Surface Characteristics of Transneptunian Objects and Centaurs from Photometry and Spectroscopy

M. A. Barucci and A. Doressoundiram

Observatoire de Paris

D. P. Cruikshank

NASA Ames Research Center

The external region of the solar system contains a vast population of small icy bodies, believed to be remnants from the accretion of the planets. The transneptunian 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 the TNO population are still limited by the faintness of these objects. The basic properties of these objects, including information on their dimensions and rotation periods, are presented, with emphasis on their diversity and the possible characteristics of their surfaces.

1. INTRODUCTION

Transneptunian objects (TNOs), also known as Kuiper belt objects (KBOs) and Edgeworth-Kuiper belt objects (EKBOs), 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 ($P < 200$ yr) of low orbital inclination and the transneptunian 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 belt 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 1 km, 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 composition 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 , making them difficult to observe spectroscopi-

cally 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 photometric and spectroscopic studies of TNOs and the emerging results.

2. OBSERVATIONAL STRATEGY AND DATA REDUCTION TECHNIQUES

2.1. Photometry

Visible- and near-infrared (NIR)-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, yielding color indices, rotational properties and estimates of the sizes of TNOs. The color indices (e.g., U-V, B-V, V-R, V-I, V-J, V-H, V-K) are the differences between the magnitudes measured in two filters, and represent an important tool to study the surface composition of these objects and to define a possible taxonomy. [The broad-band filters commonly used (and their central wavelength position in micrometers) are U (0.37), B (0.43), V (0.55), R (0.66), I (0.77), J (1.25), H (1.65), and K (2.16).]

Because of their faintness, slow proper motion, and rotation, TNOs require specific observational procedures and data reduction techniques. The typical apparent visual magnitude is about 23 or fainter, although a few objects brighter than 22 have been found. A signal-to-noise ratio (SNR) of about 30 (precision of 0.03–0.04 mag) is the photometric accuracy required for color analysis. Two problems limit the signal precision achievable: (1) the sky contribution to

the measured signal and (2) the 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, and the application of the aperture correction technique (Howell, 1989).

Even though TNOs orbit at large heliocentric distances, their motion on the sky restricts observations to relatively short exposure times. At opposition, the nonsidereal motions of TNOs at 30, 40, and 50 AU are about 4.2, 3.2, and 2.6"/h respectively, thus producing a trail of $\sim 1.0''$ in 15-min exposure time (in the worst case). Trained images 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 the point spread function (PSF) of the object is different from field stars, thus thwarting the aperture correction technique, which must be calibrated from the PSFs of nearby field stars. The proper motions of TNOs and the long exposure times needed to detect them at an adequate SNR limit the number of objects that can be observed, even with a big telescope. For each individual B, V, R, etc., magnitude obtained, 1σ uncertainties are based on the combination of several uncertainties: $\sigma = (\sigma_{\text{pho}}^2 + \sigma_{\text{ap}}^2 + \sigma_{\text{cal}}^2)^{1/2}$, 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

Reflectance spectroscopy (0.3 to 2.5 μm) provides the most sensitive and broadly applied remote sensing technique for characterizing the major mineral phases and ices present on TNOs. At visible and NIR 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 NIR 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 , and 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 absorption features at visible wavelengths.

Although the most reliable mineralogical interpretations require measurements extending into the NIR, measurements restricted to 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. With 8-m-class telescopes, the limiting magnitude at the present time is $V = 22.5$ mag for visible spectroscopy, and the object must be brighter than ~ 21 mag (in V) for NIR 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. Careful removal of the dominant sky background (atmospheric emission bands) in the infrared and the choice of good solar analogs are essential steps to ensure high-quality data.

3. DIAMETER, ROTATIONAL PROPERTIES, AND SHAPE

Many useful physical and compositional 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, constraining the origin and evolution of this population of objects. Some of the large TNOs might conserve their original angular momentum, while many others suffered collisional 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, 50000 Quaoar, is resolved in an HST image at 40.4 ± 1.8 milliarcsec, yielding a diameter of 1260 ± 190 km (Brown and Trujillo, 2003). Only a few objects have been observed at thermal and millimetric wavelengths and thus have directly determined diameters and albedos (Table 1), 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 an albedo of 0.04–0.05, which is common for dark objects and cometary nuclei (e.g., Lamy *et al.*, 2004). This assumption introduces a large uncertainty in the size estimates; for instance, if we instead used 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 1 a fairly complete list of the most reliably determined

TABLE 1. Dynamical type (Centaurs and classical, Plutinos and scattered for the TNOs), rotational period, lightcurve amplitude, diameters, albedo, and spectral signature characteristics for each object (numbers shown in brackets are references).

