FAST ROTATION OF A SUBKILOMETER-SIZED NEAR-EARTH OBJECT 2011 XA3

SEITARO URAKAWA1, KATSUHIKO OHTSUKA2, SHINSUKE ABE3, TAKASHI ITO4, AND TOMOKI NAKAMURA5

1 Bisei Spaceguard Center, Japan Spaceguard Association, 1716-3 Okura, Bisei, Ibara,
Okayama 714-1411, Japan; urakawa@spaceguard.or.jp
2 Tokyo Meteor Network, 1-27-5 Diasawa, Setagaya-ku, Tokyo 155-0032, Japan
3 Department of Aerospace Engineering, College of Science and Technology,
Nihon University, 7-24-1 Narashinodai, Funabashi, Chiba 274-8501, Japan
4 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
5 Department of Earth and Planetary Material Sciences, Graduate School of Science,
Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan

Received 2013 December 13; accepted 2014 March 3; published 2014 April 16

ABSTRACT

We present light curve observations and their multiband photometry for near-Earth object (NEO) 2011 XA3. The light curve has shown a periodicity of 0.0304 ± 0.0003 days (= 43.8 ± 0.4 minutes). The fast rotation shows that 2011 XA3 is in a state of tension (i.e., a monolithic asteroid) and cannot be held together by self-gravitation. Moreover, the multiband photometric analysis indicates that the taxonomic class of 2011 XA3 is S-complex, or V-type. Its estimated effective diameter is 225 ± 97 m (S-complex) and 166 ± 63 m (V-type), respectively. Therefore, 2011 XA3 is a candidate for the second-largest, fast-rotating, monolithic asteroid. Moreover, the orbital parameters of 2011 XA3 are apparently similar to those of NEO (3200) Phaethon, but F/B-type. We computed the orbital evolutions of 2011 XA3 and Phaethon. However, the results of the computation and distinct taxonomy indicate that neither of the asteroids is of common origin.

Key words: minor planets, asteroids: individual (2011 XA3 – Phaethon)

1. INTRODUCTION

The physical properties of asteroids provide us with important clues to clarify the compositions, strengths, and impact history of planetesimals that were formed in the early solar system. One representative method for investigating the physical properties of asteroids is the observation of their light curves. Light Curve observations are able to deduce the rotational status and shapes of asteroids. Past observations found that the diameters of most asteroids, rotating shorter than 2.2 hr, were smaller than 200 m (Pravec & Harris 2000). The fast-rotating asteroids have structurally significant tensile strength (so-called monolithic asteroids) because such asteroids must overcome their own centrifugal force. On the other hand, the slow-rotating asteroids larger than 200 m in diameter are maintained by their gravity, or the cohesive force of bonded aggregates (Richardson et al. 2009). Some such asteroids are rubble piles structurally (Abe et al. 2006). The near-Earth object (NEO), 2001 OE84, has the largest diameter among fast-rotating asteroids whose rotational periods are reasonably determined in the Asteroid Light Curve Database (LCDB) with quality code U ≥ 2 (Warner et al. 2009). When the geometric albedo $p_V$ is 0.18, its diameter and rotational period are ~700 m and 29.1909 minutes, respectively (Pravec et al. 2002). Hicks et al. (2009) has reported that the diameter and rotational period of the NEO 2001 FE90 are 200 m and 28.66 minutes, assuming the geometric albedo $p_V$ of 0.25. The diameter and rotational period of 2001 VF2 are 145–665 m and 1.39 hr (Hergenrother & Whiteley 2011). Despite searches devoted to their detection, few fast-rotating asteroids clearly larger than 200 m have been found (Pravec et al. 2000; Whiteley et al. 2002; Kwiatkowski et al. 2010a, 2010b). A numerical simulation indicates that fast-rotating asteroids are provided by the collisional disruption of parent bodies (Asphaug & Scheeres 1999). The relationship between the diameter and rotational period of ejecta in a laboratory impact experiment is similar to that of monolithic asteroids (Kadono et al. 2009). Moreover, explorations by Near-Earth Asteroid Rendezvous (NEAR) and Hayabusa spacecrafts have discovered that the shapes of boulders on NEOs (433) Eros (mean diameter of 16.84 km) and (25143) Itokawa (mean diameter of 0.33 km) resembled those of monolithic asteroids (Michikami et al. 2010). Therefore, monolithic asteroids are thought to be generated by impact craterings or catastrophic disruptions on the parent bodies. The Rosetta and the NEAR spacecrafts have determined the size-frequency distributions of boulders on the main belt asteroid (21) Lutetia (mean diameter of 95.76 km) and Eros (Thomas et al. 2001; Küppers et al. 2012). In the case of Lutetia, the largest boulder is ~300 m in diameter. The power law index, $\alpha$, of the cumulative size-frequency distribution, $N(>D) \propto D^{-\alpha}$, is about −5 and becomes shallower in regions smaller than 150 m, where $N$ is the number of boulders and $D$ is the diameter of boulders. A similar trend in slope is also shown for Eros. When we hypothesize that the size-frequency distributions of the boulders on Lutetia and Eros are recognized as the typical size-frequency distribution of impact ejecta, some ejecta smaller than 150 m can escape from the parent object and are likely to become small and fast-rotating asteroids. To confirm such a hypothesis, we need to clearly demonstrate how the fast-rotating asteroids inhabit from 150 m, or less, to subkilometer size through the examination of gradual but steady observational data accumulations.

