Lightcurves of the Karin family asteroids

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Abstract

The Karin family is a very young asteroid family created by an asteroid breakup 5.8 Myr ago. Since the members of this family probably have not experienced significant orbital or collisional evolution yet, it is possible that they still preserve properties of the original family-forming event in terms of their spin state. As we carried out a series of photometric observations of the Karin family asteroids, here we report an analysis result of lightcurves including the rotation period of eleven members. The mean rotation rate of the Karin family members turned out to be much lower than those of NEAs or smaller MBAs (diameter \(D < 12\) km), and even lower than that of larger...
MBAs ($D > 130$ km). We investigated a correlation between the peak-to-peak variation magnitude reduced to zero solar phase angle and the rotation period of the eleven Karin family asteroids, and found a possible trend that elongated members have lower spin rate, and less elongated members have higher spin rate. However, this has to be confirmed by another series of future observations.

**Keywords:**
Asteroids, Photometry, Lightcurve

1. **Introduction**

Asteroid families are remnants of catastrophic disruption and reaccumulation events between small bodies in the solar system (e.g. Michel et al., 2003). Each member of asteroid families could provide us with clues about the family-formation events that created them. However, since the ages of asteroid families are generally old ($\sim$Gyr), it is quite likely that the family members have undergone significant orbital, collisional, and spin-state evolution that masks properties of original family-forming events.

A sophisticated numerical technique devised by Nesvorný et al. (2002) changed the above situation. Using their method, they detected three young asteroid families in the main belt: the Karin family ($\sim$5.8 Myr old), the Iannini family ($\sim$5 Myr old), and the Veritas family ($\sim$8 Myr old). These families are remarkably younger than previously known asteroid families, and more and more younger asteroid clusters are being recognized (e.g. Nesvorný and Vokrouhlický, 2006; Vokrouhlický and Nesvorný, 2008, 2009). Having these discoveries in our hand, there are many interesting aspects of
the study of young asteroid families: their spin period distribution, their shape distribution, and possible detection of tumbling motion.

We expect that the young family members preserve some properties of the original family-forming event in their spin period distribution. Although there are several laboratory experimental studies on the spin period distribution of collisional fragments (e.g. Fujiwara et al., 1989; Nakamura and Fujiwara, 1991; Kadono et al., 2009), it is hard to directly apply their results to real collisions between small solar system bodies in the gravity-dominant regime. Thus, observations of spin rate of the young asteroid family members can be a unique opportunity to collect information on large-scale collisions.

As for the asteroid spin period distribution, it is now widely known that the Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect may spin up or spin down 10-km-sized asteroids on a $10^8$ yr timescale, and smaller asteroids could spin up or down even faster (e.g. Rubincam, 2000; Bottke et al., 2006). However, as the ages of the young asteroid families are substantially shorter than the timescale of the YORP effect, each of the family members perhaps statistically retains its initial spin status just after the family-formation event. In the case of old asteroid families, such as the Koronis family, the YORP effect has changed the initial spin rate since the family-formation events (e.g. Slivan, 2002; Slivan et al., 2003; Vokrouhlický and Čapek, 2002; Vokrouhlický et al., 2003). Comparison between the spin period distribution of old and young asteroid families can serve as a help in the timescale estimate of the YORP effect.

In addition to the spin state statistics, the shape distribution of the young asteroid family members is important for understanding the fragmentation
and reaccumulation process of small solar system bodies in comparison with laboratory collisional experiments. It may help us estimate the efficiency of the fragmentation and reaccumulation process, such as how angular momentum is distributed to each of the remnants. Also, it is possible to get an estimate of the satellite/binary forming efficiency at family-formation collisional events.

The young asteroid families also draw our attention in terms of possible detection of tumbling motion (a.k.a. non-principal axis rotation). The study of a celestial body’s tumbling motion gives us important insights into energy dissipation and excitation processes, as well as internal structure of the body. Tumbling motion could be excited by collisions of small projectiles, but it will be damped quickly unless the excitation continues. This is the main reason why the tumbling motion of the small solar system bodies has been confirmed only within a few tens of lightcurves (e.g. Harris, 1994; Pravec and Harris, 2000; Paolicchi et al., 2002; Mueller et al., 2002; Warner et al., 2009). However, the age of the young family asteroids is quite short, and we may be able to observe their tumbling motion before it has totally decayed.

