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Lightcurve, Color and Phase Function Photometry of the OSIRIS-REx Target Asteroid (101955) Bennu ☆

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ABSTRACT

The NASA OSIRIS-REx mission will retrieve a sample of the carbonaceous near-Earth Asteroid (101955) Bennu and return it to Earth in 2023. Photometry in the Eight Color Asteroid Survey (ECAS) filter system and Johnson–Cousins *V* and *R* filters were conducted during the two most recent apparitions in 2005/2006 and 2011/2012. Lightcurve observations over the nights of September 14–17, 2005 yielded a synodic rotation period of 4.2905 ± 0.0065 h, which is consistent with the results of Nolan et al. (2013). ECAS color measurements made during the same nights confirm the B-type classification of Clark et al. (Clark, B.E., Binzel, R.P., Howell, E.S., Cloutis, E.A., Ockert-Bell, M., Christensen, P., Barucci, M.A., DeMeo, F., Lauretta, D.S., Connolly, H., Soderberg, A., Hergenrother, C., Lim, L., Emery, J., Mueller, M. [2011]. Icarus 216, 462–475). A search for the 0.7 μm hydration feature using the method of Vilas (Vilas, F. [1994]. Icarus 111, 456–467) did not reveal its presence. Photometry was obtained over a range of phase angles from 15° to 96° between 2005 and 2012. The resulting phase function slope of 0.040 magnitudes per degree is consistent with the phase slopes of other low albedo near-Earth asteroids (Belskaya, I.N., Shevchenko, V.G. [2000]. Icarus 147, 94–105).

1. Introduction

Inner Solar System asteroids are the direct remnants of the original building blocks of the terrestrial planets. The presence of volatiles and complex organic compounds in primitive meteorites has indicated that carbonaceous asteroids are a source of volatiles and organics on Earth. Their chemical and physical nature, distribution, formation, and evolution are fundamental to understanding planet formation and the origin of life. Sample return from a carbonaceous asteroid is the goal of the NASA New Frontiers-class mission OSIRIS-REx. Scheduled for launch in 2016, OSIRIS-REx will rendezvous with and collect samples from the near-Earth Asteroid (101955) Bennu (formerly 1999 RQ$_{36}$). These samples will then be returned to Earth for analysis in 2023 (Lauretta et al., 2010).

An extensive multi-wavelength campaign was conducted both before and after the selection of Bennu as the target of OSIRIS-REx. Today Bennu is one of the best-characterized near-Earth asteroids ever. The asteroid was a 15th magnitude object when discovered on September 11, 1999 by the Lincoln Laboratory Near Earth Asteroid Research (LINEAR) survey (Williams, 1999). Since discovery there have been three opportunities to conduct ground-

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☆ Based on observations with the VATT: the Alice P. Lennon Telescope and the Thomas J. Bannan Astrophysics Facility and on observations obtained at the Southern Astrophysical Research (SOAR) telescope, which is a joint project of the Ministério da Ciência, Tecnologia, e Inovação (MCTI) da República Federativa do Brasil, the U.S. National Optical Astronomy Observatory (NOAO), the University of North Carolina at Chapel Hill (UNC), and Michigan State University (MSU).

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and space-based observations. During the discovery 1999–2000 apparition Bennu passed within 0.015 AU of Earth and peaked in brightness at 14th magnitude. During the 2005–2006 apparition it approached to within 0.033 AU of Earth and brightened to 16th magnitude. The most recent apparition extended from mid-2011 to mid-2012 when it approached to within 0.177 AU of Earth resulting in a much fainter peak magnitude of ~19th magnitude.

Bennu resides on a low delta-V orbit with respect to Earth making it easily accessible for sample return (Binzel et al., 2004). With a semi-major axis of 1.126 AU and perihelion of 0.897 AU, its orbit is classified as an Apollo-type. Currently the orbit of Bennu approaches to within 0.0027 AU (1.05 lunar distances) of Earth's orbit. This Minimum Orbit Intercept Distance (MOID) will steadily decrease resulting in a cumulative Earth impact probability of order 10^{-3} during the later decades of the 22nd century, making Bennu one of the most potentially hazardous known asteroids (Milani et al., 2009; Chesley et al., 2012).

Comparative analysis of visible to near-infrared reflectance spectra identifies Bennu as a spectral B class asteroid with spectral similarities to CI and/or CM meteorites (Clark et al., 2011). The dynamical evidence suggests an inner Main Belt, low inclination origin for Bennu. In particular, the Polana asteroid family, which is composed of B-type objects, is identified as a probable source (Campins et al., 2010).

Radar observations from the Goldstone and Arecibo radio telescopes found Bennu to be an irregular spheroid with a mean diameter of 493 m with evidence of a single boulder and no craters down to a resolution of 7.5 m (Nolan et al., 2013). There is also no evidence of any satellites larger than the resolution limit. The existence of an equatorial ridge, similar to those seen on other near-Earth asteroids such as (66391) 1999 KW_4, suggests that Bennu may have experienced a rotationally-induced splitting event in the past and could have been a binary asteroid at one point or have lost material migrating to the equator (Scheeres et al., 2006; Walsh et al., 2008; Jacobson and Scheeres, 2011; Walsh et al., 2012).

