

RESULTS FROM THE ESO LARGE PROGRAM ON TRANSNEPTUNIAN OBJECTS AND CENTAURS

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Abstract. BVRI photometry of 107 TNOs and Centaurs establishes the range of spectral gradients to be between -5 to $55\%/100$ nm (with one exception). A cluster of very red Cubewanos is firmly identified in orbits of low inclination and eccentricity beyond 40 AU from the Sun. Further correlations between surface colours and dynamical parameters (inclination and perihelion distance) are suggested for Cubewanos and scattered disk objects, but lack complete confidence for their reality. Plutinos and Centaurs do not show any clear correlation between surface colours and orbital parameters. We present in this paper 12 spectra obtained in the visible region and nine of them for which we obtained also near infrared spectra up to 2.4 microns. A few other objects have been observed, but the data are still under reduction and analysis. The principal reported results obtained are: (i) a wide range of visible slopes; (ii) evidence for surface variations on 2001 PT₁₃; and (iii) possible detection of few percent of water ice (1999 TC₃₆, 2000 EB₁₇₃, 1999 DE₉, 2001 PT₁₃, 2000 QC₂₄₃, 1998 SG₃₅).

1. The ESO Large Program on TNOs and Centaurs

Concept: After a number of uncoordinated precursor programs at ESO telescopes at the end of the last decade, a consortium of scientists (see the list of authors of this paper) has proposed a comprehensive observing and analysis project to be performed within the frame work of an ESO Large Program: 'Physical Studies of Transneptunian Objects (TNOs) and Centaurs'. The project was accepted to be executed at Cerro Paranal and La Silla during ESO period 67 to 70, i.e., from April 2001 until March 2003. The main goal of the project is the development of a



taxonomic classification scheme of these icy bodies in the outer solar system, the identification of evolutionary tracks and their relationships with dynamical classes, the exploration of the surface chemistry of the objects and its correlation with taxonomic classes. The proposed observing campaigns at the ESO Very Large Telescope VLT and the New Technology Telescope NTT comprise multi-colour broadband filter photometry of 60–70 objects in the visible and about 25 objects in the near-IR wavelength range for the taxonomy analysis AND low-dispersion spectroscopy in the visible and near-IR of about 15–20 objects each for surface composition studies. The ESO Program Committee has allocated in total 242 h VLT time and 3 nights at the NTT for this Large Program. The workhorse instruments for the proposed type of observations are FORS1 and ISAAC at VLT Unit Telescopes 1 (Antu) and 3 (Melipal). Broadband photometry of some brighter targets is also conducted with SUSI2 at the La Silla NTT.

Observing modes and target selection: The majority of the photometry targets are observed in service mode (SM) at the VLT with the exceptions of brighter ones that are either imaged at the NTT or during VLT spectroscopy runs in visitor mode (VM). Experience from previous programs has shown that the SM targets have to be selected among objects that allow safe detection in the fields of view of the instruments, i.e., objects with at least 2 observed oppositions. For the BVRI measurements we selected targets with V brightness of 22.5–24 mag, for JHK photometry the objects need to be brighter than 22.5 mag in V. The SM targets are requested to be observed under clear to photometric dark sky conditions with seeing better than 0.8". These constraints together with the chosen integration times guarantee a minimum signal-to-noise-ratio (S/N) for the individual objects of 30–50 in BVRI and 20–40 in JHK. In terms of fulfilment of the observing requirements this part of our program can be considered as almost 100 percent successful.

The spectroscopy part of the program is performed in visitor mode only, although originally requested and approved for SM observations. The targets had to be selected among brighter objects, i.e., brighter than 22.5 mag in V for spectroscopy in the visible wavelength range and brighter than 20.5 mag in V for the near-IR spectroscopy. Quasi-simultaneous broadband photometry of the targets is taken during spectroscopy runs. Visible and near-IR spectroscopy runs are scheduled within a few days from each other in order to guarantee observations of the same object under similar phase angles. However, this scheduling usually does not allow to correlate the rotational phase of the objects for the measurements in both wavelength ranges. The exposure times of the targets aimed for a S/N of about 3–10 per wavelength pixel element which through wavelength binning allowed improvements by a factor of 3–5.

