COLOURS AND COMPOSITION OF THE CENTAURS

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Abstract. Centaurs are widely believed to come from the Edgeworth-Kuiper belt, located beyond the orbit of Neptune. From here they can be injected into the inner part of the Solar System through planetary perturbations or mutual collisions. Due to their origin and dynamical evolution, Centaurs are supposed to constitute a transition population of objects from the large reservoir of Trans-Neptunian Objects (TNOs) to the active bodies of the inner Solar System. On the basis of the present knowledge of the physical properties of Centaurs and TNOs a similarity between the two populations appears evident. This is the strongest observational constraint supporting the theory of common origin.

1. Introduction

The first Centaur discovered, 2060 Chiron, was found by Kowal in 1978. At that time it was classified as an asteroid but later, due to its cometary activity, it was reclassified as comet 95P/Chiron. Since then the sample of known Centaurs has increased to 45 objects.

Centaurs are located between Jupiter and Neptune on unstable planet-crossing orbits and have dynamical lifetimes of about 10^6–10^7 years (Hahn and Bailey, 1990; Holman and Wisdom, 1993; Asher and Steel, 1993). They are believed to come from the Edgeworth-Kuiper belt (EKB) (Levison and Duncan, 1997; Durda and Stem, 2000) and to have been scattered into their present orbits by gravitational instabilities and collisions. Levison et al. (2001) also investigated the possibility that Long Period Comets, coming from the Oort cloud, may be perturbed into Centaur-like orbits. Since Centaurs accreted at low temperature and large solar distances, they did not suffer strong thermal processes and must still contain relative pristine material from the EKB (Hahn and Malhotra, 1999). For this reason, the investigation of the physical properties of this new population can give an insight into the material of the protoplanetary nebula at these distances from the Sun and into the processes which governed the early phase of the formation of the bodies of the Solar System.

Due to their dynamical characteristics, Centaurs are believed to constitute a transition population between Trans-Neptunian Objects (TNOs) and short-period comets (Levison and Duncan, 1997), even considering that typical sizes of comets are between 1 and 10 km.

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In the following we limit our discussion to the objects classified as Centaurs, as listed in the Minor Planet Center web page (http://cfa-www.harvard.edu/iau/lists/Centaurs.html).

2. Physical Properties from Photometry

Due to the intrinsic faintness of Centaurs, the present knowledge of their physical properties is so far rather limited.

2.1. ALBEDOS AND DIAMETERS

On the basis of the cumulative luminosity function shown in Figure 1, Sheppard et al. (2000) found a Centaur size distribution consistent with a $q \sim 3.5 \pm 0.5$ differential power law, estimating a population of about 10^7 objects larger than 1 km in radius, with about 100 bodies larger than 50 km in radius, and a current total mass of about 10^{-4} terrestrial masses. The presence of coma has been detected only in the case of 2060 Chiron.

Albedos and diameters have been computed for only 4 objects (2060 Chiron, 5145 Pholus, 8405 Asbolus and 10199 Chariklo): the albedo values obtained range between 4 and 17%, while diameters are between 66 and 300 km. For all the other known Centaurs we have just an estimation of the diameter, computed from the absolute magnitude assuming an albedo of about 0.05, and ranging between 40 and 300 km.

2.2. ROTATIONAL PROPERTIES AND PHASE CURVES

The rotational properties of Centaurs are still poorly known. So far the rotational periods of few of them have been reported: 2060 Chiron (Bus et al., 1989), 5145 Pholus (Buie and Bus, 1992), 8405 Asbolus (Brown and Luu, 1997), 32532 2001 PT_{13} (Farnham, 2001a; Ortiz et al., 2002, 2003), 54598 2000 QC_{243} (Ortiz et al., 2002, 2003), 33128 1998 BU_{48} (Sheppard and Jewitt, 2002), and 2002 PN_{34} (Ortiz et al., 2003) have rotational periods between 4 and 12 hours, while 31824 1999 UG_5 (Peixinho et al., 2001; Gutierrez et al., 2001), 10199 Chariklo (Peixinho et al., 2001; Alexandrino et al., 2001), and 2002 GO9 (Ortiz et al., 2003) have longer rotational periods.

Most of the available light-curves have small amplitude, with the exception of Pholus which has a larger amplitude. The pole direction has been computed only for Pholus by Farnham (2001b) who gave also an estimate of the semi-major axes. For 2060 Chiron, Fulle (1994) proposed a spin axis orientation from a model of the dust coma.

