOs, with models when available. Looking at the near-infrared spectra we have a wide variety of characteristics. Several objects show almost flat and featureless near-infrared spectra, while some others show signatures diagnostic of water and hydrocarbon ices, and/or minerals that can be present on their surfaces. The visible spectra of TNOs and Centaurs are in general featureless, and their gradients vary widely. For TNOs, the slopes in the visible range are distributed as a continuum. This has been interpreted as being due to the balance of different ageing and rejuvenating processes which alter their surfaces. Laboratory experiments simulating the so-called 'space weathering' on initially ice-rich bodies show 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 on mixtures of rocks and ices produces an irradiation mantle which is hydrogen-poor, carbon rich, and dark [4,5], and is characterised by a red spectrum. Subsequent collisions, revealing 'fresh' material excavated from layers below the surface [6], or re-condensation of gas and dust after temporary cometary-like activity [7], or further exposure to space weathering processes [8], can then again flatten the spectra. The presently observed distribution of the visible slopes of TNOs could 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 [7,9]. The objects belonging to the group of Pholus should have been recently injected into the planetary region from the EKB and should have an old surface covered by a red irradiation

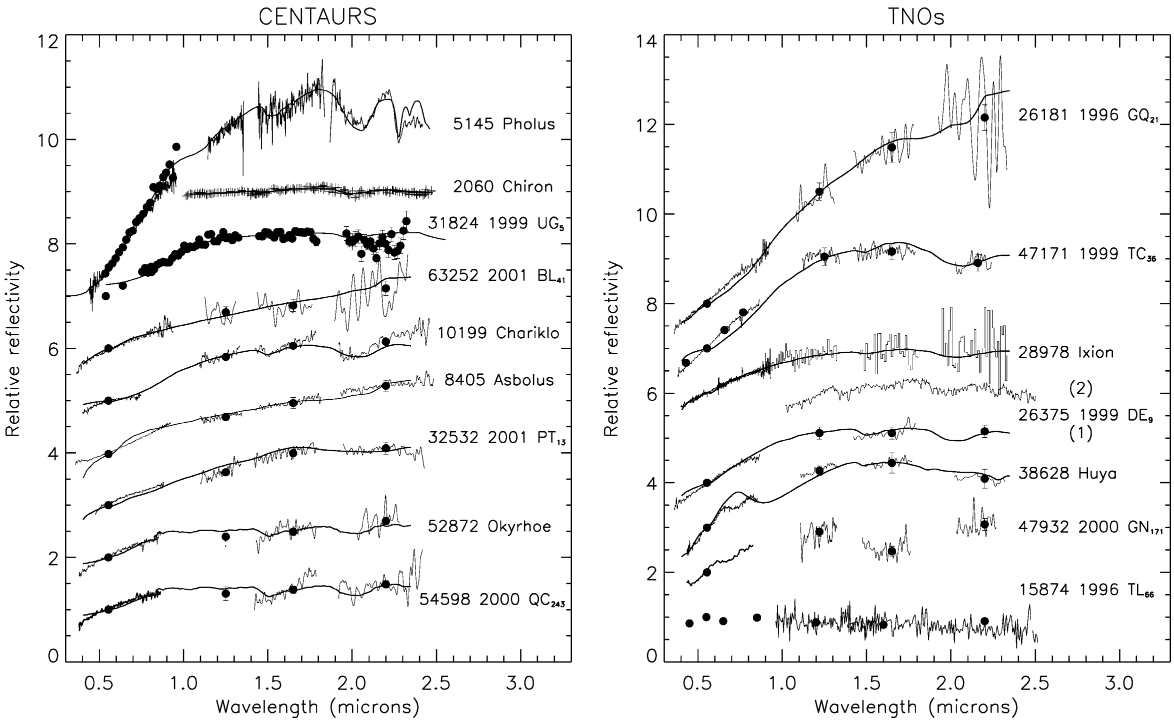

Fig. 1. Spectra up to 2.5 µm of Centaurs and TNOs. The continuous lines superimposed on the spectra are the models of the surface composition suggested for each object. The spectra are normalised at 0.55 µm, except the spectrum of (2060) Chiron normalised at 1.25 µm and the spectrum (2) of (26 375) 1999 DE_9 which is normalised at 2.22 µm. Spectra are shifted by one unit for clarity.

mantle. 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.

3.1. Surface composition

Several attempts have been performed to interpret the obtained spectra of TNOs and Centaurs by modelling their surface composition with appropriate intimate or geographical mixtures of minerals and ices (Fig. 1). As an example, the red slopes of many of these visible spectra are reproduced supposing the presence on the surface of organic compounds (e.g., tholins or kerogen). Low albedo objects can be modelled with a high percentage of amorphous carbon.

