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

Multicolour photometry of trans-Neptunian objects: surface properties and structures

Alain Doressoundiram [a,*], Hermann Boehnhardt [b]

[a] *LESIA, observatoire de Paris, UMR CNRS 8109, 92195 Meudon Principal cedex, France*
[b] *Max-Planck-Institut für Astronomie, Heidelberg, Germany*

Presented by Pierre Encrenaz

Abstract

Trans-Neptunian Objects (TNOs) and Centaurs display the widest colour range among solar system objects. Moreover, recent observational results revealed: (1) the existence of a family of classical TNOs (also called Cubewanos) with very red colours in dynamically 'cold' orbits beyond about 40 AU from the Sun; and (2) a few correlations among the dynamically 'hot' Cubewanos. Other TNO populations and the Centaurs show no obvious and systematic trends. The article describes the observations and reduction techniques applied for the photometry of these distant and faint solar system objects and provides a brief overview on the results and their links with formation and evolution scenarios of these primitive bodies in the outer solar system. ***To cite this article: A. Doressoundiram, H. Boehnhardt, C. R. Physique 4 (2003).***

Résumé

Photométrie multi couleurs des objets transneptuniens : propriétés de surface et structures. Les objets transneptuniens (TNOs) et les Centaures sont caractérisés par une extrême diversité de couleurs unique dans le Système Solaire. Récemment, des observations ont révélé : (1) l'existence d'une famille de TNOs Classiques (aussi appelés Cubewanos) aux couleurs très rouges et sur des orbites dynamiquement « froides » au-delà de 40 UA du Soleil ; et (2) quelques corrélations parmi les Cubewanos dynamiquement « chauds ». La distribution des couleurs des autres populations de TNOs et de Centaures ne montre aucune structure claire et évidente. L'article décrit les observations et les techniques de réductions utilisées pour la photométrie de ces objets faibles et distants et fournit un bref aperçu des résultats et leurs liens avec les scénarios de formation et d'évolution de ces objets primitifs du Système Solaire externe. ***Pour citer cet article : A. Doressoundiram, H. Boehnhardt, C. R. Physique 4 (2003).***

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Mots-clés : Système Solaire ; Ceinture de Kuiper ; Objets transneptuniens ; Photométrie

1. Introduction

The Trans-Neptunian Objects (TNOs), also called Kuiper Belt Objects, are small bodies of the solar system that orbit around the Sun beyond Neptune. The TNOs are extremely primitive remnants from the early accretional phase of the solar system and

* Corresponding author.
E-mail address: Alain.Doressoundiram@obspm.fr (A. Doressoundiram).

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Table 1
List of broad-band filters commonly used

Type	λ_c (μm)	Type	λ_c (μm)
U	0.37	I	0.77
B	0.43	J	1.2
V	0.55	H	1.6
R	0.66	K	2.2

they may contain the most primitive and least altered material [1]. However, because of their small sizes and large heliocentric distances, these objects are very faint and therefore difficult to study.

Dynamically, the Kuiper Belt is strongly shaped, and three main populations are usually distinguished within this region. The resonant TNOs are trapped in mean motion resonances with Neptune, in particular the 2 : 3 at 39.4 AU (the so-called *Plutinos*), and are usually on highly eccentric orbits. However, they are safe from close encounters with Neptune by a resonant protection mechanism. The less excited classical TNOs, also called *Cubewanos*, populate the region between the 2 : 3 and the 1 : 2 (at 47.7 AU) resonances. Finally, the *Scattered* TNOs make up a less clearly defined population and are mainly objects with high eccentricity e and semi-major axis $a > 48$ AU that were presumably placed in these extreme orbits by a weak interaction with Neptune [2]. The Centaurs, finally, represent a dynamical family of objects in unstable orbits with semi-major axes between Jupiter and Neptune. Their dynamical lifetime is, as is the case for Centaurs, a few million years [3]. Long-term orbital integrations suggest that perturbations of the TNOs by the giant planets provide a source for the Centaurs and, finally, also the short-period comets [3,4]. The structure, origin, and respective importance of these populations is still a subject of great debate. The reader is referred to [5] for a more complete review.

Because of the faintness of these objects, spectroscopic studies are difficult and possible only for a handful of brighter objects. On the other hand, multi-colour broadband photometry of a much larger number of TNOs allows a compositional survey of these bodies, using a statistical approach. As of June 2003, about 800 TNOs have been discovered. From this population, about 150 objects have broadband colours measured. In this paper, we will review the knowledge gained from these multi-colour photometric surveys.

2. Observations and data reduction

2.1. Observational strategy

Visible and near-infrared CCDs with broadband filters operating in the wavelength range of 0.3 to 2.5 microns provide the basic set of photometric observations, including light curve studies, for most of the discovered objects. Usually, optical and or infrared CCD imagers are used to obtain multi-colour photometry of the objects (e.g., B–V). Table 1 gives the common filters used for this kind of observations, together with their approximate central wavelengths.

Because of their specific and unique nature, observations of Trans-Neptunian objects require adapted observational procedures and data reduction techniques. What makes TNOs challenging objects for those who try to measure, for example, colours and light-curves? In brief, they are *faint*, they *move*, they are *rotating*.

