Surface Color Variation of a New-Born Family Asteroid, Karin

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Abstract

We present current results of our long-term campaign of photometric observations of the new-born Karin family asteroids, especially those of (832) Karin. (832) Karin, an S-type main belt asteroid, is the largest member of the Karin family. This asteroid is likely a large fragment of a disruption event in the main asteroid belt about 5.8 million years ago. We obtained multi-color photometric observations of this asteroid in 2003 and in 2004. We have reported potential surface color variation of this asteroid that indicates the existence of both mature and fresh surfaces on this asteroid. However, as of September 2004, this asteroid apparently does not show a strong surface color difference, which might give us some insight into its spin axis orientation and shape. This is quite an interesting result, but it has to be confirmed by future observations.

Key words: Solar system: minor planets, asteroids

1. Introduction

Asteroid families are the outcome of catastrophic collisions of asteroids that lead to their breakup into fragments. They could give us important clues to how disruption events occurred and to what dynamics and physics has dominated over the history of asteroids. However, it has long been believed that asteroid families are as old as 10^9 years, undergoing significant orbital and collisional evolution that masks the properties of the original collisions. Newer, more fresh information about the formation of asteroid families have been sought for a long time.

In 2002, a sophisticated numerical integration technique identified a very young asteroid family, the Karin family (Nesvorný et al. 2002). The Karin family is as young as only about 5.8 million years old. This family consists of about 70 asteroids with sizes ranging from about 1.5 km to 20 km in diameter (Nesvorný & Bottke 2004). While most asteroid families are very old and have lost fresh information in their origin, 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 (1) spin period distribution of fresh asteroid fragments, (2) possible tumbling (non-principal axis rotation) of asteroids, and (3) surface color variation of new asteroids just after a breakup event.

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. In this paper, we focus on showing the result of our multicolor observation of the largest member of this family, (832) Karin. This observation has originated from the above motivation (3), and is related to the general difference of the reflectance spectrum of S-type asteroids from that of ordinary chondrites. Although S-type asteroids (like the Karin family members) are very common in the inner main belt, their reddened reflectance spectra are different from those of ordinary chondrites, the most common meteorites. Though there had been little observational confirmation on the relation between asteroid age and the degree of surface alteration, space weathering had been thought responsible for the spectral mismatch (Sasaki et al. 2001). In particular, 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. Space weathering has been thought to occur in regolith rather than on rock, so an old surface would not be expected to have a different color than a younger one unless some old regolith was retained. Though this might be unlikely in a large collision, Sasaki et al. (2006) recently showed that rock surface without regolith can also space-weather by laboratory experiments. Therefore, if the mixture of these two surfaces is detected by multicolor observation of this asteroid, it could have significant implication for research on the evolution of asteroid surface (Chapman 1996; Clark et al. 2002).

As preceding research of this paper, Sasaki et al. (2004) have presented their spectrum observing results in near-infrared wavelengths that indicate the existence of both fresh and mature surfaces on (832) Karin. In Section 2, as complementary observations in visible wavelengths to what Sasaki et al. (2004) have done, we describe the method and results of our multicolor observations of (832) Karin. Section 3 goes to some discussions and interpretation of the results. Part of the result of our 2003 observation has already been presented in Yoshida et al. (2004). However, for us to compare the results of multicolor observations of (832) Karin obtained at two different opportunities in order to give some thought on its rotation property, we need to summarize our previous results in 2003 in contrast to the new results in 2004.

2. Multicolor observations of (832) Karin

In this section, first we briefly describe how we have obtained lightcurves of the Karin family asteroids in our campaign of photometric observations of young asteroid family members. Next we move on to presenting our main result of this paper, multicolor photometry of (832) Karin, following the description of our multicolor observing method.

