(85989) 1999 JD₆ : a first Barbarian asteroid detected by polarimetry in the NEA population

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ABSTRACT

Context. To investigate the physical properties of the surface layers of small Solar System objects, we take advantage of the phase-angle dependence of the linear polarization degree, which varies with albedo, composition, and other factors. In particular, the angle at which the positive and negative are reversed is a polarimetric parameter known as inversion angle. A group with large inversion angles (the so-called Barbarians) is unusual and is also noteworthy because of their association with meteorites.

Aims. We identified an object with such a large inversion angle in the near-Earth asteroids and derived previously unknown parameters, including the maximum polarization degree. By comparing the polarimetric parameters and spectral properties of meteorites, we inferred the surface conditions based on the degree of polarization of the asteroid.

Methods. We carried out multiband polarization imaging observations of an L-type near-Earth asteroid, (85989) 1999 JD₆, at the Hokkaido University Observatory in 2015 and 2019, covering a wide range of phase angles 30°–105°. Of the polarimetric parameters, we derived the maximum value, inversion angle, and the slope at that angle from the phase angle–polarization degree curve.

Results. We found that the inversion angle and the maximum polarization degree of 1999 JD₆ are 27° and 13%. The inversion angle is significantly larger than those of the majority of all asteroids observed before, but is consistent with that of Barbarian asteroids. 1999 JD₆ is the first example belonging to this group that is also among the near-Earth asteroids.

Conclusions. We claim that 1999 JD₆ is a member of the Barbarians and has rougher surface particles than lunar regolith.

Key words. minor planets, asteroids: individual: 1999 JD₆ – polarization

1. Introduction

Light reflected from the surface of an asteroid is polarized to varying degrees. Because light radiated from the Sun is unpolarized, we attribute this polarization degree to the optical properties of the asteroid surface (e.g., composition, roughness, and structure). By examining the degree of polarization of the asteroid, the physical properties resulting from polarization can therefore be determined.

The degree of the linear polarization of small Solar System objects such as asteroids, comets, and moons also depends on the phase angle (the angle between the Sun and the observer as seen from the object). From this phase angle–polarization degree curve (Muinonen et al. 2002), the main polarization characteristics parameterize the maximum and minimum values of the polarization, the phase angle of the negative to positive reversal point (i.e., inversion angle), and the slope at that point. Research has been conducted using these polarimetric parameters to investigate the relation between taxonomic type, albedo, and particle size (Belskaya et al. 2015 and references therein). Statistical analyses at low phase angles (typically $\alpha < 30^\circ$) that target main-belt asteroids have been performed in many previous studies (Cellino et al. 1999; Belskaya et al. 2003, 2009, 2017; Gil-Hutton 2007; Gil-Hutton et al. 2008, 2014, 2017; Gil-Hutton & Cañada-Assandri 2011, 2012; Cañada-Assandri et al. 2012;

Gil-Hutton & García-Migani 2017; López-Sisterna et al. 2019). These studies reported similar trends in polarimetric slope, minima, and inversion angles for each asteroid classification type.

Observations around a phase angle of 90°–100° yield maximum polarization values ($P_{\max}$). This observational geometry can only be achieved for objects that are within the Earth orbit (i.e., the Moon, near-Earth asteroids, and comets). If limited to asteroids alone, the number of known $P_{\max}$ objects is small, and there are many unknown polarimetric behaviors. Comets are roughly divided into high- $P_{\max}$, ~30%, and low- $P_{\max}$, ~10%, groups (Levasseur-Regourd et al. 1996), but Kiselev et al. (2001, 2004) and Jewitt (2004) reported that gas in the coma reduced the degree of polarization. The degrees of polarization of two comet nuclei, which can be regarded as an analogs of asteroidal surfaces, have also been obtained, which indicate possibly higher values (Jockers et al. 2005; Kuroda et al. 2015; Kwon et al. 2018). Polarimetric studies of the Moon have shown the color dependence of the phase angle–polarization curve and the well-known Umow law (Umow 1905), which correlates albedo and $P_{\max}$ with particle size (Dollfus 1998; Shkuratov et al. 2011 and references therein).

New knowledge obtained in the past few years has described asteroids with large inversion angles (Cellino et al. 2006) and asteroids with extremely high $P_{\max}$ (Kuroda et al. 2018;

Table 1. Observational summaries of (85989) 1999 JD₆

Date	UT	Filter ^(a)	Exp. ^(b) (N ^(c)) [s]	Vmag ^(d) [V]	<i>r</i> ^(e) [au]	Δ ^(f) [au]	α ^(g) [°]	ϕ ^(h) [°]
2015-06-14	16:05:29–16:39:13	<i>R</i> _C	360(1)	17.8	1.301	0.486	44.84	238.8
2015-07-16	12:00:36–16:08:01	<i>R</i> _C	60(1),30(27)	14.5	1.080	0.112	53.87–54.21	208.4–208.0
2015-07-19	13:06:44–17:36:19	<i>R</i> _C	90(1),40(2), 30(20),20(3)	14.0	1.052	0.081	62.77–63.54	201.8–201.3
2015-07-20	11:24:24–17:29:24	<i>R</i> _C	60(18),30(28)	13.9	1.043	0.072	67.15–68.49	199.5–198.8
2015-07-22	17:16:23–17:20:46	<i>R</i> _C	120(1),60(2)	13.8	1.023	0.056	83.32	191.3
2015-07-23	13:02:20–13:33:24	<i>R</i> _C	60(3),30(6)	14.0	1.014	0.052	91.80–91.96	184.1–183.8
2015-07-24	15:34:12–16:03:38	<i>R</i> _C	60(5)	14.4	1.003	0.049	105.09–105.26	117.0–114.9
2019-05-30	15:57:55–16:23:39	<i>R</i> _C	360(1)	17.8	1.426	0.532	30.88	213.7
2019-06-02	14:18:06–15:34:31	<i>R</i> _C	900(1)	17.8	1.423	0.524	29.57	207.0
2015-07-16	12:13:16–16:15:52	<i>V</i>	30(27)	14.5	1.079	0.111	53.89–54.22	208.3–208.0
2015-07-19	13:29:22–17:59:47	<i>V</i>	30(15)	14.0	1.051	0.081	62.83–62.61	201.8–201.3
2015-07-20	11:35:19–15:42:55	<i>V</i>	30(27)	13.9	1.043	0.073	67.18–67.09	199.5–199.0
2015-07-23	14:01:21–14:39:36	<i>V</i>	120(1),60(6)	14.0	1.014	0.052	92.24–92.45	183.4–183.1

Notes. ^(a)Employed filters (*V*: center 545, width 87 nm *R*_C: center 641, width 149 nm). ^(b)Typical exposure time per frame. ^(c)Number of sets counted as one in the four directions of the half-wave plate. ^(d)Apparent visual magnitude. ^(e)Heliocentric distance. ^(f)Geocentric distance. ^(g)Solar phase angle. ^(h)Position angle of the scattering plane (in degrees E of N).