Name	Type	Rotation Periods (h)	Amplitude (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 ₂ O 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 ₂ O 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]	0.25 [11]	≈ 748	—	H ₂ O ice
		6.25 ± 0.01 [12]	$0.12-0.33$ [12]			Variation
20000 Varuna	Classical	6.3442 ± 0.0002 [13]	0.42 [13]	1060 ± 220 [14]	0.038 ± 0.022 [14]	H ₂ O ice
		6.3576 ± 0.0002 [14]	0.42 [14]	900 ± 145 [15]	$p_R = 0.07 \pm 0.03$ [15]	
26308 (1998 SM ₁₆₅)	Classical	7.966 [16]	0.56 [16]	≈ 411	—	
		7.1 [11]	0.45 [11]			
26375 (1999 DE ₉)	Scattered	No variation over 24 h [17]		≈ 682	—	Hydrous silicates
28976 Ixion	Plutino			1065 ± 165 [23]	—	No features
31824 Elatus	Centaur	13.25? [18]	0.24 [18]	≈ 57	—	H ₂ O ice?
		13.41 ± 0.04 [19] (single peak)	0.102 [19]			Variation?
32532 Thereus	Centaur	8.3 [22]	0.16 [22]	≈ 95	—	Surface variation
		8.3378 ± 0.0012 [20]	0.18 [20]			
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 Huya	Plutino	No variation over 24 h [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 ₂ O ice
47932 (2000 GN ₁₇₁)	Plutino	8.329 ± 0.005 [17]	0.61 [17]	≈ 375	—	Nonident.
52872 Oxyrhoe	Centaur			≈ 33	—	H ₂ O ice?
54598 (2000 QC ₂₄₃)	Centaur	4.57 ± 0.04 [22] (single peak)	0.7 [22]	≈ 180	—	H ₂ O ice?

*Descriptions of the spectra and related references are given in section 5.

When the albedo is not available (—) an approximate diameter has been computed assuming an albedo of 0.05.

References: [1] Marcialis and Buratti (1993); [2] Fernández 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] S. Sheppard (personal communication, 2003); [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] Gutiérrez et al. (2001); [19] Bauer et al. (2002); [20] Farnham and Davies (2003); [21] Peixinho et al. (2002); [22] Ortiz et al. (2002); [23] D. Jewitt (personal communication, 2003).

results is presented. The faintness of these objects makes the analysis of the lightcurves difficult. In a photometric study by Sheppard and Jewitt (2002), 9 of 13 objects measured showed no detectable variation, implying a small amplitude, or a period ≥ 24 h, or both. Some objects show hints of variability that might yield a lightcurve with higher-quality data. The rotational periods seem to range between 6 and 15 h, but a bias effect can exist because of the difficulty in determining long periods and the faintness of these objects.

3.3. Shape

Stellar occultations and photometric observations can give important but limited information on the shape of these bodies, although 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 WW₃₁ (Veillet et al., 2002).

The lightcurve is the only technique currently available to give constraints on the shape. The amplitude can give

some indication on the elongation of the body. Assuming a triaxial ellipsoid shape with semimajor axes $a > b > c$ and no albedo variation, we can estimate the lower limit of the semimajor axis ratio: $a/b \geq 10^{0.4\Delta m}$.

A few large TNOs seem to have elongated shapes (Sheppard and Jewitt, 2002). For example, using $\Delta m = 0.61$ mag (see Table 1) for 47932 (2000 GN₁₇₁), an estimate of $a/b \geq 1.75$ can be obtained. Sheppard and Jewitt, analyzing 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 to search for relationships among physical properties and orbital characteristics.

4.1. Color Diversity

One of the most puzzling features of the objects in the Kuiper belt, and one that has been confirmed by numerous

Fig. 1. B-V vs. V-R plot of the transneptunian objects. The different classes of TNOs are represented: Plutinos, classical, and scattered. The star represents the colors of the Sun. From *Doressoundiram et al.* (2002).

surveys, is optical color diversity. This diversity is peculiar to the outer solar system bodies and exceeds that of the asteroids, cometary nuclei, and small 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 Fig. 1). The different dynamical classes (e.g., Centaurs, Plutinos, classical, and scattered) seem to share the same color diversity. However, *Tegler and Romanishin* (1998) concluded earlier, on the basis of the visible (B-V vs. 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 of 32 objects (*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, 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. They cautiously concluded that almost all the color-color distributions are compatible with both a continuous and a 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 Fig. 1 that include the I filter ($\sim 0.77 \mu\text{m}$) or J filter ($\sim 1.2 \mu\text{m}$) do not show any evidence of color bimodality (see *Boehnhardt et al.*, 2001; *Jewitt and Luu*, 2001).

The information contained in the color indices can be converted into a very-low-resolution reflectance spectrum, as illustrated in Fig. 2. Reflectance spectra have been computed using BVRJ color data of the object (with the color of the Sun removed). [The reflectance spectrum $R(\lambda)$ is given by $R(\lambda) = 10^{-0.4 [(M(\lambda) - M(V)) - (M(\lambda) - M_{\text{Sun}}(V))]$, where M and M_{Sun} 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, $0.55 \mu\text{m}$).] The spectra range from neutral or slightly red to very red, 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 abrupt and significant changes in the spectral slope (within the error bars) over the whole wavelength range. This result was confirmed by *McBride 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 ($0.4 \mu\text{m}$) to the J ($1.2 \mu\text{m}$) regime.

Fig. 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).

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 radiation processing and solar or galactic cosmic-ray irradiation both tend to the reddening of surfaces of all airless objects. 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*). Another resurfacing process resulting from possible sporadic cometary activity has been suggested (*Hainaut et al., 2000*). Resurfacing by ice recondensation from a temporary atmosphere produced by intrinsic gas and dust activity might be an efficient process affecting the TNOs closest to the Sun (the Plutinos).

