ROTATIONAL PROPERTIES OF THE MARIA ASTEROID FAMILY

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ABSTRACT

The Maria family is regarded as an old-type (∼3 ± 1 Gyr) asteroid family that has experienced substantial collisional and dynamical evolution in the main belt. It is located near the 3:1 Jupiter mean-motion resonance area that supplies near-Earth asteroids to the inner solar system. We carried out observations of Maria family asteroids during 134 nights from 2008 July to 2013 May and derived synodic rotational periods for 51 objects, including newly obtained periods of 34 asteroids. We found that there is a significant excess of fast and slow rotators in the observed rotation rate distribution. The one-sample Kolmogorov–Smirnov test confirms that the spin rate distribution is not consistent with a Maxwellian at a 92% confidence level. From correlations among rotational periods, amplitudes of light curves, and sizes, we conclude that the rotational properties of Maria family asteroids have been changed considerably by non-gravitational forces such as the YORP effect. Using a light-curve inversion method, we successfully determined the pole orientations for 13 Maria members and found an excess of prograde versus retrograde spins with a ratio \((N_p/N_r)\) of 3. This implies that the retrograde rotators could have been ejected by the 3:1 resonance into the inner solar system since the formation of the Maria family. We estimate that approximately 37–75 Maria family asteroids larger than 1 km have entered near-Earth space every 100 Myr.

Key word: minor planets, asteroids: general

Online-only material: color figures, figure set

1. INTRODUCTION

An asteroid family is a group of asteroidal objects in the proper orbital element space (\(a, e, \) and \(i\)), considered to have been produced by a disruption of a large parent body through a catastrophic collision (first identified by Hirayama 1918; see Cellino et al. 2009, and references therein). Family members have usually similar surface properties such as spectral taxonomy types (Cellino et al. 2002), Sloan Digital Sky Survey (SDSS) colors (Ivezić et al. 2002; Parker et al. 2008), and visible geometric albedo (Masiero et al. 2011). Therefore, an asteroid family can be seen as a natural solar system laboratory and is regarded as a powerful tool to investigate space weathering (Nesvorný et al. 2005) and non-gravitational phenomena such as the Yarkovsky and YORP (Yarkovsky–O’Keefe–Radzievskii–Paddack) effects.

The Maria asteroid family has long been known as one of the Hirayama families (Hirayama 1922) and is a typical old population (∼3 ± 1 Gyr) (Nesvorný et al. 2005) that is expected to have experienced significant collisional and dynamical evolution in the history of the inner solar system. The Maria family is located close to the outer border of the 3:1 mean-motion resonance (MMR; ∼2.5 AU) with Jupiter; thus, it might be regarded as a promising source region candidate for a couple of giant S-type near-Earth asteroids (NEAs), 433 Eros and 1036 Ganymed (Zappalà et al. 1997). Our knowledge about the properties of the Maria family, however, is still limited. To date, rotational periods of the family members among 3230 cataloged objects (Nesvorný 2010) have been known only for 58 of the relatively large asteroids (LCDB;11 2013 March), accounting for less than 2% of the family. The study of the rotational properties of an asteroid family, i.e., rotational period, pole orientation, and overall shape of the light curve, can offer a unique opportunity to obtain insight both on the collisional breakup process and on the dynamical evolution of asteroids. Paolicchi (2005) proposed that the statistical properties of the spin period and pole orientation contain information on the collisional transfer of angular momentum of small bodies. Laboratory experiments (Holsapple et al. 2002, and reference therein) from catastrophic disruption events show that the distribution of asteroidal spin periods resembles a Maxwellian, which implies that members have reached an approximate equilibrium status after a chain of isotropic collisions. There must be differences between the behavior of laboratory experiments and the catastrophic collisions of asteroids in their natural environment due to various approaches on scaling law (see, e.g., Mizutani et al. 1990; Housen & Holsapple 1990; Housen et al. 1991; Davis et al. 1994). Giblin et al. (1998) have detected that, on average, the smaller asteroids rotate faster from the catastrophic disruption experiments, and it has already been predicted by the semi-empirical model of catastrophic impact processes by Paolicchi et al. (1996). In addition, this tendency is also found in spin rate-size distribution from the Asteroid Lightcurve Database

11 http://www.minorplanet.info/lightcurvedatabase.html
(LCDB; Pravec et al. 2002; Warner et al. 2009), as well as in a statistical analysis of C- and S-type main-belt asteroids (MBAs; Nesvorný & Bottke 2004; Vokrouhlický et al. 2006; Milani et al. 2010). The dynamical evolution of the family members due to the Yarkovsky effect tends to spread the members out in semimajor axis, over the evolution time. For this reason, the dispersions of the semimajor axes can be used as a clue to estimate the age of an asteroid family (Bottke et al. 2001; Kaasalainen et al. 2001) is a powerful tool to obtain rotational properties, especially pole orientation, from timeseries photometric data. Hanuš et al. (2011) derived 80 new asteroid models based on the combination of classical dense-in-time (hereafter dense) and sparse-in-time (hereafter sparse) photometric light-curve data. They found the distribution of pole latitudes for small asteroids ($D < 30$ km) in the main belt to be depleted near the ecliptic plane, an effect attributed to the YORP thermal effect.

There are several observational studies on the rotational properties of asteroid families. Slivan (2002) and Slivan et al. (2003) discovered an alignment of the spin vectors in the Koronis family, which is commonly referred to as the Slivan effect. Kraszczyński et al. (2012) showed that the distribution of rotational periods in the Flora asteroid family is non-Maxwellian. Taking advantage of the analysis of light curves obtained from Flora family members, Kraszczyński (2013) recently found the Slivan effect in the Flora family. Alvarez-Candal et al. (2004) tried to find correlations among rotation periods, light-curve amplitudes, and sizes of objects for the Themis, Eos, and Maria families, but no specific relationship was found. Ito and Yoshida (2010) focused on the observation of young asteroid families, which are expected to have experienced little collisional and orbital evolution. In general, we have some difficulty in obtaining high signal-to-noise ratio (S/N) light curves, especially for smallest and hence faintest family members.

The purpose of this paper is to investigate the rotational properties of the Maria family: rotation periods, orientations of the spin axis, and shapes, mainly based on our observations but also with data available in the literature. In Section 2 we describe the photometric observations of the Maria family asteroids with an introduction on the several telescopes we used. In Section 3 we explain the method of data reduction and acquisition from the available dense and sparse data sets from the AstDyS (Asteroids Dynamic Site) database. Light-curve plots for each asteroid are given in Figure 9 in the Appendix. Using the light-curve inversion method, we derive the orientations of spin axis for 13 Maria asteroids. The results of this analysis and related discussions about the rotational properties of the Maria family are given in Section 4. Finally, in Section 5 we summarize our conclusions.

2. OBSERVATIONS

Observations of the Maria family asteroids were conducted during 134 nights from 2008 July to 2013 May, using 0.5 m to 2 m class telescopes at seven observatories in the Northern Hemisphere. We used CCD cameras on the Wise Observatory (WO) 0.46 m telescope in Negev desert, Israel, the Tubitak Ulusal Güzlemevi (TUG) 1.0 m telescope in Bakırlıtepe, Turkey, the Bohyunsan Optical Astronomy Observatory (BOAO) 1.8 m telescope on Bohyunsan, Korea, the Sobaeksan Optical Astronomy Observatory (SOAO) 0.6 m telescope on Sobaeksan, Korea, the Korea Astronomy and Space Science Institute (KASI) 0.6 m telescope in Jincheon, Korea, the Lemmonsan Optical Astronomy Observatory (LOAO) 1.0 m telescope on Mt. Lemmon, USA, and the Calar Alto (CA) Astronomical Observatory 1.2 m telescope in Almeria, Spain. The details of the observatories and instruments are shown in Table 1.

