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Opposition effect of Trojan asteroids

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ABSTRACT

CCD-photometry of three Jupiter Trojan asteroids were carried out to study their opposition effect. We obtained well-sampled magnitude–phase curves for (588) Achilles, (884) Priamus, and (1143) Odysseus in the maximal attainable phase angle range down to 0.1–0.2°. The magnitude–phase relations have a linear behavior in all observed range of phase angles and do not show any non-linear opposition brightening. We have not found any confident differences between phase slopes measured in B, V and R bands. The values of the measured phase slopes of Trojans are different from available data for Centaurs. They are within the range of phase slopes measured for some low-albedo main belt asteroids, also exhibit a linear behavior down to small phase angles. An absence of non-linear opposition brightening puts constraints on the surface properties of the studied objects, assuming very dark surfaces where single scattering plays dominating role.

We also determined the rotation periods, amplitudes, the values of color indexes B–V and V–R, and the absolute magnitudes of these asteroids.

1. Introduction

The majority of atmosphereless celestial bodies show the brightness opposition effect (OE). For asteroids, the opposition effect was first discovered for (20) Massalia as pronounced nonlinear increase in brightness close to opposition (Gehrels, 1956). At present magnitude–phase relations with good phase angle coverage and good accuracy were measured for less than 100 asteroids. All good-quality phase curves show a linear behavior in the phase angle range 5–25° with a slope correlating with asteroid albedo (e.g., Belskaya and Shevchenko, 2000). The phase slope increases when surface albedo decreases assuming that shadowing (both mutual shadowing among particles and shadowing due to surface roughness) is the main mechanism responsible for the phase angle behavior in this phase range (e.g., Muinonen et al., 2002). At smaller phase angles (<5°) a nonlinear increase of 0.1–0.4 mag is typically observed. An opposition surge is usually explained by the coherent backscattering enhancement which is more effective for high albedo surfaces (e.g., Muinonen et al., 2002).

The OE amplitudes defined as an increase in magnitude at close to zero phase angle relative to the extrapolation of the linear part were found to be smallest for low albedo asteroids (Belskaya and Shevchenko, 2000). Moreover, a few low-albedo asteroids had not revealed a nonlinear increase in brightness (Harris and Young, 1989; Harris et al., 1992; Piironen et al., 1994; Shevchenko et al., 1996, 2008). French (1987) pointed out a possible absence of the opposition surge for the Trojan Asteroid (1173) Anchises. These asteroids belong mainly to the P-type spectral class, which are believed to contain the most primitive objects in the asteroid belt.

Initial purpose of our new observations was to check whether opposition effect is inherent for a D-type asteroid. For observations we chose the Trojan Asteroid (588) Achilles and initiated a wide observational program joined efforts of several observatories to obtain detailed magnitude–phase dependence with maximal possible phase angle coverage. Preliminary results of these observations showing an absence of opposition surge down to phase angle of 0.1° were presented at 40th Lunar and Planetary Science Conference (Shevchenko et al., 2009). Independently, phase curve observations of nine Trojans, including (588) Achilles, were carried out by Schaefer et al. (2010). They obtained phase dependences not corrected for asteroid rotation with a diversity of phase slopes, including negative values. Based on these data Schaefer et al.

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(2010) have concluded that surface properties of Trojans are significantly different from main-belt asteroids, and thus strongly support the idea that Trojans were captured from the outer Solar System (see Schaefer et al., 2010).

In this paper we present photometric observations of three Trojans, namely (588) Achilles, (884) Priamus, and (1143) Odysseus, which allows us to obtain high quality phase curves of these objects and show their similarity to low albedo asteroids.

2. Observations

Our CCD-observations of Jupiter Trojan asteroids were carried out in 2007, 2008 and 2010. To decrease an influence of weather conditions and to obtain comprehensive data on the asteroid magnitude–phase dependence we performed coordinated observations from four observatories, namely Kharkiv Observatory (KhO) with the 70-cm reflector, Simeiz Observatory (SO) with the 1-m reflector, Rozhen Observatory (RO) with the 2-m reflector, and Maidanak Observatory (MO) with the 1.5-m reflector. The method of CCD observations and reduction is described by Krugly et al. (2002). The brightness measurements of asteroids and comparison stars on CCD-images were done using the aperture photometry package (ASTPHOT) developed at DLR by S. Mottola (Mottola et al., 1995). The absolute calibrations of the magnitudes were performed with standard star sequences from Landolt (1992) and Skiff (2007). We used the same set of the comparison and standard stars in the observations at different observing sites to avoid any possible systematic errors. The accuracy of the resultant absolute photometry is within 0.01–0.03 mag.

We devoted special attention to take into account the influence of rotational lightcurves on magnitude–phase relations. Distinguishing between rotational and phase angle effects is particularly important for low-albedo asteroids. The changes in each asteroid's magnitude due to rotation are comparable or even larger than the opposition effect amplitudes, typically <0.25°. Neglecting the rotational effects can produce a large scatter in values of phase slopes, including the appearance of negative values, as seen in Schaefer et al. (2010).

