Proceedings Title IAU Symposium
Proceedings IAU Symposium No. 236, 2006
A.C. Editor, B.D. Editor & C.E. Editor, eds.

DOI: 00.0000/X000000000000000X

NEA Rotations and Binaries

P. Pravec[a], **A.W. Harris**[b], **B.D. Warner**[c]

[a]Astronomical Institute, Academy of Sciences of the Czech Republic, Fričova 1, CZ-25165 Ondřejov, Czech Republic

[b]Space Science Institute, 4603 Orange Knoll Ave., La Canada, CA 91011, USA

[c]Palmer Divide Observatory, 17995 Bakers Farm Rd. Colorado Springs, CO 80908, USA

Abstract. Of the nearly 3900 near-Earth asteroids (NEAs) known as of June 2006, 325 have estimated rotation periods, with most of those determined by lightcurve analysis led by a few dedicated programs. NEAs with diameters down to 10 meters have been sampled. Observed spin distribution shows a major changing point around diameter of 200 meters. Larger NEAs show a barrier against spins faster than 11 d^{-1} (period about 2.2 h) that shifts to slower rates (longer periods) with increasing lightcurve amplitude (i.e., with increasing equatorial elongation). The spin barrier is interpreted as a critical spin rate for bodies in a gravity regime; NEAs larger than 200 meters are predominantly bodies with tensile strength too low to withstand a centrifugal acceleration for rotation faster than the critical spin rate. The cohesionless spin barrier disappears at sizes less than 200 meters where most objects rotate too fast to be held together by self-gravitation only, so a cohesion is implied in the smaller NEAs.

The distribution of NEA spin rates in the cohesionless size range ($D > 0.2$ km) is highly non-Maxwellian, suggesting that mechanisms other than just collisions have been at work. There is a pile up just in front of the barrier, at periods 2–3 h. It may be related to a spin up mechanism crowding asteroids to the barrier. An excess of slow rotators is observed at periods longer than 30 hours. A spin-down mechanism has no obvious lower limit on spin rate; periods as long as tens of days have been observed.

Most NEAs appear to be in their basic spin states with rotation around principal axis with maximum moment of inertia. Tumbling objects (i.e., bodies in excited, non-principal axis rotation) are present and actually predominate among slow rotators with estimated damping timescales longer than the age of the solar system. A few tumblers observed among fast rotating coherent objects appear to be either more rigid or younger than the larger (cohesionless) tumblers.

An abundant population of binary systems has been found among NEAs. The fraction of binaries among NEAs larger than 0.3 km has been estimated to be $15 \pm 4\%$. Primaries of binary systems concentrate at fast spin rates (periods 2–3 h) and low amplitudes, i.e., they lie just below the cohesionless spin barrier. The total angular momentum content in binary systems suggests that they formed from parent bodies spinning at the critical rate. The fact that a very similar population of binaries has been found among small main belt asteroids suggests a binary formation mechanism that may not be related to close encounters with the terrestrial planets.

1. Introduction

During the last dozen years our data set on rotations of near-Earth asteroids (NEAs) has increased enormously. Most of the data have been obtained by a few dedicated programs (see, e.g., Pravec et al. 1998, Mottola et al. 1995a, Krugly et al. 2002) that placed a high priority within their observational strategies on suppressing selection effects against slow rotators as well as low amplitude objects, and on resolving complex lightcurves of tumblers and binaries among NEAs. Radar observations contributed to the rotation data as well, and they resolved more than half of the NEA binaries known to date (see Ostro et al., 2006).

Of the nearly 3900 near-Earth asteroids (NEAs) known as of June 2006, 325 have estimated rotation periods, 14 tumblers have been identified, and 30 binary systems have been found. In this paper, we present an overview of a few of the things we learned from the data.

2. Data Set

The principal method of asteroid period estimation is rotational lightcurve photometry. By using the harmonic series analysis proposed by Harris et al. (1989), period estimation from dense lightcurve data is mostly straightforward. There are selection effects against low amplitude and long period objects with the lightcurve technique, but they have been largely suppressed by the observational strategies of the dedicated NEA photometry programs, which allocated telescope time when and as needed to resolve more difficult cases. This led not only to suppressing the bias against low amplitude/long period NEAs, but also to resolving complex lightcurves of tumbling asteroids and binary systems, which show more than a single period.