Data reduction and analysis: The basic data reduction products of the photometry are absolute broadband filter magnitudes in BVRI and JHK, filter colours and spectral gradients. The magnitude (equivalent to sizes), colour and gradient data

are correlated with each other and with orbital parameters to associate and explore taxonomic classes and their colour properties through statistical methods. This exercise is applied to our database alone and to an even larger dataset merging our results with those published in literature. The spectra are reduced to relative reflectivity units that allow to determine spectral gradients and to identify absorption features that may be indicative for the surface chemistry. Each spectrum covering a wider wavelength range is modelled through a Hapke reflectance modelling code to constrain and, if possible, to quantify the surface composition of the targets. In a final phase of the project it is foreseen to correlate spectral properties with the photometric taxonomy of the objects.

Status of the program: The observations of the program were completed in March 2003. In total, 84 objects were measured in BVRI and 28 in JHK. Spectra of 23 objects were taken in the visible and of 14 in near-IR. The data reduction and analysis is still on-going. Results are already published (Barucci et al., 2002; Boehnhardt et al., 2002; Lazzarin et al., 2003; Dotto et al., 2003; Doressoundiram et al., 2003) or are in press (de Bergh et al., 2004) or will be submitted soon (for instance two new photometry papers).

Here, we present results from the BVRI photometry and the visible and near-IR spectroscopy as they are available up to now (April 2003).

2. Results

2.1. PHOTOMETRY

BVRI spectral gradients: the database of BVRI observations contains 107 objects compiled from the large program and other published data of brighter objects (i.e., obtained by collaborators of our team at the same ESO VLT telescopes and instruments, using the same observing techniques and reduced in the same way as the observations of the large program; Boehnhardt et al., 2001; Delsanti et al., 2002). The broadband magnitudes allow to obtain the spectral gradients (Boehnhardt et al., 2001) as a measure of the intrinsic reddening of the objects. The histograms in Figure 1 show the spectral gradient distribution of the various dynamical classes of the TNOs (i.e., Cubewanos or classical disk objects CDOs, Plutinos, scattered disk objects SDOs) and of the Centaurs. With one exception the spectral gradients of all objects fall between -5 and $45\%/100$ nm. The Cubewanos show a pronounced peak for spectral gradients between 15 and $35\%/100$ nm that is caused by a population of red objects in circular and low inclination orbits beyond 41 AU. Plutinos and SDOs have similar, but distinctly different distributions of spectral gradients peaking at lower reddening. For Centaurs the distribution peaks below $15\%/100$ nm (as for Plutinos and SDOs), but it may have a 'gap' in the medium reddening range. Since the number statistics of objects is low, the latter conclusion is still uncertain.

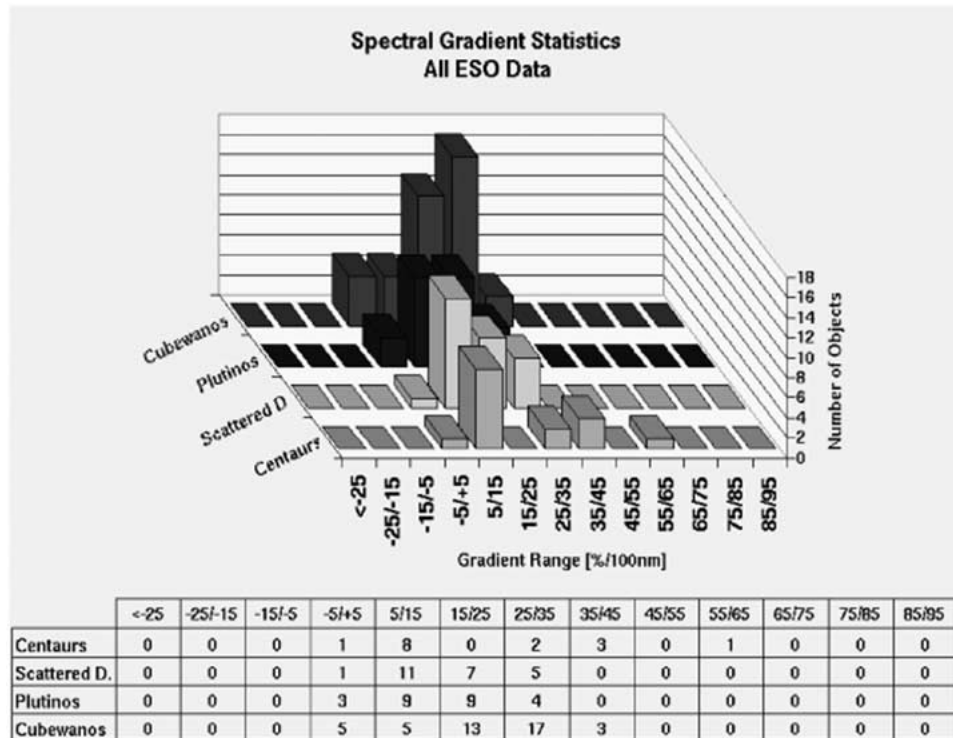


Figure 1. Spectral gradient histograms of the sample of 107 objects in our database sorted by dynamical classes.