The stony ingredient of TNOs is most likely silicates. Although their detection is difficult, since they may be covered by ice and/or organic material, the presence of olivine has been suggested on the surface of several objects ((5145) Pholus, (2060) Chiron, (52 872) 1998 SG_{35}, (54 598) 2000 QC_{243}).

No correlations have been found between the infrared spectral characteristics, the behaviours of the visible part of the spectrum, and the orbital parameters. Two scattered objects, (15 874) 1996 TL_{66} [10] and (26 181) 1996 GQ_{21} [11], have completely different spectral behaviours. Moreover, 1996 TS_{66} and (19 308) 1996 TO_{66}, both classified as classical objects, have different near-infrared spectra: the spectrum of 1996 TS_{66} is flat and featureless [12], while that of (19 308) 1996 TO_{66} shows evidence of the presence of water ice [13]. The two Plutinos (47 171) 1999 TC_{36} [14] and 38 628 Huya (also known as 2000 EB_{173}) [15], despite their comparable dynamical characteristics, have different visible and near-infrared spectra which have been modelled with different mixtures of minerals and ices. The feature at about 2.3 µm, probably due to the presence of methanol ice, has been detected only on the spectrum of (5145) Pholus [16] but may be present in the spectrum of (15 789) 1993 SC [17]. Absorption bands of methane ice are suspected in the spectrum of the classical TNO (50 000) Quaoar [18].

Spectral features indicating some percentage of water ice have been detected for seven Centaurs and seven TNOs. Other objects belonging to these populations do not show the presence of water ice. This is surprising, in that Centaurs and TNOs most likely accreted at large solar distances and likely contain water and/or hydrocarbon ices.

Several efforts have been devoted to model these spectra and to investigate the mechanisms which alter minerals and particles present on the surfaces of these bodies. As an example, the failure to detect water ice in the spectra of several Centaurs and

TNOs may be due to the presence of the already mentioned irradiation crust, or perhaps due to the presence of mixtures of ices and some darker materials which reduce spectral features.

Further laboratory experiments are in progress to model and investigate the mechanisms which alter water and/or hydrocarbon ices or inhibit the detection of their signatures.

The spectrum of (5145) Pholus, reported in Fig. 1, has been modeled using carbon black combined with an intimate mixture of Titan tholins, olivine, water ice and methanol ice, with an albedo at 0.55 µm of 0.06 [16]. The surface of (2060) Chiron is modeled with water ice and olivine [7]. The spectrum of (31 824) 1999 UG5, obtained on 22 September 2000 [19], is modeled with a mixture of amorphous water ice, amorphous carbon, Triton tholin, methanol ice and olivine. A second one obtained one day later shows different spectral behavior and has been modeled with a different mixture of minerals and ices. This is a significant point, since amorphous water ice has not been definitely identified anywhere in the Solar System. (63 252) 2001 BL41 [11], (26 181) 1996 GQ21 [11] and (8405) Asbolus [20] have been modeled with geographical mixtures of tholins, ice tholin, amorphous carbon. The spectrum of (10 199) Chariklo [21] is modeled with a geographical mixture of tholins, amorphous carbon and water ice. Those of (52 872) Okyrhoe (1998 SG35) and (54 598) 2000 QC243 are modeled with geographical mixtures of kerogen, olivine and water ice [14]. The spectra of (47 171) 1999 TC36 [14], and (32 532) 2001 PT13 [22] have been modeled with geographical mixtures of tholins, ice tholin, amorphous carbon and water ice. The water ice bands in the spectrum of (28 978) Ixion are somewhat uncertain [23]. (26 375) 1999 DE9 has been observed by [11] (spectrum (1) in Fig. 1) and by [12] (spectrum (2) in Fig. 1). The two spectra show slightly different spectral behaviors. In the spectrum (2) water ice bands, at about 1.5 and 2 µm have been weakly detected [12]. The spectrum (1) is incomplete and cannot confirm the presence of water ice [11]. The spectrum of (38 628) Huya (2000 EB173) is modeled by a mixture of tholins, amorphous carbon, water ice, and jarosite (a hydrous iron sulfate) [15]. The spectra of (15 874) 1996 TL66 [10] and (47 932) 2000 GN171 [15] are also shown in Fig. 1.