2.1. Lightcurve observation procedure

Throughout our lightcurve observations of the Karin family asteroids, basically we use R band filter because asteroids are generally brightest in the R band wavelength. Exposure time is 40 seconds for (832) Karin and 2–5 minutes for other darker family members so that asteroids have the appearance of point sources. We also observe several Landolt photometric standard stars (Landolt 1992) to determine extinction coefficients. Photometric reduction and aperture photometry are performed using the apphot/IRAF package. Magnitudes of the asteroid at different air masses are corrected by the extinction coefficient. Asteroid brightness is 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 & Lupishko (1989). Principally it is an iterative repetitions of frequency analysis and fitting to Fourier series. We use Lomb's Spectral Analysis (Lomb 1976) or the WindowCLEAN analysis (Roberts et al. 1987) for the frequency analysis of lightcurves, and fit the data with an eighth order Fourier series (Dermawan et al. 2002). 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.

The resulting rotation periods, peak-to-peak variations of the lightcurves, and the solar phase angles of (832) Karin are listed in Table 1 for each of our 2003 and 2004 observations. Combining the new lightcurve data obtained in 2004 with the data that we had taken in 2003, not only at VATT but at other observatories with smaller telescopes (see Yoshida et al. (2004) for the detail of our series of observations in 2003), we could recalculate absolute magnitude H and slope parameter G of this asteroid in R band (Fig. 1). More specifically, we calculated mean magnitudes of Karin by reducing its heliocentric and geocentric distances to unity in each consecutive observing run, and plotted them as a function of solar phase angle. The phase curve of Karin was then fitted using the (H, G) magnitude system approved by International Astronomical Union (Bowell 1989) that contains absolute magnitude and slope parameter as free parameters. Our best estimate of these parameters of Karin using the combined data of 2003 and 2004 is $H = 11.04 \pm 0.07$ and $G = 0.20 \pm 0.11$ (Fig. 1). These values are so close to what we had obtained using only the 2003 observation data, $H = 11.03 \pm 0.02$ and $G = 0.19 \pm 0.04$ (cf. Fig. 3 of Yoshida et al. (2004)), that we believe we can say they are consistent. Detailed lightcurve data of the Karin family asteroids other than (832) Karin will be presented in our

Table 1. Some rotation properties of (832) Karin. P is rotation period (hour), δM is peak-to-peak variation magnitude, and α is the solar phase angle (degree).

	P	δM	α	lightcurve
2003 September	18.35 ± 0.02	0.70 ± 0.02	$\sim$14	Fig. 2(a)
2004 September	18.35 ± 0.02	0.44 ± 0.01	21.7	Fig. 2(d)