4.2. Correlations

To date, B-V, V-R, and V-I colors are available for more than 150 objects, while only a few tens of them have V-J colors determined (*Davies et al., 1998, 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 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 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?

On 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, *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 surface compositional and/or texture variation. The issue of the color heterogeneity remains ambiguous.

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, finding four “classes” showing a quasicontinuous 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. A larger dataset is

Fig. 3. Inclination vs. B-R color plot of classical objects. The linear least-squares fit has been plotted to illustrate the correlation. From *Doressoundiram et al. (2002)*.

needed in order to investigate the real compositional taxonomy of the transneptunian 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, a result 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 (Plate 18). This feature was first quantified by *Trujillo and Brown (2002)*, who found a significant 3.1σ correlation between 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 that did not include the scattered objects (Fig. 3). 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 Del-santi (2002)*, as well as *Doressoundiram et al. (2002)*, found also significant correlations with orbital eccentricity (e) and perihelion distance (q) for the classical TNOs, although less strong than with (i). *Levison and Stern (2001)* also found that low- i classical TNOs are smaller (greater H). 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 reso-

nant objects included in their sample that completely masks the correlation.

Hainaut and Delsanti (2002) analyzed a combined dataset of 91 Centaurs and TNOs. Although 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, but the trend is opposite for the Plutinos (faint H tends to be bluer). *Doresoundiram et al.* (2002) did not find any correlation with size in their homogeneous but smaller dataset. These conflicting results require confirmation by the analysis of a larger dataset, but in any case the physical interpretation remains difficult.

Although hypothetical, the collisional resurfacing scenario offers the advantage of making relatively simple predictions concerning the color correlation within the Kuiper belt. Basically, the most dynamically excited objects should be most affected by energetic impacts, and thus should have the most neutral colors. Several authors (*Hainaut and Delsanti*, 2002; *Doresoundiram et al.*, 2002; *Stern*, 2002) have found a good correlation between the color index and $V_k(e^2 + i^2)^{1/2}$, apparently because both i and e contribute to the average encounter velocity of a TNO.

Considering that optical and infrared colors are correlated, one could presume that the correlations found between orbital parameters and optical colors can be generalized to infrared colors. Indeed, the V-J observations have a much wider spectral range and are therefore likely to be more robust in showing color correlations. However, such statistical analysis is still tentative because of the relatively few V-J colors available. The first such attempt made by *McBride et al* (2003) seems to support the color and perihelion distance, as well as 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 NIR 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 a few data are 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.* (2003). The spectra show a generally featureless behavior with a difference in the spectral gradient ranging from neutral to very red. The com-

puted reflectance slopes range from 0 or slightly negative (in the case of Chiron) up to 58%/100 nm for Pholus or Nessus, which are the reddest known objects in the solar system. The computed slopes vary a little as a function of the wavelength range analyzed, but do not seem to be related to the perihelion distance of the objects.

Broad absorptions have been found only for two Plutinos: 38628 Huya and 47932 (2000 GN₁₇₁). In the spectrum of 47932 (2000 GN₁₇₁), an absorption centered at around 0.7 μ m has been detected with a depth of ~8%, while in the spectrum of 38628 Huya two weak features centered at 0.6 μ m and at 0.745 μ m have been detected with depths of ~7% and 8.6% respectively (*Lazzarin et al.*, 2003). These features are very similar to those due to aqueously altered 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.*, 2003).

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 NIR and rigorously modeled. In fact, these objects are faint, and even observations with the largest telescopes [Keck and the Very Large Telescope (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 [European Southern Observatory (ESO), Chile] are shown in Fig. 4, with the best model fitting of the data. The general spectral characteristics are listed in Table 1.

A general review of Centaurs is presented in *Barucci et al.* (2002a), while details of a few objects, recently observed, are discussed below.

8405 Asbolus has yielded controversial results: *Brown* (2000) and *Barucci et al.* (2000a) observed it, finding no spectral signatures in the NIR. Later, *Kern et al.* (2000), using the HST, obtained several (1.1–1.9 μ m) spectra, which revealed a significantly inhomogeneous surface characterized on one side by water ice mixed with unknown low-albedo constituents. They speculated 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) re-observed 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; *Shkuratov et al.*, 1999), *Romon-Martin et al.* (2002) modeled the complete spectrum from 0.4 to 2.5 μ m with several mixtures of Triton tholins, Titan tholins, ice tholins, amorphous carbon, and olivine. None of the models successfully matched the visible part

Fig. 4. V + NIR spectra of two TNOs and five Centaurs obtained at VLT, ESO, with FORS and ISAAC. The spectra, normalized to 1 on V, 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 is shown for each spectrum (see section 5 for details).

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. 4). The steep red spectral slope is the principal characteristic of the data that forces the use of organic compounds (kerogen, tholins, etc.) in the models. Kerogen is necessary to reproduce the red slope of spectra in the visible region, while 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). Both Titan and ice tholins are synthetic macromolecular compounds, produced from a gaseous mixture of $\text{N}_2:\text{CH}_4$ (Titan tholins) or an ice mixture of $\text{H}_2\text{O}:\text{C}_2\text{H}_6$ (ice tholins).