Ito et al. 2018). More than two dozen objects in the main-belt asteroids, including candidate objects, belong to the first group (Cellino et al. 2019). The group name “Barbarians” comes from the name of the first discovered asteroid (234 Barbara). Sunshine et al. (2008) suggested that some of these asteroids possessed the so-called calcium aluminum-rich inclusion (CAI) from their near-infrared spectral characteristics, and their corresponding meteorites were of CV class, such as the Allende meteorite. Barbarians have only been found within main-belt asteroids larger than 40–50 km in diameter, with the exception of the possible members of the Watsonia and Brangäne families (Cellino et al. 2019).

Only two asteroids with high $P_{\max}$ have been found; unlike comets, which are composed of dust, it was unexpected that small airless objects would have such a high degree of polarization. In general, the polarization is considered to depend on the multiple scattering ratio of the surface layer, which explains the high polarization of (152679) 1998 KU₂ with very low albedo. Because the other (3200) Phaethon has an intermediate albedo, it is unlikely that they have similar surface properties. In any case, the particle size of the surface layer has been proposed to be the cause of the high observed polarization (Kuroda et al. 2018; Ito et al. 2018).

Our target, the near-Earth asteroid (85989) 1999 JD₆, was classified as K-type asteroid from the visible spectrum (Binzel et al. 2001; de León et al. 2010), and was later identified as L-type asteroid with the aid of the near-infrared spectrum (Binzel et al. 2019). Other physical characteristics derived from photometric and radar observations also show that it is a contact binary, with a maximum diameter of 2 km (Marshall et al. 2015), albedo 0.05–0.11 (Campins et al. 2009; Thomas et al. 2011; Reddy et al. 2012; Mainzer et al. 2014; Nugent et al. 2016), rotation period 7.6638 h $\pm$ 0.0001 h, and rotation amplitude 1.16 mag $\pm$ 0.05 mag (Szabó et al. 2001; Polishook & Brosch 2008). In consideration of these fundamental physical parameters, we aim to investigate the surface state of small Solar System objects through polarization characteristics. We here study a polarimetric observation of 1999 JD₆ in the visible wavelength at a phase angle from 30°–105°.

Section 2 describes the details of our observation and analysis. Section 3 reports the maximum value of the degree of polarization and the inversion angle derived from the phase angle-polarization degree curve. Based on the results, we discuss in Sect. 4 the possibility that 1999 JD₆ belongs to the Barbarians, and we report the particle size of the surface layer estimated from the comparison of meteorites.

2. Observations and analysis

2.1. Polarimetric observation

Polarimetric measurements of the near-Earth asteroid (85989) 1999 JD₆ were performed using the polarization mode of the Multi-Spectral Imager (MSI) installed on the 1.6 m Pirka telescope at the Hokkaido University Observatory (MPC Observatory code: Q33; Watanabe et al. 2012). The MSI is an instrument mounted on the Cassegrain focus of the Pirka telescope. The camera of the MSI is a Hamamatsu Photonics ImagEM C9100-13 (electron multiplier CCD, 512 pixels $\times$ 512 pixels, 16 μ m pixel^{−1}), and 0.389'' pixel^{−1} in normal resolution. This polarization mode derives the Stokes parameters (Q and U) by rotating a half-wave plate to 0°, 45°, 22.5°, and 67.5° using a Wollaston prism as a polarization element. Because one polarization degree was calculated from the data set obtained at these four angles, the exposure time per shot was kept short. This also reduced the effect of changes in brightness due to asteroid spins and in sky conditions. In addition, to reduce the specificity of the detector, a dithering pattern was applied at three places in the RA direction.

Our observations were made in June–July, 2015 and May–July, 2019, covering a phase angle of 30°–105°. We obtained four nights of data with the *V* band and nine nights with the *R*_C band (Table 1).

2.2. Analysis

The procedure for deriving the degree of linear polarization was the same as that of Kuroda et al. (2018). The acquired images

were analyzed using the Image Reduction and Analysis Facility (IRAF; Tody 1993) and SExtractor (Bertin & Arnouts 1996). In particular, we processed bias subtraction, flat-field correction, and cosmic-ray removal in dedicated scripts (MSIRED) on IRAF.

Because the ordinary and extraordinary lights form an image with the mask interposed in one frame, we measured both light fluxes by the aperture photometry method. The aperture size was examined within a range of one to five times at intervals of 0.1 based on the full width at half maximum (FWHM) of the Moffat function (Moffat 1969) and optimized to a size where the signal-to-noise ratio (S/N) was near the maximum value and stable. For the typical stellar image FWHM size of 1.6–4.3'', the aperture was in the range of 2.5–4.0 times the FWHM. The background value was the mean value within a ring that was three FWHM wide, starting 2 pixels outside the aperture circle. Moreover, by premasking stars other than the target body, contamination in the aperture and the sky background was minimized. When the S/N of a single frame was lower than 100, the measurement was carried out for combined frames of each half-wave plate.

The components of the normalized Stokes parameters (Bohren & Huffman 1983; Tinbergen 1996), Q/I and U/I , were derived from the following formula:

$$\frac{Q}{I} = \left(\sqrt{\frac{I_{e,0}/I_{o,0}}{I_{e,45}/I_{o,45}}} - 1 \right) / \left(\sqrt{\frac{I_{e,0}/I_{o,0}}{I_{e,45}/I_{o,45}}} + 1 \right), \quad (1)$$

and

$$\frac{U}{I} = \left(\sqrt{\frac{I_{e,22.5}/I_{o,22.5}}{I_{e,67.5}/I_{o,67.5}}} - 1 \right) / \left(\sqrt{\frac{I_{e,22.5}/I_{o,22.5}}{I_{e,67.5}/I_{o,67.5}}} + 1 \right), \quad (2)$$

where $I_{o,\nu}$ and $I_{e,\nu}$ stand for the ordinary (o) and extraordinary (e) intensities at a given set of half-wave plate position angles in degree (ν). The degree of linear polarization (P) and the position angle of polarization (θ_p) are defined as

$$P = \sqrt{\left(\frac{Q}{I}\right)^2 + \left(\frac{U}{I}\right)^2}, \quad (3)$$

and

$$\theta_p = \frac{1}{2} \tan^{-1} \left(\frac{U}{Q} \right), \quad (4)$$

respectively. The obtained degree of polarization was corrected for polarization efficiency and instrument polarization and was converted into the celestial coordinate system. The observation data from 2015 were applied to the same correction values as Ishiguro et al. (2017). Because these values are known to change over time, we used the newly derived correction terms to calibrate the 2019 data. The instrument polarization was corrected using the unpolarized standard stars (HD 14069, HD 154892, and HD 212311), and the zeropoint of the position angle of the celestial plane was determined using strongly polarized standard stars (BD+64d106, HD 155197, HD 155528, HD 161056, HD 204827, and Hiltner 960; Turnshek et al. 1990; Schmidt et al. 1992). These detailed values are given in Table A.1. According to the common approach of quantifying the polarization for Solar System objects, we represent the degree of linear polarization (P_r) and the position angle of polarization (θ_r) referenced to the scattering plane (Zellner & Gradie 1976) as

$$P_r = P \cos(2\theta_r), \quad (5)$$

Table 2. Nightly weighted mean values of our polarimetric observations.

