# Asteroid Rotations

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The rotations of asteroids larger than ~40 km in diameter have a distribution close to Maxwellian that suggests that they are either original bodies of the asteroid main belt or its largest, collisionally evolved remnants. Small asteroids (0.15 < D < 10 km) show significant excesses of both slow and fast rotations, a "barrier" against spins faster than ~12 rotations per day, and some of them are binary systems on inner-planet-crossing orbits with a characteristic fast rotation of their primaries. These small asteroids are collisionally derived fragments, mostly with negligible tensile strength (rubble-pile or shattered interior structure). They mostly gained angular momentum through collisions, but noncollisional factors have also affected their spins and perhaps shapes. In the intermediate size range (10 < D < 40 km), the populations of large and small asteroids overlap. Most tiny asteroids smaller than D ≈ 0.15 km are rotating so fast that they cannot be held together by self-gravitation and therefore must be coherent bodies. They likely are single fragments of the rubble that make up larger asteroids from which the smaller ones are derived.

## 1. INTRODUCTION

The fundamental characteristic of asteroid rotation is the rotational angular momentum. The angular momentum vector ($\bar{L}$) as well as the inertia tensor ($\hat{I}$) are changed through collisions and other processes of asteroid evolution. They are related with the angular velocity vector ($\vec{\omega}$)

$$\bar{L} = \hat{I}\vec{\omega} \tag{1}$$

The inertia tensor is generally a symmetric tensor containing six independent components. A convenient choice of the system of coordinates in the asteroid-fixed frame gives zero nondiagonal components. The diagonal components $I_x \leq I_y \leq I_z$ are then the principal moments of inertia; the axes are called the principal inertia axes.

In a general rotation state, the spin vector $\vec{\omega}$ is not constant due to the varying moment of inertia about the instantaneous spin axis; its direction and size change on a timescale usually on the order of the rotation period. The excited rotational motion has been described by, e.g., *Samarasinha and A'Hearn* (1991) and *Kaasalainen* (2001). The complex rotation results in a stress-strain cycling within the body. Since the asteroid is not a completely rigid body, the excess rotational energy is dissipated in the asteroid's interior and the spin state asymptotically reaches the lowest energy state, which is a rotation around the principal axis of the maximum moment of inertia $I_z$. The energy-dissipation profile may be complex, but a reasonable estimate of the timescale $\tau$ of damping of the excited rotation to the lowest energy state of principal-axis rotation has been derived by *Burns and Safronov* (1973) assuming a low-amplitude libration

$$\tau \sim \frac{\mu Q}{\rho K_3^2 R^2 \omega^3} \tag{2}$$

where $\mu$ is the rigidity of the material composing the asteroid, Q is the quality factor (ratio of the energy contained in the oscillation to the energy lost per cycle), $\rho$ is the bulk density of the body, $K_3^2$ is a dimensionless factor relating to the shape of the body with a value ranging from ~0.01 for a nearly spherical one to ~0.1 for a highly elongate or oblate one, R is the mean radius of the asteroid, and $\omega$ is the angular velocity of rotation. *Harris* (1994) estimates the parameters in equation (2) and expressed the damping timescale as

$$\tau = \frac{P^3}{C^3 D^2} \tag{3}$$

where $P = 2\pi/\omega$ is the rotation period, D is the mean diameter of the asteroid, and C is a constant of ~17 (uncertain by a factor of ~2.5) for P in hours, D in kilometers, and $\tau$ in billions ($10^9$) of years. For most asteroids, the damping timescale is much shorter than the characteristic timescale of events causing excitation of their rotations; all but the slowest rotators and one very small superfast rotator (2000 $WL_{107}$; P. Pravec et al., in preparation, 2002) have been found with rotations close to principal-axis rotation states.

*Efroimsky* (2001) has argued for an even shorter damping timescale than above, although observationally, the transition from principal-axis rotation to "tumbling" seems fairly consistent with the above damping timescale. The reader can find more details on the theoretical efforts to estimate the damping timescale in the chapter by *Paolicchi et al.* (2002).

With groundbased observations, we cannot directly measure the asteroid angular momentum vector. The observable parameter is the spin vector; the angular momentum can be estimated from that parameter using equation (1) with an estimate of the moment of inertia based on the asteroid shape, size, and bulk density. Among methods of derivation of the spin vector from ground based observations, the most frequently used one is lightcurve observations. [For the general analysis of disk-integrated data obtained by lightcurve observations, see *Kaasalainen et al.* (2002).] Lightcurve observations are relatively inexpensive in terms of equipment needed but require a lot of observing time (often many nights over several years) to gather enough data for a full solution of the spin vector. Nevertheless, an estimate of the period of rotation and some indication of the shape can be obtained much more easily, often from observations of only a few nights. Thus data on rotation rates, along with amplitudes of variation, are the most abundant. Most studies of rotation characteristics of asteroids are based mainly on lightcurve-derived rotation rates. Likewise, most of the results that we review and present in this chapter are based on analyses of asteroid rotation rates.

