Icarus 248 (2015) 222–229

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

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

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ARTICLE INFO

Article history:
Received 27 November 2013
Revised 25 September 2014
Accepted 28 September 2014
Available online 22 October 2014

Keywords:
Trans-neptunian objects
Trojan asteroids
Collisional physics

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.

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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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http://dx.doi.org/10.1016/j.icarus.2014.09.050
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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

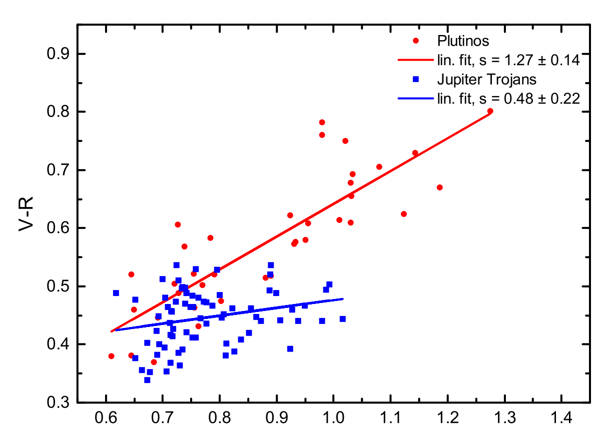

Fig. 1. $V-R$ vs. $B-V$ plots for the Plutinos and the Jupiter-Trojans. The linear fits and the appropriate values of slopes are indicated for each population.

Delsanti, 2002) (Hainaut et al., 2012), available at http://www.sc.eso.org/ohainaut/MBOSS, which is used in this work. Our goal is to suggest an explanation for the noticeable difference in the "slopes" of the two distributions in the plot.

The $B-V$ vs. $V-R$ indices are quite significantly correlated in both the considered populations, although the correlation is remarkably stronger in the case of the Plutinos. The Spearman Rank-order correlation test (Press et al., 1992) indicates that the number of standard deviations by which the sum-squared difference deviates from the null-hypothesis (i.e. no correlation at all) is 5.2 for the Plutinos and 2.3 for the Jupiter Trojans. These values have been computed using the subroutine *spear* from the Numerical Recipes book (Press et al., 1992).

The difference in the color indexes distribution of the two population is evident (Fig. 1). Nevertheless, to measure the difference, we computed the slope of the linear fit and its standard mean error of each set using the subroutine *lfit*[1]. In the case of the Plutinos we obtained the value of the slope of 1.27 ± 0.14, while the value obtained for the Jupiter Trojans is 0.48 ± 0.22; values that do not overlap neither taking into account their respective uncertainties. To avoid deviations caused by outliers, we computed the linear fits minimizing the absolute deviation, using the routine *medfit*,[1] which resulted as 1.34 for the Plutinos and 0.50 for the Jupiter Trojans and the mean absolute deviation for the dependent variable – the (V–R) color – is 0.07 in both cases, which proves that the previous results are robust, and the difference in the quantity of the correlation is taken as significant.

This simple finding seems to suggest that the surface colors of Plutinos and Jupiter Trojans are not determined by space weathering but by their different original composition. In fact the flux of solar wind ions, decreases as the inverse of the squared distance from the Sun, and then one would expect that Jupiter Trojans are more altered than the more distant Plutinos, contrarily to what is observed. In the next we will show that the collisional timescales for Jupiter Trojans are much shorter than for Plutinos and that the competition between ion induced space weathering and collision resurfacing explains the color differences of the two populations.

3. Collisional timescales

The surface of an object can be modified by physical impacts. The time, in which the whole surface of a body is modified by collisions is called collisional timescale τ. For a target body (TB) of physical radius R, it can be expressed as (Gil-Hutton, 2002):

$$\tau = \frac{1}{\dot{S_a}} \tag{1}$$

where $\dot{S_a}$ is the specific rate of collisional gardening:

$$\dot{S_a} = \frac{\dot{S}}{4\pi R^2} \tag{2}$$

The rate of surface modification $\dot{S}$ due to collisions is given by an integral:

$$\dot{S} = \int_{a_{min}}^{a_{max}} \dot{N}(a)\; A_E(a)\, da, \tag{3}$$

where $\dot{N}(a)$ is the number of collisions between the target body and impactors of physical radius a from the interval $(a,\; a+da)$; and $A_E(a)$ is the area covered by the corresponding ejecta. The number of collisions can be expressed as:

$$\dot{N}(a) = P_I\;(R+a)^2\, dN(a),$$

where P_I is the intrinsic probability of collision defined by Wetherill (1967) as the probability of collision per unit time, per unit cross section and per number of colliding pairs; $dN(a)$ is the number of objects with radii in the interval $(a,\; a+da)$. It is expressed as:

$$dN(a) = CR^{-\alpha},$$

where C is a normalization constant related to the total number of objects in the given size interval and α is the distribution-size power-law index.

We assume values for the intrinsic probability of collision of $P_I = 7.0\times10^{-18}\ \mathrm{yr^{-1}\ km^{-2}}$ for the Jupiter-Trojans (Dell'Oro et al., 1998), and $P_I = 3.9\times10^{-22}\ \mathrm{yr^{-1}\ km^{-2}}$ for the Plutinos (Dell'Oro et al., 2013).

The estimation of the size distribution of the observed Trojans population is given by Jewitt et al. (2000):

$$dN(a) \approx 1.5\times10^{6}\left(\frac{1\ \mathrm{km}}{a}\right)^{3}. \tag{4}$$

For the Plutinos of radius $a < 60$ km (Kenyon et al., 2008), we adopt the following differential size distribution:

$$dN(a) \approx 7.5\times10^{9}\left(\frac{1\ \mathrm{km}}{a}\right)^{4}. \tag{5}$$

The lower limit of integral (3) corresponds to the radius of the smallest particle in the population and it is taken as a variable in the model. For each value of a_{min}, the value of the constant C is computed using the normalization values given in Eqs. (4) and (5) for the Jupiter-Trojans and the Plutinos respectively.