Date	Filter ^(a)	α ^(b) [°]	$P_r \pm \sigma_{P_r}$ ^(c) [%]	$\theta_r \pm \sigma_{\theta_r}$ ^(d) [°]
2015-06-14	R_C	44.84	1.80 ± 2.32	-163.4 ± 30.0
2015-07-16	R_C	54.05	5.65 ± 0.06	-181.5 ± 0.3
2015-07-19	R_C	63.18	7.39 ± 0.08	-181.5 ± 0.3
2015-07-20	R_C	67.84	8.24 ± 0.06	-181.6 ± 0.2
2015-07-22	R_C	83.32	11.01 ± 0.51	-181.6 ± 1.7
2015-07-23	R_C	91.88	12.32 ± 0.07	-181.3 ± 0.2
2015-07-24	R_C	105.17	13.26 ± 0.29	-2.4 ± 0.7
2019-05-30	R_C	30.88	0.56 ± 0.84	-189.5 ± 40.7
2019-06-02	R_C	29.57	0.38 ± 0.62	-174.5 ± 48.1
2015-07-16	V	54.08	6.01 ± 0.08	-182.1 ± 0.4
2015-07-19	V	63.35	8.01 ± 0.12	-182.0 ± 0.4
2015-07-20	V	67.58	8.81 ± 0.09	-182.0 ± 0.3
2015-07-23	V	92.35	13.04 ± 0.09	-182.0 ± 0.3

Notes. ^(a)Employed filters (V: center 545, width 87 nm R_C : center 641, width 149 nm). ^(b)Solar phase angle. ^(c)Degree of linear polarization with respect to the scattering plane. ^(d)Position angle of the polarization with respect to the scattering plane (in degrees E of N).

and

$$\theta_r = \theta_p - (\phi \pm 90^\circ), \quad (6)$$

where ϕ represents the position angle of the scattering plane (see Table 1). We added or subtracted 90° to ϕ so that the inside of the bracket was in the range of 0° and 180° (Chernova et al. 1993). The results of the polarization degrees (P and P_r) and position angles (θ_p and θ_r) for each night are listed in Table 2. The errors on these quantities were determined to apply the law of error propagation to the flux error and uncertainty of each correction term; see Ishiguro et al. (2017) for more information on error estimation. Because our polarization measurements were obtained on different nights, there are variations in the error bars caused by changes in brightness due to rotation and sky conditions.

3. Results

3.1. Degree of linear polarization for multibands

Linear polarization degrees for 1999 JD₆ were derived at phase angles of 29.6° – 105.3° in the R_C band and at phase angles 53.9° – 92.5° in the V band (Fig. 1). As described in Sect. 2, the data in the four angles of the half-wave plate are needed to determine a single linear polarization degree. We derived the weighted mean value using the continuous data (P_r and θ_r) taken in the dithering mode. In our observational range, the maximum value of the polarization degree was $13.38\% \pm 0.56\%$ at a phase angle of 105.26° , and the minimum value was $0.39\% \pm 0.61\%$ at a phase angle of 29.57° . We obtained these values in the R_C band. When this is converted into the V band at the same phase angle, we expect that the polarization degree reaches about 14%. Table 1 shows only nightly average values of the phase angle, the linear polarization degree, and the polarization position angle. The individual numerical values are listed in Table B.1.

The polarization curve of the phase angle of 1999 JD₆ tends to be smaller than that of 1998 KU₂ (Kuroda et al. 2018) and Phaethon (Ito et al. 2018; Devogèle et al. 2018a), which both exhibited extremely high degrees of polarization. However, it

Fig. 1. Phase angle–polarization degree curve of 1999 JD₆. The data are the nightly weight means (see Table 2). The symbols in the legend indicate each of the nightly data, with the V band in green and the R_C band in red. The June 14, 2015, data, which had a noticeably larger error bar, had faint magnitude and poor sky conditions, but were adopted because no other data were available around this phase angle.

Fig. 2. Comparison of the linear polarization degrees of 1999 JD₆ and other near-Earth asteroids in the red region (about 650 ± 50 nm). The open circles indicate data corresponding to 1999 JD₆. Other symbols denote data for (152679) 1998 KU₂ (open black crosses; Kuroda et al. 2018), (3200) Phaethon (cyan triangles; Ito et al. 2018; Shinnaka et al. 2018), (1566) Icarus (blue squares; Ishiguro et al. 2017), (1685) Toro (green pluses; Kiselev et al. 1990), (4179) Toutatis (orange crosses; Ishiguro et al. 1997; Mukai et al. 1997), and (33342) 1998 WT₂₄ (dark green diamonds; Kiselev et al. 2002). 1999 JD₆ exhibits a different polarimetric behavior than was reported in previous studies.

is larger than in S-complex (Kiselev et al. 1990; Ishiguro et al. 1997, 2017) and E-type (Kiselev et al. 2002) asteroids, as shown in Fig. 2. There is no counterpart to asteroids that shows similar polarimetric behavior in the positive branch to 1999 JD₆. The R_C-band data were obtained until a phase angle of 100°, but there appeared to be no maximum. Comparing the V- and R_C-band gradients of polarization (henceforth referred to as polarimetric color) of the four nights observed in the multibands, we found that the difference in the degree of polarization tends to increase in proportion to the phase angle. We denote polarimetric bluing when the polarimetric color tends to increase with respect to the phase angle, and polarimetric reddening when it tends to decrease. This polarimetric bluing has also been observed in (25143) Itokawa (Cellino et al. 2005). In contrast, the polarimetric reddening trend with phase angle has been found for

Fig. 3. Relation between rotational phase and polarization degree of 1999 JD₆. The open squares, open circles, and crosses indicate individual data obtained on July 16, 19, and 20, 2016, respectively (see Table B.1). The plotted data are the deviations after subtracting the increasing portion of the polarization degree from the phase angle. Both bands (V band in green and R_C band in red) show small but similar fluctuations in the rotation phase (light curve from Vaduvescu et al. 2017). Our data provide insufficient coverage of the rotational phase to confirm its repeatability.

(1566) Icarus (Ishiguro et al. 2017) and Phaethon (Shinnaka et al. 2018).