## 2. DISTRIBUTIONS OF ROTATION RATES

In this section, we review analyses of distributions of asteroid rotation rates and also redo some of these analyses using new data. We use the compilation of asteroid lightcurve data maintained by A. W. Harris and available on the Internet (e.g., the IAU Minor Planet Center Web site, http://cfa-www.harvard.edu/iau/lists/LightcurveDat.html). The version used here is dated March 1, 2001, and contains rotation periods and lightcurve amplitudes of 984 asteroids with quality codes Rel ≥ 2. *Harris and Young* (1983) define the Rel quality code scale used in the data tabulation. Here it suffices to note that Rel = 2 corresponds to period determinations that are accurate to ~20%, or in error at most due to some cycle ambiguity or number of extrema per rotation cycle, in rare cases perhaps even off by a factor of 2, but not more. Higher reliabilities have no significant ambiguity. Errors of the period estimates of 970 asteroids of the sample are not greater than a few tens percent, so they are suitable for statistical analyses. For another 14 objects, lower limits on their periods have been estimated and we plausibly take a value of 1.5× the lower limit as an estimate of the period in those cases. Omitting them would lead to an increase of the bias against slow rotators, which is nevertheless inevitably still present in the sample due to the lightcurve technique used. Asteroid diameter estimates are mostly from the IRAS Minor Planet Survey (*Tedesco et al.,* 1992); for objects with no other diameter estimate available, diameter is estimated from absolute magnitude and an assumed albedo typical for their taxonomic or orbital class. The uncertainty of such diameter estimates is likely within a factor of 1.5, and almost certainly within a factor of 2.

### 2.1. Spin Rate vs. Size

In Fig. 1, the spin rate vs. diameter is plotted using the data for 984 asteroids. The geometric mean spin rate has been computed using the "running box" method described in *Pravec and Harris* (2000). Briefly, the geometric mean spin rate $\langle f \rangle$ is computed within a box of 50 objects, shifted down in diameter by one object each time. Slowly rotating asteroids with $f < 0.16 \langle f \rangle$ are excluded from the computation, since their excess would affect the computation significantly. The computed geometric mean spin rate is thus representative of the population of the asteroids with the slow rotators excluded. The computation has been stopped at D = 0.15 km. The abrupt change of the rotation properties around this diameter does not warrant a use of the method over the boundary. We note that the choice to use the geometric rather than arithmetic mean rate has the advantage that it is less sensitive to outlying extreme values and its results are the same for P (spin period) as for f (spin rate) in the analysis. We also did the analysis with the arithmetic mean spin rate and obtained similar results, so the choice to use the geometric rather than arithmetic mean spin rate is not critical for the conclusions.

In Fig. 2, the computed $\langle f \rangle$ vs. diameter is shown in detail. Arrows at the bottom of the diagram show positions of every fiftieth object (starting from the twenty-fifth) to indicate the resolution in diameter. Points of the curve shifted by 50 objects or more are independent; thus there are only about 19 fully independent points in the curve. The formal $\pm 1\sigma$ uncertainty of the computed $\langle f \rangle$ is represented with the dashed curves; it is about 10% at any diameter.

The geometric mean spin rate is about 3.0 $d^{-1}$ for the largest asteroids (mean D ~ 200 km) and decreases to 1.8 $d^{-1}$ as D decreases to ~100 km. Then it increases to about 4.0 $d^{-1}$ as D decreases down to ~10 km. The "wavy" deviations from a monotonic increase of the computed $\langle f \rangle$ between 10 and 100 km may not be real, as the peaks and troughs differ by ~2σ or less and, moreover, occur at intervals similar to the resolution in D in that size range. This suggests that statistical variations in the sample are a cause of the deviations. Only the local minimum of $\langle f \rangle$ at D ~ 40 km is marginally significant at ~3σ. Below D = 10 km, there is apparently only a small increase of $\langle f \rangle$ with decreasing diameter, but more data are needed to establish its statistical significance. Below we discuss the rotation characteristics in different size ranges.

### 2.2. Large Asteroids (D > 40 km)

Several researchers have estimated a lower bound diameter of the "large asteroid" group on a basis of statistical

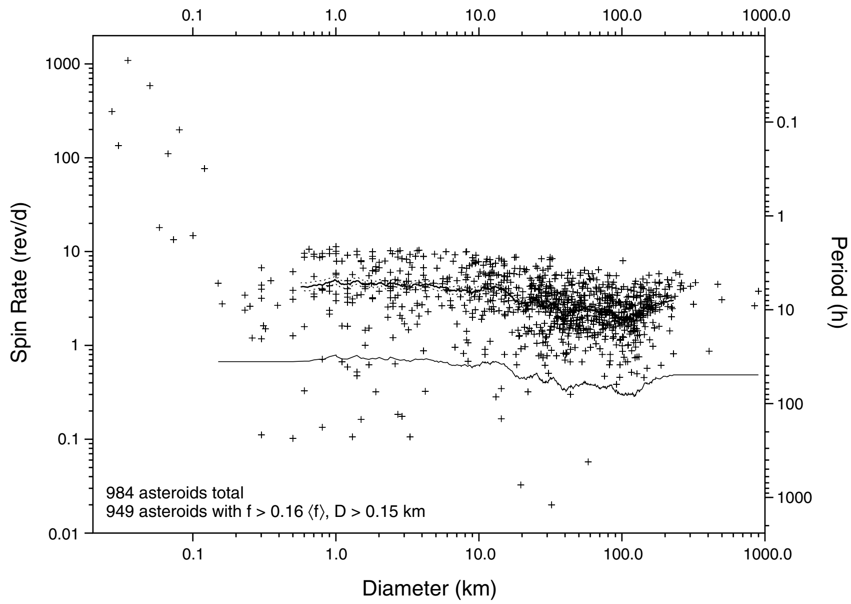


**Fig. 1.** Asteroids' spin rate vs. diameter plot. The bold solid curve is the geometric mean spin rate ⟨f⟩ vs. diameter; the thin solid curve is the limit f = 0.16 ⟨f⟩ used for excluding slow rotators.

