Polarimetry and BVRI Photometry of the Potentially Hazardous Near-Earth Asteroid (23187) 2000 PN_9*

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***Based on observations carried out at the Asiago Astrophysical Observatory, Italy*

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Abstract

The results of V band polarimetric observations of the potentially hazardous near-Earth asteroid (23187) 2000 PN_9 at large phase angles are presented as well as its photometric observations in BVRI bands. Observations were made in March-April 2006 during its close approach to the Earth using the 1.82-m Asiago telescope (Italy) and the 0.7-m telescope at the Chuguevskaya Observational Station (Ukraine). We obtained polarimetric measurements at the phase angle of 115°, the largest phase angle ever observed in asteroid polarimetry. Our data show that the maximum value of the polarization phase curve reached 7.7% and occurred in the phase angle range of 90–115°. The measured values of linear polarization degree, BVRI colors and magnitude-phase dependence correspond to the S-type composition of this asteroid. Based on our observations the following characteristics of the asteroid (23187) 2000 PN_9 were obtained: a rotation period of 2.5325 ± 0.0004 h, a lightcurve amplitude of 0.13 mag, an albedo of 0.24 ± 0.06 and a diameter of 1.6 ± 0.3 km.

Key Words: Asteroids, Near-Earth objects, surfaces; Polarimetry, photometry.

1. Introduction

Asteroid (23187) 2000 PN_9 discovered by LINEAR is a near-Earth asteroid (NEA) with a semimajor axis of 1.84 AU and an orbital eccentricity of 0.59 (Apollo group). The asteroid makes periodic close approaches to the Earth and is categorized as a Potentially Hazardous Asteroid (see http://cfa-www.harvard.edu/iau/lists/Dangerous.html). Optical and radar observations of the asteroid were made in 2001 when it approached within 0.061 AU of the Earth. They revealed a rotational period of 2.5325 hours with a lightcurve amplitude of 0.15 mag (http://www.asu.cas.cz/~ppravec/neo.html) and roughly spherical shape with an estimated diameter of 1.7 km (Busch et al., 2006). The next close approach of the asteroid (23187) 2000 PN_9 occurred in March 2006 which was nearly three times closer to the Earth (0.020 AU) than in 2001. We have used this favorable opportunity for polarimetric observations of the asteroid in order to determine its albedo and compositional type.

The paper presents results of the V-band polarimetric observations of 2000 PN_9 at large phase angles near the maximum of polarization phase dependence as well as its photometric observations in the BVRI bands.

2. Observations

2.1. Polarimetry. Observations were carried out in service mode at the 1.82-m Asiago telescope (Italy) using the Asiago Faint Object Spectrographic Camera (AFOSC). The AFOSC polarimeter consists of a double Wollaston prism which splits the incoming light into four polarized beams at 0°, 45°, 90°, and 135°, separated by 20 arcsec (Pernechele et al. 2003). These four beams are sufficient to determine the Stokes parameters I, Q and U simultaneously with a single exposure. The CCD has 1024x1024 pixels (the pixel size is 24 μm), providing a total field of view of 8.14x8.14 arcmin, with a pixel scale of 0.473 arcsec/px. The input field has been masked at the telescope focal plane by a field selective mask to avoid the overlap of the final images on the CCD detector. The four output beams emerge collimated from the double Wollaston prism and are then focused on the CCD detector by the focal camera of AFOSC. The final image is formed by four strips from which the I, Q, and U parameters can be extracted. From the analysis of several unpolarized and polarized standard stars, it is seen that the instrumental polarization is fairly constant and always below 0.4%, while the systematic errors in the position angle are below 1.5 degrees (Desidera et al. 2004).

