Letter

Photometric observations of the potentially hazardous asteroid (99942) Apophis from Kawabe Cosmic Park

Fumi YOSHIDA,1,2,∗,† Ryo ISHIMARU,2 Osamu OKUDAIRA,2 Ko ISHIBASHI,2 Peng K. HONG,2 Takafumi MATSUI,2 and Myung-Jin KIM3

1University of Occupational and Environmental Health, Japan, 1-1 Iseigaoka, Yahata, Kitakyusyu, Fukuoka 807-8555, Japan
2Planetary Exploration Research Center, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan
3Korea Astronomy and Space Science Institute, 776 Daedeok-daero, Yuseong-gu, Daejeon 34055, Republic of Korea
∗E-mail: fumi-yoshida@med.uoeh-u.ac.jp
†Based on data using the 1 m telescope at Kawabe Cosmic Park operated by Hidakagawa-machi, Wakayama, Japan.

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Abstract

Asteroid (99942) Apophis is a potentially hazardous asteroid. The Korea Astronomy and Space Science Institute (KASI) recently proposed a rendezvous mission with Apophis, with a planned asteroid observation campaign to help determine the mission strategy in advance. In this study, we performed multicolor photometric observations of Apophis using the 1.0 m telescope at Kawabe Cosmic Park on 2021 March 10. The visible colors (g′, r′, and i′) of Apophis were obtained. The average colors of Apophis during our observations were as follows: g′ − r′ = 0.618 ± 0.021 and r′ − i′ = 0.180 ± 0.021. No significant color variation was observed in r′ − i′, but a slight variation may have occurred in g′ − r′ during the observation period of 4.63 hr. The obtained colors appeared to match those of an Sq-class asteroid, which is the asteroid type previously determined for Apophis by Binzel et al. (2009, Icarus, 200, 480) using the visible to near-infrared (0.55–2.45 μm) reflectance spectrum.

Key words: methods: observational — minor planet, asteroid: individual ((99942) Apophis) — techniques: photometric

1 Introduction

Asteroid (99942) Apophis is recognized as the most potentially hazardous near-Earth asteroid. Belonging to the Aten group, it was discovered in 2004 June and was predicted to impact Earth in 2068. However, recent observations via powerful radio antennas during the approaching passage of Apophis on 2021 March 5 provided an opportunity for the re-estimation of Apophis’s orbit, which subsequently ruled out the possibility of an Earth impact in 2068.

The Korea Astronomy and Space Science Institute (KASI) science team, which is planning a rendezvous
mission with Apophis (Moon et al. 2020), carried out an Apophis observation campaign from 2021 February to March. As Apophis was relatively close to Earth during this period, the asteroid could be observed even with a small telescope.

To date, the following physical characteristics of Apophis have been determined.

Diameter: The equivalent diameter is 0.34 ± 0.04 km according to Goldstone and Arecibo radar observations (Brozović et al. 2018) and the light-curve-derived shape (Pravec et al. 2014). In contrast, diameters of 375 ± 14 m (Müller et al. 2014) and 380–393 m (Licandro et al. 2016) have been reported based on infrared observations.

Albedo: A radar albedo of 0.25 ± 0.11 obtained from Goldstone data and an optical albedo (p_r) of 0.35 ± 0.10 were reported by Brozović et al. (2018). Licandro et al. (2016) also reported a p_r range of 0.24–0.33.

Rotation period: The rotation period is 30.56 ± 0.01 hr; however, the asteroid is in a state of non-principal axis rotation (tumbling) (Pravec et al. 2014). The amplitude of the light curve is approximately 1 mag; thus, an elongated shape model has been proposed (Pravec et al. 2014).

Spectrum type: Binzel et al. (2009) investigated the visible to near-infrared (0.55–2.45 μm) reflection spectra, finding that Apophis’s spectrum is similar to that of Sq-class asteroids, which most closely resemble LL ordinary chondrites. Reddy et al. (2018) recently presented a more detailed interpretation of the existing reflectance spectra. They supported the results of Binzel et al. (2009), showing more precisely that Apophis is an LL ordinary chondrite. Meanwhile, Lin et al. 2018 classified Apophis as S-type based on multicolor observations performed on 2013 January 18, 29, and 30. Although Apophis was S-type based on the criteria, the reflectance spectra of Apophis, shown in Appendix B of Lin et al. 2018, is between that of an S- and Q-type. If the classification had been fragmented, they may have classified Apophis as an Sq-type.