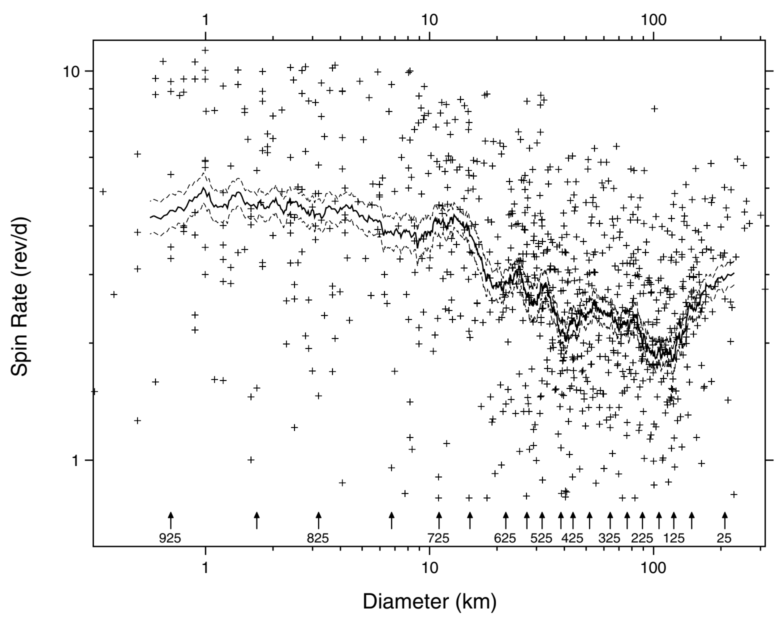


**Fig. 2.** The densest part of Fig. 1 shown in detail. The dashed curves represent ±1σ errors of ⟨f⟩ (solid curve) computed from variance of a sample within the running box.

analyses of the asteroid rotation properties. Recent estimates range generally from 30 to 50 km (e.g., *Fulchignoni et al.,* 1995; *Donnison and Wiper,* 1999). *Pravec and Harris* (2000) give a lower limit of 40 km based on their study, which shows that larger deviations from Maxwellian distribution (see below) start to occur in the 30–40-km-diameter range. We repeat the analysis using the larger dataset and come to the same conclusion. The occurrence of several relatively rapidly rotating asteroids and one very slow rotator at diameters just above 30 km indicates that the lower diameter limit of the large asteroid group is about 35 km with an uncertainty of several kilometers; the error being dominated by likely systematic errors of the asteroid diameter estimates themselves. For the analyses presented below, we adopt as the lower limit a diameter of 40 km, consistent with the work by *Pravec and Harris* (2000).

The Maxwellian distribution has the form

$$n(f) = \sqrt{\frac{2}{\pi}}\,\frac{Nf^2}{\sigma^3}\exp\left(\frac{-f^2}{2\sigma^2}\right) \qquad (4)$$

where n(f) df is the fraction of objects in the range (f,f + df), N is the total number of objects, and σ is the dispersion. Instead of σ, one can as well use $\overline{f^2}$, the mean squared spin frequency of the distribution, where $\overline{f^2} = 3\sigma^2$ for the Maxwellian distribution. A distribution of spin rates of asteroids is Maxwellian if all the three components of $\vec{\omega}$ are distributed according to a Gaussian with zero mean values and equal dispersions. It is plausible to expect that this is a typical outcome for a collisionally evolved system (*Salo,* 1987). However, deviations from the Maxwellian distribution of rotation rates are expected because of, e.g., an inhomogeneous sample. In fact, it is known that the sample of asteroids is inhomogeneous; they have different masses and material properties. Nevertheless, it still makes sense to compare observed distribution with a Maxwellian: If it is close to Maxwellian, it suggests that the system is collisionally relaxed. If it is not, we must investigate the deviations in detail.

Comparisons of histograms of asteroidal spin rates with a Maxwellian distribution have been done by many researchers (e.g., *Harris and Burns,* 1979; *Farinella et al.,* 1981; *Binzel et al.,* 1989; *Fulchignoni et al.,* 1995; *Donnison and Wiper,* 1999). They generally have found that the spin-rate distribution is Maxwellian for larger asteroids but non-Maxwellian below a certain diameter. They use, however, an assumption of a constant dispersion (or, equivalently, mean spin rate) for asteroids of all sizes in each investigated sample. We know that this is an incorrect assumption; the mean spin rate varies considerably with size (as shown in Figs. 1 and 2).