Though this paper deals with near-Earth asteroids, we point out that so far there has not been found any significant difference between parameters of near-Earth asteroids and those of more distant asteroids (main belt, Mars-crossers) other than that would be attributable to a size dependence in a given parameter. It should be noted that the sample of spin rates of main-belt/Mars-crossing (MB/MC) asteroids is abundant only at sizes larger than 3 km, so there is actually little overlap between the NEA and the MB/MC samples in size; spin rates data above 3 km basically refer to MB/MC asteroids, while those below 3 km are mostly of NEAs. Extending the sample of MB/MC asteroid spin rates to km-sized bodies will be needed to study possible differences between them and the NEA population.†

3. Spin barrier

Asteroids with sizes from a few hundred meters up to about 10 km show a barrier against spins faster than f about 11 d^{-1} (period about 2.2 h), see Fig. 1. The limit shifts to slower rates (longer periods) with increasing lightcurve amplitude (i.e., with increasing equatorial elongation). The dependence of the spin limit on equatorial elongation is shown in Fig. 2, where limiting curves for cohesionless elastic-plastic solid bodies with the angle of friction $\phi = 90^\circ$ and with bulk densities 1, 2, 3, 4, 5 g/cm^3 are plotted. The angle of friction in real asteroids is unknown, but it is expected to be on an order of 40° (Richardson et al., 2005). Considering that Holsapple (2001, 2004) calculated that the critical spin frequency for $\phi = 40^\circ$ is about 10% lower than that for $\phi = 90^\circ$ and that amplitudes of a few asteroids close to the spin barrier were measured at higher solar phases so they probably need to be corrected to lower values to represent the equatorial axes ratio, we get that 99% of measured NEAs larger than 0.2 km rotate slower than

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† Dermawan (2004) has made a first attempt to obtain a sample of spin rates of main belt asteroids with sizes comparable to NEAs, using the Subaru telescope with a wide field imaging system. He reports a significant fraction of super-fast rotators (periods under 2 hours) among MBAs extending up to sizes larger than 1 km. If true, this would mark a provocative departure from the properties of NEAs. However, upon examining the lightcurves presented in the Dermawan thesis, we find the results questionable due to insufficient observational coverage, and having to press too close to the intrinsic noise level of the observations seeking periods.