2.1.1. They are faint

First of all, the most challenging point is that the Trans-Neptunian population represents some of the faintest objects in the Solar System. The typical apparent visual magnitude of a TNO is about 23 mag, although a few objects brighter than 22 mag have been found. Another criterion is the minimum signal-to-noise ratio (SNR) of the photometry: typically, SNR ~ 30 (corresponding to an uncertainty of 0.03–0.04 mag) is required to accomplish the spectral classification. Indeed, the differences between the known types of minor bodies (which to a first order look like the Sun) are much more subtle than for stellar types, so considerably higher photometric accuracy is necessary. The more limited the range of wavelengths, the higher the accuracy needed to distinguish objects of different type. However, to reach such a SNR goal, one needs to overcome two problems: (i) the sky contribution which could be important and critical for faint objects not only in the infrared, but also for visible observations; and (ii) the contamination by unseen background sources such as field stars and galaxies. For instance, the error introduced by a 26 mag background source superimposed on a 23 mag object is as large as 0.07 mag. One solution to alleviate these problems is the use of a smaller synthetic aperture for the flux measurement of the object. This method is described in the next section.

2.1.2. They move

TNOs, while at very remote heliocentric distances, do have still noticeable motion that restricts the exposures to relatively short integration time. At opposition, the motion rates of TNOS at 30, 40 and 50 AU are, respectively, about 4.2, 3.2 and 2.6″/hr, thus producing a trail of $\sim 1.0''$ in a 15 min exposure time in the worst case. Trailed objects have devastating effects on the SNR, since the flux is diluted over a larger area of background sky which in turn introduces higher noise. Thus, increasing exposure time will not necessarily improve the SNR for the TNO photometry. For practical purposes, the exposure time is chosen such that the trailing due to the object's motion does not exceed the size of the seeing disk. One alternative could be to follow the object at its proper motion. In this case, however, one faces another problem: the point spread function of the object (PSF) would be obviously different from that of the field stars. Moreover, the so called aperture correction technique used very frequently for accurate TNO photometry would become very difficult since this method requires the PSF calibration of nearby field stars (see next section). As a consequence of the proper motion of TNOs, the number of objects that can be observed with high SNR at big telescopes is indeed limited.

2.1.3. They are rotating

TNOs, like the asteroids, rotate and have most probably elongated shapes or variable surface reflectivity. The rotation rates measured up to now, are typically around 6–12 hours [6] – although this range may be strongly biased by observational selection effects. Measurements in individual filters may lead to erroneous colour indices, if the exposures in the two respective filters are separated by a significant time interval. To eliminate systematic errors in the colours caused by rotational light curve variations, one needs to intersperse observations through the full filter set with multiple observations through the same filter, so that interpolations can be performed (e.g., V–B–V–R–V–I–V).

2.2. Data reduction techniques

The data reduction consists of the basic reduction steps applicable for the visible or near-IR photometric data sets, i.e., bias and flatfield corrections, cosmic ray removal, alignment and co-addition of the jittered images, flux calibration through standard stars.

The brightness of the object is frequently measured through the so-called aperture correction technique [7,8] as justified by the faintness of the TNOs. The basis of this method is that the photometric measurement is performed by using a small aperture of the order of the size of the seeing disk. Consequently, the uncertainty in the measurement is reduced because less noise from the sky background is included in the aperture. However by doing so, one looses light from the object. Thus, to determine how much light is thrown away, the so-called 'aperture effect' is calibrated using a large number of nearby field stars. This is reasonable as long as the motion of TNOs during each exposure is smaller than the seeing, and hence the TNOs' point spread functions (PSFs) are comparable to those of field stars. For all the photometry, the sky value can be computed as the median of a sky annulus surrounding the object. The advantages in the use of a small aperture are: (i) a decrease in the contribution of the sky, which could be important and critical for faint objects; and (ii) a reduction of the risk of contamination of the photometry by unseen background sources.

3. What can be learned from multi-colour photometry of TNOs

Many useful physical parameters of TNOs can be derived from broadband photometry. These parameters include absolute magnitude, size, colour and spectral gradient.

3.1. Colours

From the individual magnitude measurements, colours are computed which provide an indication of surface colour properties of TNOs. The colour indices measured (e.g., U–V, B–V, V–R, V–I, V–J, V–H, V–K) are the differences between the magnitudes obtained in two filters, or in other words: the F_1–F_2 colour index (where F_1 and F_2 is any of the UBVRIJHK filters) measures the ratio of the surface reflectance approximately valid for the central wavelengths λ_1 and λ_2 of the corresponding filters.

3.2. Reflectance spectrum

The information contained in the colour indices can be converted into a very low resolution reflectivity spectrum R_F using:

$$R_F = 10^{-0.4(M_F - M_F\mathrm{sun})}.$$

Where M_F and $M_F$sun are the magnitude in filter F of the object and of the Sun, respectively. Normalizing the reflectivity to 1 at a given wavelength (conventionally, the V central wavelength is used), we have:

$$R_{F,V} = 10^{-0.4[(M_F - M_V) - (M_F - M_V)\mathrm{sun}]}.$$

See Hardorp [9] and Hartmann et al. [10] for the colours of the Sun for the filters commonly used to compute reflectivity spectra.

