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Space weathering and the color–color diagram of Plutinos and Jupiter Trojans

M.D. Melita [a],*, Z. Kaňuchová [b], R. Brunetto [c], G. Strazzulla [d]

[a] Instituto de Astronomía y Física del Espacio (IAFE), Buenos Aires, Argentina
[b] Astronomical Institute of Slovak Academy of Sciences, SK-059 60 T. Lomnica, Slovakia
[c] Institut d'Astrophysique Spatiale, CNRS, UMR-8617, Université Paris-Sud, bâtiment 121, F-91405 Orsay Cedex, France
[d] INAF-Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95123 Catania, Italy

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ABSTRACT

The Jupiter Trojan asteroids and the Plutinos are two peculiar populations. They are dynamically resonant, therefore with heliocentric distances relatively bounded for long timescales, as a farely general rule. As a consequence, some correlation with the surface color properties of their respective members is expected. Indeed, there are apparent differences in the $B-V$ vs. $V-R$ color–color diagram of the two populations. Using a simple model based on the surface color due to the contribution of two components, one pristine and one altered, we find as plausible that the difference is due to the interplay of space weathering by energetic cosmic-radiation and collisional effects.

1. Introduction

The study of the physical properties of small objects in the outer Solar System may give information on the processes and original composition in the early outer protoplanetary disk. However, since the compositions of these small bodies are derived mostly through visible and near-infrared reflectance spectroscopy (e.g. Barucci et al., 2008), observations may strongly be biased by a large variety of post-accretion surface alteration processes. The surfaces of atmosphere-less bodies are in fact irradiated by a large variety (in terms of energy and mass) of cosmic and solar wind ions, by UV photons, and bombarded by interplanetary dust. Collisions of the bodies with various-sized objects, from similar size to small grains, also reset and contribute to the current state of their surface and sub-surface composition.

The majority of small outer Solar System objects lack distinguishing absorption features apart from some hints of water ice (Barkume et al., 2008). Hence optical and near-infrared slopes (colors) are mostly used for characterization. Observed spectral properties and potential correlations between colors and orbital parameters of trans-neptunian objects (TNOs) have been studied by many authors (e.g. Doressoundiram et al., 2008, and references therein). It is largely agreed upon that complex organic materials can be responsible for the red spectral slopes observed on some of these bodies (Cruikshank et al., 1998; Doressoundiram et al., 2008). The observed spectral variety of TNOs as the result of space weathering processes altering the surface spectra and resurfacing agents that restore the original colors were studied by Luu and Jewitt (1996). Recently, such so called classical collisional resurfacing scenario has been discussed to explain the observed spectral variations of Centaurus 10199 Chariklo (Guilbert et al. (2009)). Its spectrum was in fact reproduced by considering the contribution of two different materials – the highly processed one, and the underlying less processed one. The collisional resurfacing scenario has been revisited and discussed by several authors (Gil-Hutton, 2002; Cooper et al., 2003; Thébault and Doressoundiram, 2003), and more recently it has been questioned by the observational evidence that the colors of primary and secondary bodies among small binary TNOs are very closely correlated (Benecchi et al., 2009). Since impact erosion rates depend on object size, the observed pattern would be inconsistent with a time-dependent irradiation-induced surface coloration (Grundy, 2009).

In a recent review of many laboratory experiments and observational data, Dalle Ore et al. (2011) characterize the properties, origins and evolution of the red materials in the Solar System. They conclude that the actual color is due to their presolar origin (nature), and/or to their processing by e.g. ion irradiation (nurture). Discriminating between different possibilities is in some cases difficult (e.g. because of the lack of observations at wavelengths higher than 2.5 μm). The red colors observed on some objects are often a combination of weathering (nurture) and primordial composition (nature).

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* Corresponding author.

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A number of unanswered questions remain to be clarified. As an example: why objects belonging to groups (such as Trojans or Plutinos) i.e. sharing the same distance from the Sun and thus having similar irradiation and resurfacing history, still have different colors? In this work we focus on two, spatially distinct populations of objects – Plutinos (i.e. a trans-neptunian population) and Jupiter Trojans.

Observational evidences of some similarities in the physical characteristics and recent dynamical modeling suggest a common origin of Jupiter Trojans and TNOs (short-period comets and Centaurs as well) in the primordial outer disk (e.g. Barucci et al., 2008, and references therein). However, the outer solar disk may be fairly chemically heterogeneous and covers enough range of heliocentric distances that different populations could have originated from compositionally different locations (different volatile species snow lines, delivery of organics and mineral components on dust particles through large-scale disk mixing, see e.g. Ciesla and Charnley (2006)). Jupiter Trojans are thought to have been captured from a larger population of small bodies (planetesimals) that existed in the planetary region (~5–30 AU) when the giant planets formed (Nesvorný et al., 2013). Modeling within the so called Nice model, indicate Trojans may have been captured by a "jumping" Jupiter during the early dynamical instability among the outer planets (Nesvorný et al., 2013). The possible common origin and composition of Jupiter Trojans and Plutinos is still a question.

