Physical Characteristics of TNOs and Centaurs

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The external region of the Solar System contains a vast population of small solid bodies, believed to be remnants from the accretion of the planets. The Trans-Neptunian Objects (TNOs) and Centaurs (located between Jupiter and Neptune) are probably made of the most primitive and thermally unprocessed materials of the known Solar System. Although the study of these objects has rapidly evolved in the past few years, especially from dynamical and theoretical points of view, studies of the physical and chemical properties of TNO population are still limited by the faintness of these objects. TNOs and Centaurs have surfaces showing dramatically different colors and spectral reflectances, from neutral to very red. Some spectra are featureless, while some others show signatures of water ice, hydrocarbons; some show also variation with the rotation. The basic properties of these objects are presented, with emphasis on their diversity and the possible characteristics of their surfaces.

1. INTRODUCTION

Trans-Neptunian objects (TNOs) are presumed to be remnants of the solar nebula that have survived over the age of the Solar System. The connection of the short-period comets (P<200 y) of low orbital inclination and the Trans-Neptunian population of primordial bodies (TNOs) has been established and clarified on the basis of dynamics *(Fernández 1999),* and it is generally accepted that the Kuiper Disk is the source region of these comets. Centaur objects appear to have been extracted from the TNO population through perturbations by Neptune. While their present (temporary) orbits cross the orbits of the outer planets, Centaurs do not come sufficiently close to the Sun to exhibit normal cometary behavior, although 2060 Chiron has a weak and temporally variable coma.

We do not know if the traditional and typical short-period comets, which have dimensions of a few kilometers to less than one kilometer, are fragments of TNOs or if they are themselves primordial objects. The surface material of TNOs may not survive entry into the inner Solar System *(Jewitt 2002)* where it can be observed and (eventually) sampled, so it is particularly important to investigate the compositions of TNOs, which may be the most primitive matter in the Solar System. The surfaces of the Centaurs may represent intermediate stages in the compositional evolution of TNOs to short-period comets.

As a consequence of their great distances and relatively small dimensions, TNOs and Centaur objects are very faint; the first one, discovered by Jewitt and Luu *(Jewitt et al. 1992)* at magnitude ~22.8 was some 7400 times fainter than Pluto. Even the brightest TNOs presently known are magnitude ~19.6, making them difficult to observe spectroscopically with even the largest telescopes. The physical characteristics of Centaurs and TNOs are still in a rather early stage of investigation. Advances in instrumentation on telescopes of 6- to 10-m aperture have enabled spectroscopic studies of an increasing number of these objects, and significant progress is slowly being made.

We describe here the photometric and spectroscopic studies that have been made and are in progress, and review the results that are beginning to emerge as an increasing number of objects are examined

2. OBSERVATIONAL STRATEGY AND DATA REDUCTION TECHNIQUES

2.1 Photometry

Visible- and near-infrared-wavelength CCDs with broad-band filters operating in the range of 0.3 to 2.5 μm provide the basic set of observations on most objects discovered so far. An ideal instrument for a full range of photometric observations would be a dual optical-infrared CCD camera to obtain multicolor photometry of the objects. The colors indices (e.g. U-V, B-V, V-R, V-I, V-J, V-H, V-K)[1] are the differences measured between the magnitudes obtained in two filters, and represent an important tool to study the surface composition of these objects and to define a possible taxonomy.

Because of their unique nature, TNOs require specific observational procedures and data reduction techniques. What makes TNOs challenging objects to those seeking to measure, for example, colors and light-curves? Most importantly, their faintness, combined with their slow motion and rotation. We will discuss below the specific issues that have to be taken into account in order to avoid systematic errors.

First, 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 Trans-Neptunian object is about 23 or fainter, though a few objects brighter than 22 have been found. Also we need a signal-to-noise ratio (SNR) of about 30 (precision of 0.03-0.04), which is the photometric accuracy required to accomplish the color analysis. However, to achieve such signal precision, one needs to overcome two problems: i) the sky contribution to the measured signal which is critically important to evaluate for faint objects not only in the infrared but also in the visible spectral region, ii) contamination of the signal by unseen background sources, such as field stars and galaxies. For instance, the error introduced by a magnitude 26 background source superimposed on an object of magnitude 23 is as large as 0.07 mag. One solution for alleviating these problems is the use of a very small synthetic aperture around the object when measuring its flux on a CCD image. Thus, both the noise from the sky and the probability of contamination from unseen background sources are significantly reduced. However in this procedure, some light from the object is lost. To determine the quantity of light lost, an aperture correction technique is used, as described in the next section.

Even though TNOs orbit at large heliocentric distances, they still have significant motion on the sky that restricts observations to relatively short exposure times. At opposition, the non-sidereal motions of TNOs at 30, 40 and 50 AU are respectively about 4.2, 3.2 and 2.6"/hr, thus producing a trail of ~1.0" in 15 minutes exposure time, in the worst case. Trailed images

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[1] The broad-band filters commonly used (and their central wavelength position in μm) are: U(0.37), B(0.43), V(0.55), R(0.66), I(0.77), J(1.25), H(1.65), K(2.16).

have devastating effects on the SNR since the flux is diluted over a larger and noisier area of background sky. Thus, increasing exposure time will not improve the SNR. Practically, exposure times should be chosen so that the trail length does not exceed the seeing disk. One alternative would be to follow the object at its proper motion. But in this case, another problem arises, since the point spread function (PSF) of the object is different from field stars. This thwarts the aperture correction technique, which must be calibrated from the PSFs of nearby field stars (see below). As a consequence of the proper motion of TNOs, the number of objects that can be observed even with a big telescope at good SNR is limited. For example, only objects brighter than V ≈ 23.5 can be measured in good conditions (4-m class telescope, SNR ≈ 30).

TNOs rotate around their axis. The rotation rates are typically around 6-15 hours and the resulting variation of their brightness can be important (see Table I). As a consequence, measurements in individual filters may lead to erroneous color index if single observations in the two filters are separated by a significant time span. To eliminate systematic errors in the colors caused by rotational light-curve variations, one needs to intersperse observations through other filters with multiple observations through the same filter so that interpolation can be performed (e.g. V-B-V-R-V-I-V).