3.3. *Spectral gradient*

The spectral gradient S is a measure of the reddening of the reflectivity spectrum between two wavelengths. It is expressed in percent of reddening per 100 nm:

$$S(\lambda_2 > \lambda_1) = (R_{F_2,V} - R_{F_1,V})/(\lambda_2 - \lambda_1),$$

where λ_1 and λ_2 are the central wavelengths of the F_1 and F_2 filters, respectively.

If several filters are measured (BVRI), the spectral gradients can be averaged over the main colours (B–V, V–R, R–I) in order to obtain the overall slope of the reflectivity spectrum in the visible wavelength range.

3.4. *Absolute magnitude*

The absolute magnitude of a TNO is the magnitude at zero phase angle and at unit heliocentric and geocentric distances. Geometrical effects are removed by reducing the M_F visual magnitude (in the F filter) to the absolute magnitude $M_F(1,1,0)$ using the following equation

$$M_F(1,1,0) = M_F - 5\log(r\Delta) - \alpha\beta,$$

where r, Δ and α are respectively the heliocentric distance (AU), the geocentric distance (AU) and the phase angle (deg.). The term $\alpha\beta$ is the correction for the phase brightening effect [11]. However, the phase function is completely unknown for most of the TNOs. Based on a first phase curve study of a few TNOs, Sheppard and Jewitt [6] have shown almost linear and fairly steep phase curves in the range of phase angles from 0.2 to 2 deg. They found an average beta of 0.15 mag/deg. A similar steep slope was found for Centaurs. This implies a possible considerable error in H calculations disregarding the phase correction.

3.5. *Size*

Size is the most basic parameter defining a solid body. Unfortunately, the sizes of TNOs cannot be measured directly, as the objects are not observationally resolved. Assuming a value for the surface albedo p, the absolute magnitude $M_F(1,1,0)$ can be converted into the radius R of the object [km] using the formula by Russell (1916) [12]

$$pR^2 = 2.235 \times 10^{16} 10^{0.4(M_F\mathrm{sun} - M_F(1,1,0))},$$

where $M_F$sun is the magnitude of the Sun in the filter F. Owing to the lack of available albedo measurements, it has become the convention to assume an albedo of 0.04, common for dark objects and cometary nuclei. However, one should be aware of the fact that the sizes are purely indicative and are largely uncertain. For instance, if we would use, instead, an albedo of 0.14 (i.e., the albedo of the Centaur 2060 Chiron), the results for size estimates would have to be divided by a factor of about two.

4. Colour diversity

4.1. *Colour–colour plots*

Colour–colour plots were originally used to display the differences in the reflectivity of TNOs and Centaurs. Fig. 1 shows the V–R versus B–V plot for more than 100 TNOs (Cubewanos, Plutinos, Scattered disk objects) and Centaurs. The objects show different surface colours: most of the objects have larger colour indices both in B–V and V–R than the Sun, i.e., they appear ‘redder’ than the Sun. However, there are a few objects that are slightly ‘bluer’ than the Sun. The spread of objects (along approximately the diagonal in the V–R versus B–V plot) indicates a wide range in surface reflectivity with only a few outliers (those away from the diagonal in Fig. 1). In most cases, colour–colour plots appear to be too crowded to evidently show potential colour groupings among the objects. Compared to short-period comets that are believed to be the primordial and