1999 JD₆ has an elongated shape (Marshall et al. 2015) and a wide range of literature values for the albedo, from 0.05 to 0.11 (Campins et al. 2009; Thomas et al. 2011; Reddy et al. 2012; Mainzer et al. 2014; Nugent et al. 2016). Because polarization and albedo are closely related, we investigated the change in polarization with the rotation phase. The data collected on July 16, 19 and 20, 2015, which consist of many measurement points, show slight fluctuations around the rotation phase 0.0–0.2 and 0.35–0.65 (see Fig. 3). The plotted data were subtracted from the phase angle-dependent polarization changes. As the data specify the rotation phase, we used the light-curve data acquired eight days before our observation (Vaduvescu et al. 2017). Several large asteroids and the 5.8 km sized asteroid Phaethon have reported rotational variations of the degree of polarization smaller than 0.3% (Degewij et al. 1979; Cellino et al. 2016b; Nakayama et al. 2000; Takahashi et al. 2004, 2009; Belskaya et al. 2010; Borisov et al. 2018). However, our measurements are not accurate enough to assess this threshold. No variation in phase with the object rotation is detectable, and the scatter of the data appears to be compatible with the measurement uncertainties.

3.2. Polarimetric parameters

Polarimetric parameters in the R_C band were derived using the Lumme and Muinonen function (Lumme & Muinonen 1993; Goidet-Devel et al. 1995; Penttilä et al. 2005), as shown in Fig. 4. This function is defined by the following expression:

$$P(\alpha) = b (\sin \alpha)^{c_1} (\cos (0.5\alpha))^{c_2} \sin (\alpha - \alpha_0), \quad (7)$$

where b , c_1 , c_2 , and α_0 denote positive constants. By definition, the derivative of $P(\alpha)$ at α_0 represents the polarimetric slope (i.e., $h = \frac{dP}{d\alpha}|_{\alpha=\alpha_0}$). Equation (7) is an empirical equation and may not apply to the polarization phase angle change of any asteroid, but no other function can cover small to large phase angles. Because we lack small-angle data in our observations, we attempted to perform a function fit by fixing the minimum

Table 3. Estimates of polarimetric parameters.

Object	$\alpha_0 \pm \sigma_{\alpha_0}$ ^(a) [°]	$h \pm \sigma_h$ ^(b) [%/°]	χ^2	Method/reference
(85989) 1999 JD ₆	22.6 ± 1.4	0.117 ± 0.014	114.2	L-M ($P_{\min}$ = K types)
(85989) 1999 JD ₆	22.2 ± 1.6	0.114 ± 0.014	127.0	L-M ($P_{\min}$ = L types)
(85989) 1999 JD ₆	26.9 ± 0.7	0.150 ± 0.001	42.2	L-M ($P_{\min}$ = Barbarians)
(85989) 1999 JD ₆	25.2 ± 0.4	0.117 ± 0.001	54.3	MCMC ($P_{\min}$ = K types)
(85989) 1999 JD ₆	25.2 ± 0.4	0.116 ± 0.001	54.7	MCMC ($P_{\min}$ = L types)
(85989) 1999 JD ₆	27.0 ± 0.4	0.150 ± 0.001	47.2	MCMC ($P_{\min}$ = Barbarians)
(172) Baucis	28.11 ± 0.02	0.1173 ± 0.0042	–	Cellino et al. (2016a)
(234) Barbara	27.3	0.206 ± 0.005	–	Gil-Hutton et al. (2008)
(234) Barbara	29.4 ± 0.1	–	–	Devogèle et al. (2018b)
(387) Aquitania	28.51 ± 0.02	–	–	Cellino et al. (2016a)
(402) Chloe	32.0 ± 0.4	–	–	Devogèle et al. (2018b)
(679) Pax	28.23 ± 0.90	0.1825 ± 0.0046	–	Cellino et al. (2016a)
(980) Anacostia	29.11 ± 0.02	–	–	Cellino et al. (2016a)
Barbarians	28.46 ± 1.69	0.1512 ± 0.0478	–	López-Sisterna et al. (2019)
K types(Bus)	21.96 ± 2.32	0.1422 ± 0.0588	–	López-Sisterna et al. (2019)
L types(Bus)	20.12 ± 1.97	0.1116 ± 0.0223	–	López-Sisterna et al. (2019)

Notes. ^(a)Inversion angle. ^(b)Polarimetric slope parameter.

Fig. 4. Comparison of phase-polarization curves under two fitting methods. The left and right panels demonstrate curve fitting using the nonlinear least-squares method (the Levenberg-Marquardt algorithm) and the Markov chain Monte Carlo method, respectively, using Eq. (7). The open red circles indicate the R_C band data of 1999 JD₆ in this work. The solid blue, dashed purple, and dotted cyan lines correspond to the Barbarians, L-type, and K-type asteroids, that is, the values of $P_{\min}$ we used for the fit. Both methods yielded similar convergent solutions in the Barbarian model.

polarization value ($P_{\min}$ at $\alpha_{\min}$). Specifically, from the spectral types of 1999 JD₆, we adopted -0.846% at 9.75° and -0.794% at 8.18° , the mean values of $P_{\min}$ for K and L types, and the Barbarian mean value of -1.410% at 12.21° (López-Sisterna et al. 2019). This is a parameter estimation by this function, therefore we tried to fit it with two different methods. When fitting with the nonlinear least-squares method (Levenberg–Marquardt algorithm), the chi-square values (χ^2) of fitting with $P_{\min}$ of K and L types and Barbarians were 114.2, 127.0, and 42.2, respectively (left panel of Fig. 4). In the Markov chain Monte Carlo (MCMC) method (Salvatier et al. 2016), the difference in the chi-square values of each case is small (54.3, 54.7, and 47.2, respectively) because the three fitting results converge to close models (see the right panel of Fig. 4). Employing the $P_{\min}$ of Barbarians, both methods yielded similar convergence solutions. We therefore conclude that this model (i.e., Barbarians) is the best solution for calculating the parameters of 1999 JD₆. In fitting the Levenberg–Marquardt method, the maximum polarization degree obtained is $13.0\% \pm 0.8\%$ at a phase angle of $107.0^\circ \pm 3.1^\circ$, the inversion angle is $26.9^\circ \pm 0.7^\circ$,

and the slope is $0.150\%/^\circ \pm 0.001\%/^\circ$. According to the MCMC method, the maximum is $12.9\% \pm 0.1\%$ at a phase angle of $106.4^\circ \pm 0.5^\circ$, the inversion angle is $27.0^\circ \pm 0.4^\circ$, and the slope is $0.150\%/^\circ \pm 0.001\%/^\circ$. Table 3 shows the polarimetric parameters derived above, and for comparison, the values of the major Barbarians members and the average values of K and L types and Barbarians.