Although the sample of available phase curves is still limited, very different values of the slope parameter have been obtained, ranging from –0.13 for 31824 1999 UG_5 (Bauer et al., 2002) G to 0.15 for 10199 Chariklo (McBride et al., 1999).

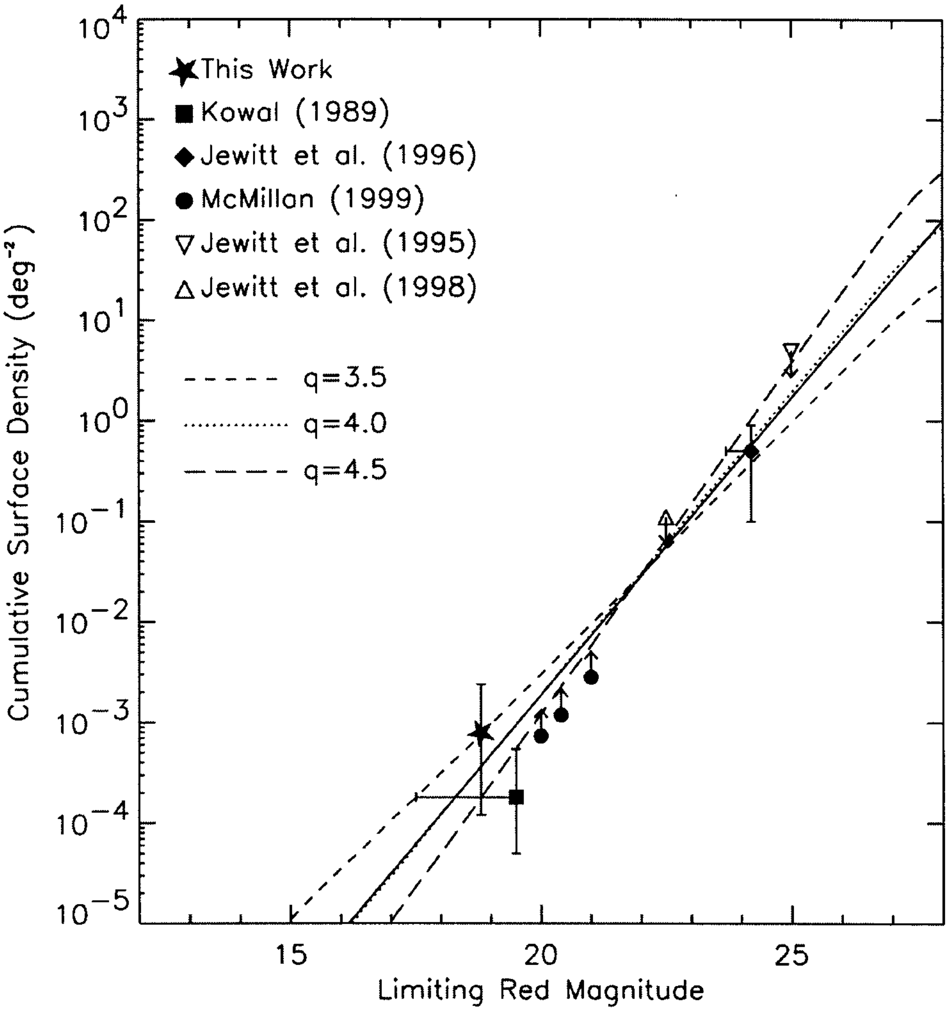

Figure 1. Simulation of the cumulative luminosity function of Centaurs by Sheppard et al. (2000). The solid line is the fit obtained by the same authors for the TNOs, vertically shifted.

2.3. COLOUR INDEXES

The largest observational database on Centaurs is given by visible and near-infrared colour indexes. The first results on this topic were published by Davies et al. (1998) who postulated a colour based link with TNOs. Figure 2 reports the presently known colour indexes of Centaurs as taken from Hainaut and Delsanti (2002) (the MBOSS colour database http://www.sc.eso.org/~ohainaut/MBOSS). The main characteristic is the variety of colours. The population of Centaurs includes both neutral and very red objects. Several authors (Barucci et al., 2000a, 2001; Doressoundiram et al., 2001, 2002; Boehnhardt et al., 2002, 2003; Hainaut and Delsanti, 2002)

