Surface Composition of Centaurs: insights into the thermal evolution of TNOs

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Surface Composition of Centaurs: insights into the thermal evolution of TNOs

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ABSTRACT

This study examines the 0.6 - 5.3 μm reflectance spectra obtained with JWST/NIRSpec spectrograph of five Centaurs: 52872 Okyrhoe (1998 SG35), 32532 Thereus (2001 PT13), 136204 (2003 WL7), 250112 (200278 KY14), and 310071 (2010 KR59). Our analysis uncovers two distinct compositional groups within the Centaur population: water-rich and carbon-rich objects, echoing findings in the trans-Neptunian object (TNO) population. Significant variations in spectral-class distribution suggest differing surface compositions, especially in their upper layers. Centaurs, when passing through the giant planet region and experiencing heightened temperatures, exhibit less icy and more refractory surfaces than TNOs due to volatile species sublimation. Spectral models indicate a high abundance of amorphous silicates, signifying a substantial presence of "primitive" (or cometary-like) dust rich in such silicates. Similar populations (comets, Jupiter Trojans, Main Belt Comets, and D-type Asteroids) with comparable initial compositions are expected to exhibit spectral traits evolving due to thermal effects.

1. INTRODUCTION

Centaurs are icy bodies, short-time residents ($< 10^7$ yr) in the region between Jupiter's and Neptune's orbits, objects with semi-major axes $a \leq 30.1$ au and Tisserand invariant respect to Jupiter $T_J > 3.05$ according to Gladman et al. (2008) criteria. Centaurs are scattered objects originating from the trans-Neptunian belt (TNB), and they contribute to a dynamical cascade which supplies Jupiter Family Comets (JFCs) to the inner solar system (Levison & Duncan 1997; Nesvorný et al. 2017). Being closer to the Sun than the less accessible TNOs, yet not as processed as the rapidly evolving JFCs, they are a key population to understand in an investigation of the origin of our solar system.

Spectroscopy in the 0.6-5 μm region of icy-bodies provides critical information on surface composition. Ices, solid complex organic materials and silicates can be identified in the 1-5 μm region. Recently, Pinilla-Alonso et al. (submitted, hereafter NPA23), present near-infrared reflectance spectra of 54 trans-Neptunian objects (TNOs), a sample that represents the diversity of the TNO population, observed as part of the JWST GO-1 large program "Discovering the Surface Composition of the trans-Neptunian Objects, Icy Embryos for Planet Formation" (DiSCo-TNOs; PID 2418). These data were obtained using the Prism/CLEAR grating/filter pair of the Integral Field Unit (IFU) of the Near-Infrared Spectrograph (NIRSpec) (Closs et al. 2008; Böker et al. 2022). The Prism/CLEAR grating/filter pair was used to acquire low-resolving power ($30 < R < 300$) spectra in the range 0.6-5.3 μm for all objects. Additional details about the data acquisition and reduction can be found in Sec. 4 and in NPA23. Using different cluster techniques applied to the reflectance spectral data in the $0.75 - 5.0$ μm range, NPA23 identified three spectral types of TNOs, each one named after the shape of the spectrum in the 3-μm region: Bowl (25% of the sample), Double-Dip (43%), and Cliff (32%). De Pra et al. (submitted, hereafter MdP23) have shown that all 54 TNOs in this sample have evident signatures of CO_2 ice and roughly half of them also have strong signatures of CO ice.

In broad terms, NPA23 conclude that there are three compositional groups in the trans-Neptunian region, each separated by the dominant chemical species in the surface: the Bowl-type, dominated by water and silicates, the Double-dip which are dominated CO_2 and CO-ices, and the Cliff dominated by carbon ices and complex organics. They propose that the three groups provide a picture of the ice retention lines in the Solar System that likely occurred in the outer protoplanetary disk, just before a major planetary migration. Recent results strengthen NPA23 hypothesis (Nesvorný et al. 2020; Pirani et al. 2021; Marsset et al. 2023). A detailed description of each TNO spectral type is in NPA23.

In the TNB the objects surface compositions predominantly evolve due to the competition of two resurfacing effects: irradiation and collisions (Gil-Hutton 2002, and references therein). In surfaces originally rich in molecular ices (such as H_2O, CO_2 , NH_3, CH_4, etc) long-term irradiation results in the formation of complex organic molecules that reside in an "irradiation mantle". Collisions erode this mantle, covering the surface with fresh (non-irradiated) materials. For Centaurs that venture closer to the Sun an additional resurfacing process may occur due to increased insolation triggering phase transitions for their icy components and subsequent outgassing from their surfaces, which may entrain solid particles producing a dust coma. A portion of the entrained dust particles will fail to reach escape velocity and fall again to the surface, forming a "dust mantle". Some Centaurs ($\sim 10\%$), show comet-like activity even at heliocentric distances $r > 5.2$ au (Jewitt 2009) where temperatures are such that water ice is not sublimating: the process is thus not a good driver for cometary activity amongst Centaurs. Other phase transitions are more likely to occur, such as the crystallization of amorphous water ice (AWI), which is efficient up to 10-12 au, and releases trapped volatiles (Jewitt 2009; Guilbert-Lepoutre 2012). Davidsson (2021) suggested that the segregation of volatiles from CO_2 would be more efficient beyond 10 au where AWI crystallization rates drop rapidly. In the pre-JWST era, few strong detection of gaseous CO were reported, indicating that the sublimation of CO is not driving the activity of Centaurs (Drahus et al. 2017). However, there are notable exceptions where detections of CO have been reported for 2060 Chiron (Womack & Stern 1999), 174P/Echeclus (Wierzchos et al. 2017), and 29P/Schwassmann-Wachmann 1, where the latter is known to display strong CO emission (Senay & Jewitt 1994; Crovisier et al. 1995; Gunnarsson et al. 2008; Roth et al. 2023; Bockelée-Morvan et al. 2022). Therefore, the recent JWST observations of active Centaurs will certainly change our understanding of that population (e.g., the first detection of CO_2 in an active Centaur 39P/Oterma (Harrington Pinto et al. 2023) and a diversity of the CO to CO_2 abundance ratios seen in the first six active Centaurs observed by JWST through Cycle 1 GO 2416 (McKay et al. (2021); A. McKay and C. Schambeau, personal communications).

