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To cite this version:

Maria Antonella Barucci, Frédéric Merlin, Aurélie Guilbert, Catherine de Bergh, Alvaro Alvarez-Candal, et al.. Surface composition and temperature of the TNO Orcus. Astronomy and Astrophysics - A&A, 2008, 479, pp.L13-L16. 10.1051/0004-6361:20079079 . hal-03732890

HAL Id: hal-03732890

https://hal.science/hal-03732890v1

Submitted on 23 Oct 2022

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A&A 479, L13–L16 (2008)
DOI: 10.1051/0004-6361:20079079
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Astronomy & Astrophysics

Letter to the Editor

Surface composition and temperature of the TNO Orcus*

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Received 16 November 2007 / Accepted 19 December 2007

ABSTRACT

Aims. The aim of this paper is to investigate the surface composition of the Transneptunian Object (TNO) Orcus.
Methods. High quality observations have been carried out with the new instrument SINFONI at the Very Large Telescope (VLT) of ESO.
Results. Crystalline water ice, and possibly ammonia ice, have been found from spectroscopic observations of the TNO Orcus between 1.4 and 2.4 μm.
Conclusions. The existence of such ices on the surface of Orcus may indicate a renewal mechanism on the surface and geological activity. The presence of ammonia on the surface of Orcus, if confirmed, could have important implications for the composition of the primitive solar nebula and the formation of the TNO population.

Key words. Kuiper Belt – techniques: spectroscopic – methods: observational

1. Introduction

Transneptunian objects (TNOs) contain key information on how accretion proceeded in the early solar system. The study of physical properties of TNOs is fundamental to understand their origin and evolution. Only a few large TNOs have been discovered recently (Brown 2008). 90482 Orcus is a large TNO with a diameter estimated by Spitzer of 946 ± 72.3/74.1 km and an albedo of 19.3% (Stansberry et al. 2008). Up to now only six TNOs or satellites of TNOs (Pluto, Charon, Eris, 2005 FY_9, Sedna and 2003 EL_{61}) have larger diameters than Orcus.

Orcus belongs to the Plutino dynamical class, as it is in the 3:2 resonance with Neptune with an orbit shaped similarly to that of Pluto. A satellite was discovered by HST observations in February 2007 (Brown & Suer 2007) at 0.25 arcsec from Orcus with a magnitude difference of 2.7. Assuming an albedo similar to that of the primary, the magnitude suggests a quite substantial diameter of around 220 km for the satellite. Recent observations of the satellite orbit suggest a density for Orcus comparable to that of Charon (Brown 2007, private communication). Ortiz et al. (2006) determined a possible rotational period of 10.08 ± 0.01 hr for Orcus and an amplitude of 0.04 ± 0.02, considering only a single peak.

Spectroscopic observations in the near-infrared with the Galileo telescope (Fornasier et al. 2004) showed the presence of water ice at the surface of Orcus. Subsequent observations at ESO-VLT (de Bergh et al. 2005) suggested that the water ice was in the crystalline state. Both observations were modeled with mixtures of water ice and carbonaceous compounds. Further K-band spectra taken with the Gemini telescope confirmed a water ice signature at 2 μm corresponding to less than 50% of the surface fraction (Trujillo et al. 2005). The visible spectrum of Orcus is nearly flat (neutral color) and featureless (Fornasier et al. 2004; de Bergh et al. 2005).

In this paper we report one of the highest quality near infrared spectra obtained to date on the TNO population.

2. Observations and data reductions

Orcus was observed on January 24, 2007, in the near infrared with the 8 m Yepun telescope (ESO-VLT facility at the Paranal Observatory in Chile). We used the new instrument SINFONI (Spectrograph for INtegral Field Observations in the Near Infrared) to obtain simultaneous spectra in the H and K bands, in the no-AO mode. Orcus was observed for 100 min, while its airmass ranged from 1.099 to 1.061, and with a stable seeing of 0.5″ throughout the exposure time. The solar analog, Landolt 98-978, was observed just before the object at airmass 1.1 with the same instrumental settings, in order to provide the needed calibration to correct the spectrum from the solar response and from the telluric features.