Based on the motivations mentioned above, we began a series of photometric observations of the young asteroid families in November 2002. In this paper, we focus on the current result of our lightcurve observation of the Karin family asteroids through the R-band imaging that we had carried out until May 2004, and summarize the result for eleven Karin family members whose rotation period we determined.

Section 2 describes details of our observation. Section 3 summarizes the method of lightcurve analysis (3.1) and resulting lightcurves (3.2). Section 4
2. Observations

During the period from November 2002 to May 2004, we observed and determined the rotational periods of eleven Karin family members, including the largest member, (832) Karin. Table I shows the list of the observatories, the telescopes, and field of views of the instruments that we used for our observations.

We used the $R$-filter for our lightcurve observations because it is widely known that brightness of the reflected light in optical wavelengths from most asteroids becomes the highest in the $R$-band. In our observations all the telescopes were driven at the sidereal tracking rate, and the exposure time was limited by the moving rate of asteroids as well as by the seeing size during the observing periods. As typical main belt asteroids (MBAs) having the semimajor axis $a = 2.8$ AU move at the speed of $\sim 0.55''/\text{min}$ at its opposition, and as the typical seeing size at the observatories was from $1.0''$ to $3.0''$, we chose a single exposure time of two to eight minutes so that an asteroid has an appearance of a point source. We continued the $R$-band imaging for a particular asteroid throughout a night except when we took images of standard stars: an “asteroid per night” strategy. Every night we observed several Landolt photometric standard stars (Landolt, 1992) at several airmasses to determine extinction coefficients (note that we used the standard stars just for this purpose, not for calibrating zero-points to the standard system). Before and/or after each of the observing nights, we took dome flats or twilight sky flats for flat-fielding. After the observation, we applied a standard data
reduction procedure against the data: bias subtraction and flat division.

Brightness of an asteroid was measured relative to that of a field star located on the same frame as the asteroid. We chose the field stars from the USNO–A2.0 star catalogue\textsuperscript{1}. We corrected the magnitude of asteroids using the extinction curve obtained on each of the observing nights, using the standard star observation. Table 2 is the summary of our observational details.

3. Analysis and results

3.1. Method of analysis

To construct synthesized lightcurves of asteroids from the observational data, we followed a sequence proposed by \textcite{Harris and Lupishko, 1989}. The actual procedure is described in our previous publications (\textcite{Dermawan et al., 2002, 2011; Yoshida et al., 2004}). Principally, it is an iterative repetition of frequency analysis and fitting to Fourier series. We employed two different algorithms to examine periodicities in the lightcurve data: Lomb’s Spectral Analysis (LSA, \textcite{Lomb, 1976}) and the WindowCLEAN Analysis (WCA, \textcite{Roberts et al., 1987}). WCA incorporates a discrete Fourier transform as well as the CLEAN algorithm (\textcite{Högbohm, 1974}), and \textcite{Mueller et al., 2002} adopted WCA when they detected multiple rotational periodicities of asteroid (4179) Toutatis. When the frequency analysis has been done, we fit the lightcurve with a Fourier series. We have to be particularly careful when we combine the lightcurves derived from several observing runs because they generally

\textsuperscript{1}http://tdc-www.harvard.edu/catalogs/ua2.html
have different zero-level magnitudes. We combine the lightcurves of multiple observing runs based on these zero-levels to obtain our final result.

Once we have obtained the lightcurve of an asteroid, we estimate the peak-to-peak variation magnitude of its lightcurve. It is widely known that a peak-to-peak variation of an asteroid’s lightcurve becomes larger when we observe an asteroid with a large solar phase angle. For example, Zappalà et al. (1990) found an empirical relationship between the peak-to-peak variation magnitude of an asteroid and its solar phase angle as $A(\alpha) = A(0) (1 + m\alpha)$ where $A(\alpha)$ is the raw peak-to-peak variation magnitude of the lightcurve when the solar phase angle = $\alpha$, and $A(0)$ is that when the asteroid is situated at a location with $\alpha = 0$. The parameter $m$ is empirically determined as 0.030, 0.015, or 0.013 degree$^{-1}$ for S-, C-, M-type asteroids, respectively. We assume $m = 0.030$ for the Karin family asteroids as they are regarded as S-type.

