Composition and Surface Properties of Transneptunian Objects and Centaurs

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Centaurs and transneptunian objects are among the most primitive bodies of the solar system and investigation of their surface composition provides constraints on the evolution of our planetary system. An overview of the surface properties based on space- and groundbased observations is presented. These objects have surfaces showing a very wide range of colors and spectral reflectances. Some objects show no diagnostic spectral bands, while others have spectra showing signatures of various ices (such as water, methane, methanol, and nitrogen). The diversity in the spectra suggests that these objects represent a substantial range of original bulk compositions, including ices, silicates, and organic solids. The methods to model surface compositions are presented and possible causes of the spectral diversity are discussed.

1. INTRODUCTION

The investigation of the surface composition of transneptunian objects (TNOs) and Centaurs provides essential information on the conditions in the early solar system at large distances from the Sun. The transneptunian and asteroid belts can be considered as the "archeological sites" where the nature of planet-building material may be examined. The investigation of the properties of these icy bodies, as remnants of the external planetesimal swarms, is essential to understanding the formation and the evolution of the population. The knowledge of the compositional nature of the whole population can provide constraints on the processes that dominated the evolution of the early solar nebula as well as of other planetary systems around young stars. Even though space weathering due to solar radiation, cosmic rays, and interplanetary dust can affect the uppermost surface layer of these bodies (see chapter by Hudson et al.), and energetic collisions could have played an important role (see chapter by Leinhardt et al.), TNOs represent the most pristine material available for groundbased investigation.

Studies of the physical properties of these objects are still limited by their faintness, and many open questions remain concerning their surface composition. Compositional determination remains a technically challenging practice for these astronomical targets. Several irregular satellites (see chapter by Nicholson et al.) seem to have a Kuiper belt origin. Some of these have been well studied, but their distinct histories preclude direct interpretation in terms of the transneptunian region. Pluto and its satellite Charon remain the best observed TNOs (see chapters by Stern and Trafton and Weaver et al.), although the system formation remains a puzzling question.

2. OBSERVATIONAL TECHNIQUES

Photometry has been the most extensively used technique to investigate the surface properties of these remote objects, since most of them are extremely faint. Many different photometric observations have been performed, particularly in the visible region, providing data for a large number of objects.

Photometric surveys have observed more than 130 objects and have revealed a very surprising color diversity. Various statistical analyses have been applied and a wide range of possible correlations between optical colors and physical and orbital parameters have been investigated (see chapters by Tegler et al. and Doressoundiram et al.).

Phase functions and polarimetry provide additional information on surface properties. The behavior of polarization phase angle depends on properties of the upper surface layer, such as albedo, particle size distribution, porosity, heterogeneity, etc. These characteristics can be constrained through numerical modeling of light scattering by the surface material, taking into account the chemical and mineralogical composition (see chapter by Belskaya et al.). Measuring thermal fluxes in the far-infrared is also a fundamental technique for albedo determination (see chapter by Stansberry et al.).

However, these techniques can provide only limited constraints on the surface composition of the population. For instance, colors can be influenced not only by composition, but also by scattering effects in particulate regoliths and by viewing geometry. Colors cannot, in general, be used to determine composition, but they can be used to classify objects into groups. A new taxonomy based on color indices (B–V, V–R, V–I, V–J, V–H, and V–K) has been derived that identifies four groups: BB, BR, IR, and RR. The BB group contains objects with neutral colors, the RR group contains those with very red colors (the reddest among the solar system objects), and the other two groups have intermediate behaviors (*Barucci et al.,* 2005b; chapter by Fulchignoni et al.). The physical significance of color diversity is still unclear, although it is reasonable to assume that the different colors reflect intrinsically different composition and/or different evolutional history.

The most detailed information on the compositions of TNOs can be acquired only from spectroscopic observations. The wavelength range between 0.4 and 2.5 μm provides the most sensitive technique available from the ground to characterize the major mineral phases and ices present on TNOs. Diagnostic spectral features of silicate minerals, feldspar, carbonaceous assemblages, organics, and water-bearing minerals are present in the visible (V) and near-infrared (NIR) spectral regions. At the near-infrared wavelengths there are also signatures from ices and hydrocarbons. Cometary activity has been detected on several Centaurs (*Luu and Jewitt,* 1990; *Pravdo et al.,* 2001; *Fernandez et al.,* 2001; *Choi and Weissman,* 2006). Weakly active Centaurs or TNOs could also show fluorescent gaseous emission bands.