SINFONI slices the field of view into 32 image-slitlets which are re-directed toward the grating and then re-imaged on the detector. To improve our estimation of the background, the target was shifted on different positions of the SINFONI field between each 600 s exposure. The reduction was performed using the SINFONI pipeline version 1.6 which provides a robust wavelength calibration (accuracy of 0.0005 μm per pixel) and a good correction of the skylines.

The processed spectra were extracted using QFitsView, a 3D-visualization tool developed for SINFONI. The extraction is

* Based on observations performed at the European Southern Observatory (ESO), proposal 178.C-0867.

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20079079

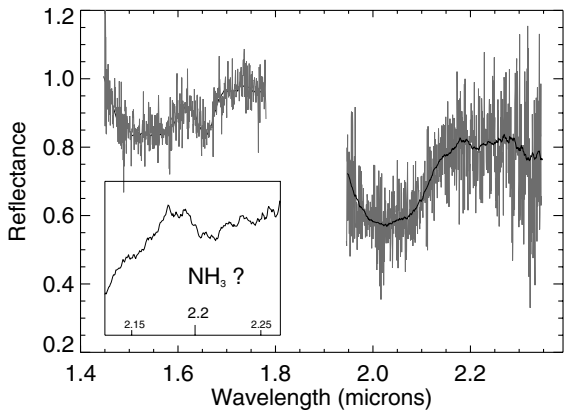

Fig. 1. Reflectance spectrum of Orcus (R = 1500), normalized to unity at 1.55 μm, with the smoothed spectrum (R = 100). The strong absorption bands are due to crystalline water ice. A weak band is present around 2.2 μm, reported at larger scale in the small square, and tentatively assigned to hydrated ammonia (see text). Other bands are noted beyond 2.25 μm, but they are in lower signal to noise level portions of the spectrum.

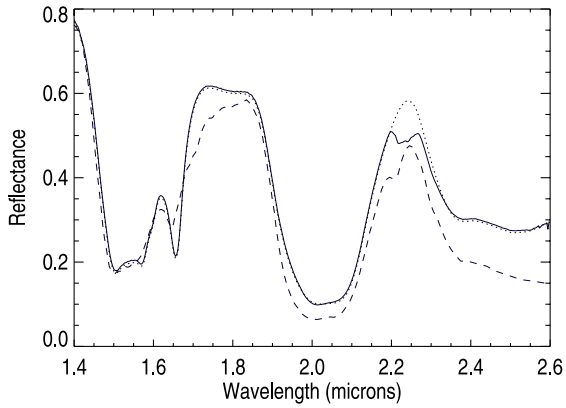

Fig. 2. Reflectance spectra of some of the ices used in our models. Dilution of ammonia in crystalline water ice induces shifts in the wavelength of the ammonia band near 2.21 microns. Increasing the amount of diluted ammonia in crystalline water ice tends to reduce the depth of the band at 1.65 micron. Dotted line represents H_2O ice in crystalline phase, continuous line is an intimate mixture of pure crystalline H_2O ice and 3% of pure NH_3 and dashed line is NH_3 (1%) diluted in crystalline H_2O ice.

performed using an aperture selected as a compromise between the maximum gathered flux and the minimum residual sky contribution, and we use in this case an aperture corresponding to a 1″ radius.

The target's spectrum was then divided by the solar analog's spectrum. The resulting spectrum (Fig. 1) was finally degraded to a resolution of about 100 by means of a running box to increase the S/N ratio.

3. Analysis and spectral models

The spectrum of Orcus, of high S/N and unique quality, shows very deep H_2O absorptions at 1.5 and 2.0 μm (Fig. 1). The clear feature at 1.65 μm indicates unambiguously the presence of the crystalline phase of water ice. The 1.65 μm band is large and deep (12%), as on Charon (Cook et al. 2007), Quaoar (Jewitt & Luu 2004), 2003 EL_{61} (Merlin et al. 2007), and icy satellites of giant planets (i.e., Grundy et al. 2006; Emery et al. 2005).