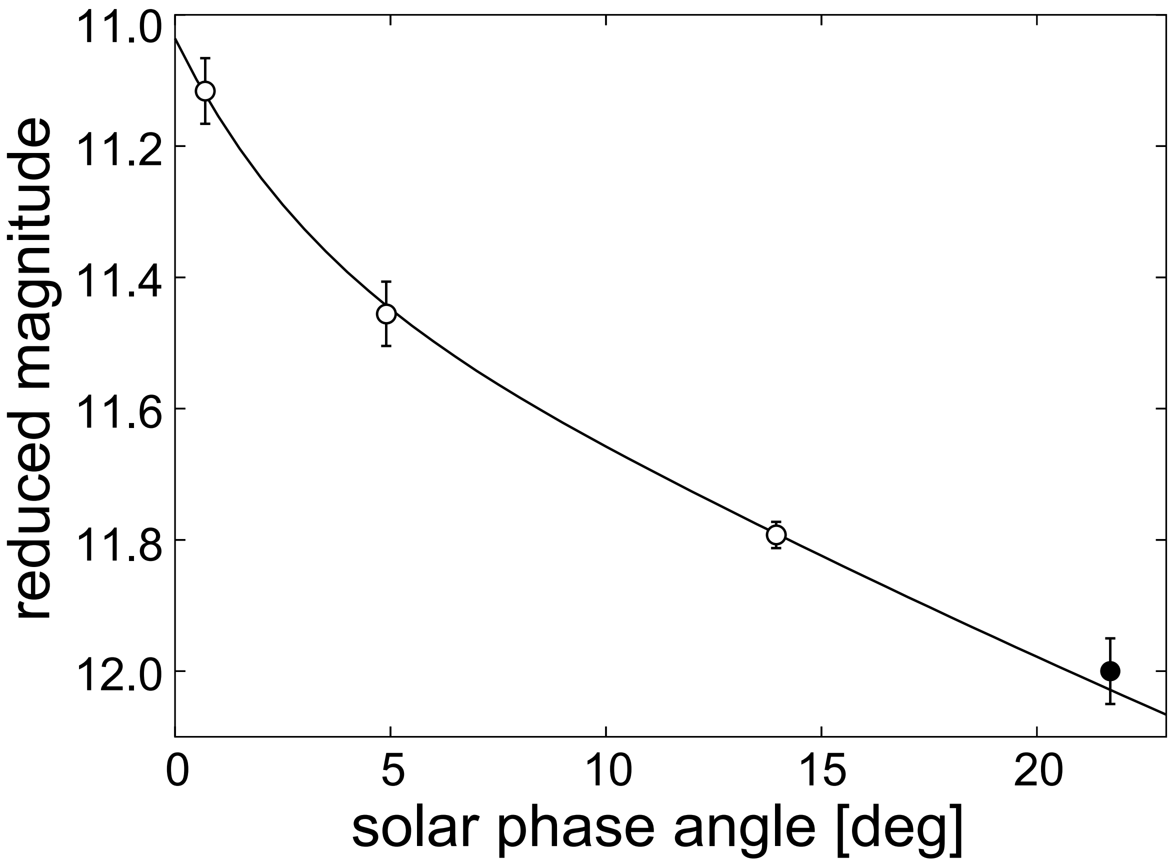

Fig. 1. Solar phase curve of (832) Karin calculated by the combining the lightcurve data in our 2003 and 2004 observations. Open circles (○) are for the 2003 data, and the filled circle (•) is for the 2004 data. Errorbars denote the RMS errors measured for each of the observing runs. Absolute magnitude H of this asteroid in R band reduced to the zero solar phase angle is estimated $H = 11.04 \pm 0.07$. Slope parameter in this band is estimated $G = 0.20 \pm 0.11$. Consult Yoshida et al. (2004) as well as Table 1 for the details of the 2003 data points.

forthcoming publications.

2.2. Multicolor observation procedure

We twice performed multicolor observations of (832) Karin, in September 2003, and in September 2004 after an interval of one year, using the 2k × 2k CCD of the 1.8 m Vatican Advanced Technology Telescope (VATT) on Mt. Graham, Arizona, USA. As far as we recognized, the weather during our 2003 and 2004 observations was good: the sky conditions

Table 2. Major parameters during our multicolor observations of (832) Karin. From the left, UT referring to the mid-time of each night, R.A. and DEC. of the asteroid at the time of the UT, 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.A.	DEC.	r	Δ	λ	β	α
2003–09–26.19	21 46 09.10	−11 53 00.2	2.666	1.803	324.8	1.5	13.36
2003–09–27.19	21 45 49.21	−11 55 05.7	2.666	1.811	324.7	1.5	13.68
2003–09–28.17	21 45 30.91	−11 57 03.3	2.665	1.819	324.6	1.5	13.99
2003–09–29.17	21 45 13.56	−11 58 56.7	2.665	1.827	334.5	1.5	14.30
2004–09–22.44	05 40 32.40	+23 34 17.7	2.706	2.442	63.8	0.2	21.71
2004–09–23.44	05 41 22.18	+23 34 28.7	2.707	2.429	64.1	0.2	21.68
2004–09–24.45	05 42 10.76	+23 34 38.1	2.707	2.417	64.3	0.2	21.64

were photometric in both occasions. Some of the major parameters of the asteroid 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. Exposure time is 40 seconds for R and I bands, 60 seconds for V band, and 120 seconds for B band. 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. As in the the lightcurve observations in R band, we observe several Landolt standard stars. See Table 3 for the list of standard stars we used in our series of observations.

Though the exposure time for (832) Karin is as short as 40–120 seconds, the total time required for exposure and CCD readout for each image amounts to about 3 minutes. Hence, each of these observation sequences takes about 40 minutes. 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–R is $\sqrt{\delta V^2 + \delta R^2}$ where δV and δR are the photometry errors of the V and R images (i.e. basically the square root of the counts, calculated by the apphot/IRAF package).