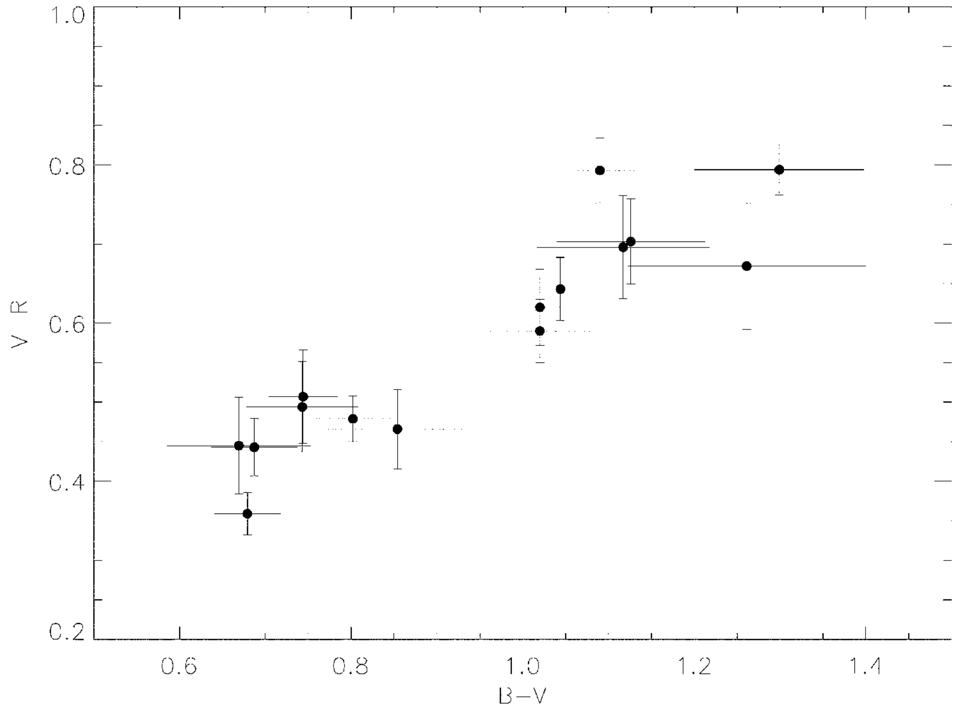

Figure 2. Colour indexes of Centaurs.

compared colours of Centaurs with those of TNOs, finding very similar ranges of colour variation: this is the strongest observational constraint in supporting the theory of the common origin of these two populations. No correlation has been found for Centaurs between colour indexes and perihelion distance (Lazzarin et al., 2003). As in the case of TNOs, the reason why the colour indexes of Centaurs have such a huge range of variation, is far from being understood. This colour diversity can perhaps be due to an intrinsic difference in composition or to a different degree of surface alteration, due to the balance between collisions and/or cometary activity vs. space weathering processes. Luu et al. (2000) and Doressoundiram et al. (2001) suggested the presence of two distinct groups among Centaurs, one very red like Pholus and one more similar to Chiron with neutral colour. 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.

3. Visible and Near-Infrared Spectroscopy and Modelling

An essential tool to investigate the surface composition of the atmosphereless bodies of the Solar System is spectroscopy. 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. Around 2.2–2.3 micron are the signatures of CH_4, C_2H_2, C_2H_4, C_2H_6, while spectral features at 1.52 and 2.03 micron could be due to water ice, and structures at 1.66, 1.72, 1.79 micron can be related to the presence on the surface of CH_4. Although the available sample of visible and near-infrared spectra of Centaurs is so far limited to about ten objects, we can infer some useful information about the composition and the evolution of these objects.

Figure 3 shows a sketch of the visible and near-infrared spectra now available for Centaurs and some of the compositional models so far published for these objects. The models of 52872 Okyrhoe (already known as 1998 SG_{35}) and 54598 2000 QC_{243} (Dotto et al., 2003a), 32532 2001 PT_{13} (Barucci et al., 2002), 8405 Asbolus (Romon-Martin et al., 2002), 10199 Chanklo (Dotto et al., 2003b) and 63252 2001 BL_{41} (Doressoundiram et al., 2003) have been obtained using a radiative transfer model, similar to the Hapke model (Doute and Schmitt, 1998). The Hapke scattering theory has been applied by Cruikshank et al. (1998) to model the spectrum of 5145 Pholus, and by Bauer et al. (2002) to obtain the first attempts at modelling their data of 31824 1999 UG_5. These models, of course, are not unique: different mixtures of minerals and ices can produce spectra which fit the observations and the limitations are primarily related to the sample of materials for which reliable optical constants are available. Nevertheless this modelling procedure allows us to have some hints on the surface composition of these objects and to infer some constraints on their origin and evolution.