The NEA 2000 PN9 was observed during two consecutive nights on March 6 and 7, 2006, when it was at phase angles of 115 and 90.7 degrees, respectively. Nine exposures of 60 seconds each were acquired in the Johnson V band centered at 5474 Å with a bandpass of 899 Å. We discarded three of them due to the tracking problem so the total exposure time for the asteroid was 360 seconds each night. The observational procedure included bias and flat field acquisitions, together with the observation of polarized and unpolarized standard stars (taken from Schmidt et al., 1992; Turnshek et al., 1990) during each night to calibrate the instrumental polarization. The flat field images were acquired in two different sets corresponding to the adapter position of 0° and 90° to average the polarization induced by the reflections on the dome screen of the flat field lamp. The images were bias subtracted and then divided by the flat field. Aperture photometry was then performed for the four polarimetric channels, properly subtracting the sky contribution. The evaluation of polarimetric parameters has been performed following the procedure described in Fornasier et al. (2006).

Aspect data of observations and the final results are reported in Table 1. It contains the UT time at the mean time of observations, the heliocentric r and geocentric Δ distances, the phase angle α, the position angle of the scattering plane φ, the polarization degree P and the position angle θ in the equatorial coordinate system, and the calculated values of the polarization degree P_r and position angle θ_r in the coordinate system referring to the scattering plane as defined by Zellner and Gradie (1976b). The measured degree of the linear polarization is about 7.6% at both phase angles.

2.2. Photometry. Observations were carried out in the standard Johnson-Cousins BVRI photometric system using the 0.7-m telescope at the Chuguevskaya Observational Station (70-km to the south-east of Kharkiv). We used the CCD camera SBIG ST-6UV (375x242 pixels, field of view of 10.5x8 arcmin, and a pixel scale of 1.7x2.0 arcsec/px). The integration time was in the range of 30–300 seconds, giving an uncertainty of a single measurement about 0.01–0.03 mag (rms). To compensate for the asteroid movement during the integration time a correction of the telescope tracking was applied. Absolute calibration of the data was done with standards from Skiff (2007). The image reduction included dark subtraction and flat-field correction of the raw images. A standard aperture photometry routine was performed with the AstPhot software developed by S. Mottola (Mottola et al. 1995). The method of observations and data reduction is described in more details by Krugly et al. (2002).

Aspect data and magnitudes are given in Table 2. It contains the mean time of observations in UT, the heliocentric (r) and geocentric (Δ) distances, the solar phase angle (α), the photometric band, the mean magnitudes reduced to unit distances from the Sun and the Earth together with their standard deviations, and the number of measurements *N* used to obtained the mean value.

2. Results and discussion

Our photometric observations covered the phase angle range from 51 to 74 degrees. We search for the rotation period using a Fourier analysis method similar to that described by Harris et al. (1989). We found that P= 2.5325 ± 0.0004 hours gives minimal dispersion however a number of longer periods can not be fully excluded by our observations. We adopted the above-mentioned value since it coincides with the value 2.5325 ± 0.0001 hours measured by P. Pravec et al. in the 2001 opposition and given as pre-published value at http://www.asu.cas.cz/~ppravec/neo.html. The composite lightcurve in the R band corresponding to this rotational period is shown in Fig.1a. All magnitudes were reduced to the phase angle of 74.5 deg using the phase coefficient of 0.027 mag/deg. The lightcurve is characterized by a small amplitude of 0.13 mag and an asymmetric shape with a half-amplitude difference in the levels of primary and secondary maxima. This shape of the lightcurve can be explained by the high phase angles of the observations at which shadowing effects due to a large-scale surface roughness led to noticeable changes in the intensity of scattering light. According to the relationship between lightcurve amplitude and phase angle proposed by Zappala et al. (1990), the zero phase angle amplitude of (23187) 2000 PN_9 should be about 0.04 mag based on S-type composition (see below). A small lightcurve amplitude is in good agreement with the roughly spherical shape of the asteroid found from radar observations (Busch et al., 2006).

Observations in different photometric bands made on March 10 are shown versus rotational phase in Fig.1b. Measured BRI magnitudes were reduced to the V magnitude using corresponding colour indexes given in Table 3. One can see a good agreement of BVRI measurements made in the vicinity of the lightcurve primary maximum.

The rotational phases associated with our polarimetric observations are indicated in Fig.1a. Polarimetric observations made on March 6 and 7 are related to the surface seen in the neighborhood of the same lightcurve's minimum.