Grundy & Schmitt (1998) showed that the wavelength of the band of crystalline water ice at 1.65 μm strongly depends on temperature. This band was used to determine the temperature of crystalline water ice on other TNOs whose spectrum is dominated by water ice (on Charon, by Cook et al. 2007; or on the TNO 136108 (2003 EL_{61}), by Merlin et al. 2007). We use the method described in Merlin et al. (2007) to determine the central position of the band in Orcus spectrum. We find the minimum of the band close to 1.6561 ± 0.0009 μm, which corresponds to a temperature of 44 K. However, taking into account a possible contribution of amorphous water ice (see further) and possible effects due to irradiation (see Merlin et al. 2007, for more details about temperature constraints) this value of 44 K should be considered as an upper limit to the temperature.

In addition, an absorption feature appears in the spectrum of Orcus around 2.2 μm (see Fig. 1). This band has a depth of 10% and is centered around 2.216 ± 0.001 μm. This feature is somewhat similar to that observed on Charon by Brown & Calvin (2000), Dumas et al. (2001), and Cook et al. (2007), on Miranda by Bauer et al. (2002) and suggested on Quaoar by Jewitt & Luu (2004), and attributed to a combination of pure ammonia and ammonia hydrate (Brown & Calvin 2000). It should be noted that, for Charon, the ammonia is not distributed uniformly; the band is more noticeable on the leading hemisphere and there is a slight difference in the wavelength positions (2.1995 and 2.2131 μm, respectively) between the two hemispheres (Cook et al. 2007). Concerning Quaoar, the presence of an absorption feature at 2.2 μm has been confirmed by Schaller & Brown (2007), but is assigned instead to methane ice. It should also be noted that ammonia has not been detected on any icy satellite of the outer planets other than Miranda.

NH_3 ice has two bands in the near-infrared range, the first at 2.0 μm, completely hidden by the water ice absorption band in our case, and a second one between 2.24 and 2.21 μm, depending on the hydration state of the ammonia (see Fig. 3 of Schmitt et al. 1998; and Moore et al. 2007). The absorption band of pure NH_3 ice appears at 2.24 μm while the center of the band we observe is close to 2.21 μm, which would imply that NH_3, if present on the surface of Orcus, would be hydrated. As methane ice also has a band around 2.2 μm, we considered the possibility that methane is present on Orcus as well.

To investigate the surface properties of this object, we ran a radiative transfer model, based on the Hapke theory (1981 and 1993). To account for the presence of the absorption feature near 2.2 μm, we first considered ammonia in pure or diluted state with water ice (see Fig. 2). We find that only small amounts of ammonia ice diluted in crystalline water ice must be present to conserve the 1.656 μm band. The optical constants of ammonia come from Roush (personal communication) for the diluted states and from Schmitt et al. (1998) for the pure state.

A mixture of crystalline and amorphous water ice, combined with ammonia ices, provides the best fit of the absorption bands. The optical constants of water ice used in our models are those of amorphous water ice at 38 K from Schmitt et al. (1998) and crystalline water ice at 40 K from Grundy & Schmitt (1998). With only these compounds, however, we cannot reproduce the blue slope of the spectrum in the near infrared. Therefore, as was done for Charon by Cook et al. (2007), we introduce an additional "blue component" in our model. Several phyllosilicates show this kind of behavior (Trujillo et al. 2007, including a weak feature at 2.2 μm, but they also present some other absorption bands. For the sake of simplicity, we choose to introduce in our

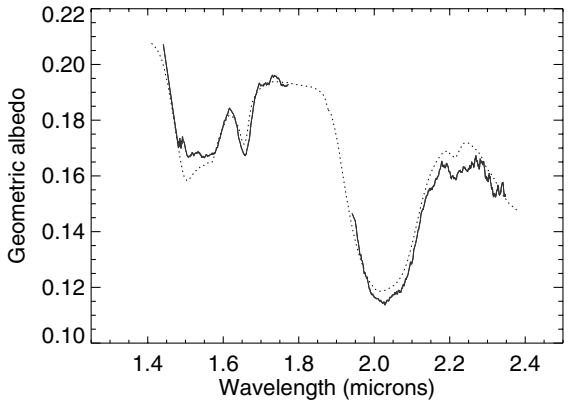

Fig. 3. The dotted line superimposed on the observed spectrum (solid line) is the synthetic spectrum which gives the best χ^2. It corresponds to a spatial mixture of crystalline water ice, amorphous water ice, ammonia hydrate and a "blue" component (see text). The geometric albedo of Orcus is from Stansberry et al. (2008).