3.2. Lightcurves

Fig. 1 shows all the lightcurves that we obtained in the series of observations. Rotation period $P$, reduced peak-to-peak variation magnitude $A(0)$, solar phase angle $\alpha$ during the observation, and the lightcurve quality code (Lagerkvist et al., 1989) are summarized in Table 3. As for the rotation period $P$, we chose the most reliable peak value from the periodicity analysis results by LSA and WCA (figures not shown).

Since Fig. 1 and Tables 2 and 3 describe most of our results, we just give supplementary information for two of the objects as follows:
(832) Karin. The results of our lightcurve observation of this asteroid are already published (Yoshida et al. (2004) for the observation in 2003, and Ito and Yoshida (2007) for the observation in 2004). Since our 2004 observation was mainly for multi-color photometry of this asteroid, here we just present our 2003 observation result from Yoshida et al. (2004). Note that we obtained the same spin period, $P = 18.35 \pm 0.02$ hours, from both our observations in 2003 and 2004. This is largely consistent with the value that Binzel (1987) obtained in their 1984 observation, $P = 18.82 \pm 0.10$ hours.

(28271) 1999CK16. We observed this asteroid twice from two different oppositions: from November to December 2002 and in March 2004. The rotation periods that were derived from both the observations are close to each other.

4. Discussions

The spin period distribution of asteroids is often compared with the Maxwellian distribution (e.g. Binzel et al. 1989). Unfortunately, the number of our lightcurve samples is still far from being sufficient for such a detailed statistical discussion. Here, let us just compare the mean value of the rotation rate $1/P$ of the eleven Karin family asteroids that we observed with those of NEAs, smaller MBAs ($D < 12$ km), and larger MBAs ($D > 130$ km). According to Table 2 of Binzel et al. (2002, p. 265), the mean values of the rotation rate of NEAs, smaller MBAs, and larger MBAs are $4.80 \pm 0.29$ rev/day, $4.34 \pm 0.23$ rev/day, and $2.90 \pm 0.12$ rev/day, respectively. On the other hand, from our present work, the mean rotation rate of the Karin family asteroids turned out to be $\sim 0.93$ rev/day, or $\sim 0.98$ rev/day excluding
(832) Karin. The mean rotation rate of the Karin family members is much lower than those of the NEAs and the smaller MBAs, and even lower than that of the larger MBAs. This may be quite an interesting fact, considering the widely believed hypothesis that most of the smaller MBAs are collisional remnants.

According to Table 2 of Binzel et al. (2002, p. 265), the reduced peak-to-peak variation magnitude of the NEAs, the smaller MBAs, and the larger MBAs is 0.29, 0.28, and 0.19, respectively. Meanwhile, the average reduced peak-to-peak variation magnitude of the Karin family members is 0.23–0.27. The average value excluding (832) Karin, 0.23–0.24, is close to that of the small MBA group with \( D < 12 \) km, rather than that of the larger MBAs. This is consistent with our conventional knowledge that asteroid remnants, such as the smaller MBAs or the young family asteroids, are more likely to have an elongated (and irregular) shape than a spherical shape compared with larger asteroids that can be parent bodies of asteroid families.

We summarized our main result of the spin period \( P \) and the peak-to-peak variation magnitude \( A(0) \) of the eleven Karin family members in Fig. 2. In Fig. 2(a) that shows the relation between \( A(0) \) and \( 1/P \), you may see a slight trend from the top left to the bottom right, which tells us that elongated asteroids have a lower spin rate, and those less elongated asteroids have a higher spin rate. A similar trend has been recognized in fast-rotating sub-

\[^2\text{It is } \sim 0.26 \text{ if we choose the value 0.06 for (28721) 1999CK}_{16}, \sim 0.23 \text{ if we exclude (832) Karin and choose the value 0.06 for (28721) 1999CK}_{16}, \sim 0.27 \text{ if we choose the value 0.17 for (28721) 1999CK}_{16}, \text{ and } \sim 0.24 \text{ if we exclude (832) Karin and choose the value 0.17 for (28721) 1999CK}_{16}.\]
km-size MBAs (Nakamura et al., 2011). If the rotational angular momentum given to each remnant is nearly equally distributed when an asteroid family is formed, it is possible that the smaller the remnant is, the faster its rotation becomes (which is already confirmed by laboratory experiments such as Kadono et al. (2009)). However, whether the “trend” really exists depends on how many more lightcurve samples of the Karin family members are obtained from now. Also, the size range of our observing target is somehow limited within $D=3$–$5\text{ km}$ except (832) Karin (Fig. 2(b)(c)), possibly causing the appearance of the “trend”. We are aware that, at present, the number of lightcurve samples is not large enough to reach a definite conclusion on our conjecture.