10199 Chariklo, after the first detection of water ice by Brown and Koresko (1998) and by Brown et al. (1998), was observed again by Dotto et al. (2003a), who still confirmed water ice detection and showed small spectral behavior variation (Fig. 4).

32532 (2001 PT₁₃), now named Thereus, was 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 spectrum 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. 4). For the other spectrum an acceptable model with an albedo of 0.06 and 90% amorphous carbon, 5% Titan tholin, and 5% water ice was obtained.

Dotto et al. (2003b) observed two Centaurs: 52872 (1998 SG₃₅), now named Oxyrhoe, and 54598 (2000 QC₂₄₃) in the H and K regions, giving tentative models of these two bodies with similar percentages of kerogen (96–97%), olivine (1%), and water ice (2–3%) (Fig. 4).

63252 (2001 BL₄₁) has been observed by Doressoundiram et al. (2003). A model with 17% Triton tholin, 10% ice tholin, and 73% amorphous carbon fits the spectrum.

31824 Elatus was found by Bauer et al. (2002) to have markedly different spectral reflectance when observed on two successive nights. While one spectrum shows a rather neutral reflectance, 1.2–2.3 μm , the other shows a strong red reflectance extending to 2.3 μm , with absorption bands approximately matched by a model using amorphous H_2O ice.

The TNOs are even fainter than Centaurs, and only a few spectra are available, generally with very low SNR. Although only a small number have been observed to date, their surface characteristics seem to show wide diversity. 15874 (1996 TL₆₆) and 28978 Ixion have flat featureless spectra similar to that of water ice contaminated with low-albedo, spectrally neutral material (Luu and Jewitt, 1998; Licandro et al., 2002). 15789 (1993 SC), observed by Brown et al. (1997), shows features that may 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 and found a featureless spectrum. The difference in these results requires resolution, best accomplished with additional (and higher-quality) data. McBride et al. (2003) show that 1993 SC is one of the reddest TNOs studied so far.

38628 Huya has been observed by many authors (Brown et al., 2000; Licandro et al., 2001; Jewitt and Luu, 2001; deBergh et al., 2003) and appears generally featureless in the NIR [except Licandro et al. (2001) and de Bergh et al. (2003) show that a possible feature appears beyond 1.8 μm]. The interpretation of these spectra is challenging.

19308 (1996 TO₆₆) shows an inhomogeneous surface with clear indications of water ice absorptions at 1.5 and 2 μm . A model of water ice mixed with some other minor components matches the region 1.4–2.4 μm (Brown et al., 1999). 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), while 26181 (1996 GQ₂₁), observed by Doressoundiram et al. (2003), shows a featureless spectrum interpreted with a geographical mixture model composed of 15% Titan tholin, 35% ice tholin, and 50% amorphous carbon (Fig. 4).

In contrast, 26375 (1999 DE₉) 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. An absorption near 1 μm may be consistent with olivine. If the presence of the hydroxyl group is confirmed, this might imply the presence of liquid water and a temperature near the melting point for at least a short period of time. The H region has been re-observed by *Doresoundiram et al.* (2003), but because of the low SNR, they were not able to confirm the 1.6- μm feature.

47171 (1999 TC₃₆), observed by *Dotto et al.* (2003b) in the J, H, and K region, shows a weak absorption around 2 μm , and the surface composition has been interpreted with a mixture of 57% Titan tholin, 25% ice tholin, 10% amorphous carbon, and 8% water ice (Fig. 4).

In some cases repeated observations of the same object give different results, sometimes because of inferior quality data (see Table 1), but in other cases the surfaces may be variable on a large spatial scale. A few objects in addition to 31824 Elatus clearly show surface variations, such as 19308 (1996 TO₆₆) and 32532 Thereus. While the models noted here represent the best current fit to the data, they are not unique and depend on many free parameters, such as grain size, albedos, porosity, etc.

6. MODELING SURFACE COMPOSITION

We have already noted the modeling results of a few Centaurs and TNOs by various investigators, and 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 semiempirical Hapke model (Hapke, 1981, 1993) has been most widely used, while other models incorporating additional physical configurations (e.g., layers of transparent or

semitransparent 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., H₂O 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 the presence or absence of absorption bands arising from minerals, ices, and organic solids.

The case of Centaur 5145 Pholus (Fig. 5) 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 H₂O ice (2.0 μm) and (probably) methanol ice (CH₃OH) at 2.27 μm . A Hapke

Fig. 5. 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.

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 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. 5.

7. CONCLUSIONS

One of the most puzzling features of the Kuiper belt, 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 NIR. Statistical analyses point to 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, and no firm conclusions can be drawn regarding correlation of colors with size or heliocentric distance. The correlations of color with i , e , and q are important because they may be diagnostic of some physical effects of processing the surfaces of TNOs. The 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 blueing should vary significantly with the rate and efficiency of collisions 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. Thébaud and Doressoundiram (2003) 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 ob-

served in the belt: e , i , V_{rms} , and particularly q , but there are also clear departures from the observed color distribution. For example, the Plutinos became uniformly bluer in the simulations.