Table 3. Landolt standard stars for our observations of (832) Karin. From the left, name of the standard star, R.A. and DEC. of the star, date (UT) when we used the star.

Name	R.A.	DEC.	Date (UT)
MARK_A1	20 43 58	−10 47 11	2003–09–27, 28, 29
MARK_A2	20 43 54	−10 45 32	2003–09–27, 28, 29
SA92_249	00 54 34	+00 41 05	2003–09–26, 28
SA92_250	00 54 37	+00 38 56	2003–09–26, 28
SA92_276	00 56 27	+00 41 53	2003–09–27, 29
SA95_218	03 54 50	+00 10 08	2003–09–29
SA95_276	03 54 46	+00 25 54	2004–09–22, 23, 24
SA113_337	21 40 49	+00 27 55	2003–09–26, 27, 28
SA113_339	21 40 56	+00 27 57	2003–09–26, 27, 28
SA115_271	23 42 41	+00 45 10	2003–09–27, 28, 29,
			2004–09–22, 23, 24

2.3. Multicolor observing results

The resulting time variation of the surface color of (832) Karin in our 2003 observation (Yoshida et al. 2004) is briefly summarized in Fig. 2(b). For reference, we show the lightcurve of this asteroid during the summer to autumn of 2003 obtained from three telescopes including VATT (Fig. 2(a)). As seen in Fig. 2(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 shown in Fig. 2(e), as well as this asteroid's lightcurve obtained at this observation (Fig. 2(d)). This time we obtained the color data of this asteroid over almost the entire period of its rotation.

Looking at Fig. 2(b), which shows major results of the 2003 multicolor observation, the V–R value is almost constant throughout the rotation. The change in 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 (more precisely, 0.20–0.24). 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–$I = 0.705$ (Rabinowitz 1998) from our original color data. The relative reflectance is normalized at a wavelength of the V filter, 5394.84Å. Then, as shown in Fig. 2(c), we found that the relative reflectance of this asteroid at long wavelengths (i.e. in I band) is much larger at the rotation phase ~ 0.2 than at other phases. The steep slope of the relative reflectance in Fig. 2(c) at phase ~ 0.2 should be called "red", as is often seen in regular S-type asteroids (Sasaki et al. 2001; Clark et al. 2002).

Note that the magnitude errors in Fig. 2(b) look smaller than the magnitude errors