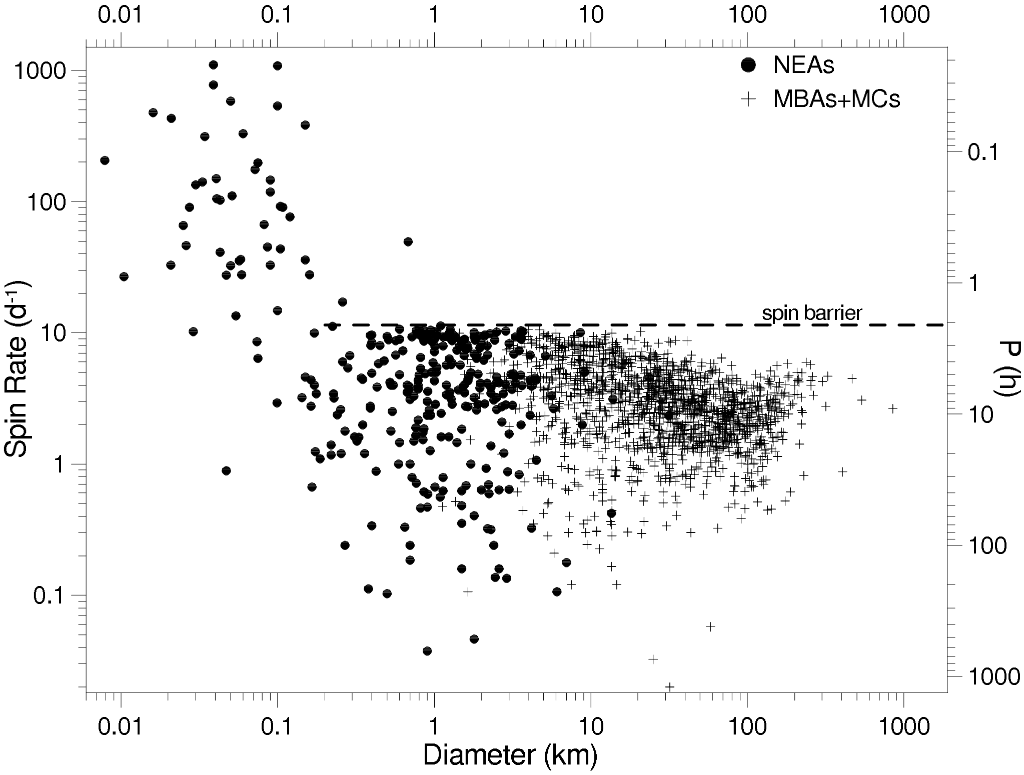

Figure 1. The spin barrier in spin rate (f) vs diameter (D) apparent at sizes from a few hundred meters to about 10 km.

the limit for bulk density of 3 g/cm^3 (data compiled by Harris et al., 2006). See Harris (1996) and Pravec and Harris (2000) for earlier data on the spin limit.

The spin barrier is interpreted as a critical spin limit for bodies in a gravity regime; NEAs larger than 0.2 km are predominantly bodies with tensile strength too low to withstand a centrifugal acceleration for rotation faster than the critical spin rate.

Above $D = 3$ km, an upper limit on the tensile strength given by the spin barrier is higher than a scaled tensile strength of cracked but coherent rocks, so the existence of the spin barrier does not constrain whether asteroids in the size range 3–10 km are strengthless objects or just cracked but coherent bodies. Below $D = 3$ km, the maximum possible tensile strength allowed by the spin barrier for a majority of asteroids in the size range is too low for them to be cracked but coherent bodies; this implies that a cohesionless structure is predominant among asteroids with $D = 0.2$ to 3 km (Holsapple, 2006).

The cohesionless spin barrier disappears at sizes less than 200 meters where most objects rotate too fast to be held together by self-gravitation only, so a cohesion is implied in the smaller NEAs.

The distribution of NEA spin rates in the cohesionless size range ($D > 0.2$ km) is highly non-Maxwellian, see Fig. 3. It suggests that mechanisms other than just collisions were involved. There is a pile up just in front of the barrier, at spin rates 9–10 d^{-1}(periods 2–3 h). It may be related to a spin up mechanism crowding asteroids to the barrier. An excess of slow rotators is observed at periods longer than 30 hours. A spin-down mechanism has no obvious lower limit on spin rate; periods as long as tens of days have

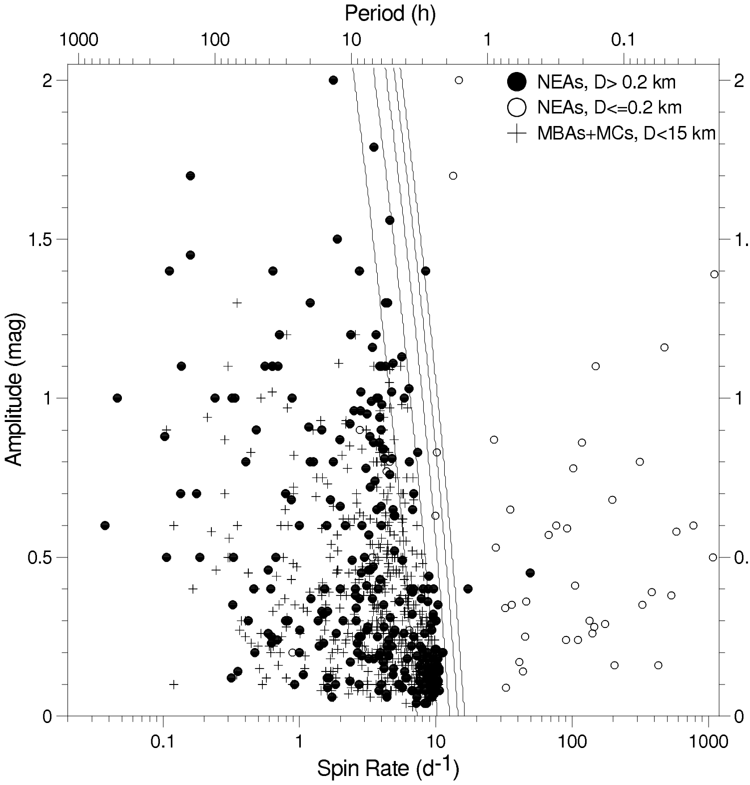

Figure 2. The spin barrier in amplitude (A) vs spin rate (f). The curves are limits for cohesionless elastic-plastic solid bodies with the angle of friction $\phi = 90°$ and with bulk densities 1, 2, 3, 4, 5 g/cm^3, from left to right.

been observed. The YORP effect appears to be a qualitatively consistent explanation (see Bottke et al. 2002, 2006).