In this paper we analyze the reflectance spectra of the five Centaurs observed as part of the DiSCo-TNOs program: 52872 Okyrhoe (1998 SG35), 32532 Thereus (2001 PT13), 136204 (2003 WL7), 250112 (2002 KY14), and 310071 (2010 KR59). None of these Centaurs reveal present activity, so their uncontaminated reflectance spectra provide crucial information on their surface composition. Some of their orbital and known physical properties are presented in Table 1. We derive compositional information and compare with the reflectance spectra of their precursors, the TNOs. This dataset provides a unique opportunity to study the properties of small TNOs and the thermal effects on their surface composition.

2. RESULTS

2.1. *Centaur spectral characteristics and classes*

Using the same clustering analysis as in NPA23, we found that Thereus and 2003 WL7 belong to the Bowl-type, and 2002 KY14 belongs to the Cliff-type, while the remaining two Centaurs, Okyrhoe and 2010 KR59, do not fit in any spectral classes in NPA23 (see Fig. 1). They have a unique spectrum significantly different from the spectrum of any observed TNO, that we describe and analyze below. NPA23 also performed a Principal Component Analysis (PCA) using three components, and show that in PC1 vs PC2 plots Bowl-types are extremely well separated from Double-dip and Cliff types while Double-dip and Cliff show a more continuous distribution. In Fig. 2 we show the PC1 and PC2 of the five Centaurs projected on that of the TNOs in DiSCo sample. We note that both misfit Centaurs are close to the Bowl TNOs and well separated from the other two classes, and that the Cliff Centaur is well separated from Cliff TNOs.

Additionally, the spectra of four Centaurs in the same spectral region were obtained in the framework of the 1st Cycle program of Guaranteed Time "Kuiper Belt Science with JWST" (Proposal 1273, PI J. Stansberry), two of them are Cliff-type, one is

Bowl-type, and the following has a spectrum very similar to that of Okyrhoe (J. Stansberry, personal communication). Finally, the reflectance spectrum of the active Centaur C/2014 OG392 (PANSTARRS) (C. Schambeau, personal communication) is compatible with a Cliff-type. Despite the reduced sample size for Centaur surface reflectance spectra obtained with JWST (only 10 in total), our results suggest that there are significant differences between the spectral-class distribution of Centaurs and TNOs: (1) while 43% of the TNOs in the NPA23 sample have a Double-Dip spectral class, no observed Centaur exhibits this type of spectrum; (2) 3/10 of the observed Centaurs have a reflectance spectral class that has not been observed in any TNO.

We next explore whether there are also differences between the observed Cliff and Bowl Centaurs as compared to the Cliff and Bowl TNOs. In Fig. 1 we compare the spectra of Thereus and 2003 WL7 with that of Bowl-type TNOs (upper panel) and the spectrum of 2002 KY14 with that of Cliff-type TNOs (lower panel). A first look of Thereus and 2003 WL7 spectra show that their shape is very similar to that of Bowl TNOs, and the slope in the 0.7 - 2.0 μm range of both objects is in the "reddish" range of the colors of the TNOs. Some small differences exist, for instance, there is a hint of shallower water-ice absorption bands at 1.5 and 2.0 μm although the bowl-shaped band at 3 μm is of similar depth and width to that of the other Bowl TNOs. While 2003 WL7 resembles the average bowl, Thereus shows some differences: the continuum at 3.6 μm is slightly smaller than that of TNOs and the wide band between 3.5 and 5.0 μm is slightly shallower. There are also small but not significant differences when comparing the depth of the CO_2 fundamental band at $\sim$4.27 μm for the Centaurs in Table 2 and those of the TNOs in MdP23. While Thereus' band depth (36.3 $\pm$ 3.5) is similar to the mean value for the group of Bowl-type TNOs, 35.31 $\pm$ 8.20, 2003 WL7 presents a slightly deeper band (43.8 $\pm$ 4.1). As most Bowl TNOs, Thereus and 2003 WL7 spectra do not show the CO band at $\sim$4.68 μm. On the other hand, the Cliff Centaur 2002 KY14 spectrum presents significant differences respect to that of Cliff TNOs: the depth of the 3 μm band (attributed to -OH and -NH in complex organics, plus -OH of methanol, and possibly some amorphous water) of 2002 KY14 is shallower (the reflectance of TNOs at 3.05 μm is 3 times larger) but the band between 3.3 and 3.6 μm is at least as deep as in Cliff TNOs and wider with a local maximum at 4.1 μm, compared to 3.7 μm for the median Cliff reflectance; the fundamental CO_2 band at 4.26 μm is also shallower (the CO_2 band depth is only 35.31 $\pm$ 8.20 while the mean band depth of the Cliff TNOs is 76.76 $\pm$ 14.84); there is no evidence of the 4.68 μm CO band, we detect an absorption band centered at 4.62 μm that we attribute to the C$\equiv$N stretching in complex organics also detected in Cliff TNOs (see NPA23); 2002 KY14 presents a weak absorption band at 2.27 μm but not the 2.34 μm observed in Cliff TNOs attributed to the asymmetric and symmetric combination modes of the -CH_3 group due to the presence of methanol ice; the band at 4.9 μm attributed to OCS (carbonyl sulfide) in NPA23 is slightly deeper in 2002 KY14, other weak bands between 1.5 and 2.0 μm detected in Cliff TNOs are not seen in 2002 KY14 spectrum.