The a_{max} is equal to the radius of the largest projectile of velocity v which does not shatter the target of radius R (if the density of the TB is equal to that of the impactor), and is given by:

$$a_{max} = R(5\beta v^2 - 1)^{-1/3},$$

where β is the crater excavation coefficient. We have adopted two values for this parameter $\beta = 1\times10^{-8}\ \mathrm{g\ erg^{-1}}$ (Petit and Farinella, 1993), corresponding to main belt asteroids and $\beta = 5\times10^{-6}\ \mathrm{g\ erg^{-1}}$, for icy bodies (Giblin et al., 2004).

We note that the smaller is the βparameter, the larger is the radius a_{max}. Thus, the rate of surface rejuvenation (Eq. (3)) is increasing, i.e. the collisional timescale is shortening with the decreasing values of crater excavation coefficient β.

The area covered by ejecta A_E is related to the area of the crater A_c created by an impactor of the radius a and the velocity v as:

$$A_E = l\times A_c(R, a, v),$$

where l is a mean scaling factor. For the simplicity, we assumed the paraboloid form of a crater. Therefore the depth d and the area A_c of the crater are related as:

$$A_c = \pi\; d^2.$$

We estimate the depth of the crater using an empirical scaling law relating the crater volume V_g and the parameters of the impactor (Holsapple, 1993):

$$V_g = K_1\left(\frac{m}{\rho}\right)\left(\frac{ag(a)}{v^2}\right)^{\frac{-3\mu}{2+\mu}}, \tag{6}$$

where ρ is the density of the impactor (which we assume to be equal to the density of the target body), $g(a)$ is the surface gravity of an impactor of radius a; v is the impact relative velocity, which we assume to be proportional to the local orbital velocity $\sqrt{\frac{G\ M_\odot}{r}}$ at the heliocentric distance r; m is the mass of an impactor, and $K_1 = 0.24$ and $\mu = 41$ are constants common to both small body populations (Holsapple, 1993).

[1] Numerical recipes, Press et al. (1992).

A mean value of bulk density of asteroids is ≈ 2 g cm^{-3} (Carry, 2012). Actually, the density is found to be dependent on the asteroid's taxonomic type and mean densities vary from 1.38 ± 0.02 g cm^{-3} to 5.32 ± 0.07 g cm^{-3} (Krasinsky et al., 2002) for asteroids defined by Bell et al. (1989) as carbonaceous and metallic, respectively. Carry (2012) give even wider range of density values: 0.96 ± 0.27 g cm^{-3} for Cg type, and 9.56 ± 0.22 g cm^{-3} for D type in DeMeo et al. (2009) taxonomy. To investigate the range of variation of the collisional timescale on the bulk density we have adopted two extreme values: $\rho_1 = 7$ g cm^{-3} representating rocky objects, and a value $\rho_2 = 1$ g cm^{-3} more correspondent to icy objects.

Let's note that we estimate the rate of surface modifications $\dot{S}$ (Eq. (2)), and subsequently the collisional timescale, only in orders of magnitude, as our approximation does not take into account different crater morphologies due to e.g. impact angle variations.

We have computed the collisional timescale for the Jupiter Trojans τ_T and the Plutinos τ_P using Eqs. (1)–(3). Several relevant values of the target body radius R were considered and the limit of impactor radius a_{min} varied between 100 m and 0.1 m. Two values of the impactor density (and the target as well) and two values of the crater excavation coefficient β were supposed.

The results for the "rocky case" when the volume density is $\rho_1 = 7$ g cm^{-3} for both Trojans and Plutinos population are given in Fig. 2. Collisional timescale depends on the chosen size of the smallest impactors in the population; and it gets shorter with the increasing size of the target bodies. Plutinos of radius $\sim$60 km are resurfaced by collisions in order of 10^4–10^7 years, when the crater excavation coefficient $\beta = 1 \times 10^{-8}$ g erg^{-1} is used. Trojans, under the same physical conditions, are resurfaced by collisons in one/two orders of magnitude faster. Using $\beta = 5 \times 10^{-6}$ g erg^{-1}, the collisional timescales are around three orders of magnitude longer.

Similarly, we estimated the collisional timescale for the "icy case", when the volume density of the colliding bodies is $\rho_2 = 1$ g cm^{-3}. The collisional timescales are longer than in the "rocky case" for both considered values of parameter β (Fig. 3).

Comparing Figs. 2 and 3 we have found the stronger dependency of the timescale on the parameter β than the density, within the chosen range of parameters.

3.1. Microimpacts

Physical collisions that have been considered in the previous section produce an alteration of a surface layer with a thickness much larger than the typical thickness of a layer affected by the solar wind ions.

Since we are interested in alterations that can be of a much smaller thickness, we are also going to consider the effects of microimpacts separately. To estimate the amount of dust particles that impact on a Jupiter-Trojan asteroid or on a Plutino we scale the estimated mass of dust that fall on the Earth. It is estimated to be between 20,000 tons and 40,000 tons of 1 mm – 1 μm dust particles per year (Liou et al., 1999).

We assume simply that the rate of mass that falls on the Earth ($\frac{dM_{\oplus}}{dt}$) can be expressed as:

$$\frac{dM_{\oplus}(a_d)}{dt} = m(a_d)\pi R_{\oplus}^2 \; n_d(1\ \mathrm{AU}) \; \delta v_{\oplus},$$

where a_d is the mean radius of the dust particles and $m(a_d)$ its mass for a bulk density of 1 g cm^{-3}, $R_{\oplus}$ the radius of the Earth, $n_d(1\ \mathrm{AU})$ the number density of dust at 1 AU and $\delta v_{\oplus}$ the mean encounter velocity, which we assume as proportional to the orbital velocity. We also consider that the number density of the dust decreases with heliocentric distance as r^{-1} (Liou et al., 1999).