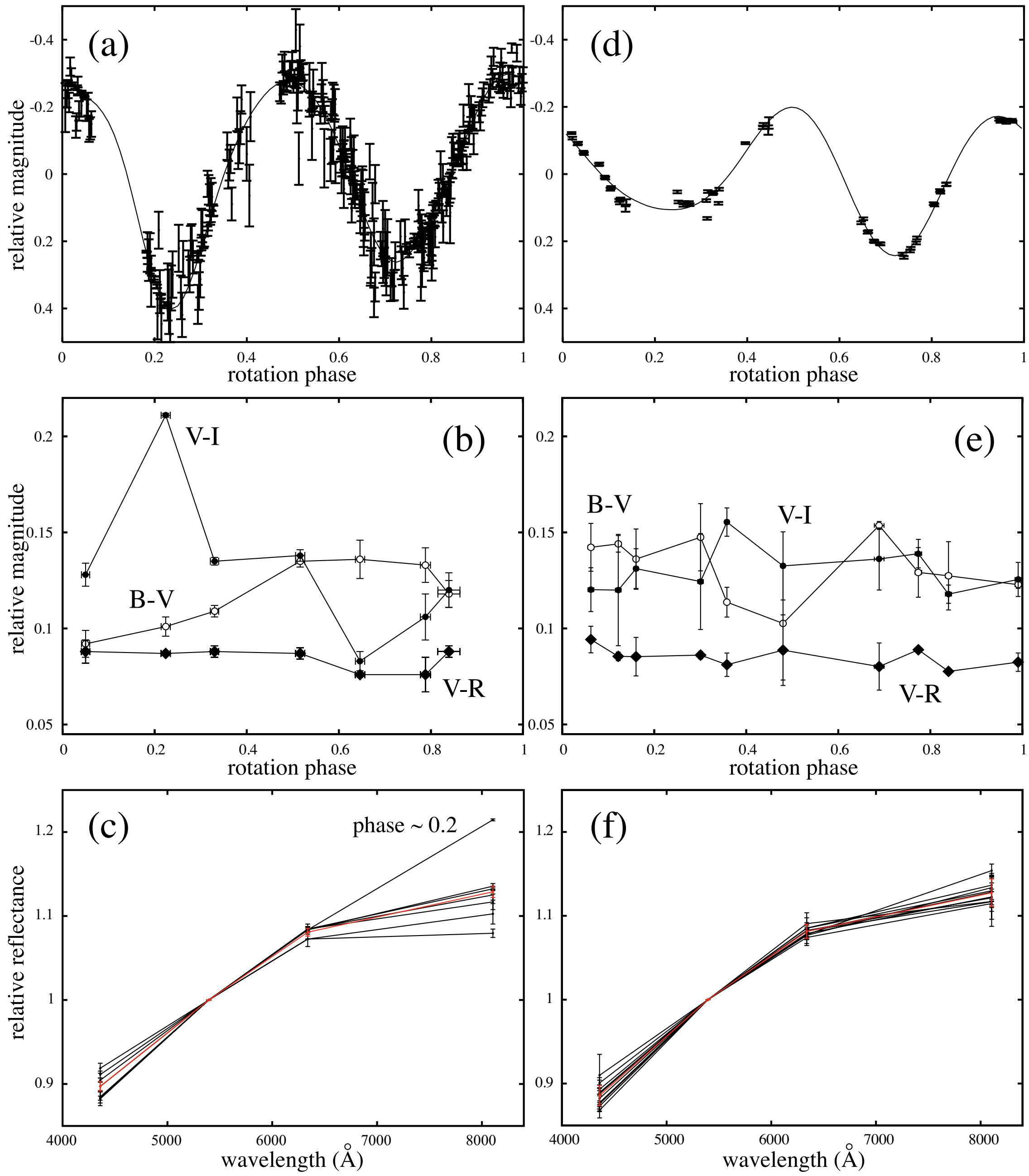

Fig. 2. Lightcurve, relative magnitude, and wavelength dependence of relative reflectance of (832) Karin in our two observations at VATT in September 2003 and September 2004. The left three panels (a)(b)(c) are for the 2003 observation, and the right three panels (d)(e)(f) are for the 2004 observation. (a) and (d): Lightcurves in R band. Note that in (a) we have included the data not only from VATT, but the data from two other smaller telescopes (the 1.0 m Schmidt telescope at the Kiso Observatory, and the 0.4 m telescope at the Fukuoka University of Education, both in Japan) with larger errorbars. (b) and (e): Relative magnitude of B–V, V–I, and V–R. Note that each symbol represents average magnitude of roughly ± 0.02 of the rotation phase fraction at the nominal phase point, because one observation sequence takes about 40 minutes, slightly less than 0.04 of the rotation phase fraction of this asteroids. (c) and (f): Wavelength dependence of relative reflectance in B, V, R, and I band normalized at the V band wavelength, 5394.84Å. The orange lines denote the average spectra in our 2003 and 2004 observations.

in Fig. 2(a), which might seem strange. This is because we have used lightcurve data from two other smaller telescopes in Fig. 2(a), not only that from the 1.8 m VATT, while we drew Fig. 2(b) with only the data from the 1.8 m VATT. If you compare Fig. 2(d) and Fig. 2(e) for both of which we used only the data from VATT, you can see that the magnitude errors in Fig. 2(e) are as large as, or larger than, those in Fig. 2(d), which seems reasonable.

In our 2004 observation results, lightcurve of (832) Karin (Fig. 2(d)) looks different from what we saw a year before (Fig. 2(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. 2(e) does not show any particularly remarkable anomaly, unlike what was seen in Fig. 2(b) in September 2003. The wavelength dependence of the relative reflectance of this asteroid in Fig. 2(f) is more like that of phase $\neq 0.2$ in Fig. 2(b) in September 2003 than that of phase ~ 0.2.

