Mem. S.A.It. Suppl. Vol. 26, 47

Memorie della
Supplementi

The spin rate distribution of Jupiter Trojans

S. Mottola[1], M. Di Martino[2], and A. Carbognani[3]

[1] Institute of Planetary Research, German Aerospace Center (DLR), Rutherfordstrasse 2, 12489 Berlin, Germany, e-mail: stefano.mottola@dlr.de
[2] INAF - Torino Astronomical Observatory (INAF-OATo), Strada Osservatorio 20, 10025, Pino Torinese, Torino, Italy
[3] Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA), Lignan 39, 11020 Nus, Aosta, Italy

Abstract. Jupiter Trojans represent a population of asteroids dynamically decoupled from the Main Belt. They show rather uniform spectral characteristics and geometric albedos. The distribution of their rotational properties (spin rates, light curve amplitudes and spin axis orientation) carries information about their origin and about the processes that controlled their evolution. For this reason, comparing the rotational properties of the Trojans with those of Main Belt asteroids (MBAs) can help provide a better understanding of both populations. We recently published the observational results from a uniform and unbiased survey of rotational properties of Jupiter Trojans carried out during the past two decades. This body of observations provide a statistically significant sample which is the basis for our analysis.

Key words. Minor planets, asteroids: Trojans

1. Introduction

Trojan asteroids consist of two numerous groups of bodies that share the heliocentric orbit with Jupiter and librate around the two triangular Lagrangian points L4 and L5 of the Jupiter-Sun system. As of May 21 2013, 5854 Jupiter Trojans have been discovered - 3856 and 1998 for L4 and L5, respectively (numbered and unnumbered). The full list is available on the web page of the Minor Planet Center (MPC).

The orbital mean semi-major axis is 5.20 ± 0.06 AU and their eccentricity is low, with a mean value of 0.074 ± 0.04. The mean orbital inclination is 13° ± 8°, higher than that of the MBAs (7.5° ± 5°). As a consequence, the Trojans are widespread above and below the ecliptic plane. The Trojans surface is dark, with a relatively narrow distribution of the geometric albedo and a mean value ranging somewhere from $p_V = 0.041 \pm 0.002$, from a ground-based radiometric survey of 32 Trojans (Fernandez et al., 2003), to $p_V = 0.07 \pm 0.03$, from Wide-field Infrared Survey Explorer (WISE) observations of over 200 objects (Grav et al., 2011).

The mean density (or bulk density), is an important parameter for understanding the asteroid structure. For Trojans, the bulk density of only known for two objects: 617 Patroclus, with an average density of 0.8 g cm^{-3} (Marchis et al., 2006a), recently updated to 1.08 ± 0.33 g cm^{-3} (Muller et al., 2010), and 624 Hektor with a value of about 2.4 g cm^{-3} (Marchis et al., 2006b). Patroclus' density suggests that at least a good fraction of the Trojans are low-density bodies. Such a low density could be either the result of their structural properties - as a high porosity that would make them underdense with respect to the density of their constituents - or to the presence of low-density materials as ices. The latter scenario would make Jupiter Trojans similar to extinct or dormant comets. To date, however, neither cometary activity, nor spectral signature of ices has been detected on Trojans. (Dotto et al., 2006).

A fundamental reason for the study of Trojan asteroids is that they are dynamically isolated from the Main Belt. The differences in the rotational properties of MBAs and Trojans can therefore contain a record of the different internal structure, formation mechanism and evolution of the two populations. (Binzel & Sauter, 1992). The purpose of this work is a comparative analysis between rotational properties of Trojans and MBAs aimed at obtaining information on the physical nature and the origin of the first population.

2. The samples

Our Trojan sample was constructed using rotation period data from (Mottola et al., 2011) and from the Asteroid Light Curve Data Base (in short, ALCDB) (Warner et al., 2009). In order to obtain a uniform sample, we only considered medium-to large-sized Trojans (size range 40-180 km). Known binary objects were excluded, as their spin rate is driven by their orbital evolution. This selection results in a total of 117 objects for the Trojan sample.

The control sample was compiled from ALCDB by selecting C- and S-type asteroids in the same size range. M-type asteroids were excluded because they are known to have on average a faster spin rate. Binary objects and members of established dynamical families were also excluded. The control sample is comprised of 295 objects.