Our observations were planned in such way to obtain full rotational lightcurve coverage and to reduce all measurements to a rotational lightcurve maximum. The mean time of observations, ecliptic coordinates (longitude λ and latitude β) at the epoch 2000.0, distances to the Sun r and to the Earth Δ, phase angle α, magnitudes reduced to the primary rotational lightcurve maximum and their errors are listed in Table 1 for each of the observed asteroids. The observations were carried out mainly in two spectral bands, V and R of the Johnson–Cousins system. Several observations were also performed in B and I bands to define broad-band colors of the asteroid surface. On days where there are no magnitude entries for a particular band, no observations were made in that band.

We present composite rotational lightcurves of each object which were constructed according to the procedures described by Harris and Lupishko (1989) and Magnusson and Lagerkvist (1990). Data from each night, denoted by different symbols in the figures, were shifted along the magnitude axis in order to obtain the best fit. The values of these shifts are displayed in the figures. Our original data are presented as the supplementary material to the on-line version of the present paper. Below we briefly describe the obtained results on each object.

2.1. (588) Achilles

The asteroid is a very dark object that orbits around the Sun in Jupiter Lagrangian point L_4 and was classified as D-type asteroid characterizing by a steep red slope spectrum (Tholen, 1989). Its diameter and albedo were obtained from MSX and IRAS satellite data (Tedesco et al., 2002a,b) and equal to 140.8 km, 0.031, and 135.5 km, 0.033, respectively. The Earth-based observations in the infrared spectral bands with the Keck telescope (Fernandez et al., 2003) pointed out an albedo of 0.038–0.051 and a diameter of 138.6–160.8 km depending on assumed thermal model parameters.

Previous photometric observations of Achilles were performed by Zappalà et al. (1989) and Angeli et al. (1999), however the full lightcurve was not measured. The rotation period was estimated to be near 7 h (Angeli et al., 1999).

Our long-term observations allowed us to determine the unambiguous value of the synodic rotation period of (588) Achilles is equal to 7.306 ± 0.001 h. The composite rotational lightcurves in the R band for the 2007 and 2008 oppositions constructed with this period are presented in Fig. 1a–c. R(0.08) and R(3.99) are magnitudes obtained at angles 0.08° and 3.99°. The maximal lightcurve amplitude is equal to 0.11 mag with about a 0.04 mag difference seen between the primary and secondary maxima. Observations during the 2008 opposition have shown a decrease in the lightcurve amplitude to 0.03 mag and increase in brightness. It gives an indication that in 2008 the asteroid was observed closer to a pole direction as compared to the 2007 opposition. We have not found any differences exceeding observational errors between rotational lightcurves obtained in the V and R bands and between pre- and post-opposition. Mean color indexes for the 2007 opposition are found to be: B–V = 0.70 ± 0.03, V–R = 0.43 ± 0.03, R–I = 0.47 ± 0.04 mag. The mean absolute magnitude H for this asteroid in the 2007 opposition, i.e. corresponding to the mean lightcurve, is equal to 8.47 ± 0.03 mag. This value is different from H = 8.67 that is listed by MPC (www.minorplanetcenter.net).

Our determination of the rotation period and amplitude of Achilles (Shevchenko et al., 2009) is in a good agreement with successive publications on photometry of this asteroid (Schaefer et al., 2010; Stephens, 2010; Mottola et al., 2011). Schaefer et al. (2010) carried out photometric observations in July–September 2007 and obtained magnitude–phase relation for average magnitudes per nights. They were not able to determine the rotation period since the observations were performed for a short runtime during each night. Mottola et al. (2011) performed observations of (588) Achilles for two nights in July 1994 and obtained a rotation period of 7.32 ± 0.02 h with an amplitude 0.31 mag. Stephens (2010) observed this asteroid for three nights in 2009 and found the rotation period 7.312 h. The rotational lightcurve amplitude was equal to 0.11 mag during the 2009 apparition. The variations of rotational lightcurve amplitude seen at different oppositions give constraints on the pole position of Achilles. We estimate the pole longitude to be 175 (or 355) ± 15°, and the pole latitude lies close to the ecliptic plane.

The obtained observational data allowed us to remove the influence of the rotational lightcurve on the magnitude phase angle behavior and to obtain the comprehensive phase curve of (588) Achilles. The phase dependences of brightness in the B, V and R bands are shown in Fig. 2. They cover the phase angle range from 0.08° to 9.7°. One can see that the magnitude linearly increases with phase angle. It can be fit well by a line with the phase coefficients of 0.046 ± 0.003, 0.045 ± 0.001 and 0.043 ± 0.001 mag/deg for the B, V and R bands, respectively. Any evidence of the opposition surge toward small phase angles has not been found down to the phase angle as low as 0.08°.

2.2. (884) Priamus

The asteroid orbits around the Sun in Jupiter Lagrangian point L_5 and is classified as a D-type asteroid by Tholen (1989). The albedo and diameter were estimated by Fernandez et al. (2003) from