For reference, we calculated the average 2003 and 2004 spectra, and drew them in Fig. 2(c)(f) as orange lines. They look similar, which means that the mature area of Karin's surface is not so large, and does not have a large influence on its averaged spectrum.

3. Discussion

3.1. Interpretation of the observing results

The surface color variation of (832) Karin that we observed in September 2003 suggests that this asteroid possibly 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 ("red") surface, once the parent body surface, and had been exposed to space radiation or particle bombardment over a long time. However, so far we do not have a very good explanation for the unexpected color mismatch between the 2003 and 2004 multicolor observations: (832) Karin did not show a mature (red) surface in September 2004, exhibiting only a fresh surface with low relative reflectance at longer wavelengths. The key to solving this problem might lie in the difference in the amplitude of two lightcurves in Fig. 2(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. 3). Following Sasaki et al.'s (2004) 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. 3, 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. 3, 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.

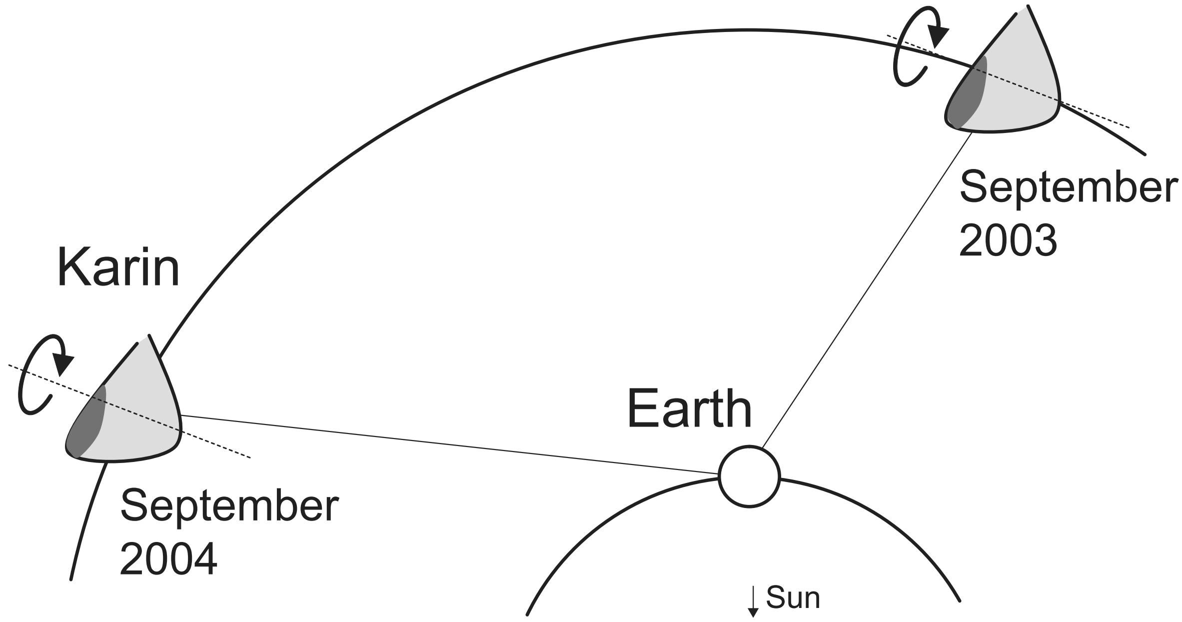

Fig. 3. A rough schematic illustration of the orbital configuration of (832) Karin and the Earth in September 2003 and September 2004. Relative location of the two bodies is determined by the solar phase angle in Table 2. The Earth was roughly at the same position at our 2003 and 2004 observations. We 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).

The existence of the color variations found in our 2003 observation has been supported by a near-infrared spectroscopic observation of this asteroid that was performed at nearly the same time as our observation. Sasaki et al. (2004) 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, 2003, close to the date of our 2003 observation. As a result, Sasaki et al. (2004) 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. 2(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. (2004) 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. 2(b) and (c)).

