Inversion Angle of Phase-polarization Curve of Near-Earth Asteroid (3200) Phaethon

Yoshiharu Shinnaka1,2, Toshihiro Kasuga2,3, Reiko Furusho2,4, Daniel C. Boice5, Tsuyoshi Terai6, Hirotomo Noda7, Noriyuki Namiki7, and Jun-ichi Watanabe8

1 Laboratory of Infrared High-resolution Spectroscopy (LIH), Koyama Astronomical Observatory, Kyoto Sangyo University, Motoyama, Kamigamo, Kita-ku, Kyoto 603-8555, Japan; yoshiharu.shinnaka@cc.kyoto-su.ac.jp, yoshiharu.shinnaka@nao.ac.jp
2 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
3 Department of Physics, Kyoto Sangyo University, Motoyama, Kamigamo, Kita-ku, Kyoto 603-8555, Japan
4 Tsu University, 3-8-1 Tahara, Tsu, Yamanashi 400-0052, Japan
5 Scientific Studies and Consulting, 171 Harmon Drive, San Antonio, TX 78209, USA
6 Subaru Telescope, National Astronomical Observatory of Japan, 650 North A’ohoku Place, Hilo, HI 96720, USA
7 RISE project, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
8 Public Relation Center, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

Abstract

As a function of the solar phase angle, $\alpha$, the linear polarization degree (referred to the scattering plane, $P_r$) of solar system objects is a good diagnostic for understanding the scattering properties of their surface materials. We report the $P_r$ of Phaethon over a wide range of $\alpha$ from 19°1 to 114°3. The derived phase-polarization curve shows that the maximum of $P_r$, $P_{\text{max}}$, is $>42.4\%$ at $\alpha > 114°3$, a value significantly larger than those of the moderate albedo asteroids ($P_{\text{max}} \sim 9\%$). The phase-polarization curve classifies Phaethon as $B$-type as well as $M$- and $K$-type asteroids, in the polarimetric taxonomy, being compatible with the spectral property. We compute the geometric albedo, $p_g$, of 0.14 ± 0.04 independently by using an empirical slope-albedo relation, and the derived $p_g$ is consistent with previous results determined from mid-infrared spectra and thermophysical modeling. We find no periodic variation of $P_r$ in our polarimetric data in the range from 0 up to 7.208 hr (e.g., less than twice the rotational period). We also find significant differences between our $P_r$ during the 2017 approach toward Earth and that in 2016, implying that Phaethon has a region with different properties for light scattering near its rotational pole.

Key words: minor planets, asteroids: general – minor planets, asteroids: individual ((3200) Phaethon) – techniques: polarimetric

Supporting material: machine-readable table

1. Introduction

Asteroid (3200) Phaethon is an Apollo-type near-Earth asteroid with a diameter of 5.1 ± 0.2 km and a rotational period of 3.603958 ± 0.0002 hr (Hanuš et al. 2016). It has a large orbital inclination (22°2) and small perihelion distance (0.14 au). The surface of Phaethon has a geometric albedo, $p_g$, of 0.122 ± 0.008 using a thermophysical model to its mid-infrared spectra (Hanuš et al. 2016). Phaethon is thought to be a collisional family member of asteroid (2) Pallas (Lemaître & Morbidelli 1994). Lemaître & Morbidelli (1994) found that the typical $p_c$ of the members of the Pallas Collisional Family (PCF) is larger than that of other $B$-type asteroids. Phaethon is also likely the parent body of the Geminid meteor shower because of their orbital association (Whipple 1983; Williams & Wu 1993; de León et al. 2010). Recently, the small brightening and comet-like tails of Phaethon observed near perihelion in 2009, 2010, and 2012 were found to be caused by small dust grains produced by thermal fracture and/or desiccation cracking of surface materials and released by the solar radiation pressure (Jewitt & Li 2010; Jewitt et al. 2013; Li & Jewitt 2013). Because these current mass-loss events are not sufficient to explain the activity of the Geminids (Li & Jewitt 2013), Phaethon probably released a large amount of dust particles in the past, possibly due to comet-like activity driven by water ice sublimation.