The red Cubewano cluster: The peak in the Cubewano spectral gradient histogram is resolved in Figures 2 and 3: a cluster of very red CDOs with low eccentricity ($e < 0.05$) and low inclination ($i < 5$ deg) orbits beyond ~ 40 – 41 AU from the Sun (first suggested by Tegler and Romanishin, 2000 from a much smaller dataset). The cluster members have similar dynamical and colour properties and may represent the first taxonomic family in the belt. Space-weathering is claimed to be responsible for the reddening of the TNO surfaces (Strazzulla and Johnson, 1991). As can be seen from Figure 3, the range of reddening is much wider at the inner edge of the Edgeworth-Kuiper belt and remains about constant across the objects with orbits that come closer than ~ 35 AU to the Sun.

‘Correlation families’: Several authors published colour data for CDOs and SDOs suggesting a correlation between reddening and inclination (Trujillo and Brown, 2002; Doressoundiram et al., 2002). In Figure 3 plots of the spectral gradients of CDOs and SDOs versus inclination in our dataset (that is by a factor of about 2 larger than any other data used before) are displayed together with trending lines obtained from linear regression fits of the data. The statistical interpretation of the colour properties is inconclusive and, at best, one may want to speculate on a

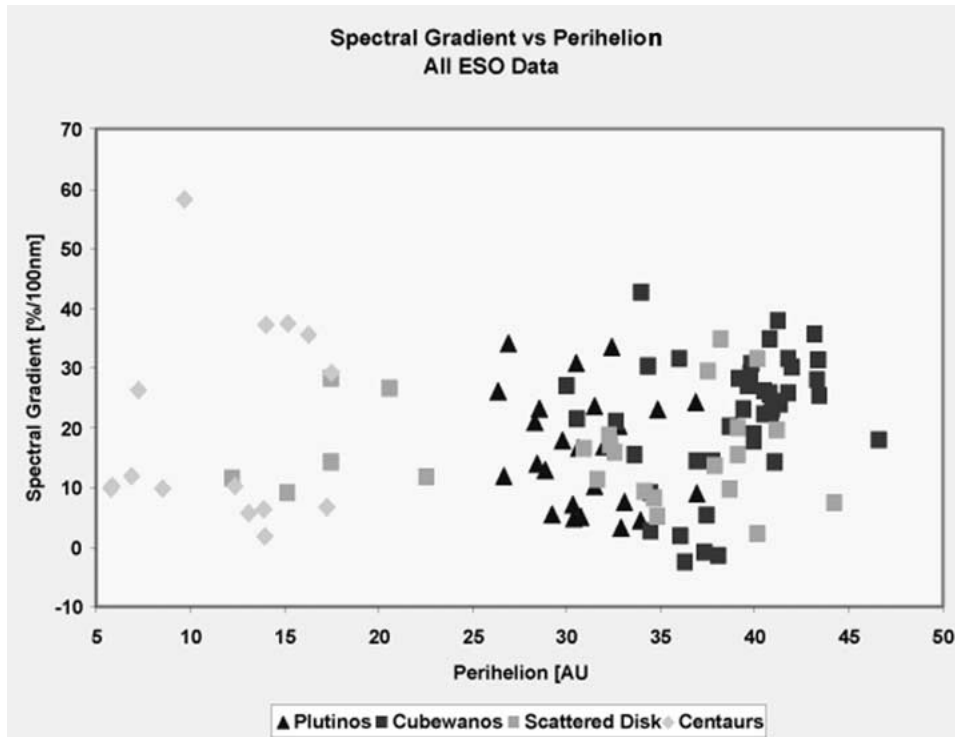


Figure 2. Spectral gradients of Cubewanos, Plutinos, SDOs and Centaurs versus perihelion distance.

reddening trend with inclination for CDOs, while for SDOs both parameters appear to be widely uncorrelated. And even for CDOs the reddening-inclination trend may become marginal, if one removes the objects of the red Cubewano cluster from the fit sample.