The computed models are not unique, since different mixtures of minerals and ices can match the observed spectra. Nevertheless they give an indication of the possible surface composition of these objects. An important commonality of the models is that they all use organic materials (tholins or kerogen) to achieve the red color exhibited by most Centaurs and TNOs, consistent with the results of [24] and [25]. Additional information on quantitative modeling of Centaurs and TNOs is found in [26].

3.2. Visible spectra: aqueous alteration features

Only two of the 24 TNOs and Centaurs for which visible region spectra were recorded show features in their spectra. Absorption features have been seen in spectra of (47 932) 2000 GN_{171} and (38 628) Huya recorded in 2001 [27]. In the visible spectrum of (47 932) 2000 GN_{171} there is one absorption feature centered at about 0.71 µm (depth ∼8%). In the case of (38 628) Huya, two weak features are present, one centered at about 0.59 µm (maximum depth of ∼7%), and another one, a little deeper (8.6%) centered around 0.74–0.75 µm. The same objects were re-observed in 2002 but these features were not detected [15]. This may call in to question the reality of the features, but on the other hand the material responsible for these absorptions may not cover the surface of the objects uniformly, assuming that different hemispheres of the bodies were observed in 2001 and 2002. It is important to repeat the observations to confirm the presence or absence of these features.

A possible explanation for these features is that they are due to hydrated minerals [15]. This is not the first time that the existence of hydrated silicates at the surface of TNOs has been suggested and discussed. Several authors [28,29] have been looking specifically for such compounds in TNOs for several years by means of visible spectroscopy and photometry, and [12] have tentatively attributed two weak features detected in the infrared spectrum of a TNO to hydrated silicates incorporating OH within their crystal structure. Hydrated silicates, which are common on Earth and on Mars, have been found in carbonaceous chondrites and at the surfaces of some dark asteroids, and may be present in comets. However, given the low temperatures in the EKB (∼40–50 K), it seems difficult to produce the liquid water required to hydrate the minerals (temperatures above 273 K are needed). A mechanism, called hydrocryogenic alteration, which operates at lower temperatures (between 200 and 273 K), could be invoked: the aqueous alteration occurs in a mixture of dust and ice in thin water layers at dust/ice interfaces [30]. This mechanism, which occurs on Earth in terrestrial permafrost has been considered for comets. Radiogenic heating and impacts (during accretion or collisions between TNOs) might have produced enough heating to make aqueous alteration possible.

Hydrated silicates have also been detected in interplanetary dust particles and micrometeorites. It has been proposed that the hydrated minerals in these materials, and, perhaps, comets were in fact formed in the solar nebula. The aqueous alteration could have occurred on grains when the nebula started to cool.

3.3. Heterogeneous surface composition

Several TNOs and Centaurs show different spectral characteristics when observed at different viewing geometry. For (10 199) Chariklo slight differences have been detected between the spectra obtained during two different observing sessions, separated by a year [21]. (8405) Asbolus showed small spectral variations over short time scales, with slight changes in the spectral slope from 0.8 and 1.0 µm [31]. Moreover the comparison of these spectra with that obtained by [32] gives an inconsistent indication of water ice on the surface of this object.

(31 824) 1999 UG_5 show differences in the spectra obtained by [19] during two nights (21 and 22 September 2000), although the 21 September data are of poor quality in the near-infrared.

Strong differences are evident in the spectra of (32 432) 2001 PT_{13} obtained during two different observing runs, carried out one month apart [22]. Spectral features typical of water ice are detectable in one spectrum and not in the other one. Unfortunately, the spectrum which shows these features was obtained in non-photometric conditions and it is not possible to calibrate the relative reflectance of the J, H, and K spectra. The presence of water ice on the surface of this object can be only suggested, and further observations are needed to confirm this hypothesis.

In the case of (15 789) 1993 SC the spectra obtained by [17] and [12], both of poor quality, are completely different: the first one shows features at 1.62, 1.79, 1.95, 2.2, and 2.32 µm, while none of these features appear in the second spectrum. The possible heterogeneity can be only confirmed by further observations.

For (19 308) 1996 TO_{66} a 'patchy' surface is suggested on the basis of the different intensity of the water ice bands found in two spectra recorded one day apart [13].

In some cases, such as (10 199) Chariklo, the detected surface differences are not too strong. In some others ((19 308) 1996 TO_{66} and (32 432) 2001 PT_{13}) the supposed heterogeneity is more evident and would imply a different surface composition and/or a different surface structure.

3.4. Relationship with short-period comets: the case of Chiron

Due to their dynamical properties, Centaurs are considered to be a transition population between TNOs and short-period comets, although the ranges of dimensions of the two populations are completely different. The typical sizes of comets are between 1 and 10 km, while the dimensions of the presently known Centaurs range between 20 and 150 km in radius. In this context, the most interesting object is Chiron, the first discovered Centaur and the only one to have shown cometary-like activity so far.