Therefore we scale the rate of mass that fall on the body of radius R at the heliocentric distance r as:

$$\frac{dM_R(a_d)}{dt} = \frac{dM_{\oplus}(a_d)}{dt} \times \frac{R^2}{R_{\oplus}^2} \times \frac{1\ \mathrm{AU}}{r(\mathrm{AU})^{1.5}}.$$

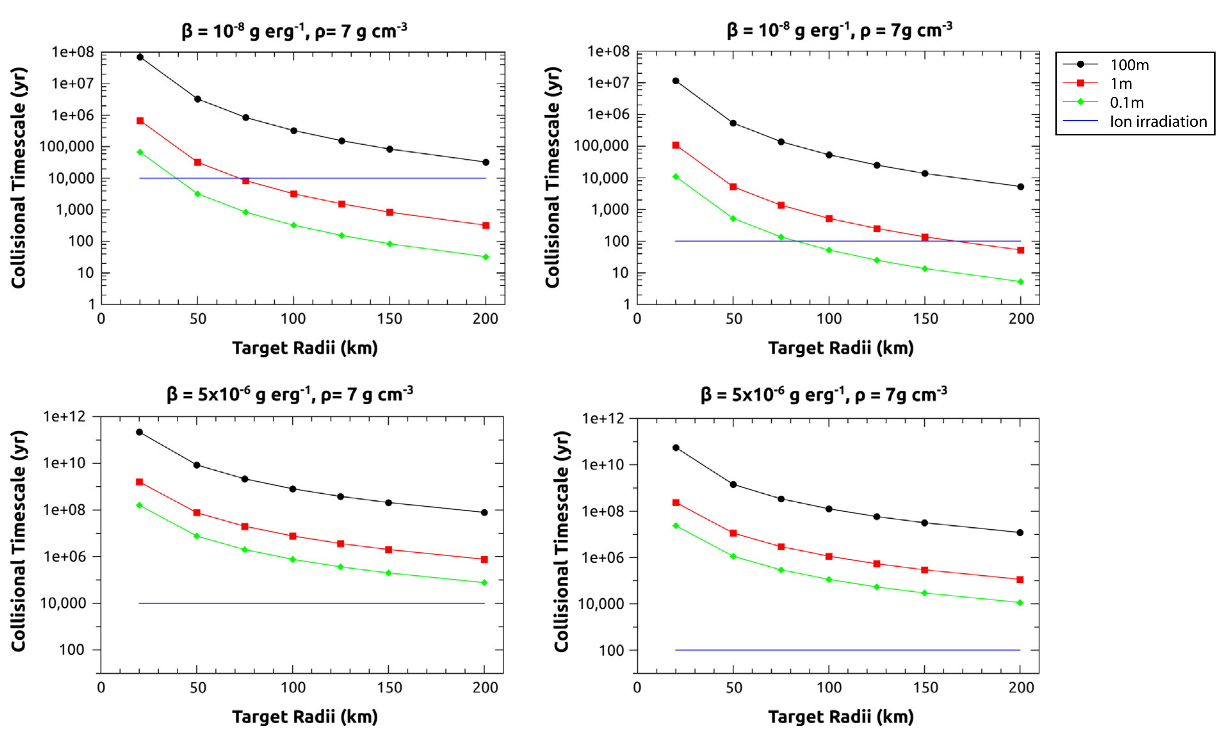

Fig. 2. Collisional gardening timescale for a bulk density of $\rho_1 = 7$ g cm^{-3}. The case of Jupiter-Trojans correspond to the right column and the Plutinos to the left column. The suggested solar wind ion bombardment timescales are indicated by the horizontal lines (see Section 4 for details).