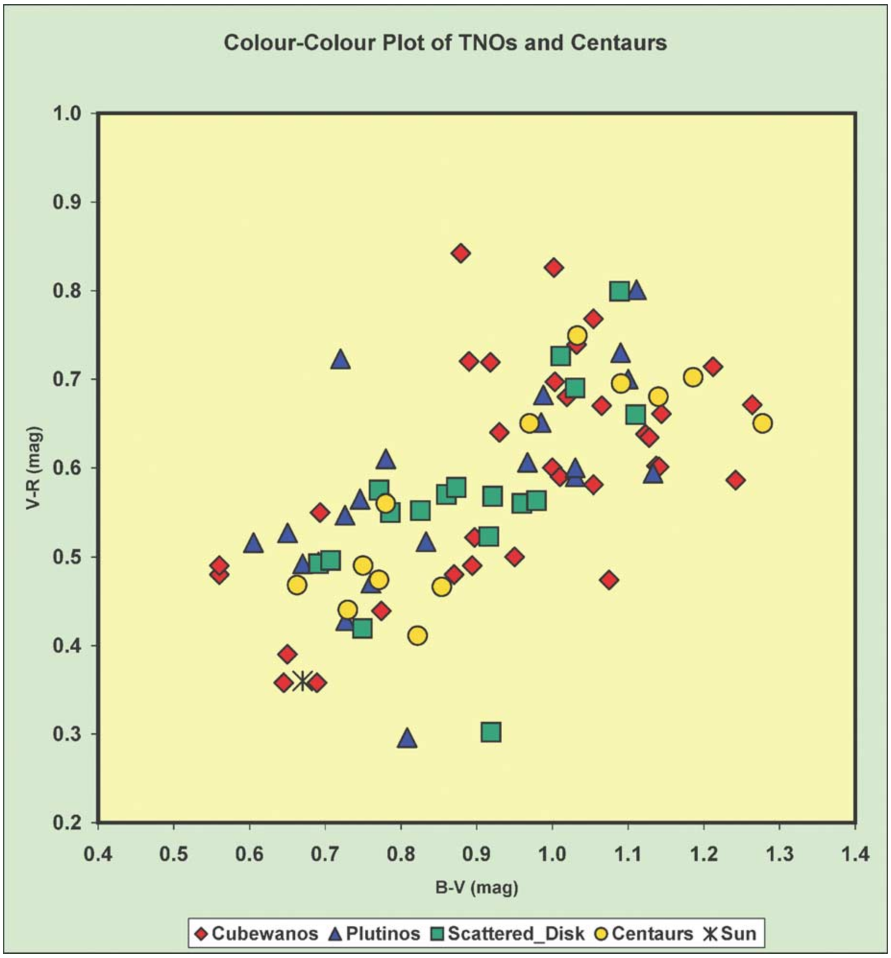


Fig. 1. V–R versus B–V colours of TNOs and Centaurs. The plot shows, in total, 86 objects (Cubewanos, Plutinos, Scattered disk objects and Centaurs) and the Sun.

dynamical relatives, the colour range of TNOs is wider (by a factor of about 2), meaning that many TNOs are much redder than typical short-period comet nuclei [13]. This suggests that changes of surface colours may happen during the few million years of transition phase and lifetime of a comet [14].

The situation in the near-infrared wavelength range is less conclusive (see Fig. 2): the colour–colour plot H–K versus J–H shows almost neutral colours in H–K for the majority of objects, while a wider range of colours – mostly to the red – is found in J–H. A number of clear outliers exist, and it is certainly worthwhile to verify these results in particular by new observations before a more serious interpretation can be started. It is, however, noteworthy to mention that the measured Plutinos have very little scatter in H–K, while their J–H covers the widest range of all dynamical classes. The total dataset is too heterogeneous and sparse to allow any sensitive conclusions on near-infrared spectral properties of the different dynamical classes – hence our further discussion of spectral properties of TNOs and Centaurs in the sections below will focus on photometry in the visible wavelength range.

In summary: the differences in the colours of TNOs and Centaurs are definitely larger in the visible than in the near-IR wavelength region where the object colours become close solar almost independent on how red the objects appear in the visible.

4.2. Spectral gradients

The spectral gradient defines the amount of reddening of the object spectrum compared to that of the Sun (see previous section). Since the visible spectra of TNOs and Centaurs are mostly featureless and with an almost constant slope, spectral gradients derived from BVRI photometry can be used to characterize the surface reflectivity in the visible wavelength range.