Chiron was discovered in 1978 and initially classified as an asteroid. Later on, a non-asteroidal brightening was reported by [33], and the presence of a resolved coma was discussed by [34] and [35]. The first spectra obtained when the object showed a coma and dust emission were featureless, flat and in some cases even displayed a negative spectral slope [36–38]. Further observations [7,39] carried out during a period of low cometary-like activity, showed spectral signatures at 1.5 and 2.0 µm that are usually attributed to water ice. More recently, [20] detected a new period of cometary activity, combined with flat and featureless spectra; no water ice spectral features were detected in these observations in 2001.

All this information seems to confirm, as suggested by [7], that the detection of water ice on the Chiron spectra is related to the cometary-like activity. Water ice features were detectable when Chiron was not active. Until 1996 and again in 2001, Chiron was active and spectrally featureless, probably due to the presence of dust on the surface.

4. Differences with Pluto and Charon

Pluto and its satellite Charon are dynamically indistinguishable from some TNOs that are known as 'Plutinos' in the 3 : 2 resonance with Neptune. However, the spectrum of Pluto is very different from those of the Plutinos observed so far. In the spectrum of Pluto we detect absorption bands due to nitrogen ice, methane ice and carbon monoxide ice, in addition to water ice [40,41]. Pluto being much brighter (larger size and higher albedo) than other TNOs allows the acquisition of spectra of much higher quality. Weakly absorbing compounds like nitrogen or carbon monoxide are easier to detect. However, the spectrum is dominated by the methane which, if present in comparable amounts on other Plutinos (or other TNOs), would have been easily identified. Weak methane ice absorptions have been detected in the spectrum of the brightest known TNO, (50 000) Quaoar [18]. A shift in the wavelength of the methane bands indicates that CH_4 occurs not as a pure ice, but in a matrix, perhaps of amorphous water ice. Why are there such differences between Pluto and the other TNOs? The larger size of Pluto compared to that of TNOs detected so far may be the main reason. Indeed, because of higher gravity, Pluto retains a sublimation atmosphere (which is in fact dominated by nitrogen) and recondensation can occur on the surface. Furthermore, due to the large obliquity and high orbital eccentricity of Pluto, an important migration of volatile material across the surface likely occurs on seasonal timescales. Thus the surface is very active, and an irradiation crust, if formed, is quickly 'refreshed'.

Charon has a spectrum much more similar to that of other TNOs. Water ice is seen in the spectrum of Charon but there most likely is a spectrally bland, dark contaminant. The presence of NH_3 ice on Charon has been reported by [42]. If correct, this is very important. Other observers have seen the same absorption bands. The albedo of Charon (about 0.38) is higher than that of the TNO Quaoar (about 0.12) which has about the same size. Differences may be due to the fact that Charon has been subjected

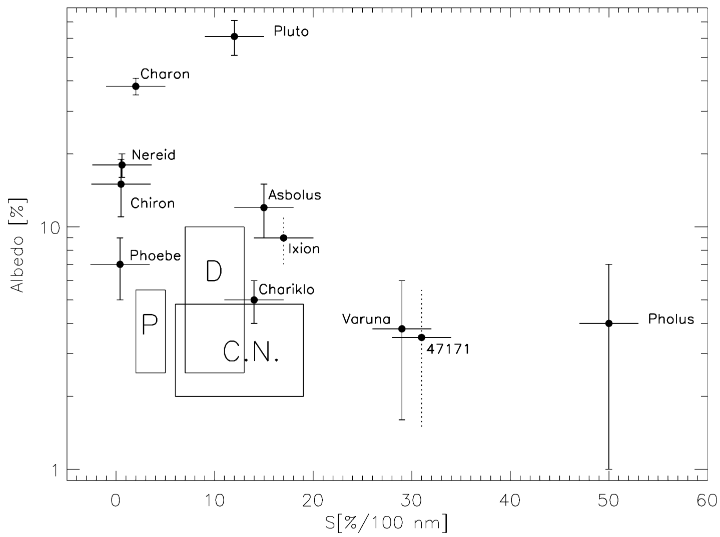

Fig. 2. Visible albedo values versus visible spectral slopes of Centaurs and TNOs, compared with P- and D-type asteroids, cometary nuclei (CN) and satellites Phoebe and Nereid. This figure is adapted from [47] with the few other data in the literature ([48] for the albedo of Pholus; [49] for the albedo of Varuna; [50] for the albedos of Pluto and Charon; [51] for the spectral slope of Charon; [52] for the spectral slope of Nereid; [45] for the albedo and the slope of Phoebe, and for the slope of Nereid; [53] for the albedos of Ixion and (47 171) 1999 TC36; [23] and [14] for the spectral slopes of Ixion and (47 171) 1999 TC_{36}, respectively).

to important tidal heating due to its formation (most probably the collision of Pluto with a very large body) and proximity to the larger Pluto.