The slopes of the visible spectra shown in Figure 3, have been reproduced by kerogen or tholin, already used as colour agent of the surface of bodies of the outer region of the Solar System. Kerogens are complex organic compounds essentially made of C, H and O interlocked in a disordered structure. Triton and Titan tholins are nitrogen-rich organic substances produced by the irradiation of gaseous mixtures of N_2 and CH_4: 99.9% of N_2 and 0.1% of CH_4 for Triton tholins (McDonald et al., 1994) and 90% of N_2 and 10% of CH_4 for Titan tholins (Khare et al., 1984), while ice tholins are synthetic macromolecular compounds, produced from an icy mixture of H_2O:C_2H_6.

The spectra of *54598 2000* QC_{243} and *52872 Okyrhoe*, shown in Figure 3, have been modelled by Dotto et al. (2003a) with a geographical mixture of kerogens, olivines and few percent of water ice. In these cases kerogen produced the best match to the slope of the visible part of the spectra. Olivines have been included in these models to fit the value of the photometric observations in the J filter, while water ice, even in small amounts, was the only choice to reproduce the spectral

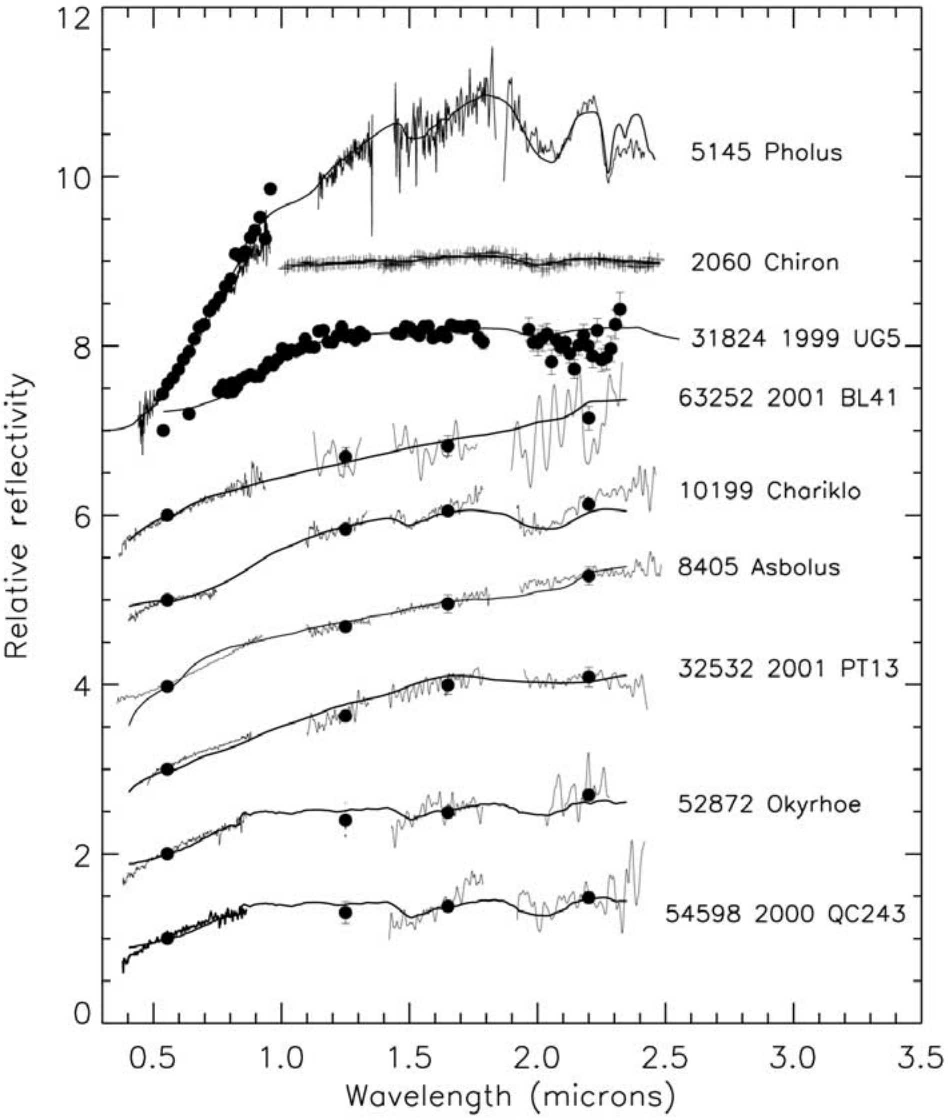

Figure 3. Visible and NIR spectra of Centaurs. The superimposed continuous lines are tentative modelling of the surface composition of each body. The spectra are normalized at 0.55 micron, except the spectrum of Chiron which is normalized at 1.25 micron. Spectra are shifted by one unit for clarity.

