

Detection of large color variation in the potentially hazardous asteroid (297274) 1996 SK

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Abstract Low-inclination near-earth asteroid (NEA) (297274) 1996 SK, which is also classified as a potentially hazardous asteroid, has a highly eccentric orbit. It was studied by multi-wavelength photometry within the framework of an NEA color survey at Lulin Observatory. Here, we report the finding of large color variation across the surface of (297274) 1996 SK within one asteroidal rotation period of 4.656 ± 0.122 hours and classify it as an S-type asteroid according to its average colors of $B - V = 0.767 \pm 0.033$, $V - R = 0.482 \pm 0.021$, $V - I = 0.801 \pm 0.025$ and the corresponding relative reflectance spectrum. These results might be indicative of differential space weathering or compositional inhomogeneity in the surface materials.

Key words: minor planets, asteroids: individual: PHA (297274) — techniques: photometric

1 INTRODUCTION

The main asteroid belt, located between the orbits of Mars and Jupiter, is composed of a population of small bodies with a primitive composition. The largest member, (1) Ceres, with a diameter of 914 km, will be visited by the DAWN spacecraft in 2015. In addition to (1) Ceres, the other asteroids, (2) Pallas (544 km), (4) Vesta (525 km) and (10) Hygiea (431 km) are the most massive examples, which might be classified as dwarf planets. Smaller objects, in the range down to km and sub-km, are mostly ejecta from impact cratering and/or catastrophic fragments via a collisional process (Bottke et al. 2002, 2005). Yoshida et al. (2004) discussed in detail the collisional evolution of asteroid families using the young Karin family as an example. They pointed out that photometric measurements of members of an asteroid family could provide important clues about the corresponding orbital evolution, internal composition and surface effects due to the process of space weathering (Clark et al. 2002; Sasaki et al. 2001). Because of the long-term gravitational perturbations of Jupiter and Saturn, some of the collisional fragments could be injected into orbits intercepting the orbits of terrestrial planets, which could potentially cause surface impact events. These scattered stray bodies are further classified as Amor asteroids if their perihelion distances (q) are between 1.3 AU and 1.017 AU, Apollo asteroids if their semi-major axis $a > 1.0$ AU and $q < 1.017$ AU, and Aten asteroids if $a < 1.0$ AU and the aphelion distance $Q > 0.983$ AU. As shown by Bottke et al. (2002),

the majority of these asteroids that cross the orbits of terrestrial planets come from the inner asteroid belt, even though some of them could have originated from the middle or outer asteroid belt, or from a comet.

Among the near-earth asteroids (NEAs), which are the general term for the Apollo and Aten asteroids, a number of them have non-zero probability of hitting Earth in the future. For example, it has been estimated that the total number of a subgroup of NEAs called potentially hazardous asteroids (PHAs) with $D > 100$ m is approximately 4700 ± 1450 (Mainzer et al. 2012). Close monitoring and in-depth investigations of the basic physical properties of PHAs, like sizes, shapes and compositions, are therefore important. In addition, PHAs could also represent a source of very valuable natural resources for space exploration and utilization because of their relatively easy access. With these key issues in mind, we have initiated a cooperative project at the Space Science Institute, Macau University of Science and Technology, together with the Astronomy Institute, National Central University, to produce a photometric survey of the taxonomical types of NEAs in low inclination orbits. In this work we report the results of an interesting object, (297274) 1996 SK, which is both an Apollo asteroid and PHA, based on observations taken on 2012 May 22 and 23, at Lulin Observatory, Taiwan. The observations are described in Section 2. The results of the data analysis are given in Section 3. In Section 4, a summary and discussion on the implications of the physical properties of the color variation will be given.