We carried out Apophis light curve observations and multicolor photometry at the Kawabe Cosmic Park in response to the observation campaign proposed by the KASI science team. As the weather was not stable during our observation period and the sky was only clear for the first day, we abandoned the objective of obtaining the light curve of the entire rotation phase and measuring the average magnitude at each observing band. Therefore, we report on the color change on the surface of Apophis, which has not yet been reported, using data from the first observation collected via multiple photometry. This paper is not only the first report on the color change on the surface of Apophis but also the first scientific report on multicolor photometric observations using the reorganized instrumentation of the 1.0 m telescope at Kawabe Cosmic Park.

2 Observation methods

We obtained the g’ − r’ and r’ − i’ colors of Apophis using the 1.0 m telescope at Kawabe Cosmic Park, located at 135°13’12”E and 33°53’27”N, at an altitude of approximately 100 m. We utilized the FLI PL09000 CCD camera field of view 11’ × 11’1, and the SDSS g’ (central wavelength 475.5 nm), r’ (628.5 nm), and i’ (769.5 nm) filters.2 We had planned to observe Apophis for several nights; however, the weather conditions allowed only one night of photometric observations on 2021 March 10. All analyses and results in this study were based on data collected on 2021 March 10.

The exposure time was 120 s for Apophis. The sequence of the filter exchange was r’-g’-r’-i’-r’-r’on. The photometric standard stars PG 0918+029D (RA, Dec) = (09h21m34s,

Table 1. Observation logs of Apophis.*

| MJD  | Air mass | Filters | Object         |
|------|----------|---------|----------------|
| 59283.400095 | 1.476 | r’-g’-r’-i’-r’-r’| PG 0918+029D |
| 59283.451635 | 1.402 | r’-g’-r’-i’-r’-r’| PG 0918+029D |
| 59283.461755 | 1.985 | r’-g’-r’-i’-r’-r’| PG 1047+003A |
| 59283.469884 | 1.863 | r’-g’-r’-i’-r’-r’| PG 1047+003A |
| 59283.487620 | 1.334 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.493787 | 1.313 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.506888 | 1.496 | r’-g’-r’-i’-r’-r’| PG 1047+003A |
| 59283.51087 | 1.190 | r’-g’-r’-i’-r’-r’| PG 0918+029D |
| 59283.523379 | 1.271 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.531319 | 1.267 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.539058 | 1.266 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.546973 | 1.269 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.555657 | 1.275 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.580384 | 1.317 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.588396 | 1.339 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.596466 | 1.365 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.603417 | 1.400 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.613204 | 1.436 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.621004 | 1.478 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.629201 | 1.339 | r’-g’-r’-i’-r’-r’| PG 0918+029D |
| 59283.638460 | 1.386 | r’-g’-r’-i’-r’-r’| PG 0918+029D |
| 59283.647057 | 1.671 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.654898 | 1.749 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.664255 | 1.860 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.672734 | 1.980 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.680634 | 2.113 | r’-g’-r’-i’-r’-r’| Apophis |
| 59283.689212 | 1.837 | r’-g’-r’-i’-r’-r’| PG 0918+029D |
| 59283.698840 | 1.984 | r’-g’-r’-i’-r’-r’| PG 0918+029D |
| 59283.745668 | 1.861 | r’-g’-r’-i’-r’-r’| PG 1047+003A |
| 59283.754476 | 1.994 | r’-g’-r’-i’-r’-r’| PG 1047+003A |

*Values in this table were collected at the center of the filter sequence.
Fig. 1. Portion of an image frame of Apophis (13′ × 7.6′).

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3 Results

The magnitudes of the asteroids observed at different airmasses were corrected using the extinction coefficient of each band. In table 2, merr is the photometric error measured in each band. In this observation, the asteroid was observed with the filter exchange sequence of r′–g′–r′–i′–r′.

As the time of imaging with different filters is different, when calculating the color of the asteroid from its brightness obtained with each band, we had to manage the light variation due to rotation of the asteroid. To minimize the effect of light variation, we interpolated the brightness of the asteroid in the r′ band taken before and after the g′ or i′ band, calculating the r′-band magnitude of the asteroid at the time of imaging with the g′ or i′ band. We then used the r′-band magnitude to derive the g′ − r′ and r′ − i′ colors. The r′ mag in table 2 is a value derived by interpolating the r′-band magnitude at the time when the g′ or i′ image was taken using the r′-band light curve. Colorerr was derived via appropriate error propagation from the photometric error of the magnitude for each band used in the color calculation. The average colors of Apophis during the observation were g′ − r′ = 0.618 ± 0.021 and r′ − i′ = 0.180 ± 0.021.