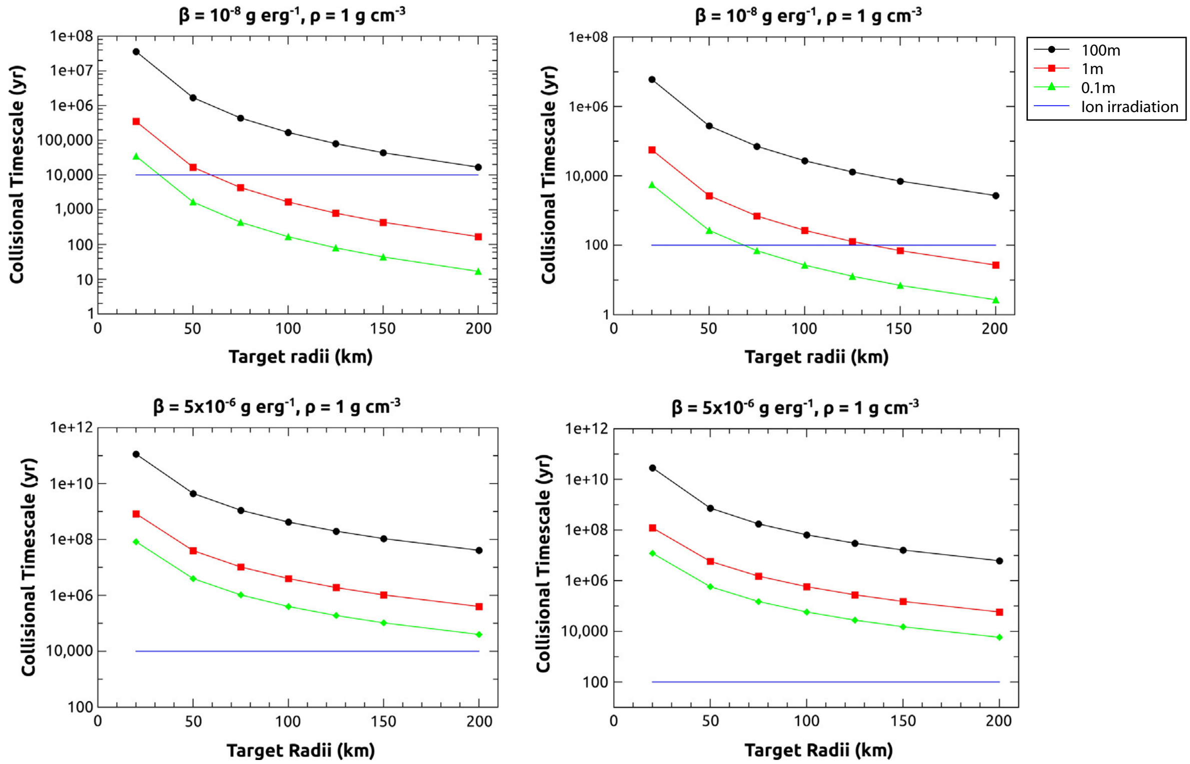

Fig. 3. Collisional gardening timescale for a bulk density of $\rho_2 = 1$ g cm^{-3}. The case of Plutinos correspond to the left column and the Jupiter Trojans to the right column. The suggested solar wind ion bombardment timescales are indicated by the horizontal lines (see Section 4 for details).

The volume V_Y of the crater produced in the strength regime is given by an expression analogous to Eq. (6) used in the gravity regime (Holsapple, 1993), but the specific gravitational energy of the target is replaced by its specific strength energy:

$$V_Y = K_1 \left(\frac{m}{\rho}\right)\left(\frac{Y}{v^2}\right)^{\frac{-3\mu}{2+\mu}},$$

where Y is a constant that characterizes the surface strength of the material, which we assume as 10 Pa for water ice (Holsapple, 1993). We compute the area affected by the crater A_d, assuming a paraboloid geometry. Hence the rate of the surface alteration $\dot{S_d}$ by dust impacts with particles of the mean radius a_d for a target object of radius R is:

$$\dot{S_d} = \frac{dn_d(r)}{dt} A_d(a_d),$$

where $\frac{dn_d(r)}{dt}$ is obtained as $\frac{1}{m(a_d)} \times \frac{dM_R(a_d)}{dt}$ and

$$\tau_d = \frac{1}{\dot{S_{ed}}},$$

where $\dot{S_{ed}}$ is the specific rate of the collisional gardening by dust:

$$\dot{S_{ed}} = \frac{\dot{S_d}}{4\pi R^2}.$$

The values of τ_d for a 100 km target, for different values of the mean dust radius are given in Fig. 4.

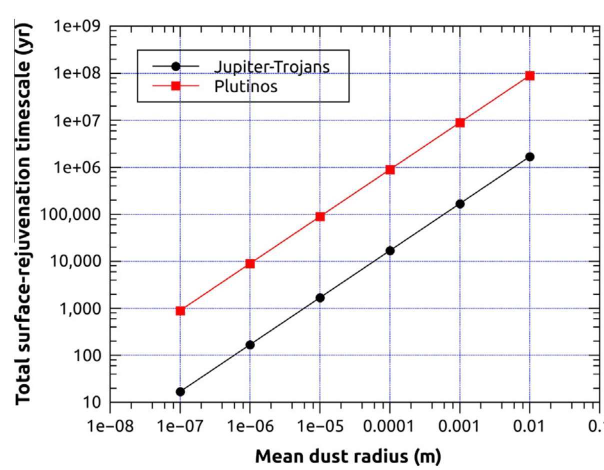

Fig. 4. Total surface rejuvenation timescales of a 100 km radius target due to microimpacts as a function of the mean dust radii.

4. Model

The model we are going to discuss, is based on many laboratory experiments that have been conducted in the last 10 years by the group at the Laboratorio di Astrofisica Sperimentale in Catania (LASP-Catania) (e.g. Strazzulla et al., 2005) and by other groups (see e.g., Sasaki et al., 2001; Loeffler et al., 2008, 2009). In Catania, investigated materials include carbon-based species such as frozen hydrocarbons (Brunetto et al., 2006a), red bitumens (asphaltite and kerite – Moroz et al., 2004), and different kinds of silicates (Brunetto and Strazzulla, 2005; Brunetto et al., 2006b; Strazzulla et al., 2005).

Kaňuchová et al. (2010) have also studied the effects of space weathering on a silicate (olivine) covered with a layer of polystyrene that was chosen as a template for organic materials of low volatility. Such materials – macromolecules or molecular solids including C-bearing icy mixtures – could be very abundant on small objects in the outer Solar System, where they could be accreted directly from the nebular material at the beginning of the Solar System or they could be produced by energetic processing of simple ices (e.g., Palumbo et al., 2008).

The global findings of those experiments have been summarized by Kaňuchová et al. (2012) and used to show how an appropriate combination of resurfacing by impacts or even sublimation and solar wind/cosmic ion bombardment weathering can reproduce the whole range of colors observed on the outer Solar System small bodies. Here we apply that simple model for the surfaces of members of the two small bodies populations here discussed.

The time necessary to produce, in a given astrophysical context, the same effect as measured in laboratory can be estimated. The timescale for the solar wind ions effect on an object at specified heliocentric distance is estimated by calculating the total dose (eV/molecule) deposited by the ion (through elastic and inelastic collisions) used in the laboratory and that due to solar wind ion flux. The calculations are done by using the SRIM (Stopping power and Range of Ions of Matter) code (Ziegler et al., 2008). For details of the procedure see Kaňuchová et al. (2012) and references therein.

