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Distribution and Evolution of Asteroid Rotation Rates [and Discussion]

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Distribution and evolution of asteroid rotation rates

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Data on the rotational characteristics of more than 300 asteroids are currently available and it is now clear that the distribution of the rotation rates is non-random. A plot of rotation rate against asteroid diameter shows large dispersion but is distinctly V-shaped. The minimum of this curve at *ca.* 120 km may separate primordial asteroids from their collision products. There is also evidence that rotation rate depends on type classification, and weak evidence that it may also depend on family membership. Recent bias-free observations suggest that the marked rise of rotation rate with decreasing diameter D for those asteroids with $D < 120$ km cannot be completely accounted for by observational selection effects. A significantly large subset of the small asteroids have exceptionally long rotation periods suggestive of either a different nature and origin, or a peculiar history. Models that have been proposed to account for these results are discussed.

1. Introduction

Previous studies of asteroid rotation rates failed to reach conclusive results for a variety of reasons. Most data on asteroid characteristics, particularly their rotation rates, have a very high dispersion, and trends in the data did not become apparent until the data set was sufficiently large. Data on the rotation of more than 300 asteroids are now available, but some of these data are of poor quality, even for statistical purposes, and must be removed in some way that does not prejudice the conclusions. Furthermore, since asteroidal rotation rate probably depends on a variety of factors, for example, diameter, type classification and family membership, the separate effects of these parameters must be assessed before useful conclusions can be reached. Only in recent years, largely because of the extensive and careful work of A. W. Harris, E. Tedesco, and other observers, particularly those in Europe, has the data set been of sufficient proportion that statistical analyses have been able to reach firm conclusions.

The type of bias that observational selection introduces into the data set is well-understood, but the extent of the bias has always been difficult to assess. Recent work by Binzel (1984) suggests that observational selection may not over-distort the data, and thus that the structure revealed in the data requires a physical rather than an operational explanation.

The most important recent finding is that the distribution of rotational frequency with diameter is V-shaped (Dermott *et al.* 1984; Lagerkvist 1983). Dobrovolskis & Burns (1984) have already proposed an interesting angular momentum drain mechanism that may account for this distribution. Problems with this and other mechanisms are discussed below.

The emphasis of this paper, as in our previous work on this subject (Dermott & Murray 1982; Dermott *et al.* 1984) is to use statistical methods to show the separate influence of various factors on the observed distributions of frequencies and to reveal those areas in which further observations would be particularly effective.

2. Nature of the distribution

Previous studies of the distribution of asteroid rotation rates (see, for example, McAdoo & Burns 1973; Harris & Burns 1979; Tedesco & Zappalà 1980) have tended to use linear correlation coefficients on the data set as a whole. This approach is obviously inadequate since a distribution can be markedly non-random without being linear. This is the case for asteroid rotation frequencies.

The distribution of asteroid diameters and rotation frequencies is shown in figure 1*a*. The data are derived from an earlier version of the Harris & Young (1983) data set: differences between the data sets are described in Dermott *et al.* (1984). The four largest asteroids are not shown in figure 1*a* but they are included in the data set analysed in subsequent figures. The dashed lines denote the stability limits for gravitationally bound 'rubble piles' of material of densities 2 and 3 g cm^{-3} according to the work of Weidenschilling (1981). It appears that these limits provide a reasonable upper bound for the spin rates of most asteroids. The data shown in figure 1*a* are ordered by diameter, and divided into separate bins with nine asteroids in each bin. The mean diameter and frequency for each sample is calculated and the results are shown in figure 1*b*. The error bars denote the variance of the mean as derived from the variance of the sample. The V-shaped distribution already apparent in figure 1*b* is not dependent on the size of the bin (Dermott *et al.* 1984). Figure 1*c* shows the result of using a moving average with a bin size of 27 asteroids on the same set of data. This serves to confirm the trend shown in figure 1*b* and illustrates that although the distribution is significantly non-random it is also nonlinear and hence the use of linear correlation coefficients on the data set as a whole is inappropriate.

