CHAPTER 1

Lightcurves of the Karin family asteroids II.

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We present the first results of a long-term campaign of photometric observations of the Karin family asteroids. This family is very compact, and is supposed to be extremely young, with an estimated age of about 5.8 Myrs. The purpose of our observations is to determine the rotational properties, the colors and hopefully the overall shapes of the largest possible number of family members, since this might provide important information about the physics of the original break-up event that quite recently produced this family. The lightcurves that we have already obtained for twelve objects are of a generally good quality. We have also obtained some indication that the largest member of the family, (832) Karin, might exhibit some color variation across its surface. This might be an interesting result, but it has to be confirmed by future observations.

1. Introduction

The Karin family was recognized quite recently, with the estimated age of only about 5.8 million years.[1] This family consists of about 70 asteroids with sizes ranging from about 1.5 km to 20 km in diameter.[2] Most asteroid families are very old, and they have undergone significant collisional and dynamical evolution since their formation, which likely masks the properties of the original collisions. But the remarkably young Karin family asteroids possibly preserve some signatures of the original collisional event that formed the family. This extraordinary feature of the Karin family provides us with several significant opportunities for the research of young asteroids such as potentially detecting tumbling motion, obtaining distribution of rotation period, and estimating the shapes of newly-created asteroid fragments.

Driven by these motivations, we have begun a program since November 2002 to observe the lightcurves of all the Karin family members. The potential result derived from our observation could be a strong constraint on laboratory and numerical experiments of collisional fragmentation.[3] In the first part of this article, we report our preliminary results concerning the lightcurves of the twelve Karin family members, though detailed statistical discussions will be presented in a separate paper.[4] Next, we move on to the result of our multicolor observation of the largest member of this family, (832) Karin. Since (832) Karin is the largest fragment of a recent asteroid disruption, it is possible that this asteroid has both young and old surfaces together: a young surface that was exposed from the interior of the parent body by the family-forming disruption, and an old surface that used to be the parent body surface exposed to space radiation over a long time. If the mixture of these two surfaces is detected by our multicolor observation, it could have significant implication for research on the evolution of asteroid surface spectra.

We briefly report the lightcurves of several Karin family members in Section 2. In Section 3 we describe our multicolor observations of (832) Karin in 2003 as well as in 2004. The method and results of our multicolor observations are summarized in this section. Section 4 goes to some discussions and interpretation of the results.

2. Lightcurves of the Karin family asteroids

For our lightcurve observations of the Karin family asteroids, we have used eight telescopes: The 90-inch Bok reflector at the Steward Observatory (AZ, USA), the 1.8-m Vatican Advanced Technology Telescope (AZ, USA), the 1.5-m telescope at Maidanak Observatory (Uzbekistan), the 1-m telescope at Lulin Observatory (Taiwan), the 1-m Schmidt telescope at Kiso Observatory (Japan), the 0.5-m telescope at the National Astronomical Observatory (Japan), the 0.4-m telescope at Fukuoka University of Education (Japan), and the 0.25-m telescope at Miyasaka Observatory (Japan). We used R-band filter all through the observations because asteroids are generally brightest in the R-band wavelength. Exposure time was 2–8 minutes so that asteroids had the appearance of point sources. We also observed several Landolt photometric standard stars[5] to determine extinction coefficients. Photometric reduction and aperture photometry were performed using the APPHOT/IRAF package. Magnitudes of the asteroid at different air masses were corrected by the extinction coefficient at each band. Asteroid brightness was measured with respect to that of the field stars in the USNO-A2 catalogue in the same frame.

Lightcurves from the photometric data are constructed following the procedure proposed by Harris and Lupishko.[6] Principally it is an iterative repetitions of frequency analysis and fitting to Fourier series. We use Lomb's Spectral Analysis[7] or the WindowCLEAN analysis [8] for the frequency analysis of lightcurves, and fit the data with an eighth order Fourier series.[9] We have to be particularly careful when we combine the lightcurves of several observing runs because they generally have different zero-level magnitudes. We combine the lightcurves of multiple observing runs based on these zero-levels to obtain our final result.