As mentioned in Sect. 3.1, the albedo is an essential factor in considering the degree of polarization. According to Gil-Hutton et al. (2008) and Lupishko et al. (2020), in (172) Baucis, (234) Barbara, and (599) Luisa, known as Barbarian asteroids, their albedos using the polarimetric slope were reported to be smaller than the literature values from thermal infrared observations. Therefore we tried to derive the geometric albedo of 1999 JD₆ using the well-known slope-albedo law. Based on the study of scattering characteristics (Zellner et al. 1974; Dollfus et al. 1989), the following equation holds between the geometric albedo (p_V) and the polarimetric slope (h):

$$\log p_V(h) = C_1 \log h + C_2, \quad (8)$$

where C_1 and C_2 represent constants. We applied $C_1 = -0.989 \pm 0.047$ and $C_2 = -1.719 \pm 0.040$ (Lupishko 2018), $C_1 = -1.111 \pm 0.031$ and $C_2 = -1.781 \pm 0.025$ (Cellino et al. 2015), $C_1 = -1.207 \pm 0.067$ and $C_2 = -1.892 \pm 0.141$ (Masiero et al. 2012) as these constants and calculated the geometric albedos of 1999 JD₆ for our polarimetric slope ($h \sim 0.150\%/^\circ$) as $p_V(h) = 0.125 \pm 0.016$, $p_V(h) = 0.136 \pm 0.011$, and $p_V(h) = 0.127 \pm 0.044$, respectively.

The slope parameters applied to this equation were calculated from the R_C band, but the V band was assumed to have similar values of slope parameters. The geometric albedo obtained from previous thermal infrared studies (Campins et al. 2009; Thomas et al. 2011; Reddy et al. 2012; Mainzer et al. 2014; Nugent et al. 2016) is in the range of 0.05–0.11, and our calculated values are above the upper limit. Unexpectedly, we obtained values that are higher than in the literature values, but 1999 JD₆ was found to deviate from the relationship that satisfies the majority of asteroids, as well as other Barbarians.

Table 4. Comparison of polarimetric parameters for meteorites.

Object	$\alpha_0 \pm \sigma_{\alpha_0}^{(a)} [^\circ]$	$P_{\max} \pm \sigma_{P_{\max}}^{(b)} [\%]$	$\alpha_{\max} \pm \sigma_{\alpha_{\max}}^{(c)} [^\circ]$	$h \pm \sigma_h^{(d)} [^\circ/\%$	Ref.
1999 JD ₆ (R_c band)	26.9 ± 0.7	13.0 ± 0.8	107.0 ± 3.1	0.150 ± 0.001	This work (L-M)
1999 JD ₆ (R_c band)	27.0 ± 0.4	12.9 ± 0.1	106.4 ± 0.5	0.150 ± 0.001	This work (MCMC)
NWA 4768					
<200 μm (Green)	25 ± 1	20.5	111	0.18 ± 0.02	Hadamcik et al. (2011)
<50 μm (Green)	25 ± 1	19.3	115	0.17 ± 0.01	Hadamcik et al. (2011)
<200 μm (Red)	25 ± 1	16.4	112	0.17 ± 0.02	Hadamcik et al. (2011)
<50 μm (Red)	25 ± 1	12.4	116	0.13 ± 0.01	Hadamcik et al. (2011)
Allende					
<500 μm (Green)	25 ± 1	25	123	0.18 ± 0.02	Hadamcik et al. (2011)
<50 μm (Green)	24.5 ± 1	16	123	0.15 ± 0.01	Hadamcik et al. (2011)
<500 μm (Red)	29 ± 1	29	123	0.18 ± 0.02	Hadamcik et al. (2011)
<50 μm (Red)	30 ± 1	17	123	0.17 ± 0.02	Hadamcik et al. (2011)
<20 μm (Red)	29.5 ± 1	10	115	0.13 ± 0.01	Hadamcik et al. (2011)

Notes. ^(a)Inversion angle. ^(b)Maximum of polarization degree. ^(c)Solar phase angle at the maximum of polarization degree. ^(d)Polarimetric slope parameter.

4. Discussion

4.1. New member of Barbarian asteroids

We found that 1999 JD₆ has an uncommonly large inversion angle, $\alpha_0 \sim 27.0^\circ$. Considering that primary feature of Barbarian asteroids is a large inversion angle, we propose that 1999 JD₆ is the first of the Barbarians to be detected in the near-Earth asteroids. Although our data do not reach the negative branch, we assumed $P_{\min}$ in our limited data set and derived the reasonable solution from fitting the empirical equation. It is unlikely that the polarimetric behavior has no negative branch, and considering the previous researches, the slope parameter, $h \sim 0.150^\circ/\%$, becomes more loose. Such a large inversion angle is a known characteristic of the Barbarians, of which (234) Barbara was the first example (Cellino et al. 2006). A select group of the Barbarians were previously classified as S, K, L, and A type through visible spectroscopy (SMASS; Bus & Binzel 2002). Compared with the Bus classification, the polarimetric parameters of the Barbarians indicate significant differences from other taxonomic types (López-Sisterna et al. 2019). With a focus on inversion angles and slope parameters, their values with error bars for 1999 JD₆ are within the typical range of the Barbarians. Moreover, 1999 JD₆ exhibits different polarimetric characteristics from those of other K- and L-type asteroids, except for the Barbarians (see Table 3). According to Devogèle et al. (2018b), these were reported to be L type in the Bus-DeMeo classification (Demeo et al. 2009) extended to the near-infrared wavelength. The spectrum of 1999 JD₆ has been reported in several studies, including Bus & Binzel (2002), Lazzarin et al. (2005), de León et al. (2010), Reddy et al. (2012), and Binzel et al. (2019). Evaluated together with the Bus-DeMeo classification by Binzel et al. (2019), 1999 JD₆ has been classified as an L type. However, it appears to have characteristics that are intermediate between K and L types (top panel in Fig. 5), and it is not remarkable at an absorption band around 2 μm , which is associated with CAI minerals (bottom panel in Fig. 5). The obvious difference between the spectrum of 1999 JD₆ and that of other Barbarians may be caused by the mineral composition ratio and the degree of subsequent alterations, considering spectral fitting models (Devogèle et al. 2018b).