For estimating the degree of completeness of the sample we took all Trojans, with at least 1 observed opposition, from the list on the MPC web site, marked the asteroids with a known period and computed the effective diameter with the H values given in the same list and using the Trojan average geometric albedo

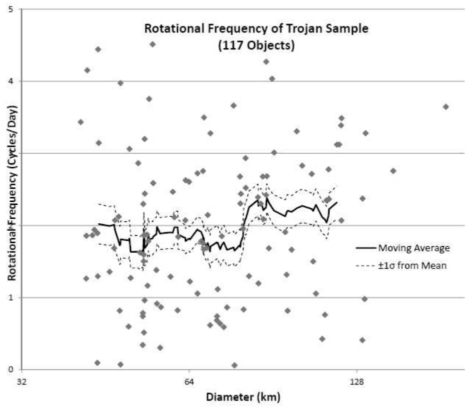

Fig. 1. The spin-size distribution of the Jupiter Trojans.

from WISE. In this way we could easily estimate the degree of completeness at a given limit diameter, by simply counting the bodies which have a well established period, and ratioing to the total number of objects down to that limit size. The result of this completeness estimate is shown in Table 1. As we can see, the sample for the known asteroids is complete down to a diameter of 60 km. The present study considers objects in the diameter range from 40–180 km, for which the degree of completeness - 79 % - is still very good.

3. Spin-size distribution

The scatter plot in Fig. 1 shows the distribution of the rotational frequency versus object size for the Trojan sample. A moving average with a size of 21 objects is used to smooth the data, and is represented as a solid line. The dashed lines correspond to $\pm 1\sigma$ around the mean.

The spin rate distribution exhibits a step-function behavior around a diameter of about 80 km. The difference in rotation rate between the objects smaller and larger than 80 km, however, is detected at a level of about 2σ, and has therefore limited statistical significance.

4. Comparison with MBAs

The histogram on Fig. 2 shows the binned distributions of the rotational frequency of the

Table 1. Completeness of the Trojan sample. The D_{eff} column represents the lower bound of the effective diameter. The second column shows the total number of asteroids with diameter equal or larger than D_{eff}. The third column shows the corresponding number of Trojans with known period, while the last column shows the completeness estimate.

D_{eff} (km)	Trojans from MPC list	Trojans with known period	Completeness (%)
100	10	10	100
70	36	36	100
60	59	59	100
55	73	71	97
50	95	88	93
45	123	106	86
40	151	119	79
35	201	125	62
30	283	132	47

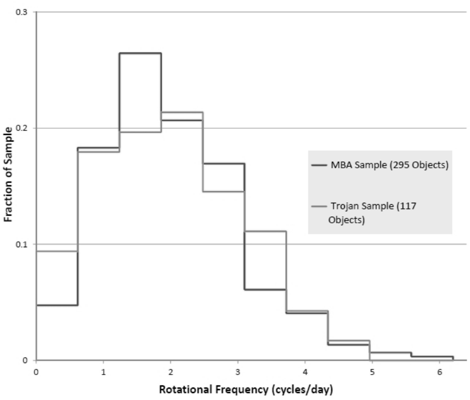

Fig. 2. Comparison of the rotational frequency Trojan – MBAs

Trojan and MB samples in the 40-180 km size range. The two distributions appear different, with the Trojan sample having an excess of slow rotators and a flatter maximum. A Kuiper nonparametric statistical test rejects the null hypothesis that the two samples belong to the same population at the 5% significance level.

5. Maxwellian distribution

It has been shown that the distribution of normalized spin rates of larger MB asteroids (> 40 km) follows a 3-dimensional Maxwell distribution (Pravec et al., 2008). This is the configuration that would be expected if the orientation of the spin vectors is isotropic in space, and each component of the angular velocity follows a Gaussian distribution, as it is expected in the case of a relaxed population under the effect of random collisions (Harris & Burns, 1979). On the contrary, smaller MB asteroids (3 km $< D <$ 15 km) strongly depart from a Maxwellian behavior, which has been interpreted as due to the YORP effect (Pravec et al., 2008).

In Fig. 3 we can see a dichotomy in the distribution of the cumulative rotation frequencies of the Trojans. For values higher than about 2 rot day^{-1}, the distribution tends to be close to the Maxwellian curve, while for lower values it tends to be closer to a uniform distribution. A Kuiper statistical test shows that the rotational frequency distribution of our sample is not compatible with a 3-dimensional Maxwell distribution, neither in its absolute form, nor in its normalized form, at the 5% significance level.

6. Possible mechanism

We identify three possible mechanisms to explain the difference of the ensemble rotational properties of the Trojans and MB asteroids.