Evidence that the trends shown in figure 1*c* are real is provided in figures 1(*d*)–(*f*) where the data are divided into various independent subsets, each exhibiting the same V-shaped behaviour. In figure 1*d* the data have been divided into family and non-family asteroids following the classification by Williams (1979). Members of a given family have similar orbital elements and are assumed to have originated from the collisional breakup of a common parent body. The majority of asteroids fall into one of three broad type classifications: S-, C- and M-type asteroids. Dividing the data set according to this classification (figure 1*e*) the same V-shaped distribution is observed with some evidence for a lateral displacement of each curve. It also appears that on average, and within a given diameter range, M asteroids rotate faster than S asteroids, which in turn rotate faster than C asteroids. This is evidence that asteroids which have been classified by their surface properties alone have different bulk properties. Dividing the C-type asteroids into family and non-family asteroids (figure 1*f*) yields evidence that within any type the family members appear to rotate faster than the non-family members. This may reflect differences in collisional histories, since family members may have acquired higher spin rates during the collisional disruption of their parent bodies.

One curiosity is the possible existence of a significant subset of small asteroids with very long rotational periods (Farinella *et al.* 1981; Dermott *et al.* 1984). Such asteroids may have had different rotational histories and it has been suggested that their low spin rates may reflect a tidal de-spinning effect due to the presence of an orbiting companion. However, we also note that comets have rotational periods much longer than those of asteroids of a similar size (see the paper by Wallis in this symposium). Perhaps some of the small asteroids with exceptionally long rotational periods are degassed comets?