The reddening of Cubewanos versus perihelion distance q suggests yet another trend (see Figure 4): CDOs with q between ~ 36 and 40 AU may show an increase of the spectral gradient with increasing perihelion distance (confidence of above 85 percent). It is not obvious that collision resurfacing could account for this behaviour (since for instance SDOs do not show such a correlation). However, recondensation from a temporary atmosphere that could be produced by ice sublimation from the upper surface layers is suggested (Hainaut et al., 2000; Boehnhardt et al., 2001) as an alternative resurfacing process for TNOs, and indeed, according to theoretical calculations (Delsemme, 1982), N_2 and CO ice may be capable to sublimate at distances up to 40 AU and more. It is, however, noteworthy that the same CDO population that shows the reddening trend with increasing q displays a similar reddening trend with inclination as described above (see Figures 3 and 5). The situation of the correlations surface reddening versus inclination and versus perihelion distance remains unresolved with the present dataset.

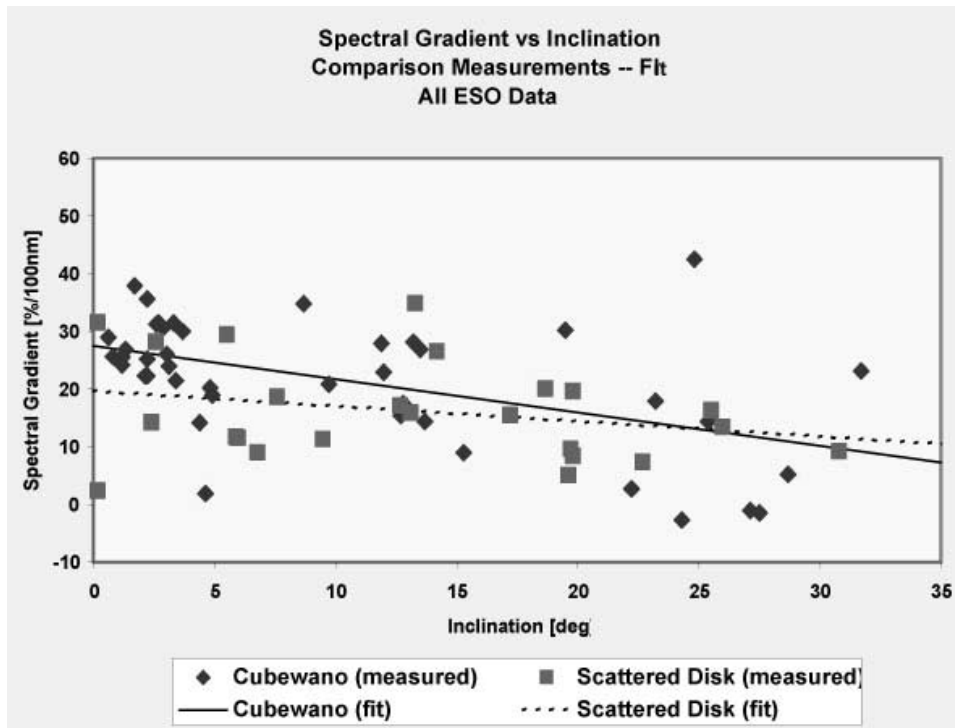


Figure 3. Spectral gradients of Cubewanos and scattered disk objects versus inclination. The trending lines are plotted separately for both dynamical object classes.

Attempts to obtain further correlations between surface reddening and orbital parameters were unsuccessful so far for all dynamical classes of TNOs and Centaurs. Considering the weak correlations of the reddening versus inclination or perihelion distance trends mentioned above and the large scatter of the data around the trending lines, it may be too early to claim the existence of further ‘colour’ families in the Edgeworth-Kuiper Belt (except the red Cubewano cluster).

2.2. SPECTROSCOPY

Visible spectroscopy: Twelve TNOs and Centaurs are analysed so far (Lazzarin et al., 2003). The spectra show a general featureless behavior with a difference in the spectral gradient spanning from neutral to very red. The computed reflectance slopes range from 10 up to 56%/100 nm.