Because of its small perihelion distance, the surface temperature of Phaethon exceeds 1000 K (Ohtsuka et al. 2009; Boice 2017) and receives high solar radiation pressure near perihelion. These effects are expected to cause small grains with radius of <1 mm to be blown off its surface (Jewitt & Li 2010) and thermal metamorphism of surface materials. Various observational, experimental, and theoretical studies suggest that its surface is covered by rocks with coarser grain size and contains hydrated minerals (Licandro et al. 2007; de León et al. 2010; Hanuš et al. 2016). The linear polarization degree referred to the scattering plane, $P_r$ (Zellner & Gradie 1976), as a function of the solar phase angle, $\alpha$ (i.e., Sun-object-observer angle) is a good diagnostic for understanding the scattering properties of surface materials. Here we call this relation the “phase-polarization curve.” The $P_r$ in the large $\alpha$ region is controlled primarily by the properties of individual particles in the medium (Hapke 2012). At the lower phase angle region (at $\alpha < \sim 40°$), the phase-polarization curve has been used for the polarimetric classification for asteroids (Belskaya et al. 2017) and the estimation of $p_c$ by using an empirical slope-albedo relation (Cellino et al. 2015). Recent polarimetric results in the positive polarization branch of Phaethon during the 2016 and 2017 approaches toward Earth suggest that Phaethon has an extremely high $P_r$ compared to other solar system bodies (Ito et al. 2018; Devogèle et al. 2018); however, there was no measurement of $P_r$ of Phaethon around the inversion angle ($\alpha < 30°$).
2. Observations and Data Reduction

The polarimetric survey of Phaethon was performed for 13 consecutive nights from UT 2017 December 9 to 21 using the Polarimetric Imager for Comets (PICO; Ikeda et al. 2007) mounted on the 50 cm Telescope for Public Outreach9 at the Mitaka Campus of the National Astronomical Observatory of Japan. We used the standard Johnson-Cousins R-band filter (its bandpass is 483–799 nm; Bessell 2005) for all observations of Phaethon. Due to favorable weather conditions, we obtained a high-quality data set in the range of solar phase angle from 19°12 through 114°30 (Table 1). The ranges of heliocentric and geocentric distances of Phaethon were 1.13–0.94 au and 0.15–0.07 au, respectively. The elevation of all observations was over 28°. Finally, 3560 frames (890 sequences) of Phaethon were acquired during the survey. We excluded frames where stationary field stars and cosmic-rays overlapped Phaethon as judged by eye, leaving 3248 frames (812 sequences) that were analyzed. Details of PICO with the 50 cm telescope are described in Appendix A.

All of the selected PICO data were reduced using the standard reduction procedure for imaging observations of a point-source object (dark subtraction, flat-fielding, aperture photometry with the APPHOT package) described in Ikeda et al. (2007) with a custom PyRAF script that uses IRAF10 via Python developed by our group. We also applied a moving-circular aperture to photometry of Phaethon with an elongated shape on the images taken under sidereal tracking on 2017 December 17 (developed by Yoshida & Terai 2017). To calibrate the instrumental polarizations and offset in the position angle between the celestial and instrumental coordinates, we also observed unpolarized standard stars, completely polarized light obtained through a Glan–Taylor prism, and strong polarized standard stars. The degree of linear polarization, P, and the position angle, \( \theta \), from normalized Stokes parameters, \( q \equiv Q/I \) and \( u \equiv U/I \), are converted by the following expressions (Tinbergen 1996): 

\[
P = \sqrt{q^2 + u^2} \quad \text{and} \quad \theta = \frac{1}{2} \arctan(u/q).
\]

Details of the polarization calibrations, correction of instrumental polarizations, and error estimations are described in Appendix B and Kawabata et al. (1999).

In general, the degree of linear polarization, \( P \), and position angle, \( \theta \), in the scattering plane (containing the object, the Sun, and Earth at the time of observation) have been used to compare with other solar system objects. \( P \) and \( \theta \) are expressed in \( P = P_{\text{el}} \cos(2\theta_{\text{el}}) \) and \( \theta = \theta_{\text{el}} - (\phi \pm 90°) \), respectively, where \( \phi \) is the position angle of the scattering plane and the sign is chosen to satisfy \( 0° \leq (\phi \pm 90°) \leq 180° \) (Chernova et al. 1993). \( P_{\text{el}} \) and \( \theta_{\text{el}} \) are the linear polarization degree and polarimetric position angle in celestial coordinates, respectively. Position angles in the scattering plane at the mid-time of each sequence were calculated using JPL’s HORIZONS system.11 The resultant weighted mean of \( P \) and \( \theta \) on each date was computed and is summarized in Table 2.