At the end of this paper, we would like to consider the possibility that any of the Karin family members still possesses tumbling motion. From the result that we have presented in the previous sections, we plotted the rotation period of the eleven Karin family asteroids on a diagram that shows the relation between rotation period $P$ and diameter $D$ in Fig. 3. For this figure we estimated the diameter of the Karin family members from its absolute magnitude $H$ using the relationship $\log_{10} D = 3.1295 - 0.5 \log_{10} p - 0.2H$ where $p$ is the albedo of an asteroid (Bowell and Lumme, 1979). We used the absolute magnitude values of the asteroids listed on the Lowell asteroid orbital elements database\footnote{ftp://ftp.lowell.edu/pub/elgb/astorb.html}. We assumed the albedo value of $p = 0.21$ for the S-type Karin family asteroids (cf. Yoshida and Nakamura, 2007).

For comparison, we also plotted the $(D, P)$ relation of 3,745 previously
known asteroids listed on the PSI PDS lightcurve database whose orbital periods are known to a certain credibility. For these asteroids, we applied the mean albedo of $p = 0.081$ following Ryan and Woodward (2010) to all the asteroids, assuming their absolute magnitude $H$ listed in the Lowell asteroid orbital elements database mentioned above. Also, among these asteroids we highlighted 31 possible tumblers in green so that we can compare their $(D, P)$ relation with that of the Karin family asteroids.

Theoretically, the damping timescale of the tumbling motion of a celestial body $T_d$ (Gyr) can be expressed in its relationship between $P$ (hours) and $D$ (km) as in the following equation by Harris (1994), a reconsideration of a theory by Burns and Safronov (1973):

$$P \sim 17D^{\frac{2}{3}}T_d^{\frac{1}{3}}.$$  \hspace{1cm} (1)

Evidently, smaller and slower rotators have longer damping timescales of the tumbling motion. In Fig. 3 we drew two damping timescales of tumbling motion using diagonal lines calculated by Eq. (1). The upper solid blue line in Fig. 3 indicates the $(D, P)$ relation of asteroids when their damping timescale $T_d = 5.8$ Myr, equivalent to the age of the Karin family. The lower dashed blue line in Fig. 3 indicates that of asteroids when their damping timescale $T_d = 4.6$ Gyr, almost equivalent to the age of the entire solar system. You can see from Fig. 3 that many of the Karin members that we observed are

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4 http://sbn.psi.edu/pds/resource/lc.html as of April 30, 2012 (V12.0). Among the lightcurve datafile data/lc_summary.tab, we selected the asteroids only with the lightcurve reliability of 2, 2+, 3 or higher.

5 Among all the lightcurve data in data/lc_summary.tab, we selected the asteroids having the credible tumbling flag T or T+.
located below the upper solid line for $T_d = 5.8$ Myr, indicating that they can still maintain the tumbling motion, if any, since their dumping timescale $T_d$ is possibly longer than their age, 5.8 Myr. Although in the present analysis we did not detect clues on the tumbling motion of the Karin family members, several family members with relatively long rotational periods such as (7719) 1997GT$_{36}$, (43032) 1999VR$_{26}$, or (71031) 1999XE$_{68}$ are still candidates as tumbling asteroids.
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Table 1: Observatories and instruments. $E$ is the elevation of the observatory (m), $D_t$ is the diameter of the telescope mirror that we used (m), and FOV denotes the field of view of the imaging system that we used for our purpose. The full observatory names and the telescope names are as follows: Steward: the 2.3 m telescope (“Bok”) at the Steward Observatory (Kitt Peak, Arizona, USA). Vatican: the 1.8 m telescope (“VATT”) at the Vatican Observatory (Mt. Graham, Arizona, USA). Maidanak: the 1.5 m telescope (“AZT”) at Maidanak Observatory (Uzbekistan). Lulin: the 1 m telescope at the Lulin Observatory (Taiwan). Kiso: the 1 m telescope at the Kiso Observatory (Nagano, Japan). Fukuoka: the 0.4 m telescope at the Fukuoka University of Education (Fukuoka, Japan).