4. Non-principal axis rotators

The first detection of an asteroid in non-principal axis rotation state, near-Earth asteroid 4179 Toutatis, was made with radar (Hudson and Ostro, 1995). Since then, a couple more NPA rotators have been found also by using radar (see Ostro et al., 2006).

The lightcurve photometry technique has provided data on more NPA rotators (tumblers) among near-Earth asteroids. Several NEAs showed deviations from single periodicity attributable to NPA rotation (Pravec et al., 2005; a few latest detections pre-published on Pravec's web page†). In a few cases where abundant data have been obtained, a fit with 2-dimensional Fourier series indicates two basic periods plus their linear combinations (Pravec et al. 2005; see also Kaasalainen 2001).

In Fig. 4, the f–D data with tumblers highlighted are plotted. All but the largest are near-Earth asteroids. (The largest, at $D = 58$ km, is the main belt asteroid 253 Mathilde, which was found to be in NPA rotation state by Mottola et al., 1995b.) From the plot, it is apparent that tumblers larger than a few hundred meters are generally slow rotators, while three fast rotating tumblers were found in the size range from 10 to a few hundred meters.

† http://www.asu.cas.cz/~ppravec/newres.htm

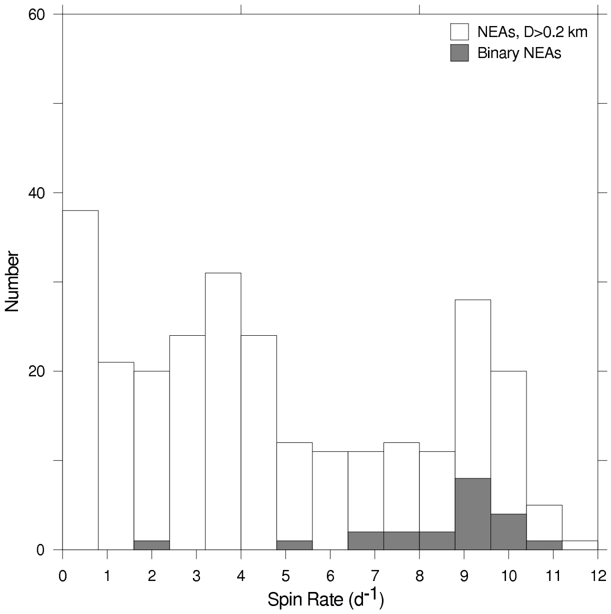

Figure 3. Excess at spin rates $f < 0.8$ d^{-1} (slow rotators) and $f = 9$–10 d^{-1} (pile up below the spin barrier). Binary primaries concentrate in the pile up.

An intepretation of the distribution of tumblers in the f–D parameter space uses estimated damping time scales based on the theory by Burns and Safronov (1973) and with "rubble pile" parameters estimated by Harris (1994). Tumblers are predominant among asteroids larger than a few hundred meters and with a damping time scale longer than the age of the solar system; most asteroids in the range for which abundant data have been obtained show NPA rotation. The small fast rotating tumblers found among coherent objects (that lie above the spin barrier) are more rigid or younger than the larger (cohesionless) tumblers (Pravec et al., 2005).

5. Binaries

As of mid-2006, 30 binary systems had been found among near-Earth asteroids. Twenty of them were resolved with radar observations (see Ostro et al., 2006), and 15 were resolved with the photometric technique (see Pravec et al., 2006; and two new ones by Reddy et al., 2005, 2006a, b); five were detected by both techniques.