The measured values of the linear polarization degree of NEA (23187) 2000 PN_9 are shown in Fig.2 together with available polarimetric observations of other near-Earth asteroids. Our observations were made at the largest phase angle α=115° ever observed in asteroid polarimetry. They have shown that the maximum of the asteroid polarization phase curve reached $P_{max}\geq$7.7% and occurred in the phase angle range of 90–115°. The similarity of the measured values of the polarization degree of (23187) 2000 PN_9 lets us assume that the polarization maximum occurs in the middle of the observed phase angle range, i.e. α_{max}=103±12°. Previous polarimetric observations at phase angles higher than 90° were made only for the two asteroids (1685) Toro and (4179) Toutatis, both being S-types. In spite of the rather large uncertainty in these measurements (see Fig. 2) the following estimations of polarization maximum value and position were made: P_{max}=8.5±0.7%, α_{max}=110±10° for 1685 Toro (Kiselev et al. 1990) and P_{max}=7.0±0.2%, α_{max}=107±10° for 4179 Toutatis (Ishiguro et al. 1997). We applied to both datasets a trigonometrical fit (Lumme and Muinonen 1993) which was shown to reproduce polarization-phase dependence for various atmosphereless bodies. In particular, the fit is able to predict the entire positive branch for the Moon from the negative branch only (Lumme and Muinonen 1993). The result of the joint fit for the observations of (1685) Toro and (4179) Toutatis is shown in Fig.2 together with the confidence bands at 0.95 confidence level. One can see that observations of (23187) 2000 PN_9 are in agreement with those for the two S-type asteroids and are at the upper limit of the confidence band. Such similarity in the polarization behavior near P_{max} lets us to assume that the asteroid (23187) 2000 PN_9 also has an S-type surface composition. Although asteroids of other types have not been studied at very large phase angles, the available measurements at smaller phase angles of low-albedo (C-type) and high-albedo (E-type) asteroids show polarization-phase dependences completely different from the moderate-albedo asteroids (see Fig.2). The C-type asteroids have a deep polarization minimum and a steeper linear slope of the polarization curve, and E-type asteroids have surfaces characterized by the lowest polarization values in the asteroid population. The moderate-albedo surfaces have polarization parameter values located in between those for the low-albedo C and high-albedo E-asteroids. Thus, as one can see from Fig.2, even a single polarimetric measurement at phase angles α>50-60° is enough to distinguish between low-, moderate- and high-albedo surfaces. Our polarimetric observations allows us to firmly conclude the moderate albedo surface of the asteroid and to assume S-type composition as the most probable, although other moderate albedo types (L, Q, M) cannot be fully ruled out.

To obtain an albedo value from polarimetric observations, a few empirical correlations are usually used to relate the albedo with the polarimetric parameters, such as polarimetric slope, minimum and maximum of polarization (e.g., Bowell and Zellner, 1974). A correlation between P_{max} and albedo is still not established for asteroids although it was extensively studied for the Moon and in the laboratory for lunar, meteorite and terrestrial samples of various grain sizes (Dollfus et al., 1971, Bowell and Zellner, 1974, Geake and Dollfus, 1986, Shkuratov and Opanasenko, 1992). The value and position of polarization maximum were found to be highly sensitive not only to the surface albedo *p* but also to the regolith grain size. According to Dollfus et al. (1971) the polarization is higher for larger grain sizes. This effect can be, at least partly, caused by albedo changes with grain sizes and does not destroy the linear correlation found between log (P_{max}) and log (p).

To estimate an albedo of (23187) 2000 PN_9 we used the following relationship

$$\log(p) = C_1 \log(P_{max}) + C_2$$

with two sets of the coefficients C_1 and C_2 corresponded to different grain sizes. We used C_1=–0.71 and C_2=–0.23 as found for lunar fines with the grain sizes <50 μm (Bowell and Zellner 1974), and C_1=–0.75 and C_2=–0.03 found for terrestrial samples with the grain sizes ~200-340 μm (Geake and Dollfus 1986). Note that the value of P_{max} is expressed in percent.