All telescopes except for the BOAO 1.8 m and the CA 1.2 m telescopes were guided at sidereal tracking rate. For sidereal tracking of asteroids, we considered two factors: (1) the apparent motion of the asteroid should be less than the FWHM of the stellar profiles on each observatory; (2) the S/N of the asteroid measurement should be at least 50. Accordingly, the maximum exposure time did not exceed 300 s while tracking at sidereal rate during the observations. Because several asteroids were relatively faint, some images taken with the BOAO 1.8 m telescope were acquired through a non-sidereal tracking mode that corresponded to the predicted motion of the objects. On the other hand, the CA 1.2 m telescope was tracked with a tracking vector halfway between sidereal rate and that of asteroids. In this way both asteroids and the background stars were trailed by the small amount. We made time-series observations mainly

| Telescope | Observing Date Range | λ | φ | Altitude (m) | Instrument | Pixel Scale (′ pix⁻¹) |
|-----------|----------------------|---|---|-------------|------------|---------------------|
| WO 0.46 m | 2008 Jul 6–Dec 4     | 34:45:48 | 360:00 | 875 | SBIG ST-10 | 1.10 |
| TUG 1.0 m | 2012 Jun 20–2013 Mar 6 | 30:19:59 | 360:00 | 2538.6 | SI 4K CCD | 0.62 |
| BOAO 1.8 m | 2012 Apr 15–2013 Mar 10 | 128:58:36 | 360:00 | 1143 | e2v 4K CCD | 0.43 |
| SOAO 0.6 m | 2012 Feb 4–2013 May 8 | 128:27:27 | 360:00 | 1354 | e2v 2K CCD | 1.02 |
| KASI 0.6 m | 2012 Jan 10–Oct 12 | 127:28:31 | 360:00 | 87 | SBIG ST-4 | 1.06 |
| LOAO 1.0 m | 2012 Jun 28–2013 Apr 3 | 249:12:41 | 360:00 | 2776 | e2v 4K CCD | 0.80 |
| CA 1.2 m | 2012 Jul 12–19 | 2:32:45 | 360:00 | 2173.1 | e2v 4K CCD | 0.63 |

Notes.

a Abbreviations: WO = Wise Observatory, TUG = Tubitak Ulusal Güzlemevi (Turkish National Observatory), BOAO = Bohyunsan Optical Astronomy Observatory, SOAO = Sobaeksan Optical Astronomy Observatory, KASI = Korea Astronomy and Space Science Institute, LOAO = Lemmonsan Optical Astronomy Observatory, CA = Calar Alto.

b Eastern longitude and geocentric latitude of each observatory.

c SI 4K CCD, e2v 4K CCD, and e2v 2K CCD were configured with $2 \times 2$ binning.

12 http://hamilton.dm.unipi.it/ast dys
with Johnson $R$ filter in order to characterize the rotational states of the asteroid, since the $R$-band filter with an optical imager is the most sensitive to small bodies in the solar system.

2.1. Target Selection

The Maria asteroid family consists of 3230 known members with identification based on the Hierarchical Clustering Method (Nesvorný 2010). The latest family classification is available at the AstDyS Web site.\(^{13}\) As of 2013 November, the database lists 2085 Maria members based on synthetic proper orbital elements of numbered asteroids. We checked the membership as listed in the AstDyS and found that most of our target asteroids were confirmed as Maria members except for asteroids 652, 4122, 5977, 13679, 19184, 19333, 32116, 43174, 50511, 109792, and 114819. However, memberships of an asteroid family can be subject to some unavoidable uncertainties, since they depend on the data sets of proper orbital elements available at the epoch of family search, on the adopted identification technique, and on membership assignment criteria.

We investigated the cumulative distribution $N (<H)$ of absolute magnitudes $H$ for all the members of the Maria family. We used a power-law approximation of $N (<H) \propto 10^{-\gamma H}$ in the magnitude range between 12 and 14.5 and obtained $\gamma \sim 0.54$ (see Figure 1). The value of $\gamma$ obtained is close to the steady-state mass distribution of collisional fragmentation for which Dohnanyi (1969) derived $\gamma = 0.5$, but discordant with a considerably steeper distribution constructed by Pareto power laws (e.g., Tanga et al. 1999). This power-law index implies that the Maria family has undergone a significant collisional and dynamical evolution and has currently reached an equilibrium state (e.g., Dohnanyi 1969; O’Brien & Greenberg 2003; Bottke et al. 2005). The slope depends highly on the number of objects brighter than 12th absolute magnitude, while the slope is thought to have been contaminated by observational bias for objects fainter than $H = 14.5$ mag. We chose our targets in the $H$ range between 12 and 14.5; the total number of targets in this magnitude range is 981. The catalogued absolute magnitudes in the standard ($H, G$) system have large uncertainties due to the transformation from an observed magnitude system to the Johnson $V$ system, and to the phase correction (see Cellino et al. 2009, for more details). It might either overestimate or underestimate the size distribution of a family.

We generated ephemerides for each object from the 981 target asteroids using the JPL Horizons service,\(^{14}\) then produced target lists of observable asteroids during any given night. Because the rotational periods of most targets are unknown, we decided to observe one or two target asteroids per night at least, assuming typical rotational periods between 2 and 24 hr. Since a preliminary rotational light curve of an asteroid is determined only after a prompt data reduction, it is better to allocate follow-up observation so as to cover its full-phased light curve. For the sake of increasing the observational efficiency, we developed an observation scheduler to carry out asteroid follow-up observation in a timely manner. When we input observational parameters such as initial rotational period, observed time, and observatory code, the scheduling program suggests to the user the next proper observing time to cover gaps in the light curve.

2.2. Coordinating the Observations

Our observations were focused on asteroids in the Maria family that lack a known rotational period. To increase the number of observable asteroids as much as possible, we observed two objects alternately on a single night with the BOAO 1.8 m, TUG 1.0 m, and CA 1.2 m telescopes. Moreover, further observations during the years 2012-2013 were also performed for 21 targets at the Wise telescope in 2008, and spin axis information was obtained from published light curves (see Section 3.2 for more details).

It is difficult to cover the entire rotational phase of asteroids with rotational periods longer than 8 hr during a single night. In addition, if the rotational period of an asteroid aliases with 24 hr, the rotational period of the Earth, it is essentially impossible to have a fully covered light curve from a single observatory. A network of follow-up telescopes can be used to solve these problems. In order to maximize phase coverage of an asteroid, taking advantage of a network observation at different time zones, we organized observation campaigns with three observatories in Korea (UT + 9 h), Turkey (UT + 2 h), and USA (UT − 8 h). These network observations were carried out in 2012 with TUG and LOAO on June 28 and 30; BOAO and TUG on October 12, 14, and 19; and SOAO and TUG on October 12, 14, and 17. In order to calibrate all the data gathered from various observatories, the same CCD fields obtained during the previous observations were taken in the next runs.

The detailed observational circumstances of each asteroid are listed in Table 2: UT date corresponding to the mid time of the observation, the topocentric equatorial coordinates (R.A. and Decl., J2000), the heliocentric ($r$) and the topocentric distances ($\Delta$), the solar phase (sun-asteroid-observer’s) angles ($\alpha$), the apparent predicted magnitude ($V$), and the telescopes used.