The photometric technique of asynchronous binary detection, described in Pravec et al. (2006), is based on deconvolution of a lightcurve of the binary asteroid where (at least) one of its components rotates with a period different from orbital period. For a full, regular detection of the binary system, it has to show mutual events –occultations and/or eclipses– among the components of the binary system. From such data, the rotation period of the primary as well as orbital period together with a size ratio, or its lower limit in a case of partial events, are directly derived. A unique resolution of whether a rotational lightcurve component belongs to the primary is routinely done using the fact that the primary's rotational variation does not go away during mutual events while the secondary's variation, detected in cases where the amplitude is apparent even if diluted by the light of the primary, disappears when the smaller body is fully hidden behind the larger body.

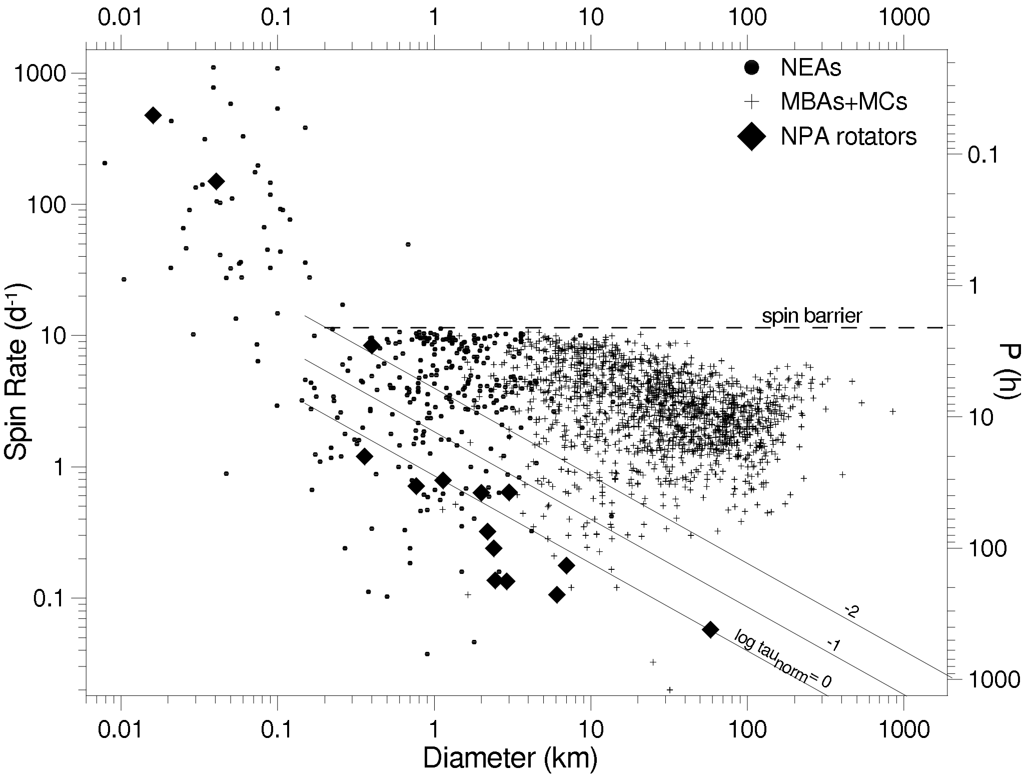

Figure 4. Tumbling asteroids in spin rate (f) vs diameter (D). Tumblers predominate below the line of constant damping times scale of 4.5 byr ($\log \tau_{norm} = 0$) at sizes larger than a few hundred meters; see text.

Pravec et al. (2006) simulated their binary NEA photometric survey and they estimated that $15 \pm 4\%$ of near-Earth asteroids larger than 0.3 km are binary systems with a secondary-to-primary mean diameter ratio $D_s/D_p \geqslant 0.18$. They found that the concentration of binaries with $D_s/D_p \geqslant 0.18$ is particularly high among NEAs smaller than 2 km in diameter, and that the abundance of such binaries decreases significantly among larger NEAs. Secondaries show an upper size limit of $D_s = 0.5$–1 km. Systems with $D_s/D_p < 0.5$ are abundant, but larger satellites are significantly less common.

