Similar origin for low- and high-albedo Jovian Trojans and Hilda asteroids?*,**

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ABSTRACT

Hilda asteroids and Jupiter Trojans are two low-albedo ($p_r \sim 0.07$) populations for which the Nice model predicts an origin in the primordial Kuiper Belt region. However, recent surveys by WISE and the Spitzer Space Telescope (SST) have revealed that $\sim 2\%$ of these objects possess high albedos ($p_r \geq 0.15$), which might indicate interlopers – that is, objects not formed in the Kuiper Belt – among these two populations. Here, we report spectroscopic observations in the visible and/or near-infrared spectral ranges of twelve high-albedo ($p_r > 0.15$) Hilda asteroids and Jupiter Trojans. These twelve objects have spectral properties similar to those of the low-albedo population, which suggests a similar composition and hence a similar origin for low- and high-albedo Hilda asteroids and Jupiter Trojans. We therefore propose that most high albedos probably result from statistical bias or uncertainties that affect the WISE and SST measurements. However, some of the high albedos may be true and the outcome of some collision-induced resurfacing by a brighter material that could include water ice. Future work should attempt to investigate the nature of this supposedly bright material. The lack of interlopers in our sample allows us to set an upper limit of 0.4% at a confidence level of 99.7% on the abundance of interlopers with unexpected taxonomic classes (e.g., A-, S-, V-type asteroids) among these two populations.

Key words. techniques: spectroscopic – minor planets, asteroids: individual: Jovian Trojans – minor planets, asteroids: individual: Hildas

1. Introduction

Jupiter Trojans and Hilda asteroids are small primitive bodies located beyond the snow line, around the L4 and L5 Lagrange points of Jupiter at $\sim 5.2$ AU (Trojans) and in the 2:3 mean-motion resonance with Jupiter near 3.9 AU (Hilda asteroids). Their origin remains a major challenge to current theories of the formation of the solar system.

There are two current models, the Grand Tack (Walsh et al. 2011) and the Nice model (Morbidelli et al. 2005; Levison et al. 2009), each one addressing distinct epochs of the early dynamical evolution of the solar system, and which – when taken together – make key predictions on the origin of both the Hilda and the Jupiter Trojan populations. The Grand Tack model addresses the early dynamical evolution of the solar system 3 to 5 Myr after its formation; it suggests that Jupiter roamed inward as close as the present location of Mars (\sim 1.5 AU) and then outward. This migration profoundly influenced the solar system, causing a substantial radial mixing of planetesimals throughout the solar system and making Mars smaller than it should have been. The Nice model addresses the late dynamical evolution of the solar system \sim 700 Myr after its formation; it suggests that a large portion of both the Trojans and the Hilda asteroids formed in more distant regions – typically in the primordial transneptunian disk, the precursor of the Kuiper Belt – and subsequently chaotically migrated towards the inner solar system as a consequence of the outward migration of all four giant planets.

Taken together, these models suggest that the immediate precursors of both the Hilda asteroids and Jupiter Trojans are Kuiper Belt objects (Nice model) and that the latter are not a homogeneous population (Grand Tack model), comprising a large portion of objects formed at large heliocentric distances ($\geq 10$ AU) and a minor fraction of planetesimals formed closer to the Sun ($\leq 3$ AU). The Trojans and Hilda asteroids could therefore represent a condensed or mixed version of the primordial solar system, very much like the asteroid belt.

Until recently, telescopic observations of both populations had only focused on the brightest, that is, the largest, objects. Their spectroscopic observations in the visible (Dahlgren & Lagerkvist 1995; Dahlgren et al. 1997; Bus & Binzel 2002; Lazzerro et al. 2004; Fornasier et al. 2004, 2007; Dotto et al. 2006; Roig et al. 2008) and near-infrared (NIR; Dumas et al. 1998; Dotto et al. 2006; Yang & Jewitt 2011; Emery et al. 2011) have revealed uniformly red and featureless spectra, and their albedo measurements (Fernández et al. 2003) have indicated low values ($\sim 0.07$) for both populations.

However, more recent measurements with the Spitzer Space Telescope (SST, Fernández et al. 2009) and with WISE (Grav et al. 2011, 2012a,b) have revealed a small group ($\sim 1.7\%$ of the total population) of presumably bright ($p_r \geq 0.15$) objects among both Hilda asteroids and Jupiter Trojans, which might indicate a minor fraction of interlopers – that is, objects not originating from the Kuiper Belt region, with a reflectance spectrum.