For two Plutinos, 38628 (2000 EB₁₇₃) and 47932 (2000 GN₁₇₁) wide absorption bands are found. In the spectrum of 47932 (2000 GN₁₇₁), an absorption centered at around 0.7 μm is detected with an 8% depth, while in the spectrum of 38628 (2000 EB₁₇₃) two weak features centered at 0.6 μm and at 0.745 μm are seen with depths of ~ 7 and 8.6%, respectively. These features are very similar to those due to aqueously altered minerals, found in the C-type main belt asteroids. The two

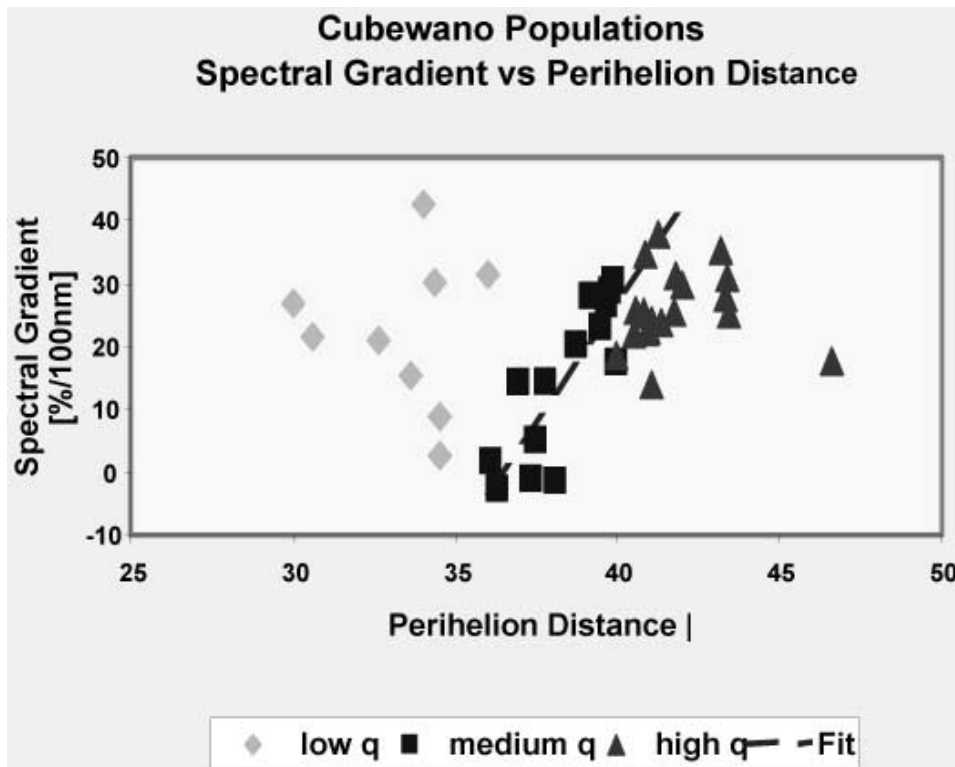


Figure 4. The CDO reddening correlation with perihelion distance (squares: medium q).

objects were re-observed about one year after the first run and they did not show the same features. This could be explained with variation on the surface composition of the two objects. More observations are scheduled to check these features which, if confirmed, could provide very important constraints on the origin and the evolution of TNOs and Centaurs.

Near-IR spectroscopy: Some of the objects observed in the visible are also observed in the infrared region (JHK bands) and a model of their surface composition is obtained using the visible and the infrared spectra and connecting the different spectral ranges via relative photometry. The lack of albedo does not allow one to constrain the modelling attempt, but assuming dark surfaces, model spectra are computed and fitted to the observations in order to interpret the different behaviours of the obtained spectra (see Figures 6 and 7).

Modeling of the combined spectra: We have observed the Centaur 32532 (PT₁₃) just after its discovery (Barucci et al., 2002). Infrared spectra from 1.1 up to 2.4 μm are obtained at two different epochs one month apart, and the spectra seem to be quite different indicating differences on the surface composition (Figure 6). One