The value of the maximum polarization for (23187) 2000 PN_9 was adopted as P_{max} $=7.7^{+0.5}_{-0.1}$%. The upper limit was estimated assuming typical polarization-phase behaviour near the polarization maximum (see the fitted line in Fig.2). We found albedos of 0.14 and 0.20 for the case of fine and coarse regolith, respectively. Asteroid regolith grain size is estimated to be typically 50-100 μm (e.g., Li et al., 2004) which is between the grain sizes considered above. For this reason we consider the mean value 0.17 the most probable albedo of the asteroid. It is important to note that in the empirical relationship "P_{max} – albedo" the albedo values correspond to a phase angle of 5°. To calculate the geometric albedo we need to take into account the opposition brightening. The mean increase in brightness inherent to the moderate-albedo surfaces from 5° to zero phase angle is about 1.4 (see Belskaya and Shevchenko, 2000) which gives an albedo p_V=0.24±0.06. The uncertainty comprises possible sources of errors, the largest of which is due to unknown regolith properties of the asteroid.

Note that the similarity of the value and position of the polarization maximum found for three S-type NEAs ((1685) Toro, (4179) Toutatis, and 2000 PN_9) assumed a similarity in their surface albedo and texture. The albedo estimation of 2000 PN_9 is in agreement with the values for Toro and Toutatis, in the 0.14–0.24 range, which were determined by different techniques (see Davis and Neese, 2005).

To estimate the diameter of NEA 2000 PN_9 we need to calculate its absolute magnitude. Our photometric observations were carried out in the range of 51.2–74.5°. Numerous estimations of the asteroid magnitude were made during its astrometric observations in 2000–2006 in the wider phase angle range from 11 to 113° (see the NEODys database http://newton.dm.unipi.it/cgi-bin/neodys/neoibo). The accuracy of these magnitude estimations are typically about 0.2–0.3 mag which usually makes them unsuitable for phase dependence analysis. However, it is of interest for an asteroid of nearly spherical shape (as in the case of 2000 PN_9) when changes in magnitude due to rotation and different aspects of observations do not introduce additional scatter in the magnitude-phase dependence. We considered only those magnitude measurements from the NEODys database which were made in the V and R standard bands and used V–R=0.48 mag to reduce V magnitudes to the R band. About 7% of 287 available magnitudes were found to have more than 1^m deviation from the mean magnitude-phase curve and were rejected from further consideration. We also averaged the magnitude measurements taken at the same phase angle and considered the standard deviation as a measure of their uncertainty. For a single measurement an uncertainty of 0.3 mag was adopted.

The obtained magnitude phase dependence is shown in Fig. 3. It also includes our measurements in the R band in the 2006 apparition reduced to the mean lightcurve (see Table 1). All available data agree within the estimated accuracy of measurements. We performed weighted HG and linear fits with the weight of each value inversely proportional to the corresponding error squared. The following parameters were derived: the absolute magnitude H_R=15.68 ± 0.13 mag, the slope parameter G= 0.20±0.09, and the phase coefficient 0.027±0.001 mag/deg. The linear fit was applied in the phase angle range $11<\alpha<80°$. It is interesting to note that observations at larger phase angles noticeably deviate not only from the linear fit but also from the HG function. A similar drop in magnitude at very large phase angles was found for the small main-belt S-type asteroid (5535) Annefrank (Newburn et al. 2003) observed in the phase angle range of 47-134° during the Stardust spacecraft fly-by.

Another way to calculate the absolute magnitude of an asteroid from photometric observations at large phase angles is to use a well-measured phase curve of a comparable type asteroid taking into account the similarity of the opposition effect for the main asteroid classes (see Belskaya and Shevchenko, 2000). We compared the phase dependences of the NEA 2000 PN_9 and the Q-type asteroid (1862) Apollo (Harris et al. 1987) which is the only moderate albedo NEA observed in detail at a wide phase angle range of 0.2 to 89° (Fig.3). One can see the good agreement of their phase behavior which is more evidence favoring a moderate albedo surface for the NEA 2000 PN_9. Assuming similar opposition brightening for both asteroids we obtained H_R=15.73 mag. The value practically coincides with that obtained by the HG-fit described above.