(832) Karin was observed in 1984 by Binzel.[10] Here we report new observations of (832) Karin at 2003 opposition and additional observations at 2004 opposition (see also Section 3). We report lightcurves for the first time for the rest of the selected objects. Moreover, 1999 CK16 was observed at two oppositions (2002 and 2004). All this information together with additional information obtained from future lightcurve data will be used to increase our knowledge of these objects, not only of their rotational periods, but of other features such as their pole axis.[11]

All the lightcurves that we have determined are displayed in Figs. 1 and 2. The resulting rotation periods, peak-to-peak variations of the lightcurves, and the solar phase angles are listed in Table 1. Looking at Figs. 1 and 2, it is obvious that some of the asteroids, such as Einer, 1997 GT36, or Svojsik, need more and better observations to obtain more accurate lightcurves. Our preliminary data analysis, though the result is not apparent from the figures, indicates that a few members might perform so-called tumbling motions (i.e. non-principle axis rotation).

3. Multicolor observations of (832) Karin

We twice performed multicolor observations of the largest member of the Karin family, (832) Karin, in September 2003, and in September 2004 after an interval of one year.

3.1. *Observation procedure*

For our multicolor observation of (832) Karin, we used the 2k × 2k CCD of the 1.8-m Vatican Advanced Technology Telescope (VATT) on Mt. Graham, Arizona, USA. Our first observation was performed in September

Table 1. Some properties of the Karin family asteroids. P is rotation period (hour), δM is peak-to-peak variation magnitude, and α is the solar phase angle (degree). Lightcurves of all asteroids are shown in Fig. 1 and Fig. 2. For (832) Karin and (28271) 1999CK16, we had two opportunities to observe their lightcurves: 2003 and 2004 for (832) Karin, 2002 and 2004 for (28271) 1999CK16.

Asteroid	P	δM	α	Figure #
(832) Karin (2003)	18.35 ± 0.02	0.61 ± 0.02	1–14	1(a)
(832) Karin (2004)	18.35 ± 0.02	0.61 ± 0.01	21.7	1(b)
(28271) 1999CK16 (2002)	5.64 ± 0.06	0.08 ± 0.04	3.1	1(c)
(28271) 1999CK16 (2004)	5.64 ± 0.03	0.21 ± 0.02	8.4	1(d)
(4507) 1990FV	6.58 ± 0.04	0.49 ± 0.03	7.9	1(e)
(16706) Svojsik	6.72 ± 0.07	~ 0.3	12.7	1(f)
(10783) 1991RB9	7.33 ± 0.04	0.50 ± 0.02	5.6	1(g)
(40912) 1999TR171	7.81 ± 0.08	0.35 ± 0.02	1.5	1(h)
(69880) 1998SQ81	9.14 ± 0.01	0.08 ± 0.01	5.3	2(a)
(13765) Nansmith	10.51 ± 0.01	0.09 ± 0.02	11.3	2(b)
(11728) Einer	13.62 ± 0.05	0.19 ± 0.01	10.3	2(c)
(71031) 1999XE68	20.19 ± 0.41	0.45 ± 0.04	5.0	2(d)
(7719) 1997GT36	29.56 ± 0.60	0.50 ± 0.02	18.6	2(e)
(43032) 1999VR26	32.51 ± 0.04	1.00 ± 0.06	10.6	2(f)

2003, and the second one was done in September 2004. Some of the major parameters used during this observation are listed in Table 2.

The procedures of these two observations are entirely the same. We use B, V, R, and I-filters whose wavelengths are centered at 4359.32Å, 5394.84Å, 6338.14Å, and 8104.87Å. In order to remove the effect of magnitude variation due to an asteroid's rotation that could affect the asteroid's color, we always take a pair of R-band images before and after we use other filters. Hence we define one observation sequence as RR–BB–RR–II–RR–VV–RR. Each of the R magnitudes is interpolated (or extrapolated) to the value at the same UT when we use other filters for comparison.