2 OBSERVATIONS

The criteria for selecting our first set of observational targets are (1) lack of prior measurements for the lightcurves and surface color, and (2) suitability of their optical brightness for time-series photometry. Asteroid (297274) 1996 SK has an absolute magnitude $H_v = 16.866$, with a semi-major axis $a = 2.434$ AU, eccentricity $e = 0.794$ and inclination $i = 1.962^\circ$. It was close to opposition and satisfied these conditions in May, 2012. With its perihelion distance of $q = 0.5$ AU and low inclination, (297274) 1996 SK is classified as a PHA. It was observed on 2012 May 22 and 23 by multi-filter photometry using the Lulin one-meter telescope (LOT). The CCD camera used for imaging was the PI-1300B, which has 1340×1300 pixels with an effective pixel scale of $0.516''$.

The observational log is given in Table 1. The filters used were broadband Bessel BVR_I , which have central wavelengths of 442, 540, 647 and 786 nm, respectively. The R -band exposure time was 60 seconds per frame and the measurement sequence consisted of 20 continuous frames for each run. In total, seven runs were made. However, due to unstable weather on May 23, much fewer data were acquired. Three sets of B , V and I filter measurements were made in the first half night of May 22, and another set was made in the next night. The Landolt standard star fields used for color calibration were SA107 on May 22 and SA109 on May 23 (Landolt 1992). The calibrated absolute magnitudes and colors of each star are listed in Table 2. The photometric accuracy is 0.044 on average. All targets were observed with airmass between 1.2 and 2.0 during the nights.

The standard method of data processing was performed by using the IRAF program (Image Reduction and Analysis Facility, supplied by National Optical Astronomy Observatories) with the *ccdproc* package for image reduction, *apphot* for photometry and *photcal* for flux calibration with standard stars.

Table 1 Observation Log of (297274) 1996 SK

Instrument	Filter	Exposure	Date	r^*	Δ^*	$\Phi^*(^\circ)$	Airmass
LOT	B, V, R, I	60 s/frame	2012 May 22	1.454	0.443	4.218	1.28–1.97
		60 s/frame	2012 May 23	1.467	0.456	4.987	1.28–1.53

Notes: * The quantity on 16:00 UT of each date; r : Heliocentric distance (AU); Δ : Geocentric distance (AU); Φ : The phase angle of Sun-target-observer.

Table 2 Mean Calibrated Absolute V -band Magnitudes and Colors of Landolt Standard Stars Observed on 2012 May 22 and 23

Star	V^α	V^β	$(B - V)^\alpha$	$(B - V)^\beta$	$(V - R)^\alpha$	$(V - R)^\beta$	$(V - I)^\alpha$	$(V - I)^\beta$
107 459	12.284	12.252	0.900	0.915	0.525	0.370	1.045	0.940
107 457	14.910	14.887	0.792	0.830	0.494	0.507	0.964	0.971
107 456	12.919	12.875	0.921	0.918	0.537	0.549	1.015	1.035
107 592	11.847	11.895	1.318	1.204	0.709	0.389	1.357	1.050
107 599	14.675	14.671	0.698	0.727	0.433	0.463	0.869	0.898
107 600	14.884	14.863	0.503	0.540	0.339	0.358	0.700	0.715
107 601	14.646	14.632	1.412	1.441	0.923	0.949	1.761	1.787
107 602	12.116	12.116	0.991	0.934	0.545	0.367	1.074	0.962
109 949	12.828	12.829	0.806	0.805	0.500	0.503	1.020	1.024
109 954	12.436	12.435	1.296	1.305	0.764	0.756	1.496	1.491
109 956	14.639	14.644	1.283	1.269	0.779	0.788	1.525	1.533

α : Magnitudes and color indices from Landolt (1992); β : Mean values measured from this study.

3 RESULTS

Figure 1 shows the raw lightcurves of (297274) 1996 SK observed on May 22 and 23. Differential photometry was acquired from the reference stars, which do not show variability over time. The reference stars were chosen so that they have R -band magnitude brighter than 17.0 in the USNO-A2.0 catalog.