3. Results and Discussion

We report the phase-polarization curve of Phaethon over a wide range of \( \alpha \) from 19°1 through 114°3 and find that \( P \) grows steadily through \( \alpha \) of 114° (Figure 1, Table 2). The expected maximum linear polarization degree, \( P_{\text{max}} \), of Phaethon is \( >42.4% \) (3σ lower limit) and \( \alpha_{\text{max}} \alpha \) at \( P_{\text{max}} \) is located at \( >114° \). This value is consistent with other polarimetric observations of Phaethon (Ito et al. 2018; Devogele et al. 2018). The derived \( P_{\text{max}} \) at \( \alpha_{\text{max}} \) of Phaethon are more than four times larger than those values for the moderate albedo asteroids (e.g., \( P_{\text{max}} < ~9\% \); Lupishko 2014; Ishiguro et al. 2017, at \( \alpha_{\text{max}} \sim 100° \); Geake & Dollfus 1986; Lupishko 2014), implying peculiar surface properties of Phaethon. To explain Phaethon’s large linear polarization degree, Ito et al. (2018) pointed out the interpretations: relatively large grains, high surface porosity, and lower \( P_{\text{r}} \) than the current estimations.

3.1. Polarimetric Classification and Geometric Albedo

To derive an inversion angle, \( \alpha_{\text{inv}} \left[°\right] \), at which \( P_{\text{r}} \) changes its sign, and a polarimetric slope at \( \alpha_{\text{inv}} \ h \left[\% \ deg^{-1}\right] \), we computed the best fit of the phase-polarization curve at

---

Note. UT date is the mid-time of the first and final sequences. \( \phi \) and \( \alpha \) are the angle of the scattering plane and the solar phase angle of the observations, respectively. \( T_{\exp} \) is the exposure time of each frame in seconds and number of sequences. UP, GT, and SP in the column of polarimetric standard stars indicate unpolarized standard stars, fully linearly polarized light from the Glan–Taylor prism, and strong polarized standard stars, respectively, chosen from Serkowski (1974), Schmidt et al. (1992), and Wolff et al. (1996).

| UT Time in 2017 | \( \phi \) (°) | \( \alpha \) (°) | \( T_{\exp} \) (s × sequence) | Polarmetric Standard Stars |
|-----------------|---------------|---------------|-------------------------------|--------------------------|
| Dec 9 12:16:13–17:46:49 | 203.34–200.28 | 19.31–19.21 | 30 × 93 | HD 65583 (UP, GT), HD 204827 (SP) |
| Dec 10 10:56:02–16:57:46 | 189.85–185.70 | 19.12–19.19 | 30 × 94 | HD 65583 (UP, GT), HD 204827 (SP) |
| Dec 11 10:46:27–16:31:51 | 172.50–167.81 | 19.81–20.19 | 30 × 99 | HD 214923 (UP, GT), HD 204827 (SP) |
| Dec 12 12:20:02–16:32:54 | 151.07–147.33 | 22.28–22.92 | 20 × 5 + 30 × 72 | HD 432 (UP, GT), HD 204827 (SP) |
| Dec 13 10:15:17–15:12:28 | 131.90–127.55 | 26.43–27.71 | 30 × 76 | HD 214923 (UP, GT), HD 204827 (SP) |
| Dec 14 11:29:57–15:58:44 | 110.04–107.00 | 34.46–35.95 | 30 × 60 | HD 39587 (UP, GT) |
| Dec 15 09:10:53–11:01:58 | 115.53–112.38 | 43.30–44.56 | 20 × 44 | HD 39587 (UP, GT), HD 19820 (SP) |
| Dec 16 09:00:58–13:17:53 | 80.00–77.93 | 56.68–59.26 | 20 × 72 + 30 × 21 | HD 39587 (UP, GT), HD 19820 (SP) |
| Dec 17 09:23:30–12:34:53 | 70.52–69.66 | 71.50–73.45 | 20 × 41 | HD 39587 (UP), HD 432 (GT), HD 19820 (SP) |
| Dec 18 08:52:14–12:03:59 | 66.01–65.68 | 85.18–86.93 | 30 × 64 | HD 39587 (UP, GT), HD 19820 (SP) |
| Dec 19 08:57:50–11:21:10 | 64.71–64.70 | 97.11–98.22 | 30 × 44 | HD 39587 (UP, GT), HD 19820 (SP) |
| Dec 20 08:37:34–10:28:23 | 65.29–65.39 | 106.54–107.19 | 60 × 20 | HD 39587 (UP, GT), HD 19820 (SP) |
| Dec 21 08:48:10–09:48:26 | 66.83–66.91 | 114.03–113.30 | 120 × 7 | HD 154345 (UP, GT), HD 19820 (SP) |

---

9 https://www.nao.ac.jp/en/access/mitaka/facilities/50cm-telescope.html
10 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

11 https://ssd.jpl.nasa.gov/horizons.cgi
horizontal axes are the degree of linear polarization, $(\alpha, \beta)$, and the systematic error of PICO. 