We now investigate the characteristics of the "misfit" Centaurs Okyrhoe and 2010 KR59. In some way, the shape of their spectra may resemble Bowl type TNOs in that they have red slopes below 2.5 μm and show a "bowl" shaped absorption at 3 μm. However, the differences between both of the "misfit" Centaur spectra and the median of the Bowl-type TNO spectral class are more significant than are the similarities (see Fig. 1 mid panel): (1) the 3 μm band is much shallower than in the Bowl type TNO spectra; (2) the 1.5, 2.0, and 4.5 μm water-ice bands and the 3.10 μm Fresnel peak are very weak or absent; and (3) the CO_2 fundamental band is absent. Following NPA23 criteria we therefore assign this spectral class to be "Shallow-type" due to the shape of the 3 μm band. Okyrhoe and 2010 KR59 spectra present a 3μm band with similar reflectance in the valley of the band, but 2010 KR59's reflectance rises to a larger value at 3.6 μm. As noticed in Sect. 4, 2010 KR59 spectrum is noisier and with a higher uncertainty than the rest of the DiSCo sample 5, affecting this region in particular. This is due to a background star being too close to the target during the observations, affecting this region. However, we cannot discard the possibility that the difference in the shape from 3.3 to 3.6 μm is real and indicative of compositional differences.

2.2. *Surface composition of Centaurs and the effects of cometary-like activity*

Surface composition is studied here by means of a surface scattering model using the optical constants of several materials expected to be on small, icy bodies in order to fit their spectra as described in Sec. 4.2. Reasonably good fits were obtained for Bowl and Shallow-type Centaurs (see Fig. 3) using H_2O and CO_2 ices, solid complex organics (Tholins) and amorphous silicates (Pyroxenes and Olivines). Details of the models are included in Sec. 4.2. Unfortunately, as with the Cliff TNOs, we still do not find satisfactory models for Cliff Centaur 2002 KY14.

The coarse surface composition of the Bowl Centaurs derived from the models shown in Fig. 3 is $\sim$ 50% ices (water and CO_2 -ice in $\sim$ 5:3 to 4:1 ratio), $\sim$ 30% amorphous silicates, and $\sim$ 10-20% complex organics (see Sec. 4.2). This is in agreement with CO_2 band peak positions measured in MdeP23 which indicate that CO_2 is in an intimate mixture with H_2O. Shallow-type have much more amorphous silicates $\sim$ 70-80%, no CO_2, less water-ice (10-20%), and less complex organics ($\sim$7-8%) than Bowls. The loss of CO_2 and the much larger amount of silicates in Shallow-type Centaurs support the thermal surface weathering mechanism previously proposed (see Sect. 1): activity due to sublimation of volatiles and the deposition of solid particles on the surface forming a dust mantle.

Even if we cannot yet model Cliff spectra, the information of the materials on the surface of 2002 KY14 and its comparison with TNO Cliff spectra presented in Sec. 2.1 suggests a similar resurfacing mechanism occurred. First, 2002 KY14 has lower levels of CO_2 , CO, and CH_3OH compared to the Cliff TNOs. The depletion of these volatile molecules is compatible with sublimation activity. Second, the species responsible for the 4.62 μm absorption feature in their spectra have remained, suggesting that the carrier is non-volatile. The latter point is consistent with the hypothesis in NPA23 that "the 4.6 μm feature is most probably dominated by the -CN (triple bond) band of complex organics" and provide additional support to the entire interpretation of the Cliff-type spectrum proposed in NPA23. Third, only a part of the 4.9 μm band is likely OCS, the feature at 4.93 μm can be attributed to olivine, in agreement with the overall pattern. Finally, the shape of C–H stretching absorptions of aliphatic (chain-like), conjugated, and aromatic hydrocarbons in the 3.33 to 3.6 μm range begins to resemble (albeit somewhat larger) that found in meteorites and cometary dust (see e.g. Raponi et al. 2020). The hypothesis that 2002 KY14 has a weathered surface due to activity is also supported by the very low value of its geometric albedo $p_V = 0.06 \pm 0.01$, indicative of the presence of a larger abundance of dark materials (silicates and/or complex organics) than on the surface of the mean TNO Cliff objects that have a mean geometric albedo of $p_V = 0.12 \pm 0.05$.

3. DISCUSSION

The spectroscopic analysis of Centaurs and trans-Neptunian Objects (TNOs) using JWST data reveals that two of the three compositional groups in the TNO population identified in NPA23, one with water rich (Bowl-type) and the other with carbon rich objects (Cliff-type), are also present in the Centaur population. However, we observed significant disparities in their spectral-class distribution when compared to TNOs, indicative of variations in the composition of the upper layers of their surface. Notably, their distinct thermal evolution plays a crucial role in shaping these disparities. The key findings from our analysis highlight a general trend: as Centaurs traverse the giant planet region, experiencing increased surface temperatures that trigger phase transitions such as the sublimation of volatiles like CO or CO_2 , cometary activity can be sustained, and their surface undergoes chemical transformations. Specifically, the surface of Centaurs appear to transition from an ice-rich state to become less icy and more refractory.

Activity at large heliocentric distances has also been detected in long period comets (LP), even at $r > 15$ au, providing additional support to the activation hypothesis described above. C/2014 UN_{271} (Bernardinelli-Bernstein) was active at $r \approx$ 23-24 au (Bernardinelli et al. 2021; Kelley et al. 2022), C/2010 U3 (Boattini) at $r \approx$ 26au (Hui et al. 2019) and C/2017 K2 (PanSTARRS), at $r = 23.7$ au (Hui et al. 2018). In the case of C/2014 UN_{271}, Bolin et al. (2023) reported the detection of emission features from the vibrational bands of the gas-phase of CO and CO_2 in JWST/NIRSpec with the comet at $r = 18.2$ au.

It is important to address the presence of CO on the surfaces of TNOs and its potential significance in driving activity when scattered into the Centaur region. While CO signatures are indeed observed in TNOs, this CO is likely a result of irradiation processes rather than originating from primordial internal sources (see MdP23). Multiple studies, including (Davidsson 2021; Gkotsinas et al. 2022; Lisse et al. 2022; Parhi & Prialnik 2023), suggest that CO should have completely sublimated from the upper kilometer-scale layers of most TNOs. This implies that the detected CO on TNO surfaces is superficial and may not be the primary driver of sustained activity within the Centaur region.