| Name    | Longitude | Latitude          | $E$  | $D_t$ | FOV       |
|---------|-----------|-------------------|------|-------|-----------|
| Steward | 111°36'01.6"W | 31°57'46.5"N   | 2071 | 2.29  | 4.5' × 4.5' |
| Vatican | 109°53'31.25"W | 32°42'04.69"N | 3191 | 1.8   | 6.8' × 6.8' |
| Maidanak | 66°53'47.08"E | 38°40'23.95"N | 2593 | 1.5   | 8.5' × 3.5' |
| Lulin   | 120°52'25"E   | 23°28'07"N     | 2862 | 1.0   | 11.5' × 11.2' |
| Kiso    | 137°37'42.2"E | 35°47'38.7"N   | 1130 | 1.05  | 50' × 50'  |
| Fukuoka | 130°35'44.7"E | 33°48'45.3"N   | 70   | 0.40  | 5.75' × 4.36' |
Table 2: Aspect data of observed asteroids. Date of observations (mid-time of the observing night) in UT, ecliptic longitude $\lambda$ (deg), ecliptic latitude $\beta$ (deg), solar phase angle $\alpha$ (deg), and abbreviated codes of the observatories (ST: Steward, VA: Vatican, MA: Maidanak, LU: Lulin, KI: Kiso, and FU: Fukuoka)

| Date (UT)   | $\lambda$   | $\beta$ | $\alpha$ | Obs. |
|-------------|-------------|---------|----------|------|
| (832) Karin |             |         |          |      |
| 2003-07-31.65 | 334.8       | 1.5     | 9.80     | FU   |
| 2003-08-01.64 | 334.7       | 1.5     | 9.42     | FU   |
| 2003-08-02.69 | 334.5       | 1.5     | 9.02     | FU   |
| 2003-08-03.73 | 334.3       | 1.5     | 8.62     | FU   |
| 2003-08-06.76 | 333.8       | 1.5     | 7.42     | FU   |
| 2003-08-09.07 | 333.3       | 1.5     | 6.22     | FU   |
| 2003-08-22.64 | 330.7       | 1.6     | 0.85     | FU   |
| 2003-08-23.64 | 330.5       | 1.6     | 0.61     | FU   |
| 2003-09-03.63 | 328.2       | 1.6     | 4.70     | FU   |
| 2003-09-04.63 | 328.0       | 1.6     | 5.13     | FU   |
| 2003-09-05.63 | 327.8       | 1.6     | 5.54     | KI   |
| 2003-09-26.19 | 324.8       | 1.5     | 13.36    | VA   |
| 2003-09-27.19 | 324.7       | 1.5     | 13.68    | VA   |
| 2003-09-28.17 | 324.6       | 1.5     | 13.99    | VA   |
| 2003-09-29.17 | 334.5       | 1.5     | 14.30    | VA   |