We model the surface of Jupiter Trojans and Plutinos as composed of two components: component 1 is constituted by a material characterized by a flat spectrum – i.e. having solar colors, these can be for instance pure water ice or completely dehydrogenated carbons; component 2 is composed of materials whose colors can be affected by energetic processing (for instance silicates, complex organics, C-bearing ices, etc.). In the case of Trojans, the component 1 is assumed to be dark, of visual albedo $\sim$4% (Fernandez et al., 2003); the component 1 of Plutinos is assumed to be of high albedo $\approx$80–100%, representing water ice. As template of component 2 material we use polystyrene irradiated with different ion fluences because it is able, upon ion irradiation, to cover a very wide range of colors and, at the highest doses it is carbonized and has a flat spectrum and a low albedo (see Kaňuchová et al., 2012, for details on experiments and characteristics of sample).

The values of the modeled color indexes have been obtained by a simple system of equations:

$$B - V = 2.5 Log \frac{X\ Refl_V 1 + Y\ Refl_V 2}{X\ Refl_B 1 + Y\ Refl_B 2}, \quad (7)$$

where $B-V$ is the resulting color index; X = fraction of the component 1; Y = fraction of the component 2; $X+Y=1$. $Refl_V1 = Refl_B1$ are the reflectances of the component 1 that are equal because of their assumed flat spectrum. $Refl_V2$ and $Refl_B2$ are the reflectances of the chosen laboratory sample. For the details see (Kaňuchová et al., 2012).

In Table 1 we list the values of ion fluences (and total doses) used to irradiate the sample in laboratory and the corresponding astronomical timescales at heliocentric distance of Trojans and Plutinos; considering the effects of solar wind protons.

Table 1
Characteristics of the sample irradiated in laboratory and used in the model. Columns report: step of irradiation (No), 400 keV Ar^{++} ion fluence (F = ions/cm^2), total energy dose (D = eV/16u), solar wind timescales at 5 AU (40 AU) for 1 keV protons (years).

No	F ions/cm^2	D eV/16u	Solar wind timescales (yrs)	
			At 5 AU	At 40 AU
1	6.3×10^{12}	1.2	7.5	4.5×10^2
2	1.9×10^{13}	3.7	2.2×10^1	1.4×10^3
3	3.8×10^{13}	7.4	4.3×10^1	2.7×10^3
4	7.5×10^{13}	14.7	8.5×10^1	5.4×10^3
5	1.5×10^{14}	29.4	1.8×10^2	1.1×10^4
6	2.3×10^{14}	45.1	2.8×10^2	1.8×10^4
7	6.0×10^{14}	117.6	6.8×10^2	4.3×10^4
8	4.3×10^{15}	842.5	5.0×10^3	3.2×10^5

The time in which the surface of the object can be modified by the solar wind ions is counterbalanced by the collision timescale in which the surface is completely renovated (i.e. it is excavated and fresh original material is exposed). Thus, the population of objects can be characterized by a "mean level of space weathering", i.e. the mean value of dose absorbed by the surface of individual objects. For this reason, we search for the relevant "isoquant". i.e. a line in the color–color diagram that represents the same amount of time exposure. Several isoquants representing a different level of weathering were calculated using Eq. (6), with laboratory samples as component 2 (see Table 1), fixed reflectance of component 1 and changing the X/Y ratio.

The color difference along the isoquant line is due to different fractions of the two considered surface components. Looking at the Fig. 1 we can say that the color distribution of Trojans can be characterized by the isoquant, that corresponds to a time of about 10^2 years. (The isoquant was calculated using the sample No. 4 as component 2 in Eq. (7)). The color of Plutinos is characterised by an isoquant corresponding to a time of 10^4 years see Fig. 2).

In the second step, we estimate the fraction of the processed C-bearing material, using which, the proposed model is able to cover the whole color distribution of objects. To make an estimation, we analyzed several possible "evolutionary tracks" of objects which are receiving higher and higher energy doses. The objects were characterized by different ratios of surface components.

For two chosen fractions of components 2 (50% and 15% for Trojans) we plot on Fig. 5 the values of the experimental color indexes calculated using Eq. (7) corresponding to a different dose received by the surface material – in eV per atomic mass unit – from the impinging solar wind ions.

The numbers in the plot identify the step of sample irradiation, as listed in Table 1. Zero indicates the sample before irradiation.

We find that the colors of all Trojan asteroids can be covered using the model with a fraction of processed carbonaceous matter smaller than 15%. The results for Plutinos are shown in Fig. 6. For varying values of received dose, to contain all the objects within our model a large fraction of processed carbonaceous matter is needed – about 90%.

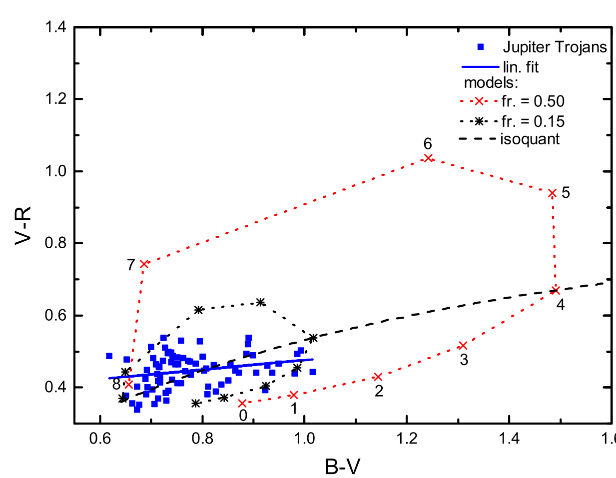

Fig. 5. $V-R$ vs. $B-V$ color diagram of the Jupiter Trojans asteroids with visual colors contained in the MBOSS catalog. The linear fit of the data, the values obtained by a model with albedo of the component 1 equal to 4% and fractions of organic compounds equal to 15% and 50%. Isoquant is a theoretical trend of color distribution of objects differing in the amount of surface component 2, weathered to the same level (85 yrs). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