A question might occur to some readers as the spectrum change of Karin in our 2003 observation looks too sudden from the red part (phase ~ 0.2) to the normal part (phase ~ 0.35). However, there are a couple of evidence that shows this change was somewhat gradual, rather than sudden: First, in addition to the V–I anomaly at phase ~ 0.2 in Fig. 2 (b), we can see a gradual increase in B–V magnitude until the rotation phase reached ~ 0.5. This is compatible with the change of space weathering degree: laboratory simulation of space weathering suggested that weathered reflectance has a smaller B–V value than unweathered reflectance (Sasaki et al. 2001). Also, In Fig. 2 of Sasaki et al. (2004) where time variation of near-infrared spectrum of Karin that was observed almost at the same time as our 2003 observing is shown, we can see a gradual change of the spectral slope at the phase = 0.30–0.35 from quite red to normal ($zJ \rightarrow JH \rightarrow wK$). We will be able to observe the gradual change of the spectrum in much more detail if we take a look at the spectrum of this asteroid around this phase with a higher time resolution.

There is an apparent small inconsistency between our and Sasaki et al.'s observations in 2003 September as to 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 et al.'s (2004) result claims that the mature surface appeared when the phase was around 0.3. We can think of a way to interpret the two different datasets without inconsistencies (see Table 4 for summary). As we see in Table 2 and Fig. 2 of Sasaki et al. (2004), they observed a strongly "red" spectrum of this asteroid at phase = 0.30–0.31 through zJ grizm. Following this discovery, they found a spectrum that was moderately red through JH grizm (phase = 0.31–0.32), and a spectrum that was only slightly red through wK grizm (phase = 0.32–0.33). Sasaki et al. (2004) did not obtain any data for the rotation phase smaller than 0.30.

On the other hand, as we have seen in Fig. 2(b), we observed a "red" feature of this asteroid in optical B, V, R, I bands at phase 0.20–0.24 (note that the observation sequence RR–BB–RR–II–RR–VV–RR takes about 40 minutes, which is a little less than 0.04 of the rotation phase fraction of (832) Karin), typically seen as the anomalously large V–I and small B–V values (Yoshida et al. 2004). Then, at phase 0.31–0.35, V–I got back to normal, while B–V remained relatively small. This might indicate that we still observed slightly "red" surface of this asteroid at this phase: as we mentioned above, weathered reflectance can have a smaller B–V value than unweathered reflectance. When phase were 0.35 or larger, neither of Sasaki et al. or we observed the red feature of this asteroid. So, admitting that there occurred a quick but smooth change in this asteroid's color between phase = 0.30 to phase = 0.35 in 2003 September, the two different datasets presented by Sasaki et al. (2004) and Yoshida et al. (2004) could both be interpreted.

Here we also have to add details as to what we observed in our 2003 observation. Though

Table 4.

phase	band	red or not?	reference
0.20–0.24	B,V,R,I	red	Fig. 2(b)
0.30–0.31	zJ	strongly red	Sasaki et al. (2004) Table 2, Fig. 2
0.31–0.32	JH	moderately red	Sasaki et al. (2004) Table 2, Fig. 2
0.31–0.35	B,V,R,I	slightly red(?)	Fig. 2(b)
0.32–0.33	wK	slightly red	Sasaki et al. (2004) Table 2, Fig. 2
0.34–0.35	zJ	not red	Sasaki et al. (2004) Table 2, Fig. 2
0.36–0.37	JH	not red	Sasaki et al. (2004) Table 2, Fig. 2
0.37–0.38	wK	not red	Sasaki et al. (2004) Table 2, Fig. 2

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. 2(b)) at the rotation phase corresponding to the minimum brightness of this asteroid (Fig. 2(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.

3.2. Future observation

The photometric information of (832) Karin, if its surface color variation is real, 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. Having the present information in visible wavelengths in hand, we need to obtain spectrum information of this asteroid in near-infrared wavelengths, which will be a meaningful extension of Sasaki et al.'s (2004) observing results.

Our long-term campaign of photometric observations 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 ($\sim$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. In addition to the Karin family, recent studies have 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 (Nesvorný et al. 2003). 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 particular, since the space weathering process on C-type asteroids has been not well known yet, the Veritas family asteroids are very nice sample for getting information on space weathering effect on C-type asteroids. 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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