Since the exposure time for each image is 2–3 minutes, each of these sequences takes about 40 minutes. While taking R-band images consecutively for the lightcurve observation that we described in the previous section, we performed the multicolor observing sequence several times with intervals of a few hours. Since we were able to observe this asteroid for 4–5 hours every night, we repeated this procedure seven times in our 2003 observation and ten times in our 2004 observation. As a result, we obtained color differences such as V–I or B–V. We calculated the errors of these values from the photometry error of each of the B, V, R, and I images: For example, the error of V–I is $\sqrt{\delta V^2 + \delta R^2}$ where δV and δR are the photometry errors of the V and R images.

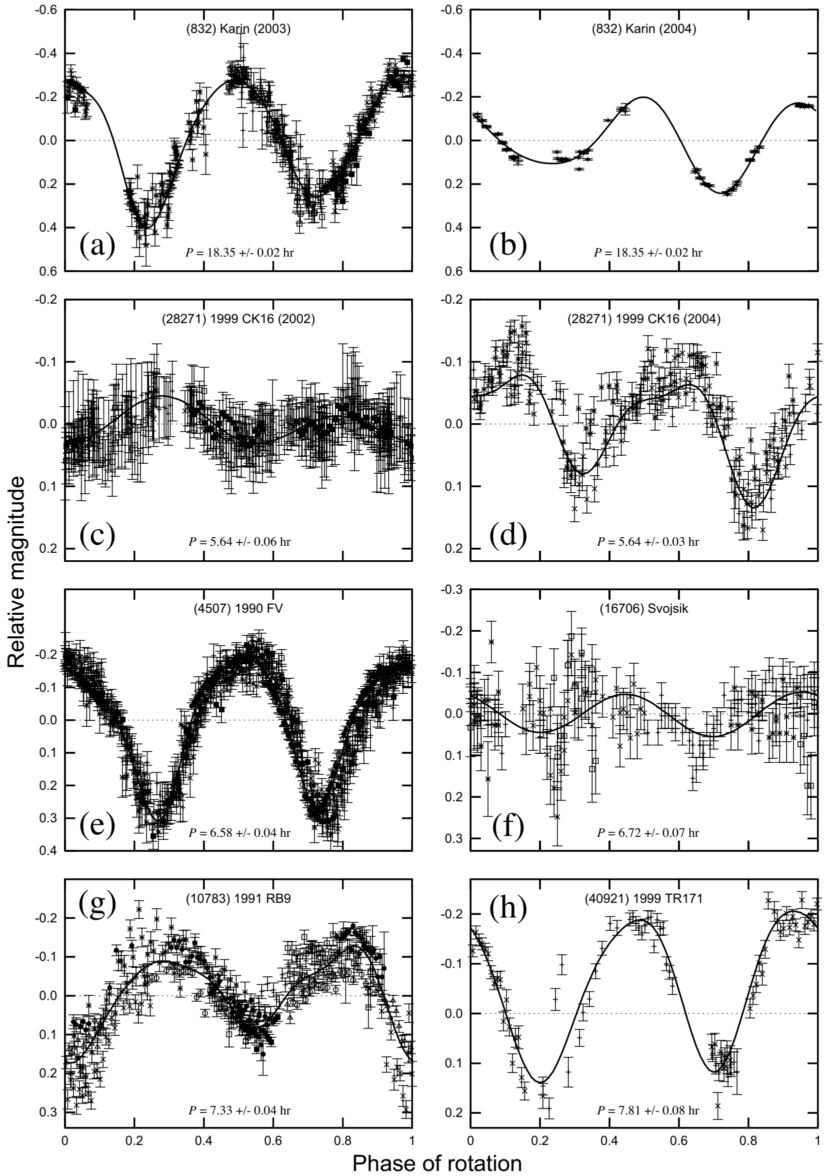

Fig. 1. Lightcurves of six Karin family members.