3. DATA REDUCTION AND ANALYSIS

All observational data reduction procedures were performed using the Image Reduction and Analysis Facility (IRAF) software package. Individual images were calibrated using the standard processing routine of the IRAF task noao.imred.ccdred.ccdproc. Bias and dark frames with relatively high standard deviations were not used for analysis. Twilight sky flats were acquired before sunrise and after sunset and combined to produce a master flat image for each night.

\(^{13}\) http://hamilton.dm.unipi.it/~astdys2/propsynth/numb.members

\(^{14}\) http://ssd.jpl.nasa.gov/?horizons
### Table 2
Observational Circumstances of the Maria Asteroid Family Members

| Asteroid | UT Date (YY/MM/DD) | R.A. (hr) | Decl. (deg) | r (AU) | Δ (AU) | α (deg) | V (mag) | Telescope |
|----------|-------------------|----------|-------------|--------|--------|--------|---------|-----------|
| 575 Renate | 2012/12/26.7 | 6.99 | +44.61 | 2.760 | 1.826 | 7.86 | 14.97 | SOAO |
| 652 Jublatrix | 2012/05/20.7 | 16.53 | −12.46 | 2.675 | 1.678 | 4.68 | 15.07 | SOAO |
| 660 Crescentia | 2012/01/10.4 | 2.07 | −4.80 | 2.750 | 2.444 | 20.76 | 14.30 | KASI |
| 695 Bella | 2012/01/28.7 | 10.17 | −5.59 | 2.885 | 2.004 | 10.51 | 13.78 | KASI |
| 727 Nipponia | 2008/07/06.8 | 17.07 | −6.07 | 2.770 | 1.864 | 11.67 | 13.90 | WO |
| 787 Moskva | 2008/07/07.0 | 10.00 | +9.41 | 2.240 | 1.829 | 26.55 | 14.16 | WO |
| 875 Nympha | 2008/10.0 | 3.51 | +15.37 | 2.414 | 2.308 | 26.55 | 14.16 | WO |
| 879 Ricarda | 2012/02/22.3 | 9.48 | −3.95 | 2.818 | 1.865 | 6.59 | 16.00 | LOAO |
| 897 Lysistrata | 2008/08/05.0 | 3.32 | +29.02 | 2.604 | 2.618 | 22.39 | 15.61 | WO |
| 1158 Lada | 2008/09/25.0 | 7.90 | +34.29 | 2.354 | 2.556 | 23.28 | 15.79 | WO |
| 1160 Illyria | 2012/02/14.4 | 1.71 | +22.27 | 2.336 | 2.532 | 22.95 | 16.05 | KASI |
| 1215 Boyer | 2012/02/16.4 | 1.76 | +22.56 | 2.338 | 2.556 | 22.72 | 16.07 | KASI |
| 1996 Adams | 2012/02/26.6 | 9.38 | +30.63 | 2.832 | 2.198 | 9.32 | 16.39 | SOAO |
| 2151 Hadwiger | 2012/01/28.7 | 12.79 | +10.30 | 2.466 | 1.818 | 20.17 | 15.36 | KASI |
| 2429 Schurer | 2012/02/20.7 | 11.41 | +20.27 | 2.641 | 1.688 | 7.17 | 15.97 | SOAO |
| 3055 AnnaAlov | 2013/03/20.6 | 12.05 | +1.11 | 2.647 | 1.651 | 0.53 | 15.81 | SOAO |
| 3158 Anga | 2012/06/30.9 | 19.38 | +0.68 | 2.698 | 1.747 | 9.50 | 16.49 | TUG |
| 3786 Yamada | 2012/07/03.0 | 16.77 | −1.47 | 2.838 | 1.881 | 8.16 | 15.35 | SOAO |
| 3970 Herran | 2008/08/26.0 | 3.09 | +11.29 | 2.351 | 1.892 | 24.65 | 16.78 | WO |
| 4104 Alu | 2013/01/22.9 | 9.70 | +38.46 | 2.800 | 1.882 | 8.84 | 16.71 | TUG |

Note: Δα, Δv, and Telescope columns are not visible in the provided image.
| Asteroid   | UT Date (YY/MM/DD) | R.A. (hr) | Decl. (deg) | r (AU) | Δ (AU) | α (deg) | V (mag) | Telescope |
|------------|-------------------|-----------|-------------|--------|--------|---------|--------|-----------|
| 4122 Ferrari | 2012/12/25.6      | 7.24      | +14.73      | 2.597  | 1.637  | 5.96    | 15.91  | SOAO      |
| 4673 Bottte  | 2012/02/07.7      | 10.72     | +27.46      | 2.470  | 1.529  | 8.71    | 15.28  | KASI      |
| 4851 Vodop'yanova | 2012/04/27.6     | 13.51     | −10.76      | 2.593  | 1.602  | 4.89    | 16.31  | SOAO      |
| 5326 (1988 RT6) | 2012/06/24.9      | 19.77     | +2.51       | 2.229  | 1.312  | 14.79   | 16.06  | TUG       |
| 5977 (1992 TH1) | 2012/07/01.1      | 22.30     | −6.23       | 2.373  | 1.636  | 20.47   | 16.26  | TUG       |
| 6458 Nouda   | 2008/08/06.9      | 22.27     | +10.86      | 2.193  | 1.265  | 14.17   | 16.12  | SOAO      |
| 7601 (1994 US1) | 2013/03/08.6      | 11.11     | +27.54      | 2.925  | 1.985  | 7.59    | 16.97  | BOAO      |
| 7644 Cslewis  | 2012/06/23.9      | 17.55     | −6.51       | 2.548  | 1.566  | 7.558   | 17.25  | TUG       |
| 8653 (1990 KE) | 2012/08/10.9      | 23.00     | +8.34       | 2.371  | 1.459  | 13.69   | 16.48  | TUG       |
| 9175 Graun   | 2012/12/18.6      | 6.52      | +42.69      | 2.792  | 1.853  | 7.38    | 16.51  | SOAO      |
| 11129 Hayachine | 2012/10/14.5      | 1.92      | +22.20      | 2.687  | 1.715  | 5.95    | 16.79  | BOAO      |
| 11931 (1993 DD2) | 2012/11/27.6      | 5.34      | +44.68      | 2.406  | 1.485  | 10.74   | 16.24  | SOAO      |
| 12740 (1992 EX8) | 2013/03/13.5      | 5.99      | +41.17      | 2.822  | 1.922  | 9.75    | 16.71  | SOAO      |
| 13679 Shinanogawa | 2012/02/17.9      | 5.81      | +35.59      | 2.870  | 2.442  | 19.43   | 17.61  | BOAO      |
| 15288 (1991 RN27) | 2012/10/19.6      | 3.42      | +39.12      | 2.606  | 1.759  | 14.14   | 16.81  | TUG       |
| 17157 (1999 KP6) | 2012/06/28.9      | 19.41     | −1.00       | 2.282  | 1.323  | 11.09   | 15.99  | TUG       |
| 18144 (2000 O048) | 2008/08/07.0      | 23.44     | −6.17       | 2.185  | 1.277  | 15.48   | 16.78  | TUG       |
| 18841 Hruska  | 2013/03/09.6      | 11.14     | +28.02      | 2.463  | 1.521  | 9.36    | 16.49  | BOAO      |
| 19184 (1991 TB6) | 2012/10/18.9      | 3.52      | +21.92      | 2.357  | 1.441  | 12.22   | 17.09  | TUG       |
| 19233 (1996 YT1) | 2012/08/10.9      | 21.58     | −2.86       | 2.416  | 1.417  | 5.29    | 16.41  | TUG       |
| 19495 (1998 KZ8) | 2012/12/24.6      | 6.11      | +21.39      | 2.396  | 1.413  | 1.04    | 15.11  | SOAO      |
| 19557 (1999 JC79) | 2012/06/23.9      | 19.82     | −7.05       | 2.297  | 1.352  | 12.22   | 16.50  | TUG       |
| 20378 (1998 KZ46) | 2012/11/26.6      | 4.70      | +26.29      | 2.337  | 1.357  | 3.73    | 15.76  | BOAO      |
| 21816 (1999 TE31) | 2012/10/19.9      | 1.37      | +16.35      | 2.356  | 1.365  | 3.07    | 16.85  | SOAO      |
| 24004 (1999 RQ57) | 2012/10/14.8      | 1.03      | +22.64      | 2.552  | 1.575  | 5.74    | 16.78  | TUG       |
| 29393 (1996 NA3) | 2012/08/28.6      | 15.24     | +7.03       | 2.535  | 1.585  | 9.56    | 16.65  | SOAO      |
| 31554 (1999 EJ2) | 2012/06/24.9      | 18.13     | +1.58       | 2.393  | 1.433  | 10.35   | 16.34  | TUG       |
| 32116 (2000 LD4) | 2012/06/30.9      | 18.05     | +1.55       | 2.396  | 1.442  | 10.83   | 16.37  | TUG       |
| 33229 (1998 FC124) | 2012/10/16.8      | 23.85     | −6.34       | 2.280  | 1.355  | 12.08   | 16.18  | TUG       |
Instrumental magnitudes of asteroids were obtained using the IRAF `apphot` package; aperture radii were set to be equal to the FWHM of the typical stellar profile on each frame in order to maximize the S/N (Howell 1989). The light curves of most asteroids were constructed based on relative magnitudes, that is, the difference between the instrumental magnitude of an asteroid and the average magnitude of each comparison star.