Using the Plavchan algorithm (Plavchan et al. 2008) to compute the periodogram, the spin period of (297274) 1996 SK was found to be 4.656 ± 0.122 hours. The uncertainty in the frequency was estimated based on the method of Horne & Baliunas (1986). The periodogram and the folded lightcurve from the R -band measurements along with the rotation phase are shown in Figure 2. The lightcurve shows that (297274) 1996 SK has a rather smooth configuration. For an asteroid that has an ellipsoidal shape, the peak-to-peak variation (Δm) of the lightcurve can be used to calculate the ratio of the long axis to short axis (a/b) according to the formula $\Delta m = 2.5 \log(a/b)$.

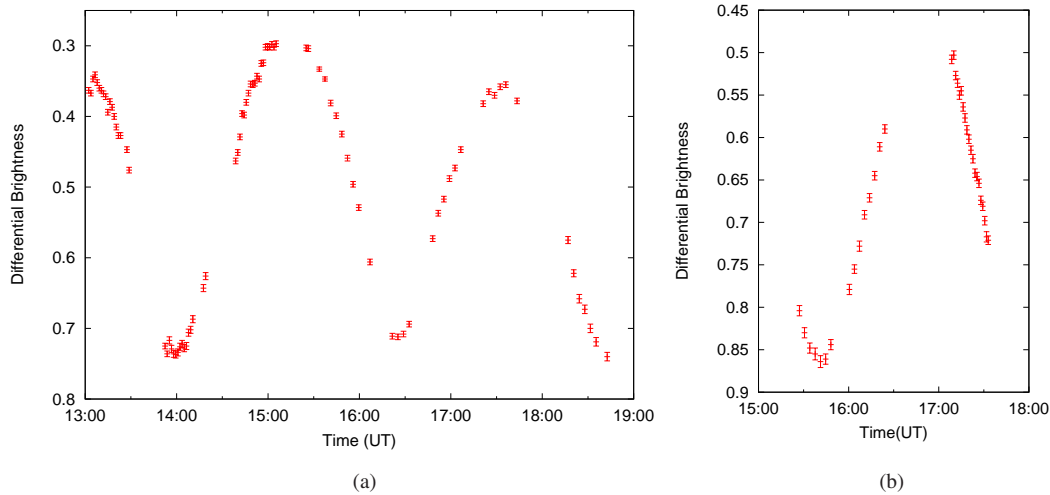


Fig. 1 The diagrams are the raw lightcurves of (297274) 1996 SK on (a) 2012 May 22 in terms of Universal Time (UT) and (b) 2012 May 23.

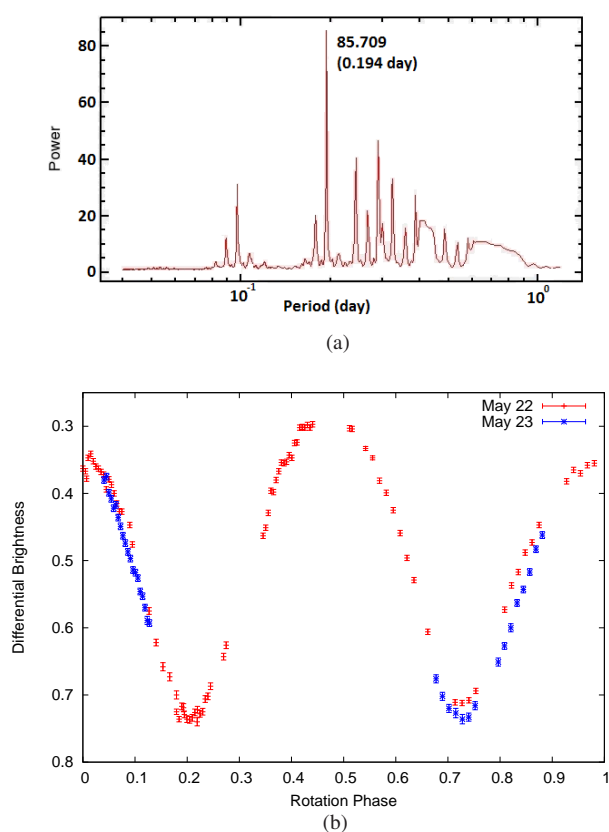


Fig. 2 The periodogram (a) and folded lightcurve (b) of (297274) 1996 SK consisting of both the data on 2012 May 22 and 23. The differential brightness is normalized to be consistent over two days.