The data reduction consists of the basic reduction steps corresponding to the respective visible or near-IR photometric data set, i.e., bias and flatfield corrections, cosmic ray removal, alignment and co-addition of the jittered images, and flux calibration through standard stars.
As noted above, the brightness of the object is measured by means of an aperture correction technique *(Howell 1989)*. 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. Then, to determine how much light from the TNO is lost, the so-called "aperture effect" is calibrated using a large number of nearby field stars. This is reasonable as the motion of TNOs during each exposure is smaller than the seeing disk, 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 that it i) decreases the contribution of the sky which could be important and critical for faint objects, and ii) minimizes the probability of contamination from unseen background sources. We see two main limitations to this method: first, each imaging instrument has its own pattern of image distortion across the field which is modulated by seeing and is color dependent. This problem can be overcome by analyzing in the images as many bright isolated stars as possible and preferentially stars in the vicinity of the object. Stars with highly deviating PSFs (i.e. resolved galaxies or saturated/contaminated stars) are rejected. This results in a final mean PSF calculated with several tens of stars that serves for the correction of small aperture measurements. The distortion effect is thus reflected in the standard deviation of the fit, which in turn contributes to the photometric error. Secondly, the TNO and stars do not have rigorously the same PSF since usually the images are slightly trailed for the TNOs. However, depending on the seeing and trailing conditions, one can choose an aperture large enough to minimize this error (with the goal of less than 0.01 mag). Of course, objects trailed significantly will make the aperture correction technique inapplicable. In conclusion, performing the photometry with the aperture correction technique offers large improvements in the accuracy and in the reliability of the measurement, provided that one checks and takes into account the limitations of the method.

For each individual B, V, R, etc… magnitude obtained, one-sigma uncertainties are based on the combination of several uncertainties:

$$\sigma = (\sigma_{pho}^{2} + \sigma_{ap}^{2} + \sigma_{cal}^{2})^{1/2}$$

where the photometric uncertainty (σ_{pho}) is based on photon statistics and sky noise, the uncertainty on the aperture correction (σ_{ap}) is determined from the dispersion among measurements of the different field stars, and σ_{cal} is the uncertainty derived from absolute calibration through standard stars.

2.2 Spectroscopy

Spectrographs covering the range 0.3 to 2.5 μm are dedicated instruments to obtain the surface mineralogical (and ice) compositions of some of the brightest objects. Visible and near-infrared reflectance spectroscopy provides the most sensitive and broadly applied remote sensing techniques for characterizing the major mineral phases and ices present within TNOs. At visible and near-infrared wavelengths, recognizable spectral absorptions arise from the presence of the silicate minerals pyroxene, olivine, and sometimes feldspar, as well as primitive carbonaceous assemblages, and organic tholins. The near-infrared wavelength region carries signatures from water ice (1.5, 1.65, 2.0 μm), other ices (CH_4 around 1.7 and 2.3 μm, CH_3OH at 2.27 μm, or NH_3 at 2 and 2.25 μm), and solid C-N bearing material at 2.2 μm. Water-bearing minerals such as phyllosilicates also exhibit distinct absorption features at visible wavelengths.

Although the most reliable mineralogical interpretations require measurements extending into the near infrared, measurements in the visible wavelengths (0.3-1.0 μm) can be used to infer information on the composition, particularly for the especially “red” objects, whose reflectance increases rapidly with wavelength in this region (see below).

Spectroscopic observations face the same problems as photometric observations due to the specific nature of TNOs discussed in the previous section. Those problems are difficult to overcome, if not impossible. The faintness of the objects restricts the potential candidates even more stringently than photometry. For instance, with 8-m class telescopes, the limiting magnitude at the present time is V=22.5 mag for visible spectroscopy and object must be brighter than ~21 mag (in V) for near IR spectroscopy. On the same large aperture telescope, the exposure time required is between one and several hours for the faintest objects. During long exposures the rotation rate is not negligible and the resulting spectra probably arise from signals from both sides of the object.

The reduction of spectroscopic data follows the standard procedure: bias and flatfield corrections, cosmic ray removal, wavelength calibration, response and flux calibration through standard stars, and alignment and co-addition of the jittered spectra. The critical steps concern the dominant sky background (atmospheric emission bands) in the infrared and the choice of solar analogs.

In order to remove the contribution from the Sun, the spectrum of the TNO is divided by the spectrum of a solar analog obtained at the same airmass as the object. Such solar analogs have been studied by *Hardorp (1978).* The problem is that the Hardorp stars are too bright for the large aperture telescopes (V ≤ 6 mag.) and pose the obvious problem of saturation. There are also lists of faint stars with spectral classifications similar to the Sun that have reliable infrared photometry (e.g., *Carter and Meadows 1995*), and these can be used when suitable spectroscopic standards are unavailable. Alternatively, observers use synthetic, C-type asteroid or even A0 type stars, but without completely satisfactory results, or sometimes a private and unpublished list of good solar analogs.

3. DIAMETER, ROTATIONAL PROPERTIES AND SHAPE

Many useful physical and chemical parameters of TNOs can be derived from broadband photometry. Size, rotational properties and shape are the most basic parameters defining a solid body. The rotation spin can be the result of the initial angular momentum determined by formation processes, and for this reason the study of the rotational properties can constrain the origin and evolution of this population of objects. Some of the large TNOs might be partially differentiated and might conserve their original angular momentum. Many others suffered collision processes and do not retain the memory of the primordial angular momentum.

3.1 Diameter

The sizes of TNOs cannot be measured directly, as the objects are not in general spatially resolved. At the time of writing the largest known TNO (*2002 LM_{60}*) is resolved in an HST image at 40.4±1.8 milliarcseconds, yielding a diameter of 1260 ± 190 km *(Brown and Trujillo, 2002*). Only few objects have been observed at thermal and millimetric wavelengths and thus have directly determined diameters and albedos (Table I), while for the majority an indication of the diameter can be obtained from the absolute magnitude, assuming an albedo value. With an assumed value for the surface albedo p_V of an object, the absolute magnitude (*H*) can be converted into the diameter *D* [km] using the formula from *Harris and Harris (1997*). Owing to the lack of available albedo measurements, it has become the convention to assume the albedo of 0.04-0.05 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 used, instead, an albedo of 0.14 (i.e. the albedo of the Centaur 2060 Chiron), all the size estimates would have to be divided by about two.

3.2 Rotational period

The observed variations of brightness with time allow the determination of the rotational period of a body. In Table I a fairly complete list of the most reliably determined results is presented. The faintness of these objects makes the analysis of the lightcurves difficult. Recently, *Sheppard and Jewitt (2002)* observed 13 objects to measure light variation. Nine of them showed no measurable variations, implying a small amplitude, or a period ≥ 24 hr, or both. A few of Sheppard and Jewitt's objects show hints of variability that might yield a lightcurve with higher quality data. The rotational periods seem to range between 6 and 15 hours, but a bias effect can exist due to the difficulty in determining long periods, and to the faintness of these objects.