In order to choose a set of comparison stars, we inspected the FWHM of the typical stellar profile on each frame in order to maximize the S/N (Howell 1989). The light curves of most asteroids were constructed based on relative magnitudes, that is, the difference between the instrumental magnitude of an asteroid and the average magnitude of each comparison star.

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that show the least amount of light variation in each field. Finally, we selected three to five comparison stars with a typical scatter of 0.01–0.02 mag. The observation time (UT) was corrected for light-travel time.

### 3.1. Rotational Period and Light Curve

Out of 134 nights of observations in total, we obtained 218 individual light curves for 74 Maria family members and derived synodic rotational periods for 51 objects, including obtained periods for 34 asteroids for the first time. In order to find the periodicity of the light curve, the Fast Chi-Squared (\( F\chi^2 \)) technique (Palmer 2009) was employed. In addition, we checked the result with the discrete Fourier transform algorithm (Lenz & Breger 2005). In most cases for rotational periods, these two different techniques present similar results within the statistical errors. The \( F\chi^2 \) technique presented here represents the observed magnitudes as a Fourier time series truncated at the harmonic \( H \):

\[
\Phi_H([A_0,2H,f],t) = A_0 + \sum_{h=1...H} A_{2h} \sin(h2\pi ft) + A_{2h} \cos(h2\pi ft).
\]

(1)

In practice, we fit the fourth-order Fourier function and also obtained the highest spectral power with the discrete Fourier transform algorithm. As a result, the final rotational period was determined assuming a double-peaked light curve. We present the resultant composite light curves of observed asteroids in Figure 9 in the Appendix, folded with their synodic periods.

In the approximation of a triaxial body with uniform albedo, the peak-to-peak variations in magnitude are caused by the change in apparent cross section of the rotating body, with semi-axes \( a \), \( b \), and \( c \), where \( a > b > c \) (the body rotates along the \( c \) axis). According to Binzel et al. (1989), the light-curve amplitude varies as a function of the polar aspect viewing angle \( \theta \) (the angle between the rotation axis and the line of sight):

\[
\Delta m = 2.5 \log \left( \frac{a}{b} \right) - 1.25 \log \left( \frac{a^2 \cos^2 \theta + c^2 \sin^2 \theta}{b^2 \cos^2 \theta + c^2 \sin^2 \theta} \right).
\]

(2)

The lower limit of axis ratio \( a/b \) can be expressed as \( a/b = 10^{0.4\Delta m} \), which corresponds to an equatorial view (\( \theta = 90^\circ \)). The peak-to-peak variation in light curve becomes larger when we increase the solar phase angle. The following empirical relationship between these two parameters was found by Zappala et al. (1990):

\[
A(0^\circ) = \frac{A(\alpha)}{(1 + ma)}
\]

(3)

where \( A(0^\circ) \) is the light-curve amplitude at zero phase angle and \( A(\alpha) \) is the amplitude measured at solar phase angle \( \alpha \). These authors also found that average \( m\)-values are 0.030, 0.015, and 0.013 \( \text{deg}^{-1} \) for S, C, and M-type asteroids, respectively. We adopted the constant \( m \) of 0.03 for our analysis, as the Maria family is known as a typical S-type asteroid family.

### 3.2. Light-curve Inversion with Dense and Sparse Data

In order to derive the orientation of the spin axis using disk-integrated photometric data, dense light curves obtained over three or four apparitions are essential (Kaasalainen et al. 2002). However, due to a limited amount of dense data sets, the light-curve inversion method using only sparse data (Kaasalainen et al. 2004) and a combination of sparse and dense data (Ďurech et al. 2009; Hanuš et al. 2011) has been improved during the past decades.

We obtained the available dense data set by matching objects with the Maria family members from the following three data sources. In the MPC (Minor Planet Center) Light Curve Database,\(^{15}\) we downloaded light curves for the 17 Maria asteroids. From the online Web site of COURSES de rotation d’asteroides et de com`etes (CdR,\(^{16}\) operated by R. Behrend), a total of 140 individual light curves for 13 objects were acquired. Another three light curves were found in the Asteroid Photometric Catalog (Lagerkvist & Magnusson 2011) from NASA’s Planetary Data System.

Most sparse photometric data sets are a by-product of worldwide astrometric surveys, such as the Catalina Sky Survey and the Siding Spring Survey. Detailed instructions for obtaining the sparse data from the AstDys site are in Hanuš et al. (2011); we follow their methodology. According to very recent analysis by the same authors (Hanuš et al. 2013, private communication), only sparse data sets from the USNO in Flagstaff (MPC code 689), the Catalina Sky Survey (703), and the La Palma (950) were useful for determining the shape modeling of asteroids. Combining the dense and the sparse light-curve data sets from the AstDys, we computed the pole orientation for 16 objects and determined 13 unique solutions.

### 4. RESULTS AND DISCUSSIONS

#### 4.1. Rotational Properties of the Maria Asteroid Family

Our observations from seven observatories yielded 218 individual light curves for 74 Maria asteroids. Among them we derived synodic rotational periods for the 51 members with a reliability code \( \geq 2 \). For the 23 objects with a reliability code of 1, we set a lower bound to the periods except for 879 Ricarda, for which the rotation period is known. The reliability parameters follow the definition by Lagerkvist et al. (1989).

1. Very tentative result, may be completely wrong.
2. Reasonably secure result, based on over half coverage of the light curve.
3. Secure result, full light-curve coverage, no ambiguity of period.
4. Multiple apparition coverage, pole position reported.