5. Relationships with dark asteroids and satellites

To help us interpret the available data on TNOs, it is interesting to compare what we know about these objects with data on some other small bodies of the outer solar system that have dark and/or red surfaces and are more accessible to observations.

Asteroids in the outer part of the main belt or sharing Jupiter's orbit (the jovian Trojans) are essentially P-type and D-type asteroids. Their spectra are generally featureless. Many have quite red surfaces (but never as red as the reddest TNOs or Centaurs – see Fig. 2). Very few models have been made, except for the largest Trojan 624 Hektor (D-type) for which a model containing a mixture of Mg-rich pyroxene and elemental carbon provided a reasonable fit to its visible-near infrared spectrum extended to 3.6 microns [43]. However, based on their spectral shapes, the reddest D-type and P-type asteroids are generally assumed to contain kerogen-like material on their surface, by analogy with material found in carbonaceous chondrites, or lightly processed organics like tholins.

It has been suggested that some irregular satellites of the giant planets could be captured EKB objects. Irregular satellites are small bodies with high-inclination eccentric orbits located far away from their central planet. The best-studied ones are Phoebe, satellite of Saturn, and Nereid, satellite of Neptune. In the visible, Phoebe has a flat spectrum resembling that of C-type asteroids. However, in the near-infrared, weak water ice absorption bands are present [44,45], indicating that this body cannot have formed in the asteroid belt but originated instead in the outer solar system. Given the low albedo of Phoebe, the water ice must be mixed with some dark material. Amorphous carbon has been included in models. Nereid, which also has a nearly flat spectrum from 0.4 to 2.2 µm, has stronger water ice absorptions and is also much brighter [45,46]. It looks more like some regular satellites of Uranus that are covered with 'dirty' water ice which is believed to have been processed in part by energetic particles from the magnetosphere of the planet.

Fig. 2 is adapted from [47] and reports, as a function of the visible spectral slope, the albedos so far known for Centaurs, TNOs, including the Pluto-Charon system, compared with the albedo of some satellites, D-type and P-type asteroids, and cometary nuclei. The most evident characteristics are that cometary nuclei, and P- and D-type asteroids are clustered, while the positions of Centaurs and TNOs, even including the system Pluto-Charon, are spread-out in this plane: at each value of visible spectral slope can correspond several values of albedo, implying the relation between albedo and 'colours' is not linear. The main reason for this can be related to the mechanisms which have altered the surfaces of Centaurs and TNOs. The effect of space weathering processes depends on the material forming the surface. We know that starting from an ice-rich surface, ion bombardment and microimpacts produce a crust whose spectrum is redder and albedo is darker than the original surface. Conversely, [8] showed that space weathering processes can alter a low albedo and spectrally red surface, flattening the spectra without changing on the albedo value. These two mechanisms, combined with cometary-like activity, which resurface the objects and cover their surfaces with debris, are believed to be able to produce the variety in colours and albedos today observable among TNOs and Centaurs.

6. Conclusions

The available sample of visible and near-infrared spectra of Centaurs and TNOs is rather limited, but the most evident property is the huge variety of their spectral characteristics:

- both these populations include objects with very red and neutral spectra;
- some of the obtained spectra are featureless, while some others show several spectral features diagnostic of surface minerals and/or 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 may have heterogeneous surface compositions;
- evidence of some aqueous alteration processes has been detected in the spectra of two Plutinos. Further observations to confirm these detections and the possible heterogeinity of the surfaces of these objects are needed. The confirmation of aqueous alteration in the EKB would have implications for the history of the solar nebula and, more generally, the role of comets in bringing material to the Earth.

The presently available data sample on TNOs and Centaurs is still too limited to give much insight into the thermal and physical status and evolution of these populations.

The determinations of a larger number of rotational periods, as well as the improvement of the number and quality of available visible and near-infrared spectra, are the most important tasks for the immediate future. Such information will allow us to increase our knowledge of the physical properties of these bodies, to investigate in more detail their links with the other small body populations in the outer Solar System (e.g., small icy satellites and the Pluto-Charon system) and to obtain information about the early Solar System.

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