3.3 Shape

Close-up images of TNOs and Centaurs have not yet been obtained from space missions and will not be obtained in the next decade. Stellar occultations and photometric observations can give some clues on the shape of these bodies. A stellar occultation can give the cross-section of the bodies in the perpendicular plane. No occultation results are available at the present time due to the lack and the difficulty of precise predictions. About 5 % of the total number of TNOs seem to have companion objects and are therefore binary (*Noll et al. 2002*) . The first object discovered to have a companion was *1998* WW_{31} *(Veillet et al. 2002).* The lightcurve is the only technique at the present available to give contraints on the shape. The amplitude can give some indication on the elongation of the body. Assuming a triaxial ellipsoid shape with semi-axes a>b>c and no albedo variation, we can estimate the lower limit of the semi-axis ratio:

$a/b \geq 10^{0.4\Delta m}$.

Large TNOs (D>250km) should generally have a spherical shape due to gravitational spherical compression. From the analysis of *Sheppard and Jewitt (2002)* it seems that few large TNOs can have elongated shapes. In fact, as an example, using the $\Delta m=0.61$ mag (see Table 1) in the case of 47932 (2000 GN_{171}), an estimate of $a/b \geq 1.75$ can be obtained. Sheppard and Jewitt, analysing all the available lightcurves found that over 22 objects, 32% have $\Delta m \geq 0.15$ mag, while 23% have $\Delta m \geq 0.4$mag.

4. TRENDS AND COLOR PROPERTIES

From broadband photometric observations, colors and spectral gradients are used for statistical analysis and search for evidence of relationships between physical properties and orbital characteristics.

4.1 Color Diversity

One of the most puzzling features of the Kuiper Belt, which has been confirmed by numerous surveys, is the optical color diversity that seems to prevail among the observed TNOs. Such a great color diversity is peculiar to the outer Solar System bodies and is not observed among asteroids, cometary nuclei, or planetary satellites. Originally pointed out in *Luu and Jewitt (1996a)*, this color diversity is an observational fact that is widely accepted by the community *(e.g., Barucci et al. 2000b, Doressoundiram et al., 2001; Jewitt and Luu 2001; Delsanti et al. 2001; Tegler and Romanishin, 2000; Boehnhardt et al. 2002 and references therein*). Colors range continuously from neutral (flat spectrum) to very red. (see Figure 1). The different dynamical classes (e.g. Centaurs, Plutinos, Classicals and Scattered) seem to share the same color diversity. However, Tegler and Romanishin concluded earlier, in 1998, on the basis of the visible (B-V versus V-R) colors derived from 11 TNOs and 5 Centaurs, that there are two distinct populations: one with objects having neutral or slightly red colors similar to the C asteroids, and the other one including the reddest objects known in the Solar System. They confirmed this result later on a larger dataset (*Tegler and Romanishin, 2000*) but with a lesser separation between the two populations in a color-color plot. Other groups working on this subject could not confirm this bimodality of color distribution. In particular, *Doressoundiram et al. (2002)*, on the basis of a larger and homogeneous BVR dataset of 52 objects (actually the largest homogeneous dataset published to date), did not see any clear and significant bimodality of color distribution. *Hainaut and Delsanti (2002)* have performed some statistical tests on a combined color dataset of 91 Centaurs and TNOs. Their results were very cautious: they concluded that almost all the color-color distributions are compatible with both continuous and bimodal distribution. High quality data with very small error bars will be necessary to establish the final word on this issue.

On the other hand, and paradoxically, there is a complete consensus for continuous color diversity when the color analysis is extended to longer wavelengths. For instance color-color plots similar to Figure 1 including the I filter (~0.77μm) or J filter (~1.2μm) do not evidence any color bimodality (see *Boehnhardt et al., 2001 or Jewitt and Luu, 2001).*

The information contained in the color indices can be converted into a very low-resolution reflectance spectrum, as illustrated in Figure 2. Reflectance spectra have been computed using BVRIJ color data of the object (with the color of the Sun removed[2]). The spectra range from neutral/slightly red objects to very red objects, thus confirming the wide and continuous diversity of surface colors suggested by the individual color-color diagrams. Almost all the objects are characterized by a linear reflectance spectrum, with no sudden and significant changes in the spectral slope (within the error bars) over the whole wavelength range. This result was confirmed by *Mc Bride et al. (2003)* on a large dataset of 29 mostly simultaneous V-J colors. They found their V-J colors broadly correlated with published optical colors, thus suggesting that a single coloring agent is responsible for the reddening from the B (0.4μm) to the J (1.2 μm) regime. This remarkable property may help identify the agent among the low-albedo minerals with similar colors *(Jewitt and Luu, 2001).*

The extreme color diversity seen among the outer Solar System objects is usually attributed to the concomitant action of two competing mechanisms acting on the TNOs over the age of the Solar System. First, space weathering due to solar radiative processing and solar or galactic cosmic-ray irradiation both tend to redden all objects' surfaces. Second, the resurfacing effect of mutual collisions among TNOs would regularly restore neutral-colored ices to the surface. This is the so-called collision-resurfacing hypothesis CRH *(Luu and Jewitt, 1996a*). Collisions and irradiation have reworked the surfaces of TNOs, especially in the inner part of the belt, and extensive cratering can be expected to characterize their surfaces *(Durda and Stern,* 2000). In addition to these two processes, another resurfacing process resulting from possible sporadic cometary activity, has been also recently evoked *(Hainaut et al., 2000)* as a process worthy of consideration. Resurfacing by ice recondensation from a temporary atmosphere produced by intrinsic gas and dust activity might also be an efficient process affecting the closest to the sun TNOs (e.g. Plutinos).

4.2 Correlations

To date, B-V, V-R, and V-I colors are available for more than one hundred objects, while only a few tens of them have V-J colors determined *(Davies et al., 1998 Davies et al., 2000, Jewitt and Luu 1998, McBride et al. 2003).* A few of them have measured J-H and H-K colors. With this significant dataset, especially in the visible spectral region, we can now

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[2] The reflectance spectrum R(λ) is given by:
$R(\lambda) = 10^{-0.4\,[(M(\lambda) - M(V)) - (M(\lambda) - M(V))sun]}$
where *M* and *Msun* are the magnitude of the object and of the Sun at the considered wavelength. The reflectance is normalized to 1 at a given wavelength (conventionally, the *V* central wavelength, 0.55 μm).

extend physical studies of TNOs from merely description to extended characterization by performing statistical analysis and deriving some potentially significant trends. Some of the outstanding questions TNOs investigators would like to answer with these studies include:

1) Are the surface colors of the Centaur and TNOs homogeneous?
2) Is it possible to define a taxonomy, as for the asteroids?
3) Are there any trends with physical and orbital parameters? For instance, are there any trends in color with size?