Extensive infrared observations covering near-, mid-, and thermal-infrared wavelengths find a very low albedo of 0.030–0.045 (Emery et al., 2010; Clark et al., 2011; Müller et al., 2012). Observations from the Spitzer and Herschel space telescopes also find a thermal inertia of $600 \pm 150\,\mathrm{J\,m^{-2}\,s^{-0.5}\,K^{-1}}$ (Emery et al., 2010) which is similar to other sub-kilometer near-Earth asteroids (Delbo and Tanga, 2009; Emery et al., 2010).

In this paper, we present characterization and discussion of the photometric properties of Bennu at visible wavelengths including determinations of rotation period, phase function, and colors in the Eight Color Asteroids Survey (ECAS) as well as in the Johnson–Cousins UBVRI filter systems.

2. Observations and data reduction

All lightcurve and phase function observations were obtained with University of Arizona Observatories telescopes located in southeastern Arizona during the 2005–2006 and 2011–2012 apparitions. Lightcurve and ECAS color photometry were acquired at the Kuiper 1.54-m reflector on the nights of 2005 September 14–17 UT. Additional Harris *R*-band phase function photometric measurements were obtained between 2005 and 2012 at the Vatican Observatory VATT 1.8-m reflector (on 2006 April 30 and 2012 May 15) and the Kuiper 1.54-m (all other dates). Dates and observational circumstances for the lightcurve photometry and ECAS/*VR* color photometry are presented in Table 1. Dates and observing circumstances for the phase angle photometry are presented in Table 4.

The observations from 2005 to 2006 were obtained with thinned Loral 2048 × 2048 CCDs with 15-μm pixels. The camera system used at the Kuiper 1.5-m was 'CCD32' while 'CCD26' was used at the VATT 1.8-m. During 2011–2012, the Mont4k was used on the Kuiper 1.5-m. The Mont4k is a Fairchild CCD486 4096 × 4097 CCD with 15-μm pixels (Randall et al., 2007). The instrument provides a FOV of 9.7′ × 9.7′ and plate scale of 0.42″/pixel when binned 3 × 3. The SOAR 4.2-m and SOI instrument were used in remote queue observing mode to collect *V*- and *R*-band data in order to determine the *V*–*R* color index. The SOAR Optical Imager (SOI) instrument is a mini-mosaic of two E2V 2 K × 4 K CCDs covering a 5.3′ × 5.3′ field-of-view. The images were binned 2 × 2 resulting in a plate scale of 0.154″/pixel.

All data were reduced with the IRAF software package. The images were bias-subtracted and flat-fielded with twilight and night sky flat images using tasks in the CCDRED package. The APPHOT package was used to perform aperture photometry of Bennu and photometric standard stars. In order to compensate for variable seeing and maximize signal-to-noise, the average FWHM was measured for each image and the photometric aperture was set to a radius of 2 ∗ FWHM (Howell, 1989). Sky background was measured with a circular ring aperture of radius 20 pixels and width of 10 pixels. The sky aperture was centered on the position of the measured source.

Photometric ECAS reference stars from Tedesco et al. (1982) and *V*- and *R*-band reference stars from Landolt (1992) were observed at multiple airmasses on each night in order to determine the photometric zero point and extinction coefficient. Standard star observations were reduced following the same method as the Bennu observations with the same 2 ∗ FWHM photometric apertures and sky background annuli.

All telescopes were tracked at the rate of the motion of the asteroid. During the 2011–2012 apparition Bennu was always fainter than $V = 19$. Due to its faintness a number of 30–60 s exposures were co-added along the motion of the asteroid in order to increase S/N on the Kuiper and VATT telescopes.

3. Results and analysis

3.1. Rotation period

Time-series photometry was obtained with the University of Arizona Kuiper 1.5-m over four consecutive nights on 2005 September 14–17 UT. Observations were made using multiple ECAS filters though the *w* (0.705 μm) filter was primarily used. Preliminary period determination was conducted with the Asteroid Lightcurve (ALC) software package (version 0.96) provided by P. Pravec. Observations were corrected for light travel time and changes in heliocentric distance (r), geocentric distance (Δ), and phase angle (α). Observing circumstances are listed in Table 1.

3.1.1. Period determination

A 10th order Fourier series fit finds a synodic rotation period of 4.2905 ± 0.0065 h with an amplitude of 0.16 magnitudes (Fig. 1). This result is twice the value of 2.146 h found in 1999 by Krugly et al. (2002). The discrepancy is likely due to their not observing a total rotation period during any of the 1999 nights. As a result, they incorrectly arrived at a sub-multiple (P/2) of the real period. By comparison, three of our four nights covered a complete rotation giving more credence to the 4.2905 h synodic period.

Observing geometry changed sufficiently over the course of the four nights to use the phase angle bisector (PAB) approximation to determine the difference between the synodic and sidereal period (Harris et al., 1984; Pravec et al., 2005). The minimum difference between the synodic and sidereal period was calculated at 0.0071 h. The lightcurve observations by themselves were not sufficient to determine the direction of rotation or whether the