Computational models to check the validity of the CR scenario, such as those of Thébaud and Doressoundiram (2003), show that the origin of the color diversity is still unclear. The solution might lie in a better understanding of the physical processes involved, 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 of 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 also seem 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 elongated shapes. As opposed to the Centaurs, the color distribution of cometary nuclei does not seem to match that of TNOs (Jewitt, 2004); the very red color seems absent among comets. 2060 Chiron can be considered an example of a temporarily 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 hydrocarbon ices. A few objects show features attributable to the presence of hydrous silicates, but this still needs to be confirmed. Several models of the spectral reflectance of TNOs and Centaurs have been proposed, but each is subject to the limitations imposed by the quality of the astronomical spectra, the generally unknown albedo, and to the limited library of materials for which optical constants have been determined. The models of red objects all use organic materials, such as tholins and kerogen, because common minerals (and ices) cannot provide a sufficiently red color.

The H_2O absorption bands detected so far on a few objects are generally weak. 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. Thus H_2O ice

has to be present even if it is not detectable on the spectra, but its absorption bands can be reduced to invisibility by the presence of low-albedo, opaque materials. Additionally, 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 by excavating material from the subsurface. 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 that are dark, hydrogen-poor, and carbon-rich, and show red spectra. These red spectra may become flat again, e.g., as demonstrated by Moroz *et al.* (2003), who simulated an aging effect of a dark organic sample (asphaltite) by ion irradiation. Many processes may 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 a decade has 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 groundbased observations. In the near future, space missions such as the Space Infrared Telescope Facility (SIRTF) and Gaia will substantially improve our knowledge of their physical properties. SIRTF will observe the thermal radiation of more than 100 TNOs and thereby 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-sized 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 closeup views of as many as five solid bodies beyond Neptune.

REFERENCES

- Altenhoff W. J., Menten K. M., and Bertoldi F. (2001) Size determination of the Centaur Chariklo from millimeter-wavelength bolometer observations. *Astron. Astrophys.*, 366, L9–L12.
- Barucci M. A., Lazzarin M., and Tozzi G. P. (1999) Compositional surface variety among the Centaurs. *Astron. J.*, 117, 1929–1932.
- Barucci M. A., de Bergh C., Cuby J.-G., Le Bras A., Schmitt B., and Romon J. (2000a) Infrared spectroscopy of the Centaur 8405 Asbolus: First observations at ESO-VLT. *Astron. Astrophys.*, 357, L53–L56.
- Barucci M. A., Romon J., Doressoundiram A., and Tholen D. J. (2000b) Composition surface diversity in the Trans-Neptunian Objects. *Astron. J.*, 120, 496–500.
- Barucci M. A., Fulchignoni M., Birlan M., Doressoundiram A., Romon J., and Boehnhardt H. (2001) Analysis of Trans-Neptunian and Centaur colours: Continuous trend or grouping? *Astron. Astrophys.*, 371, 1150–1154.
- Barucci M. A., Cruikshank D. P., Mottola S., and Lazzarin M. (2002a) Physical properties of Trojans and Centaur Asteroids. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), pp. 273–287. Univ. of Arizona, Tucson.
- Barucci M. A. and 19 colleagues (2002b) Visible and near-infrared spectroscopy of the Centaur 32532 (PT13). ESO Large Program on TNOs and Centaurs: First spectroscopy results. *Astron. Astrophys.*, 392, 335–339.
- Bauer J. M., Meech K. J., Fernández Y. R., Farnham T. L., and Roush T. L. (2002) Observations of the Centaur 1999 UG₅: Evidence of a unique outer solar system surface. *Publ. Astron. Soc. Pacific*, 114, 1309–1321.
- Boehnhardt H., Tozzi G. P., Birkle K., Hainaut O., Sekiguchi T., Vlair M., Watanabe J., Rupprecht G., and the Fors Instrument Team (2001) Visible and near-IR observations of Trans-Neptunian objects. Results from ESO and Calar Alto telescopes. *Astron. Astrophys.*, 378, 653–667.
- Boehnhardt H. and 17 colleagues (2002) ESO Large Program on physical studies of Trans-Neptunian Objects and Centaurs: Visible photometry — First results. *Astron. Astrophys.*, 395, 297–303.
- Brown M. E. (2000) Near-infrared spectroscopy of centaurs and irregular satellites. *Astron. J.*, 119, 977–983.
- Brown M. E. (2001) The inclination distribution of the Kuiper belt. *Astron. J.*, 121, 2804–2814.
- Brown M. E. and Koresko C. D. (1998) Detection of water ice on the Centaur 1997 CU₂₆. *Astrophys. J. Lett.*, 505, L65–L67.
- Brown M. E. and Trujillo C. (2003) Direct measurement of the size of the large Kuiper belt Quaoar. *Astron. J.*, in press.
- Brown M. E., Blake G. A., and Kessler J. E. (2000) Near-infrared spectroscopy of the bright Kuiper belt object 2000 EB₁₇₃. *Astrophys. J. Lett.*, 543, L163–L165.
- Brown R. H., Cruikshank D. P., Pendleton Y. J., and Veeder G. (1997) Surface composition of Kuiper belt object 1993 SC. *Science*, 276, 937–939.
- Brown R. H., Cruikshank D. P., Pendleton Y., and Veeder G. J. (1998) Identification of water ice on the Centaur 1997 CU₂₆. *Science*, 280, 1430–1432.
- Brown R. H., Cruikshank D. P., and Pendleton Y. J. (1999) Water ice on Kuiper belt object 1996 TO₆₆. *Astrophys. J. Lett.*, 519, L101–L104.
- Buie M. W. and Bus S. J. (1992) Physical observations of (5145) Pholus. *Icarus*, 100, 288–294.
- Cruikshank D. P. and 14 colleagues (1998) The composition of Centaur 5145 Pholus. *Icarus*, 135, 389–407.
- Davies J., Spencer J., Sykes M., Tholen D., and Green S. (1993) (5145) Pholus. IAU Circular 5698.
- Davies J. K., McBride N., Ellison S. L., Green S. F., and Ballantyne D. R. (1998) Visible and infrared photometry of six centaurs. *Icarus*, 134, 213–227.
- Davies J. K., Green S., McBride N., Muzzerall E., Tholen D. J., Whiteley R. J., Foster M. J., and Hillier J. K. (2000) Visible and infrared photometry of fourteen Kuiper belt objects. *Icarus*, 146, 253–262.
- De Bergh C., Boehnhardt H., Barucci M. A., Lazzarin M., For-