The primaries of NEA binaries are mostly fast rotators with low equatorial elongations, most of them lying in the pile up in front of the spin barrier (see Figs. 3, 5, 6). The distribution of their rotation periods is concentrated between 2.2 and 2.8 h and has a tail up to ~ 4 h. Orbital periods show an apparent cut-off at $P_{orb} \sim 11$ h; closer systems with shorter orbital periods have not been observed, which is consistent with the Roche limit for strengthless bodies. Secondaries are more elongated on average than primaries. Most, but not all, of their rotations appear to be synchronized with the orbital motion; non-synchronous secondary rotations may occur especially among wider systems with $P_{orb} > 20$ h.

A population of asynchronous binary asteroids among main belt asteroids (MBAs) smaller than 10 km was found recently (see Pravec et al. 2006, and references therein; examples of recently detected ones see, e.g., Warner et al. 2005, 2006; Pray et al. 2006a, b; Higgins et al. 2006a, b; Jakubík et al. 2005; Cooney et al. 2006). The asynchronous

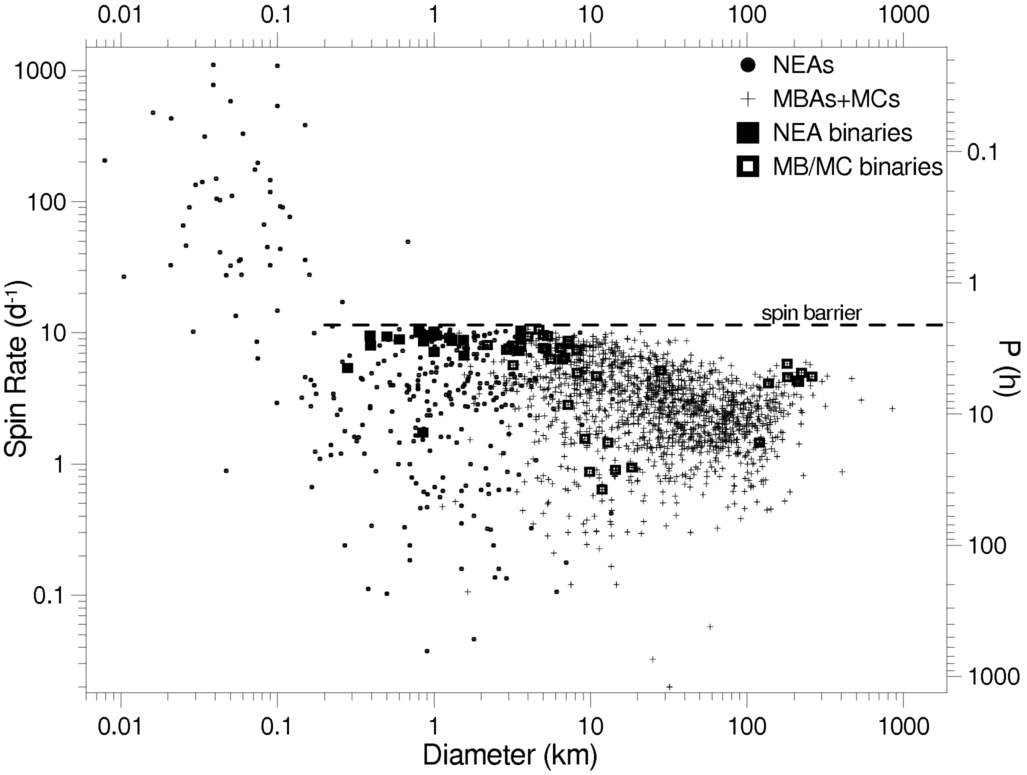

Figure 5. Primaries of binary NEAs in spin rate (f) vs diameter (D). Primaries of binary systems among MB/MC asteroids are also plotted, for comparison.

MBA binaries are similar to the NEA binaries in most characteristics. The only prominent difference is that, unlike NEA binaries which concentrate at sizes $D_p < 2$ km ($D_s < 1$ km), the asynchronous main belt binaries extend up to nearly 10 km in D_p (their satellites are up to 3 km in D_s). Some smaller differences in other parameters appear to be a size dependence only (see below).

In addition to the asynchronous binaries population among NEAs as well as small MBAs, there is also a smaller population of fully synchronous, nearly equal sized binaries (D_s/D_p nearly 1). Such systems appear to be infrequent among NEAs, with only one such system having been found so far, 69230 Hermes (Margot et al. 2006; see also Pravec et al. 2006, and reference therein). Among small MBAs, a few such systems with sizes around 10 km have been found by Behrend et al. (2006) and Kryszczynska et al. (2005). The abundance (fraction) of fully synchronous, nearly equal-sized binaries among small MBAs has not yet been precisely estimated. It seems, however, that they are abundant only in a narrow size range just around the diameter of 10 km; see the “tail” of the distribution of primary spins to frequencies around 1 d^{-1} around $D = 10$ km in Fig. 5.