| Date (UT) | $\lambda$   | $\beta$ | $\alpha$ | Obs. |
|-----------|-------------|---------|----------|------|
| (7719) 1997GT36 |             |         |          |      |
| 2003-10-14.16 | 315.5       | 0.9     | 18.39    | ST   |
| 2003-10-15.15 | 315.6       | 0.9     | 18.53    | ST   |
| 2003-10-16.14 | 315.6       | 0.9     | 18.66    | ST   |
| Date       | Percent | Strength | 100 Percent | Code |
|------------|---------|----------|-------------|------|
| 2003–10–17 | 315.7   | 0.8      | 18.79       | ST   |
| (10783) 1991RB9 |        |          |             |      |
| 2004–03–24 | 236.6   | 1.7      | 14.94       | ST   |
| 2004–03–26 | 236.0   | 1.8      | 14.51       | ST   |
| 2004–03–27 | 235.9   | 1.8      | 14.30       | ST   |
| 2004–05–07 | 229.9   | 2.3      | 1.12        | LU   |
| 2004–05–09 | 229.4   | 2.3      | 0.76        | LU   |
| 2004–05–10 | 229.2   | 2.3      | 0.83        | LU   |
| 2004–05–11 | 229.0   | 2.3      | 1.04        | LU   |
| 2004–05–13 | 228.6   | 2.3      | 1.74        | MA   |
| (11728) Einer |        |          |             |      |
| 2003–05–08 | 251.9   | 3.0      | 8.57        | VA   |
| 2003–05–09 | 251.7   | 3.0      | 8.20        | VA   |
| 2003–06–29 | 242.3   | 2.1      | 11.97       | LU   |
| 2003–06–30 | 242.2   | 2.1      | 12.26       | LU   |
| (13765) Nansmith | | | | |
| 2003–09–29 | 47.2    | 1.3      | 14.20       | VA   |
| 2003–10–15 | 45.1    | 1.4      | 8.53        | ST   |
| 2003–10–16 | 45.0    | 1.4      | 8.14        | ST   |
| 2003–10–23 | 38.5    | 0.9      | 5.10        | KI   |
| 2003–10–24 | 38.7    | 0.9      | 4.67        | KI   |
| 2003–10–26 | 39.2    | 0.9      | 3.80        | KI   |
| 2003–10–27 | 39.4    | 0.9      | 3.36        | KI   |
| 2003–10–17 | 44.8    | 1.4      | 7.73        | ST   |
| Date       | a2  | AU  | a1 | MA  | Type |
|------------|-----|-----|----|-----|------|
| 2003–12–23 | 34.8| 1.0 | 17.66 | ST |      |
|            |     |     |      |     | (16706) Svojsik |
| 2003–05–08 | 187.4| 2.5 | 12.33 | VA |      |
| 2003–05–09 | 187.3| 2.5 | 12.63 | VA |      |
| 2003–05–10 | 187.2| 2.5 | 12.88 | VA |      |
| 2003–05–11 | 187.2| 2.5 | 13.15 | VA |      |
|            |     |     |      |     | (28271) 1999CK16 |
| 2002–11–17 | 64.7| −1.2| 4.48 | LU |      |
| 2002–12–01 | 64.6| −1.3| 1.71 | LU |      |
| 2002–12–03 | 64.2| −1.3| 2.55 | LU |      |
| 2002–12–04 | 64.0| −1.3| 2.95 | LU |      |
| 2002–12–05 | 63.8| −1.3| 3.36 | LU |      |
| 2004–03–24 | 161.1| −1.3| 7.81 | ST |      |
| 2004–03–26 | 161.0| −1.2| 8.56 | ST |      |
| 2004–03–27 | 160.6| −1.3| 8.90 | ST |      |
|            |     |     |      |     | (40921) 1999TR171 |
| 2003–07–20 | 300.5| −3.1| 1.62 | LU |      |
| 2003–07–21 | 300.3| −3.1| 1.37 | LU |      |
|            |     |     |      |     | (43032) 1999VR26 |
| 2003–08–01 | 342.8| −4.3| 12.14 | MA |      |
| 2003–08–02 | 342.7| −4.3| 11.79 | MA |      |
| 2003–08–03 | 342.5| −4.3| 11.44 | MA |      |
| 2003–08–04 | 342.4| −4.3| 11.10 | MA |      |
| 2003–09–22 | 333.3| −4.2| 9.32 | VA |      |
| 2003–09–27 | 332.6| −4.1| 11.12 | VA |      |
| Date       | RA       | Dec      | V magnitude | L категории | Type |
|------------|----------|----------|-------------|--------------|------|
| 2003–09–28.18 | 332.5    | −4.1     | 11.44       | VA           |      |
| 2003–09–29.17 | 332.4    | −4.1     | 11.78       | VA           |      |
| (69880) 1998SQ81 |          |          |             |              |      |
| 2003–09–22.44 | 20.4     | −1.7     | 7.72        | VA           |      |
| 2003–09–26.47 | 19.6     | −1.8     | 6.10        | VA           |      |
| 2003–09–27.41 | 19.5     | −1.8     | 5.71        | VA           |      |
| 2003–09–28.45 | 19.3     | −1.8     | 5.28        | VA           |      |
| 2003–09–29.34 | 19.1     | −1.9     | 4.90        | VA           |      |
| 2003–10–14.33 | 15.9     | −2.0     | 1.84        | ST           |      |
| (71031) 1999XE68 |          |          |             |              |      |
| 2003–09–01.87 | 353.2    | −2.3     | 5.05        | MA           |      |
| 2003–09–02.86 | 353.0    | −2.4     | 4.66        | MA           |      |
| 2003–09–03.85 | 352.8    | −2.4     | 4.27        | MA           |      |
| 2003–09–26.34 | 348.1    | −2.6     | 5.21        | VA           |      |
| 2003–09–28.27 | 347.7    | −2.7     | 5.96        | VA           |      |
Table 3: Major observational results. $P$ is the rotation period (hours), $A(0)$ is the reduced peak-to-peak variation magnitude, $\alpha$ is the solar phase angle during our observation (deg), QC is the quality code of the lightcurves, and the panel designation in Fig. 1. For (28271) 1999CK₁₆, * denotes the observation result in 2002, and † denotes the observation result in 2004.