From the lightcurve of (297274) 1996 SK, Δm was 0.44, which means that a/b is about 1.50. However, since the above a/b value is obtained by assuming that the asteroid was observed at an aspect angle (i.e., the angle between the line of sight and spin axis) of 90° , the actual axial ratio (a/b) may be more than that. The diameter of the asteroid (D) can be calculated by using the formula $\log D = 3.130 - 0.5 \log A - 0.2H$, where H is the absolute magnitude and A is the surface albedo (Yoshida et al. 2004). Assuming $A = 0.2$ (corresponding to the mean albedo of S-type asteroids) and $H = 16.866$ mag for (297274) 1996 SK, its diameter is 1.28 km. The long axis and the short axis can be computed to be 1.57 km and 1.05 km, respectively.

Table 3 summarizes the results of color measurements obtained on March 22 and 23. The multi-wavelength observations of (297274) 1996 SK at several different times allow us to estimate the color indices and to examine possible changes in its surface color during rotation.

Figure 3 displays the color variations at four phases of rotation observed on the two days. It reveals that both $B - V$ and $V - I$ colors vary significantly, but the change in $V - R$ is comparatively small. The maximum changes between the phase 0 to 0.5 for $B - V$, $V - R$ and $V - I$ are 0.258, 0.058 and 0.146, respectively. Such a large range of color variation indicates the possible presence of surface heterogeneity on (297274) 1996 SK.

The brightness magnitudes of the B , V and I bands follow the general trend of the R -band lightcurve. The average values of $B - V = 0.767 \pm 0.016$, $V - R = 0.482 \pm 0.021$ and $V -$

Table 3 A Summary of the Color Measurements of (297274) 1996 SK on 2012 May 22 and 23

UT_V	V	$B - V$	$V - R$	$V - I$	Airmass*
May 22					
13:30:36	16.259 ± 0.006	0.840 ± 0.012	0.520 ± 0.007	0.769 ± 0.008	1.553
13:31:58	16.270 ± 0.006	0.835 ± 0.012	0.511 ± 0.007	0.769 ± 0.008	1.546
14:20:46	16.390 ± 0.007	0.652 ± 0.013	0.459 ± 0.009	0.847 ± 0.009	1.373
14:22:10	16.386 ± 0.006	0.644 ± 0.012	0.475 ± 0.008	0.859 ± 0.008	1.370
15:07:03	16.063 ± 0.005	0.748 ± 0.010	0.472 ± 0.007	0.827 ± 0.007	1.297
15:08:26	16.065 ± 0.005	0.741 ± 0.010	0.478 ± 0.007	0.832 ± 0.007	1.296
May 23					
17:34:31	16.495 ± 0.007	0.906 ± 0.017	0.457 ± 0.009	0.707 ± 0.012	1.523
Mean	16.275 ± 0.016	0.767 ± 0.033	0.482 ± 0.021	0.801 ± 0.023	

Notes: * The airmass is displayed for the time when the V -band was observed because the $BVR I$ observations in each color measurement were obtained in sequential order during a short time interval of 11 min.

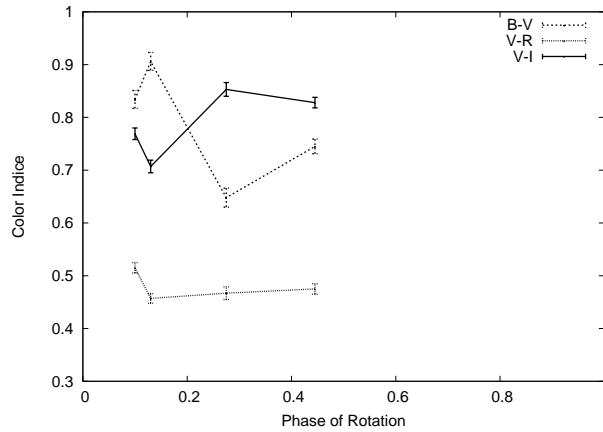


Fig. 3 Surface color variations of PHA (297274) 1996 SK over the phase of rotation.