The purpose of our study is to obtain the rotational period and the taxonomic class of NEO 2011 XA3. Since apparent brightness increases when NEOs closely encounter the Earth, the observations of NEOs are suitable for the elucidation of physical properties of subkilometer-sized asteroids, revealing that the taxonomic class confines the albedo and increases the estimated accuracy of the diameter. 2011 XA3 was discovered by the Panoramic Survey Telescope and Rapid Response System on 2011 December 15. The absolute magnitude, $H = 20.402 \pm 0.399$ (JPL Small-Body Database6), indicates that the object is a subkilometer-sized asteroid. The orbital parameters are reduced

6 http://ssd.jpl.nasa.gov/sbdb.cgi
to \( a = 1.48 \) AU, \( e = 0.93, i = 28.1^\circ, \Omega = 273.6^\circ, \) and \( \omega = 323.8^\circ \) based on more than 100 astrometric observations of this asteroid. Its orbit is apparently similar to those of NEO (3200) Phaethon, \( a = 1.27 \) AU, \( e = 0.89, i = 22.2^\circ, \Omega = 265.3^\circ, \) and \( \omega = 322.1^\circ, \) though there is a difference in the semi-major axis. Phaethon is the parent body of the Geminids, one of the most intense meteor showers of the year. Moreover, the Phaethon Geminid complex (hereafter, PGC) like 2005 UD and 1999 YC, which are objects dynamically linked with Phaethon and the Geminids, are proposed (Ohtsuka et al. 2006, 2008). In fact, the B/F/C taxonomy of 2005 UD and 1999 YC is shared by Phaethon (Jewitt & Hsieh 2006; Kinoshita et al. 2007; Kasuga & Jewitt 2008). We also investigate whether 2011 XA3 is a member of PGC with the multiband photometry and by calculating the orbital motion of both 2011 XA3 and Phaethon. In this paper, we deal with the following. In Section 2, we describe the observations and their data reduction. In Section 3, we mention the results of rotational period, taxonomic class, and the orbital simulation. In Section 4, we discuss the relationship between 2011 XA3 and Phaethon. Moreover, we focus on the heating effect due to the close perihelion distance of 2011 XA3. Finally, we summarize the physical properties of 2011 XA3 and mention the observation efficiency of subkilometer-sized NEO using small- and medium-aperture telescopes.

2. OBSERVATIONS AND DATA REDUCTIONS

2.1. Observations

We conducted the photometric observation of 2011 XA3 using the 1.0 m/3 telescope and the 0.5 m/2 telescope at the Bisei Spaceguard Center (BSGC).\(^7\) The observational circumstances and the states of 2011 XA3 are listed in Tables 1 and 2, respectively. Both telescopes were operated using the non-sidereal tracking mode. The detector of the 1.0 m telescope consisted of four CCD chips with 4096 \( \times \) 2048 pixels. We used one CCD chip to obtain as many images as possible by shortening the processing time. The field of view (FOV) for one CCD chip is \( 1^\circ 14 \times 0^\circ 57 \) with a pixel resolution of \( 1^\prime 0 \). The observations on 2011 December 16 focused on the astrometry using the 1.0 m telescope with an exposure time of 150 s in \( 2 \times 2 \) binning. Individual images were taken with a commercially available short-pass (long-wavecut) filter indicating \( W \) in Table 1 with and effective wavelength ranging from 490 nm to 910 nm. Though the observation took place over a short term of about 45 minutes, we also used the data for the period analysis of the light curve observations. The light curve observations were mainly carried out on 2011 December 19 using the 0.5 m telescope. The detector of the 0.5 m telescope is Apogee U42 CCD with 2048 \( \times \) 2048 pixels. The FOV is \( 1^\circ 67 \times 1^\circ 67 \) with a pixel resolution of \( 2^\prime 9 \). The images were obtained with an exposure time of 120 s using the \( W \) filter (Okumura et al. 2011). At the same time, multiband photometry was conducted using the 1.0 m telescope with Sloan Digital Sky Survey (SDSS) \( g', r', i', \) and \( z' \) filters. We also measured the flux of 83 standard stars from SDSS Data Release 8 (Aihara et al. 2011), in which stars were imaged around the same air mass with 2011 XA3. These objects have the \( r' \)-band magnitudes of about 14 mag to 16 mag and classification code 1 (= primary), quality flag 3 (=good), and object class 6 (= star). One set of observations was made using three consecutive images for each filter. The filters were changed in the following sequence: three \( g' \) images (2011 XA3) \( \rightarrow \) three \( g' \) images (standard stars) \( \rightarrow \) three \( r' \) images (2011 XA3) \( \rightarrow \) three \( r' \) images (standard stars) \( \rightarrow \) three \( i' \) images (2011 XA3) \( \rightarrow \) three \( i' \) images (standard stars) \( \rightarrow \) three \( z' \) images (2011 XA3) \( \rightarrow \) three \( z' \) images (standard stars).