Most of the known TNOs and Centaurs are too faint for spectroscopic observations, even with the world's largest telescopes. As a result, only the brightest bodies have been observed spectroscopically. The exposure times required are generally long, and as the objects rotate around their maximum inertia principal axis, the resulting spectra often contain signals from both sides of the object.

2.1. Major Spectroscopy Ground Surveys

The brightest Centaurs can be observed with small telescopes, particularly for the V range, but fainter objects have required the use of 8–10-m-class telescopes. *Luu and Jewitt* (1996) were the first to observe these distant objects. They used the Keck 1 telescope, and have continued their program since that time with observations at the Keck and Subaru telescopes on Mauna Kea.

2.1.1. European Southern Observatory (ESO) survey. As soon as VLT-ESO began operating, *Barucci et al.* (2000) and the associated team started an observational campaign in the visible and near-infrared at unit 1 Antu, unit 3 Melipan, and unit 4 Yepun. To date, about 20 objects have been observed at VLT. For most of these objects, simultaneous V + NIR spectra were measured.

2.1.2. California Institute of Technology (Caltech) survey. Brown (2000) and collaborators started observations of TNOs and Centaurs with the low-resolution infrared spectrograph at the Keck Observatory. To date, about 30 objects have been observed at Keck in H + K band.

The observational strategies vary depending on the telescope and instrumentation. In general, a sequence of observations includes several spectra of the object, solar analogs, and a series of calibration that include bias frames, flat field, and a lamp for wavelength calibration. 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. The solar analog has to be observed during the same night at the same air mass as the target. Using large telescopes, the known good solar analogs generally are too bright and cannot be used as they could saturate the instruments. Simultaneous measures of the absolute calibration are essential to adjust the different spectral pass-bands and provide reliable final spectra.

2.2. Space Surveys

Although discovery and characterization of TNOs and Centaurs are dominated by groundbased measurements, several programs with both the Hubble and Spitzer Space Telescopes are also relevant. The Hubble programs span the visible and near-infrared, detecting sunlight reflected off the surfaces. Several authors have observed with Hubble; in particular, *Noll et al.* (2000) used NICMOS to measure broadband reflectances in the near-infrared ($\lambda < 2.5$ μm) of four TNOs. A near-infrared reflectance spectrum (1–2 μm) of the Centaur 8405 Asbolus was also measured using NICMOS on Hubble (*Kern et al.,* 2000).

The Spitzer Space Telescope (*Werner et al.,* 2004) allows low- and moderate-spectral-resolution spectroscopy from 5.2 to 38 μm. Broadband imaging photometry is also possible in nine bands from 3.6 to 160 μm. The lower end of this wavelength range is sensitive to reflected sunlight from the distant (cold) TNOs and Centaurs. At longer wavelengths, however, thermal emission radiated by the bodies themselves is detected. The crossover between reflected and emitted radiation depends on surface temperature and can occur anywhere from near 6 μm for some Centaurs to ~15 μm for colder TNOs. Thermal emission measurements with Spitzer can also be used to derive sizes and albedo (see chapter by Stansberry et al.). Furthermore, thermal emission spectra offer the opportunity to detect emissivity features, which are diagnostic of surface composition. Unfortunately, spectral measurements are less sensitive than broadband measurements, so only the thermally brightest TNOs and Centaurs can be usefully detected with the spectrograph on Spitzer.

Spitzer has a relatively short lifetime due to finite supplies of cryogen to cool the detectors, but several current and pending programs are taking advantage of Spitzer for TNO studies while it lasts.

3. SPECTROSCOPY RESULTS

3.1. The Visible Spectra

Visible spectra, generally obtained with a low-resolution grism, are mostly featureless with a large variation in the spectral gradient from neutral to very red, confirming the diversity seen in broadband colors. The visible wavelength range provides important constrains on surface composition, particularly for reddest objects, whose reflectance increases rapidly with wavelength. Such ultrared slopes are usually interpreted to indicate the presence of organic material on the surface. The measured spectral slopes range between –1%/10^3 Å and ~55%/10^3 Å, with the Centaurs Pholus and Nessus being the reddest objects known up to now in the solar system. The visible range is also important for detecting aqueously altered minerals such as phyllosilicates. Three objects, all Plutinos (Fig. 1), have had reports of broad absorptions present in their visible spectra. These features are very similar to those due to aqueously altered minerals found in spectra of some main-belt asteroids, irregular satellites, and meteorites (*Vilas and Gaffey,* 1989, and subsequent papers). In the case of the three Plutinos, however, all attempts to confirm these absorptions have shown only featureless spectra. While spectral variability due to rotational modulation cannot be excluded, these detections must remain uncertain until the observations are confirmed. The presence of phyllosilicates has also been suggested by *Jewitt and Luu* (2001), who reported absorption bands (around 1.4 and 1.9 µm) in the spectrum of the Centaur 26375 1999 DE_9. All these features are rather weak, and the reality of these bands also requires confirmation.

