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Rotational variation of the linear polarization of the asteroid (3200) Phaethon as evidence for inhomogeneity in its surface properties*

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Asteroid (3200) Phaethon is a Near-Earth Apollo asteroid with an unusual orbit that brings it closer to the Sun than any other known asteroid. Its last close approach to the Earth was in 2017 mid-December and the next one will be on 2026 October. Previous rotationally time-resolved spectroscopy of Phaethon showed that its spectral slope is slightly bluish, in agreement with its B/F taxonomic classification, but at some rotational phases, it changes to slightly reddish. Motivated by this result, we performed time-resolved imaging polarimetry of Phaethon during its recent close approach to the Earth. Phaethon has a spin period of 3.604 h, and we found a variation of the linear polarization with rotation. This seems to be a rare case in which such variation is unambiguously found, also a consequence of its fairly large amplitude. Combining this new information with the brightness and colour variation as well as previously reported results from Arecibo radar observations, we conclude that there is no variation of the mineralogy across the surface of Phaeton. However, the observed change in the linear polarization may be related to differences in the thickness of the surface regolith in different areas or local topographic features.

Key words: polarization – techniques: photometric – techniques: polarimetric – minor planets, asteroids: individual: (3200) Phaethon.

1 INTRODUCTION

Linear polarization of sunlight scattered by asteroid surfaces is routinely measured and shows changes with the phase angle (the Sun–Target–Observer angle). While it is well known that the intensity of scattered sunlight varies with viewing geometry and object shape, only in a few cases a periodic variation of the degree of linear polarization, synchronous with the spin period of the object, is observed. The asteroid Vesta is such a case and it has long been known to be the only asteroid exhibiting such a variation, with the same period as the object's rotation (see Cellino et al. 2016b, and references therein). This variation must be the consequence of some heterogeneity of the asteroid's surface, for example the existence of regions characterized by different albedo, or mineralogy, or regolith properties, or a combination of the above. Some authors have reported the possible detection of a weak polarimetric modulation for a few other objects, including for example (9) Metis, (52) Europa,

* Based on data collected with 2-m RCC telescope at Rozhen National Astronomical Observatory and Omicron (west) telescope of the C2PU facility at the Calern observing station of the Observatoire de la Côte d'Azur and GOTO Telescope operated on the island of La Palma.
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and (1036) Ganymed (Nakayama et al. 2000), but Vesta is the only asteroid for which this phenomenon has been convincingly demonstrated, confirmed at different epochs, and interpreted in terms of local surface properties directly determined by *in situ* measurements by the Dawn space probe (Cellino et al. 2016b).

Asteroid (3200) Phaethon is the parent body of the Geminid meteor shower (Whipple 1983; Fox, Williams & Hughes 1984; Green, Meadows & Davies 1985; Gustafson 1989; Williams & Wu 1993), and the real physical nature of this object (asteroid or comet?) has been a long-debated subject (Chamberlin et al. 1996). It is also an Apollo asteroid (Near-Earth-asteroid with semimajor axis larger than the Earth's $a > 1$ au, but perihelion distances $q < 1.017$ au) with an unusual orbit that brings it closer to the Sun than any other named asteroid ($q \simeq 0.14$ au). Its last close approach to the Earth was in 2017 December (2017 Dec 16 23:00, $\Delta = 0.0689$ au) and the next one is not until 2026 October. Recently, Kinoshita et al. (2017) reported rotationally time-resolved spectroscopy of Phaethon. Their main result is that the slope of the asteroid's spectrum is slightly blue, in agreement with its known B/F-type taxonomy, but at some rotational phases, it changes to slightly red. Those authors' interpretation is that Phaethon has a red spot on its surface. Also, Ito et al. (2018) published polarimetric observations of Phaethon during its last apparition.