Attempting to account for different sizes of asteroids, *Pravec and Harris* (2000) normalize each spin rate to the geometric mean spin rate at the given size and test that distribution for consistency with a Maxwellian. This approach should eliminate a size-dependent part of the sample inhomogeneity. They find that the distribution of spin rates of large asteroids is nearly Maxwellian, with only a small deviation among the fastest rotators. We repeat the analysis with the larger sample and the result is plotted in Fig. 3. The most extreme outlying point, at $D \approx 100$ km and $f \approx 8$ $d^{-1}$ (see Fig. 2), is the asteroid 522 Helga (*Lagerkvist et al.,* 2001). They note an ambiguity in their solution and that

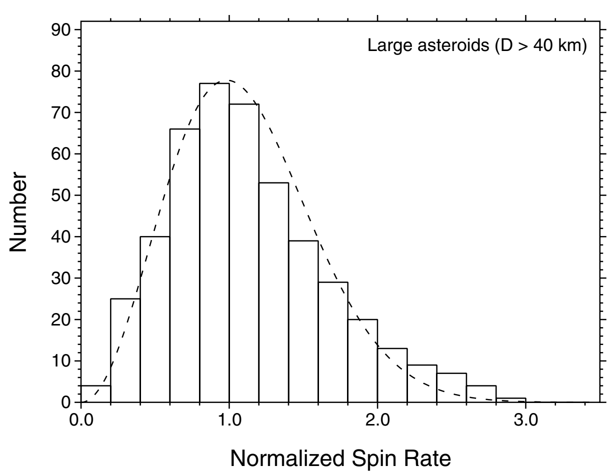


**Fig. 3.** Histogram of $f/\langle f \rangle$ for 460 asteroids with $D > 40$ km. The dashed curve is the corresponding Maxwellian distribution.

Helga's period may be ~7 $d^{-1}$, which is not so extreme, and the determination is quite uncertain, only barely of Rel = 2. Thus, we exclude this point from a statistical test below. According to a $\chi^2$ test, the observed distribution of spin rates of large asteroids is only marginally different from a Maxwellian distribution. The hypothesis that the distribution is Maxwellian can be rejected at the 95% confidence level, but not at the 99% level. An excess occurs at normalized spin rates from 2.2 to 2.8. Cheking it in detail, we have found that this is at least partly caused by M-type asteroids that have a mean spin rate 1.46× (formal error ±0.17) the mean spin rate of "primitive" (BCDFGPT) and "differentiated stony" (SQAEVR) asteroids. Actually, most asteroids in the excess of $f/\langle f \rangle$ from 2.2 to 2.8 for which a taxonomic class is known are M types. So, a fully sufficient explanation of the marginally significant deviation of the distribution of spin rates of large asteroids from Maxwellian is the presence of the faster-than-average-rotating population of M-type asteroids. An explanation of their greater mean spin rate is, however, uncertain. A theory by *Harris* (1979) predicts that the mean spin rate depends on a square root of the bulk density, which would be consistent with their expected properties. On the other hand, estimated bulk densities of C and S types differ significantly as well, and we see no difference between the mean spin rates of the "primitive" and the "differentiated stony" classes.

A plausible explanation of the minimum of $\langle f \rangle$ at $D \sim 100$ km is an effect proposed by *Dobrovolskis and Burns* (1984) called "angular momentum drain." They point out that if the characteristic velocity of impact ejecta is in the range of the surface escape velocity of the asteroid, then more of the ejecta coming out of a crater in a prograde sense with respect to the asteroid's rotation will escape than ejecta coming out in a retrograde sense. This asymmetric distribution of escaping ejecta produces a recoil that may lead to a slowing of the spin rate with many impacts. The surface escape velocity in the size range of the minimum in spin frequency at ~100 km diameter is ~100 m/s, plausibly in the right range corresponding to typical impact ejecta velocities. *Cellino et al.* (1990) describe a similar effect (calling it "angular momentum splash") based on the same concept and working on marginally catastropic disruptions. Tidally slowed binary asteroids cannot account for the reduction in mean spin without substantially broadening the distribution, since only a small fraction of the population can be binaries.

The large asteroid group includes 22 "jovian" and "transjovian" asteroids (Trojans, Centaurs, and transneptunian objects). Their number is too small for a thorough separate statistical analysis but the present group is indistinguishable from main-belt rotational properties. We therefore include them together with large main-belt asteroids in the analysis described above, but of course excluding them would not alter the results for the main-belt asteroids. When a significantly larger sample of these distant objects is available in the future, it may be possible to find some differences in their rotational properties.

In general, the rotational properties of asteroids larger than D = 40 km suggest that they are either original bodies of the main asteroid belt or their largest, collisionally relaxed remnants.

### 2.3. Small Asteroids (0.15 km < D < 10 km)

Below D ≈ 40 km, the distribution of the rotation rates is non-Maxwellian, with excesses both at the fast and slow spins. The range between 10 and 40 km is where a steep increase of the mean spin rate occurs (Fig. 2). We consider this range as a transitional region where the large and small asteroid groups overlap. Since the samples are mixed there, we do not study this region in detail. We also note that some objects in this diameter range are recognized members of dynamical (Hirayama) families. Some of the families have specific rotation distributions likely related to specific formation conditions of the families (e.g., see *Binzel et al.,* 1989); this can contribute to the non-Maxwellian distribution of spin rates in the range 10 < D < 40 km as well.