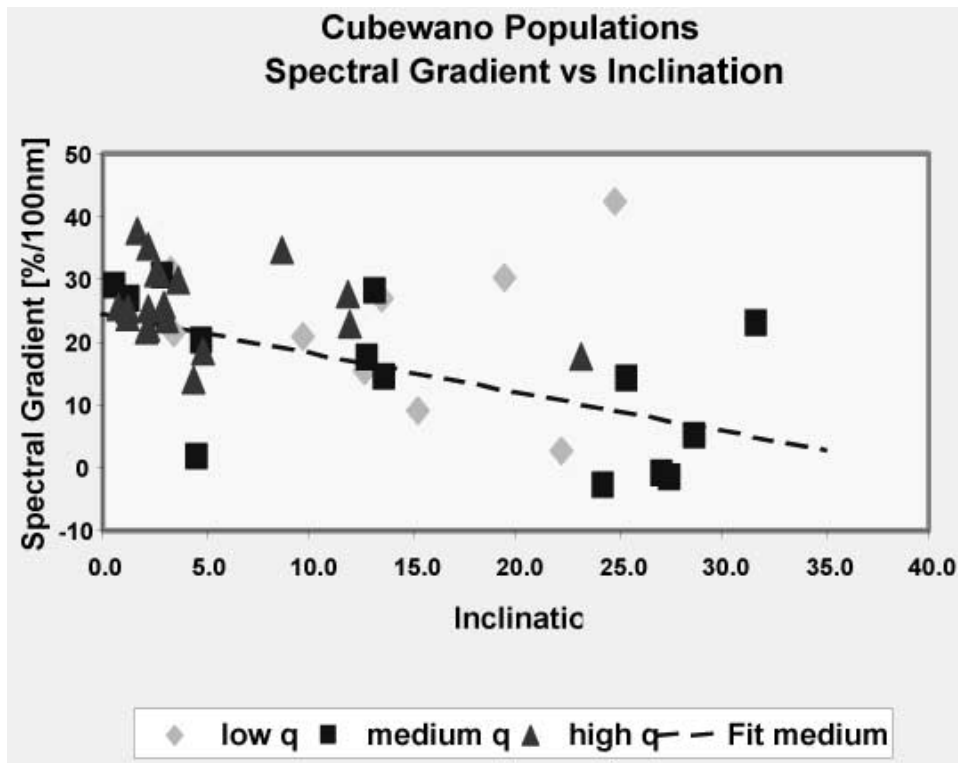


Figure 5. The CDO reddening correlation with inclination (squares: medium q).

of the observations shows tentative evidence for the presence of water ice on the surface of the object, however, the match of the observed spectrum by crystalline water ice is not optimum. The upper spectrum shown in Figure 6 seems to be well fitted with a model containing a geographical mixture of 15% Titan tholin, 70% amorphous carbon, 3% Olivine and 12% ice tholin, altogether assuming an albedo of 0.09.

For the other spectrum a model with an albedo of 0.06 and 90% amorphous carbon, 5% Titan tholin and 5% water ice is obtained. Both Titan and ice tholins are synthetic macromolecular compounds produced from a gaseous mixture of $N_2 : CH_4$ (Titan tholins) or an ice mixture of $H_2O : C_2H_6$ (ice tholins) (Sagan and Khare, 1979). Titan tholin is the only material that is able to reproduce the unusual red slope between 0.4 and 1.2 μm .

Three more Centaurs, 1998 SG₃₅, 2000 QC₂₄₃ (Dotto et al., 2002) and 2001 BL₄₁ (Doressoundiram et al., 2003), were observed within our program. A tentative model is computed for 1998 SG₃₅ and 2000 QC₂₄₃ with similar percentages of Kerogen (96–97%), olivine (1%), and water ice (2–3%), while for 2001 BL₄₁ a model with 17% Triton tholin, 10% ice tholin and 73% amorphous carbon with albedo 0.08 is obtained. Triton tholin (a compound produced from a more nitrogen-