The information on rotational characteristics from our light-curve data sets with other physical properties is summarized in Table 3; diameter and albedo information were mainly acquired from the WISE IR data (Masiero et al. 2011) with the exception of those marked with A (AcuA, Asteroid catalog using Akari; Usui et al. 2011) and M (mean albedo value of 0.254 for the Maria family asteroid), while the taxonomic information is compiled from Neese (2010) and Hasselmann et al. (2012). We used the data sets only with a reliability code \( \geq 2 \) for our analysis. The light curves for 23 objects denoted with Q Notes of 1 did not cover even half-phased periods due to the following three reasons: (1) very low amplitude of the light curve (smaller 3\( \sigma \)); (2) variation of brightness much longer than observing time; (3) data interruption due to bad weather or instrument conditions. We examined a lower bound to the periods for those 23 objects to consider the influence of selection bias, i.e., favoring observations of faster rotators. Although all 23 objects

\(^{15}\) http://www.minorplanetcenter.net/light_curve
\(^{16}\) http://obswww.unige.ch/~behrend/page_cou.html
Table 3

Physical Properties of the Maria Asteroid Family Members

| Asteroid      | $P_{rot}$ (hr) | $A(0)$ (mag) | Q Notes | Diameter (km) | Albedo | Type |
|---------------|----------------|--------------|---------|---------------|--------|------|
| 7601 (1994 US1)| 3.45           | 0.18         | 3       | 11.8          | 0.221  | S1   |
| 4673 Borile   | 2.64           | 0.13         | 3       | 12.5          | 0.290  | S1   |
| 4851 Vodop'yanova | 4.90     | 0.17         | 3       | 7.2           | 0.254  | M   |
| 5326 (1988 RT6) | >6            | ⋯             | 1       | 7.4           | 0.296  | LS2  |
| 7037 (1992 TH) | 12            | ⋯             | 1       | 11.8          | 0.154  | ⋯    |
| 6589 Nouda    | 4.203          | 0.56         | 3       | 7.5           | 0.181  | ⋯    |
| 7601 (1994 US1)| 3.74           | 0.31         | 3       | 7.3           | 0.190  | S2   |
| 7644 Cislewis | 2.31           | 0.22         | 3       | 5.8           | 0.174  | ⋯    |
| 8653 (1990 KE) | >14            | ⋯             | 1       | 6.6           | 0.254  | M   |
| 9175 Graun    | 25.8           | 0.12         | 3       | 7.9           | 0.308  | ⋯    |
| 11129 Hayachine | 17.57     | 0.17         | 2       | 6.2           | 0.350  | ⋯    |
| 11931 (1993 DD2)| 19.87     | 0.09         | 3       | 6.7           | 0.363  | ⋯    |
| 12740 (1992 EX9) | >10          | ⋯             | 1       | 9.1           | 0.285  | ⋯    |
| 13679 Shimanogawa | >8           | ⋯             | 1       | 5.7           | 0.308  | S2   |
| 15288 (1991 RN27) | 7.14      | 0.13         | 3       | 9.3           | 0.188  | L2   |
| 17157 (1999 KP6) | 3.72      | 0.14         | 3       | 6.4           | 0.296  | L2   |
| 18144 (2000 OQ48) | 3.10      | 0.24         | 3       | 3.5           | 0.437  | SQ2  |
| 18841 Hruska  | 6             | 0.11         | 2       | 7.3           | 0.212  | ⋯    |
| 18881 (1999 XL195) | 2.98     | 0.18         | 3       | 9.7           | 0.173  | ⋯    |
| 19184 (1991 TB6) | 4.99      | 0.36         | 3       | 6.7           | 0.129  | ⋯    |
| 19333 (1996 YT1) | 2.83      | 0.16         | 3       | 5.6           | 0.268  | ⋯    |
| 19495 (1998 KZ8) | 2.33      | 0.12         | 3       | 6.3           | 0.342  | ⋯    |
| 19557 (1999 JC79) | >5         | ⋯             | 1       | 8.4           | 0.230  | S2   |
| 20578 (1998 KZ46) | 5.14      | 0.31         | 3       | 7.9           | 0.236  | LS2  |
| 21816 (1999 TE31) | >20       | ⋯             | 1       | 4.6           | 0.206  | ⋯    |
| 24004 (1999 RQ57) | 5.68      | 0.43         | 3       | 9.1           | 0.254  | M   |
| 29820 (1996 CN3) | ⋯          | 1            | 6.6      | 0.254        | M   |
| 31554 (1999 EJ2) | >12         | ⋯             | 1       | 7.5           | 0.240  | LS2  |
| 32116 (2000 LD4) | >8          | ⋯             | 1       | 6.0           | 0.254  | M   |
| 33229 (1998 FC124) | >15       | ⋯             | 1       | 5.4           | 0.377  | ⋯    |
| 33489 (1999 GF9) | 6.74      | 0.55         | 3       | 6.0           | 0.198  | L2   |
| 33548 (1999 JC13) | 3.97      | 0.27         | 3       | 4.8           | 0.227  | L2   |
| 33646 (1999 JX82) | 3.33      | 0.09         | 3       | 5.2           | 0.218  | L2   |
| 34035 (2000 OQ27) | >10        | ⋯             | 1       | 5.8           | 0.276  | ⋯    |
| 34502 (2000 SE157) | 4.71      | 0.05         | 3       | 5.7           | 0.344  | Q2   |
| 34529 (2000 SD212) | 3.71      | 0.50         | 3       | 5.2           | 0.261  | ⋯    |
| 34572 (2000 SY310) | 6.64      | 0.40         | 3       | 7.3           | 0.252  | ⋯    |
| 39148 (2000 WM93) | 7.55      | 0.13         | 2       | 4.1           | 0.315  | ⋯    |
| 40664 (1999 RF196) | 9.61      | 0.17         | 2       | 3.5           | 0.368  | ⋯    |
| 41510 (2000 QU171) | >24       | ⋯             | 1       | 4.8           | 0.207  | ⋯    |
| 42704 (1998 MB32) | >12        | ⋯             | 1       | 5.3           | 0.333  | ⋯    |
| 42835 (1999 SS56) | 2.49       | 0.14         | 3       | 5.4           | 0.222  | ⋯    |
| 43174 (1999 XF180) | >16       | ⋯             | 1       | 5.5           | 0.214  | ⋯    |
| 49653 (1999 JO85) | >8          | ⋯             | 1       | 5.5           | 0.209  | ⋯    |
| 49923 (1999 XQ174) | 5.21       | 0.15         | 3       | 5.3           | 0.329  | L2   |

Notes. Synodic rotational periods ($P_{rot}$) from our analysis, the light-curve amplitude $A(0)$ obtained using Equation (3), and the reliability parameters (Q Notes) follow the definition by Lagerkvist et al. (1989; see Section 4.1 for more details). For 34 objects marked with boldface, the rotational periods are presented for the first time. Diameter and albedo information were acquired mainly from the WISE IR data (Masiero et al. 2011) with the exception of those marked with $\bar{A}$ (Asteroid catalog using AKARI; Usui et al. 2011) and M (assuming mean albedo value of 0.254 for the Maria family asteroids), while taxonomic types from (Neese 2010) are indicated with “L” and types from the SDSS-based Asteroid Taxonomy (Hasselmann et al. 2012) are marked with “2.”

Figure 2. Rotational rate distribution for the 92 Maria family members and the best-fit Maxwellian curve (dashed line). The 51 objects from our observations are marked with shaded bars. If we added to this graph the upper bounds for the rotational frequencies for the 23 objects with a reliability code of 1 (see Table 3), the new objects would populate bins 1–5, thereby increasing the excess of slow rotators.