3.2. *Observation results*

The resulting time variation of the surface color of (832) Karin in our 2003 observation[12] is summarized in Fig. 3(b). For reference, we show

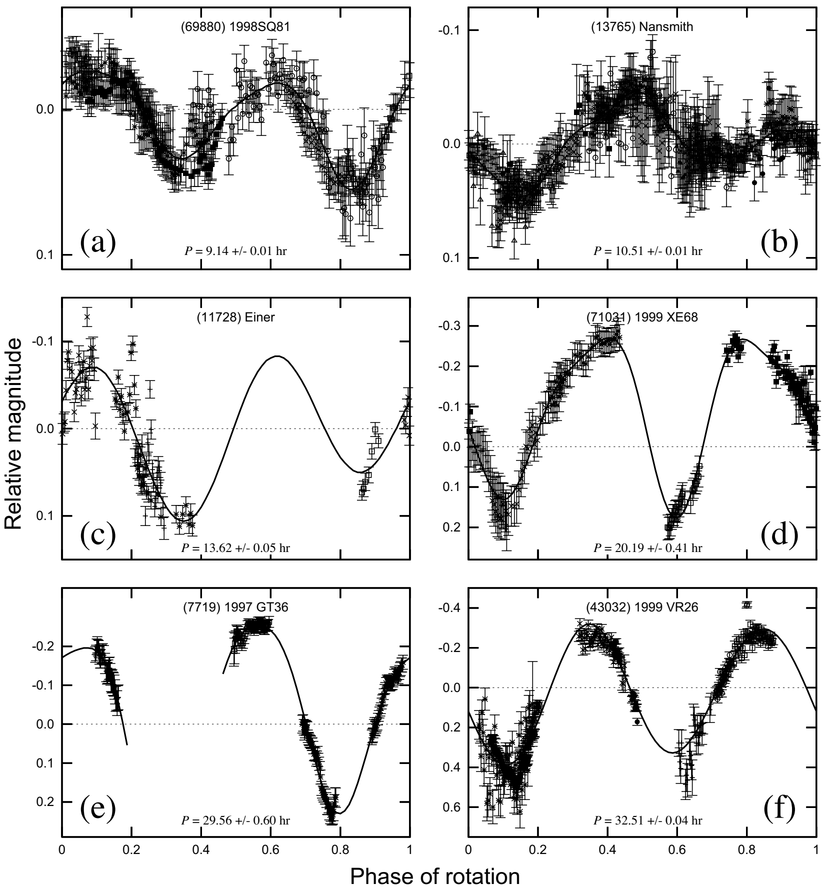

Fig. 2. Lightcurves of another six Karin family members.

the lightcurve of this asteroid during the summer to autumn of 2003 obtained from a couple of telescopes including VATT (Fig. 3(a), equivalent to Fig. 1(a)). As seen in Fig. 3(b), we obtained the color data of this asteroid for over more than 80% of its rotational period at this observation.

The results of our 2004 multicolor observation are summarized in Fig. 3(e), as well as this asteroid's lightcurve obtained at this observation (Fig. 3(d), equivalent to Fig. 1(b)). This time we obtained the color data of this asteroid over almost the entire period of its rotation.

Looking at Fig. 3(b), which shows major results of the 2003 observation, the $V{-}R$ value is almost constant throughout the rotation. The change in

Table 2. Major parameters during our multicolor observations of (832) Karin. From the left, UT referring to the mid-time of each night, distances (AU) between the asteroid and the Sun (r) and the Earth (Δ), the ecliptic longitude (λ) and latitude (β), and the solar phase angle (α) of this asteroid. The unit of angles is degree.