Sunshine et al. (2008) and Devogèle et al. (2018b) argued that the polarimetric behaviors of the Barbarians are the result

Fig. 5. Spectroscopic similarities of 1999 JD₆ and others. *Top panel:* spectra of 1999 JD₆ (red circles) and the Barbarians (172) Baucis (green squares), (234) Baraba (cyan diamonds), (679) Pax (blue crosses), and the range of K type (purple triangles) and L type (black pluses) according to the Bus-DeMeo classification (Demeo et al. 2009; Binzel et al. 2019). The spectra refer to textual data obtained from MITHNEOS¹. *Bottom panel:* compares the spectra of the CV3-type Allende (cyan crosses) and CO3-type Lance (green pluses) meteorites with those of 1999 JD₆ (red and blue circles). The 1999 JD₆ spectra are multiplied by the albedo within the literature values that best match the respective meteorite data. At the side where the wavelength is longer than 0.6 μm , it matches Allende well, while at the blue side, Lance is matched well. The scaled spectra of the meteorites were obtained from the RELAB² database.

of the high content of spinel-bearing minerals on their surfaces. Devogèle et al. (2018b) also indicated that based on the spectroscopic properties of the Barbarians, their composition fits with the mixed minerals of the matrix, MgO-rich olivine fluffy CAI, in CV3 meteorites. On the other hand, the CV3 meteorites belong to the primitive meteorites with low albedos. There are discrepancies with the fact that the Barbarians have intermediate

¹ <http://smass.mit.edu/minus.html>

² <http://www.planetary.brown.edu/rehab/>

Fig. 6. Phase angle dependence of polarimetric color for 1999 JD₆ and size-dependent meteorites. The open red circles and solid lines represent data corresponding to 1999 JD₆. The polarimetric data of two meteorites, CO3-class NWA 4868 and CV3-class Allende, have been measured under deposited layer conditions in the laboratory (Hadamcik et al. 2011). The blue squares and cyan triangles adjacent to the dotted lines show a grain size of $<50\ \mu\text{m}$ and $<200\ \mu\text{m}$ for the NWA 4868 meteorite, respectively. The orange crosses and dark green diamonds adjacent to the dashed lines denote $<50\ \mu\text{m}$ and $<500\ \mu\text{m}$ Allende meteorite particles, respectively.

albedos between about 0.15 and 0.20, as reported in Cellino et al. (2016a). Gil-Hutton et al. (2008) mentioned the possibility that asteroids with large inverse angles have coarse-grained regoliths of dark particles mixed with fine-grained white inclusions. In their scenario, a mixture of two components with different geometric albedos affects the polarization parameters, so that the albedo-slope relationship equation as in Eq. (8) has been interpreted as inapplicable. In general, the near-Earth asteroids are assumed to have been the source or common parent body of the meteorites. The presence of 1999 JD₆ in low albedo ($P_v \sim 0.08$) is of interest in this respect, although this study is unable to link any specific CV3 meteorite to it. In addition, the CAI abundance mismatch between meteorites and asteroids may also be resolved.

In the range of phase angles we measured, the polarization degrees of 1999 JD₆ were always higher in the V band than in the R_c band. The Umow law (Umow 1905), which states that the polarization degree is inversely proportional to reflectance, is well known. This law also corresponds to the case of 1999 JD₆. The spectropolarimetry of (236) Honoria at $\alpha = 9.1^\circ$ and (599) Louisa at $\alpha = 26.9^\circ$, identified as Barbarian, displayed a positive gradient of both polarization and reflectance concerning wavelength in the case of Honoria (Bagnulo et al. 2015). Considering these results at the negative branch and the polarimetric color of this study, we suggest that the polarimetric wavelength gradient varies from positive to negative and the difference increases with the phase angle, as partially mentioned in Bagnulo et al. (2015). Even within the same Barbarians, there are objects whose spectroscopic and polarimetric features do not coincide with each other. Thus, we propose that other surface structures (particle size, porosity, etc.) can be derived by evaluating polarimetric features in addition to surface composition (e.g., spectroscopic features).

The geometry of 1999 JD₆ indicates that it is a contact binary, with an estimated diameter of approximately $0.7 \times 2\ \text{km}$ (Marshall et al. 2015). This object would qualify as the smallest of the Barbarian group; as previously observed, Barbarian members are tens of kilometers in size within the main-belt asteroids. If the size of the surface regolith depends on the size

of the asteroid (Gundlach & Blum 2013), the polarimetric behavior of Barbarians may be attributable to a specific grain size. We elaborate on the surface particle size of 1999 JD₆ in Sect. 4.2.

4.2. Estimation of the regolith grain size

We derived the surface particle size of 1999 JD₆ by comparing the polarization characteristics of 1999 JD₆ and two meteorites. Spectra of well-known Barbarian asteroids, (387) Aquitania and (980) Anacostia, present a strong $2\ \mu\text{m}$ absorption feature (Burbine et al. 1992). Such spinel-enriched meteorites have similar features to CO and CV chondrite meteorites, which possess a high abundance of CAI (Sunshine et al. 2008). Against this background, we compared the polarization properties of 1999 JD₆ with those of Allende (CV3) and NWA 4768 (CO3) meteorites.

Hadamcik et al. (2011) reported the results of measuring these meteorites with multiple particle sizes of polarized light in green (543.4 nm) and red (632.8 nm). The polarimetric parameters (P_{max} , α_{max} , and h , and α_0) are similar to the $25\text{--}50\ \mu\text{m}$ of Allende or $50\text{--}200\ \mu\text{m}$ of NWA 4768, as shown in Table 4. α_{max} is about 10 degrees larger for both meteorites than for 1999 JD₆. However, this may be due to the fitting gap around P_{max} of 1999 JD₆. As a further constraint, we introduced the phase angle change of the polarimetric color, shown in Fig. 6. The color variation in the phase angle is polarimetric reddening for Allende and polarimetric bluing for NWA 4768. The latter seems to match the slight phase bluing for 1999 JD₆. However, while the slope of NWA 4768 varies little with particle size, that of Allende is closer to flat with smaller particle size. Assuming that the composition of 1999 JD₆ is similar to that of the Allende meteorite, the grain sizes are probably between 25 and $50\ \mu\text{m}$ because the polarimetric parameters and polarimetric color trends are similar.

The shape model constructed from the radar and light curves by Marshall et al. (2017) shows that 1999 JD₆ is a contact binary, with a peanut-like overall shape. Because the amplitude of the light curve is large (approximately 1 mag.), their maximum and minimum points correspond to bipartite and single faces, respectively. We acquired the polarization degrees around two maxima and minima, and the polarimetric variations were consistent within the observational errors, as shown in Fig. 3. This fact indicates that there is almost no difference in the surface states between the two objects that form the contact binary. In other words, we conclude that the overall surface of 1999 JD₆ is uniform, with no significant differences in albedo or particle size.

5. Conclusions

We have performed multiband polarimetric observations of the near-Earth asteroid (85989) 1999 JD₆ over a wide range of phase angles. A summary of our findings is listed below.

1. The linear polarization degree of more than 13% in the R_c band, which is close to the maximum, exhibited a new trend compared to previously observed near-Earth asteroids.
2. The inversion angles obtained from the function fitting are as large as 27° and are consistent with those of popular Barbarians. It is the first Barbarian identified by polarimetry among the near-Earth asteroids. It is noteworthy that this asteroid is the smallest Barbarian identified so far.
3. Based on comparisons with laboratory measurements of the meteorites, we can interpret that the surface of 1999 JD₆ is covered with $25\text{--}50\ \mu\text{m}$ grains that are rougher than those on the Moon.

In future work, additional examples of polarimetric observations of asteroids at high phase angles and measurements of meteorites under various conditions (e.g., particle size and porosity) may advance our understanding of the surface of asteroids.