features at 1.5 and 2.0 micron. The models shown in Figure 3 are composed of 96% kerogen, 1% olivine, and 3% water ice for 54598 2000 QC_{243} with an albedo of 0.04 at 0.55 micron, and by 97% kerogen, 1% olivine, and 2% water ice for 52872 Okyrhoe with an albedo of 0.03 at 0.55 micron.

The spectrum of *5145 Pholus* reported in Figure 3 is very red in the visible part, and shows several spectral signatures: the bands at 1.5 and 2 micron are typical of water ice, while the structure at about 2.3 micron can be related to the presence on the surface of methanol ice. The continuous line superimposed in Figure 3 to the spectrum of Pholus is the model by Cruikshank et al. (1998), consisting of carbon black combined with an intimate mixture of Titan tholins, olivine, water ice, and methanol ice with an albedo at 0.55 micron of about 0.06.

A mixture of Titan and Triton tholins, amorphous carbon, and water ice has been also suggested for modelling the surface of *10199 Chariklo*. This Centaur was observed by Brown et al. (1998) and Brown and Koresko (1998), who detected the presence of spectral feature at 1.5 and 2 micron, typical of water ice. Dotto et al. (2003b) observed Chariklo during two different oppositions (April 2001 and March 2002) obtaining spectra with slightly different characteristics. They modelled the spectra of Chariklo with two different geographical mixtures of Triton and Titan tholins, amorphous carbon, and water ice in slightly different percentages and small differences in the albedo values. Also in this case small percentages (2%) of water ice were necessary to model the spectral features at 1.5 and 2.0 micron. The spectral differences detected have been interpreted as due to a possible slightly heterogeneous composition of the surface of this Centaur.

Small percentages of water ice have been also suggested to be present on the surface of *31824 1999* UG_5. Bauer et al. (2002) observed this Centaur during two nights (21 and 22 September 2000) obtaining two different near-infrared spectra. To interpret these data they considered two different models, which include 17 and 13% of water ice, respectively, and have a mean optical albedo at 0.55 micron of 0.05. In Figure 3 the spectrum obtained on 22nd September is reported. The corresponding model is composed by 13% amorphous water ice, 66% amorphous carbon, 14% Titan tholin, 3% methanol ice and 4% olivine. The model best-fitting the observation of 21st September is composed by 17% amorphous water ice, 41% amorphous carbon and 42% Triton tholin. The authors interpreted the observed spectral diversity as probably due to localized differences in the surface composition of this object.

8405 Asbolus has been observed by several authors. Barucci et al. (2000b) and Brown (2000) obtained spectra without any indication of the presence of water ice on the surface of this body. Kern et al. (2000) obtained different spectra of Asbolus. They found that a feature at about 1.6 micron, present in the first series of spectra, disappeared in the last three spectra. They interpreted this as being due to a heterogeneous surface composition of Asbolus with one side probably covered by water ice. Romon-Martin et al. (2002) repeated near-infrared spectroscopic observations of this body over a complete rotational period and did not find any change at 1.6

micron. A change from 0.8 to 1.0 micron in some of the spectra obtained seems to indicate a heterogeneous surface. Figure 3 shows the model published by Romon-Martin et al. (2002) which consists in a geographical mixture of 15% Triton tholin, 8% Titan tholin, 37% amorphous carbon and 40% ice tholin.

The model of *63252 2001* BL_{41} shown in Figure 3 has been published by Doressoundiram et al. (2003) and consists of a geographical mixture of 17% Triton tholin, 10% ice tholin, and 73% amorphous carbon with an albedo of 0.08 at 0.55 micron.