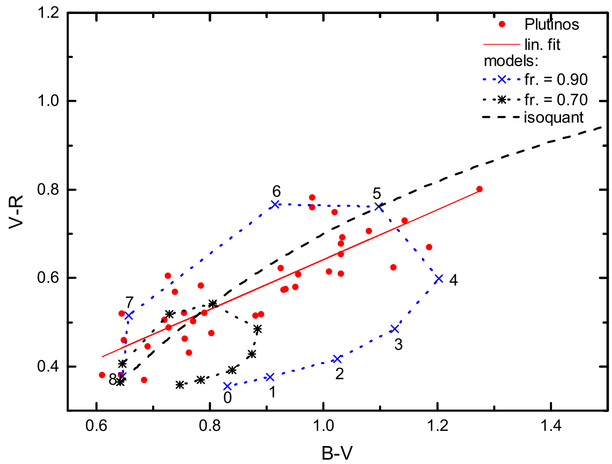

Fig. 6. $V - R$ vs. $B - V$ color diagram of the Plutinos with visual colors contained in the MBOSS catalog. The linear fit of the data, the values obtained by a model with albedo of the unweathered component equal to 100% and fractions of organic compounds equal to 70% and 90% isoquant is a theoretical trend of color distribution of objects differing in the amount of surface component 2, weathered to the same level (10^4 yrs). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

In our model, the surface of the two studied populations of small Solar System bodies is supposed to be composed of two components.

The colors of the Trojans can be reproduced using the combination of a dark material of visual albedo ~0.04 and <15% of a fresher organic material that is processed "in average" for about 10^2 yrs.

After this time of the exposure to the solar-wind ions, the surface can be altered by a collision. In fact, looking at Fig. 2 we can see that surface of Trojans can be completely renovated by collisions in 10^2–10^3 years. The agreement between the estimation of the ion irradiation timescale and the collisional timescale is achieved, if the crater excavation coefficient is taken as characteristics for an icy body, and if the cut-off radius in the distribution is between 0.1 m and 1 m for objects with radius approximately 60 km.

According to Emery et al. (2006) the surface of Trojans is composed of silicate grains embedded in a transparent matrix (although an extremely high porosity has also been invoked). In fact, the polystyrene, which we have used as the template of organic materials, is transparent in the VIS–NIR spectral range, and becomes red and dark when irradiated. At higher doses, when saturation occurs (Kaňuchová et al., 2012), the spectrum becomes dark and again "flat".

We note that there is a remarkable variation in the collisional timescale of surface rejuvenation depending on the target body radius: the smaller is the target, the longer time is necessary for its whole resurfacing. Therefore one may expect small bodies to be more affected by ion radiation than the larger counterparts. This result is in correspondence with the observations in the Jupiter-Trojans clouds, where large back-ground objects in both swarms tend to be redder (Roig et al., 2008) and more neutral spectra correspondent with more irradiated surfaces are more abundant in the smaller objects. This is because the time that larger objects have to accumulate radiation is shorter, since collisional rejuvenation occurs faster.

On the other hand, the color distribution of Plutinos can be reproduced using an higher amount of modified organic material – up to 90% with a reflectance in the visual spectra ~10% (Kaňuchová et al., 2010) and a material of high albedo and flat spectrum. The presence of dark organic material in the icy surfaces is expected as product of irradiation processes of methane and/or methanol ices (Dalle Ore et al., 2011; Brunetto et al., 2006a).

According to our model based on the ion irradiation laboratory experiments, the surface material of the Plutinos is processed by ions for ≈10^4 yrs before being rejuvenated. In order of magnitudes, this estimation is in good agreement with the collisional resurfacing timescale estimation for the icy bodies smaller than 60 km, and the size of the smallest impactor in the population is in the range from 0.1 m to 1 m.

Our estimation of the timescale of surface rejuvenation by dust τ_d is valid in the range of the mean dust radius between 1 μm and 1 mm. We notice that in the case of the Jupiter-Trojans τ_d is noticeably larger than the ion-radiation timescale and in the case of the Plutinos the timescale is about 10^4 yrs if the mean dust radius is about 1 μm.

6. Conclusions

We have presented the curves in the color–color diagram (isoquants) describing the balance between space weathering and collisional resurfacing for two populations – Plutinos and Jupiter Trojans. We have estimated the average time of the surface exposure of Trojans to be ~10^2 years, while the average exposure time of Plutinos is much higher: ~10^4 years. According to our results we expect only small amount (<15%) of red altered organic material on the surface of Trojans. On the other hand, high amount (up to 90%) of material altered by higher doses, thus more red, organic material is supposed to be present on the surface of Plutinos.

This implies that, using a simple model based on the surface color due to the contribution of two components, one pristine and one altered, the difference in color distributions of these populations can be explained as due to the interplay of space weathering by energetic cosmic-radiation and collisional effects.

In the case of the Jupiter-Trojans the surface rejuvenation timescale due to physical collisions can be of the order of 100 yrs, corresponding to the ion-irradiation timescale, if the cut-off radius in the distribution is between 0.1 m and 1 m for objects with radius approximately 60 km. For the Plutinos, the surface rejuvenation timescale due to physical collisions can be of the order of the ion-irradiation timescale, i.e. 10^4 yrs, if the cut-off radius in the distribution is between 0.1 m and 1 m for objects in the same size range and assuming the same value of the crater excavation coefficient.

Irradiation timescale of the Plutinos can be balanced by the resurfacing timescale both by micro-impacts as well as by physical collisions with massive objects. In the case of the Jupiter-Trojans the re-juvenation due to micro-impacts occurs on a much longer timescale.