All 92 members of our observations

Figure 3. The distribution of rotational rates for 92 Maria family members used in this study and the corresponding...
best-fit Maxwellian curve. The 51 objects obtained from our observations are marked with shaded bars. It can be obviously seen that asteroids rotating faster and slower considerably exceed the fitted distribution. From the Kolmogorov–Smirnov test, the compatibility between the observed distribution and the fitted Maxwellian is completely inconsistent at a 92% confidence level. This non-Maxwellian distribution is also found in other old-type asteroid families, such as the Koronis family (Slivan et al. 2008) and the Flora family (Kryszczyńska et al. 2012), with ages of 2.5 ± 1.0 Gyr and 1.0 ± 0.5 Gyr (Nesvorný et al. 2005), respectively.

Laboratory experiments of catastrophic collisions (Holsapple et al. 2002, and references therein) and numerical simulations (Asphaug & Scheeres 1999; Michel et al. 2001) showed that the rotational frequency of fragments approximates the Maxwellian distribution. Accordingly, this inconsistency with our measurements suggests that the members belong to an old family and have had their rotational properties modified by non-gravitational forces operating over a long period of time; the spin rate change, in particular, can be attributed to the YORP effect. Rubin cam (2000) found that the spin states of pseudo-Gaspra and pseudo-Eros can significantly evolve on a 100 Myr timescale, which is far shorter when compared to their break-up and collisional processes. Hanuš et al. (2011) found that the spin vectors of the MBAs with $D < 30$ km were significantly affected by the YORP thermal effect. The size range of most of the 92 Maria members used in this study is distributed between 1.5 km and 30 km (see Figure 3).

We examine the correlation between the rotational frequency (cycles day$^{-1}$) and diameter (km) in Figure 4. Among the 92 Maria family asteroids used for this study, 4 objects might be regarded as interlopers. In terms of the visible geometric albedo $p_v$, two asteroids 3094 Chukokkala and 4860 Gubbio possess very low albedos, 0.068 and 0.037, respectively, provided that the mean value of albedo for the Maria family asteroids is 0.254, very low albedos, 0.068 and 0.037, respectively, provided that however, they do not affect the overall tendency in Figure 4.

In the results obtained from our observations, there is an apparent systematic trend toward larger dispersion of rotational frequency with decreasing size. The rotation of small asteroids can be easily accelerated or decelerated due to the YORP effect. Moreover, all asteroids larger than 22 km rotate more slowly than 4.8 hr (5 cycles day$^{-1}$), quite similar to what was found for the Flora family (Kryszczyńska et al. 2012).

Figure 5 shows the correlation between the rotational frequencies (cycles day$^{-1}$) and light-curve amplitude (magnitude), as well as compared with the size of asteroids. The sizes of various circles indicate the diameter of each asteroid. Asteroids larger than 15 km in size are marked with the blue circles. The dashed horizontal line represents a light-curve amplitude of 0.5 (magnitude). The colored curves represent approximate critical rotational frequencies for bulk densities of 1.5, 2.0, and 2.5 g cm$^{-3}$, respectively. This figure separates into two plots in the Appendix.
We can see two features in Figure 5: there is no object with both fast rotation (faster than 6 cycles day\(^{-1}\)) and large light-curve amplitudes (>0.6 mag). Despite an insufficient number for large peak-to-peak variation, few highly elongated objects tend to rotate slowly. This could be explained by the break-up limit of the elongated rubble pile; it makes sense that the more elongated an object is, the easier it can be shattered during its spin-up process. The colored curves in Figure 5 approximate the critical rotational period \(P_c\) for bulk densities of 1.5, 2.0, and 2.5 g cm\(^{-3}\), respectively, adopted from (Pravec & Harris 2000):

\[
P_c \approx 3.3 \sqrt{\frac{1 + \Delta m}{\rho}}
\]

where \(P_c\) is the period in hours, \(\rho\) is the bulk density in g cm\(^{-3}\), and \(\Delta m\) is the amplitude of the light-curve variation in magnitude. It is apparent from Figure 5 that there is no object against “spin barrier” (Pravec & Harris 2000) for bulk density of 2.5 g cm\(^{-3}\). In addition, elongated objects are located far from the spin rate limit.

The other feature seen in Figure 5 is that no objects larger than 15 km have amplitude of light curve larger than 0.5 mag except for 4860 Gubbio, regarded as an interloper. Small objects (<15 km) with various shapes are spread out in this plot. If an elongated rubble pile asteroid is disrupted by a non-gravitational force such as the YORP effect, it might have less elongated, namely, more spherical, shape as a result. Figure 5 separates into two plots (Figures 10 and 11) in the Appendix.

4.2. Yarkovsky Footprints on the Maria Asteroid Family

The Yarkovsky effect plays a significant role in the dynamical evolution of asteroid orbits. The study of this non-gravitational thermal force on the asteroid family has been improved dramatically during the past decades in several families, such as Koronis (Bottke et al. 2001), Flora (Nesvorný et al. 2002), and Eos (Vokrouhlický et al. 2006). Semimajor axis drift, in accordance with either the sense of rotation or various sizes of asteroids, by the Yarkovsky effect results in a V-shape in the proper semimajor axis and absolute magnitude plane (Nesvorný & Bottke 2004; Vokrouhlický et al. 2006; Milani et al. 2010). The analysis for drift in semimajor axis allows us to estimate the age of an asteroid family (Bottke et al. 2001; Nesvorný et al. 2005).

To find the Yarkovsky footprints in the Maria asteroid family, we investigate the pole orientation of the members. We examined sense of rotation for the 16 members that were observed during at least three apparitions and successfully determined the pole orientations for the 13 objects by the combination with sparse data from the AstDyS site. The summary of pole solutions for the Maria family asteroids is listed in Table 4. Due to an intrinsic symmetry of the problem (Kaasalainen et al. 2002), ground-based observations of objects with a small orbital inclination are affected by an ambiguity in the determination of the ecliptic longitude of the pole axis direction, resulting in two solutions that are placed 180 deg apart and are statistically indistinguishable. We adopted the lower chi-squared solution marked with boldface for this study and estimated the uncertainty of the pole orientation to be 5–20 deg, depending on the number of dense and sparse data sets. Out of 13 asteroids, the information on spin axis of 4 objects was also found in DAMIT (Database of Asteroid Models from Inversion Techniques; Durech et al. 2010). For the pole orientation, the lower chi-squared value marked with boldface is preferred.