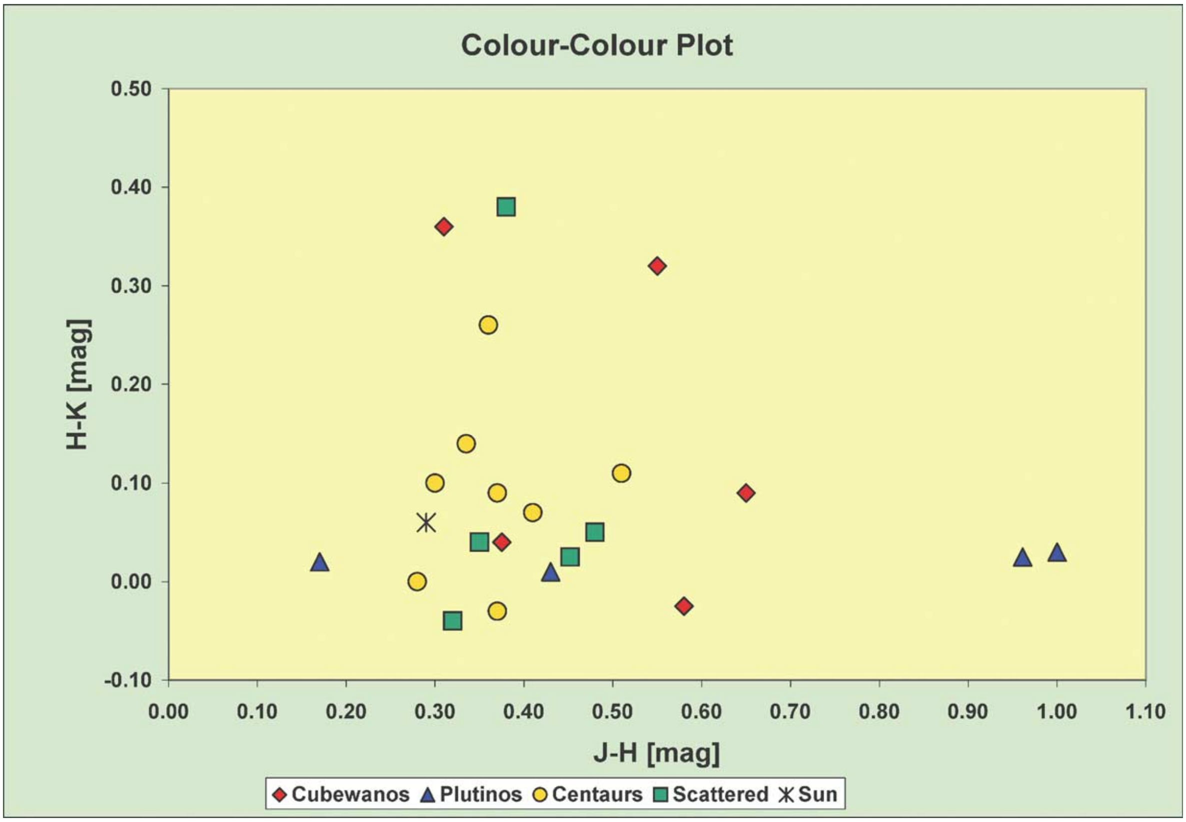


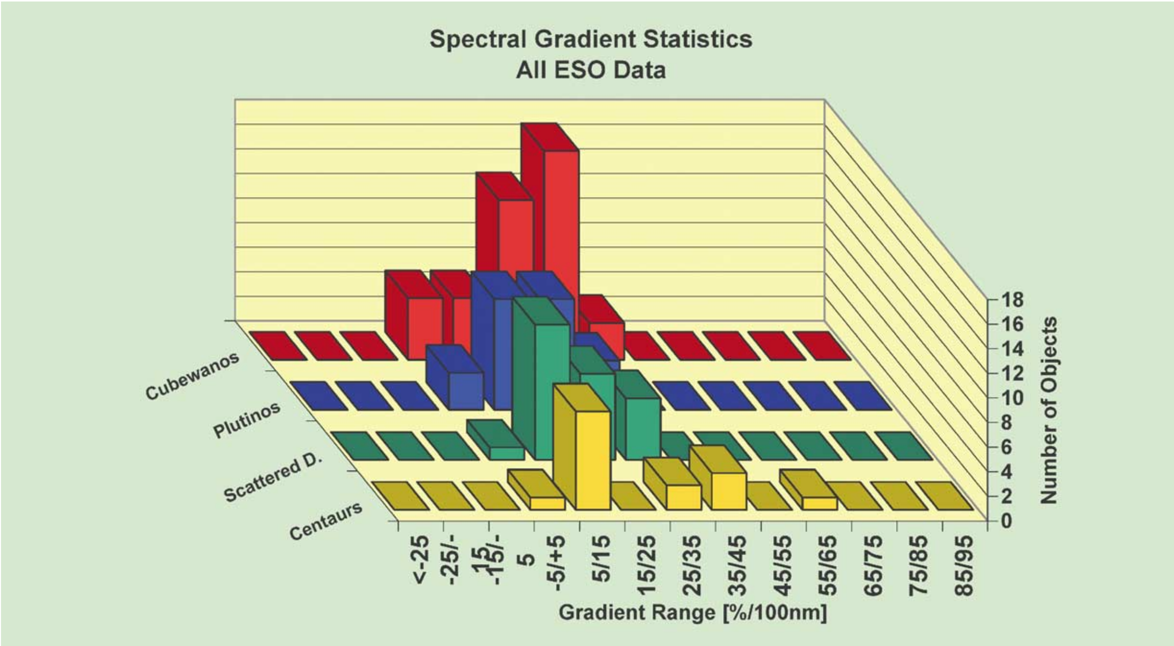
Fig. 2. H–K versus J–H colours of TNOs and Centaurs. The plot shows, in total, 22 objects (Cubewanos, Plutinos, Scattered disk objects and Centaurs) and the Sun.

They are intimately related to the constitution of the surface of the objects, although at present it is not possible to draw any detailed conclusions on specific surface properties.

Fig. 3 shows the histogram distribution of spectral gradients among TNOs and Centaurs obtained from BVRI broadband photometry. The overall range of spectral gradients appears to be very similar among the four dynamical classes (from −5 to 45%/100 nm), while the slope distributions of the individual classes show distinct differences. Most noteworthy are: the peak in the histogram of the Cubewanos at high reddening values and the lack of Centaurs with medium reddening (the latter may still be a statistical selection effect though).

4.3. Resurfacing scenarios

The red colour of the TNOs and Centaurs is usually attributed to the effects of surface aging and darkening due to high-energy radiation and ion bombardment in interplanetary space, also called space weathering [15]. Blue surface colours could be produced by major collisions through deposits of fresh icy material from the body interior or from the impactor. The estimated time scale for both types of colour resurfacing are of the order of 10 million years [16,17]. The observed colour range can be modelled by computer simulations involving both effects [18]. However, these results are unfortunately not yet discriminative for conclusions on the physical nature of TNO and Centaur surfaces. Resurfacing on much shorter time scale could happen due to ice re-condensation from a temporary atmosphere produced by intrinsic gas and dust activity [19,20]. According to theoretical calculations [21], N_2 and CO ice may be capable to sublimate at distances up to 40 AU and more. This ice sublimation process works quite efficiently for Pluto as well as possibly for Charon and for Chiron, but certainly it does not work for all objects, since crust formation may prevent the development of surface activity and/or the heat source in the bodies may not be strong enough to cause such activity. Impacts and atmospheric re-condensation can potentially also produce an inhomogeneous surface coverage with local region of different light scattering and absorption properties. These inhomogeneities may be detectable through colour variations over the rotation period: there is one TNO (1996 TO_{66}) known for which at least a marginal detection of surface colours with rotation phase is reported [22]. The intriguing context with this



	<-25	-25/-15	-15/-5	-5/+5	5/15	15/25	25/35	35/45	45/55	55/65	65/75	75/85	85/95
Centaurs	0	0	0	1	8	0	2	3	0	1	0	0	0
Scattered D.	0	0	0	1	11	7	5	0	0	0	0	0	0
Plutinos	0	0	0	3	9	9	4	0	0	0	0	0	0
Cubewanos	0	0	0	5	5	13	17	3	0	0	0	0	0

Fig. 3. Spectral gradients of TNOs and Centaurs. The histograms show the number of objects per spectral gradient interval. The database of spectral gradients has 107 objects, all measured at telescopes of the European Southern Observatory ESO (updated from Boehnhardt et al. [25]).

object is that it has changed rotation period in a short time interval, an effect that could be connected to an recent resurfacing event [18].