- nasier S., Romon-Martin J., Tozzi G. P., Doressoundiram A., and Dotto E. (2003) Hydrated silicates at the surface of two Plutinos? *Astron. Astrophys.*, in press.
- Delsanti A. C., Boehnhardt H., Barrera L., Meech K. J., Sekiguchi T., and Hainaut O. R. (2001) BVRI photometry of 27 Kuiper belt objects with ESO/Very Large Telescope. *Astron. Astrophys.*, 380, 347–358.
- Doressoundiram A., Barucci M. A., Romon J., and Veillet C. (2001) Multicolor photometry of Trans-Neptunian objects. *Icarus*, 154, 277–286.
- Doressoundiram A., Peixinho N., De Bergh C., Fornasier S., Thébault Ph., Barucci M. A., and Veillet C. (2002) The color distribution of the Kuiper belt. *Astron. J.*, 124, 2279–2296.
- Doressoundiram A., Tozzi G. P., Barucci M. A., Boehnhardt H., Fornasier S., and Romon J. (2003) Spectroscopic investigation of Centaur 2001 BL₄₁ and transneptunian objects (26181) 1996 GQ₂₁ and (26375) 1999 DE₉. ESO Large Program on TNOs and Centaurs. *Astron. J.*, 125, 2721–2727.
- Dotto E., Barucci M. A., Leyrat C., Romon J., Licandro J., and de Bergh C. (2003a) Unveiling the nature of 10199 Chariklo: Near-infrared observations and modeling. *Icarus*, 164, 122–126.
- Dotto E., Barucci M. A., Boehnhardt H., Romon J., Doressoundiram A., Peixinho N., de Bergh C., and Lazzarin M. (2003b) Searching for water ice on 1999 TC₃₆, 1998 SG₃₅ and 2000 QC₂₄₃. ESO Large Program on TNOs and Centaurs. *Icarus*, 162, 408–414.
- Douté S. and Schmitt B. (1998) A multilayer bi-directional reflectance model for the analysis of planetary surface hyperspectral images at visible and near-infrared wavelengths. *J. Geophys. Res.*, 103, 31367–31390.
- Durda D. D. and Stern S. A. (2000) Collision rates in the present-day Kuiper belt and Centaurs regions: Application to surface activation and modification on comets, Kuiper belt objects, Centaurs and Pluto-Charon. *Icarus*, 145, 220–229.
- Farnham T. L. and Davies J. K. (2003) The rotational and physical properties of the Centaur 32532 (2001 PT₁₃). *Icarus*, 164, 418–427.
- Fernández J. A. (1999) Cometary dynamics. In *Encyclopedia of the Solar System* (P. R. Weissman et al., eds.), pp. 537–556. Academic, San Diego.
- Fernández Y. R., Jewitt D. C., and Shepard S. S. (2002) Thermal properties of two Centaurs Asbolus and Chiron. *Astron. J.*, 123, 1050–1055.
- Gutiérrez P. J., Ortiz J. L., Alexandrino E., Roos-Serote M., and Doressoundiram A. (2001) Short term variability of Centaur 1999 UG₅. *Astron. Astrophys.*, 371, L1–L4.
- Hainaut O. R. and Delsanti A. C. (2002) Colors of minor bodies in the outer solar system. *Astron. Astrophys.*, 389, 641–664.
- Hainaut O. R., Delahodde C. E., Boehnhardt H., Dotto E., Barucci M. A., Meech K. J., Bauer J. M., West R. M., and Doressoundiram A. (2000) Physical properties of TNO TO₆₆. Lightcurves and possible cometary activity. *Astron. Astrophys.*, 356, 1076–1088.
- Hapke B. (1981) Bidirectional reflectance spectroscopy. 1. Theory. *J. Geophys. Res.*, 86, 3039–3054.
- Hapke B. (1993) *Theory of Reflectance and Emittance Spectroscopy*. Cambridge Univ., New York. 455 pp.
- Harris A. W. and Harris A. W. (1997) On the revision of radiometric albedos and diameters of Asteroids. *Icarus*, 126, 450–454.
- Howell S. B. (1989) Two-dimensional aperture photometry — Signal-to-noise ratio of point-source observations and optimal data-extraction techniques. *Publ. Astron. Soc. Pacific*, 101, 616–622.