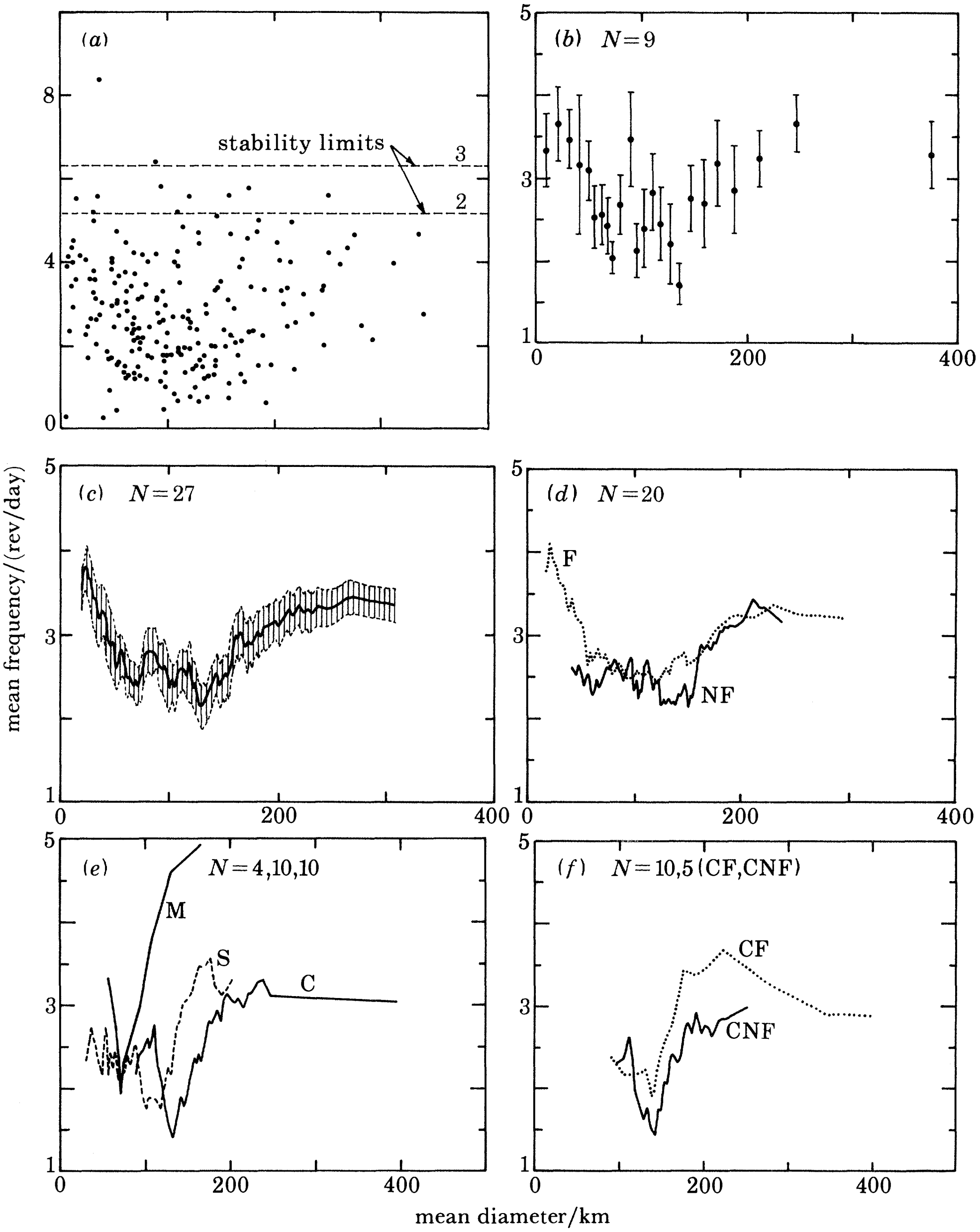

FIGURE 1. Rotational frequencies and diameters of 217 asteroids (excluding data on the four largest asteroids in the population) are shown in (*a*). The stability limits in (*a*) are those of gravitationally bound rubble-piles of densities 2 and 3 g cm^{-3}. The other plots show mean frequencies and mean diameters of asteroids ordered by diameter and grouped in bins of N. In (*b*) we show independent groups of $N = 9$. The plots in (*c*)–(*f*) are running means. The dashed curves in (*c*) are the envelopes of the 1σ error bars of the means. In (*d*) F and NF refer to family and non-family asteroids. In (*e*) M, S and C refer to M-, S- and C-type asteroids. In (*f*) CF and CNF refer to C-type family asteroids and C-type non-family asteroids. (Copyright of Academic Press.)

3. SELECTION EFFECTS

Although the trends shown in figure 1 are undoubtedly real in the sense that they exist in the data set, there remains the possibility that the data may be subject to various observational selection effects. For example, the nature of the observing process introduces a preference towards asteroids with short rotational periods and large amplitude lightcurves. In addition, large diameter asteroids are easier to observe. The trend on the right side of the V-shaped distribution is in the opposite direction to the trend expected if a short period and large diameter bias existed. However, the trend on the left side is in agreement with such a bias. This does not imply that such a bias is producing the trend, but only that before drawing conclusions about the asteroid population as a whole we must determine the possible extent of observational selection effects.

In the main belt (between 2.2 and 3.3 AU) there are 236 catalogued asteroids with magnitudes $B(1,0) < 9.68$. This limiting magnitude corresponds to $B(a,0) = 14$ at 3.3 AU. We can be reasonably confident that this data set is complete, since very few, if any, asteroids with $B(a,0) < 14$ remain to be discovered. Figure 2*a* shows the completeness of accurately known periods in this sample as a function of diameter for the asteroids which have been classified as C- and S-types. Of these asteroids, 85 are S-type and 57 of these have measured periods of a quality at least as good as that used in our data set. Although C-type asteroids are generally larger than S-type they are much darker (typical albedos are *ca.* 0.16 and *ca.* 0.04 respectively) and they are therefore more difficult to observe. From figure 1*e* we see that the minima in the S and C rotational frequency distributions occur in the region of 100–140 km, while figure 2*a* shows that it is precisely in this diameter range that there is a severe shortage of observations of C-type asteroids (the data set is only 30 % complete). As a result, the physical reality of this minimum for the C-type asteroids will require an extensive observing programme in the intermediate size range. The situation regarding S-type asteroids is more promising since the data set is already 80–90 % complete in this size range. Therefore the reality of the minimum could be tested by a relatively modest observational programme that would extend the 90 % completeness level for S-type asteroids down to a diameter *ca.* 90 km.