4.4. Correlations and surface properties

The efforts to identify groups of objects with similar spectral characteristics and thus – maybe – similar surface properties and evolution have provided evidence for correlations between spectral gradients and orbital parameters for certain objects. At present, the study of links between photometric reddening and other physical parameters of the objects such as size, albedo or chemical constitution is much harder and with mostly inconclusive results, since the available database is very sparse. We will thus focus here on what is known from the statistical correlation analysis of dynamical and photometric properties of TNOs and Centaurs.

4.4.1. The red Cubewano cluster

The peak in the Cubewano spectral gradient histogram is resolved in Fig. 3: a cluster of very red classical TNOs with low eccentricity ($e < 0.05$) and low inclination ($i < 5^\circ$) orbits beyond $\sim$40 AU from the Sun (first suggested by Tegler and Romanishin [23] from a much smaller dataset, now confirmed by Doressoundiram et al. [24], Boehnhardt et al. [25]). The cluster members have similar dynamical and surface properties, and they may represent the first taxonomic family in the Kuiper Belt. Considering the resurfacing scenarios introduced before, space weathering appears to be the dominant effect for these objects. A few outliers exist and may indicate that other processes could play a role at a lower level of efficiency, however still important enough to significantly modify the surface colours of a few individual objects of this dynamical group.

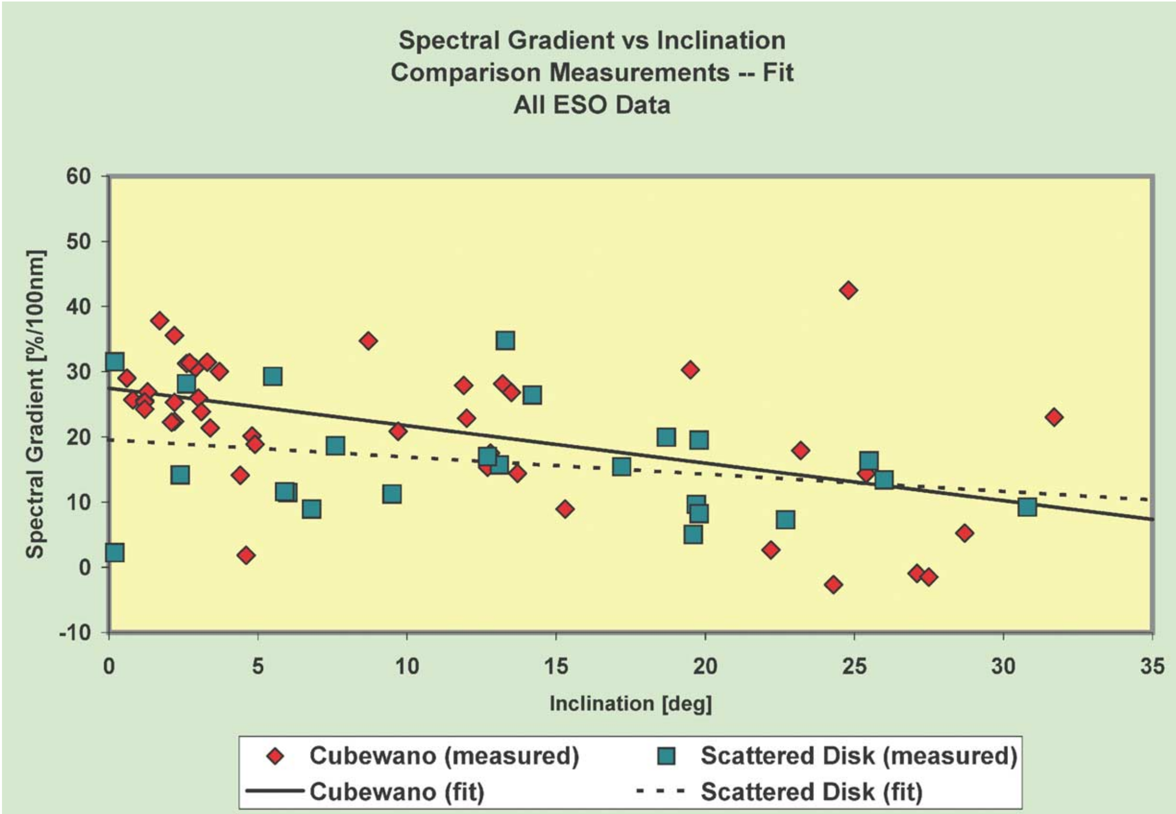


Fig. 4. Spectral gradients versus inclination for classical TNOs (Cubewanos) and Scattered disk objects. The cluster of red Cubewanos is indicated by the dotted circle. Possible trends between the spectral gradient versus inclination are plotted as full line for the Cubewanos and as broken line for the Scattered disk objects.