* Reflectance spectra presented in this paper are available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/568/L7
** Based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere, Chile (ESO program ID: 091.C-0247).
Table 1. Observation circumstances.

| No. | Name         | Group | Date         | Instrument | AM  | Exp. time (s) | D (km) | p_v | Ref. |
|-----|--------------|-------|--------------|------------|-----|---------------|--------|-----|------|
| 1162| 1930 AC      | Hilda | 2013-08-29   | X-Shooter  | 1.464−1.501 | 2 × 880/900/900 | 40.38 ± 0.30 | 0.186 ± 0.037 | 1    |
| 3290| 1973 SZ₄     | Hilda | 2013-08-28   | X-Shooter  | 1.201−1.277 | 3 × 880/900/900 | 10.18 ± 0.30 | 0.324 ± 0.055 | 1    |
| 5023| 1985 TG₃     | Trojan| 2013-04-13   | X-Shooter  | 1.400−1.716 | 3 × 880/900/900 | 27.85 ± 3.51 | 0.173 ± 0.093 | 2    |
| 9713| 1973 SP₁     | Trojan| 2013-04-14   | X-Shooter  | 1.370−1.652 | 3 × 880/900/900 | 18.65 ± 3.38 | 0.168 ± 0.086 | 2    |
| 11249| 1971 FD      | Trojan| 2013-08-28   | X-Shooter  | 1.065−1.070 | 2 × 880/900/900 | 9.97 ± 0.88  | 0.371 ± 0.097 | 1    |
| 2013-09-01| SpeX      |       | 1.288−1.631  |                     | 26 × 120                  |
| 13331| 1998 SU₅₂   | Trojan| 2013-04-15   | X-Shooter  | 1.313−1.460 | 3 × 880/900/900 | 17.68 ± 1.54 | 0.171 ± 0.033 | 2    |
| 14669| 1999 DC     | Hilda | 2013-12-13   | SpeX       | 1.002−1.023 | 30 × 120                  | 16.11 ± 0.66 | 0.206 ± 0.038 | 1    |
| 15529| 2000 AA₈₀  | Trojan| 2013-04-16   | X-Shooter  | 1.295−1.431 | 3 × 880/900/900 | 16.43 ± 1.33 | 0.198 ± 0.093 | 2    |
| 24452| 2000 QU₁₆₀ | Trojan| 2013-08-28   | X-Shooter  | 1.402−1.426 | 880/900/900                  | 18.69 ± 0.99 | 0.184 ± 0.029 | 2    |
| 32430| 2000 QG₃    | Trojan| 2013-08-29   | X-Shooter  | 1.447−1.520 | 2 × 880/900/900 | 13.37 ± 0.55  | 0.157 ± 0.007 | 2    |
| 63284| 2001 DM₄₈  | Trojan| 2013-04-13   | X-Shooter  | 1.267−1.548 | 3 × 880/900/900 | 12.27 ± 0.68/10.26 ± 1.32 | 0.129 ± 0.026/0.252 ± 0.050 | 1/3   |
| 2013-09-01| SpeX      |       | 1.275−1.593  | 3 × 880/900/900 |                         |
| 65227| 2002 ES₄₆  | Trojan| 2013-04-14   | X-Shooter  | 1.335−1.626 | 3 × 880/900/900 | 13.58 ± 1.51/14.04 ± 0.10 | 0.126 ± 0.035/0.179 ± 0.003 | 1/3   |
| 2013-04-16| SpeX      |       | 1.341−1.487  | 3 × 880/900/900 |                         |

Notes. D: effective diameter; p_v: optical albedo. Exp. times for X-Shooter are given for the UVB/ VIS/NIR arms. The asterisk indicates objects for which the signal has been partially extrapolated in the K-band.

References. 1) Grav et al. (2012a), 2) Grav et al. (2011, 2012b), 3) Fernández et al. (2009).
was obtained by dividing each asteroid average spectrum by the average solar star spectrum.

3. Results

The X-Shooter and SpeX reflectance spectra were normalized to unity at 1 μm and are shown in Fig. 1 for Trojans and in Fig. 2 for Hilda asteroids. A comparison of our spectra with those of low-albedo Hilda asteroids and Jovian Trojans (Dahlgren & Lagerkvist 1995; Dahlgren et al. 1997; Fornasier et al. 2004, 2007; Roig et al. 2008; Emery et al. 2011) suggests that both populations have very similar spectral properties (Fig. 3). This spectral similarity is confirmed by placing the objects into the taxonomic system of Bus (1999) for the X-Shooter spectra (using only the visible portion of our spectra to avoid the saturation problem in the K band) and in the DeMeo et al. (2009) system for the NIR (SpeX) spectra. Whereas all Trojans appear to be D-types based on the visible range alone, a comparison of their complete visible and NIR spectra with the average DeMeo et al. (2009) spectra for X-, T- and D-types reveals that their average spectrum is closer to the T-type. The only exception is (24452) 2000 QU167, which has a bluer slope that is consistent with X-types. Hilda asteroids have slightly redder slopes than Trojans, with values in between those of the T- and D-type spectra 1.