Recently we began a study of overall characteristics of the few known populations of small binaries (both synchronous and asynchronous) among NEAs as well as MBAs. Among the main underlying questions of the study are what all the systems have in common, and whether some apparent differences might be due only to a size dependence of formation/evolution mechanisms.

The first thing that we examined (Pravec and Harris, in preparation) is the angular

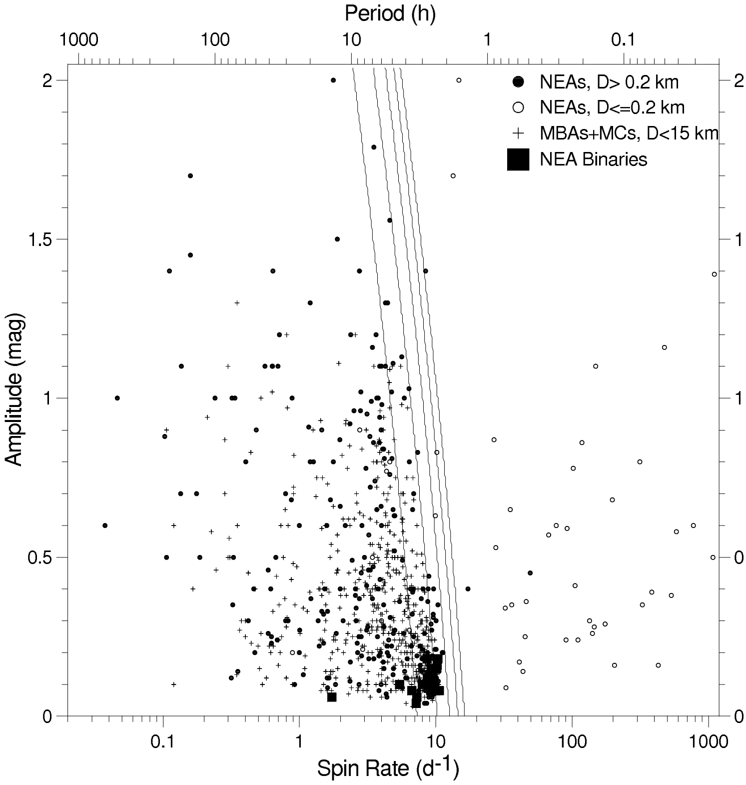

Figure 6. Primaries of binary NEAs in amplitude (A) vs spin rate (f). See also caption to Fig. 2.

momentum content in binary systems. We found that all the small binaries (both synchronous and asynchronous, from NEAs to MBAs) have a total angular momentum very close to, but not generally exceeding, the critical limit for a single body in a gravity regime. It suggests that asteroid binaries with D_p about 10 km and smaller formed from parent bodies spinning at the critical rate (at the gravity spin limit for asteroids in the size range). Some small differences between characteristics of MBA and NEA binaries may be due to a size dependence of formation/evolution mechanisms. A suggested explanation of the apparent tendency to slower primary rotations and longer orbital periods with increasing size is that larger systems may be more tidally evolved. Over-all, known binaries among NEAs to main belt asteroids have characteristics so similar when corrected for effects of size depedence that they may be a part of a common binary population in which the same mechanism is related to the critical spins of their parent bodies.

6. Conclusions

Rotations and binary properties suggest that NEAs larger than 200 m are predominantly cohesionless structures held together by self-gravitation. Superfast rotations of most smaller asteroids indicate that they are held together by some cohesive forces.

Binary properties suggest that they originated from critically spinning cohesionless bodies. A similar binary population has been observed among small MB/MC asteroids;

it suggests that a binary formation mechanism may not be related to encounters with the major planets.

Acknowledgements

The work at Ondřejov was supported by the Grant Agency of the Czech Republic, Grant 205/05/0604. The work at Space Science Institute was supported by grant NAG5-13244 from the NASA Planetary Geology-Geophysics Program.

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