- Hiroi T., Bell J. F., Takeda H., and Pieters C. M. (1993) Modeling of S-type asteroid spectra using primitive achondrites and iron meteorites. *Icarus*, 102, 107–116.
- Hiroi T., Zolensky M. E., and Pieters C. M. (2001) The Tagish Lake meteorite: A possible sample from a D-type asteroid. *Science*, 293, 2234–2236.
- Jewitt D. (2002) From Kuiper belt object to cometary nucleus: The missing ultra-red matter. *Astron. J.*, 123, 1039–1049.
- Jewitt D. (2004) From cradle to grave: The rise and demise of comets. In *Comets II* (M. C. Festou et al., eds.), this volume. Univ. of Arizona, Tucson.
- Jewitt D. and Kalas P. (1998) Thermal observations of Centaur 1997 CU₂₆. *Astrophys. J. Lett.*, 499, L103–L109.
- Jewitt D. and Luu J. (1998) Optical and infrared spectral diversity in the Kuiper belt. *Astron. J.*, 115, 1667–1670.
- Jewitt D. and Luu J. X. (2001) Colors and spectra of Kuiper belt objects. *Astron. J.*, 122, 2099–2114.
- Jewitt D. and Sheppard S. S. (2002) Physical properties of Trans-Neptunian object 20000 Varuna. *Astron. J.*, 123, 2110–2120.
- Jewitt D., Luu J., and Marsden B. G. (1992) 1992 QB₁. IAU Circular 5611.
- Jewitt D., Aussel H., and Evans A. (2001) The size and albedo of the Kuiper-belt object 20000 Varuna. *Nature*, 411, 446–447.
- Kern S. D., McCarthy D. W., Buie M. W., Brown R. H., Campins H., and Rieke M. (2000) Compositional variation on the surface of Centaur 8405 Asbolus. *Astrophys. J. Lett.*, 542, L155–L159.
- Khare B. N., Sagan C., Arakawa E. T., Suits F., Callcott T. A., and Williams M. W. (1984) Optical constants of organic tholins produced in a simulated Titanian atmosphere — From soft X-ray to microwave frequencies. *Icarus*, 60, 127–137.
- Lamy P. L., Toth I., Fernández Y. R., and Weaver H. A. (2004) The sizes, shapes, albedos, and colors of cometary nuclei. In *Comets II* (M. C. Festou et al., eds.), this volume. Univ. of Arizona, Tucson.
- Lazzarin M., Barucci M. A., Boehnhardt H., Tozzi G. P., de Bergh C., and Dotto E. (2003) ESO Large Program on physical studies of Trans Neptunian Objects and Centaurs: Visible spectroscopy. *Astron. J.*, 125, 1554–1558.
- Lellouch E., Moreno R., Ortiz J. L., Paubert G., Doressoundiram A., and Peixinho N. (2002) Coordinated thermal and optical observations of Trans-Neptunian object (20000) Varuna from Sierra Nevada. *Astron. Astrophys.*, 391, 1133–1139.
- Levison H. F. and Stern S. A. (2001) On the size dependence of the inclination distribution of the main Kuiper belt. *Astron. J.*, 121, 1730–1735.
- Licandro J., Oliva E., and Di Martino M. (2001) NICS-TNG infrared spectroscopy of trans-neptunian objects 2000 EB₁₇₃ and 2000 WR₁₀₆. *Astron. Astrophys.*, 373, L29–L32.
- Licandro J., Ghinassi F., and Testi L. (2002) Infrared spectroscopy of the largest known Trans-Neptunian object 2001 KX₇₆. *Astron. Astrophys.*, 388, L9–L12.
- Luu J. X. and Jewitt D. (1996a) Color diversity among the Centaurs and Kuiper belt objects. *Astron. J.*, 112, 2310–2318.
- Luu J. X. and Jewitt D. (1996b) Reflection spectrum of the Kuiper belt object 1993 SC. *Astron. J. Lett.*, 111, L499–L503.
- Luu J. X. and Jewitt D. (1998) Optical and infrared reflectance spectrum of Kuiper belt object 1996 TL₆₆. *Astrophys. J. Lett.*, 494, L117–L121.