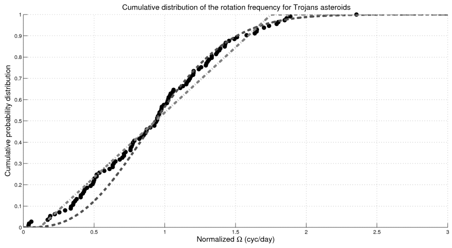

Fig. 3. Comparison among the cumulative Maxwellian distribution of the rotation frequency (dashed line), the uniform distribution (point-dash line), and the observed one (black points), for Trojan asteroids.

6.1. Collisional evolution

Collisions represent a most important mechanism that drives the rotation characteristics of an asteroidal population. The degree of collisional evolution of a population depends on the number density of the objects, on their intrinsic collision probability and on the mutual impact velocities. The mean collision velocity in the Trojan clouds is about 5 km s^{-1}, similar to that in the Main Belt, see (Dell'Oro et al., 2001) and (Pravec et al., 2008). This similarity is due to the lower Keplerian velocities at the heliocentric distance of the Trojan clouds being compensated by the higher average orbital inclinations of the Trojans. The number of objects larger than 2 km in each Trojan cloud is roughly half of the number of MBAs in the same size range (Nakamura & Yoshida, 2008). On the other hand, the intrinsic collision probability for Trojans is about twice that of the MBAs (Dell'Oro et al., 2001), which compensates for the lower number of interacting bodies.

Since the Trojans are dynamically stable over a long period of time, it is reasonable to expect that they also experienced a similarly intense collisional evolution as the MBAs. Therefore, a different collisional evolution does not appear to be a viable candidate for explaining the observed differences in the distributions of the spin rates.

6.2. YORP effect

The YORP effect is a non-gravitational force resulting from thermal photon re-emission which, due to asymmetries in the body's surface, induces a torque that can change the spin of the object. This effect, however, is very small for large asteroids. Following (Rubincam, 2000), we estimate that a 40-km Trojan with a conservative density of 1 g/cm^3 and a shape asymmetry as that of (243) Ida would need a time longer than the age of the solar system to significantly change its spin. Larger objects would need a longer time, proportional to D^2. Therefore the YORP effect does not seem capable to justify the observed difference in the rotational properties between Trojan and MB asteroids.

6.3. Cometary outgassing

This scenario postulates that the Trojan asteroids resemble dormant or depleted cometary nuclei. In this picture, localized subsurface ice reservoirs, or pockets, are sporadically exposed by impacts. As a result, sublimation of the ice occurs, which results in the formation of gas jets. The assumption that the pockets are localized in a particular region of the asteroid results in a net effect which builds up with time. Even if the lifetime of a particular jet is short-lived, a particular pocket can be repeatedly activated by subsequent impacts.

In fact, it is not sufficient to have a release of gas triggered from the impacts, as suggested for the activation of Main Belt Comets, to have a modified rotation frequency distribution, because these processes do not guarantee that the torque has always the same direction for a long time period. This condition can be achieved by assuming that the areas that can be activated are well localized and therefore not all the impacts give rise to an emission of gases. Superimposed to the weak gas emission there will be the normal collision events that tend to makes the frequency distribution a Maxwellian. The concurrent action of these two physical processes can potentially explain the frequency distribution of the Trojans.

6.3.1. Monte Carlo outgassing model

In order to qualitatively verify the effects of regional outgassing episodes on the spin distribution of an asteroidal population, we have adopted a Monte Carlo approach. An original population of 10^6 synthetic objects was generated, which follows the biased size distribution of the Trojan sample used in our analysis.

For this purpose, the cumulative size distribution of our sample has been approximated with an exponential function of the form $N(\geq D) = ae^{-D/d}$, with $a = 546$ and $d = 30$ km. The original spin rate of each object has been randomly drawn from a Maxwell distribution with a sigma corresponding to the best-fit Maxwellian to the data.

In order to model the spin change introduced by this effect, we use the formalism introduced by (Jewitt, 1997) to describe the angular velocity change of a cometary nucleus due to outgassing. In this formalism, the fractional change in the spin angular velocity due to asymmetric outgassing is expressed as:

$$\frac{\Delta\omega}{\omega} = k_T \left(\frac{\Delta M}{M}\right)\left(\frac{V_{th}}{V_{eq}}\right) \tag{1}$$

where $\Delta M/M$ is the fractional change in mass, V_{th} is the outgassing velocity, V_{eq} is the tangential velocity at the equator. The dimensionless constant k_T is a measure of the effective moment arm of the outgassing, with $k_T = 0$ for perfectly radial outgassing and $k_T = 1$ for tangential emission.