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Appendix A: Correction terms of MSI in 2019 and 2015

The polarimetric observation data of MSI need to correct polarization efficiency, instrument polarization and the zeropoint

of the position angle of the celestial plane. Table A.1 presents the correction terms, which were calculated based on data obtained in 2019 June and September. See also Ishiguro et al. (2017) for the 2015 correction terms.

Table A.1. Correction terms of MSI in 2019 and 2015.

Terms	V	R_C	Note
2019 (This work)			
Polarization efficiency [%]	99.71 ± 0.02	99.60 ± 0.01	
Instrument polarization of q [%]	1.151 ± 0.012	0.830 ± 0.011	HD 14069, HD 154892, and HD 212311
Instrument polarization of u [%]	0.446 ± 0.012	0.304 ± 0.011	HD 14069, HD 154892, and HD 212311
Zeropoint of the position angle of the celestial plane [°]	3.43 ± 0.15	3.17 ± 0.13	BD+64d106, HD 155197, HD 155528, HD 161056, HD 204827 and Hiltner 960
2015 (Ishiguro et al. 2017)			
Polarization efficiency [%]	99.97 ± 0.02	99.98 ± 0.01	
Instrument polarization of q [%]	0.963 ± 0.029	0.703 ± 0.033	BD+32 3739 and HD 212311
Instrument polarization of u [%]	0.453 ± 0.043	0.337 ± 0.020	BD+32 3739 and HD 212311
Zeropoint of the position angle of the celestial plane [°]	3.82 ± 0.38	3.38 ± 0.37	HD 204827, HD 154445, and HD 155197

Appendix B: Individual measurement data of 1999 JD₆

Table B.1 shows the linear polarization degree, the polarization position angle, the phase angle, and the Modified Julian Date.

Table B.1. Measurement results of our polarimetric observations.

MJD [day]	Filter ^(a)	α ^(b) [°]	$P \pm \sigma_P$ ^(c) [%]	$\theta_P \pm \sigma_{\theta_P}$ ^(d) [°]	$P_r \pm \sigma_{P_r}$ ^(e) [%]	$\theta_r \pm \sigma_{\theta_r}$ ^(f) [°]
57187.682190	R_C	44.837	2.15 ± 2.35	-14.56 ± 29.98	1.80 ± 2.32	-163.37 ± 29.98
57219.501945	R_C	53.870	5.46 ± 0.22	-63.33 ± 1.18	5.45 ± 0.22	-181.68 ± 1.18
57219.506411	R_C	53.878	5.61 ± 0.18	-64.00 ± 0.93	5.59 ± 0.18	-182.34 ± 0.93
57219.517233	R_C	53.900	5.51 ± 0.17	-63.82 ± 0.91	5.50 ± 0.17	-182.14 ± 0.91
57219.527175	R_C	53.920	5.93 ± 0.21	-61.51 ± 1.06	5.93 ± 0.21	-179.81 ± 1.06
57219.614324	R_C	54.095	5.49 ± 0.26	-62.09 ± 1.43	5.49 ± 0.26	-180.21 ± 1.43
57219.626165	R_C	54.119	5.62 ± 0.27	-64.36 ± 1.41	5.60 ± 0.27	-182.46 ± 1.41
57219.637011	R_C	54.141	5.90 ± 0.21	-63.43 ± 1.04	5.89 ± 0.21	-181.50 ± 1.04
57219.647897	R_C	54.163	5.73 ± 0.18	-63.46 ± 0.93	5.72 ± 0.18	-181.51 ± 0.93
57219.658765	R_C	54.185	5.80 ± 0.17	-63.64 ± 0.86	5.79 ± 0.17	-181.66 ± 0.86
57219.669623	R_C	54.207	5.53 ± 0.17	-63.42 ± 0.89	5.52 ± 0.17	-181.42 ± 0.89
57222.548558	R_C	62.765	7.27 ± 0.25	-69.21 ± 0.96	7.27 ± 0.25	-181.03 ± 0.96
57222.553579	R_C	62.786	7.46 ± 0.21	-69.79 ± 0.78	7.45 ± 0.21	-181.60 ± 0.78
57222.559010	R_C	62.809	7.43 ± 0.24	-69.47 ± 0.91	7.42 ± 0.24	-181.26 ± 0.91
57222.570099	R_C	62.856	7.35 ± 0.25	-69.41 ± 1.04	7.34 ± 0.26	-181.17 ± 1.04
57222.636567	R_C	63.136	6.79 ± 0.32	-70.93 ± 1.36	6.76 ± 0.32	-182.52 ± 1.36
57222.649200	R_C	63.189	7.17 ± 0.64	-70.80 ± 2.86	7.15 ± 0.64	-182.35 ± 2.86
57222.706804	R_C	63.434	7.61 ± 0.43	-71.52 ± 1.49	7.57 ± 0.43	-182.92 ± 1.49

Notes. ^(a)Employed filters (V : center 545, width 87 nm R_C : center 641, width 149 nm). ^(b)Solar phase angle. ^(c)Degree of linear polarization. ^(d)Position angle of polarization (in degrees E of N). ^(e)Degree of linear polarization with respect to the scattering plane. ^(f)Position angle of the polarization with respect to the scattering plane (in degrees E of N).

Table B.1. continued.