$I = 0.801 \pm 0.025$ for (297274) 1996 SK can be compared with the known colors from different taxonomies of NEAs determined by previous observations archived in the “Data Base of Physical and Dynamical Properties of NEAs” published by the European Asteroid Research Node. These results are plotted in Figure 4, which shows the $B - V$ and $V - R$ terms that are generally classified into S-group (S, Q, R-types etc.), X-group (X, E-types etc.) and C-group (C, F, B-types etc.) of NEAs. This indicates that the surface color of (297274) 1996 SK is located on the boundary between S-group and X-group asteroids.

Figure 5 illustrates the average relative reflectance spectrum of (297274) 1996 SK obtained by subtracting the solar colors $B - V = 0.665$, $V - R = 0.367$ and $V - I = 0.705$ (Howell 1995) from its colors. It falls into the spectral region of S-type asteroids, so (297274) 1996 SK should be classified as a member of S-type objects. It is interesting to note that Rabinowitz (1998) reported color measurements of (297274) 1996 SK in October, 1996 with $V - R = 0.430 \pm 0.070$ and $V - I = 0.678 \pm 0.0587$. These values are close to the corresponding results obtained on May 23 (see Table 3 and Fig. 6), which are closer to the spectra of Q-type asteroids, but there are still significant differences from values taken at other times. The possible implication will be discussed later.

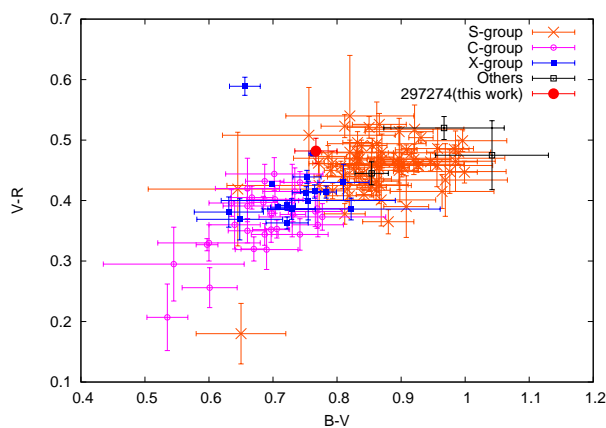


Fig. 4 The color-color diagram of NEAs with known color indices in different taxonomic types [α] and (297274) 1996 SK observed from this work. α means all references listed below (Betzler et al. 2010; Carbognani 2008; Dandy et al. 2003; Hapke 2000; Hergenrother et al. 2009; Hicks et al. 2011a,b, 2012a,b,c,d,e,f,g,h; Hicks & Dombroski 2012; Hicks et al. 2013a,b; Jewitt & Hsieh 2006; Jewitt 2013; Karashevich et al. 2012; Pieters et al. 2000; Ye 2011).

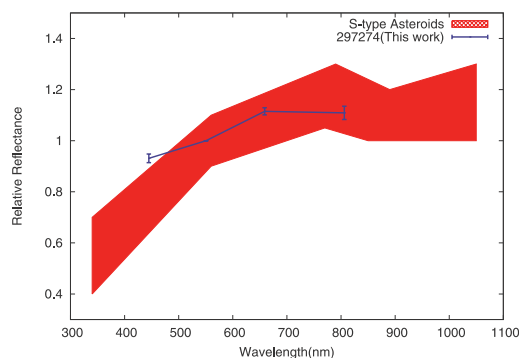


Fig. 5 Relative reflectance spectrum of (297472) 1996 SK from our data (*thick line*) in comparison with integrated spectra of S-type asteroids from data archived by the “Small Bodies Node.” The shaded area indicates the range of spectra from S-type asteroids.