4.4.2. 'Correlation families'

Several authors published colour data for classical TNOs and scattered disk objects suggesting a correlation between reddening and inclination [23,26]. Fig. 4 plots the available spectral gradients of objects from these two dynamical classes versus inclination and indicates the trending lines obtained from linear regression fits of the data: at best, one may want to speculate on a reddening trend with inclination for Cubewanos, while for scattered disk objects both parameters appear to be widely uncorrelated. However, first simulations performed by Thébault and Doressoundiram [27] predict a correlation between surface reddening with eccentricity rather than inclination. An interesting aspect of the suspected inclination-reddening correlation is mentioned by Doressoundiram et al. [20]: there seems to be a parallel trend of smaller absolute magnitude (or possibly larger size) *and* 'bluer' colours for objects in higher inclination orbits.

Exploration of the reddening of Cubewanos versus perihelion distance q reveals yet another trend (see Fig. 5): classical TNOs with perihelion distance q between $\sim$36 and 40 AU show an increase of the spectral gradient with increasing q. It is not obvious that the collision resurfacing scenario, if validated, can account for this behaviour (since for instance scattered disk objects do not show such a correlation). Here, resurfacing by intrinsic activity may be an interesting explanation scenario. It is, however, noteworthy that the same population of classical TNOs that shows the reddening trend with increasing q displays a similar reddening trend with inclination as described above (see Fig. 6). Attempts to obtain further correlations between surface reddening and orbital parameters have not been successful so far for all dynamical classes of TNOs and Centaurs.

Considering the weak correlation coefficients found for the reddening trends versus inclination or perihelion distance 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 Kuiper Belt. However, if confirmed, the inclination-colour correlation would suggest, though does not prove, a resurfacing scenario through collision, while a perihelion distance versus colour correlation would favour atmospheric re-condensation to produce neutral colours in Cubewanos.

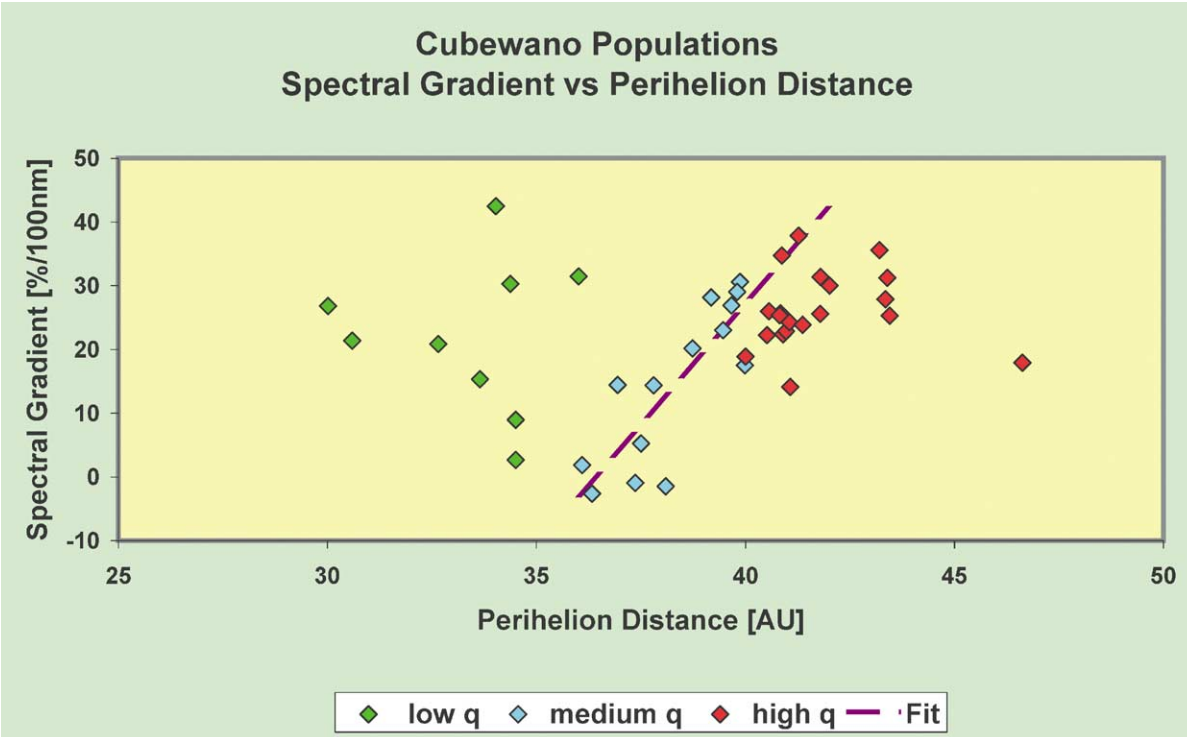


Fig. 5. Spectral gradients versus perihelion distance for Cubewanos. The objects with visible photometry data available are sorted in three groups: those with perihelion beyond 40 AU (red), those with perihelion between 36 and 40 AU (blue) and those with perihelion inside 35 AU (green). The trend between spectral gradient and perihelion distance for the second group is plotted as broken line.