In 2002 Barucci et al. published two spectra of *32532 2001* PT_{13} obtained during two different months. These spectra showed differences in the near-infrared spectral behavior: in one of them there was the possible presence of signatures of water ice in small amounts, while in the other one these features were not evident. In order to interpret these spectra in terms of surface composition of this object, Barucci et al. (2002) modelled the observed spectral features with two different models. The spectrum obtained on October (shown in Figure 3) was modelled with a geographical mixture of 70% amorphous carbon, 15% Titan tholin, 12% ice tholin and 3% olivine with an albedo of 0.09. The spectrum obtained on September was modelled with a geographical mixture of 90% amorphous carbon, 5% Titan tholin, 5% water ice with an albedo of 0.06. Since the spectrum of September was acquired during a non photometric night, and photometric data are not available to constrain the reflectance of J, H, and K spectra, further observations of this object are clearly needed.

The most interesting Centaur is *2060 Chiron*, the only one with cometary activity. The spectra of Chiron obtained until 1996 were featureless and, in some cases, even with a negative reflectivity gradient in the visible part (Luu and Jewitt, 1990; Luu et al., 1994; Barucci et al., 1999). The spectra published later than 1996 by Foster et al. (1999) and Luu et al. (2000) showed the presence of spectral signatures at 1.5 and 2 micron interpreted as probably due to the presence of water ice on the surface of this Centaur. More recently, Romon-Martin et al. (2003) published further photometric and spectroscopic data obtained on June 2001, showing that Chiron reached at that time a high level of activity. The spectra obtained during these observations did not show any absorption features, and water ice was not detected. This seems to support, as suggested by Luu et al. (2000), that the detection of water ice is strongly related to cometary activity and is not possible when the object is active. In the case of Chiron, water ice was detected from 1996 until 2001, during a period of low activity, and was undetectable before 1996 and again on 2001 during high activity. The spectrum reported in Figure 3 is from Luu et al. (2000). The superimposed model consists of water ice and olivine.

4. Discussion

On the basis of the discussion in the previous section, we can summarise the present knowledge of the population of Centaurs as follows:

- The known albedo values of Centaurs range from 4 to 17%, the diameters range from 66 to 300 km, while the rotational periods range from a few hours to tens of hours.
- The population of Centaurs shows a variety in colour comparable to that of TNOs, including both objects with flat and very red visible spectra. A possible dichotomy suggested by some authors has yet to be confirmed by observations.
- So far complete visible and near-infrared spectra are available for a tenth of the Centaurs.
- Water ice, even in small percentages, has been detected on the surface of 6 objects (2060 Chiron, 5145 Pholus, 10199 Chariklo, 31824 1999 UG_5, 52872 Okyrhoe, and 54598 2000 QC_{243}), while 63252 2001 BL_{41}, and 8405 Asbolus seem not to contain detectable water ice on their surfaces.
- Further observations are needed to confirm the presence of water ice on the surface of 32532 2001 PT_{13} and 31824 1999 UG_5.
- 10199 Chariklo, 8405 Asbolus, 31824 1999 UG_5, and 32532 2001 PT_{13} show some indication of compositional heterogeneity.
- 2060 Chiron showed temporary cometary-like activity, combined with flat and featureless spectra. Observations carried out when the object was not active showed the spectral features at 1.5 and 2 micron, typical of water ice.

The study of Centaurs represents a unique opportunity to investigate primitive bodies at the frontiers of the Solar System, but the presently available data sample is still not enough to give a complete scenario of the origin and the evolution of these bodies. Although it is widely believed that Centaurs come from the Edgeworth-Kuiper belt, we still do not know the processes which governed their formation and migration to the present orbits, and we can only suggest tentative explanations of the observed physical and dynamical properties.

The detected diversity in colour and composition, may be explained with different degrees of surface alteration due to the balance between ageing (space weathering) and rejuvenating (collisions or cometary activity) processes. Laboratory experiments have shown that space weathering processes can produce a dark colour and spectrally red radiation mantle (Strazzulla, 1997, 1998) or flatten originally red spectra (Moroz et al., 2003). But, in the case of Centaurs the distribution of colour indexes seems to show a dichotomy which could be caused by a present or past cometary activity which has rejuvenated part of the population.

Also the failure to detect water ice is still not fully understood. Centaurs accreted at large heliocentric distances and must contain water and/or hydrocarbon ices. The formation of the radiation crust, or the presence of mixtures with materials which hide the spectral features of ices, are both mechanisms supposed to be able to hide the ices present on the surface of Centaurs.

Further observations from space and ground are clearly needed. Moreover, laboratory experiments are already in progress in order to interpret the surface composition of TNOs and Centaurs in terms of evolutionary state, by investigating the properties of minerals and ices on the surface of these bodies and modelling the alteration processes which are supposed to have modified their pristine surfaces.

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