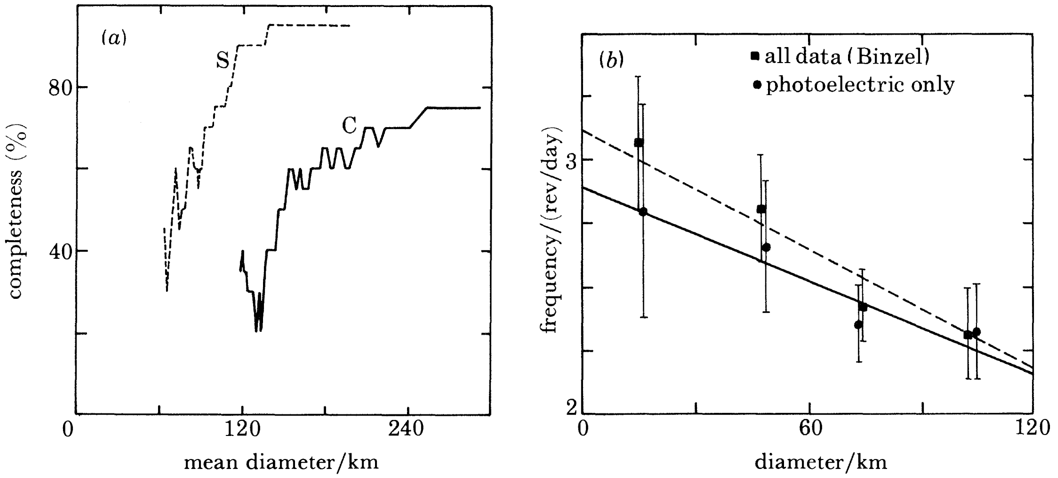

FIGURE 2. (*a*) Fractions of the known populations of S- and C-type asteroids, with diameters greater than some limit D and with statistically useful rotational periods, are shown as a function of D. (*b*) A comparison by Binzel (1984) of the mean frequencies of photoelectric data and of all data, that is, of photoelectric data plus photographic data for asteroids with diameters under 120 km. (Copyright of Academic Press.)

Recognizing the need to reduce selection effects in the data set, Binzel & Mulholland (1983) did a bias-free observing program of asteroids with diameters under 30 km. Their results have been added to various other data sets by Binzel (1984) who concludes that the tendency for spin rate to increase with decreasing diameter for small asteroids is physically real and not a product of observational selection effects alone. Binzel considers in fact that it is the photographic data which are particularly prone to selection effects. For example, the photographic technique appears to have a lightcurve amplitude threshold of 0.2 magnitudes below which the detection of magnitude differences is very difficult. Using somewhat conservative non-parametric statistical tests, Binzel also concludes that family members rotate faster than non-family members. By analysing lightcurve amplitudes he concludes that there is a significant tendency for the amplitude to increase with decreasing diameter but only for diameters $D < 120$ km; no such trend exists if only those asteroids with $D < 90$ km are considered. Binzel also finds that the lightcurve amplitudes of Earth- and Mars-crossing asteroids are significantly larger (implying more elongated shapes) than similar-sized bodies in the main belt.

4. Possible mechanisms

The tendency for low spin rates in the size range $50 < D < 150$ km was first noted by Tedesco & Zappalà (1980) and has been demonstrated to successively higher significance by Farinella *et al.* (1981), Dermott & Murray (1982) and Dermott *et al.* (1984). There is also good evidence that the spin rate depends on taxonomic type with a possible additional dependence on family membership.

The detailed model of the evolution of asteroid rotation rates proposed by Harris (1979) implied a relatively flat distribution of spin rate as a function of diameter except for the smallest asteroids (*ca.* 1 km diameter) where the spin rate should rise sharply. Harris also claimed that the mean rotation rate $\langle\omega\rangle \propto \rho^{\frac{1}{2}}$, where ρ is the asteroid density. We can see from figure 1*e* that this would imply a mean density for M-type asteroids nearly twice that of S- or C-type asteroids.

Tedesco & Zappalà (1980) and Dermott *et al.* (1984) suggested that the lower spin rate in the intermediate size range asteroids may mark the transition between 'primordial' and collisionally evolved (fragmented) asteroids. Binzel (1984) claims that his results on the distribution of lightcurve amplitudes and diameters supports this suggestion, although the exact turning point is still uncertain. Davis *et al.* (1979) suggest that if the energy partitioning into ejecta is more efficient than the 10% implied by laboratory experiments then the cumulative effect of collisions would be to slow the spin rates. However, the dividing line between 'primordial' and 'fragmental' bodies then increases to several hundred kilometres and is no longer in the size range where the minimum in the data occurs.

A more promising explanation has recently been put forward by Dobrovolskis & Burns (1984). They point out that ejecta from impacts preferentially escape in the direction of rotation of the asteroid. Therefore, even if the collision flux of objects is isotropic there is a net braking of the asteroid due to the preferential re-impact of debris ejected in the retrograde sense. This effect only operates on an intermediate size range, since for large asteroids, most of the ejecta re-impact, while for small asteroids most of the ejecta are lost (see figure 3). On the basis of laboratory measurements of ejecta velocities they claim that the effect is most efficient at *ca.* 100 km. Figure 4*a* shows their calculated diameter–frequency curves for three different models of asteroids which they classify as 'soft', 'medium', and 'hard'. Figure 4*b* compares the curves for the 'hard' asteroids (with and without modelling of angular momentum drain) with the observed distribution of rotation rates.