As for the first point, we note that there is a general agreement between colors measured by different observers at random rotational phases suggesting that color variation is rare. However, some investigators have included in their observational strategy, the measurement of the colors of a single object several times during a run in order to monitor any such color changes with the rotational phase. For instance, *Doressoundiram et al. (2002)* have highlighted a few objects among the 52 objects of their survey, for which color variation has been found and thus that may be diagnostic of true compositional and/or texture variation on the surface of these objects (see also section 5 for discussion of 8405 Asbolus case). Obviously, the issue of the color anisotropy is still ambiguous and needs more attention by investigators.

The TNOs exhibit a wide range of V-J colors. Based on a sample of 22 BVRIJ data, *Barucci et al. (2001)* made the first statistical analysis of colors of TNOs population and they found four “classes” showing a quasi-continuous spreading of the objects between two end members (those with neutral spectra and those with the reddest known spectra). The most important contribution in discriminating the “classes” comes from the V-J reflectance. This fact shows the necessity of the V-J color in any taxonomic work. Actually, the available visible-NIR data were insufficient to allow Barucci et al. to interpret the meaning of the grouping. A larger dataset is needed in order to investigate on the real compositional taxonomy of the Trans-Neptunian and Centaur objects

Jewitt and Luu (1998) presented a linear relationship between V-J and body size, implying that the smaller objects are systematically redder. This result was subsequently invalidated by *Davies et al. (2000)* on a much larger dataset. Such a relationship, if found, would have been important because it is a prediction of the collisional resurfacing hypothesis.

Objects with perihelion distances around and beyond 40 AU are *mostly* very red. This characteristic was originally pointed out by *Tegler and Romanishin (2000)*, who also noticed, as did *Doressoundiram et al. (2001)*, that Classical objects with high eccentricity and inclination are preferentially neutral/slightly red, while Classical objects at low eccentricity and inclination are mostly red (Fig.3). This feature was first quantified by Trujillo and Brown (2002), who found a significant 3.1σ correlation between object’s optical color and orbital inclination (*i*) for Classical and Scattered objects. A similar but stronger correlation (3.8σ) was later found by *Doressoundiram et al. (2002)* on a homogeneous dataset of 22 Classical objects and not including the Scattered objects (Fig.4). It is noteworthy that such a correlation was not seen among the Plutinos or the Centaurs. Instead, Plutinos appear to lack any clear color trends. *Hainaut and Delsanti (2002)*, as well as *Doressoundiram et al. (2002)* found also significant correlations with orbital excentricity (*e*) and perihelion distance (*q*) for the classical TNOs, though less strong than with *i*. Strikingly, Jewitt and Luu (2001) did not find any correlation with color in their sample of 28 B-I color indices. This apparent discrepancy is certainly due to the high proportion of resonant objects included in their sample that completely masks the correlation.

It is noteworthy that *Hainaut and Delsanti (2002),* performed an extensive analysis on a combined dataset of 91 Centaurs and TNOs. Though large, this dataset is not homogeneous, as the colors were collected and combined from different sources. They found a trend for Classicals with faint H to be redder than the others. Moreover, they found the opposite trend for the Plutinos (faint H tend to be bluer). *Doressoundiram et al. (2002*) did not find any of these trends in their homogeneous but smaller dataset. Of course, these opposite trends need to be confirmed by a larger observational dataset, and still the physical interpretation remains difficult. No correlation has been found with parameters such as size or heliocentric distance.

The collisional resurfacing scenario remains hypothetical and is still the subject of great discussion. It offers, nevertheless, the advantage of making relatively simple predictions concerning the color correlation within the Kuiper Belt. Basically, the most dynamically excited objects should be the ones most affected by energetic impacts, and thus should have the most neutral colors. It is thus very tempting to check the correlation between the color index and $V_k(e^2+i^2)^{1/2}$, since both *i* and *e* should contribute to the average encounter velocity of a TNO. Such a relationship has been investigated by several authors *(Hainaut and Delsanti,2002, Doressoundiram et al., 2002, Stern, 2002*) and the correlation seems very good.

Considering that optical and infrared colors are correlated, one could presume that the correlations found between orbital parameters and optical colors may be generalized to infrared colors. Indeed, the V-J observations have a much wider spectral range and so, are likely to be more robust in showing color correlations. However such statistical analysis is still tentative due to the relatively few V-J colors available. First such attempt done by Mc Bride et al (2003) seems to support the color and perihelion distance, and the color and inclination relationships.

5. VISIBLE AND INFRARED SPECTROSCOPY

Broadband photometric observations can provide rough information on the surface of the TNOs and other objects, but the most detailed information on their compositions can be acquired only from spectroscopic observations, especially in the near-infrared spectral region. Unfortunately, most of the known TNOs are too faint for spectroscopic observations, even with the world's largest telescopes and so far only the brightest have been observed by visible and infrared spectroscopy.

The first visible spectrum of a TNO, 15789 (1993 SC), was observed by *Luu and Jewitt (1996b*), who obtained a reddish spectrum that is intermediate in slope between those of the Centaurs 5145 Pholus and 2060 Chiron. Others have been observed subsequently, but only few data are yet available; 5 Centaurs have been observed by *Barucci et al. (1999),* 5 TNOs by *Boehnhardt et al. (2001)* and 12 TNOs and Centaurs by *Lazzarin et al. (2002).* The spectra show a general featureless behavior with a difference in the spectral gradient, ranging from neutral to very red. The computed reflectance slopes range from 0 or slightly negative (in the case of Chiron) up to 58 % /100nm for Pholus or Nessus, which are the reddest known objects in the Solar System. The computed slope varies a little bit in function of the wavelength range analyzed, but do not seem to be related to the perihelion distance of the objects.