Furthermore, a significant distinction is apparent between Centaurs and TNOs, particularly when considering the Cliff Centaur and Cliff TNOs. It is notable that 2002 KY14 lacks CO and has a considerably lower level of CO_2 , suggesting rapid loss of these volatiles upon its entry into the giant planet region. This indicates that if CO were present as a thin layer, it would be quickly depleted. In contrast, LP comets, coming from a much further region than the TNB, may retain original CO when entering the planetary region for the first time, which could potentially explain their observed activity at greater distances. The CO detection in 2014 OG392 at ~ 10 au (C. Schambeau, personal communication) is interpreted as being consistent with processes like crystallization or segregation rather than direct sublimation.

The scattering models applied to Shallow-type Centaurs suggest that they have a very high amount of amorphous silicates. Amorphous silicates are an important component of cometary dust. Remote studies of cometary comae dust in the mid-IR commonly find spectral shapes in the 10 μm region that are dominated by amorphous silicates, with variable contributions of crystalline peaks (crystal mass fractions ranging from 20 to 75%, Wooden et al. 2017 and references therein), similarly to laboratory spectra of particles originated from comets or primitive asteroids. Amorphous silicates seem to be an important component of the surface of Jupiter Trojans as well (Martin & Emery 2023). However, other opaque phases (e.g., iron sulfides and oxides, carbon-rich materials, etc.) are present in cometary grains and in primitive meteorites, intimately mixed with the silicates at scales that are often smaller than the wavelengths, suggesting that this may also be the case of Centaurs. Thus, the high abundance of amorphous silicates found is a general indication of a high abundance of "primitive" (or cometary-like) dust. As in the case of Centaurs where the surface becomes less icy and more refractory with activity, other populations of likely similar original composition (comets, Jupiter Trojans, Main Belt Comets, and D-types), should present spectral characteristics of similar or even more evolved surfaces. In Fig. 4 we overplot the spectra of the Bowl-s Centaurs presented in this paper with the spectra of comet 67P/Churyumov-Gerasimenko from Filacchione et al. (2019) and Main Belt Comet (MBC) 238P/Read from Kelley et al. (2023).

Establishing a direct link between the orbital history of these objects and their spectral surface properties has proven more complex than initially anticipated (Melita et al., in preparation). This challenge arises partially due to the inherent difficulty in acquiring precise data regarding their individual dynamical histories, mainly owing to the chaotic nature of the problem. However, another probable reason for this complexity may be associated with an unresolved issue: the absence of Double-Dip Centaurs. A plausible explanation could be that Double-Dip TNOs transform over time into Shallow-type Centaurs very rapidly when scattered into the giant planets region. Double-Dip TNOs, characterized by a higher presence of CO and CO_2 on their surfaces, are more prone to activation at greater heliocentric distances, displaying increased levels of activity. Despite their abundance in CO and CO_2 , they contain fewer other essential molecules required for the formation of complex organics. Consequently, the activation process leads to the sublimation of CO and CO_2 , leaving behind other components like dust and water-ice particles on the surface. Further investigation is necessary to explore this hypothesis.

4. METHODS

4.1. *Observations, data reduction and reflectance spectra*

The near-infrared spectral observations presented in this work were obtained with the James Webb Space Telescope (JWST) as part of program 2418 (PI: Pinilla-Alonso) using the Integral Field Unit (IFU) of the Near-Infrared Spectrograph (NIRSpec) (Closs et al. 2008; Böker et al. 2022). For all the objects the Prism/CLEAR grating/filter pair was used to acquire low-resolving power (R from 30 to 300) spectra in the range 0.6-5.3 μm. Details of the observations are in Table 3. A detailed description of the data acquisition and reduction procedures can be found in NPA23. The final reflectance spectra of the five Centaurs are shown in Fig. 5. We must note that we had to discard a significant number of exposures of 2010 KR59 due to a background star being too close to the target, so its final reflectance spectrum is noisier and with a higher uncertainty than the others.

4.2. *Fitting reflectance spectra with scattering models*

To obtain information on the surface composition of our sample of Centaurs, we used the Shkuratov et al. (1999) model using intimate mixtures, which emulates the scattering of the light in particulate surfaces. This model requires laboratory measurements of the optical constants of different materials as an input, along with grain sizes and fractional abundances for each component. A list of the optical constants used in the modeling is provided in Table 4. An additional parameter, the porosity, has minor effects on the overall shape of the spectra and was assumed fixed at 0.5. Despite their limitations, models like Shkuratov's are valuable tools for deriving the rough surface composition of icy-bodies.

The spectra of mixtures that best fit the spectra were obtained following the Bayesian framework by MdP23. To account for the influence of temperature on the band positions of Water-ice (Mastrapa et al. 2008, 2009), we incorporated an additional parameter that allows for shifts of $\pm 0.03 \mu$m in the wavelength vector of each optical constant. We adopted a uniform prior distribution for this parameter, ensuring a comprehensive exploration of the possible wavelength shifts. Reasonably good fittings were achieved for the Bowl and Bowl-s objects within our sample, as depicted in Fig. 3, employing the materials whose fractions, particle sizes, and shifts better fit the spectra, as illustrated in Table 5. However, our attempts to replicate the spectral characteristics of the Cliff object 2002 KY14 were unsuccessful. The major difficulty in modeling this object is reproducing the 2.5-4.0 μm region, where the complex organics dominate. The inability to generate good fits to the whole spectral coverage can be attributed to the limited collection of optical constants available in the literature, especially of complex organics, and/or to the simplistic configuration of the intimate mixtures adopted here for the modeling. Acquisition of more optical constants data in the laboratory and trials using more sophisticated models are highly encouraged, but out of the scope of this work.

5. DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

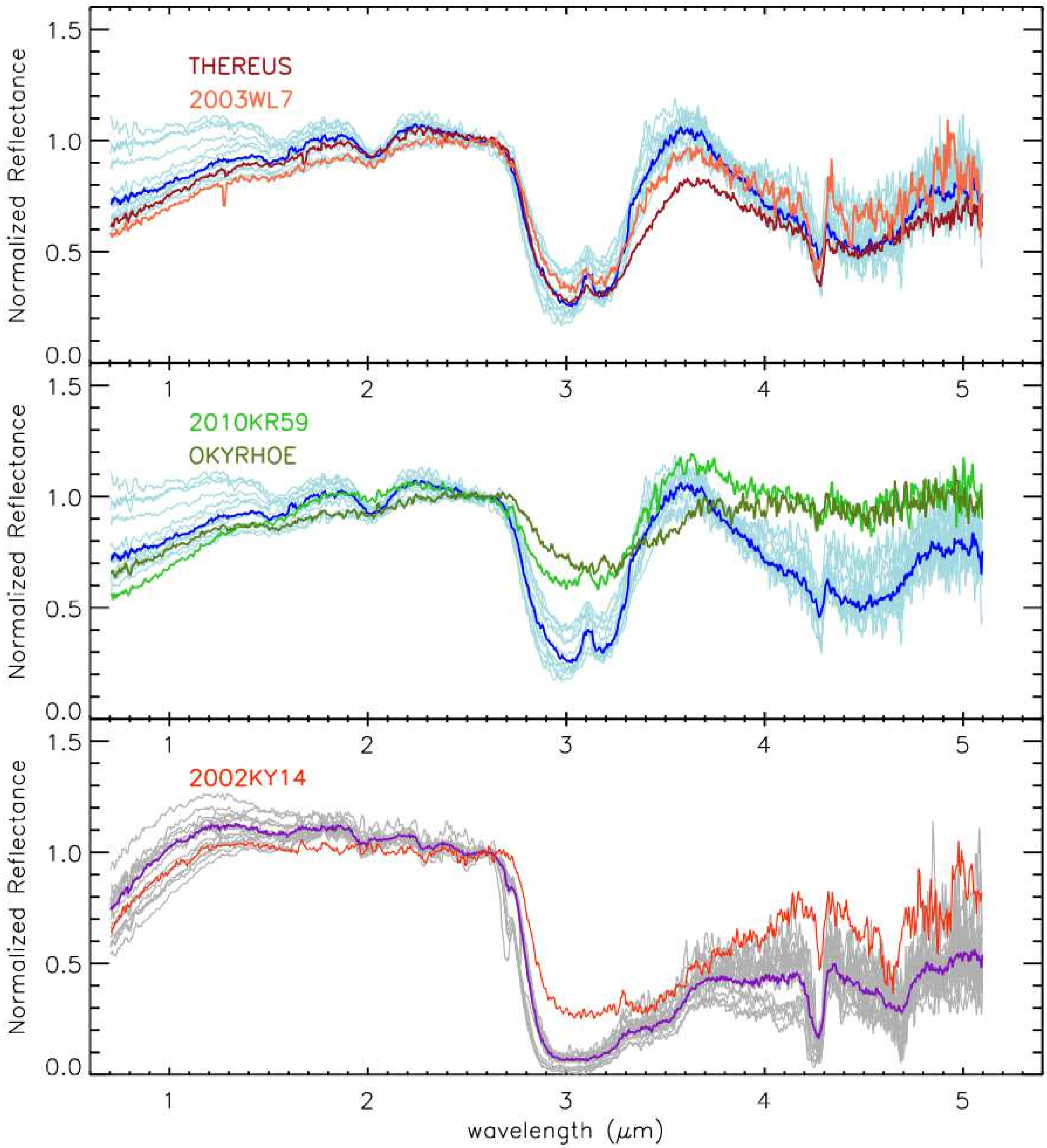

Figure 1. Comparison of the Centaurs and TNO spectra: *Upper* Thereus (in red) and 2003 WL7 (in orange) compared with the TNOs belonging to the Bowl group (in light-blue the spectra of individual TNOs, in blue the mean Bowl spectrum); *Middle* Okyrhoe (green) 2010 KR59 (light-green) compared with the TNOs belonging to the Bowl group (in light blue the spectra of individual TNOs, in blue the mean Bowl spectrum); *Lower* 2002 KY14 (in red) compared with the TNOs belonging to the Cliff group (in grey the spectra of individual TNOs, in violet the mean Cliff spectrum).