| Asteroid       | $P$     | $A(0)$    | $\alpha$ | QC | Fig. 1 |
|----------------|---------|-----------|-----------|----|--------|
| (832) Karin    | 18.35 ± 0.02 | 0.56 ± 0.02 | 0.6–14.3  | 2  | a      |
| (7719) 1997 GT₃₆ | 29.56 ± 0.60 | 0.31 ± 0.02 | 18.4–18.8 | 2  | b      |
| (10783) 1991 RB₉ | 7.33 ± 0.04  | 0.26 ± 0.02 | 0.8–14.9  | 3  | c      |
| (11728) Einer  | 13.62 ± 0.05 | 0.14 ± 0.01 | 8.6–12.3  | 2  | d      |
| (13765) Nansmith | 10.51 ± 0.01 | 0.07 ± 0.02 | 7.7–17.7  | 2  | e      |
| (16706) Svojsik  | 6.72 ± 0.07 | ~ 0.07    | 12.3–13.2 | 1  | f      |
| (28271)* 1999 CK₁₆ | 5.64 ± 0.06 | 0.06 ± 0.04 | 1.7–4.5   | 2  | g      |
| (28271)† 1999 CK₁₆ | 5.64 ± 0.06 | 0.17 ± 0.02 | 7.8–8.9   | 2  | h      |
| (40921) 1999 TR₁₇₁ | 6.74 ± 0.08 | 0.35 ± 0.02 | 1.4–1.6   | 2  | i      |
| (43032) 1999 VR₂₆ | 32.89 ± 0.04 | 0.60 ± 0.06 | 9.3–12.1  | 2  | j      |
| (69880) 1998 SQ₈₁ | 7.68 ± 0.01 | 0.08 ± 0.01 | 1.8–7.7   | 2  | k      |
| (71031) 1999 XE₆₈ | 20.19 ± 0.41 | 0.39 ± 0.04 | 4.3–6.0   | 2  | l      |
Fig. 1 Results of the lightcurve analysis of eleven Karin family asteroids. (a) (832) Karin, (b) (7719) 1997GT$_{36}$, (c) (10783) 1991RB$_9$, (d) (11728) Einer, (e) (13765) Nansmith, (f) (16706) Svojsik, (g) (28271) 1999CK$_{16}$ (observed in 2002), (h) (28271) 1999CK$_{16}$ (observed in 2004), (i) (40921) 1999TR$_{171}$, (j) (43032) 1999VR$_{26}$, (k) (69880) 1998SQ$_{81}$, and (l) (71031) 1999XE$_{68}$. The vertical axis denotes the relative magnitude referred to a field star at each observing night. Note that the lightcurve of (832) Karin in (a) is a quoted one from Yoshida et al. (2004).

Fig. 2 Relation between the rotation rate $1/P$, diameter $D$, and the reduced peak-to-peak variation magnitude $A(0)$ of the eleven Karin family asteroids that we observed. (a) $A(0)$ and $1/P$, (b) $D$ and $1/P$, and (c) $D$ and $A(0)$. The largest member, (832) Karin, is denoted as “832”. Note that as for (28271) 1999CK$_{16}$ we used its values obtained from our 2004 observation, as its $A(0)$ value in 2004 is larger than its value in 2002, being closer to their maximum.

Fig. 3 Relation between the rotation period $P$ (hours) and diameter $D$ (km) of 3,745 known asteroids (filled black circles) including 31 tumblers (filled green circles) and the eleven Karin family asteroids (filled red circles). The diagonal blue lines show the theoretical $(D, P)$ relation of asteroids when their damping timescale $T_d = 5.8$ Myr (the upper solid blue line) and when their damping timescale $T_d = 4.6$ Gyr (the lower dashed blue line) calculated by Eq. (1).
Figure 1
Figure 2
All Tumblers
Karin family
$T_d = 5.8 \text{ Myr}$
$T_d = 4.6 \text{ Gyr}$

Figure 3