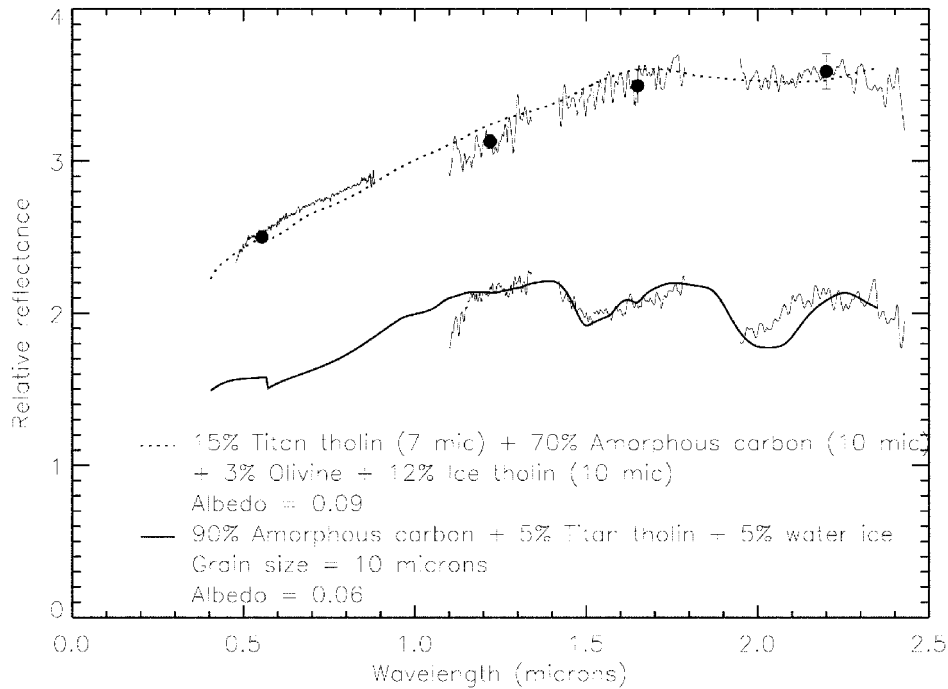


Figure 6. Two observed visible and near-IR spectra of the Centaur 32532 (PT₁₃) compared with model calculations. The spectra are shifted in relative reflectance for clarity.

rich N₂:CH₄ mixture) is used to reproduce the continuous and moderate gradient of the whole spectrum from 0.4 to 2.4 μm , Kerogen is used for the previous objects to reproduce the red slope in the visible region, while amorphous carbon allows to improve the general fit of the spectra.

Near-IR spectra were obtained for TNOs (Figure 7), even though these are usually fainter than Centaurs and thus need significantly longer integration times for similar signal-to-noise in the spectra. 38628 (2000 EB₁₇₃) was previously observed by several authors (Brown et al., 2000; Licandro et al., 2001; Jewitt and Luu, 2001): its spectrum appears in general featureless. Our observations and the one of Licandro et al. show a possible absorption feature beyond 1.8 μm . An attempt is made by de Bergh et al. (2003) to interpret the complete visible and near-IR spectrum obtained within our program by a surface material mixture of amorphous carbon, Titan tholin and some Jarosite, the latter with the intention to represent some of the signatures present in the visible spectrum (see Figure 7). The model does not fit well the spectra: the Jarosite has been included to account for the absorption band at 0.6 μm , but does not fit at all the band at 0.75 μm . No other minerals for which laboratory data are available allow a better fit to the spectral behaviour however.

47171 (1999 TC₃₆) was observed in the J, H, and K region (Figure 7). Two K spectra are available from two different nights, and they show similar characterist-