| Asteroid   | \(\lambda_1\) | \(\beta_1\) | \(\lambda_2\) | \(\beta_2\) | \(\epsilon\) | \(P_{\text{ad}}\) | \(N_{\text{LCL}}\) | \(N_{\text{USNO}}\) | \(N_{\text{USNO}}\) | \(N_{\text{DAMIT}}\) |
|------------|---------------|-------------|---------------|-------------|-------------|----------------|----------------|----------------|----------------|----------------|
| 170 Maria  | 103           | -18         | 289           | -5          | 112         | 13.131212     | 10             | 183             | 112             |                |
| 575 Renate | 6             | +3          | 183           | -19         | 105         | 3.6603283     | 5              | 108             | 191             |                |
| 652 Jubilatrix | 143        | +3-4        | 321           | +27         | 69          | 2.6620693     | 5              | 84              | 163             |                |
| 660 Crescentia | 58         | +1          | 241           | +15         | 90          | 7.9140789     | 10             | 220             | 158             |                |
| 695 Bella  | 81            | -58         | 308           | -49         | 149         | 14.2190116    | 15             | 203             | 144             | 87, -55        |
| 727 Nipponia | 172        | +11         | 333           | +5          | 89          | 5.0687459     | 10             | 239             | 185             |                |
| 787 Moskva | 132           | +11         | 334           | +44         | 55          | 6.0558066     | 30             | 164             | 132             | 126, +27       |
| 875 Nympha | 47            | +32         | 200           | +46         | 52          | 12.6212926    | 18             | 95              | 196             | 196, +41       |
| 897 Lysistrata | 109       | -55         | 299           | -29         | 136         | 11.2742816    | 7              | 186             | 134             |                |
| 1158 Luda  | 88            | +67         | 267           | +21         | 54          | 6.8750690     | 12             | 106             | 177             |                |
| 1996 Adams | 106           | +56         | 281           | +17         | 48          | 3.3111390     | 3              | 82              | 172             | 107, +55       |
| 3786 Yamada | 77           | +61         | 236           | +63         | 33          | 4.0529422     | 9              | 18              | 131             |                |
| 6458 Nouda | 63            | -2          | 240           | +21         | 81          | 4.2030968     | 9              |                | 163             |                |

Notes. The ecliptic longitude \((\lambda)\) and latitude \((\beta)\) of the asteroid pole orientation (usually the two solutions differ by 180 deg), the spin vector obliquity \((\epsilon)\) of the angle between the orbital plane and the spin pole (calculated from the lower chi-squared pole solution), the sidereal rotational period \((P_{\text{ad}})\), the number of dense light curves \((N_{\text{LCL}})\), and the number of sparse points from USNO in Flagstaff (689) and the Catalina Sky Survey (703). The information about spin axis \((\lambda, \beta)\) of four objects was also found in DAMIT (Database of Asteroid Models from Inversion Techniques; Durech et al. 2010). For the pole orientation, the lower chi-squared value marked with boldface is preferred.

17 http://astro.troja.mff.cuni.cz/projects/asteroids3D
Kryszczyńska (2013) found a similar consequence, they could have been ejected by the 3:1 MMR causes the semimajor axis of family members to decrease; the Yarkovsky drift. In the case of retrograde rotators, the Yarkovsky effect. In the case of retrograde rotators, the Yarkovsky effect can be explained with a long-term evolution by the Yarkovsky effect.

The spin axes of those five objects are very close to the ecliptic plane within their statistical errors, between 5 and 20 deg. Although an observational bias cannot be excluded, the excess of prograde rotators with respect to retrograde rotators could be explained with a long-term evolution by the Yarkovsky effect. In the case of retrograde rotators, the Yarkovsky drift causes the semimajor axis of family members to decrease; consequently, they could have been ejected by the 3:1 MMR to the inner solar system. Kryszczyńska (2013) found a similar result for the Flora family, which is located near the outer border of the $v_6$ resonance area.

Recent statistical studies by Paolicchi and Kryszczyńska (2012) indicate that there is an excess of prograde versus retrograde rotators in the main belt for asteroids smaller than 100 km. However, these authors did not find any convincing explanations for this excess, and hence this remains an open problem. On the contrary, a strong excess for retrograde rotation was found in NEAs that is completely consistent with a theoretical ratio of $2 \pm 0.2$ with respect to prograde rotators (La Spina et al. 2004). Regarding this prograde-retrograde asymmetry in MBAs and NEAs, they inferred that there is a connection between the excess of retrofitregrade NEAs and the deficiency of retrograde MBAs due to the Yarkovsky effect. However, it might be more complicated to generalize the trend to MBAs as they are too big to have been affected by the Yarkovsky drift. Another supporting example we can find is the largest NEA, 1036 Ganymed, that is regarded to be originated from the Maria family. Zappalà et al. (1997) carried out an extensive analysis of the Maria family and suggested that about 10 objects with size between 15 and 30 km have probably been injected into the 3:1 MMR with Jupiter. They proposed that a couple of giant S-type NEAs, 433 Eros and 1036 Ganymed, probably originated from the Maria family. The spectral reflectance of this asteroid is quite similar to the average spectrum of the Maria family members (Fieber-Beyer et al. 2011). Interestingly, its spin orientation is retrograde (Kaasalainen et al. 2002); moreover, it is on a high-inclination orbit of 26.7 deg.

We can easily distinguish three interlopers (that is, two lower albedo objects of 3094 Chukokkala, 4860 Gubbio, and Xe-type asteroid of 1098 Hakone) from Figure 6, while 71145 (1999 XA183) is not close to the border of the family. One distinct property of the Maria family compared to other densely populated asteroid families, such as Flora, Themis, and Eunomia, is that there is no prominent large body among the family members. The largest body in this family is not 170 Maria but 472 Roma, with a diameter 50.3 km as calculated from the WISE IR data. In the recent paper by Masiero et al. (2013), the Roma family is substituted for the name of the Maria family.

Figure 7 shows the spin vector obliquity of the Maria family members with respect to the rotational frequency (cycles day$^{-1}$) compared with those of the Koronis (violet and cyan squares) and Flora family (orange and green triangle). The five open circles (same as Figure 6) denote Maria objects for which the pole axes lie close to the ecliptic plane. The abscissa in this figure follows the definition given in Slivan (2002).

(A color version of this figure is available in the online journal.)

show the position of prograde and retrograde asteroids on a plane of proper semimajor axis (AU) versus absolute magnitude ($H$) in Figure 6. In addition, we found five rotators with the pole along the ecliptic: 170 Maria, 575 Renate, 660 Crescentia, 727 Nipponia, and 6458 Nouda, marked with open circles in Figure 6. The spin axes of those five objects are very close to the ecliptic plane within their statistical errors, between 5 and 20 deg. Although an observational bias cannot be excluded, the excess of prograde rotators with respect to retrograde rotators could be explained with a long-term evolution by the Yarkovsky effect. In the case of retrograde rotators, the Yarkovsky drift causes the semimajor axis of family members to decrease; consequently, they could have been ejected by the 3:1 MMR to the inner solar system. Kryszczyńska (2013) found a similar result for the Flora family, which is located near the outer border of the $v_6$ resonance area.

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Figure 7 shows the spin vector obliquity of the Maria family members with respect to the rotational frequency (cycles day$^{-1}$), compared with the Koronis (Slivan et al. 2009) and Flora families (Kryszczyńska 2013). In those two families, there is a conspicuous group of prograde objects. Furthermore, retrograde objects share almost the same obliquities, which is referred to as the Slivan effect (Slivan 2002). In the Maria family, on the other hand, no prominent prograde groups being in the Slivan state were found, while the data for retrograde rotation are not sufficient for a conclusion. Vokrouhlický et al. (2003) investigated several test prograde rotators chosen with various ranges of either semimajor axis or inclination in the main belt. Their preliminary results indicate that asteroids with low inclination in the outer main belt, such as 24 Themis, might be trapped efficiently in the Slivan state. This is the reason why they suggest observations of either high-inclination or inner MBAs and numerical simulations for their dynamical evolution. Skogløv
& Erikson (2002) found that orbital inclination of MBAs is the most important factor that affects the magnitude of the spin vector variation. Based on their dynamical spin evolution, if the orbital inclination is increased, also the maximum obliquity variation increases linearly.

