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The composition of "ultra-red" TNOs and centaurs

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ABSTRACT

We present an analysis of the colors available for seven trans-neptunian objects (TNOs) and three centaurs among the reddest known, aimed at characterizing their surface chemical properties. In particular we seek to obtain evidence in support of the proposed correlation between the visible coloration of the surface of TNOs and their surface compositions (Brown, M.E., Schaller, E.L., Fraser, W.C. [2011]. Astrophys. J. 739, L60).

The analysis focuses on nine available colors in the visible–near IR (0.3–4.5 μm) spectral range scaled to the V albedo to provide a proxy for the spectral shape of the objects. The colors include Spitzer IRAC data never published before, key in providing an effective constraint in the discrimination of ices contributing to the surface composition of the objects.

Compositions are obtained by comparing the data to a grid of radiative transfer models convolved by the filter response functions of the colors adopted in the spectrum-proxies to match the resolution of the observations. We find evidence suggesting the presence of hydrocarbons and/or methanol on the surfaces of most objects in our sample, supporting the hypothesis by Brown et al. (Brown, M.E., Schaller, E.L., Fraser, W.C. [2011]. Astrophys. J. 739, L60) that the coloration of red TNOs could be linked to their methanol content.

From our finding of methanol/hydrocarbon ices on the surfaces of the objects in our sample of very red TNOs and centaurs we infer that ultra-red objects in general might contain these ices and therefore might have formed in the outer part of the Solar System. We also deduce that the surfaces of most of the very red TNOs in our dataset are probably still quite pristine, and that their organic materials could have been produced by irradiation of the volatile ices whose traces are still present on their surface. Although our sample is small, we infer that the irradiation process is still in progress, as hinted by the centaurs' slightly elevated organic amounts at smaller perihelion distances. However, considering the relatively similar amounts of organics found in our data at a wide variety of perihelion distances, we also infer that it could have started before Neptune's migration.

The technique used to constrain the composition described as part of this study introduces a new approach at investigating the surface chemistry of the very small and numerous objects that constitute the bulk of the TNO and centaur populations. This innovative method has the potential to provide constraints for irradiation theories and for models of dynamical and chemical evolution of the Solar System.

1. Introduction

The formation and evolution of the Kuiper Belt has been the focus of dynamical and spectro-photometric studies for the last two decades since the first transneptunian object (TNO) beyond Pluto was discovered in 1992 (Jewitt and Luu, 1993).

Transneptunian objects and centaurs, remnants of the planetesimals, orbit the Sun beyond Neptune, and mostly between the giant planets (Gladman et al., 2008), respectively. Dynamical studies (Malhotra, 1995; Levison and Morbidelli, 2003; Gladman, 2005; Tsiganis et al., 2005; Charnoz and Morbidelli, 2007; Lykawka and Mukai, 2007, 2008) have grouped TNOs in four basic dynamical classes (Classical, Resonant, Scattered, Detached) further subdivided into subgroups to take into account variations in dynamical parameters (e.g. 'hot' and 'cold' Classical). Interactions

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of Neptune with TNOs deliver a continuing supply of centaur objects and comets to the inner planetary region (Duncan et al., 1995; Levison and Duncan, 1997; Horner and Lykawka, 2010).

Because of their large heliocentric distances TNOs are thought to be pristine and therefore interesting from the standpoint of the history and evolution of the outer Solar System. Along with centaurs, TNOs can be used as benchmarks for theories of space weathering (e.g.: Brunetto et al., 2006; de Bergh et al., 2008).

Because of their great distances and small sizes, good signal-to-noise and high spectral resolution spectra of TNOs are often difficult to obtain. If we exclude mm and sub-mm observations, for all TNOs except Pluto, the wavelength range for ground-based data (spectroscopy and photometry) is limited to up to ~2.5 μm. A survey of good-quality spectra is available from Barucci et al. (2011). Surveys of photometric colors of a large number of small TNOs (e.g., Perna et al., 2010, 2013; Ofek, 2012; Benecchi et al., 2011) show a wide range in colors, mostly uncorrelated to other physical or dynamical parameters, with the possible exception of cold Classical TNOs whose colors are predominantly red (Doressoundiram et al., 2002).

Recently, a bimodal behavior for the intermediate/small TNOs and for the centaurs has been linked to a composition effect due to the original makeup of the objects and their random placement after Neptune's migration (Dalle Ore et al., 2013; Brown, 2012; Fraser and Brown, 2012; Peixinho et al., 2012). In the laboratory, irradiation by ion bombardment of ices common in the outer Solar System has yielded a number of volatile and non-volatile products, including organics, known to be red in coloration (Strazzulla and Johnson, 1991). In particular, Brown et al. (2011) have suggested that irradiated methanol ice could be responsible for the red coloration of the surfaces of those objects that formed far enough from the Sun to retain it. On the other hand, according to Brown et al. (2011), gray objects would have surfaces devoid of methanol and rich in H_2O- and CO_2-ices, less volatile than methanol and whose color remains neutral when irradiated. In this scenario, gray objects would have formed closer to the Sun than bodies rich in methanol and other volatile ices.