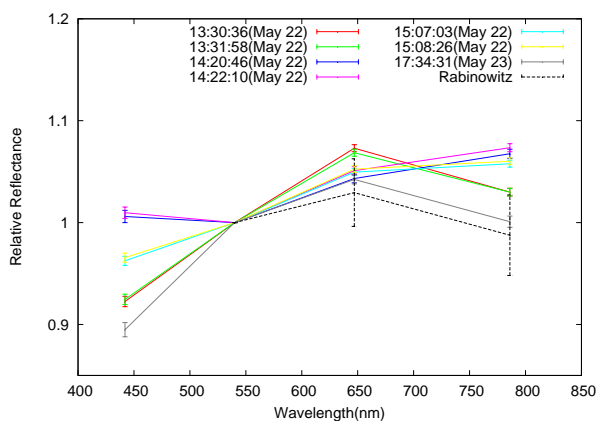


Fig. 6 A comparison of the relative reflectance spectra of (297274) 1996 SK taken at different times on March 22 and 23 with what was reported by Rabinowitz (1998).

4 SUMMARY AND DISCUSSION

Our observations of PHA (297274) 1996 SK at opposition in May, 2012 lead to the following conclusions:

- (1) The rotation period of this asteroid is found to be 4.656 ± 0.122 hours, i.e., well below the spin cutoff of 2.2 hours.
- (2) The amplitude of lightcurve variability is $\Delta m = 0.44$ indicating an elongated shape with the ratio of the long axis to the short axis (a/b) = 1.50, but this is possibly underestimated.
- (3) The average color indices of $B - V = 0.767 \pm 0.033$, $V - R = 0.482 \pm 0.021$, $V - I = 0.801 \pm 0.025$ and the corresponding surface reflectance means that (297274) 1996 SK belongs to the S-type taxonomic class. With the surface albedo assumed to be 0.2, which is a typical value of S-type asteroids, and $H_v = 16.866$, the projected long and short axes are 1.57 km and 1.05 km, respectively.
- (4) Over the rotation range of 133° , (297274) 1996 SK displays significant color changes which might imply the existence of a large change in mineralogical and/or compositional variation on its surface.

The detection of a large change in color is an important result of this work because it could mean that (297274) 1996 SK might contain various properties in its surface spectra. Because there is no information on the relation between the color measurements and the rotational phase in the work of Rabinowitz (1998), it is difficult to analyze the cause of these differences in color between our present results and his work. One thing is nearly certain; they could not be caused by a short-term effect of space weathering since the associated timescale is at least on the order of a million years (Vernazza et al. 2009). From this point of view, the existence of an inhomogeneous surface composition or the effect of differential space weathering would be the most viable explanation. The first scenario would mean that (297274) 1996 SK might contain the interface material from some differentiated region of its parent body after an impact disruption. The second scenario has been discussed by Yoshida et al. (2004) in the case of the color variation of (832) Karin – see also Sasaki et al. (2004, 2006a), Sasaki et al. (2006b) and Ito & Yoshida (2007). This could have come about by the process of micrometeoroid impact on young and older surface areas (Clark et al. 2002; Sasaki et al. 2004).

Figure 6 shows a comparison of relative reflectance spectra observed in different times, which vary from S-type to Q-type. It might be also related to the second scenario in that the asteroid has two parts, which are composed of weathered and un-weathered surfaces. It is a possibility that Rabinowitz (1998) measured the colors in the vicinity of the phase which we observed on May 23. Both possibilities mean that (297274) 1996 SK should not be covered by a homogeneous regolith layer of small particles. Could this surface cleansing be achieved by tidal breakup in previous close encounters with Earth or other terrestrial planets as proposed by Nesvorný et al. (2010)? These are issues we plan to investigate in the future.

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