2.2. Data Reduction

All images were debiased and flat-fielded. All observation time data were corrected using a light-traveled time from 2011 XA3 to the Earth. To obtain the light curve of 2011 XA3, we measured the raw magnitude of 2011 XA3 and four reference stars that were imaged simultaneously on the same field using the IRAF/APPHOT\(^8\) package. We set the radius of aperture photometry to \( \sim 1.7 \times \) FWHM for both 2011 XA3 and reference stars images, respectively. Since the reference star images are slightly elongated due to the non-sidereal tracking, the aperture radius is larger than that of 2011 XA3. We calibrated the magnitude fluctuations due to the change of atmospheric conditions using the procedures of Urakawa et al. (2011). Next, we performed the data reduction for multiband photometry. We evaluated the atmospheric extinction coefficients and conversion factors to standardize the SDSS system for each filter, in which each atmospheric extinction coefficient was calculated by the magnitude variations of the standard stars for the change in air mass. Extra-atmospheric instrumental magnitudes of both 2011 XA3 and the standard stars were derived using the obtained atmospheric extinction coefficient. The conversion factors were estimated by comparing the extra-atmospheric instrumental magnitudes with the cataloged magnitudes of standard stars. The brightness of 2011 XA3, in rotation, inevitably changes during the switching of the filter. We defined the time of recording the first \( g' \) image as the standard time, and then we calibrated an amount of brightness change for the standard time, which was estimated by the fitting curve of the light curve.

---

\(^7\) BSGC is administrated by the Japan Space Forum.

\(^8\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.
3. RESULTS

3.1. Rotational Period and Taxonomy

Assuming a double-peaked light curve, we carry out a periodicity analysis based on the Lomb–Scargle periodogram (Lomb 1976; Scargle 1982). The power spectrum from the periodogram shows a period of 0.0304 ± 0.0003 days (= 43.8 ± 0.4 minutes). The folded light curve is shown in Figure 1. Though the total observation duration was ~465 minutes over two nights, we were able to detect a number of same-shaped light curves due to a short rotational period. Therefore, the period is sufficiently reliable to study. We also obtain the maximum amplitude of 0.68 mag by the fourth-order Fourier series fitting curve. The light curve has a two-humped shape at the phase of ~0.7. The two-humped shape may result from the obscuration of surface regions by local topography, because the solar phase angle was ~40° during our observation. The taxonomic class and rotational color variation for 2011 XA3 are investigated by two color–color diagrams (Figure 2). In order to determine the taxonomic class of 2011 XA3, we should avoid the surface color variability due to surface heterogeneity of the rotating asteroid. However, the fast rotation of 2011 XA3 makes it difficult to obtain the roughly simultaneous four-color (g′, r′, i′, and z′) data. We found all of the color indexes only between the phases 0.6 and 0.8 in the light curve. The graph legend of “Phase 0.6–0.8” in Figure 2 indicates the color index of 2011 XA3 between the phases 0.6 and 0.8, and the graph legend of “Other” indicates the color index, which is calculated from the averaged g′, r′, i′, and z′ magnitude, except between the phases 0.6 and 0.8, even if four-color data were not obtained in the same phase. In other words, the graph legend of “Other” shows the color indexes obtained by assuming that there is no surface color heterogeneity. Though the color indexes in Figure 2 show that the taxonomy of 2011 XA3 is likely to be V-type, the photometric precision is insufficient to deny the possibility of S-type. We note that the classification of taxonomy, such as Q-, R-, or O-type, is difficult using this multiband photometry. Therefore, we conclude that 2011 XA3 is V-type or S-complex (S-, Q-, R-, O-, etc.). Since there is no clear difference between the color indexes of “Phase 0.6–0.8” and “Other” in Figure 2, the surface color of 2011 XA3 is macroscopically homogeneous.

3.2. Diameter and Construction

We estimated the absolute magnitude, HV, and the effective diameter for 2011 XA3. We deduced the apparent r′ magnitude of 2011 XA3 on 2011 December 19 was 16.35 ± 0.05 mag at the phase where the relative magnitude was zero in Figure 1. The apparent V magnitude is described in the following form (Fukugita et al. 1996):

\[ V = r' - 0.11 + 0.49 \left( \frac{(g' - r') + 0.23}{1.05} \right). \]  

Here, for our photometric precision requirements, the difference between AB magnitude and Vega magnitude in the V band is negligible. The reduced magnitude at the phase angle, α, is expressed as \( H(\alpha) = V - 5 \log_{10}(R \Delta) \), where \( R \) and \( \Delta \) are the heliocentric and geocentric distance in AU. The absolute magnitude is expressed as a so-called H–G function (Bowell et al. 1989):

\[ H_{V} = H(\alpha) + 2.5 \log_{10}[1 - G] \Phi_{1}(\alpha) + G \Phi_{2}(\alpha)], \]  

where \( G \) is the slope parameter depending on the asteroid’s taxonomy. When we apply \( G = 0.24 \pm 0.11 \) for S-complex and \( G = 0.43 \pm 0.08 \) for V-type (Warner et al. 2009), \( H_{V} \) becomes 20.56 ± 0.43 mag (S-complex) and 20.84 ± 0.25 mag (V-type), respectively.