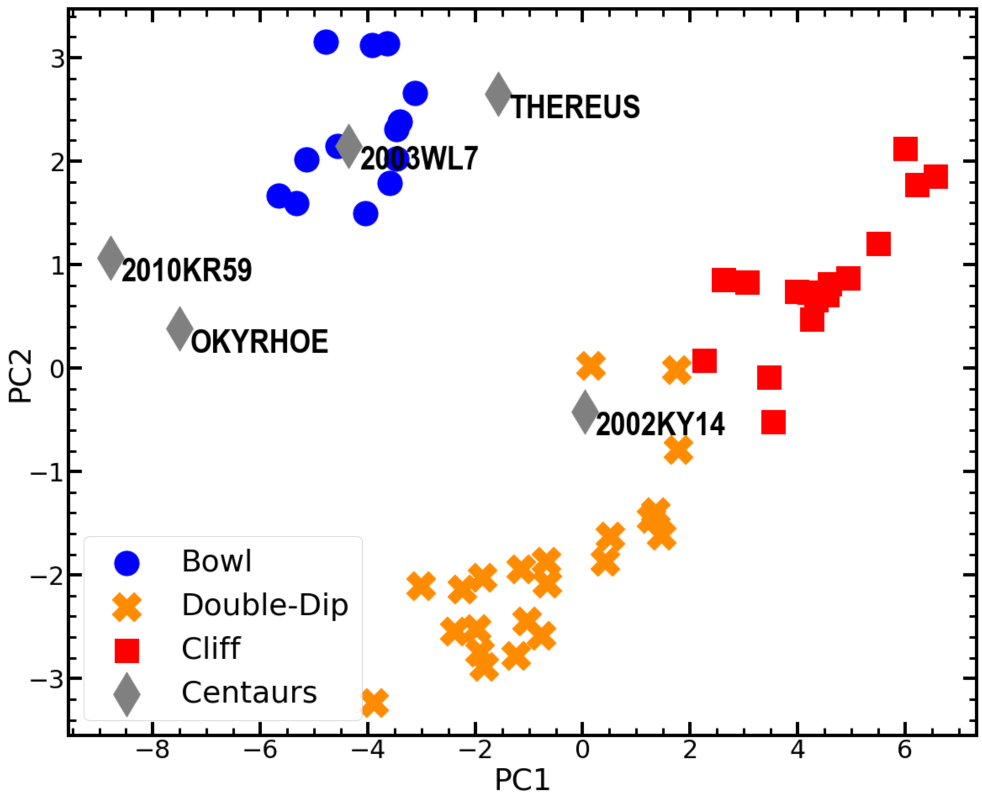

Figure 2. Principal component analysis showing the first two principal components of the five Centaurs projected over the three spectral groups of TNOs in the DiSCo dataset.

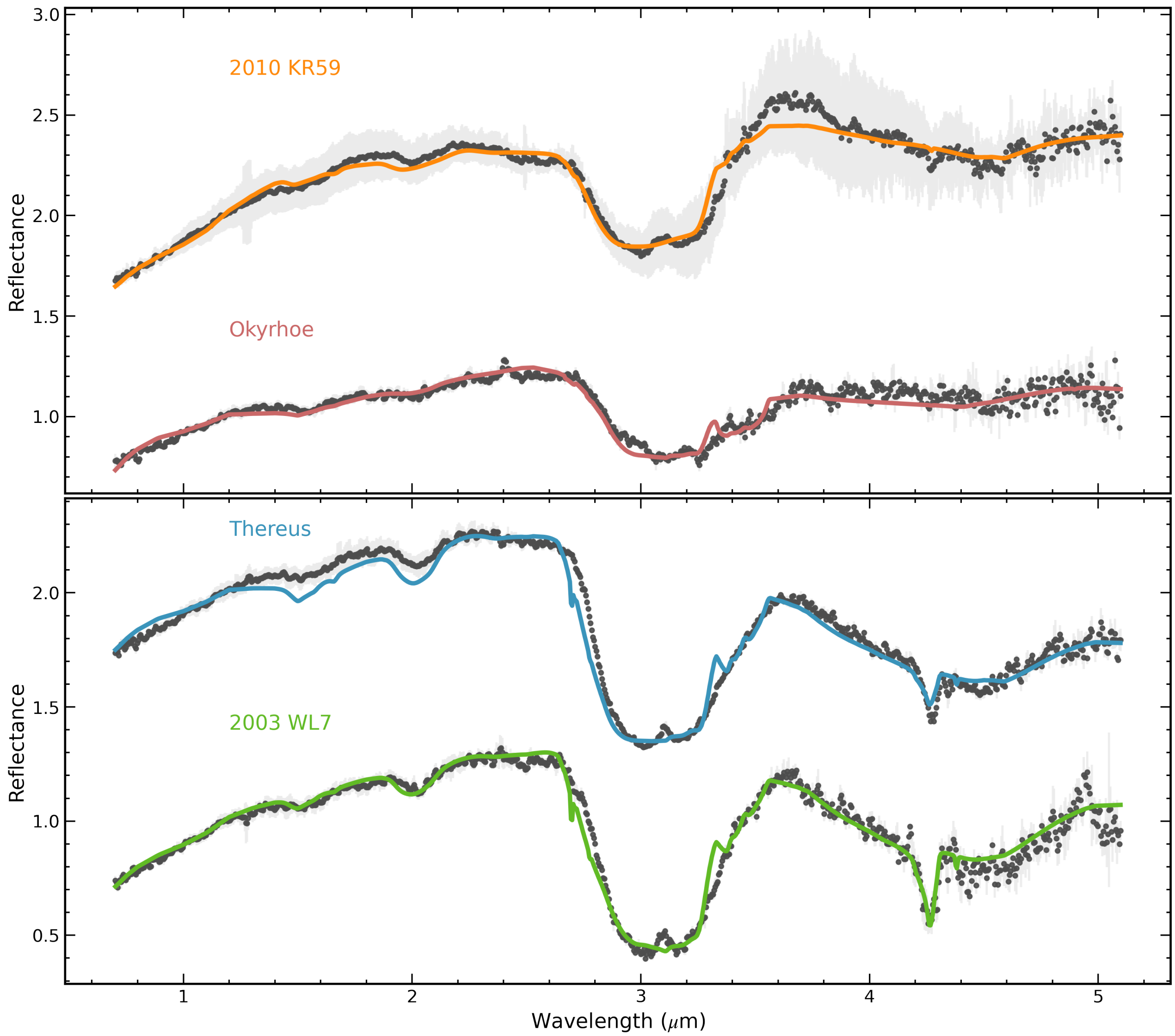

Figure 3. Results of the scattering model fitting of the Bowl and Shallow-type Centaurs presented in this paper. Fittings reasonably reproduce the general shape and most important spectral features observed thus providing a reasonable good rough composition