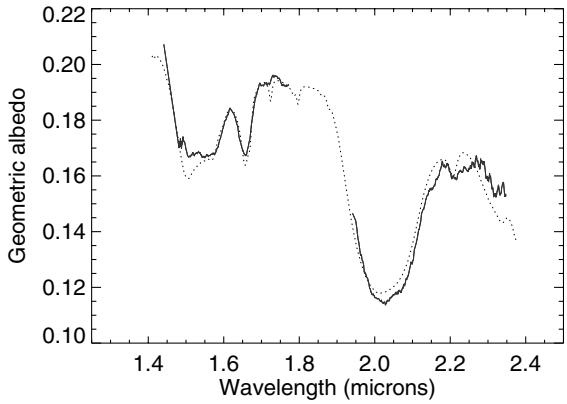

Fig. 4. Model including methane ice instead of ammonia. The dotted line superimposed on the spectrum (solid line) is the synthetic spectrum which gives the best χ^2 (including 3.3% CH_4 with grain size of 450 μm). The geometric albedo of Orcus is from Stansberry et al. (2008).

models a component that is both "blue" (linear slope without any absorption) and dark (to account for the low albedo of Orcus).

We use a mean square algorithm to obtain the model that gives the best agreement with the observations. The best fit (reported in Fig. 3) is obtained when including water ice in both states (crystalline and amorphous, respectively 15% and 17% with grain sizes of 50 and 20 microns), ammonia diluted (1%) in crystalline water ice (5% with large grain size of 250 μm), and large amounts of the blue component (63% with grain size of 40 μm). The blue component that provides the best fit is relatively dark and has a blue slope of about 5%/100 nm. The fit of the ammonia band absorption is not perfect but the general behavior of the band near 2.2 μm is reproduced, as well as the absorption band of crystalline water ice at 1.65 μm, and this is the best model that can be obtained using the available optical constants for ammonia hydrates. It should be noted that only two sets of optical constants exist for ammonia hydrates (both from Roush) and that they were both derived from reflectance spectra of not very well characterized samples of NH_3:H_2O at 80 K (from Brown et al. 1988).

We also ran a model in which ammonia is replaced by methane ice (see Fig. 4). The optical constants for methane are from Quirico & Schmitt (1997) and correspond to a temperature of 40 K. As shown in Fig. 4, the band of methane around 2.2 μm is too narrow and not centered at the right wavelength, and the fit beyond 2.25 micron is not as good as with the ammonia. Moreover the band due to methane at 1.724 μm is not present in the observed spectrum of Orcus. We cannot exclude however the presence of small amounts of methane on the surface of Orcus.

4. Discussion

The analogies between Charon and Orcus noted in de Bergh et al. 2005 (orbital properties, neutral color in the visible, deep water ice absorptions) are now strengthened by the unambiguous detection of crystalline water ice on Orcus, the detection of a feature at 2.2 μm somewhat similar to that observed on Charon, and the recent measurements of Orcus' density and visible albedo (about 0.2 compared to 0.36–0.39 for Charon) by Stansberry et al. (2008). Only small amounts of methane could be present on the surface of Charon (Cook et al. 2007), and this seems to also be the case for Orcus.

Our models indicate that, as for Charon, the best candidate to explain the 2.2 μm feature is some ammonia hydrate. However, this identification is not unique as it relies only on one feature (which is also the case for Charon); furthermore, this feature is quite weak and needs confirmation. Still higher S/N observations are obviously required.