---

**Figure 1.** Light curve of 2011 XA3. The rotation period is 0.0304 ± 0.0003 days (= 43.8 ± 0.4 minutes). The zero magnitude corresponds to the mean brightness of this asteroid.

**Figure 2.** Color–color diagram of 2011 XA3. The large capital letters in the figure represent the taxonomic classes of asteroids on the color–color diagram (Ivezić et al. 2001). The square indicates the averaged color index between 0.6 and 0.8 in the rotational phase. The filled circle indicates the averaged color index outside of phases 0.6 and 0.8.
respectively. An effective diameter of asteroids $D$ (in kilometer) is described as

$$D = 1329 \times 10^{-H_v/5} \times p_v^{-1/2},$$

where $p_v$ is the geometric albedo. Assuming the albedo of 0.209 ± 0.008 for S-complex (Pravec et al. 2012) and 0.297 ± 0.131 for V-type (Usui et al. 2013), we found the diameter of 225 ± 97 m (S-complex) and 166 ± 63 m (V-type), respectively.

Next, we estimate the axial ratio of 2011 XA3. There is a relation between the light curve amplitude and the phase angle as follows:

$$A(0) = \frac{A(\alpha)}{1 + m \alpha}.$$  

where $A(\alpha)$ is the light curve amplitude at the $\alpha^\circ$ phase angle and $m$ is the slope coefficient. In the case of an S-type asteroid, the $m$ value is 0.03 (Zappalà et al. 1990). Moreover, the $m$ value depends on the surface roughness (Ohba et al. 2003). The $m$ value is ~0.02 when we adopt the surface roughness 18° of Vesta as the representative for V-type (Li et al. 2013). Assuming that the axial ratio of 2011 XA3 is projected on the plane of the sky, the light curve amplitude is described through the lower limit to the true axial ratio of the body as

$$A(0) = 2.5 \log_{10} \left( \frac{a}{b} \right),$$

where $a$ and $b$ are, respectively, normalized long and short axis lengths. The amplitude of 2011 XA3 is 0.68 mag and the light curve data are obtained at the phase angle of ~40°. Therefore, the ratio of the long axis length to the short axis length is larger than 1.3 (S-complex) and 1.4 (V-type). The obtained physical properties of 2011 XA3 are summarized in Table 3. The construction of fast-rotating asteroids is thought to be a monolith. We confirm the validity for 2011 XA3. If 2011 XA3 is preserved only by self-gravity, the critical bulk density, $\rho$ (in g cm$^{-3}$), for a rubble pile asteroid can be written as

$$\rho = \left( \frac{3.3}{P} \right)^2 (1 + A(0)),$$

where $P$ is the rotational period in hours (Pravec & Harris 2000). Substituting the rotational period and the light curve amplitude of 2011 XA3 in Equation (6), the bulk density, $\rho$, becomes 26.3 g cm$^{-3}$. In addition to it, a more precise calculation, using a theory for cohesionless elastic–plastic solid bodies (Holsapple 2004), gives a lower limit on the bulk density of 20.5 g cm$^{-3}$ (P. Pravec 2014, private communication). These are incredible values as material of asteroids. Therefore, 2011 XA3 is not a rubble pile but evidently a monolithic asteroid.

We show the rotational period and the effective diameter in Figure 3 for registered asteroids in the LCDB and 2011 XA3. The effective diameter of 2011 XA3 on Figure 3 corresponds to the mean value between the diameter of the assumed S-complex asteroids and the diameter of the assumed V-type asteroids. The range of errors designates the upper limit diameter of the assumed S-complex asteroids and the lower limit diameter of the assumed V-type asteroids. Moreover, the rotational periods and effective diameters of 2001 OE84, 2001 FE90, 2001 VF2,
and NEO 2004 VD17 that have the possibility of being more than 200 m in diameter are plotted separately from the other asteroids in the LCDB. The nominal albedo in the LCDB for NEOs is 0.2. The absolute magnitude is deduced by assuming a $G$ of 0.15. The typical uncertainty of the absolute magnitude in the LCDB is around 0.4 mag (Hergenrother & Whiteley 2011).