The distribution of spin rates of asteroids with 0.15 < D < 10 km is strongly non-Maxwellian (see Fig. 4). There are significant populations of both slow ($f \lesssim 0.8\ d^{-1}$) and fast ($f \gtrsim 7\ d^{-1}$) rotators (*Pravec and Harris,* 2000). Several previous investigators have attempted to formally fit the distribution as a sum of Maxwellians, e.g., *Fulchignoni et al.* (1995) and *Donnison and Wiper* (1999). The fits by the outlying Maxwellians, particularly to the slow rotating population, are poor.

It is apparent in Fig. 1 that there is a "barrier" against rotations faster than f ≈ 12 rotations per day in the size range of ~1–10 km diameter. This is further apparent in Fig. 5, where we can also see that among the very fastest rotators, $f > 6\ d^{-1}$, there is a tendency toward more spherodial shape with increasing spin rates. These characteristics suggest that most of the small asteroids are loosely bound, gravity-dominated aggregates with negligible tensile strength (*Harris,* 1996; *Pravec and Harris,* 2000). They find that the "barrier" to fast rotation is at f ≈ 11 rotations per day for nearly spherical bodies, corresponding to stability for strengthless bodies of bulk density greater than ~2.5 g/cm$^3$. The maximum spin rate for a strengthless nonspherical body of a given density is less with increasing elongation of the shape, thus the "barrier" shifts to a slower rotation rate with increasing amplitude of lightcurve variation. In February 2001, Pravec et al. find that 1950 DA with D ≈ 1 km has a period of 2.12 h (results available at http://www.asu.cas.cz/~ppravec/). It can still be a strengthless object if its bulk density is >2.9 g/cm$^3$, which is plausible for a silicate body with very little porosity, that is, a "shattered" body rather

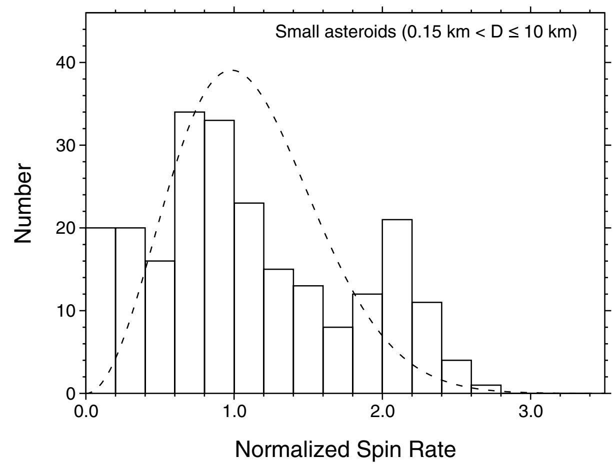


**Fig. 4.** Histogram of f/⟨f⟩ for 231 asteroids with 0.15 < D ≤ 10 km. The dashed curve is the Maxwellian distribution for the same number of objects. Of them, 164 are NEAs and Mars-crossers; most of the rest are inner main-belt asteroids.

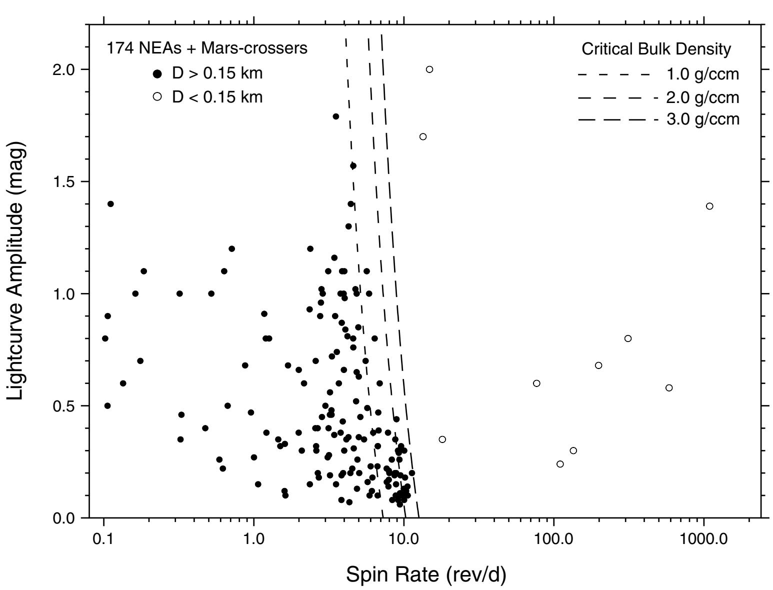


**Fig. 5.** The observed lightcurve amplitude vs. spin rate of near-Earth and Mars-crossing asteroids. The dashed curves are approximate upper limits of spin rates of bodies held together by self-gravitation only, with bulk densities plausible for asteroids; $f_c = \sqrt{\rho/(1 + \Delta m)}/3.3$ h (ρ in g/cm$^3$) (*Pravec and Harris,* 2000).

than a "rubble pile" [see definitions in *Richardson et al.* (2002)] or one with substantial metal content. Further studies should refine the placement of the "barrier" around our estimate of f ≈ 11–12 rotations per day and give a better understanding of the interior structure of the fastest rotators just below the "barrier."