Thus, we adopted H_R=15.7 mag which corresponds to H=16.2 mag. Using this value of absolute magnitude and albedo p_V=0.24 one can estimate asteroid's diameter: 1.6 ± 0.3 km. This value is in a very good agreement with the size estimation from the radar data (1.7 km).

The measured BVRI color indices also contain information on surface composition of the asteroid. The colors were measured at a single phase angle as large as 74.5 deg. Since there is no known dependence of color indexes with phase angle we avoided their direct comparison with color indexes of other objects observed at a variety of phase angles. The obtained broadband colors were converted to reflectances relative to the Sun and normalized to 0.55 microns and compared to the mean spectra of moderate albedo asteroid classes as defined by Bus and Binzel (2002). Fig.4 shows the relative reflectance of the NEA 2000 PN_9 and the mean reflectances of S and L classes which are found to match it. Within the accuracy of color measurements both classes are possible for the asteroid.

We have summarized the physical characteristics of the asteroid in Table 3. It contains both the measured and derived values of various parameters characterizing size, surface and rotational properties of NEA 2000 PN_9.

These data represent a first portrait on the potentially hazardous Apollo-type asteroid (23187) 2000 PN_9. Polarimetric measurements of this asteroid made at record large phase angle α=115° let us estimate a position and value of the maximum of linear polarization degree. It is the third asteroid after (1685) Toro (Kiselev et al. 1990) and (4179) Toutatis (Ishiguro et al. 1997) for which observations were made in the vicinity of the polarization maximum. General agreement of the polarization data for all the three asteroids is evidence supporting similar surface texture for these three objects.

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Table 1
Results of polarimetric observations for asteroid (23187) 2000 PN_9 in the V band

Date, UT	r, AU	Δ, AU	α, deg	φ, deg	P, %	σ_P, %	θ, deg	σ_θ, deg	P_r, %	θ_r, Deg
2006 March 06.8204	0.9822	0.0232	115.0	44.0	7.68	0.08	133.2	1.0	7.68	179.3
2006 March 07.8886	0.9913	0.0368	90.7	59.8	7.63	0.08	149.3	1.0	7.63	179.7

Table 2

Results of photometric observations for asteroid (23187) 2000 PN_9

Date (UT)	r (AU)	Δ (AU)	α (deg)	Band	Magnitude	N
2006 March 10.028	1.0100	0.0723	74.45	R	18.015 ± 0.020	13
2006 March 10.018	1.0099	0.0721	74.50	B	19.368 ± 0.010	5
2006 March 10.016	1.0099	0.0722	74.49	V	18.472 ± 0.011	5
2006 March 10.017	1.0099	0.0721	74.49	I	17.610 ± 0.010	4
2006 March 20.987	1.1083	0.2665	58.66	R	17.623 ± 0.040	25
2006 April 04.047	1.2379	0.5131	51.22	R	17.475 ± 0.035	14