We also investigated color variations according to the rotation phase of Apophis. The principal rotation period of Apophis is 30.56 ± 0.01 hr (Pravec et al. 2014). As the duration of the observation was 4.63 hr, we were unable to investigate color variations over the entire surface of Apophis. No significant color variation was observed in r′ − i′ during the observation period of 4.63 hr, which corresponds to approximately 15% of the rotation phase of Apophis. For g′ − r′, a slight variation may have been observed. The time variations in g′ − r′ and r′ − i′ are listed in table 2.

Figure 2 shows the Apophis light curve and the changes in g′ − r′ and r′ − i′ with the rotation phase over the entire observation period. We note that the brightness of Apophis changed by at least 0.4 mag according to its light curve. In contrast, r′ − i′ was almost constant and g′ − r′ appeared to exhibit a periodic change. Further observations are required to reveal the color variations.

+02°46′39″) and PG 1047+003A (RA, Dec) = (10h50m09s, −00°01′08″) (Smith et al. 2002) were observed between observations of Apophis at several different air masses (see table 1), with an identical exposure time and filter sequence as Apophis. The data were used to determine the extinction coefficient of each band.

The telescope was operated using sidereal tracking. The sky motion of Apophis was approximately 3.4 arcsec min−1 during the observation. We changed the telescope pointing once to ensure that Apophis did not move out of the frame. Apophis moved between field stars in the frames; however, if it was too close to the field stars, we removed these frames prior to analysis. The average seeing size at the time of observation was 5′′–5′′.5 and the elongation of Apophis was approximately 9′′ in the 2 min exposures (see figure 1). During the observation, the solar phase angle of Apophis was approximately 30°. The heliocentric and geocentric distances were 1.089 au and 0.144 au, respectively.

Standard image reduction was performed, i.e. dark subtraction and flat fielding. The observation logs are summarized in table 1. Photometric reduction and aperture photometry were performed using IRAF and the associated APPHOT package.
followed by calculation of the relative reflectance of Apophis, as shown in figure 3. For comparison, the average relative reflectance of the four taxonomic types are also shown in figure 3. Among these, the relative reflectance from our observations appears to be closer to the Sq- and Q-types. This is consistent with the results of Binzel et al. (2009), Reddy et al. (2018), and Lin et al. (2018).

over the entire surface of Apophis. However, Apophis is currently moving away from Earth; the next opportunity to observe Apophis with a small telescope will be in 2029.

Furthermore, we subtracted the solar colors (Holmberg et al. 2006) from the $g'$ − $r'$ and $r'$ − $i'$ data for Apophis, followed by calculation of the relative reflectance of

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**Table 2. Photometry measurements of Apophis.**