In addition, the Jupiter Trojan asteroids and the Plutinos are two small bodies populations that share a remarkable property – they are defined by the fact that the orbits of their members are about an orbital resonance. There are also other resonant populations in the Solar System (e.g. Kuiper belt resonant populations, Neptune Trojans, resonant Centaurs), but because of their small numbers and sparse data sets they are actually not suitable for our study. The Plutinos orbit about the 3:2 mean-motion resonance with planet Neptune and the Trojans about the 1:1 mean motion resonance with planet Jupiter. Therefore, their localization is approximately well bounded in heliocentric distance. Also to be noticed is that they are the best known resonant asteroidal populations in the outer Solar System at present. As such, since reliable statistics can be drawn, it seems plausible that the surface properties of both groups will, in some way, reflect the difference in heliocentric distance at which they are located. This, because cosmic radiation and collisional timescales would be scaled approximately equal for all members in each group.

While Trojans have been spectrally observed in different ranges so that their surface composition is partially known (see e.g. Dotto et al. (2008) for a review), most of the small TNOs are very faint and only the photometric magnitudes and the consequent color indexes (difference between the magnitudes obtained in two filters) are available providing information on their surface colors (e.g. Luu and Jewitt, 1996; Doressoundiram et al., 2008). Thus, when comparing Trojans and Plutinos in this nature vs. nurture study, we mainly have to rely on spectral colors and partially on albedos. As it was shown recently by Kaňuchová et al. (2012), the observed surface colors of the outer Solar System bodies can be considered as the result of the interplay between the space weathering and collisional resurfacing. According to Kaňuchová et al. (2012), the objects with the different ratio of weathered and pristine surface material lies on specific lines in the color–color diagrams. Here we present a model which supports this idea.

In Section 2 we show the color–color relationship for Trojans and Plutinos, and in Section 3 we estimate how does the collisional timescale correspond to the heliocentric distance. In Section 4 we study how different doses of ion irradiation can produce different correlated distributions in the $V-R$ vs. $B-V$ plot and the peculiarities of the observed distributions. We estimate the maximum irradiation timescales for both populations and the corresponding $V-R$ vs. $B-V$ color distributions obtained, as a function of the fraction of altered/unaltered areas. In Section 5 the plausibility of our results is discussed.

2. MBOSS database observations

Transneptunian objects are among the most red bodies of the Solar System. The presence of complex organic material is believed to be the origin of the dark and red appearance of TNOs and Trojans, but in the case of Trojans, no direct evidence for organics has yet been detected (Emery et al., 2006, 2011). Only features detected in spectra of Trojan surfaces are due to fine-grained silicates, possibly imbedded in a relatively transparent matrix (Emery et al., 2006), which could be a salt (King et al., 2011). According the model of Yang et al. (2013) the matrix is consistent with a deposit of salt on the surfaces of larger Trojans. The salty layer results from sublimation of a deep layer of frozen brine exposed by impacts. However, the model consistency is not an actual detection of salt and other alternatives may still be possible.

Interiors of Trojans are expected to be H_2O ice-rich, as their likely source regions lie beyond the so-called snow line. Yang and Jewitt (2007) have estimated the upper limit of the surface abundance of water ice to be 10%. Organic materials probably include a primary native component accreted during planetesimal formation, and a secondary component that is a by-product of (cosmic and/or solar wind) ion and photon irradiation of simpler C-bearing volatile ices such as CH_4, CH_3OH, etc. (Dalle Ore et al., 2011). These irradiation processes (space weathering) can produce red colored materials starting from bright and spectrally flat ices (Thompson et al., 1987; Brunetto et al., 2006a; Brunetto and Roush, 2008). The presence of water (and other) ice on the Plutinos' surfaces was confirmed (e.g. Barucci et al., 2008; Mommert et al., 2012).

As said, the two studied populations of objects may have originated in the close regions of the early Solar System; thus their pristine composition could be similar. The actual surface appearance and characteristics are however the result of different processes suffered in their early and subsequent history. For example, the surface water ice on Trojans could has been sublimated (even at the Jupiter's distance, Fernandez et al. (2009)) or its amount could has been quite reduced, as observed 10% (Yang et al., 2013).

When the $B-V$ vs. $V-R$ color–color diagram of Plutinos and jovian Trojans populations is plotted, we notice a remarkable difference in the "slopes" of the two distributions (see Fig. 1). The data plotted correspond to the MBOSS database (Hainaut and

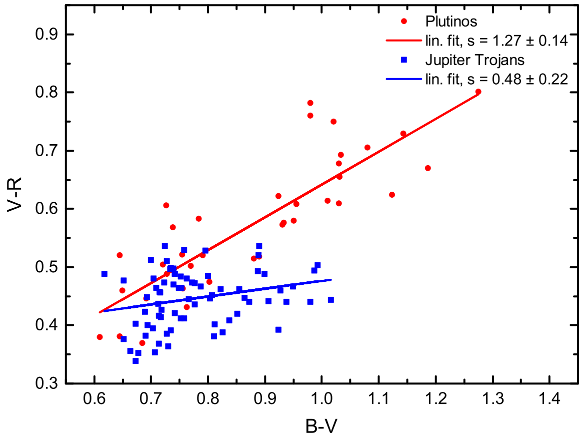

Fig. 1. $V-R$ vs. $B-V$ plots for the Plutinos and the Jupiter-Trojans. The linear fits and the appropriate values of slopes are indicated for each population.