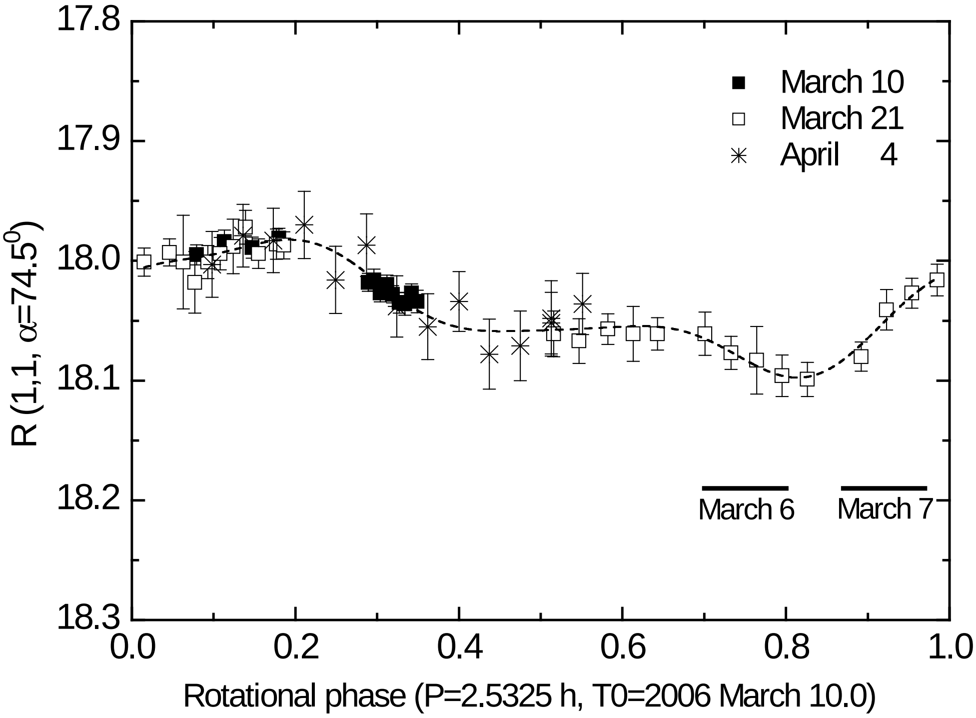
Table 3

Physical characteristics of the asteroid (23187) 2000 PN_9

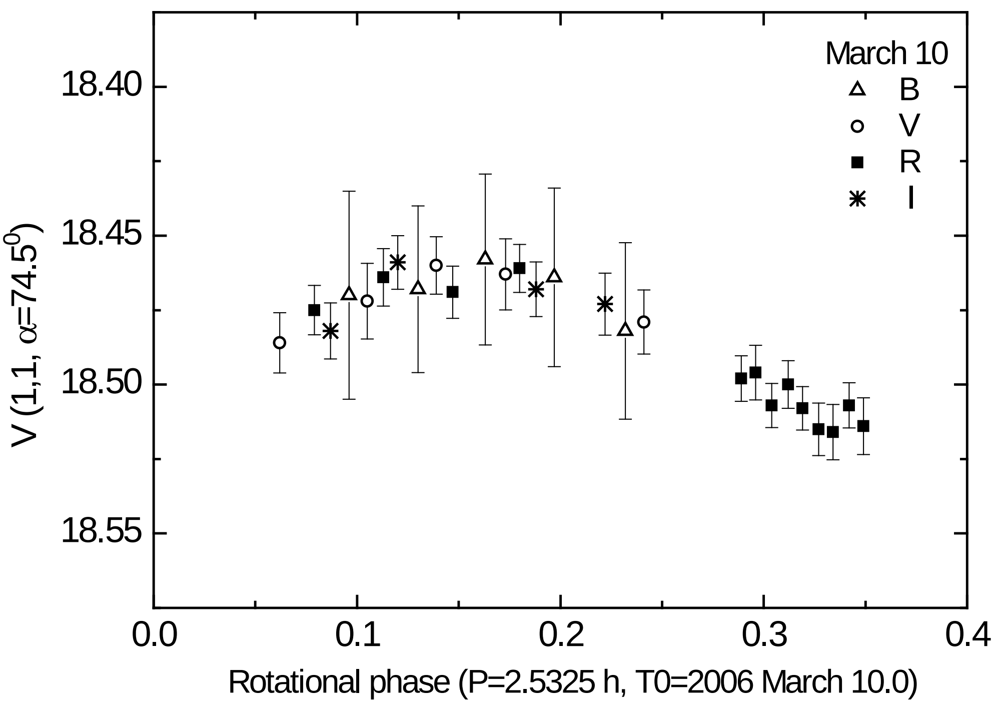
Apollo asteroid (23187) 2000 PN_9	
Taxonomic type	S (L)
Albedo	0.24 ± 0.06
Diameter	1.6 ± 0.3 km
H	16.2 ± 0.1^m
B-V[1]	0.90 ± 0.04^m
V-R[1]	0.48 ± 0.03^m
V-I[1]	0.86 ± 0.03^m
Rotation period	2.5325 ± 0.0004 h
Lightcurve amplitude	0.13^m
Phase coefficient	0.027 ± 0.002^m/deg
Linear polarization:	
P_{max}	7.7±0.1%
α_{max}	103±12°

[1]Measured at the phase angle of 74.5°

Figures



a)



b)

Figure 1. Composite lightcurve of 2000 PN_9 in the R band (a) and observations on March 10 in BVRI bands versus rotational phase (b). Rotational phases of polarimetric observations on March 6 and 7 are shown as solid lines.