| MJD       | Filter | mag   | $m_{\text{err}}$ | $r'$ mag | Color$^*$ | Color$_{\text{err}}$ | Note   |
|-----------|--------|-------|------------------|----------|-----------|-----------------------|--------|
| 59283.484543 | $r'$   | 17.087 | 0.010            |          |           |                       |        |
| 59283.486112 | $g'$   | 17.565 | 0.015            | 15.095   | 0.652     | 0.021                | $g'$ − $r'$ |
| 59283.487620 | $r'$   | 17.105 | 0.010            |          |           |                       |        |
| 59283.489129 | $i'$   | 17.340 | 0.014            | 15.084   | 0.182     | 0.020                | $r'$ − $i'$ |
| 59283.490696 | $r'$   | 17.059 | 0.010            |          |           |                       |        |
| 59283.492712 | $r'$   | 17.071 | 0.010            |          |           |                       |        |
| 59283.494279 | $g'$   | 17.536 | 0.015            | 15.088   | 0.639     | 0.021                | $g'$ − $r'$ |
| 59283.495787 | $r'$   | 17.095 | 0.010            |          |           |                       |        |
| 59283.535982 | $r'$   | 17.044 | 0.009            |          |           |                       |        |
| 59283.537551 | $g'$   | 17.447 | 0.013            | 15.052   | 0.608     | 0.018                | $g'$ − $r'$ |
| 59283.539058 | $r'$   | 17.023 | 0.009            |          |           |                       |        |
| 59283.552579 | $r'$   | 17.032 | 0.009            |          |           |                       |        |
| 59283.554148 | $g'$   | 17.478 | 0.013            | 15.040   | 0.647     | 0.018                | $g'$ − $r'$ |
| 59283.555657 | $r'$   | 17.015 | 0.009            |          |           |                       |        |
| 59283.557166 | $i'$   | 17.463 | 0.013            | 15.026   | 0.190     | 0.018                | $r'$ − $i'$ |
| 59283.558733 | $r'$   | 17.005 | 0.009            |          |           |                       |        |
| 59283.588396 | $r'$   | 17.067 | 0.009            |          |           |                       |        |
| 59283.589904 | $i'$   | 17.539 | 0.014            | 15.072   | 0.174     | 0.019                | $r'$ − $i'$ |
| 59283.591470 | $r'$   | 17.082 | 0.009            |          |           |                       |        |
| 59283.605417 | $r'$   | 17.120 | 0.010            |          |           |                       |        |
| 59283.606925 | $i'$   | 17.560 | 0.014            | 15.096   | 0.190     | 0.020                | $r'$ − $i'$ |
| 59283.608492 | $r'$   | 17.111 | 0.010            |          |           |                       |        |
| 59283.610127 | $r'$   | 17.096 | 0.010            |          |           |                       |        |
| 59283.611696 | $g'$   | 17.568 | 0.014            | 15.084   | 0.629     | 0.020                | $g'$ − $r'$ |
| 59283.613204 | $r'$   | 17.122 | 0.010            |          |           |                       |        |
| 59283.614713 | $i'$   | 17.583 | 0.014            | 15.086   | 0.164     | 0.020                | $r'$ − $i'$ |
| 59283.616280 | $r'$   | 17.108 | 0.010            |          |           |                       |        |
| 59283.617927 | $r'$   | 17.131 | 0.010            |          |           |                       |        |
| 59283.619496 | $g'$   | 17.582 | 0.015            | 15.095   | 0.616     | 0.021                | $g'$ − $r'$ |
| 59283.621004 | $r'$   | 17.131 | 0.010            |          |           |                       |        |
| 59283.622513 | $i'$   | 17.616 | 0.014            | 15.119   | 0.174     | 0.020                | $r'$ − $i'$ |
| 59283.624079 | $r'$   | 17.190 | 0.010            |          |           |                       |        |
| 59283.651822 | $r'$   | 17.379 | 0.013            |          |           |                       |        |
| 59283.653390 | $g'$   | 17.777 | 0.018            | 15.246   | 0.550     | 0.025                | $g'$ − $r'$ |
| 59283.654898 | $r'$   | 17.330 | 0.012            |          |           |                       |        |
| 59283.661179 | $r'$   | 17.382 | 0.013            |          |           |                       |        |
| 59283.662747 | $g'$   | 17.853 | 0.019            | 15.229   | 0.599     | 0.026                | $g'$ − $r'$ |
| 59283.664255 | $r'$   | 17.351 | 0.012            |          |           |                       |        |
| 59283.665764 | $i'$   | 17.814 | 0.017            | 15.227   | 0.165     | 0.025                | $r'$ − $i'$ |
| 59283.667331 | $r'$   | 17.399 | 0.013            |          |           |                       |        |
| 59283.680634 | $r'$   | 17.514 | 0.015            |          |           |                       |        |
| 59283.682144 | $i'$   | 17.940 | 0.020            | 15.336   | 0.203     | 0.029                | $r'$ − $i'$ |
| 59283.683711 | $r'$   | 17.597 | 0.015            |          |           |                       |        |

*The Colors column contains the value of $g' − r'$ or $r' − i'$, as indicated in the Note column.

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a planned KASI rendezvous mission (Moon et al. 2020), were performed using the 1.0 m telescope at Kawabe Cosmic Park. The average colors during the observation period of 4.63 hr were $g' - r' = 0.618 \pm 0.021$ and $r' - i' = 0.180 \pm 0.021$. These correspond to the average colors over approximately 15% of the rotation phase of Apophis. There was no significant color change in $r' - i'$ with rotation, but there may have been a periodic change in $g' - r'$. The relative reflectance of Apophis (wavelength range: $g'$, 475.5 nm; $r'$, 628.5 nm; $i'$, 769.5 nm) obtained in this study is consistent with the results obtained by Binzel et al. (2009) and Reddy et al. (2018), which suggest that Apophis is an Sq-type asteroid.

Although these observations did not cover the entire rotation phase of Apophis, the results further our understanding of some of Apophis’s surface properties, which will aid in planning the KASI rendezvous mission.

In addition to the FLI camera used in this observation, the 1.0 m telescope at Kawabe Cosmic Park is equipped with a three-color simultaneous imaging camera and a camera for occultation observations. Using these devices, the Kawabe Cosmic Park observatory can play an important role in observing the targets of future planetary exploration missions.

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