We estimated the diameter for 2001 OE84 in Figure 3 based on the nominal value of the LCDB. For comparison, when we adopt the nominal albedo and $G$ for 2011 XA3, the effective diameter becomes $\sim 250$ m. Indeed, the diameter includes the significant uncertainty due to the adopted albedo and absolute magnitude. We added the error bar for 2001 VF2 and 2001 FE89 which are monolithic asteroids and have roughly the same diameter as 2011 XA3. The diameter and the error range of 2001 VF2 are adopted from the values of Hergenrother & Whiteley (2011). The diameter and the error range for 2004 VD 17 are well determined as 1.99 hr and $\sim 320$ m by the visible and near-infrared spectroscopy and the polarimetry. Though the rotational period indicates that the construction of 2004 VD 17 is categorized as a monolith, the slightly shorter rotation for the spin limit of 2.2 hr is not denied to be partially fractured (Richardson et al. 2002; De Luise et al. 2007). Therefore, 2011 XA3 is a candidate of the second-largest, fast-rotating, monolithic asteroid behind 2001 OE84.

### 3.3. Orbital Evolutions

We computed the orbital motions of 2011 XA3 and Phaethon, in order to compare their evolutionary behavior and to trace their genetic relationship if possible. Indeed, the orbital similarity criterion, $D_{SH}$ (Southworth & Hawkins 1963), between 2011 XA3 and Phaethon is 0.196, suggesting that 2011 XA3 has a possible association range for the orbit of Geminids, because a $D_{SH}$ of less than 0.2 indicates a typical associating range. Here, we performed the backward and forward numerical integration of the post-Newtonian equation of motion over $\pm 30,000$ yr from initial epoch, applying the “SOLEX,” version 11.01 package, developed by Vitagliano (1997) based on the Bulirsch–Stoer (BS) integrator. Then, we also computed other possible motions of each asteroid, generating multiple “clones” at the initial epoch, and integrating them. As well as the nominal osculating orbit, other clones had slightly different orbital elements, with the $\pm 1\sigma$ error based on observational uncertainties. We generated the clones on the basis of three possible values (nominal and $\pm 1\sigma$) for five orbital elements ($a$, $e$, $i$, $\Omega$, and $\omega$), thus yielding a total of 243 ($= 3^5$) clones, including the nominal one. Coordinates and velocities of the planets, Moon, and four quasi-planets, Ceres, Pallas, Vesta, and Pluto, regarded as point masses, were based on JPL’s DE/LE406-based ephemerides. We confirmed that the results of our numerical integrations did not significantly change when we used other integration methods that we have often applied in our studies, e.g., the Adams method. Our integrator can accurately process very close encounters by means of a routine that makes automatic time-step adjustments. Furthermore, truncation and round-off errors are almost negligible for our investigation here. Although the error of the orbital energy in the computation, using the BS method, shows a linear increase with time (Chambers 1999), it has an insignificant effect on our integration of $\pm 30,000$ yr. Hence, the SOLEX is rather reliable for dealing with our issue. As initial parameters, up to date osculating orbital elements were taken from S. Nakano’s (2012, private communication) data for 2011 XA3 and the JPL Small-Body Database for Phaethon, as listed in Table 4. Figure 4 shows the $\pm 30,000$ yr orbital evolutions of 2011 XA3 and Phaethon. Over 60,000 yr, we found both the asteroids to behave with a high degree of stability with long-period secular changes according to the $\omega$-cycle, i.e., Kozai circulation (Kozai 1962). The corresponding large-amplitude oscillations in $q$--$i$ and antiphase with $e$ occur, thus the period of their cycles, $P_q = P_i = P_\omega$, which is half that of the $\omega$-cycle, $P_\omega$ (Kinoshita & Nakai 1999), suggests a typical example of the Kozai circulation. It is interesting that a spread of the 2011 XA3 clones looks rather more compact than expected, in spite of the preliminary orbital solution of 2011 XA3, which is probably due to all the clones being in the stable region of the Kozai mechanism. The $\omega$-cycle of $\sim 29,000$ yr for 2011 XA3 is shorter than that of $\sim 37,000$ yr for Phaethon. The time-lag of the orbital evolutions (or $\omega$-cycles) between 2011 XA3 and Phaethon seems to be near 0 yr since $\omega$ values of both objects are almost consistent, and is therefore not as clear as an example of 2005 UD–Phaethon (Ohtsuka et al. 2006). The $D_{SH}$ between 2011 XA3 and Phaethon is presently around the minimum, in regards to the past 30,000 yr; however, it is somewhat large when we consider their genetic relation. Furthermore, the semi-major axis of 2011 XA3 is larger than those of any other PGC. In addition, our S-complex or V-type taxonomic classification for 2011 XA3 does not correspond to the B/F-type taxonomy of Phaethon (Licandro et al. 2007). Therefore, 2011 XA3 is not a PGC member.