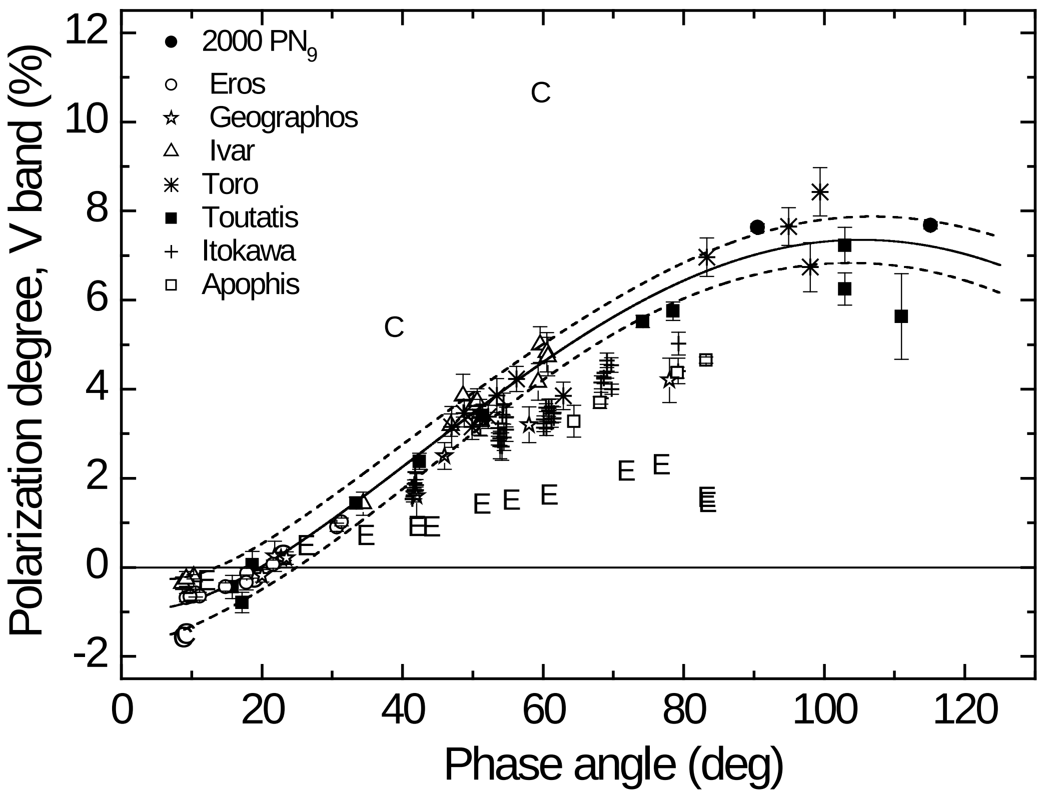


Figure 2. Polarization phase dependence of Near-Earth asteroids. The letters designate data for C-type asteroids (Kiselev et al. 1999) and E-types asteroids (Kiselev et al. 2002, De Luise et al. 2007). Different symbols represent data for moderate-albedo asteroids: 433 Eros (Zellner and Gradie, 1976a), 1620 Geographos (Vasilyev et al., 1996), 1627 Ivar (Kiselev et al., 1994), 1685 Toro (Kiselev et al., 1990), 4179 Toutatis (Lupishko et al., 1995, Mukai et al., 1997, Ishiguro et al., 1997), 25143 Itokawa (Cellino et al., 2005), 99942 Apophis (Delbò et al., 2007) and our observations of 2000 PN_9. The lines show the fit of observations of (1685) Toro and (4179) Toutatis by Lumme and Muinonen function and their confidence bands at 0.95 confidence level.