Motivated by Kinoshita et al. (2017) developments, we decided to perform time-resolved imaging polarimetry and photometry in different filters and with three different instruments. We want to investigate if there is a surface inhomogeneity and understand, in particular, which effects, including possible variations in composition and/or in size or shape of the surface regolith particles, can be responsible of what is observed.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

A multicolour phase-polarization curve of Phaethon has been obtained during the 2017 December apparition by merging measurements taken with the 2-channel focal reducer (Jockers et al. 2000) attached to the 2-m Ritchey-Chrétien-Coudé telescope at the Bulgarian National Astronomical Observatory – Rozhen and with the Torino Polarimeter (Pernechele et al. 2012) mounted on the Omicron (west) telescope of the C2PU facility at the Calern observing station of the Observatoire de la Côte d'Azur.

All the observations were obtained in the positive polarization branch, where the electric field vector of reflected light from the asteroid preferably oscillates perpendicularly to the scattering plane, with the phase angle ranging from 36° to 116°. For this investigation, we use a subset of this data obtained on the night of 2017 December 15, when we observed the object continuously to cover a full rotational period of 3.604 h (Light Curve Database, Rev. 2018-March; Warner, Harris & Pravec 2009; Hanuš et al. 2016). The observations were obtained simultaneously using polarimetric instruments in Rozhen and Calern observatories in Johnson-Cousins *BVRI* filters. The log of our polarimetric observations is given in Table 1.

In order to compare variability of the polarization with the asteroid's rotation, we carried out photometry simultaneously with the polarimetry observations to obtain a light curve of the asteroid and to see if there is a variation of its colour with rotation as well. For this purpose, we used the Calern telescope with its wide-field camera and the Gravitational-wave Optical Transient Observer (GOTO) at Roque de Los Muchachos observatory on La Palma. The photometric observations from Calern were obtained in SDSS g' and r' filters a few days earlier, on 2017 December 12.

Table 1. The log of the photometric and polarimetric observations of (3200) Phaethon obtained at Rozhen, Calern, and GOTO observatories.

Date	Obs. Type	Filter	Observatory
2017 Dec 12	Photometry	SDSS $g'r'$	Calern
2017 Dec 15	Photometry	Baader *RGB*	GOTO
2017 Dec 15	Polarimetry	*R*	Rozhen
2017 Dec 15	Polarimetry	*BVRI*	Calern

GOTO is a multitelescope facility on La Palma in the Canary Islands whose prime aim is to detect optical counterpart of gravitational wave events. At the time of the observations being reported here, three 0.4 m telescopes were attached to a common mount, each giving a field of view of 2.1 × 2.8 deg and pixel size 1.2 arcsec pixel^{-1}. It is therefore well suited to study fast moving sources such as Phaeton. Using broad-band Baader *LRGB* filters during dark conditions, we typically reach ∼20.5 mag in the *L* band with 5 min exposure time. An overview of GOTO and a detailed description of the telescope control and scheduling system can be found in Dyer et al. (2018). The GOTO observations were made on 2017 December 15 using *RGB* filters.

2.2 Data reduction

Standard reduction steps, including bias subtraction and flat-fielding, were performed for all the images obtained by all the instruments.

2.2.1 Photometry

Photometry was done using aperture photometry with a circular aperture with size 2 × FWHM. Photometry calibration was done using field stars cross-matched with the APASS (Henden et al. 2016) and the Pan-STARRS (Flewelling et al. 2016; Magnier et al. 2016) catalogues, for GOTO and Calern data, respectively. The average atmospheric extinction for both observing sites was used to compute the above-atmosphere instrumental magnitudes. In order to convert the GOTO magnitudes from the *RGB* passbands to SDSS g' and r', colour–colour and magnitude–magnitude relations were constructed and fitted using 84 cross-matched stars in the field.

Baader *B* and *G* filters are relatively narrow (B: 3850–5100 Å, G: 4950–5750 Å) and both of them together cover only the wavelength range of SDSS g'. In addition, Baader *R* filter (R: 5850-6900 Å) overlaps with SDSS r'. Consequently, we can compute the $(g' - r')$ colour in three different ways and the SDSS g' magnitude in two different ways using Baader *B* and *G*.