As a final remark, we believe that although our model explains the observed color differences among the two populations, it does not reject a contribution from initial composition or early processing of surface and sub-surface layers (by thermal or impact-induced alterations).

Acknowledgments

M.D.M. acknowledges support from CONICET PIP 11220090100461/2010 and from ANPyT-MinCyT through PICT 18/2007. The research of Z.K. has been supported by VEGA – The Slovack Agency for Science, Grant No. 2/0032/14.

References

Barkume, K.M., Brown, M.E., Schaller, E.L., 2008. Near-infrared spectra of Centaurs and Kuiper belt objects. Astron. J. 135, 55–67.

Barucci, M.A., Brown, M.E., Emery, J.P., Merlin, F., 2008. Composition and surface properties of transneptunian objects and Centaurs. Solar Syst. Bey. Nept., 143–160.

Bell, J.F., Davis, D.R., Hartmann, W.K., Gaffey, M.J., 1989. Asteroids: The big picture. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), Asteroids II. Univ. of Arizona Press, Tucson, pp. 921–945.

Benecchi, S.D., Noll, K.S., Grundy, W.M., Buie, M.W., Stephens, D.C., Levison, H.F., 2009. The correlated colors of transneptunian binaries. Icarus 200, 292–303.

Brunetto, R., Roush, T.L., 2008. Impact of irradiated methane ice crusts on compositional interpretations of TNOs. Astron. Astrophys. 481, 879–882.

Brunetto, R., Strazzulla, G., 2005. Elastic collisions in ion irradiation experiments: A mechanism for space weathering of silicates. Icarus 179, 265–273.

Brunetto, R., Barucci, M.A., Dotto, E., Strazzulla, G., 2006a. Ion irradiation of frozen methanol, methane, and benzene: Linking to the colors of Centaurs and trans-neptunian objects. Astrohys. J. 644, 646–650.

Brunetto, R., Romano, F., Blanco, A., Fonti, S., Martino, M., Orofino, V., Verrienti, C., 2006b. Space weathering of silicates simulated by nanosecond pulse UV excimer laser. Icarus 180, 546–554.

Carry, B., 2012. Density of asteroids. Planet. Space Sci. 73 (1), 98–118.

Ciesla, F.J., Charnley, S.B., 2006. The physics and chemistry of nebular evolution. In: Lauretta, D.S., McSween, H.Y., Jr. (Eds.), Meteorites and the Early Solar System II, vol. 943. University of Arizona Press, Tucson, pp. 209–230.

Cooper, J.F., Christian, E.R., Richardson, J.D., Wang, C., 2003. Proton irradiation of Centaur, Kuiper belt, and oort cloud objects at plasma to cosmic ray energy. Earth Moon Planets 92, 261–277.

Cruikshank, D.P., Roush, T.L., Bartholomew, M.J., Geballe, T.R., Pendleton, Y.J., White, S.M., Bell III, J.F., Davies, J.K., Owen, T.C., de Bergh, C., Tholen, D.J., Bernstein, M.P., Brown, R.H., Tryka, K.A., Dalle Orei, C.M., 1998. The composition of Centaur 5145 Pholus. Icarus 135, 389–407.

Dalle Ore, C.M. et al., 2011. Organic materials in planetary and protoplanetary systems: Nature or nurture? Astron. Astrphys. 533 (A98), 14.

Dell'Oro, A., Paolicchi, P., Marzari, F., Dooto, E., Vanzani, V., 1998. Trojan collision probability: A statistical approach. Astron. Astrophys. 339, 272–277.

Dell'Oro, A., Campo Bagatin, A., Benavidez, P.G., Aleman, R.A., 2013. Statistics of encounters in the trans-neptunian region. Astron. Astrophys. 558, A95, 8pp.

DeMeo, F.E., Binzel, R.P., Slivan, S.M., Bus, S.J., 2009. An extension of the Bus asteroid taxonomy into the near-infrared. Icarus 202, 160–180.

Doressoundiram, A., Boehnhardt, H., Tegler, S.C., Trujillo, C., 2008. Color properties and trends of the transneptunian objects. In: Barucci, M.A., Boehnhardt, H., Cruikshank, D.P., Morbidelli (Eds.), Solar System Beyond Neptune. Univ. of Arizona Press, Tucson, p. 585.

Dotto, E., Emery, J.P., Barucci, M.A., Morbidelli, A., Cruikshank, D.P., 2008. Troianis: The trojans in the planetary system. In: Barucci, M.A., Boehnhardt, H., Cruikshank, D.P., Morbidelli (Eds.), The Solar System Beyond Neptune. Univ. of Arizona Press, Tucson, p. 585.

Emery, J.P., Cruikshank, D.P., van Cleve, J., 2006. Thermal emission spectroscopy (5.2–38 μm) of three Trojan asteroids with the Spitzer Space Telescope: Detection of fine-grained silicates. Icarus 182, 496–512.

Emery, J.P., Burr, D.M., Cruikshank, D.P., 2011. Near-infrared spectroscopy of Trojan asteroids: Evidence for two compositional groups. Astron. J. 141, 18, id.25.

Fernandez, Y.R., Sheppard, S.S., Jewitt, D.C., 2003. The albedo distribution of jovian Trojan asteroids. Astron. J. 126, 1574–1663.

Fernandez, Y.R., Jewitt, D., Ziffer, J.E., 2009. Albedos of small jovian Trojans. Astron. J. 138, 240–250.

Giblin, I., Davis, D.R., Ryan, E.V., 2004. On the collisional disruption of porous icy objects simulating KBOs. Icarus 171, 487–505.