The Astrophysical Journal Letters, 864:L33 (8pp), 2018 September 10

| UT Time in 2017 | JD—2,458,000 | $r_{\text{H}}$ (au) | $\Delta$ (au) | $\alpha$ (°) | $P_r$ (%) | $\theta$ (°) |
|----------------|--------------|-------------------|---------------|--------------|------------|-------------|
| Dec 12:16:13–17:46:49 | 97.011262–97.249845 | 1.129–1.126 | 0.154–0.151 | 19.31–19.21 | 0.288 ± 0.002 | 3.8 ± 0.2 |
| Dec 12:16:13–17:46:49 | 97.011262–97.249845 | 1.129–1.126 | 0.154–0.151 | 19.31–19.21 | 0.288 ± 0.002 | 3.8 ± 0.2 |
| Dec 10:15:17–15:12:18 | 98.948924–99.188785 | 1.068–1.065 | 0.095–0.092 | 26.43–27.71 | 2.074 ± 0.002 | 88.8 ± 0.1 |
| Dec 12:11:57–15:58:44 | 100.082899–102.165787 | 1.051–1.049 | 0.082–0.081 | 34.46–35.95 | 4.593 ± 0.003 | 88.6 ± 0.1 |
| Dec 15:09:10:53–11:01:58 | 102.885588–102.959699 | 1.037–1.036 | 0.075–0.074 | 43.30–44.56 | 8.242 ± 0.004 | 88.5 ± 0.1 |
| Dec 16:09:08:53–13:17:53 | 103.875671–104.054086 | 1.021–1.018 | 0.070–0.069 | 56.68–59.26 | 15.453 ± 0.004 | 88.6 ± 0.1 |
| Dec 17:29:33–12:34:53 | 104.891319–105.024225 | 1.004–1.002 | 0.069–0.070 | 71.50–73.45 | 23.87 ± 0.02 | 88.3 ± 0.1 |
| Dec 18:08:52:14–12:03:59 | 105.869060–106.002766 | 0.987–0.985 | 0.074–0.075 | 85.18–86.93 | 31.71 ± 0.01 | 88.7 ± 0.1 |
| Dec 19:08:57:50–11:21:10 | 106.873495–106.973032 | 0.970–0.969 | 0.082–0.083 | 97.11–98.22 | 37.90 ± 0.03 | 88.6 ± 0.1 |
| Dec 20:08:37:34–10:28:23 | 107.859421–107.963677 | 0.953–0.952 | 0.093–0.094 | 106.54–107.19 | 40.76 ± 0.17 | 89.4 ± 0.1 |
| Dec 21:08:48:10–09:48:26 | 108.866782–108.908634 | 0.936–0.935 | 0.106–0.107 | 114.03–114.30 | 43.71 ± 0.44 | 88.4 ± 0.3 |

Note. UT date and JD are the mid-time of the start and final sequences. $r_{\text{H}}$ and $\Delta$ are the heliocentric and geocentric distances in au, and $\alpha$ is the solar phase angle in degrees. $P_r$ and $\theta$ are the degree of linear polarization in percentages and polarization position angle in degrees referred to the scattering plane, respectively. The uncertainty in each value of $P_r$ and $\theta$ includes both random errors (all sequences on each date and standard deviation of polarimetric standard stars during the survey) and the systematic error of PICO.