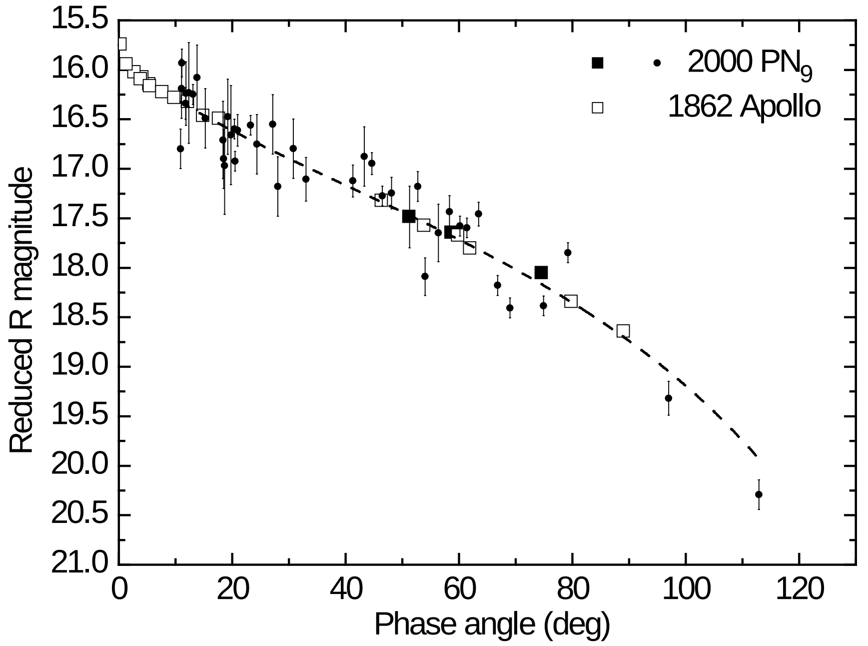


Figure 3. Magnitude-phase dependence of 2000 PN_9 in the R band fit by the HG-function (dash line). It includes both our observations (black squares) and averaged magnitude measurements from the NEODys database (dots). For comparison, the phase curve of 1862 Apollo (open squares) from Harris et al. (1987) is given shifted in magnitude to best coincide with our data on 2000 PN_9.

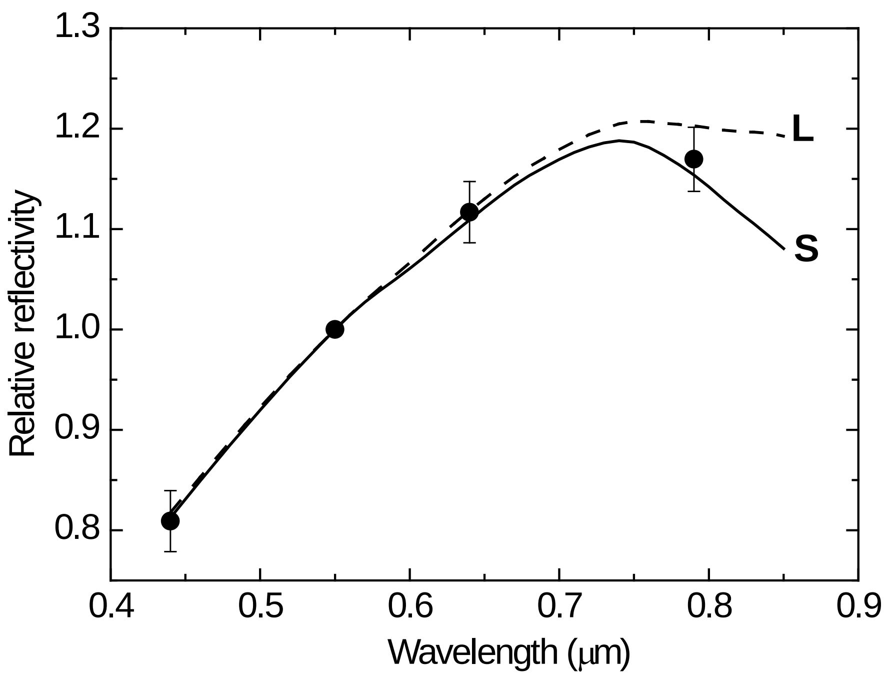


Figure 4. Relative reflectance of the NEA 2000 PN_9 and the mean reflectances of S and L classes as defined by Bus and Binzel (2002).