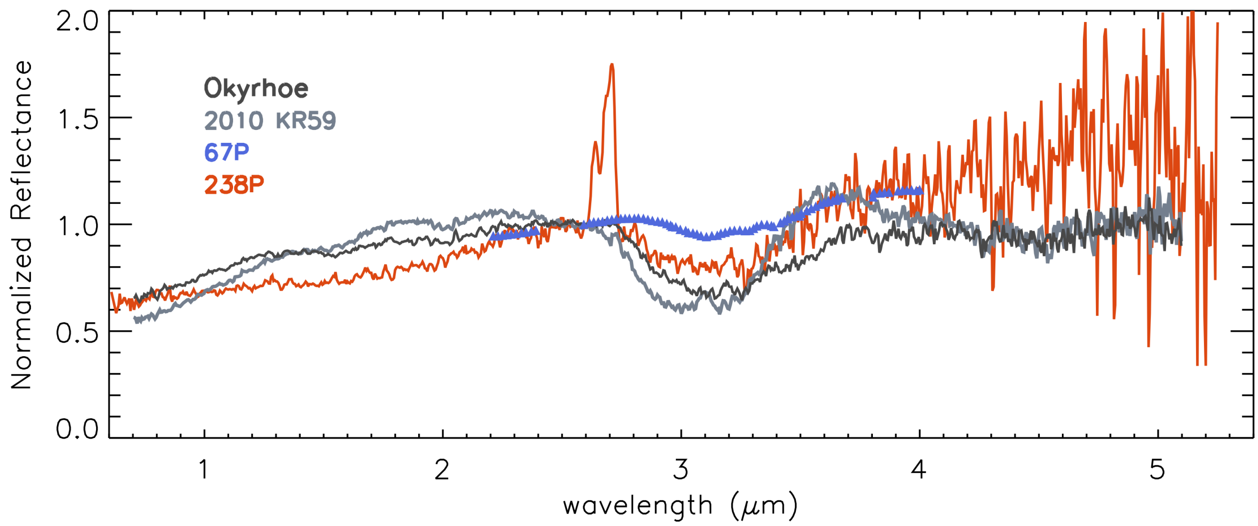

Figure 4. Comparison of Shallow-type Centaurs Okyrhoe and 2010 KR59 spectra compared with that of comet 67P/Churyumov-Gerasimenko from Filacchione et al. (2019) and MBC 238P/Read. The spectrum of 238P is the pure reflectance one obtained after subtracting to the observed one presented in Kelley et al. (2023) (Fig. 3 of the extended data), the thermal emission also presented in this paper.

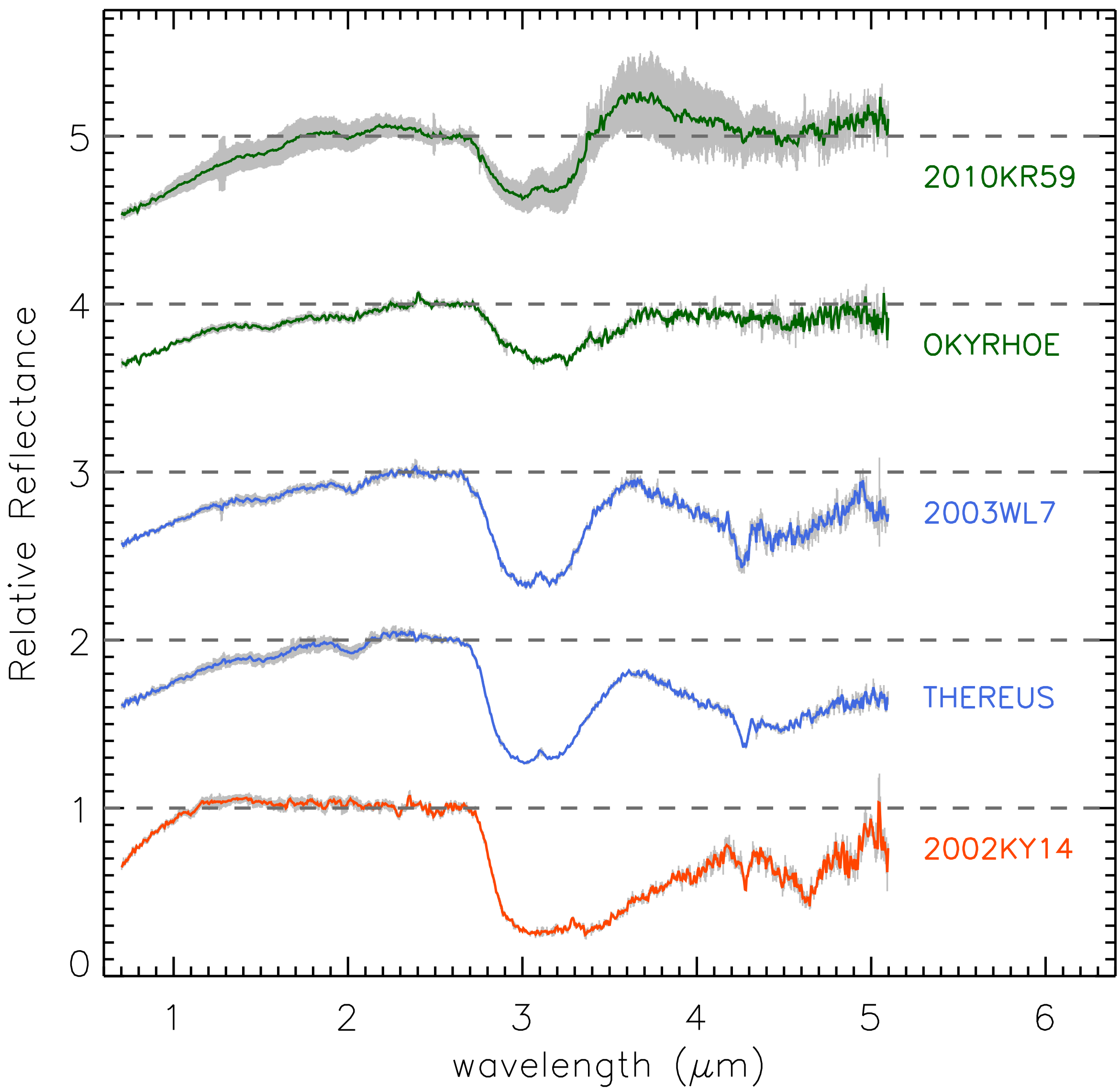

Figure 5. Reflectance spectra of the five Centaurs presented in this paper shifted in the y-axis by 1.0. In red is represented the Centaur with a Cliff-type spectrum defined in NPA2023, in blue those with a Bowl-type spectrum, and in green the two ones that belong to a spectral class that is unique between the Centaurs.