$
\begin{align*}
\alpha &< 90^\circ \\
\text{using the empirical trigonometrical function (Lumme & Muinonen 1993; Penttila et al. 2005)} & \text{by $\chi^2$ minimization with the Marquardt–Levenberg algorithm (Press et al. 1992)} \\
(\text{Figure 2). This trigonometrical function is given by $P(\alpha) = b \sin^2(\alpha) \sin^2(\alpha/2) \sin(\alpha - \alpha_{\text{inv}})$, where $b$, $\alpha_{\text{inv}}$, $c_1$, and $c_2$ are free parameters. The trigonometrical function cannot be applied mathematically to polarimetric data when a phase-polarization curve has $\alpha > 110^\circ$ (Ishiguro et al. 2017), as there is no solution of $dP(\alpha)/d\alpha$ at $\alpha > 110^\circ$ with $c_2 > 0$, in which $c_2 > 0$ is the original definition of this function (Lumme & Muinonen 1993). As a result, we applied the trigonometrical function with $c_2 < 0$ and used only limited polarimetric data at $\alpha < 90^\circ$. The derived best-fit parameters are $b = 21.33 \pm 0.44$, $\alpha_{\text{inv}} = 20.021 \pm 0.007$, $c_1 = 0.402 \pm 0.038$, and $c_2 = -1.57 \pm 0.07$, corresponding to $\alpha_{\text{inv}} = 20.271 \pm 0.007$ and $b = 0.174 \pm 0.053 \text{ deg}^{-1}$. The computed minimum $P_r$, $P_{\text{min}}$, and $\alpha$ at $P_{\text{min}}$ have large errors because there are no observations of $P_r$ at $\text{<19}^\circ$ in the polarimetric data set (Figure 2 and Table 1). The derived $\alpha_{\text{inv}}$ is consistent with that of Phaethon alone (18.8 ± 1.6; Devogèle et al. 2018). We note that these fitting results are not complete in the large $\alpha$ region ($\alpha > 90^\circ$) because of the fitting function.}
\end{align*}$

Figure 1. Phase-polarization curve of Phaethon in the R_c-band. Vertical and horizontal axes are the degree of linear polarization, $P_r$, and the solar phase angle, $\alpha$, respectively. Red circles are the observed $P_r$ of Phaethon at $\alpha$ on each date. The error bars are less than the symbol size, including both random errors (all sequences on each date and the standard deviation of polarization standard stars during the survey) and the systematic error of PICO. Orange crosses (D18) and green plus symbols (I18) are the $P_r$ of Phaethon taken on 2017 December (Devogèle et al. 2018) and during 2016 September–November (Ito et al. 2018), respectively. Black symbols are the $P_r$ of the moderate albedo asteroids (Lupishko 2014; Ishiguro et al. 2017). The horizontal black dotted line shows $P_r = 0\%$. 

The derived $\alpha_{\text{inv}}$ is likely to be a B-type as well as M- and K-type asteroid by comparing our derived $\alpha_{\text{inv}}$ and $h$ to the polarimetric taxonomy (Table 3 of Belskaya et al. 2017). Phaethon was classified as a B-type asteroid by the spectral classification of asteroids (Bus & Binzel 2002; DeMeo et al. 2009). We also confirmed that the phase-polarization curve of Phaethon at $\alpha < 40^\circ$ shows a similar trend to those of B- and F-type main-belt asteroids (Figure 4 of Gil-Hutton & Garcia-Migani 2017). Regarding the polarimetric taxonomy, a behavior of $P_r$ in the high-$\alpha$ region is unknown because mainly main-belt asteroids were used, which are difficult to acquire $P_r$ in the high-$\alpha$ region from the ground-based observatories. Moreover, the derived $\alpha_{\text{inv}}$ is larger than that of Pallas, and the derived $h$ is consistent with Pallas ($\alpha_{\text{inv}} = 18.1^\circ \pm 0.1$ and $h = 0.228\% \pm 0.003 \text{ deg}^{-1}$; Masiero et al. 2012). Belskaya et al. (2017) claimed that asteroids with much smaller $\alpha_{\text{inv}}$ have larger amount of regolith based on a relation between $P_{\text{min}}$ and $\alpha_{\text{inv}}$ for asteroids of variable taxonomy types overlapped with lunar bare rocks and fines reported in Geake & Doolfus (1986). Based on this relation, Phaethon should have smaller grains on its surface compared with Pallas. On the other hand, Delbo et al. (2007) pointed out that much smaller bodies have less regolith or less mature regolith. It is expected that the sizes of the surface materials of Phaethon are larger than those of Pallas because the diameter of Phaethon (∼5 km; Hanuš et al. 2016) is much smaller than that of Pallas (∼500 km; Carry et al. 2010). This inconsistency implies that the $\alpha_{\text{inv}}$ of an asteroid reflects the scattering properties of grains (e.g., complex refractive index) rather than the typical size of particles or rocks on the surface.
Note that the relation between $P_{\text{min}}$ and $\alpha_{\text{tan}}$ for asteroids may not be suitable for Phaethon because the $P_{\text{max}}$ of the materials that were investigated (e.g., Geake & Dollfus 1986; Belskaya et al. 2017) is significantly lower than that of Phaethon.