As already discussed by Jewitt & Luu (2004) and Cook et al. (2007), the presence of crystalline water ice and ammonia hydrates on the surface of a TNO would tend to argue for an efficient surface renewal mechanism. Indeed, extrapolation of laboratory experiments on water ice irradiation to the conditions of a TNO at 40 AU indicates that crystalline water ice on the surface of TNOs should be completely amorphized by irradiation in about 10^7 years (Cooper et al. 2003). In recent works (Barucci et al. 2008; Barkume et al. 2008), TNOs with spectra showing water-ice absorptions measured with high S/N have been shown to have the 1.65 μm band due to the presence of H_2O ice in the crystalline phase. While crystalline water ice is neither expected at these lower temperatures nor should it be stable against cosmic-ray and UV bombardment, crystalline water ice appears to be ubiquitous in the outer solar system. Brown et al. (2007) suggested that the deep water-ice absorption on the TNO spectra has to be a function of a relatively short surface exposure age implying a relatively recent collision for these objects. Both internal and external surface renewal mechanisms have been considered to explain the presence of crystalline water ice on TNOs: heating accomplished by micrometeoritic or larger impacts (impact gardening) or cryovolcanism, even if it is clear that our current understanding of the physics of the crystalline/amorphous phase transition is not complete.

Concerning ammonia, Strazzulla & Palumbo (1998) demonstrated that ammonia hydrates are easily destroyed by energetic radiation, and Cooper et al. (2003) showed that at 40 AU from the Sun it would happen in less than 10^7 years. An external source of ammonia was therefore hypothesized for Charon, as its neighbour Pluto is very rich in nitrogen (e.g., Dumas et al. 2001), whereas cryovolcanism was considered for Quaoar (Jewitt & Luu 2004) and for Charon (Cook et al. 2007). Recent models of the interiors of TNOs show that cryovolcanism, which is considered the most probable mechanism to explain geological activity

on some satellites of the outer planets (and which would be facilitated by the presence of ammonia in the interior of these bodies), may indeed be possible for TNOs larger than about 1000 km (McKinnon et al. 2008).

A firm detection of ammonia on the surface of an isolated TNO such as Orcus would also have important implications on the composition of the primitive solar nebula in regions of low density (far from the Sun), allowing us to determine if nitrogen was present mainly in the form of N_2 or NH_3 at more than 40 AU from the Sun. Early models of solar nebula condensation in the outer solar system indicated that NH_3 may have been an important condensate (Lewis 1972), while more recent models predict that, due to possible kinetic inhibition of N_2 reduction in the solar nebula, most of the nitrogen was present as N_2 (Lewis & Prinn 1980). Ammonia may be present on Miranda, as already mentioned (Bauer et al. 2002). However, the case of icy satellites of the outer solar system is peculiar, since they formed in the warm and dense subnebulae of each proto-gas-giant planet. Ammonia has been detected in a few bright comets (Bockelée-Morvan et al. 2004). Its photodissociation products, NH and NH_2, have been detected in many more comets, including Jupiter family comets. The abundance of ammonia in the nucleus is of the order of 0.5% relative to water while the amount of N_2 in comets, if present at all, is much lower (see review of Bockelée-Morvan et al. 2004). It is therefore very important to search for nitrogen compounds on the surface of TNOs and see which ones dominate, keeping in mind that the surface composition of the object does not necessarily reflect its bulk composition (in particular, as ammonia is easily destroyed, much larger amounts of ammonia could be present inside an object on which small amounts of ammonia are detected). The detection of ammonia is also very important for the geological study of TNOs, particularly for the low-melting point of cryovolcanism that it would imply.

To secure our detection of ammonia on Orcus requires still higher S/N spectra. This may be possible in the near future at the VLT by using the same instrument (SINFONI) with the adaptive optics system and the laser guide star, which are both now available. More laboratory work on ammonia hydrates, and in particular measurements of optical constants, is also required.

Acknowledgements. We are very grateful to T. Roush to have provided the optical constants for ammonia hydrates and to J. Emery for his helpful review and suggestions.

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