### Table 4

| Object | 2011 XA3 | (3200) Phaethon |
|--------|----------|----------------|
| Osculation epoch (TT) | 2012 Mar 14.0 | 2012 Sep 30.0 |
| Mean anomaly $M$ | 25.819 ± 0.074 | 105.62501443 ± 0.000000026 |
| Perihelion distance, $q$ (AU) | 0.10746 ± 0.00012 | 0.139699845 ± 0.000000031 |
| Semi-major axis, $a$ (AU) | 1.4753 ± 0.0028 | 1.271609786 ± 0.000000021 |
| Eccentricity, $e$ | 0.92716 ± 0.00019 | 0.890100587 ± 0.000000025 |
| Argument of perihelion, $\omega$ | 323.7932 ± 0.0095 | 322.1318749 ± 0.0000097 |
| Longitude of ascending node, $\Omega$ | 275.6070 ± 0.0033 | 265.280951 ± 0.000010 |
| Inclination, $i$ | 28.051 ± 0.029 | 22.2342789 ± 0.0000076 |
| Number of astrometric positions | 139 | 2368 |
| Astrometric arc | 2011 Dec 15–23 (8 days) | 1983–2012 (10364 days) |
| rms residual | 0′.28 | 0′.49 |

Reference
- S. Nakano (2012, private communication)
- JPL316

---

**Table 4**

| Initial Orbital Parameters of 2011 XA3 and Phaethon Including Their $\pm 1\sigma$ Error Estimates (Equinox J2000) |
|-----------------------------------------------------------------------------------------------------------------|
| **Object** | **2011 XA3** | **(3200) Phaethon** |
|----------------------------------|----------------|-----------------|
| Osculation epoch (TT) | 2012 Mar 14.0 | 2012 Sep 30.0 |
| Mean anomaly $M$ | 25.819 ± 0.074 | 105.62501443 ± 0.000000026 |
| Perihelion distance, $q$ (AU) | 0.10746 ± 0.00012 | 0.139699845 ± 0.000000031 |
| Semi-major axis, $a$ (AU) | 1.4753 ± 0.0028 | 1.271609786 ± 0.000000021 |
| Eccentricity, $e$ | 0.92716 ± 0.00019 | 0.890100587 ± 0.000000025 |
| Argument of perihelion, $\omega$ | 323.7932 ± 0.0095 | 322.1318749 ± 0.0000097 |
| Longitude of ascending node, $\Omega$ | 275.6070 ± 0.0033 | 265.280951 ± 0.000010 |
| Inclination, $i$ | 28.051 ± 0.029 | 22.2342789 ± 0.0000076 |
| Number of astrometric positions | 139 | 2368 |
| Astrometric arc | 2011 Dec 15–23 (8 days) | 1983–2012 (10364 days) |
| rms residual | 0′.28 | 0′.49 |

**Reference**
- S. Nakano (2012, private communication)
- JPL316
4. DISCUSSION

4.1. Relationship with Phaethon

As we mentioned in the section above, based on the taxonomic analysis and the orbital calculation, 2011 XA3 is not a PGC member. Nevertheless, Phaethon, with nominal orbital elements, has more opportunities for close encounters with 2011 XA3 than with either the Earth or the Moon: 59 times within 0.05 AU in the past 30,000 yr with 2011 XA3, in comparison with 23 times with the Earth and Moon. This indicates the possibility of a collisional event. In recent years, an unexpected brightening and a comet-like dust tail were detected on Phaethon around the perihelion (Li & Jewitt 2013; Jewitt et al. 2013). This was because thermal fractures and decomposition cracking of hydrated minerals produced the dust ejections. Whether or not the amount of dust production was enough to supply the Geminids in steady state was not concluded. The sublimation of ice inside the PGC precursor object, due to the thermal evolution, has been suggested as a possible mechanism for the breakup of the PGC precursor object (Kasuga 2009). Alternatively, an impact event cannot be denied as a possible breakup mechanism. In addition, it is interesting that there exists a rotationally S-type-like color region on Phaethon’s surface (Cochran & Barker 1984). Therefore, we infer a priori that 2011 XA3 might be a remnant candidate impacted with a potential PGC precursor.

4.2. Surface Material

Intense solar radiation heating by the perihelion distance of 0.11 AU elevates the temperature of the surface material of 2011 XA3. Assuming 2011 XA3 as S-type asteroid $p_V = 0.209$ and $G = 0.24$, we can estimate the fast-rotating model surface temperature (Lebofsky & Spencer 1989), heating up to 900 K. 2011 XA3 is heated repeatedly when it comes close to the Sun and the duration at 900 K reaches at least 3000 yr (Figure 4), which could result in unique mineralogy of the surface material of 2011 XA3. A recent sample return mission from S-type asteroid Itokawa revealed that the continuous reduction reaction from FeO to metallic Fe, due to solar proton implantation to silicates, is one of the main mechanisms for developing reduction rims of the silicate crystals on the regolith surface (Noguchi et al. 2011). The reduction rims are responsible for the space weathering of S-type asteroids. The same reactions are expected to occur on the surface of 2011 XA3 at a much higher weathering rate, because the asteroid is much closer to the Sun and the reaction takes place at an elevated temperature. At a low-temperature silicate surface, the space weathering process creates the reduction rims, consisting of amorphous silicates and metallic iron, from FeO-bearing crystalline silicates (Noguchi et al. 2011). On the other hand, at a high-temperature silicate surface on the asteroid 2011 XA3, it is expected that the reduction rims thicken, the amorphous
silicates crystallize, and the small Fe particles integrate. Our results show that 2011 XA3 shows a reflectance spectrum feature intermediate between S- and V-type (Figure 2). A meteoritic analog for the surface composition of S-type corresponds to ordinary chondrites that consist mainly of olivine, pyroxene, and plagioclase. The following reaction would take place if olivine were present on the surface:

\[(\text{Mg, Fe})_2\text{SiO}_4 + \text{H}_2 \rightarrow \text{MgSiO}_3 + \text{Fe} + \text{H}_2\text{O}. \tag{7}\]