In October 2001, after the first draft of this chapter was written, *Pravec and Kušnirák* (2001) found that 2001 $OE_{84}$ is a superfast rotator with a period of 29.19 min, thus it must have a nonzero tensile strength (cf. section 2.4). With its estimated size ~0.9 km, it is the first known coherent object in the size range 0.15 < D < 10 km, and the first one that breaks the "barrier." It shows that coherent bodies exist also in the small asteroids group but we cannot estimate their fraction well from the observed statistic of the one superfast rotator among a few hundred asteroids in the group. It is likely an exceptional object, maybe an unusually large "rubble" fragment of a larger asteroid released in a collision. The "barrier" against such fast rotations holds for all other observed asteroids in the group.

The excess of fast rotators at $f/\langle f \rangle \geq 1.7$ (corresponding approximately to f ≥ 7 revolutions per day in the diameter range of 1–10 km where the mean spin rate changes only slightly) lies just below the "barrier" (Fig. 4; the "barrier" in f is less obvious in this figure since it is somewhat smeared there due to the normalization to the computed mean spin rate). The cause of this excess of fast rotators is not quantitatively understood, but may be related to radiation pressure effects (*Rubincam,* 2000; *Bottke et al.,* 2002) or, for planet-crossing bodies, gravitational interactions with planets during close encounters (*Scheeres et al.,* 2000; *Richardson et al.,* 1998). The shapes of at least some of the bodies might be affected by spinup as well. Only asteroids with more spheroidal shapes or those whose shapes were so reconfigured during the spinup process could be spun up to the rates not much below the "barrier." The shape reconfiguration could even be associated with a loss of mass and angular momentum (see below).

A significant fraction of the observed population of fast rotators are actually binary near-Earth asteroids (*Merline et al.,* 2002; also *Pravec and Harris,* 2000, and references therein). Primaries of the observed and suspected binary NEAs are fast rotators with low amplitudes. It is probable that creation and/or evolution mechanisms of the binary NEAs are connected with the fast rotations of the strengthless bodies. A mechanism of tidal breakup of such asteroids during close encounters with the terrestrial planets has been suggested to create binary NEAs (*Bottke and Melosh,* 1996; *Richardson et al.,* 1998). An additional mechanism may be a rotational fission of strengthless asteroids when they are spun up by collisions or non-gravitational effects (see *Paolicchi et al.,* 2002). The reader can find more information on binary NEAs in the chapter by *Merline et al.* (2002).

The origin of the population of slow rotators is unclear. None of mechanisms proposed earlier has explained all observed characteristics of the slow rotator population or its specific members. Radiation pressure effects (*Rubincam,* 2000; *Bottke et al.,* 2002) are ineffective for objects larger than several kilometers. Despinning as a result of outgassing of now-extinct comet nuclei certainly cannot explain large slow rotators like 253 Mathilde or 288 Glauke. Tidal forces from close planetary encounters (e.g., *Scheeres et al.,* 2000) likewise cannot apply to these main-belt objects. Tidal evolution of binaries, such as the process that has led to the synchonization of Pluto and Charon with a period of ~6 d (e.g., *Farinella et al.,* 1981; *Weidenschilling et al.,* 1989) cannot explain periods longer than this, as the rate of transfer of angular momentum from the primary's spin to the secondary's orbit stalls out in the age of the solar system for rocky bodies the size of small asteroids when the satellite recedes out to only about a 5-d period orbit. Furthermore, the very slow rotators Mathilde, Glauke, and Toutatis are proven not binary objects. Recently *Harris* (2002) has fit the distribution of the excess of slow rotators to a function of the form $N(<f) \propto f$, and he offers another explanation for slow rotations — that they result from disintegration of high mass ratio (~1:5) binaries through the rapid transfer of rotational energy of the primary into the orbit of the secondary due to the irregular gravity field of the primary. While results of the model still do not fit the observed cumulative spin rate distribution that appears linearly proportional to f at slow rates, at least it is a plausible mechanism even for the largest slow rotators. Further, more detailed modeling should show if the theory can really fully explain the population of slow rotators.

In general, the rotational properties of asteroids with 0.15 < D < 10 km suggest that they are collisionally derived fragments, mostly with negligible tensile strength. Most of them are rubble piles or shattered bodies according to the definitions of *Richardson et al.* (2002). They mostly gain angular momentum through collisions (see also *Paolicchi et al.,* 2002) but are also affected by noncollisional effects. Their rubble-pile and shattered internal structures are likely a result of collisions that shattered either original parent bodies from which the small asteroids were derived or the small asteroids themselves but did not disperse them (e.g., see *Love and Ahrens,* 1996). We cannot, however, rule out the possibility that the rubble pile structure could be primordial in some cases.