The following equations were used for the calibration:

$$\begin{aligned}
(g' - r') &= T_{BR}(B - R)_0 + C_{BR} \\
(g' - r') &= T_{GR}(G - R)_0 + C_{GR} \\
(g' - r') &= T_{BG}(B - G)_0 + C_{BG} \\
r' - R_0 &= T_R(g' - r') + ZP_{Rr'} \\
g' - G_0 &= T_G(g' - r') + ZP_{Gg'} \\
g' - B_0 &= T_B(g' - r') + ZP_{Bg'}, \qquad (1)
\end{aligned}$$

and the fitted values of the coefficients are listed in Table 2.

Table 2. The coefficients of the transformation from GOTO *BGR* magnitudes to SDSS g' and r' ones – zero-points and slope parameters as defined in equation (1).

$T_{BR} = 0.769 \pm 0.016$	$C_{BR} = 0.313 \pm 0.006$
$T_{GR} = 1.344 \pm 0.031$	$C_{GR} = 0.398 \pm 0.005$
$T_{BG} = 1.327 \pm 0.030$	$C_{BG} = 0.267 \pm 0.007$
$T_R = 0.028 \pm 0.022$	$ZP_{Rr'} = 21.469 \pm 0.012$
$T_G = 0.451 \pm 0.021$	$ZP_{Gg'} = 21.673 \pm 0.012$
$T_B = -0.173 \pm 0.026$	$ZP_{Bg'} = 21.824 \pm 0.014$

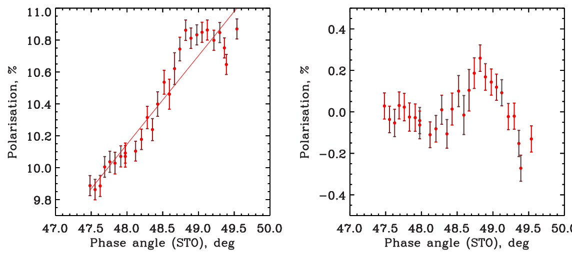

Figure 1. The phase angle (Sun–Target–Observer) dependence on the polarization is presented in the left-hand panel of the figure. The points represent the SDSS r' filter measurement from Rozhen with 1σ error bars. The solid line is the linear least-squares fit to the data, which is the behaviour we expect for this range of phase angles. The right-hand panel represents the polarization residuals after subtracting the best-fitting curve from the data.

2.2.2 Polarimetry

The flux of the object at each polarized beam was calculated using a growth-curve method but instead of following the growth of the total intensity with aperture size, we follow the stokes parameters $X/I = (S_{\parallel} - S_{\perp})/(S_{\parallel} + S_{\perp})$. This method usually gives the saturation at smaller aperture, which means that we introduce less noise. The polarization then was computed applying the so-called 'beam-swapping technique' (Bagnulo et al. 2009). The results were corrected for the instrumental polarization using unpolarized standard stars observed during the same night.

As the asteroid passed by the Earth at a very small distance, the phase angle changed significantly during the observations, so the dependence of the polarization and brightness on it during the night was stronger than on the rotation phase (see left-hand panel of Fig. 1). The values of linear polarization we obtained are among the highest ever observed for a low-albedo near-Earth asteroid. The interval of phase angle was not sufficiently covered to derive a firm determination of the $P_{\max}$ parameter, but this appears to occur at a phase angle around 130°. For more details, see Devogèle et al. (2018). At the values of phase angle used for this investigation, the linear polarization is expected to show a smooth, linear variation with increasing phase, but our measured values are not distributed as smooth as expected. A modulation synchronous with the asteroid rotation is superimposed on the linear change of linear polarization. Therefore, in order to isolate the polarization–rotation variability, a linear least-squares fit was made to the polarization–phase angle variation and removed from the data. The residuals between our data and fit are presented in the right-hand panel of Fig. 1. Then, the rotational phase for each epoch of observations was calculated, and the rotational variation of the polarization was constructed (see Fig. 2).

