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Survival of water ice in Jupiter Trojans

Aurélie Guilbert-Lepoutre *

UCLA, Department of Earth and Space Sciences, Los Angeles, CA 90095, USA
European Space Agency, ESTEC, 2201 AZ Noordwijk, Netherlands

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ABSTRACT

Jupiter Trojans appear to be a key population of small bodies to study and test the models of the Solar System formation and evolution. Because understanding the evolution of Trojans can bring strong and unique constraints on the origins of our planetary system, a significant observational effort has been undertaken to unveil their physical characteristics. The data gathered so far are consistent with Trojans having volatile-rich interiors (possibly water ice) and volatile-poor surfaces (fine grained silicates). Since water ice is not thermodynamically stable against sublimation at the surface of an object located at ~5 AU, such layering seems consistent with past outgassing. In this work, we study the thermal history of Trojans after the formation of a dust mantle by possible past outgassing, so as to constrain the depth at which water ice could be stable. We find that it could have survived 100 m below the surface, even if Trojans orbited close to the Sun for ~10,000 years, as suggested by the most recent dynamical models. Water ice should be found ~10 m below the surface in most cases, and below 10 cm in the polar regions in some cases.

1. Introduction

Jupiter Trojans (hereafter Trojans) are asteroids trapped in the L4 and L5 Lagrangian clouds of the Jupiter–Sun system. Because they share a similar orbit as Jupiter, they have been considered as useful probes to constrain the formation of the giant planet. However, as of today, we are still mostly ignorant of the origin of this small-body population, and this topic is a matter of great debate. Trojans might have formed in the Jupiter region (Marzari and Scholl, 1998; Fleming and Hamilton, 2000), near where they are found today. They could in this case provide important clues on the formation of Jupiter itself, as its core is believed to have formed from an aggregate of icy planetesimals (Fleming and Hamilton, 2000). Later in the dynamical history of the Solar System, the Lagrangian clouds might have been populated by objects formed in more distant regions, in which case the current population could include bodies formed over a large range of heliocentric distances (~5–30 AU). Trojans could have been captured either during a chaotic (Morbidelli et al., 2005; Nesvorny et al., 2013) or a smooth migration of the giant planets (Lykawka et al., 2009). They might represent the physical properties of their more distant and less accessible potential parent bodies, the Kuiper Belt Objects (KBOs). In this context, understanding the origin and fate of Trojans could lead to significant advances in our understanding of the formation and evolution of the Solar System.

Trojans appear to be a key small-body population for testing models of the Solar System dynamical evolution. The physical nature of Trojans, when understood, should provide crucial constraints on the temperature, pressure and chemical composition of the solar nebula at the time and place of their formation. A large observational effort has thus been undertaken to unveil the physical characteristics of these small bodies. Their surfaces display low albedos and colors very similar to those observed amongst comets (Jewitt and Luu, 1990). Spectroscopic data collected over a large wavelength range have revealed featureless spectra in the 0.4–4.0 μm range (Jones et al., 1990; Luu et al., 1994; Dumas et al., 1998; Emery and Brown, 2003; Yang and Jewitt, 2007; Fornasier et al., 2007; de Luise et al., 2010; Yang and Jewitt, 2011; Emery et al., 2011), while their mid-infrared spectra display a prominent feature around 10 μm attributed to the presence of fine-grained silicates at their surface (Emery et al., 2006). The inferred compositions are consistent with Trojan surfaces being made of a very porous dusty crust, possibly produced by past sublimation (Emery et al., 2006). For instance, the composition of grains at the surface of Trojan (624) Hektor (Vernazza et al., 2012) appears similar to the composition of cometary grains (Lisse et al., 2006; Brunetto et al., 2011). Emery et al. (2011) reported a possible bimodality in the near-infrared spectral slopes, consistent with previous trends reported among visible data (see Fornasier et al., 2007 and references therein). The authors argue that the two spectral groups could represent objects with different intrinsic compositions, due to different formation locations, with the reddest spectral group formed in the outer Solar System, and the other objects formed

* Corresponding author.
E-mail address: aguilber@rssd.esa.int

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in the Jupiter region. Density was determined for a few objects: it ranges from 0.8 g cm^{-3} for (617) Patroclus (Marchis et al., 2006) to 2.5 g cm^{-3} for (624) Hektor (Lacerda and Jewitt, 2007), although a recent measurement from Marchis et al. (2013) indicates a density of 1.0 g cm^{-3} for this object. This suggests that Trojans have a high volatile content, a high porosity, or both. Finally, the distribution of Trojan rotation periods may indicate possible past outgassing (Mottola et al., 2012).

Trojans could be considered as dead or dormant comets. All data gathered so far are indeed consistent with Trojans being volatile-rich objects, with surfaces made of a porous dusty crust, possibly produced by past outgassing. However, no ice has ever been reported on Trojans, nor any coma or outgassing ever detected. Did any ice, if ever present in Trojans, survive their possible cometary past? Could it be buried in the deep interior, or more interestingly in subsurface layers? In this work, we investigate the survival of water ice inside Trojans, regardless of their early thermal evolution, or their specific past cometary activity. We use a three-dimensional model to compute the thermal evolution of Trojans as a function of albedo, obliquity, rotation period and thermal inertia, in order to provide constraints on the depth at which water ice might have survived.