### 2.4. Very Small Asteroids (D < 0.15 km)

Most asteroids with absolute magnitudes H > 22 (corresponding to D ≤ 0.15 km) rotate with periods of less than 2 h. In fact, all well-derived periods for asteroids below the diameter noted are shorter than that (*Steel et al,* 1997; *Ostro et al.,* 1999; *Pravec et al.,* 2000; *Whiteley et al.,* 2002; C. Hergenrother et al., personal communication, 2001); though optical and radar observations of a few asteroids suggest longer periods, they need to be confirmed by further work. The observed rotations are so fast that the bodies are in a state of tension and cannot be held together by self-gravitation. In Fig. 1, they form a distinct group in the upper left part of the diagram. In Fig. 5, they lie in the right part of the diagram, behind the curves of maximum possible spin rates of bodies held together only by self-gravitation. They could be held together, however, by very meager bonds; even the fastest known rotator, 2000 $DO_8$, with a period of 1.30 min and a long axis of ≈80 m, has a centrifugal acceleration at the ends of the long axis of only ≈0.26 $m/s^2$, and the minimum required tensile strength for it is on the order of $2 \times 10^4$ Pa, which is $\approx 10^{-3}$ less than the typical tensile strength of well-consolidated rock (see *Ostro et al.,* 1999). While they are sometimes called "monoliths," their internal structure can, however, be almost anything except "true" rubble pile. In the framework of the definitions proposed by *Richardson et al.* (2002), they can lie anywhere except the very left side in their Fig. 1.

The very small, very fast rotating asteroids with nonzero tensile strength are likely collisional fragments of larger asteroids. The transition from larger rubble-pile to smaller "monolithic" asteroids at D ≈ 0.15 km appears surprisingly sharp. It has been proposed that this is the characteristic size of the largest "rubble" fragments that make up larger asteroids from which the smaller ones are derived (*Pravec et al.,* 2000). No known postformation spinup mechanism is so sensitive to size that it could explain the dramatic change of the rotation properties in such a narrow range around the transition diameter. The apparent truncation of the size range of the observed very fast rotators likely corresponds to the size limit of monolithic fragments from the disruption of larger asteroids. *Whiteley et al.* (2002) show that if there were "monolithic" fragments larger than the observed boundary diameter present in large asteroids, we would observe fast rotating "monoliths" also among asteroids larger than D ≈ 0.15 km. In other words, we would observe a gradual transition from slower to faster rotations in a wider size range and not the sharp transition in the very narrow range that we see. The apparent threshold size is in fair agreement with results of hydrodynamic computations by *Love and Ahrens* (1996), *Melosh and Ryan* (1997), and *Benz and Asphaug* (1999) that show that asteroids as small as a few hundred meters are gravitationally bound, strengthless rubble piles. The recently discovered superfast rotation and therefore the coherent nature of the ~0.9-km-sized asteroid 2001 $OE_{84}$ (see section 2.3) may be an exception to the scheme described above.

The very small asteroids likely gained fast spins in their creation by impacts on larger asteroids (*Asphaug and Scheeres,* 1999). They were generally in excited rotation states immediately after the creation. No lightcurve aperiodicities that would be indicative of tumbling have been observed in the sample of ten very small asteroids that we analyzed; it appears that they are relaxed to states close to principal-axis rotation. In a larger sample of a few tens of small superfast rotators that have been observed more recently, mostly by C. Hergenrother et al. (personal communication, 2001), there is one tumbling asteroid, 2000 $WL_{107}$. So, the fraction of excited rotations among superfast rotators with diameters from a few tens to a few hundred meters may be on the order of several percent; a principal axis rotation is a usual state of superfast rotators. Their damping timescales computed from equation (3) range from $10^3$ to $10^8$ yr, shorter than or comparable to their collisional and dynamical lifetimes of $10^7$–$10^8$ yr (*Farinella et al.,* 1998) if they have been created in the main belt and later delivered to near-Earth orbits. All the very small super-fast rotating asteroids are near-Earth objects. There is a considerable uncertainty, however, in the product μQ (equation (2)); the value $\mu Q = 5 \times 10^{12}$ (CGS units) chosen by *Harris* (1994) may be too small for the bodies that are likely more rigid than rubble piles. Thus, their damping timescales may be actually longer by more than 1 order of magnitude than estimated above. A statistic of their principal vs. nonprincipal axis rotations that can be derived when a much larger sample of the very small asteroids rotations is available may provide a constraint on their material properties. The rotations of the very small asteroids, however, might be influenced by postformation processes. Among them, radiation pressure effects might be particularly effective for the small bodies as they are proportional to the inverse square of the diameter. On the contrary, the bare-rock surface and the fast rotation of the bodies can reduce the effect by more than an order of magnitude (*Rubincam,* 2000). The spins of the very small asteroids can also be affected by collisions. *Farinella et al.* (1998) estimate that the timescale at which a major change of the spin occurs is $\sim 3 \times 10^7$ yr for a main-belt stony asteroid with a diameter of 100 m and a rotation period of 0.5 h; this would be shorter than its collisional lifetime of $\sim 2 \times 10^8$ yr. As a result of these spin-changing mechanisms, the present rotation rates of the very small asteroids may not be relaxed rates from their initial, postformation rotations.

## 3. SPIN-VECTOR DISTRIBUTION

A review of lightcurve techniques used for estimation of asteroid shapes, sidereal periods, and ecliptic coordinates ($\lambda_p$, $\beta_p$) of poles is given by *Kaasalainen et al.* (2002).