Gil-Hutton, R., 2002. Color diversity among Kuiper belt objects: The collisional resurfacing model revisited. Planet. Space Sci. 50, 57–62.

Grundy, W.M., 2009. Is the missing ultra-red material colorless ice? Icarus 199, 560–563.

Guilbert, A. et al., 2009. A portrait of Centaur 10199 Chariklo. Astron. Astrophys. 501, 777–784.

Hainaut, O.R., Delsanti, A.C., 2002. Colors of minor bodies in the outer Solar System: A statistical analysis. Astron. Astrophys. 389, 641–664.

Hainaut, O.R., Boehnhardt, H., Protopapa, S., 2012. Colours of minor bodies in the outer Solar System. II. A statistical analysis revisited. Astron. Astrophys. 546, A115, 20pp.

Holsapple, K.A., 1993. The scaling of the impact processes in planetary sciences. Ann. Rev. Earth Planet. Sci. 21, 333–373.

Jewitt, D.C., Trujillo, C.A., Luu, J.X., 2000. Population and size distribution of small jovian Trojan asteroids. Astron. J. 120, 1140–1147.

Kaňuchová, Z., Baratta, G.A., Garozzo, M., Strazzulla, G., 2010. Space weathering of asteroidal surfaces. Influence on the UV–Vis spectra. Astron. Astrophys. 517, A60, 10pp.

Kaňuchová, Z., Brunetto, R., Melita, M., Strazzulla, G., 2012. Space weathering and the color indexes of minor bodies in the outer Solar System. Icarus 221, 12–19.

Kenyon, S.J., Bromley, B.C., O'Brien, D.P., Davis, D.R., 2008. Formation and collisional evolution of Kuiper belt objects. In: Barucci, M.A., Boehnhardt, H., Cruikshank, D.P., Morbidelli, A. (Eds.), The Solar System Beyond Neptune (Space Science Series), pp. 293–313.

King, P.L., Izawa, M.R.M., Vernazza, P., McCutcheon, W.A., Berger, J.A., Dunn, T., 2011. Lunar Planet. Sci. 42, 1985.

Krasinsky, G.A., Pitjeva, E.V., Vasilyev, M.V., Yagudina, E.I., 2002. Hidden mass in the asteroid belt. Icarus 158 (1), 98–105.

Liou, J., Zook, H.A., Jackson, A.A., 1999. Orbital evolution of retrograde interplanetary dust particles and their distribution in the Solar System. Icarus 141, 13–28.

Loeffler, M.J., Baragiola, R.A., Murayama, M., 2008. Icarus 196, 285.

Loeffler, M.J., Dukes, C.A., Baragiola, R.A., 2009. J. Geophys. Res. (Planets) 114, 3003.

Luu, J., Jewitt, D., 1996. Color diversity among the Centaurs and Kuiper belt objects. Astron. J. 112, 2310–2318.

Mommert, M. et al., 2012. TNOs are cool: A survey of the trans-Neptunian region. V. Physical characterization of 18 Plutinos using Herschel-PACS observations. Astron. Asrophys. 541, A93, 17pp.

Moroz, L.V., Baratta, G., Strazzulla, G., Starukhina, L., Dotto, E., Barucci, M.A., Arnold, G., Distefano, E., 2004. Optical alteration of complex organics induced by ion irradiation: 1. Laboratory experiments suggest unusual space weathering trend. Icarus 170, 214–228.

Nesvorný, D., Vokrouhlický, D., Morbidelli, A., 2013. Capture of Trojans by jumping Jupiter. Astrophys. J. 768, id45, 8pp.

Palumbo, M.E. et al., 2008. Ion irradiation of astrophysical ices. J. Phys. 101, 012002.

Petit, J.M., Farinella, P., 1993. Modelling the outcomes of high-velocity impacts between small Solar System bodies. Celest. Mech. Dynam. Astron. 57, 1–28.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P., 1992. NUMERICAL RECIPES in Frotran The Art of Sceintific Computing, second ed. Cambridge University Press, Victoria, Australia.

Roig, F., Ribeiro, A.O., Gil-Hutton, R., 2008. Taxonomy of asteroid families among the Jupiter Trojans: Comparison between spectroscopic data and the Sloan Digital Sky Survey colors. Astron. Astrophys. 483, 911–931.

Sasaki, S., Nakamura, K., Hamabe, Y., Kurahashi, E., Hiroi, T., 2001. Production of iron nanoparticles by laser irradiation in a simulation of lunar-like space weathering. Nature 410, 555–557.

Strazzulla, G., Dotto, E., Binzel, R., Brunetto, R., Barucci, M.A., Blanco, A., Orofino, V., 2005. Spectral alteration of the Meteorite Epinal (H5) induced by heavy ion irradiation: a simulation of space weathering effects on near-Earth asteroids. Icarus 174, 31–35.

Thébault, P., Doressoundiram, A., 2003. Colors and collision rates within the Kuiper belt: Problems with the collisional resurfacing scenario. Icarus 162, 27–37.

Thompson, W.R., Murray, B.G.J.P.T., Khare, B.N., Sagan, C., 1987. Coloration and darkening of methane clathrate and other ices by charged particle irradiation: Applications to the outer Solar System. J. Geophys. Res. 92, 14933–14947.

Wetherill, G.W., 1967. Collisions in the asteroid belt. J. Geophys. Res. 72, 2429.

Yang, B., Jewitt, D., 2007. Spectroscopic search for water ice on Jovian Trojan asteroids. Astron. J. 134, 223–228.

Yang, B., Lucey, P., Glotch, T., 2013. Are large Trojan asteroids salty? An observational, theoretical, and experimental study. Icarus 223, 359–366.

Ziegler, J.F., Biersack, J.P., Ziegler, M.D., 2008. The Stopping and Range of Ions in Solids. Pergamon Press, New York, 321pp.