Since the reaction proceeds at high temperature, H\(_2\)O evaporates from the surface and MgSiO\(_3\) crystallizes to pyroxene for a short time. Therefore, the pyroxene/olivine ratio and Fe metal abundance are expected to increase on the surface of 2011 XA3. Interestingly, the increase of the pyroxene/olivine ratio is an opposite trend that is induced by the early thermal metamorphism that occurred in the interior of an S-type asteroid 4.6 billion years ago (Gastineau-Lyons et al. 2002). As for other components of S-type asteroids, pyroxene is more difficult to reduce than olivine (e.g., Singley & Grove 2003) and plagioclase does not contain FeO to be reduced. Therefore, a major change in mineralogy on the surface of “S-type” 2011 XA3 is an increase in the pyroxene/olivine ratio and Fe-metal abundance. If 2011 XA3 is a V-type asteroid whose meteorite analogs are HED meteorites, consisting mainly of pyroxene and plagioclase, then the mineralogical change is limited to further crystallization of individual minerals. The increase in the pyroxene/olivine ratio during high-temperature space weathering of S-type asteroids makes the mineral assemblage similar to V-type asteroids, which are rich in pyroxene. 2011 XA3 may be an S-type asteroid with a high pyroxene/olivine or a V-type asteroid. In either case, the reflectance spectrum is similar and difficult to distinguish, as we observed in the color–color diagram (Figure 2).

Last, we mention the possibility of Q-type asteroids because the color–color diagram of 2011 XA3 indicates that the intermediate between S- and V-type, and the population ration of Q-type asteroids, is more dominant in the NEO region than R- and O-type asteroids. The cause of 2011 XA3 being a monolith is thought to be the rotational fission of a rubble pile object due to the YORP effect, and the ejctor by impact craters or catastrophic disruption on the parent bodies. As we describe above, by heating the NEOs to 900 K space weathering is promoted. However, if the rotational fission and the ejection by impacts took place recently, the surface of 2011 XA3 has not been long exposed to the solar radiation. In that case, the surface color of 2011 XA3 might indicate Q-type.

## 5. SUMMARY

This study revealed the physical properties of 2011 XA3 through photometric observation. We detected the light curve periodicity to be 0.0304 ± 0.0003 days (≈ 43.8 ± 0.4 minutes). The light curve amplitude and rotational period clearly indicate that 2011 XA3 is a monolithic asteroid. The multiband photometric analysis indicated that the taxonomic class of 2011 XA3 was S-complex, or V-type. Assuming the typical albedo data for S- and V-type, we found the diameter of 2011 XA3 to range between 103–323 m, implying that it is the second-largest asteroid among fast-rotating asteroids. We also performed dynamical simulations for both 2011 XA3 and Phaethon that suggest they are not of common origin.

This study ensures the existence of subkilometer-sized, fast-rotating, monolithic asteroids, of which only a few have been discovered, including 2001 OE\(_{44}\), 2001 FE\(_{90}\), and 2001 VF\(_2\). However, the cumulative size-frequency distribution and the other physical properties for subkilometer-sized, fast-rotating, monolithic asteroids have not been well explained due to the shortage of physical observations of subkilometer-sized asteroids. To detect the fast-rotating, monolithic asteroids and deduce the physical properties, the photometric, multiband, and spectroscopic observations should be conducted immediately following the discovery of NEOs, which are listed on the NEO Confirmation Page of Minor Planet Center. Continuous observations of this kind lead us to clarify the population and size distribution of subkilometer-sized, fast-rotating, monolithic asteroids.

We acknowledge S. Nakano for his orbital solution of 2011 XA3. We also thank N. Takahashi, M. Yoshikawa, and the staff members of Bisei Spaceguard Center for their support of our observation. S. Hasegawa provided us with valuable advice regarding V-type asteroids. We also acknowledge the Japan Space Forum. Detailed and constructive review by Yolande McLean has considerably improved the presentation of this paper.