For only two Plutinos: 38628 (2000 EB_{173}) and 47932 (2000 GN_{171}) broad absorptions have been found. In the spectrum of 47932 (2000 GN_{171}), an absorption centered at around 0.7 μm has been detected with a depth of ~8%, while in the spectrum of 38628 (2000 EB_{173}) two weak features centered at 0.6 μm and at 0.745 μm have been detected with a depth of ~7% and 8.6%, respectively *(Lazzarin et al. 2002).* These features are very similar to those due to aqueously alterated minerals, found in some main belt asteroids (*Vilas and Gaffey 1989* and subsequent papers). Since hydrous materials seem to be present in comets, and hydrous silicates are detected in interplanetary dust particles (IDPs) and in micrometeorites (and probably originated in the solar nebula), finding aqueous altered materials in TNOs would not be too surprising (see *de Bergh et al. 2002).*

In the infrared region some spectra are featureless, while some others show signatures of water ice, and methanol or other light hydrocarbon ices. Very few of these objects have been well studied in both visible and near infrared and rigorously modeled. In fact these objects are faint and even observations with the largest telescopes (Keck and VLT) do not generally yield good quality spectra. The interpretation is also very difficult because the behavior of models of the spectra depends on the choice of many parameters. Some of the visible and NIR spectra obtained at VLT (ESO, Chile) are shown in Fig. 5, with the best fitting model of the data. The general spectral characteristics are listed in Table I.

Concerning Centaurs, a broad review is presented in the book **Asteroids III** by *Barucci et al. (2002a)*, while details of few objects are discussed below. The brightest Centaur, *2060 Chiron,* showed, with observations at different epochs, featureless spectra and the presence of water ice through the 2 μm absorption band, which seem correlated with its cometary activity level *(Luu et al. 2000, Romon-Martin et al. 2003).* The ice on Chiron's surface appears to be mixed with dark impurities, which might mask the spectral band.

8405 Asbolus has controversial observations: *Brown* (2000) and *Barucci et al.* (2000a) observed it and both NIR spectra show the lack of spectral signatures. Later, *Kern et al. (2000)*, using the HST, obtained several (1.1—1.9 μm) spectra, which revealed a significantly inhomogeneous surface characterized by water ice mixed with unknown low-albedo constituents. The first series of spectra showed a strong absorption band at about 1.6 μm due to H_2O ice, while spectra taken more than 1 hr later were featureless. *Kern et al.* (2000) explained this variability as a result of the rotation of the object during the observations, while speculating that the differences across the surface of Asbolus might be caused by an impact that penetrated the object's crust, exposing the underlying ice in the surface region. *Romon-Martin et al. (2002)* reobserved Asbolus at VLT (ESO, Chile) obtaining five high quality infrared spectra covering the full rotational period, and found no absorption features at any rotational phase. Using different radiative transfer and scattering models *(Douté and Schmitt, 1988, and Shkuratov et al. 1999),* Romon-Martin et al. modeled the complete spectrum from 0.4 to 2.5 μm with several mixtures of Triton tholins, Titan tholins, Ice tholins, amorphous carbon and olivine. None of the models successfully matched the visible part of the spectrum, while the best fit to the infrared part was obtained with 18% Triton tholin, 7% Titan tholin, 55% amorphous carbon and 20% Ice tholin (Fig. 5). The models are clearly not unique, due in particular to the lack of constraints that would be imposed by the presence of specific absorption features (see discussion in section 6).

10199 Chariklo was observed by *Brown and Koresko* (1998) and by *Brown et al.* (1998) and both infrared observations show spectra with clear evidence of water ice. *Brown and Koresko* (1998) modeled the spectrum by distinct surface areas of a dark, neutral color, and 3% water ice while *Brown et al.* (1998) made a model fit assuming an intimate mixture of red-colored material and higher percentage of water ice, probably in an amorphous state. *Dotto et al. (2002a)*, analyzing a complete spectrum from 0.4 up to 2.4 μm and on the basis of new infrared data, modeled the object with 9% Titan tholin, 86% carbon, 2% water ice and 23% Triton tholin.

32532 (PT_{13}) has been observed *(Barucci et al. 2002b)* from 1.1 to 2.4 μm at two different epochs and the spectra seem quite different, indicating spatial differences in the surface composition. One of the observations shows clear evidence for a small percentage of water ice. The lack of albedo information eliminates one important constraint on the modeling, but on the assumption of a low-albedo surface two models have been computed to interpret the different behavior of the two spectra. One seems to be well fitted with a model containing 15% Titan tholin, 70% amorphous carbon, 3% olivine, and 12% Ice tholin, and having an albedo of 0.09 (shown in Fig. 5). For the other spectra a model with an albedo of 0.06 and 90% amorphous carbon, 5% Titan tholin and 5% water ice has been 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). As noted by the authors, due to the lack of albedo and unambiguous diagnostic signatures, the obtained models give only an indication of the possible materials present on the surface.

Dotto et al. (2002b) observed two Centaurs: *1998 SG_{35}* and *2000 QC_{243}* in the H and K regions (Fig. 5). Tentative models fitting the entire visible-infrared spectra from 0.4 to 2.4 μm of these two bodies use similar percentages of kerogen (96-97%), olivine (1%), and water ice (2-3%). The high percentage of kerogen was necessary to reproduce the slope of spectra in the visible region while the water ice (even if in small amounts) was necessary to reproduce the behavior in the H and K bands.

The TNOs are even fainter than Centaurs and only few spectra are available, generally with very low S/N. Although only a small number have been observed to date, their surface characteristics seem to show wide diversity. *1996 TL_{66}* and *28978 Ixion* have flat featureless spectra similar to that of dirty water ice (*Luu and Jewitt*, 1998; *Licandro et al. 2002). 19308* (1993 SC), observed by *Brown et al.* (1997), show features that the authors suggest might be due to hydrocarbon ices with a general red behavior suggesting the presence of more complex organic solids. Jewitt and Luu *(2001)* also observed 1993 SC with the same telescope, but did not find any similar features. The difference in these results requires resolution, best accomplished with additional better data. *McBride et al. (2003)* show that *1993 SC* is one of the reddest of the TNOs studied so far.

38628 (2000 EB_{173}) has been observed by many authors (*Brown et al. 2000, and Licandro et al. 2001, Jewitt and Luu, 2001* and *de Bergh et al. 2002*) and appears in general featureless in the infrared region, except in *Licandro et al* and *de Bergh et al.* where a possible feature appears beyond 1.8µm. The interpretation of this spectra is challenging; de *Bergh et al. (2002)* attempted to interpret the complete visible and infrared spectrum with combination of amorphous carbon, Titan tholin and the mineral jarosite (hydrous iron sulfate) to interpolate part of the signatures present in the visible region spectrum (see Fig. 5). The model does not fit well the spectra: the jarosite has been included to match the band at 0.6 µm, but does not fit the band at 0.75 µm at all. No other available minerals give a better fit to the spectral behavior.

19308 (1996 TO_{66}*)* shows an inhomogeneous surface with clear indications of the absorptions at 1.5 and 2 µm characteristic of water ice. A model has been suggested to match the flat infrared region (1.4 –2.4 µm) with water ice mixed with some other minor components (*Brown et al.* 1999). The evidence that the intensity of water ice bands varies with the rotational phase, suggests a patchy surface. *20000 Varuna* also shows a deep water ice absorption band (*Licandro et al. 2001*).