A careful inspection of the spectra furthermore reveals that none of them displays any apparent absorption feature within the level of noise of our data set. The absence of absorption bands in the spectra of Trojans was also reported by Emery et al. (2011) for our Trojan sample and for the low-albedo objects measured by Emery et al. (2011). The NIR spectra of these authors were complemented by the visible spectra of Vilas et al. (1993), Xu et al. (1995), Bus & Binzel (2002), and Lazzaro et al. (2004), and NIR spectra have not yet been collected for a statistically significant sample. Specifically, we calculated the spectral slope over the broadest possible wavelength range (0.55–1.8 μm) both for our Trojan sample and for the low-albedo objects measured by Emery et al. (2011). The NIR spectra of these authors were normalized to unity at 1 μm. Second spectrum from multiple observations of the same asteroid are overplotted in red. The grey bands indicate possible saturation in the X-Shooter data (see Sect. 2.1).

1 Note that most authors preferentially use a broader definition of the X- and D-classes instead of using the T-class (e.g., Gil-Hutton & Brunini 2008; DeMeo et al. 2014), which explains the scarcity of T-type classification of asteroids in the literature.
the 99.7% confidence level (this result was derived from the hy-
by SST and WISE, and considering that twelve of them are
Conversely, if the high albedos are valid, we find that among
that there are no interlopers among Trojans and Hilda asteroids.
measurement errors, both our study and the WISE survey indicate
migration models. If the high albedos result from statistical mea-
Jupiter Trojan and Hilda populations (i.e., inner solar system
may shed light on the nature of this putative bright material.

Fornasier et al. (2004), and Fornasier et al. (2007). Figure 4
shows that our spectra fall within the range of the blue Trojans,
although they are on average redder. Note that they are not suf-
iciently red to fill the gap between the blue and the red Trojans
results that confirm the bimodality reported by Emery et al. (2011),
yet they narrow the gap to some extent. The redder colours of our
sample with respect to the blue Trojans from Emery et al. (2011)
are essentially due to steeper slopes in the UVB/VIS range.

4. Discussion
Our study showed that the observed twelve high-albedo Hilda
asteroids and Jupiter Trojans have the same spectral properties in
the visible and NIR ranges as the low-albedo objects. The lack of
spectral differences in our sample may suggest that the high albe-
dos were incorrectly derived by SST and WISE. This would not be
surprising considering the natural broadening of the Gaussian
error with the increasing number of objects at smaller sizes (for a
more detailed discussion, see Grav et al. 2011, 2012a). The few
high-albedo objects would therefore correspond to the outlier
measurements for which the statistical error pulled towards
higher signal.

Alternatively, if the albedo measurements are valid, we pro-
pose as a first suggestion that they result from a collision-
induced resurfacing process that exposed bright material
at the surface. Because an origin in the primordial transneptu-
nian disk is predicted for these objects (Morbidelli et al. 2005;
Levison et al. 2009), this bright material could include water ice.
However, our spectra do not show any evidence for this material
at the surface of these objects. More studies in the 3 μm region
may shed light on the nature of this putative bright material.

The lack of spectral differences in our sample allows setting
an upper limit on the fraction of potential interlopers within
Jupiter Trojan and Hilda populations (i.e., inner solar system
small bodies such as S-type asteroids) and thus constraints on
migration models. If the high albedos result from statistical mea-
surements errors, both our study and the WISE survey indicate
that there are no interlopers among Trojans and Hilda asteroids.
Conversely, if the high albedos are valid, we find that among
the fifty bright Jupiter Trojans and Hilda asteroids detected by
SST and WISE, and considering that twelve of them are
X-, T- or D-types, at most ~22% of them can be interlopers at
the 99.7% confidence level (this result was derived from the hy-
pergeometric probability distribution). Therefore, at most ~0.4%
of the ~2900 objects surveyed by SST and WISE may be inter-
lopers at the 99.7% confidence level. The paucity or absence of
interlopers among Jupiter Trojans and Hilda asteroids revealed
by our study is consistent with the results of DeMeo & Carry
(2013), who found no evidence of S-types or other unexpected
classes (e.g., A-, V-) among them based on the SDSS survey.

5. Conclusions
We have measured the visible and/or NIR spectral properties for
twelve high-albedo (p_v ≥ 0.15) Hilda asteroids and Jupiter
Trojans that are part of the fifty high-albedo objects detected by
SST and WISE out of a total of 2875 objects surveyed in both
populations. These twelve objects have the same spectral prop-
erties as their low-albedo counterparts, which suggests a simi-
lar origin for low- and high-albedo Hilda asteroids and Jupiter
Trojans. The lack of interlopers in our sample allowed us to
place an upper limit of 0.4% at a confidence level of 99.7% on
the fraction of interlopers (e.g., A-, S-, V-type asteroids) among
these two populations. This result is based on the assumption
that albedos were accurately determined by SST and WISE. If
this were not the case, both Hilda asteroids and Jupiter Trojans
probably comprise no interlopers. Future work should attempt
to determine the cause of the high albedos.

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