## REFERENCES

Abé, S., Mukai, T., Hirata, N., et al. 2006, Sci, 312, 1344
Aihara, H., Allende, P. C., An, D., et al. 2011, ApJS, 193, 29
Asphaug, E., & Scheeres, D. J. 1999, Icar, 139, 383
Bowell, E., Hapke, B., Domingue, D., et al. 1989, in Asteroids II, ed. R. P. Binzel et al. (Tucson, AZ: Univ. Arizona Press), 524
Chambers, J. E. 1999, MNRAS, 304, 793
Cochran, A. L., & Barker, E. S. 1984, Icar, 59, 296
De Luise, F., Perna, D., Dotto, E., et al. 2007, Icar, 191, 628
Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748
Gastineau-Lyons, H. K., McSween, H. Y., Jr., & Gaffey, M. J. 2002, M&PS, 37, 75
Hergenrother, C. W., & Whiteley, R. J. 2011, Icar, 214, 194
Hicks, M., Lawrence, K., Rhoades, H., et al. 2009, ATEJ, 216, 1
Holsapple, K. A. 2004, Icar, 172, 272
Ivezic, Z., Tabachnik, S., Rafikov, R., et al. 2001, AJ, 122, 2749
Jewitt, D., & Hsieh, H. 2006, AJ, 132, 1624
Jewitt, D., Li, J., & Agarwal, J. 2013, ApJL, 771, L36
Kadono, T., Arakawa, M., Ito, T., et al. 2009, Icar, 200, 694
Kasuga, T. 2009, EM&P, 105, 321
Kasuga, T., & Jewitt, D. 2008, AJ, 136, 881
Kinoshita, D., Ohtsuka, K., Sekiguchi, T., et al. 2007, A&A, 466, 1153
Kinoshita, H., & Nakai, H. 1999, CeMDA, 75, 125
Kozai, Y. 1962, AJ, 67, 591
Küppers, M., Moissl, R., Vincent, J-B., et al. 2012, P&SS, 66, 71
Kwiatkowski, T., Buckley, D. A. H., O’Donoghue, D., et al. 2010a, A&A, 509, A94
Kwiatkowski, T., Polinska, M., Loaring, N., et al. 2010b, A&A, 511, A49
Lebofsky, L. A., & Spencer, J. R. 1989, in Asteroids II, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Tucson, AZ: Univ. Arizona Press), 128
Li, J., & Jewitt, D. 2013, AJ, 145, 154
Li, J.-Y., Le Corre, L., Schroeder, S. E., et al. 2013, Icar, 226, 1252
Licandro, J., Campins, H., Mothé-Diniz, T., et al. 2007, A&A, 461, 751
Lomb, N. R. 1976, ApSS, 39, 447
Michikami, T., Nakamura, A. M., & Hirata, N. 2010, Icar, 207, 277
Noguchi, T., Nakamura, T., Kimura, M., et al. 2011, Sci, 333, 1121
Oba, Y., Abe, M., Hasegawa, S., et al. 2003, EP&S, 55, 341
Ohtsuka, K., Arakida, H., Ito, T., et al. 2008, M&PSA, 43, 5055
Ohtsuka, K., Sekiguchi, T., Kinoshita, D., et al. 2006, A&A, 450, L25
Okumura, S., Nishiyama, K., Urakawa, S., et al. 2011, PASJ, 64, 47
Pravec, P., & Harris, A. W. 2000, Icar, 148, 12
Pravec, P., Harris, A. W., Kušnirák, P., et al. 2012, Icar, 221, 365
Pravec, P., Hergenrother, C., Whiteley, R., et al. 2000, Icar, 147, 477
Pravec, P., Kušnirák, P., Šarounová, L., et al. 2002, in Proc. ACM. 2002, Large Coherent Asteroid 2001 OE\(_{44}\), ed. B. Warmbier (ESA SP-500; Noordwijk, Netherlands: ESA), 743

\(^9\) http://www.minorplanetcenter.net/iau/NEO/toconfirm_tabular.html
Richardson, D. C., Leinhardt, Z. M., Melosh, H. J., Bottke, W. F., Jr., & Asphaug, E. 2002, in Asteroids III, ed. W. F. Bottke, Jr. et al. (Tucson, AZ: Univ. Arizona Press), 501.

Richardson, D. C., Michel, P., Walsh, K. J., & Flynn, K. W. 2009, P&SS, 57, 183.

Scargle, J. D. 1982, ApJ, 263, 835.

Singletary, S. J., & Grove, T. L. 2003, M&PS, 38, 95.

Southworth, R. B., & Hawkins, G. S. 1963, SCoA, 7, 261.

Thomas, P. C., Veverka, J., Robinson, M. S., et al. 2001, Natur, 413, 394.

Urakawa, S., Okumura, S., Nishiyama, K., et al. 2011, Icar, 215, 17.

Usui, F., Kasuga, T., Hasegawa, S., et al. 2013, ApJ, 762, 56.

Vitagliano, A. 1997, CeMDA, 66, 293.

Warner, B. D., Harris, A. W., & Pravec, P. 2009, Icar, 202, 134.

Whiteley, R. J., Tholen, D. J., & Hergenrother, C. W. 2002, Icar, 157, 139.

Zappalà, V., Cellino, A., Barucci, A. M., et al. 1990, A&A, 231, 548.