In contrast, *26375 (1999* DE_9*)* shows solid-state absorption features near 1.4, 1.6, 2.00 and probably at 2.25 µm (*Jewitt and Luu, 2001*). The location of these bands has been tentatively interpreted by Jewitt and Luu as evidence for the hydroxyl group with possible interaction with an Al or Mg compound. The presence of the drop from 1.3 to 1 µm seems to be consistent with olivine absorption. If the presence of the hydroxyl group is confirmed, this would imply the presence of liquid water and a temperature near the melting point for at least a short period of time.

47171 (1999 TC_{36}*)* has been observed by *Dotto et al. (2002b)* in the J, H, and K region (Fig. 5). Two K spectra have been obtained at two different nights and they show similar behavior, with weak absorption around 2 µm. Analyzing the complete spectra from visible to infrared, the surface composition has been interpreted with a mixture of 57% Titan tholin, 25% ice tholin, 10% amorphous carbon and 8% water ice. The tholins *(Khare et al., 1984)* are the only materials (for which optical constants are available) able to reproduce the unusual red slope (0.4-1.2 µm), even if the fit is not good in the visible region, but no other combination of materials yields a better fit at these wavelengths.

Some of the results discussed here are based on inferior quality data. In some cases, repeated observations of the same object give different results (see Table I), but in some others a real variation on surface of the objects might exist. A few objects (*19308 (1996* TO_{66}*) and 32532 (2001* PT_{13}*))* clearly show surface variations. While the models noted here represent the best current fit to the data, they are not unique and depend on many parameters: grain size, albedos, porosity, etc.

6. MODELING SURFACE COMPOSITION

We have already noted the results of modeling of a few Centaurs and TNOs by various investigators, and we have seen that organic solids (tholins) are used to achieve a fit to the strong red color that most of these objects exhibit. In this section we consider some details of modeling the spectral reflectance of the solid surface of an outer Solar System body.

The goal of modeling the spectral reflectance of a planetary surface is to derive information on that object's composition and surface microstructure. Thermal emission can also be modeled, but in the case of TNOs and Centaurs, there are insufficient astronomical data of this kind to yield compositional information through a modeling approach. Compositional information can be derived from straightforward spectrum matching (e.g., *Hiroi et al. 2001)* and from linear mixing of multiple components (e.g., *(Hiroi et al. 1993)).* More rigorous and more informative quantitative modeling using scattering theory goes beyond spectrum matching and linear mixing by introducing the optical properties (complex refractive indices) of candidate materials into a model of particulate scattering. Quantitative modeling of planetary surfaces using scattering theory has progressed in recent years, as more and more realistic models are developed and tested against observational data. Multiple scattering models provide approximate, but very good solutions to radiative transfer in a particulate medium. The semi-empirical Hapke model *(Hapke 1981, 1993)* has been most widely used, while other models incorporating additional physical configurations (e.g., layers of transparent or semi-transparent components, inhomogeneous transparent grains, etc.) have begun to emerge (e.g., *Douté and Schmitt 1998, Shkuratov et al. 1999).*

Real planetary surfaces are composed of many different materials, mixed in various configurations. There can be spatially isolated regions of a pure material (e.g., H_2O ice or a pyroxene-dominant rock) or a mixture of materials (e.g., olivine, pyroxene, and opaque phases). The nature of the mixture can range widely. For example, there can be an intimate granular mixture in which each component is an individual scattering grain of a particular composition, lying in contact with grains of its own kind or a different material. Or, materials might be mixed at the "molecular level", such that a sunlight photon entering an individual grain will encounter molecules of different composition within that grain before exiting. Many other configurations, including complex layering, are also possible.

The net result of all the processes that occur on airless Solar System bodies is that they exhibit a large range of geometric albedos, differing slopes in their reflectance spectra, and in the presence or absence of absorption bands arising from minerals, ices, and organic solids.

The case of Centaur *5145 Pholus* (Figure 6) offers a view of some of the challenges in modeling Centaur and TNO surfaces (details are found in *Cruikshank et al. 1998*). This object has a steeply sloped spectrum from 0.45 to 0.95 μm, and moderately strong absorption bands at 2.0 and 2.27 μm, while the geometric albedo at 0.55 μm is 0.04. The steep red slope cannot be matched by minerals or ices, but is characteristic of some organic solids, notably the tholins. The absorption bands are identified as H_2O ice (2.0 μm) and (probably) methanol ice (CH_3OH) at 2.27 μm. A Hapke scattering model using the real and imaginary refractive indices of tholin, H_2O, CH_3OH, and the mineral olivine, plus amorphous carbon (which affects only the albedo level of the model) was found to match the spectrum from 0.45 to 2. 4 μm. The Hapke model formulation of *Roush et al. (1990)* was used. The model consisted of two components spatially separated on Pholus; the main component is an intimate mixture of 55% olivine, 15% Titan tholin, 15% H_2O ice, and 15% CH_3OH ice, with various grain sizes. In the model, the main component covers ~40% of the surface, while carbon black covers the remaining 60%.

The principal problem with this model is that the Titan tholin particles had to be only 1 μm in size, thereby violating a tenant of the Hapke theory that the particle sizes have to be significantly greater than the wavelength of the scattered light. This conflict can be resolved by using the Shkuratov modeling theory, in which very small amounts of Titan tholin can be introduced as contaminants in the water ice crystals without violating any optical constraints of the theory. *Poulet et al. (2002)* have shown that Pholus can be modeled with the Shkuratov theory using the same organic, ice, and mineral components used in the Hapke model, although in slightly different proportions, without any conflict with particle size constraints. The Poulet et al. model is also shown in Fig. 6.

Poulet et al. (2002) have compared the Hapke and Shkuratov theories, showing that the principal difference lies in the role of the phase function of individual regolith particles, where the scattering of sunlight occurs. In the Hapke model the phase function is a free parameter, while in the Shkuratov model it is predicted (and generally forward directed). There are also significant differences in the assumptions on the manner in which different constituents are physically mixed, and these have important effects on the resulting synthetic spectra that are compared with observations.