We estimate the $p_c$ independently by using the empirical slope-albedo relation in the standard $V$-filter given by

$$\log_{10} p_c = C_1 \log_{10} b + C_2,$$

where $b$ is the polarimetric slope at $\alpha_{\text{tan}}$ [% deg$^{-1}$]. $C_1$ and $C_2$ are constants ($C_1 = -0.80 \pm 0.04$ and $C_2 = -1.47 \pm 0.04$ when $p_c > 0.08$; Cellino et al. 2015). We apply this empirical relation to our polarimetric results in the $R_C$-band because no clear difference between $P_r$ in the $V$- and $R_C$-bands of Phaethon have been reported (Devogéle et al. 2018). The derived $p_c$ is equal to 0.14 $\pm$ 0.04 using our derived value of $h$ (0.174 $\pm$ 0.053 % deg$^{-1}$), corresponding to a moderate value among asteroids (Masiero et al. 2018). This value is consistent with a previous measurement of Phaethon ($p_c = 0.122 \pm 0.008$; Hanuš et al. 2016), and may be high compared with the typical cometary values ($\sim$0.04; Rickman 2017) claimed in Devogéle et al. (2018). This value is also consistent with $B$-type as well as $M$- and $K$-type asteroids (Belskaya et al. 2017). $P_r$ in the low-$\alpha$ region ($\alpha < 15^\circ$) is required to derive other polarimetric parameters (e.g., $P_{\text{min}}$ and $\alpha_{\text{tan}}$) and classify Phaethon in the polarimetric taxonomy.

In order to understand the scattering properties of Phaethon’s surface more deeply via reproducing its phase-polarization curve, we require the complex refractive index as well as the size distribution of dominant surface materials. Mukai et al. (1987) demonstrated the importance of the negative as well as the positive branches of $P_r$ in order to derive a typical complex refractive index of grain materials for comet 1P/Halley. Their result was based on the numerical calculations applying Mie theory and assuming a grain-size distribution obtained by the Vega mission (Mazets et al. 1986). To derive an absorption coefficient of the complex refractive index, the measurement of a circular polarization degree is theoretically useful (Hapke 2012). We also strongly encourage laboratory experiments to derive phase-polarization curves for various materials expected to exist on the surfaces of asteroids.

3.2. No Confirmation of Periodic Change of $P_r$

Degewij et al. (1979) reported a variation in polarization degree in the $B$-band correlated with the lightcurve for (4) Vesta. The polarization variation was interpreted as albedo inhomogeneities of its surface materials (Degewij et al. 1979). Time-resolved polarimetry is an effective method for investigating albedo heterogeneity on asteroids. Panels (a)–(m) of Figure 3 show time-domain $P_r$ of Phaethon during our polarimetric survey. We employed the phase dispersion minimization (PDM) method (Stellingwerf 1978) to search for periodicity in our polarimetric data, applying the “cyclocode” software. The best-fit period should have a very small normalized dispersion, $\Theta$, compared with the unphased data, and thus $\Theta < 1$ indicates that a good fit has been found. To apply PDM fitting, we extract variable components from all $P_r$ values until 2017 December 18 at $\alpha < 90^\circ$, with the best-fit phase-polarization curve derived by the trigonometrical function (see Section 3.1 and Figure 3(a)–(j)). Panel (n) of Figure 3 shows a PDM plot for variable components of $P_r$ of Phaethon from 2017 December 9 to 18. We find no periodic variation in the range from 0 up to 7.208 hr in our polarimetric data (e.g., individual or combined dates from 2017 December 9 to 18). Although Borisov et al. (2018) found a variation of $P_r$ with rotation on 2017 December 15, they cannot verify it in other dates. Note that our polarimetric data on December 15 and after December 17 does not cover a complete period because of weather conditions. Using the pole orientation of $(\lambda_{\text{pole}}, \beta_{\text{pole}}) = (319^\circ, -39^\circ)$ with a 5$^\circ$ uncertainty (Hanuš et al. 2016), a surface region as seen from Earth crossed from edge-on (perpendicular to pole direction) to the near north-pole direction during our survey by considering the positional relation between Earth and

---

12 http://www.toybox.rgr.jp/mp366/lightcurve/cyclocode/cyclocode.html developed by Dermawan (2004).
Phaethon at the time of these observations. Before 2017 December 18, we observed the edge-on direction (e.g., a different part of the surface at the rotational phase). This result suggests that surface materials on most regions of Phaethon have similar scattering properties (e.g., $p_v$, complex refractive index and grain size distribution).