			a	e	i	q	H	D	p_V	T_q	S'_{vis}
Number	Name	Prov Des	(au)		(°)	(au)	(mag)	(km)		(K)	(%/1000Å)
32532	Thereus	2001 PT13	10.6	0.20	20.4	8.5	9.4	62^{+3}_{-3}	$0.08^{+0.02}_{-0.01}$	95	9.48±2.01
52872	Okyrhoe	1998 SG35	8.4	0.30	15.6	5.8	11.1	35^{+3}_{-3}	$0.06^{+0.01}_{-0.01}$	115	11.27±3.22
136204	-	2003 WL7	20.1	0.26	11.2	14.9	8.8	105^{+6}_{-7}	$0.05^{+0.01}_{-0.01}$	72	11.7±2.06
250112	-	2002 KY14	12.6	0.32	19.5	8.6	10.4	47^{+3}_{-4}	$0.06^{+0.01}_{-0.01}$	94	33.42±2.46
310071	-	2010 KR59	29.8	0.56	19.7	13.0	7.7	110^{+30}_{-30}	$0.12^{+0.04}_{-0.04}$	76	23.89±4.47

Table 1. This table present the orbital semi-major axis a, eccentricity e, inclination i and perihelion distance q, the visible absolute magnitude H, diameter D, geometric albedo p_V, and surface temperature estimated at perihelion distance $T_q = T_\odot * (1 - A)^{(1/4)} * \sqrt{1/2}$ (where A is the Bond albedo), the spectral visible slope S'_{vis}. S'_{vis} values of the first four objects are from Peixinho et al. (2015), and the values for 2010 KR59 are from Bauer et al. (2013)) of the Centaurs presented in this paper. H, D and p_V values of the first four objects are from Duffard et al. (2014), and the values for 2010 KR59 are from Bauer et al. (2013).

Number	Name	Prov. Des.	Group	CO_2 Depth (%)	CO
32532	Thereus	2001 PT13	Bowl	36.3 ± 3.5	No
136204		2003 WL7	Bowl	43.8 ± 4.1	No
250112		2002 KY14	Cliff	36.3 ± 6.0	Maybe
52872	Okyrhoe	1998 SG35	Shallow	No	No
310071		2010 KR59	Shallow	No	No
mean TNO Bowl			Bowl	35.31 ± 8.20	
mean TNO Cliff			Cliff	76.76 ± 14.84	

Table 2. Results of the CO_2 fundamental band parameter of the five Centaurs presented in this paper extracted from MdP23. Detection of CO based on visual inspection are also listed. The last two lines are the mean CO_2 fundamental band parameter of the Bowl and Cliff TNOs classes computed from the data in MdP23.

Name	**Date**	**r mag**	**Groups /Int.**	**Int.**	**Tot. Int. (4p Dit.)**	**Tot.Exp. (sec)**
2002 KY14	2022/10/30	21.4	24	1	4	1459
Okyrhoe	2022/11/03	21.2	24	1	4	1459
2003 WL7	2022/11/23	21.2	24	1	4	1459
Thereus	2023/01/17	19.9	14	1	4	875
2010 KR59	2023/03/02	20.9	20	1	4	1226

Table 3. Description of the observations. From left column to the right: name of the object, date of the observation, r-SDSS magnitude at the moment of observation, number of groups per integration, number of integrations, total number of integrations, considering a 4 points dither, and total exposure time in seconds.

Optical Constant	Phase	Temperature	Ref
Carbon dioxide	-	12.5 K	Baratta & Palumbo (1998)
Water Ice	amorphous	40 K	Mastrapa et al. (2008, 2009)
Water Ice	crystalline	40 K	Mastrapa et al. (2008, 2009)
Titan tholin	-	170 K	Khare et al. (1984)
Tritan tholin	-	170 K	Khare et al. (1984)
Piroxene (P4)	-	-	Dorschner et al. (1995)
Olivine	-	-	Dorschner et al. (1995)

Table 4. Optical constants used for the models in this work.

Table 5. Fraction, particle size and shifts of the different materials used in the models shown in Fig. 3

Centaur / Material	2003 WL7			Thereus			2010 KR59			Okyrhoe		
	fraction	size (μm)	shift (μm)	fraction	size (μm)	shift (μm)	fraction	size (μm)	shift (μm)	fraction fraction	size (μm)	shift (μm)
CO2	0.21	0.15	0.0	0.10	0.25	0.0	0.00	–	–	0.00	–	–
Ice Tholin	0.14	1.57	0.0	0.21	1.89	0.0	0.07	1.92	0.01	0.08	9.39	0.0
Olivine 0	0.02	7.97	0.0	0.0	–	–	0.0	–	–	0.02	394.91	0.0
Olivine 1	0.0	–	–	0.0	–	–	0.36	18.87	-0.01	0.0	–	–
Pyroxene 2	0.27	1.73	0.0	0.22	1.39	0.0	0.36	3.39	0.0	0.74	0.34	0.0
Pyroxene 6	0.02	497.5	0.0	0.07	190.5	0.0	0.0	–	–	0.07	18.2	0.0
H_2O-ice Amo.	0.1	8.34	0.0	0.14	5.53	0.0	0.20	2.39	0.01	0.02	5.54	0.0
H_2O-ice Crys.	0.25	1.18	0.0	0.25	2.63	0.0	0.01	483.5	-0.02	0.07	2.02	-0.01

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AUTHOR CONTRIBUTIONS STATEMENT

JL, NPA, VL, MDP, BH and JS designed the observational program, NPA, MDP, RB, JL, YP, DC, BH, TM, JS, and JE conceived the science goals of DiSCo, JL and NPA conceived in particular those related to Centaurs, BH, NPA, IW, ACdSF, MDP,and CS reduced and validated the data, JL, NPA, EH, RB, MDP, ACdSF, JS, and TM performed the band identification and spectral characterization, RB, MDP, and NPA performed the clustering and the study of the band areas, JL, RB, NPA, and AGL elaborated and proposed the scenario for the interpretation of the results, JL and NPA drafted the manuscript. All authors were involved in the discussion of the results and the finalization of the manuscript.