In Hapke models of planetary surfaces, a backscattering phase function is generally used to represent the single-scattering component, while an isotropic phase function is assumed for higher orders of scattering. The Hapke model requires proportionally more red material than the Shkuratov model to achieve a fit for the red objects that are typical among asteroids and other objects in the outer Solar System. With the Hapke model and a given set of refractive indices, a fit to a red planetary object usually requires a decrease in particle size, in extreme cases leading to the conflict with geometric optics noted above. Shkuratov models of low-albedo, red objects generally avoid this problem, although even with the different formulation of the particle scattering properties, *Poulet et al. (2002)* could not reproduce the very strong red color of Pholus using intimate mixtures of particles greater than a few micrometers in size. Instead, they formulated mixtures of different materials conceptualized as small inclusions of a strongly colored material (such as a tholin) in a larger particle of more transparent material (e.g., H_2O ice). Examples of this configuration in nature are the normally clear silicate grains with inclusions of fine (0.3-10 μm) particles of magnetite and pentlandite found in the matrix material of certain meteorites (e.g., CK carbonaceous chondrites). The phenomenon of "silicate darkening" may have analogues on icy surfaces, where grains of normally clear ice might have inclusions of organic solids or minerals that strongly affect their absorbing properties.

7. CONCLUSIONS

One of the most puzzling features of the Kuiper Belt, which has been confirmed by numerous surveys, is the optical color diversity that seems to prevail among the observed TNOs (Fig 1). With the relatively few visible-NIR color datasets available, the color diversity seems also to extend to the near-infrared. Relevant statistical analyses have been performed and several studies have pointed out strong correlations between optical colors and some orbital parameters (*i, e, q*) for the Classical Kuiper Belt. On the other hand, no clear trend is obvious for Plutinos, Scattered objects or Centaurs. Another important result is the absence of correlation of colors with size or heliocentric distance for any of the populations of outer Solar System objects. The correlations found are important because there are diagnostic of some physical effects processing the surfaces of TNOs. The so-called collisional resurfacing (CR) scenario is generally invoked to explain the color diversity which could be the result of two competing mechanisms: the reddening and darkening of icy surfaces by solar and galactic irradiation, and the excavation of fresh, primordial, and thus more neutral, ices as the results of collisions. While the reddening process is believed to act relatively homogeneously throughout the belt, the collision-induced bluing should significantly vary with collision rates and efficiencies within the belt. As a consequence, the CR scenario should leave a characteristic signature with the bluer objects located in the most collisionally active regions of the belt. *Thébault and Doressoundiram (2002)* first performed deterministic numerical simulations of the collisional and dynamical environment of the Kuiper Belt to look for such a signature. Their results do match several main statistical correlations observed in the « real » belt: e, i, V_{rms} and above all q, but also clear departures from the observed color distribution, as for example the Plutinos, that became uniformly bluer in the simulations.

Such an attempt to check the validity of the CR scenario points out that the origin of the color diversity is still unclear. The solution might lie in a better understanding of the physical processes at play, in particular the fact that the long-term effect of space weathering might significantly depart from continuous reddening (see below). Another alternative would be that the Classical objects may consist in the superposition of two distinct populations, as suggested by *Levison and Stern (2001), Brown (2001), and Doressoundiram et al (2002).* One population would consist of primordial objects, with red surfaces , low inclination and small sizes, and the second population would consist of more evolved objects, with larger sizes, higher inclination and more diverse surface colors.

Centaurs and TNOs appear very similar in spectral and color characteristics, and this represents the strongest observational argument for a common origin, supporting the hypothesis that Centaurs are ejected from the Kuiper belt by planetary scattering. The rotational properties of the few available Centaurs and TNOs seem also to be similar, even though it is still difficult to interpret the distribution due to the lack of data. Judging from the observed lightcurve amplitudes, large TNOs can exist with an elongated shape. As opposed to the Centaurs, the color distribution of cometary nuclei does not seem to match that of TNOs (see chapter by Jewitt); the very red color seems absent among comets. 2060 Chiron is considered as the first example of temporary dormant comet; the other Centaurs and TNOs might be dormant comets containing frozen volatiles that would sublimate in particular heating conditions.

The wide diversity of color is confirmed by the different spectral behavior, even though only a few high quality spectra exist. The spectra show a large range of slope; some are featureless with almost constant gradients over the visible-NIR range, and some show absorption features of H_2O or light hydrocarbons ices . Few objects show features attributable to the presence of hydrous silicates, but this still needs to be confirmed. Several models have been reported as interpretation of the surface composition. Unfortunately, all the present models are just a possible indication of composition. The interpretation of the spectra is neither straightforward nor unique because the models are dependent on many parameters.

The H_2O absorption bands so far detected are generally weak, and occur on only a few objects. H_2O ice is presumed to be the principal component of the bulk composition of outer Solar System objects (formed mostly at the same low temperature of 30-40 K) and should constitute at least about 35 % of the bulk composition of this population. H_2O ice has to be present on these bodies even if it is not detectable on the spectra. Various processes of space weathering (due to solar radiation, cosmic rays and interplanetary dust), can affect the uppermost surface layer. The observed surface diversity can be due to different collisional evolutionary states and to different degrees of surface alteration due to space weathering. Collisions can rejuvenate the surface locally. On the basis of laboratory experiments, *Strazzulla (1998)* demonstrated that bombardment by high-energy radiation of mixtures of CH_3OH, CH_4, H_2O, CO_2,, CO and NH_3 ices, produces radiation mantles which are dark, hydrogen-poor and carbon rich, and which show red spectra. These red spectra may become flat again as demonstrated by *Moroz et al. (2002)* simulating an aging effect (increasing ion fluence) of a dark organic sample (asphaltite). Many processes can have altered the pristine surfaces of these objects, for which the original composition is still unclear. Laboratory experiments *(Strazzulla et al. 2002)* are in progress to simulate weathering effects on small bodies by bombardments at different fast ion fluences on several minerals and meteorites to better understand these processes.

This research field is still very young, even though ten years have passed since the discovery of the first TNO. There is a great deal of interest in the study of the physical and compositional characteristics of these objects, but our knowledge of the properties of TNOs suffers from the limitations connected with ground-based observations. In the near future, space missions like SIRFT and GAIA will substantially improve our information on their physical properties.
SIRFT will observe more than 100 TNOs in thermal radiation and make it possible to calculate the geometric albedos and dimensions of a statistically significant sample of objects in several dynamical populations. GAIA, with its all-sky astrometric and photometric survey will discover objects not observable from the ground and will enable the detection of binary objects, the discovery of Pluto-size bodies, and a better taxonomy for Centaurs and TNOs.
NASA’s New Horizons mission to the Kuiper Belt and Pluto-Charon, with an anticipated arrival at Pluto in 2016 to 2018, will offer the first close-up views of as many as five solid bodies beyond Neptune.