As a test of the Brown et al. (2011) hypothesis, we study the visible and near-infrared colors of a sample of the reddest TNOs (Barucci et al., 2012a) for which photometry in the visible, near-infrared, and Spitzer IRAC (B, V, R, I, J, H, K, S1, S2) (0.44, 0.56, 0.7, 0.9, 1.2, 1.5, 2.2, 3.6, 4.5 μm) bands are available, along with V albedos. The V albedo is an essential constraint in our analysis, allowing the approximation of the spectrum of each object with the V-albedo scaled colors. Making use of a grid of models, we determine which materials are most likely to be present on the surfaces of these objects.

2. Data description and preparation

Red TNOs are objects whose visible colors show a rapid increase with wavelength (slope, i.e. Jewitt, 2002) and are classified as RR by Barucci et al. (2005a) and Fulchignoni et al. (2008). In particular, ultra-red TNOs belong to a subset whose red coloration is most extreme. The ten objects that are part of this study were selected based on their RR class membership. Their spectra are available from Barucci et al. (2011). For these objects, published data include near-infrared spectral observations covering various wavelength ranges, all including the 1.5 and 2.0-μm H_2O bands and therefore allowing direct evaluation of the presence of H_2O ice. For some of these objects, H_2O is the only ice for which detection is possible in the limited wavelength range and with the signal-to-noise-ratio (SNR) afforded by the spectral data. For this reason rather than spectral data we adopted photometric measurements spanning an overall larger wavelength range.

The nine broad-band albedos we use in this study, corresponding to the Johnson photometric bands and the Spitzer IRAC channels 1 and 2, can be seen as a proxy for the spectral continuum of the data. The Spitzer data, listed in Table 1 with their observing circumstances, are, for those objects marked with an asterisk, published here for the first time. Fluxes and albedos were obtained following the procedure described in Emery et al. (2007). Amycus and 1993SC were not detected by Spitzer, hence only upper limits to their albedos could be calculated.

Albedos were calculated by means of $A_\lambda = p_V \times 10^{\pm 0.4(c_\lambda - c_{\lambda_\odot})}$, where A_λ is the albedo at each broad band wavelength and p_V is the albedo at the V filter wavelength (0.55 μm), $c_\lambda = (\lambda - V)$ and $c_{\lambda_\odot} = (\lambda - V)_\odot$ are the color indices of each object and the Sun respectively. Colors are from the Hainaut et al. (2012) compilation of photometric measurements, while solar colors are from Hardorp (1980) and Hartmann et al. (1982) and are listed in Table C2. The Hainaut et al. (2012) compilation lists average colors; individual measurements can be found at the original reference listed in Table C1 (key codes in Table 3). R and I albedos were missing for 2002 VE95 in the Hainaut et al. (2012) compilation; R was adopted from Barucci et al. (2012b) and considering the object's spectral shape the I value was linearly interpolated based on neighboring albedo levels.

The ultra-red TNOs are more numerous than the ten objects adopted in this study. However, not all objects in the original sample had p_V and Spitzer IRAC albedo measurements, reducing the dataset for this study to 12 objects. Of these, two objects had only one of the IRAC bands available, not enough to place sufficient constraints on the identification of the ices on the surface. Therefore, the final adopted sample consists of ten objects for which we have reliable and complete observations. Table 2 shows the p_V measurements (centered at 0.55 μm), their uncertainties, the p_V corrected for small phase angles, and respective references for the objects.

Spitzer IRAC data were obtained for all objects on two occasions. When information on the object's period was available, the observations were timed to fall on opposite hemispheres. When the period was not available, the interval between the two exposures was estimated in an attempt to sample different terrains.

Therefore our adopted dataset includes 20 partially independent sets of data where albedos from B to K are replicated and separately joined with each of the two different IRAC 1 and 2 observations. This implies that visible and JHK colors available might geographically match, in the most favorable but unlikely case, one of the two sets of IRAC observations. This is due to the limited number of available observations mostly covering the surface of an object at one longitude. It might be more problematic for those objects showing significantly different behaviors between the two Spitzer bands and therefore likely to have geographic variety in the composition of their surface. We do not have a solution to this problem but we keep it in mind when examining our results and we expect substantial composition heterogeneity to be rare.

For every object, errors at each color band were calculated accounting for the photometric uncertainty using standard error propagation formulae.

2.1. Phase angle effects and correction

When a solid body is observed at small phase angles close to opposition (phase angle $\alpha = 0°$), the apparent surface brightness increases significantly, and the calculation of the geometric albedo at a given wavelength must include a correction for this opposition effect. In the case of asteroids, for phase angles >~8°, the magnitude increase is roughly linear and between ~0.02 mag/deg (for high albedo E-type asteroids) and ~0.04 mag/deg (for low albedo C-type asteroids) (e.g., Muinonen et al., 2002). For phase angles