Date (UT)	r	Δ	λ	β	α
20030926.19	2.666	1.803	324.8	1.5	13.36
20030927.19	2.666	1.811	324.7	1.5	13.68
20030928.17	2.665	1.819	324.6	1.5	13.99
20030929.17	2.665	1.827	334.5	1.5	14.30
20040922.44	2.706	2.442	63.8	0.2	21.71
20040923.44	2.707	2.429	64.1	0.2	21.68
20040924.45	2.707	2.417	64.3	0.2	21.64

B–V is slight in the early phase of rotation, then gradually becomes larger during the period of this observation. What most draws our attention in this data is an obvious anomaly in V–I value at phase ~ 0.2. To inspect this anomaly in more detail, we calculated the wavelength dependence of the relative reflectance of this asteroid by subtracting the solar colors of B–V=0.665, V–R=0.367, and V–I=0.705[13] from our original color data. The relative reflectance is normalized at a wavelength of the V filter, 5394.84Å. Then, as shown in Fig. 3(c), we found that the relative reflectance of this asteroid at long wavelengths (i.e. in the I-band) is much larger at the rotation phase ~ 0.2 than at other phases. The steep slope of the relative reflectance in Fig. 3(c) at phase ~ 0.2 should be called "red", as is often seen in regular S-type asteroids.[14,15]

Note that the magnitude errors in Fig. 3(b) look smaller than the magnitude errors in Fig. 3(a), which might seem strange. This is because we have used lightcurve data from many other smaller telescopes in Fig. 3(a), not only that from the 1.8-m VATT, while we drew Fig. 3(b) with only the data from the 1.8-m VATT. If you compare Fig. 3(d) and Fig. 3(e) for both of which we used the only data from VATT, you can see that the magnitude errors in Fig. 3(e) are as large as, or larger than, those in Fig. 3(d), which seems reasonable.

In our 2004 observation results, lightcurve of (832) Karin (Fig. 3(d)) looks different from what we saw a year before (Fig. 3(a)). This is reasonable because the relative orbital configuration of (832) Karin and the Earth is different from our 2003 observation. A remarkable fact of this observation is that we no longer saw a particularly "red" surface on this asteroid. Time variation of relative magnitude of V–I in Fig. 3(e) does not show any definite anomaly, unlike what was seen in Fig. 3(b) in September 2003.