*Magnusson* (1986, 1990) analyses the spin vectors of 20 and 30 asteroids, respectively, and concludes that prograde rotating asteroids are in a slight majority. He notes the apparent lack of poles close to the ecliptic plane and attributes this bimodality to a possible observational selection effect; an asteroid with a pole at a low ecliptic latitude may be seen nearly pole-on in some apparitions, giving an amplitude too small for an unambiguous epoch determination. Therefore, more lightcurve observations are needed for such an asteroid than are needed for asteroid with a pole far from the ecliptic plane.

*Drummond et al.* (1988; 1991), using results for 26 asteroids, confirm the bimodality of the observed pole distribution and concur with its possible explanation due to the observational selection effect. They note, however, that it may be just a statistical fluctuation but also consider the possibility that the observed bimodality may be real and may reflect a primordial distribution of spin rates.

At present we have available a larger sample of asteroid pole estimates. The most complete spin and shape database

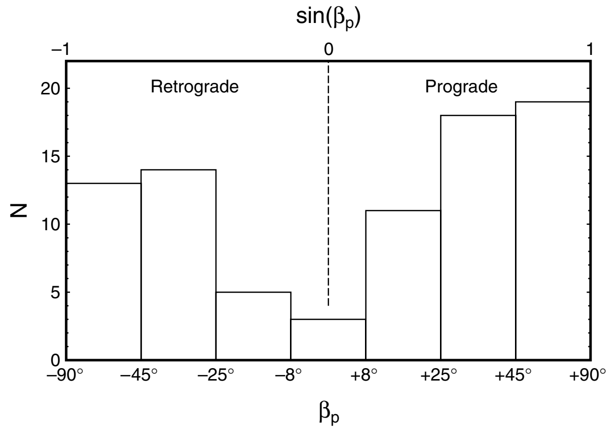


**Fig. 6.** Distribution of the ecliptic latitudes of north poles of rotations for 83 asteroids.

has been compiled by P. Magnusson and can be found at The Small Bodies Node of the NASA Planetary Data System (http://pdssbn.astro.umd.edu/) or at the Uppsala Observatory's Web site (http://www.astro.uu.se). The database contains results published in numerous papers up to 1995 (see references attached to the database). Additional spin-vector estimates were published by *Michałowski* (1996a,b), *Kryszczyńska et al.* (1996), *Erikson et al.* (1999), and *Michałowski et al.* (1995, 2000, 2001). The present sample contains estimates of spin vectors with senses of rotation for 83 asteroids, which are mostly large and bright asteroids well observed photometrically during at least a few apparitions.

Figure 6 shows the observed distribution of the sine of the ecliptic latitudes of the asteroids' north poles. The distribution is bimodal and not flat as would be expected for a random distribution of the spin vectors; the Kolmogorov-Smirnov test shows that it is not uniform at about 85% confidence level. The lack of asteroids poles close to the ecliptic plane is apparent. There are 48 asteroids with prograde rotations, 32 with retrograde rotations, and only 3 with poles at low ecliptic latitudes ($|\beta_p| < 8°$). The bimodality of the pole distributions, if real, is not understood yet but may be primordial.

## 4. CONCLUDING REMARKS

Our understanding of asteroid rotations has advanced significantly in recent years, mostly thanks to several productive observational programs that brought a wealth of new data, especially for small asteroids. A new category of very fast spinning small "monolithic" asteroids has been found. The significant population of binary systems with fast spinning primaries was found to be present among near-Earth asteroids. The population of slow rotators is better established and described now than it was 10 years ago. The study of rotation rates and amplitudes of small asteroids reveals that most of them are strengthless bodies with rubble-pile or shattered interior structure. The overall picture of rotational characteristics of asteroids and their relation to other asteroidal properties has been improved. We expect that in years to come further data from lightcurve observations and other techniques will continue supplying new information that will allow us to achieve a better understanding of many aspects of asteroid rotation characteristics and their relations to asteroid evolution processes. In the following paragraph, we mention a few directions of the work that should be particularly interesting.

It is clear that the most interesting information is likely to be gained in fields not explored well enough up to now. Observers should concentrate on inner-planet-crossing objects of all sizes. These observations are likely to lead, in addition to a general increase of the sample allowing better statistical studies, to new detections of NEA binaries and consequently to a better understanding of their characteristics, creation, and evolution; an improved description of the characteristics of the very fast rotating small "monoliths" population and the transition between "monoliths" and rubble piles around $D \approx 0.15$ km; and an increase of the sample of slow rotators so that we get new data for testing theories of their creation and evolution. It would be worthwhile to study similarly sized (a few kilometers and smaller) asteroids in the main belt so as to reveal possible differences in their properties from those of NEAs that could shed more light on processes working exclusively or preferentially on objects on inner planet-crossing orbits. Studies of distant asteroids (Trojans, Centaurs, and transneptunian objects) are needed to compare their properties to the population of large main-belt asteroids. We point out the need for each observing program to be designed so as to minimize observational biases against slowly rotating, low-amplitude, and faint objects. Such biases are present in the available sample of asteroid rotations of all sizes and orbits, and every effort to reduce them will improve our knowledge of asteroid rotations and their implications. We anticipate that 10 years from now we will have a much more detailed and complex picture of the asteroid rotational properties over wide ranges of sizes and orbits and that it will allow us to reach a more comprehensive understanding of processes of asteroid evolution.

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