The other feature seen in Figure 7 is that there are several objects with spin vector obliquities around 90 deg, that is, spin axes approximately parallel to the orbital plane. The change of semimajor axis by the diurnal component of the Yarkovsky effect is proportional to the cosine of the obliquity of an asteroid, so it will vanish when the obliquity approaches 90 deg. We can predict that the semimajor axis drift of these five objects plotted as open circles in Figures 6 and 7 will not occur. However, we can expect that the spin vector can be modified by the YORP effect.

4.3. NEA Source Region

The 3:1 MMR (∼2.5 AU) is the most prominent Jovian resonance region in the main belt, and, as such, it is an important source region of NEAs and meteors. The Maria family is located quite close to the outer border of the 3:1 MMR with Jupiter. When members of the Maria family enter this unstable region due to the Yarkovsky drift, they can escape from its membership and become NEAs. For this reason, the distribution of proper semimajor axis versus absolute magnitude is asymmetric as shown in Figure 6. The Bottke et al. (2002) model suggests that with 20% probability, the population of all near-Earth objects (NEOs; with absolute magnitude $H < 18$) originated from the 3:1 MMR region. They estimated that the number of kilometer-sized NEOs ($H < 18$) that escaped from the 3:1 MMR every million years is 100 ± 50 bodies. Similar results independently derived by Morbidelli and Vokrouhlický (2003) show that 100–160 objects larger than 1 km enter the 3:1 MMR per million years.

In order to make an order-of-magnitude estimation of the flux of the Maria members into the 3:1 MMR region, we try to determine the number of missing Maria family members. We do this by taking the difference of the original members (assuming that the distribution was originally entirely symmetric) and the number of currently known objects (the absolute magnitude of all members is brighter than 18th magnitude). To obtain the number of original members, we assume that the center of the Maria family is at about 2.562 AU (denoted with the red dashed line) since the number density with respect to the semimajor axis is at a minimum. Then we double the number of family members, with proper semimajor axis >2.562 AU as in Figure 6. This results in a total of 5368 original members. With this procedure, our preliminary result implies that 2138 Maria asteroids have been injected into the 3:1 MMR region through its dynamical evolution age of 3 ± 1 Gyr. It is well known that the dynamical lifetime of objects placed in orbital resonances is only a few million years (Gladman et al. 1997). Their numerical simulations for 3:1 MMR injected particles from the Maria family show that the fraction of particles experiencing the end-states of (1) being injected into the inner solar system and eventually colliding with the Sun or (2) being injected into a Jupiter-crossing orbit and being eventually removed from the solar system are 70% and 29%, respectively. Therefore, we may conclude that roughly 1500 objects from the Maria family had been injected into the inner solar system during 3 ± 1 Gyr, i.e., 37–75 Maria asteroids larger than 1 km every 100 Myr.

We also look into the 3:1 resonance neighborhood region to find possible candidates among Maria members residing in this unstable area. According to Morbidelli and Vokrouhlický (2003), the boundary of the 3:1 MMR region can be defined approximately by the following formulae (only for the right side of the 3:1 resonance):

$$a = 2.508 + \frac{e}{29.615} \text{ for } e \leq 0.15936,$$

$$a = 2.485 + \frac{e}{5.615} \text{ for } e > 0.15936. \quad (5b)$$

They found that the number density of asteroids sharply increases up to ∼0.015 AU from the resonance boundary, yet it is not changed considerably over the next 0.025 AU. Guillens et al. (2002) also pointed out that there is a chaotic diffusion region in the range of 0.01–0.02 AU in semimajor axis from the 3:1 resonance border. Asteroids residing in this region could enter the resonance on a timescale of 100 Myr. The oscillation of the border of the resonance could also have taken place (Morbidelli & Moon 1995; Morbidelli et al. 1995; Robutel & Laskar 2001).

Figure 8 represents all 3230 Maria asteroids projected onto a plane of proper semimajor axis and proper eccentricity. The 3:1 MMR boundary denoted with black dashed line is defined by Equation (5a). The chaotic diffusion region that has been shifted to 0.015 AU from the resonance border is represented by the red dashed line. The number of objects residing in this region is 34; they could fall into the 3:1 resonance in the coming 100 Myr, especially 114123 (2002 VX49) and 137063 (1998 WK1) (marked with green open circles), which are the most promising candidates for becoming new NEAs. Prograde (blue) and retrograde (red) rotators are the same as in Figure 6. (A color version of this figure is available in the online journal.)
Figure 9. Composite light curves of six example Maria family members.
(The complete figure set (61 images) is available in the online journal.)
5. CONCLUSIONS

We performed observations of the Maria family asteroids from 2008 July to 2013 May. From our observations for 134 nights, synodic rotational periods for 51 objects were acquired, including newly derived periods of 34 asteroids. The rotational rate distribution of the Maria family members obtained from our data sets, in addition to published light-curve data from the LCDB, indicates that there is a considerable excess of fast and slow rotators. The one-sample Kolmogorov–Smirnov test rejects the hypothesis that the spin distribution matches that of a Maxwellian at a confidence level of 92%.

From correlations among spin rates, sizes, and overall shapes of asteroids, we conclude that rotational properties of the Maria family have been altered significantly by the YORP effect. Such a substantial change of the rotational characteristic is also observed in old asteroid families such as Koronis and Flora (e.g., Slivan et al. 2008; Kryszczyńska et al. 2012). On the other hand, however, we could not detect the Slivan state in the Maria family members that have relatively higher inclination orbits between 12° and 17° than those of Koronis and Flora families.

The YORP effect is most effective in the spin-up or spin-down of small asteroids. Consequently, there is an apparent trend toward larger dispersion of rotational frequency with decreasing size in Figure 4. Regarding the correlation between rotational frequencies and the light-curve amplitude (see Figure 5), we confirm that there is no object that both is fast rotating (faster than 6 cycles day$^{-1}$) and has a large light-curve amplitude (more than 0.6 mag), thus verifying that there is no evidence of objects having high tensile strengths.

Based on the light-curve inversion method, we obtained pole orientations for 13 members to trace non-gravitational forces such as the Yarkovsky effect. The excess of prograde rotators with respect to retrograde is found with a ratio ($N_p/N_r$) of 3. The retrograde objects might have been injected into the inner solar system by entering the 3:1 MMR with Jupiter. Therefore, the overall trend of proper semimajor axis and absolute magnitude plot is non-symmetric. From our simplest arithmetic of the flux for the 3:1 MMR resonant objects from the Maria family, we estimate that approximately 37–75 Maria asteroids larger than 1 km have entered the inner solar system every 100 Myr.

For understanding these non-gravitational forces that are affecting the Maria asteroid family in detail, we need more samples in order to improve our statistical result. This is the reason why we are planning to extend our observational campaign with a network of telescopes in both hemispheres. The Yarkovsky/YORP model based on high accurate parameters such as spin status, size, albedo, density, and thermal conductivity is expected to shed new light on the dynamical evolution in the history of the inner solar system.

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APPENDIX

LIGHT CURVES OF INDIVIDUAL OBJECTS IN THE MARIA ASTEROID FAMILY

We present 61 individual light curves (with a reliability code $\geq2$) for a total of 51 Maria family members (Figure 9).
All figures were drawn as composite light curves folded with their synodic rotational period. Horizontal axes of each light curve represent rotational phase, and vertical axes are differential magnitude between instrumental magnitude of the asteroid and an average magnitude of comparison stars. Figures 10 and 11 show the correlation among rotational frequency (cycle day$^{-1}$), amplitude of the light curve (magnitude), and the size of the asteroid (km). Figure 5 was divided into Figures 10 and 11.

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