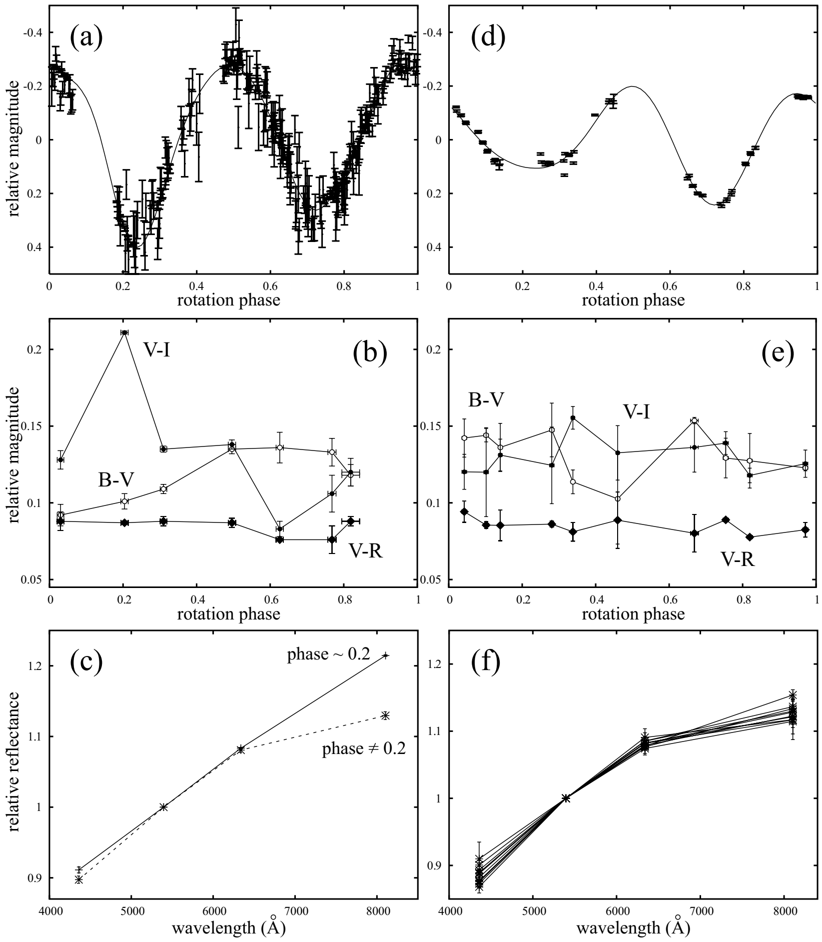

Fig. 3. Lightcurve, relative magnitude, and wavelength dependence of relative reflectance of (832) Karin in our two observations at VATT in September 2003 and September 2004. The left three panels (a)(b)(c) are for the 2003 observation, and the right three panels (d)(e)(f) are for the 2004 observation. (a) and (d): Lightcurve. Note that in (a) we have included the data not only from VATT in September 2003, but the data from other smaller telescopes with larger errorbars. (b) and (e): Relative magnitude of B–V, V–I, and V–R. (c) and (f): Wavelength dependence of relative reflectance in B-, V-, R-, and I-band normalized at the V-band wavelength, 5394.84Å.

The wavelength dependence of the relative reflectance of this asteroid in Fig. 3(f) is more like that of phase $\neq 0.2$ in Fig. 3(b) in September 2003 than that of phase ~ 0.2. In a word, (832) Karin did not show a mature (red) surface in September 2004, exhibiting only a fresh surface with low relative reflectance at longer wavelengths.

4. Discussion

4.1. *Interpretation of the observing results*

So far we do not have a very good explanation for the unexpected color mismatch between the 2003 and 2004 multicolor observations. The key to solving this problem might lie in the difference in the amplitude of two lightcurves in Fig. 3(a) and (d): The lightcurve of September 2003 has a larger amplitude than that of September 2004. In general, when we look at an asteroid from its pole direction, especially at around opposition, the brightness of the asteroid can be nearly constant. Considering the relative orbital configuration between (832) Karin and the Earth, we have drawn a rough and possible schematic figure for deducing why we did not see a red surface on this asteroid in our 2004 observation (Fig. 4). Following Sasaki et al.[16] considerations, (832) Karin might be a cone-shaped asteroid fragment with a small portion of mature surface that used to be part of the parent body's surface. If the rotation axis of this fragment is highly inclined, nearly parallel to its orbital plane as in Fig. 4, it might account for the fact that we see its red surface occasionally as it rotates at the position of September 2003. If the orbital configuration, the spin axis orientation, and the location of the red surface are as in Fig. 4, it might also be that we could not see any red surface on this asteroid in September 2004 when we were supposed to look at this asteroid from nearly the pole direction. This geometric configuration could explain why the lightcurve amplitude is smaller in our 2004 observation than in the 2003 observation, depending on the shape of this asteroid.

The surface color variation of (832) Karin suggests that this asteroid possesses an inhomogeneous surface. Judging from the recent breakup history of the Karin family, a part of it could be fresh and newly exposed by the family-forming disruption. Meanwhile there could be a mature surface, once the parent body surface, and had been exposed to space radiation or particle bombardment over a long time.

The existence of the color variations found in our 2003 observation is supported by a near-infrared spectroscopic observation of this asteroid that was performed at nearly the same time as our observation. Sasaki et al.[16] deployed the Cooled Infrared Spectrograph and Camera for OH-airglow Suppressor (CISCO) at the 8.2-m Subaru Telescope on MaunaKea, Hawaii, and observed (832) Karin in near-infrared wavelength on September 14,