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Table I – For each object the dynamical type (Centaurs and Classical, Plutinos and Scattered for the TNOs), rotational period, lightcurve amplitude, diameters, albedo and spectral signature characteristics. When the albedo is not available (--) an approximate diameter has been computed assuming an albedo of 0.05.

Name	Type	Rot. Periods (hours)	Amplit (mag).	Diameter (Km)	Albedo p_v	Spectral signatures*
2060 Chiron	Centaur	5.917813±0.000007[1]	0.04[1]	148±8[2]	0.17±0.02[2]	H_2O ice varying with activity
5145 Pholus	Centaur	9.9825±0.0040[3]	0.15[3]	190±22[4]	0.04±0.03[4]	Water ice + hydrocarbons
8405 Asbolus	Centaur	8.9351±0.0003[5]	0.55[5]	66±4[2]	0.12±0.03[2]	Controversial
10199 Chariklo	Centaur	Long ?[6]	0.31[6]	302±30[7] 273±19[8]	0.045±0.010[7] 0.055±0.008[8]	H_2O ice
15789 (1993 SC)	Plutino	15.43[9]?	0.5[9]	328±66[10]	0.022±0.013[10]	Controversial
19308 (1996 TO$_{66}$)	Classical	7.9[11] 6.25±0.01[12]	0.25[11] 0.12-0.33[12]	≈ 748	--	H_2O ice Variation
20000 Varuna	Classical	6.3442±0.0002[13] 6.3576±0.0002[14]	0.42[13] 0.42[14]	1060±220[14] 900±145[15]	0.038±0.022[14] p_R= 0.07±0.03[15]	H_2O ice
26308 (1998 SM$_{165}$)	Classical	7.966[16] 7.1[11]	0.56[16] 0.45[11]	≈ 411	--	
26375 (1999 DE$_9$)	Scattered	No variation over 24hr[17]		≈ 682	--	Hydrous silicates
28976 Ixion	Plutino			≈ 1360	--	No features
31824 (1999 UG$_5$)	Centaur	13.25 ? [18] 13.41±0.04[19] (single peak)	0.24[18] 0.102[19]	≈ 57	--	
32532 (2001 PT$_{13}$)	Centaur	8.3[21] 8.3378±0.0012[20]	0.16[21] 0.18[20]	≈ 95	--	Surface variation
32929 (1995 QY$_9$)	Plutino	7.3[11]	0.60[11]	≈ 188	--	
33128 (1998 BU$_{48}$)	Centaur	9.8-12.6[17]	0.68[17]	≈ 216	--	
35671 (1998 SN$_{165}$)	Classical	10.1±0.8[21]	0.15[21]	≈ 411	--	
38628 (2000 EB $_{173}$)	Plutino	No variation over 24hr[5]	<0.06[17]	≈ 682	--	Hydrous silic.?
40314 (1999 KR$_{16}$)	Classical	11.680±0.002[17]	0.18[17]	≈ 411	--	
47171 (1999 TC$_{36}$)	Plutino			≈ 622	--	H_2O ice
47932 (2000 GN$_{171}$)	Plutino	8.329±0.005[17]	0.61[17]	≈ 375	--	Non ident.
1998 SG$_{35}$	Centaur			≈ 33	--	H_2O ice ?
2000 QC$_{243}$	Centaur	4.57±0.04[22] (single peak)	0.7[22]	≈ 180	--	H_2O ice ?

[1] Marcialis and Buratti (1993); [2] Fernandez et al. (2002); [3] Buie and Bus (1992); [4] Davies et al. (1993); [5] Davies et al. (1998); [6] Peixinho et al. (2001); [7] Jewitt and Kalas (1998); [8] Altenhoff et al. (2001); [9] Williams et al. (1995); [10] Thomas et al. 2000); [11] Sheppard (2002); [12] Hainaut et al. (2000); [13] Jewitt and Sheppard (2002); [14] Lellouch et al. (2002); [15] Jewitt et al. (2001); [16] Romanishin et al. (2001); [17] Sheppard and Jewitt (2002); [18] Gutierrez et al. (2001); [19] Bauer et al. (2002); [20] Farnham and Davies (2002); [21] Peixinho et al. (2002); [22] Ortiz et al. (2002).
∗description of the spectra and related reference are discussed in section 5

Figures captions :

Figure 1: B-V versus V-R plot of the trans-Neptunian objects. The different classes of TNOs are represented : Plutinos, Classicals, and Scattered. The star represents the colors of the Sun. From *Doressoundiram et al., 2002.*

Figure 2. Example of reflectivity spectra of TNOs and Centaurs, normalized at the V filter (centered around 550 nm). Color gradient range from low (neutral spectra) to very high (very red spectra). From color data *of Barucci et al, 2001.*

Figure 3. Colors of TNOs and Centaurs (52 objects) in the orbital eccentricity versus semi major axis plane. The sizes of the symbols are proportional to the corresponding object's diameter. A color palette has been adopted to scale the color spread from B-R=1.01 (coded as dark blue) to B-R=1.88 (coded as red). In comparison, B-R=1.03 for the Sun and 1.97 for the Centaur 5145 Pholus (the reddest known object in the solar system). 2:3 (a~39.5 AU) and 1:2 (a~48 AU) resonances with Neptune are marked as well as the q=40AU perihelion curve. The advantage of this representation is that it offers to the eye the global color distribution of the TNOs. One can see some interesting patterns which come out from this color map. For instance, objects with perihelion distances around and beyond 40 AU are *mostly* very red. Classical objects (mostly between the 2:3 and 1:2 resonances) with high eccentricity and inclination are preferentially neutral/slightly red. Moreover, there is apparently a red color-low inclination cluster of TNOs. Contrary to Classical objects, no clear trend is obvious for Scattered TNOs (*a* > 50 UA), as well as Plutinos which lack of any trends in their surface colors. From *Doressoundiram et al (2002).*

Figure 4: Inclination versus B-R color plot of Classical objects. The linear least-squares fit has been plotted to illustrate the correlation. From *Doressoundiram et al. 2002.*

Figure 5. V+NIR spectra of 2 TNOs and 5 Centaurs obtained at VLT, ESO, with FORS and ISAAC. The spectra have been shifted in relative reflectance by 1 for clarity. The dots represent the V, J, H, and K colors, used to adjust the spectral ranges. A best-fit model has been reported on the spectra (see section 5 for details).

Figure 6: Spectrum of 5145 Pholus (lower trace) with the Hapke model of *Cruikshank et al. (1998)* (solid line). The four principal components for which complex refractive indices (n, k) were included in the model are shown schematically in the four upper traces. The model of *Poulet et al. (2002)* using the Shkuratov code is also shown.