3 RESULTS

Fig. 2 presents the results of our observations of Phaethon. The light curves obtained from C2PU and GOTO are presented with red and purple squares, respectively, and are mutually consistent within the 1σ uncertainties. The slight difference between C2PU and GOTO for rotational phases above 0.6 most probably is caused by rapidly changing geometry for these observations. The aspect angle (the angle between the asteroid spin vector and the line of sight to the observer) is changing by 10 deg, computed using the axis orientation from the latest shape model by Hanuš et al. (2016). The measured colour of the object, obtained with the same instruments, apparently shows no variation with rotation. On the other hand, the residual linear polarization, after removing the phase angle dependence trend, changes with the asteroid's rotation. It is presented in Fig. 2 with the open red circles for Rozhen and colour-coded filled circles for each different filter for Calern. The observed trend of polarization is clearly not due to measurement noise as the amplitude of the variability is >5 times of the measurement uncertainties. It is mostly anticorrelated with the photometric light curve (see Fig. 2), the maximum of polarization being reached at the minimum of the light curve, and vice versa, except for the interval of rotation phase between about 0.65 and 0.80, where the correlation is positive.

4 DISCUSSION

Information about asteroid shapes can be obtained by classical photometric observations, under the assumption that the measured brightness variation is due to a periodically changing cross-section. One single light curve can provide a determination of the spin period and some crude indication about the overall shape (a large light curve amplitude being a consequence of an elongated shape seen in favourable observing conditions). An accurate and reliable determination of the shape usually requires light curves obtained at different apparitions, corresponding to different aspect angles. Provided a sufficient number of light curves is available, this also allows to determine the orientation of the spin axis. However, it is generally difficult to identify from photometric light curves alone definitive evidence of a possible surface albedo heterogeneity due to variations in surface composition and/or regolith properties. This is the reason why polarimetry is so important. The polarization state of the scattered surface, in fact, strongly depends on surface albedo and regolith structure (Cellino et al. 2016a).

The anticorrelation between brightness and polarization of Phaethon visible in Fig. 2 is most simply interpreted by Umov's law (Umov 1905), which states that the degree of polarization is proportional to the reciprocal value of the albedo, in other words *high polarization→low albedo→low brightness*. For example Cellino et al. (2016b), comparing linear polarization measurements of Vesta with albedo maps from *Dawn* space mission, showed that the maximum of linear polarization occurs when the regions of lowest albedo are facing the observer. As a consequence, if the same phenomenon was at work in the case of Phaethon, we would be led to conclude that we find evidence of albedo variations across the surface of this asteroid. On the other hand, the fact that we did not see any variation of the colour of the object with rotation suggests that there might be no variation of the mineralogy as a function of longitude. Ito et al. (2018) discuss that high polarization, for a fixed albedo, should be caused by large particles (d ∼ 360µm). This is also supported by the blue slope of its spectrum, which usually is interpreted also in terms of larger grain sizes (Clark et al. 2010).