2. Thermal evolution modeling of Trojans

2.1. Assumption on the internal composition

The formation of a dusty mantle at the surface of comets was first studied by Brin and Mendis (1979). The idea behind this process is the following: as ice evaporates, the gas carries dust particles with it. While the smaller, lighter particles are entrained and can escape the body, the larger particles accumulate on the surface, eventually creating a porous crust. In time, the insulating effect of this mantle can completely quench any sublimation (Prialnik and Bar-Nun, 1988; Grün et al., 1993). The realistic modeling of dust mantling, and of gas flow through such a mantle, is however extremely complex (Huebner et al., 2006). In this work, we do not study this phase of thermo-physical evolution. We consider as an approximation that Trojans sustained cometary activity in the past, which resulted in the formation of an insulating crust at their surface. In our model, the crust is formed, and ice is stable underneath, so that no sublimation needs to be accounted for. This is similar to the approach of Schorghofer (2008) for Main Belt Asteroids. Our aim is to study the possibility for water ice to survive under a dust mantle, and establish the thickness of such mantle. We also check whether the conditions are met for water ice to survive at the surface of Trojans.

At the surface: The ice loss rate from the surface J_{surf} is given by:

$$J_{surf} = P_S(T)\sqrt{\frac{m}{2\pi k_B T}} \tag{1}$$

with m [kg] the molecular weight, k_B [J K^{-1}] the Boltzmann constant, T [K] the temperature, and $P_S(T)$ [Pa] the saturation vapor pressure, which is given by the Clausius–Clapeyron equation:

$$P_S(T) = \alpha e^{-E_a/k_B T} \tag{2}$$

with $\alpha = 3.56 \times 10^{12}$ Pa and $E_a/k_B = 6141.677$ K for water.

Under the surface: The loss rate from an icy layer buried under a porous crust is driven by three main parameters:

- the thickness of the crust, Δr [m],
- the diffusion coefficient, D_{Kn} [m^2 s^{-1}], which relates to the ability of gas molecules to escape through the crust by Knudsen diffusion,
- the temperature T [K].

The diffusion coefficient can be written as $D_{Kn} \sim \varphi v_{th}$, with $v_{th} = \sqrt{\frac{8k_BT}{\pi m}}$ the mean thermal velocity, and φ the material permeability. We can write the ice loss rate J from a subsurface layer buried under the porous icy crust as (assuming an ideal gas law):

$$\begin{aligned} J &= D_{Kn}\frac{1}{\Delta r}\frac{m}{k_BT}P_S(T) \\ \Rightarrow J &= \frac{2\varphi}{\Delta r}\sqrt{\frac{2m}{\pi k_B T}}P_S(T), \end{aligned} \tag{3}$$

which is in agreement with the expressions found by Fanale and Salvail (1984); Schorghofer (2008) and Gundlach et al. (2011) by a factor of the order of unity.

Both at and under the surface, the survival of water ice, after a potential episode of cometary activity, can be constrained by studying the temperature distribution in Trojans. At the surface, the water ice loss rate is $\sim 3 \times 10^{-15}$ kg m^{-2} s^{-1} at 110 K. This means that water ice could survive for the age of the Solar System below this temperature. We imposed the same low erosion rate in Eq. (3), to directly constrain the thickness of the porous dusty crust which would be required for water ice to survive, from the temperature distribution inside the crust.

2.2. Model for the temperature distribution

To explore the stability of water ice, we therefore need to determine the temperature distribution. We use a numerical model of three-dimensional heat transport: the temperature distribution is computed as a function of time and orbital position, both at the surface and inside the object. In this section, we briefly described the model, and refer to Guilbert-Lepoutre et al. (2011) for specific details on the mathematical and numerical scheme. The model solves the heat conduction equation, assuming spherical objects. Heat is transported in two different ways: it is conducted via contacts between grains, and transferred through thermal radiation within pores. Boundary conditions are: at the center of the object, the heat flux is null; at the surface, it is given by computing the thermal balance between:

- insolation, described by $(1-\mathcal{A})\frac{C_\odot}{d_H^2}\cos\xi$, with $\mathcal{A}$ the Bond albedo, $C_\odot$ the solar constant, d_H the object's heliocentric distance, and ξ the local zenith angle,
- thermal emission $\varepsilon\sigma T^4$, with ε the material emissivity, σ the Stefan–Boltzmann constant and T the temperature,
- and both lateral and radial heat fluxes, driven by the thermal conductivity κ.

We consider an initial internal structure as suggested by the observational data: a core made of a mixture of porous ice and dust (50 wt% each) uniformly distributed within the ice, and an insulating surface layer made of porous dust. The crust thickness is however the unknown parameter which we are trying to constrain. We thus start the calculations with an arbitrarily thick surface layer (Δr_0 of the order of 1 km), and compute the temperature distribution after 4 Gyr. By introducing this distribution in Eq. (3), we estimate the crust thickness Δr_1, and re-adjust the numerical grid so be very fine close to this transition between the crust ad the core. This allows to minimize the discretization errors. We iterate the calculation of the temperature distribution until the depth converges (typically 2–3 iterations in total), so to establish the crust thickness associated to each case described in the following sections.

For the structural characteristics of the crust, we use the definition of permeability given by Huebner et al. (2006): $\varphi = \frac{\psi r_p}{\tau^2}$, with ψ the porosity, r_p the average pore size and τ the tortuosity. We