Focusing on Phaethon’s polarimetric results in the $R_C$-band, Figure 1 shows that our phase-polarization curve is significantly different in the high-$\alpha$ region ($\alpha > \sim 60^\circ$) with that during 2016 (Ito et al. 2018), although it is in agreement with that during 2016 in the low-$\alpha$ region (Ito et al. 2018) and during 2017 December (Devogèle et al. 2018). Polarimetry in 2016 (Ito et al. 2018)
observed only the edge-on direction (e.g., $\sim -80^\circ$ as inclination of the north-pole direction seen from the Earth). In this case, materials causing lower polarization in the high-\(\alpha\) regions by scattering are distributed near its rotational pole, and most surface regions (except for near the rotational pole region) have similar scattering properties. The difference of scattering properties on Phaethon’s surface may reflect formation conditions in the early solar nebula and/or surface alteration after formation by the solar heating near perihelion. It is expected that not only the determination of pole orientation but also the variation of scattering properties of materials with location on Phaethon’s surface will be elucidated by detailed observations of the close flyby of Phaethon by the DESTINY+ mission (Sarli et al. 2018).

We are grateful to the staff of the Public Relation Center of the National Astronomical Observatory of Japan for their support during our observations. The authors sincerely thank Dr. Y. Ikeda, Prof. H. Kawakita, and Prof. M. Ishiguro for their valuable advice and comments. This research was supported by Grant-in-Aid for Japan Society for the Promotion of Science (JSPS) Fellows grant No. 15J10864 (Y.S.), JSPS KAKENHI grant No. 17H06459 (N.N.), and National Science Foundation Planetary Astronomy Program (USA) grant No. 0908529 (D.C.B.). The transmittance of the standard Johnson-Cousins \(RC\)-band filter made by TOPTEC (Czech Republic) was measured by using a UV-IR absorption spectrophotometer (Shimadzu, UV-3100PC) at the Advanced Technology Center of the National Astronomical Observatory of Japan.

Appendix A

Polarimetric Imager for Comets: PICO

PICO is a double-beam imaging polarimeter with a calcite Wollaston prism and rotatable half-wave plate (Ikeda et al. 2007). It obtains a pair of polarized images simultaneously that are perpendicularly polarized rays (ordinary- and extraordinary-rays) split by the Wollaston prism. A commercial SBIG STL-1001E charge-coupled device camera was used as the detector. The array was cooled to $-25^\circ$C within $\pm0.1^\circ$C by a two-stage thermoelectric system during our polarimetric survey of Phaethon on 2017 December. Before our polarimetric survey of Phaethon, we installed the standard Johnson-Cousins \(RC\)-band filter made by TOPTEC (Czech Republic). When PICO is mounted on the 50 cm Telescope for Public Outreach (F/12.06), the typical pixel scale is 0\".82 per pixel and the effective field of view of each polarized ray is $\sim6\"\times 12\"$ on the sky. To correct both a difference in transmittance of lenses used in PICO between ordinary- and extraordinary-rays and the time-dependent sky conditions, we obtained images at four
different position angles of the half-wave plate (Kawabata et al. 1999). One set of exposures at these four different angles (0°, 45°, 22.5°, 67.5°) is called a sequence.