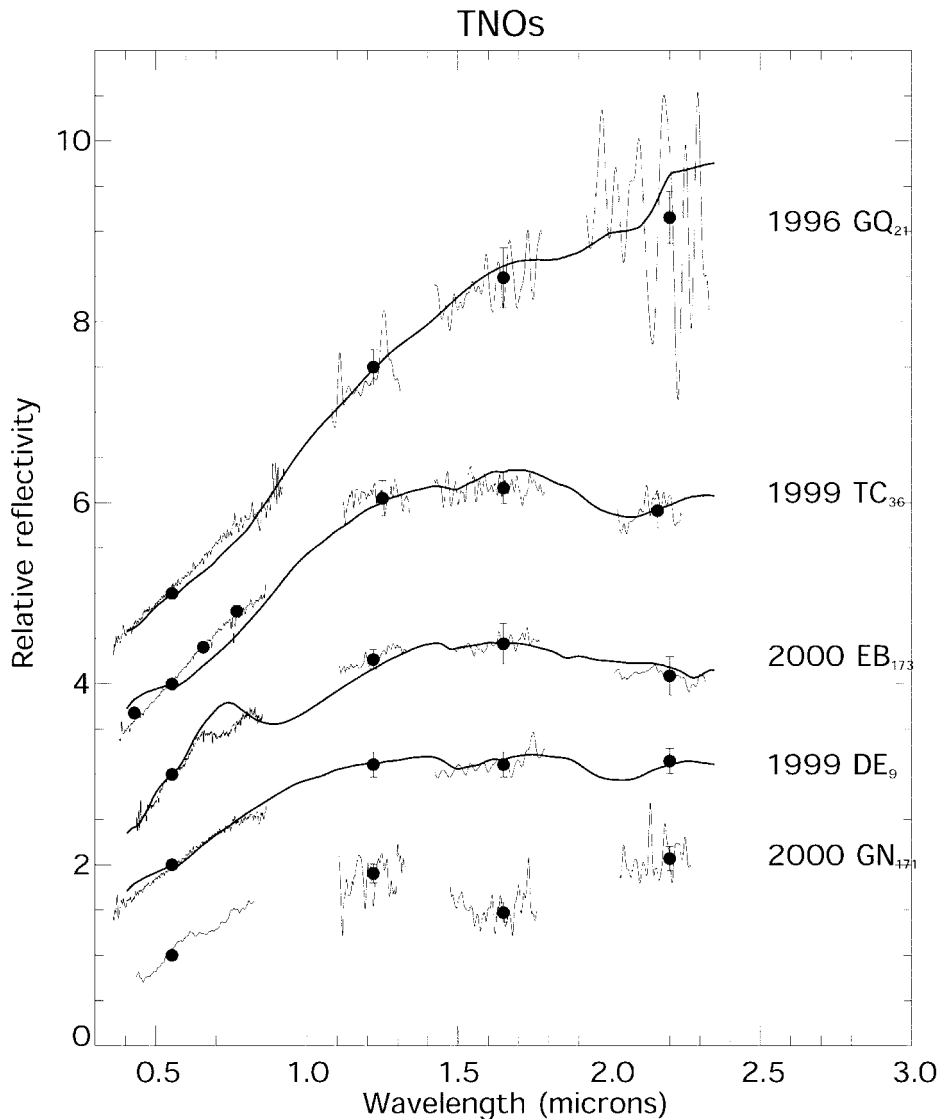


Figure 7. Comparison of more visible and near-IR spectra of TNOs with models.

ics with a weak absorption around $2 \mu\text{m}$. Dotto et al. (2003) analyze the combined visible and infrared spectra and interpret the surface of the object by a mixture of 57% of Titan tholin, 25% of ice tholin, 10% of amorphous carbon and 8% of water ice. The tholins are the only materials able to reproduce the unusual red slope (0.4– $1.2 \mu\text{m}$) in the spectra, even though the overall fit is not very good in the visible region. However, no other combination of materials is found that better reproduces the spectra at these wavelengths.

For 26375 (1999 DE₉) we obtained (due to technical problems with ISAAC at VLT-ESO) only a spectrum in H band. A tentative very uncertain model by Doressoundiram et al. (2003) combining V and H spectra plus photometric data (Figure 7) uses a mixture of 24% Titan tholin, 15% ice tholin, 54% amorphous carbon and 7% water ice. Jewitt and Luu (2001) observed 26375 (1999 DE₉) at Keck and found solid-state absorption features near 1.4, 1.6, 2.00 and probably at 2.25 μm . The location of these absorptions is interpreted by these authors as evidence for the hydroxyl group with possible interaction with an Al or Mg compound, in addition to water ice. The presence of the drop from 1.3 to 1 μm seems to be consistent with olivine absorption. We are planning to observe this object again to confirm the presence of the hydroxyl group which would imply the existence of liquid water on the surface in the past and a temperature near its melting point for at least a short period of time.

In Figure 7, the spectrum of 47932 (2000 GN₁₇₁) obtained within our program is shown as well. However, so far we are unable to model it (de Bergh et al., 2003). In the same figure the spectrum of 26181 (1996 GQ₂₁) is reported. This spectrum is featureless, but very red. Doressoundiram et al. (2003) model it by a geographical mixture composed of 15% Titan tholin, 35% ice tholin and 50% amorphous carbon.

3. Conclusion

The ESO Large Program on “the physical study of TNOs and Centaurs” completed its 2 years observing cycle in March 2003.

The broadband photometry of 107 TNOs and Centaurs has firmly established the range of spectral slopes seen in these objects and supports the existence of a cluster of Cubewanos with very red surface colours in dynamically ‘cold’ orbits close to the Ecliptic beyond ~ 40 AU from the Sun. Various other correlations between spectral slopes and orbital parameters (inclination, perihelion distance) are suggested, but do not (yet) reach the level of confidence needed to be considered as real. The explanation scenarios proposed for the confirmed and possible links between dynamical and surface properties of the objects involves space weathering for red colours, and collision or atmospheric re-condensation resurfacing for the bluish slopes. Nevertheless, the existing interpretations for the colour correlations are not based on firm modelling results and should be considered as tentative only (at least for the time being).

The spectra revealed indications for the presence of water ice at several objects. The puzzling question whether water existed partially in liquid form in these objects at least for some time in the past, is unsolved and requires further observations and analysis. Due to the lack of albedo and unambiguous diagnostic signatures, the obtained models give only indications for the possible materials present on the surfaces. The obtained models represent the best fit to the data, but they are not

unique and depend on many unknown parameters like grain size, albedo, porosity, etc.

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