By assuming that the mass ΔM lost in the time Δt is proportional to the area of the active spot and by considering that $V_{eq} = \omega r_n$, we can rewrite the former equation as:

$$\Delta\omega = ck_T \left(\frac{\Delta t}{{r_n}^2}\right) \tag{2}$$

where r_n is the nucleus radius and c is an appropriate constant. We have used this equation in our Monte Carlo simulation to generate the change in rotational frequency for each synthetic object for different values of the constant c over the period $\Delta t = 4.5$ Gyr. The value of the effective moment arm k_T was drawn from a uniform random distribution in the range (-1,1), to account for all possible jet emission geometries. With this choice, a negative moment arm would reduce the spin rate of the object, while a positive one would increase it. As a result, some of the objects invert their sense of rotation during the simulation. In the presentation of the results, however, we only plot the absolute value of the rotational frequency, as this represents the observable quantity.

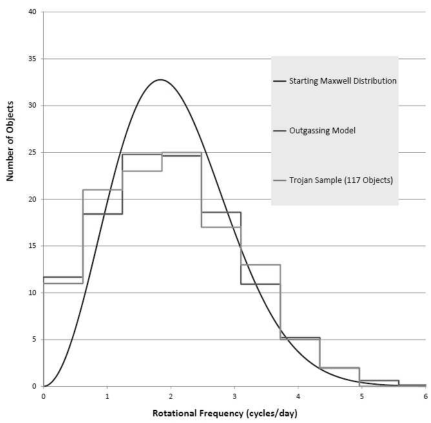

Fig. 4. The starting distribution of the spins (continuous curve) compared with the histogram of the modeled population at the end of the simulation and with the observed population.

7. Discussion

The graph on Fig. 4 shows the starting distribution of the spins (continuous curve) and the histogram of the modeled population at the end of the simulation.

The observed distribution of Trojans is also shown. We see that the synthetic population reproduces the characteristic behavior of the observed data: the flatter maximum and the excess of slow rotators.

The amount of outgassing needed to produce the best-fit c value would require that about 10% of the asteroid surface contributes to outgassing.

8. Conclusions

We have analyzed the distribution of the spin rate of Trojan asteroids and found that it significantly deviates from a 3-dimensional Maxwellian distribution - the configuration that would be expected for a collisionally – relaxed population. Through Monte Carlo modeling we have shown that the observed distribution is compatible with an initially relaxed population, subjected to a randomly oriented torque as the one that can be expected from cometary outgassing.

This finding supports the picture of the Trojans being dormant cometary nuclei that experience low-level and/or sporadic activity over long periods of time. This scenario is also reinforced by recent findings as the discovery of a bright spot on (4709) Ennomos which might be the result of recent activity(Fernandez et al., 2003).

The presence of cometary activity at Jupiter heliocentric distances is physically possible. In addition to water ice, which sublimation is significant only below 3 AU, volatiles as carbon monoxide and carbon dioxide are able to sublimate at temperatures lower than water ice. Carbon dioxide ice sublimates up to to about 10 AU, while carbon monoxide up to 25 AU, both with a rate comparable to that of the water ice at 3 AU (Sekanina, 1992).

References

Binzel, R.P., & Sauter, L.M. 1992, Icarus, 222, 238
Dell'Oro, A., et al. 2001, A& A, 336, 1053
Dotto, E., et al. 2006, Icarus, 183, 420
Fernandez, Y.R., et al. 2003, AJ, 126, 1536
Grav, T., et al. 2011, AJ, 742, 40
Harris, A., & Burns, J.A. 1979, Icarus, 40, 115
Jewitt, D.C. 1997, Earth, Moon and Planets, 79, 35
Marchis, F., et al. 2006, Nature, 439, 565
Marchis, F., et al. 2006, IAU Circular 8732
Marzari, F., et al. 1997, Icarus, 125, 39
Mottola, S., et al. 2011, AJ, 141, 170
Muller, M., et al. 2010, Icarus, 205, 505
Nakamura, T., & Yoshida, F. 2008, PASJ, 60, 293
Pravec, P., et al. 2008, Icarus, 197, 497
Rubincam, D.P., 2000, Icarus, 148, 2
Sekanina, Z. 1992, in Asteroids, Comets, Meteors 1991, Harris, A.W. & Bowell, E. eds. (Lunar and Planetary Institute, Houston, TX), 545
Warner, B., et al. 2009, Icarus, 202, 134