- Marcialis R. L. and Buratti B. J. (1993) CCD photometry of 2060 Chiron in 1985 and 1991. *Icarus*, 104, 234–243.
- McBride N., Green S. F., Davies J. K., Tholen D. J., Sheppard S. S., Whiteley R. J., and Hillier J. K. (2003) Visible and infrared photometry of Kuiper belt objects: Searching for evidence of trends. *Icarus*, 161, 501–510.
- Moroz L. V., Baratta G. A., Distefano E., Strazzulla G., Dotto E., and Barucci M. A. (2003) Ion irradiation of asphaltite: Optical effects and implications for trans-Neptunian objects and Centaurs. *Proceedings of the Conference on First Decadal Review of the Kuiper Belt* (J. Davies and L. Barrera, eds.), in *Earth Moon Planets*, in press.
- Noll K. S., Stephens D. C., Grundy W. M., Millis R. L., Spencer J., Buie M., Tegler S. C., Romanishin W., and Cruikshank D. P. (2002) Detection of two binary trans-Neptunian objects, 1997 CQ₂₉ and 2000 CF₁₀₅, with the Hubble Space Telescope. *Astron. J.*, 124, 3424–3429.
- Ortiz J. L., Baumont S., Gutiérrez P. J., and Roos-Serote M. (2002) Lightcurves of Centaurs 2000 QC₂₄₃ and 2001 PT₁₃. *Astron. Astrophys.*, 388, 661–666.
- Peixinho N., Lacerda P., Ortiz J. L., Doressoundiram A., Ross-Serote M., and Gutiérrez P. J. (2001) Photometric study of Centaurs 10199 Chariklo (1997 CU₂₆) and 1999 UG₅. *Astron. Astrophys.*, 371, 753–759.
- Peixinho N., Doressoundiram A., and Romon-Martin J. (2002) Visible-IR colors and lightcurve analysis of two bright TNOs TC₃₆ and 1998 SN₁₆₅. *New Astronomy*, 7(6), 359–367.
- Peixinho N., Boehnhardt H., Belskaya I., Doressoundiram A., Barucci M. A., Delsanti A., and the ESO Large Program Team (2003) ESO Large Program on Centaurs and TNOs: The ultimate results from visible colors. *Bull. Am. Astron. Soc.*, 35, 1016.
- Poulet F., Cuzzi J. N., Cruikshank D. P., Roush T., and Dalle Ore C. M. (2002) Comparison between the Shkuratov and Hapke scattering theories for solid planetary surfaces: Application to the surface composition of two Centaurs. *Icarus*, 160, 313–324.
- Romanishin W., Tegler S. C., Rettig T. W., Consolmagno G., and Botthof B. (2001) 1998 SM₁₆₅: A large Kuiper belt object with an irregular shape. *Proc. Natl. Acad. Sci.*, 98, 11863–11866.
- Romon-Martin J., Barucci M. A., de Bergh C., Doressoundiram A., Peixinho N., and Poulet F. (2002) Observations of Centaur 8405 Asbolus: Searching for water ice. *Icarus*, 160, 59–65.
- Roush T. L., Pollack J. B., Witteborn F. C., Bregman J. D., and Simpson J. P. (1990) Ice and minerals on Callisto: A reassessment of the reflectance spectra. *Icarus*, 86, 355–382.
- Sheppard S. S. and Jewitt D. C. (2002) Time-resolved photometry of Kuiper belt objects: Rotations, shapes and phase functions. *Astron. J.*, 124, 1757–1775.
- Shkuratov Y., Starukhina L., Hoffmann H., and Arnold G. (1999) A model of spectral albedo of particulate surfaces: Implications for optical properties of the Moon. *Icarus*, 137, 235–246.
- Stern S. A. (2002) Evidence for a collisional mechanism affecting Kuiper belt object colors. *Astron. J.*, 124, 2297–2299.
- Strazzulla G. (1998) Chemistry of ice induced by bombardment with energetic charged particles. In *Solar System Ices* (B. Schmitt et al., eds.), p. 281. Kluwer, Dordrecht.
- Strazzulla G., Dotto E., Barucci M. A., Blanco A., and Orofino V. (2002) Space weathering effects on small body surface: Laboratory fast ion bombardment. *Bull. Am. Astron. Soc.*, 34, 858.
- Tegler S. C. and Romanishin W. (1998) Two populations of Kuiper-belt objects. *Nature*, 392, 49–50.
- Tegler S. C. and Romanishin W. (2000) Extremely red Kuiper-belt objects in near-circular orbits beyond 40 AU. *Nature*, 407, 979–981.
- Thébault Ph. and Doressoundiram A. (2003) Could collisions be the cause of the color diversity in the Kuiper belt? A numerical test. *Icarus*, 162, 27–37.
- Thomas N., Eggers S., Ip W.-I., Lichtenberg G., Fitzsimmons A., Jorda L., Keller H. U., Williams I. P., Hahn G., and Rauer H. (2000) Observations of the trans-Neptunian objects 1993 SC and 1996 TL₆₆ with the Infrared Space Observatory. *Astrophys. J.*, 534, 446–455.
- Trujillo C. A. and Brown M. E. (2002) A correlation between inclination and color in the classical Kuiper belt. *Astrophys. J. Lett.*, 566, L125–L128.
- Veillet C., Parker J. W., Griffin I., Marsden B., Doressoundiram A., Buie M., Tholen D. J., Connelley M., and Holman M. J. (2002) The binary Kuiper belt object 1998 WW₃₁. *Nature*, 416, 711–713.
- Vilas F. and Gaffey M. J. (1989) Phyllosilicate absorption features in main-belt and outer-belt asteroid reflectance spectra. *Science*, 246, 790–792.
- Williams I. P., O’Ceallaigh D. P., Fitzsimmons A., and Marsden B. C. (1995) The slow-moving objects 1993 SB and 1993 SC. *Icarus*, 116, 180–185.