5. Conclusions

Broadband photometry represents the simplest observing technique to study physical properties of TNOs and Centaurs. By assuming canonical albedo values together with magnitude estimates in the visible, one can get a very first idea on the typical sizes of these primitive bodies in the solar system. Colour data and results derived from that spectral gradient estimations, provide an accurate measure of the global surface reflectivity of the objects. There is no doubt that a large number of TNOs and Centaurs have very red surface colours, in fact much redder than other solar system bodies and in particular than those in the inner solar system. Nevertheless, objects of neutral colours are also found.

Using the results of more than 100 objects it is possible to get a first glance on colour families in the Kuiper Belt: at least one cluster of objects with similar colour and dynamical properties (the red, dynamically cold Cubewanos beyond 40 AU) and some – likely – 'correlation families' (with inclination and with perihelion distance, in the former case may be also linked with a trend in absolute brightness) could be identified. Plutinos and Centaurs on the other hand do not show any trends between physical and dynamical properties, even though the physical environment does not appear to be very different on the first sight. Thus, and up to now, the proposed scenarios for resurfacing and colour changes in TNOs and Centaurs are not conclusive in a unique way and for all objects.

The current situation calls for: (1) new ideas on how to explain the colour diversities; (2) alternative analysis methods; and (3) additional observations of an even larger object sample. Addition (1): Gomes [28] has proposed a migration scenario for the dynamically hot Cubewano population that could be scattered from the primordial Uranus–Neptune region into the classical Kuiper-Belt. This scenario combined with the results from the colour studies would somehow imply that the original size distribution AND chemistry in the outer solar system changed with distance from the Sun. Addition (2): modal analysis of multi-colour data like originally developed for the identification of asteroid families [29] provide a more sophisticated statistical access to clustering of objects in colour space. Finally addition (3): the data set available for interpretation, even though it was triplicated over the last three years, is still not large enough and the efforts to collect better observations of more objects must be continued.

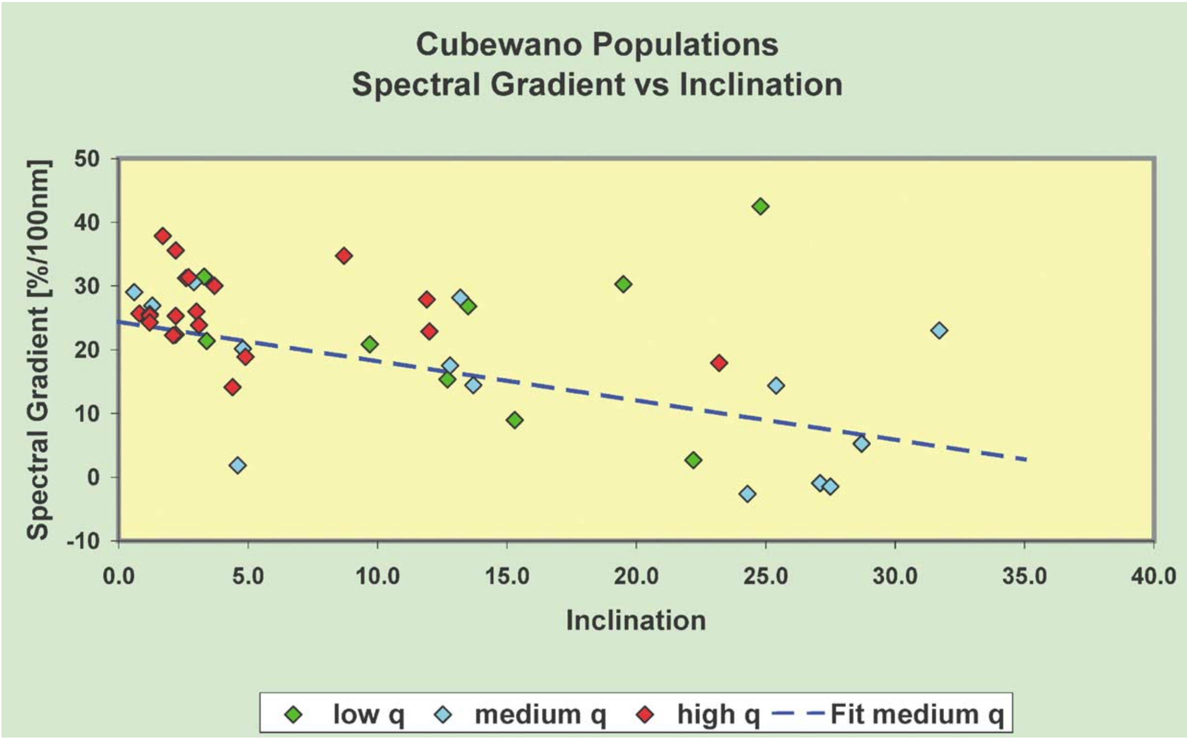


Fig. 6. Spectral gradients versus inclination for Cubewanos. The sorting (colour coding) of the objects is identical to that described in Fig. 4. The broken line indicates the trend between spectral gradient and inclination, here without objects from the cluster of red Cubewanos (red symbols with inclination below 5 deg).

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