How aqueous alteration process could have occurred far from the Sun is not well understood, but formation of hydrated minerals directly in the early solar nebula cannot be excluded. Finding aqueously altered materials in TNOs would not be too surprising (*de Bergh et al.,* 2004), since hydrous materials seem to be present in comets, and hydrous silicates are detected in interplanetary dust particles (IDPs) and in micrometeorites.

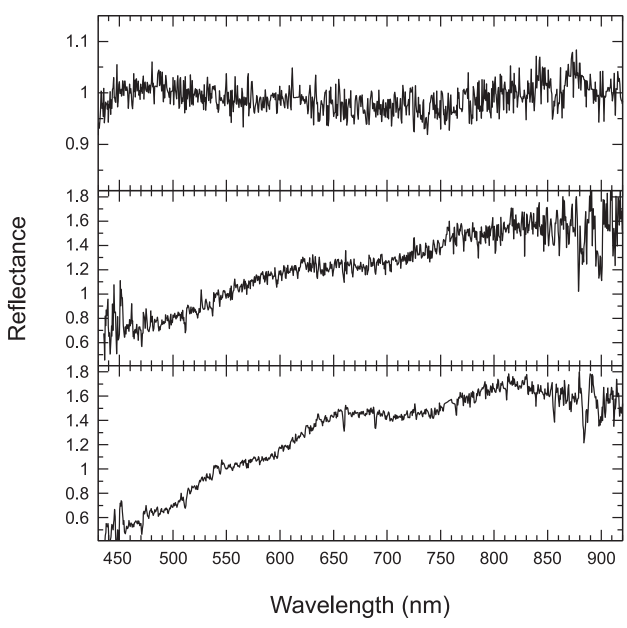

Fig. 1. Visible spectra of three TNOs showing aqueous alteration bands. The top spectrum of 2003 AZ_{84} was obtained by *Fornasier et al.* (2004b), and a continuum computed with a linear least-squares fit to the observed spectrum has been removed. The broad absorption band has been identified centered at about 700 nm. The other two spectra were obtained by *Lazzarin et al.* (2003). The 47932 (GN171) spectrum exhibits a feature around 725 nm, while 38628 Huya presents two absorption bands centered respectively at about 600 and 730 nm. On asteroids and meteorites these bands have been attributed to an $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer in iron oxides in phyllosilicates (*Vilas and Gaffey,* 1989).

3.2. Near-Infrared Spectra

The near-infrared wavelength range (1–2.5 µm) is the most diagnostic region for determining the presence of ices. Signatures of water ice are present at 1.5, 1.65, 2.0 µm, and signatures of other ices include those due to CH_4 around 1.7 and 2.3, CH_3OH at 2.27 µm, and NH_3 at 2 and 2.25 µm, as well as solid C-N bearing material at 2.2 µm. The first observations in this wavelength range were carried out on the Centaurs 2060 Chiron and 5145 Pholus (see *Barucci et al.,* 2002b, for a review on Centaurs) while the first spectrum of a TNO, 15789 (1993 SC), was obtained by *Luu and Jewitt* (1996) in the visible and by *Brown et al.* (1997) in the near-infrared. These early data showed a very noisy red dish spectrum with some features that they attributed to hydrocarbon ice, but that did not appear in higher-quality observations obtained later (*Jewitt and Luu,* 2001). In the near-infrared region some Centaur and TNO spectra are featureless, while others show signatures of ices. Reflectance spectra from 1.4 to 2.4 µm of four representative TNOs observed at Keck with various signal precision are reported in Fig. 2.

3.3. Results from Groundbased Spectroscopy

More than 40 objects have been observed spectroscopically to date, but only a few have been well studied in both the visible and near-infrared and rigorously modeled. These objects are faint and even observations with long exposure time and with the largest telescopes (Keck, Gemini, Subaru, and VLT) often do not yield high-quality spectra. All the objects observed spectroscopically in the near-infrared and available in literature have been listed in Table 1.

In Fig. 3 the visible and the near-infrared spectra of some Centaurs and TNOs observed at VLT are shown along with the best-fit spectral model. In general, TNOs and Centaurs