MJD [day]	Filter ^(a)	α ^(b) [°]	$P \pm \sigma_P$ ^(c) [%]	$\theta_P \pm \sigma_{\theta_P}$ ^(d) [°]	$P_r \pm \sigma_{P_r}$ ^(e) [%]	$\theta_r \pm \sigma_{\theta_r}$ ^(f) [°]
57222.715187	R_C	63.470	7.57 ± 0.20	-69.06 ± 0.73	7.57 ± 0.20	-180.44 ± 0.73
57222.720636	R_C	63.493	7.46 ± 0.45	-69.57 ± 1.66	7.45 ± 0.45	-180.94 ± 1.66
57222.726911	R_C	63.520	7.38 ± 0.19	-70.85 ± 0.76	7.36 ± 0.19	-182.20 ± 0.76
57222.731832	R_C	63.541	7.62 ± 0.32	-70.51 ± 1.14	7.60 ± 0.32	-181.85 ± 1.14
57223.479084	R_C	67.149	8.22 ± 0.15	-71.66 ± 0.53	8.22 ± 0.15	-181.14 ± 0.53
57223.490872	R_C	67.213	8.07 ± 0.16	-72.55 ± 0.56	8.05 ± 0.16	-181.99 ± 0.56
57223.502978	R_C	67.278	7.84 ± 0.26	-71.90 ± 0.89	7.83 ± 0.26	-181.30 ± 0.89
57223.513415	R_C	67.335	8.22 ± 0.14	-72.51 ± 0.49	8.20 ± 0.14	-181.88 ± 0.49
57223.522406	R_C	67.384	8.59 ± 0.35	-72.59 ± 1.36	8.57 ± 0.35	-181.94 ± 1.36
57223.535727	R_C	67.456	8.42 ± 0.23	-72.54 ± 0.84	8.40 ± 0.23	-181.85 ± 0.84
57223.591226	R_C	67.759	8.40 ± 0.53	-71.40 ± 1.94	8.40 ± 0.53	-180.55 ± 1.94
57223.602811	R_C	67.822	8.35 ± 0.28	-72.34 ± 0.98	8.34 ± 0.28	-181.46 ± 0.98
57223.613444	R_C	67.880	8.17 ± 0.26	-72.91 ± 0.91	8.15 ± 0.26	-181.99 ± 0.91
57223.625042	R_C	67.944	8.57 ± 0.35	-72.36 ± 1.23	8.56 ± 0.35	-181.41 ± 1.23
57223.648588	R_C	68.074	7.97 ± 1.35	-73.53 ± 4.71	7.94 ± 1.35	-182.51 ± 4.71
57223.666342	R_C	68.172	8.49 ± 0.40	-72.61 ± 1.44	8.48 ± 0.40	-181.54 ± 1.44
57223.679007	R_C	68.242	8.52 ± 0.39	-72.73 ± 1.33	8.51 ± 0.39	-181.62 ± 1.33
57223.693165	R_C	68.321	8.70 ± 0.36	-72.07 ± 1.16	8.70 ± 0.36	-180.91 ± 1.16
57223.703070	R_C	68.376	8.01 ± 0.56	-73.04 ± 1.98	7.99 ± 0.56	-181.85 ± 1.98
57223.712621	R_C	68.429	7.74 ± 0.53	-72.75 ± 2.02	7.73 ± 0.53	-181.54 ± 2.02
57223.724076	R_C	68.493	8.79 ± 0.47	-72.72 ± 1.62	8.78 ± 0.47	-181.47 ± 1.62
57225.722429	R_C	83.320	11.02 ± 0.51	-80.29 ± 1.65	11.01 ± 0.51	-181.57 ± 1.65
57226.547951	R_C	91.798	12.33 ± 0.10	-87.17 ± 0.27	12.32 ± 0.10	-181.22 ± 0.27
57226.556435	R_C	91.893	12.25 ± 0.13	-87.56 ± 0.36	12.24 ± 0.13	-181.48 ± 0.37
57226.562304	R_C	91.959	12.40 ± 0.13	-87.45 ± 0.36	12.39 ± 0.13	-181.29 ± 0.36
57227.652934	R_C	105.088	13.26 ± 0.34	24.69 ± 0.74	13.21 ± 0.34	-2.35 ± 0.92
57227.666113	R_C	105.255	13.43 ± 0.56	22.36 ± 1.21	13.38 ± 0.56	-2.54 ± 1.26
58633.674150	R_C	30.878	0.59 ± 0.84	-65.72 ± 40.68	0.56 ± 0.84	-189.45 ± 40.68
58636.622434	R_C	29.570	0.39 ± 0.61	-57.61 ± 48.11	0.38 ± 0.62	-174.64 ± 48.11
57219.511818	V	53.889	6.22 ± 0.21	-63.70 ± 1.00	6.20 ± 0.21	-182.03 ± 1.00
57219.522651	V	53.911	6.09 ± 0.21	-63.31 ± 1.03	6.08 ± 0.21	-181.61 ± 1.03
57219.533476	V	53.933	5.87 ± 0.20	-63.85 ± 1.02	5.85 ± 0.20	-182.14 ± 1.02
57219.620729	V	54.108	6.17 ± 0.38	-63.11 ± 1.81	6.17 ± 0.38	-181.21 ± 1.81
57219.631592	V	54.130	6.11 ± 0.30	-65.09 ± 1.44	6.07 ± 0.30	-183.18 ± 1.44
57219.642437	V	54.152	5.78 ± 0.25	-63.12 ± 1.28	5.78 ± 0.25	-181.18 ± 1.28
57219.653335	V	54.174	5.93 ± 0.21	-65.84 ± 1.03	5.88 ± 0.21	-183.88 ± 1.03
57219.664189	V	54.196	6.13 ± 0.20	-64.15 ± 0.95	6.11 ± 0.20	-182.17 ± 0.95
57219.675065	V	54.218	5.99 ± 0.20	-63.41 ± 0.99	5.99 ± 0.20	-181.40 ± 0.99
57222.564654	V	62.832	7.96 ± 0.21	-70.18 ± 0.76	7.94 ± 0.21	-181.96 ± 0.76
57222.643830	V	63.166	8.30 ± 0.38	-69.28 ± 1.32	8.30 ± 0.38	-180.86 ± 1.32
57222.736507	V	63.561	7.85 ± 0.28	-70.20 ± 1.02	7.84 ± 0.28	-181.52 ± 1.02
57222.741872	V	63.584	8.05 ± 0.23	-71.16 ± 0.83	8.02 ± 0.23	-182.48 ± 0.83
57222.747247	V	63.608	8.15 ± 0.27	-71.22 ± 0.97	8.12 ± 0.27	-182.52 ± 0.97
57223.485442	V	67.184	9.13 ± 0.20	-72.70 ± 0.62	9.11 ± 0.20	-182.15 ± 0.62
57223.496081	V	67.241	8.81 ± 0.23	-72.49 ± 0.73	8.79 ± 0.23	-181.91 ± 0.73
57223.507483	V	67.303	8.79 ± 0.18	-71.95 ± 0.58	8.78 ± 0.18	-181.34 ± 0.58
57223.518657	V	67.363	8.55 ± 0.20	-73.27 ± 0.66	8.51 ± 0.20	-182.63 ± 0.66
57223.540219	V	67.480	9.07 ± 0.35	-72.84 ± 1.01	9.04 ± 0.35	-182.14 ± 1.01
57223.597450	V	67.793	9.22 ± 0.47	-72.70 ± 1.44	9.20 ± 0.47	-181.83 ± 1.44
57223.608191	V	67.852	8.79 ± 0.47	-73.55 ± 1.56	8.76 ± 0.47	-182.65 ± 1.56
57223.618991	V	67.911	8.52 ± 0.33	-73.26 ± 1.13	8.49 ± 0.33	-182.33 ± 1.13
57223.652210	V	68.094	9.81 ± 0.80	-73.00 ± 2.37	9.78 ± 0.80	-181.97 ± 2.37
57226.587173	V	92.238	12.68 ± 0.35	-88.06 ± 0.76	12.66 ± 0.35	-181.51 ± 0.76
57226.596991	V	92.348	13.15 ± 0.12	-88.92 ± 0.33	13.11 ± 0.12	-182.21 ± 0.33
57226.606177	V	92.451	13.03 ± 0.13	-88.72 ± 0.42	13.00 ± 0.13	-181.86 ± 0.43