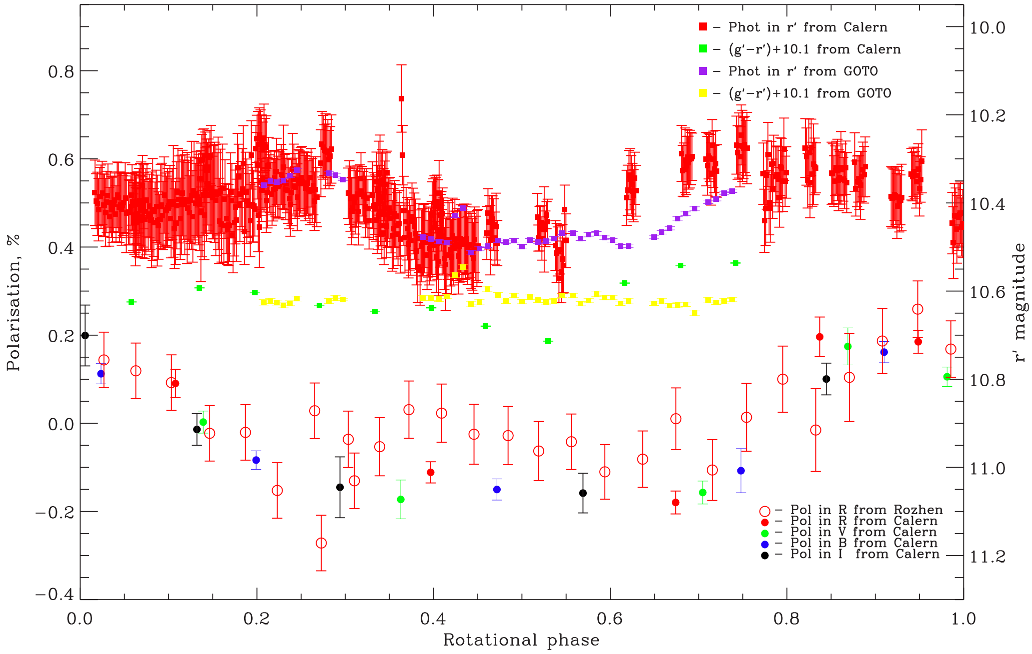

Figure 2. Comparison of the (3200) Phaethon SDSS $r^{'}$ light curve (from Calern in red and GOTO in purple) and $(g^{'} - r^{'})$ (in green for Calern and in yellow for GOTO) and the variation of the degree of linear polarization obtained from Rozhen and Calern in different filters (see text and labels for details). All error bars represent 1σ uncertainties.

A possible solution to this apparent discrepancy may be found by considering another result by Cellino et al. (2016b) for Vesta, namely that the thickness of surface regolith can play a role in determining the fraction of linear polarization of the scattered sunlight. In particular, these authors suggest that high-elevation areas on Vesta, expected to have a thinner regolith due to a higher gradient of topographic slope favouring the accumulation of regolith particles at lower altitudes, are associated with higher linear polarization. This effect seems to be so strong as to compete with the anticorrelation between polarization and albedo, leading to local violation of Umov's law (Cellino et al. 2016b). This phenomenon, qualitatively detected so far only for Vesta, seems to be at work also for Phaethon, if we look at the positive correlation between polarization and brightness at rotational phases between 0.65 and 0.80 (see Fig. 2). In contrast to Vesta, in the case of Phaethon we have no information about local topography, and we cannot make a generic interpretation, in terms of the existence of a local region on Phaethon's surface characterized by different regolith properties. Recent Arecibo radar observations of Phaethon show a concavity, or depression, at least several 100 m in extent, near the equator and a radar dark feature near one of the poles (Taylor et al. 2018). Those features might be responsible for polarization variation caused by the processes explained above.

5 CONCLUSIONS

There is a clear variation of the degree of linear polarization with rotational phase of asteroid (3200) Phaethon, and it is mostly anticorrelated with its brightness variation except in a small interval of rotation phase. On the other hand, there is no significant variation of the $(g^{'} - r^{'})$ colour with the rotation.

This anticorrelation can be explained by Umov's law. We found similarities with polarization behaviour of asteroid Vesta, which leads us to interpret our observations in a similar way, i.e. some form of heterogeneity of the asteroid's surface, such as the existence of regions characterized by different albedo, different regolith properties, or both. A less likely interpretation, not supported by our colour measurements, is a variation of the mineralogy. We also observe that Umov's law is violated for a narrow range of rotational phase and, similar to the case of Vesta, can be explained by either a small region with a steep topographic slope on the surface with a very thin regolith layer or a spot with different surface composition. Arecibo radar observations of Phaethon show a dark spot on its surface and a concavity region near the equator.

The results of our analysis of (3200) Phaethon, together with the results recently published by Ito et al. (2018) from its previous apparition and previous results for Vesta (Cellino et al. 2016b) suggest that polarimetry is diagnostic not only of surface albedo but also of other properties of the surface regolith. This is not, strictly speaking, a new discovery since it was already known that some polarimetric properties (primarily the $P_{\min} - \alpha_{\mathrm{inv}}$ relation, where $P_{\min}$ is the extreme value of polarization in the negative branch of the phase–polarization curve and α_{inv} is the inversion phase angle, where the polarization is zero and the phase–polarization curve goes from negative to positive branch and vice versa, see Cellino et al. 2016a for a recent reassessment of the subject) are diagnostic of properties such as the regolith particle size. We can conclude therefore that we are at the beginning of a new era in asteroid polarimetry. Effects that were previously underestimated are now more routinely found to play an important role in asteroid polarimetric measurements. This is largely a result of the availability of new and better detectors and of a renewed interest in this field of investigation by several research teams.

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