**Appendix B**

**Derivation of Linear Polarization Degree**

After extracting counts for the eight independent images (pairs of perpendicularly polarized images at four position angles of the half-wave plate), we calculate normalized Stokes parameters, q (≡ Q/I) and u (≡ U/I), of the ith sequence in instrumental coordinates as follows:

\[ q_{\text{inst}}(i) = \frac{Q(i)}{I(i)} = \frac{1 - a_1(i)}{1 + a_1(i)} \]  

and

\[ u_{\text{inst}}(i) = \frac{U(i)}{I(i)} = \frac{1 - a_2(i)}{1 + a_2(i)} \]  

with

\[ a_1(i) = \sqrt{\frac{I_{\ell,0'}(i)/I_{\ell,0''}(i)}{I_{\ell,45'}(i)/I_{\ell,45''}(i)}} \]  

and

\[ a_2(i) = \sqrt{\frac{I_{\ell,225'}(i)/I_{\ell,225''}(i)}{I_{\ell,675'}(i)/I_{\ell,675''}(i)}} \]  

where \( I_{\ell,q} \) and \( I_{\ell,q'} \) are the ordinary and extraordinary intensities at the angle of the half-wave plate, \( \Psi \), of the ith sequence (Kawabata et al. 1999). In order to calibrate the instrumental polarizations (offset from the zero-point of \( q \) and \( u \) and instrumental depolarization) and offset in the position angle between the celestial and instrumental coordinates, we also observed unpolarized standard stars, completely polarized light obtained through a Glan–Taylor prism, and strong polarized standard stars. After calibrating the instrumental polarizations, the derived \( q \) and \( u \) with systematic mean errors are in celestial coordinates (\( q_{\text{cel}} \pm \sigma_{q_{\text{cel}}} \) and \( u_{\text{cel}} \pm \sigma_{u_{\text{cel}}} \)). We obtain multiple sequences of Phaethon on each date and calculated the weighted mean of \( q_{\text{cel}} \) and \( u_{\text{cel}} \) on each date as given by

\[ q_{\text{cel}} = \frac{\sum_{i=1}^{n} (q_{\text{cel}}(i)/\sigma_{q_{\text{cel}}}(i))}{\sum_{i=1}^{n} (1/\sigma_{q_{\text{cel}}}(i))} \]  

and

\[ u_{\text{cel}} = \frac{\sum_{i=1}^{n} (u_{\text{cel}}(i)/\sigma_{u_{\text{cel}}}(i))}{\sum_{i=1}^{n} (1/\sigma_{u_{\text{cel}}}(i))} \]  

with an error of

\[ \sigma_{q_{\text{cel}}} = \sqrt{\frac{1}{\sum_{i=1}^{n} (1/\sigma_{q_{\text{cel}}}(i))}} \]  

and

\[ \sigma_{u_{\text{cel}}} = \sqrt{\frac{1}{\sum_{i=1}^{n} (1/\sigma_{u_{\text{cel}}}(i))}} \]  

respectively. Here the degree of linear polarization, \( P \), and the position angle, \( \theta \), from normalized Stokes parameters (\( q \) and \( u \)) are converted by the following expressions (Timbergen 1996):

\[ P = \sqrt{q^2 + u^2} \]  

\[ \theta = \frac{1}{2} \tan(u/q) \]

The systematic error of \( P \) of PICO was estimated to be \( \delta P_{\text{sys}} = (P/85)\% \) over the entire field of view (Ikeda et al. 2007). More details of the polarization calibrations, correction of instrumental polarizations, and error estimations are described in Kawabata et al. (1999).

**Appendix C**

**Polarimetric Results of Phaethon in the R_c-band**

Table 3 is the time-domain summary of the polarimetric results of Phaethon in the \( R_c \)-band (812 sequences in total) taken by the PICO polarimeter mounted on the 50 cm Telescope for Public Outreach at the Mitaka Campus of the National Astronomical Observatory of Japan in Tokyo, Japan.

| UT Date | JD—2,458,000 | \( \alpha (^\circ) \) | \( P_c (\%) \) | \( \theta_c (^\circ) \) |
|---------|--------------|----------------|--------------|----------------|
| 2017 Dec 9 | 97.0122 | 19.313 | −0.43 ± 0.23 | 155 ± 10 |
| 2017 Dec 9 | 97.0203 | 19.309 | −0.62 ± 0.21 | 167 ± 9 |
| 2017 Dec 9 | 97.0228 | 19.308 | 0.54 ± 0.21 | 65 ± 7 |
| 2017 Dec 9 | 97.0252 | 19.307 | −0.28 ± 0.21 | 30 ± 11 |
| 2017 Dec 9 | 97.0275 | 19.306 | 0.41 ± 0.21 | 79 ± 13 |

Note. JD is the Julian date at the middle time of each sequence. \( \alpha \) is the solar phase angle of Phaethon. \( P_c \) and \( \theta_c \) are the degree of linear polarization and position angle in the scattering plane, respectively.

(This table is available in its entirety in machine-readable form.)