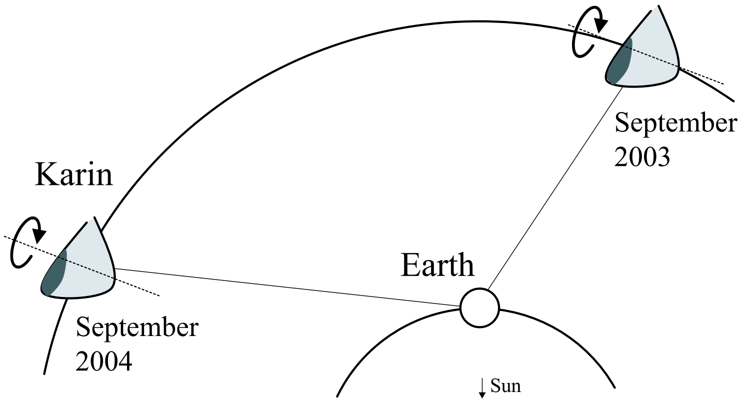

Fig. 4. A rough schematic illustration of the orbital configuration of (832) Karin and the Earth in September 2003 and September 2004. Relative location of the two bodies is determined by the solar phase angle in Table 2. The Earth was roughly at the same position at our 2003 and 2004 observations. We assume that rotation axis of this (maybe) cone-shaped asteroid is almost parallel to its orbital plane, and it has a small portion of red surface (dark gray area).

2003, close to the date of our 2003 observation. As a result, Sasaki et al.[16] obtained the near-infrared spectra of this asteroid at three different rotational phases; 0.30–0.33, 0.34–0.38 and 0.45–0.51 in our Fig. 3(a). They found a significant difference in the slope between the spectrum obtained at phase = 0.30–0.33 and the others. The former is similar to the spectra of ordinary S-type asteroids (i.e. “red” spectrum), while the latter two match well with the spectra of ordinary chondrites. Sasaki et al.[16] interpreted this asteroid's spectrum difference as being due to the mixed distribution of matured and fresh surfaces. This trend of color variation is quite similar to what we obtained in our 2003 observation (Fig. 3(b) and (c)).

A small inconsistency between our and Sasaki's observations is the difference in the rotation phase where the “red” spectrum was observed: In our 2003 result, the surface of (832) Karin seemed mature when the rotation phase was ~ 0.2, while Sasaki's result claims that the mature surface appeared when the phase was around 0.3. We think this mismatch was caused by an uncertainty in rotational period determination, and does not have a significant influence on our assertion that this asteroid had a red surface at the rotation phase around 0.2–0.3 when seen in September 2003.

Here we also have to add details as to what we observed in our 2003 observation. Though the existence of old and mature surface on (832) Karin is surely interesting, we need to be aware that the detection of the mature surface could be caused by an artificial effect. In our 2003 observation, the major color change occurred only through the I band color (Fig. 3(b)) at the rotation phase corresponding to the minimum brightness of this asteroid (Fig. 3(a)). Hence, another explanation might be possible: "The apparent magnitude of this asteroid was close to the instrumental limit in the I band color sensitivity, and the derived I magnitudes are not correct." This hypothesis will be denied or confirmed by our future observations.

4.2. *Future observation*

Our observation of the Karin family asteroids has just begun, and will continue getting better and more accurate lightcurves of more asteroids until we cover all the members (~ 70) of this family. We also need to return to the same asteroids more than once in order to determine their spin axis orientation and shape.

From the photometric information of (832) Karin, if its surface color variation is real, this could be a firm explanation of the relationship between the spectrum of the asteroid surface and its dynamical history. We will keep observing this asteroid, which sometimes shows us a red surface and sometime does not, to determine its rotational and shape properties. We anticipate that the observation of this asteroid at the opposition in March 2006, when this asteroid will be observed at a different aspect angle from the Earth, will add to our knowledge of this intriguing asteroid.

Recent study has revealed that there are many more asteroid families that are as young as the Karin family: For example, an S-type cluster called the Iannini family is about 5 Myr-old, and a C-type cluster called the Veritas family is about 8.3 Myr-old.[17] We have also started photometric observation research on some of these young asteroid families to compare their characters with that of the Karin family as well as of well-known old families. In the near future, an impending deluge of large-scale sky surveys will yield a far larger amount of information with much higher accuracy about younger (and probably smaller) asteroid families, which will be critical keys to understanding of the collisional and dynamical evolution of the main belt asteroids.

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