The angular momentum drain mechanism described by Dobrovolskis & Burns (1984) may

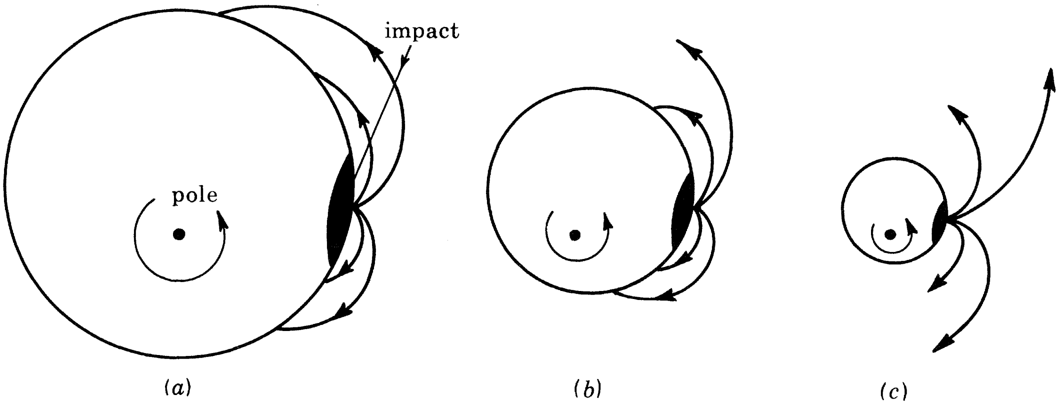

Figure 3. Asteroid rotation causes ejecta from an impact crater to be distributed asymmetrically. In (*a*) all the ejecta from craters on large asteroids are retained. In (*c*) all the ejecta from craters on small asteroids are lost but the specific angular momentum and the spin of the asteroid are unchanged. In (*b*) the ejecta from craters on 'intermediate'-sized asteroids are lost preferentially in the prograde direction and the spin of the asteroid is reduced.

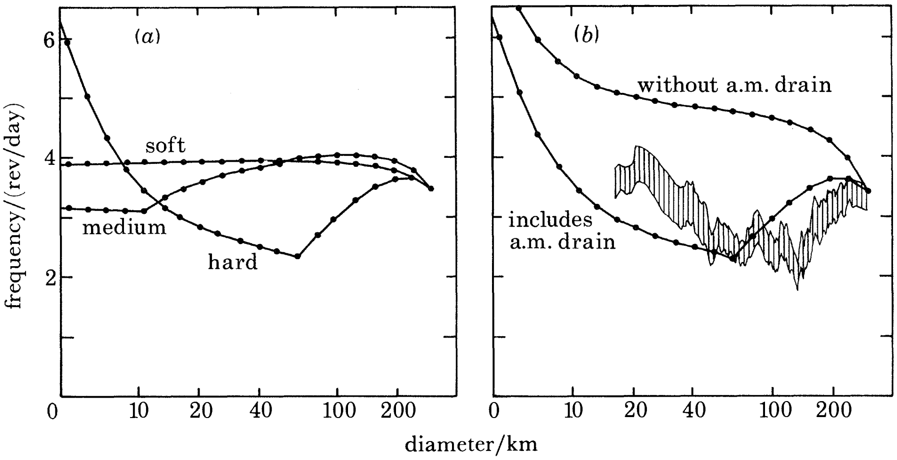

Figure 4. (*a*) Asteroidal rotation rate as a function of diameter for 'soft', 'medium' and 'hard' asteroids as calculated by Dobrovolskis & Burns (1984). In (*b*) the curve labelled 'hard' in (*a*) is compared with the observed distributions of rotation rates and with the predicted rotation rates obtained when the angular momentum drain term is neglected. (Copyright of Academic Press.)

have an important influence on the observed distribution, but only if the 'impact strengths' of the asteroids lie within a certain range (between *ca.* 3×10^5 and 3×10^6 J m^{-3}). The actual strengths of the asteroids are, of course, unknown. Estimates of the strengths of the more common types of meteorite are available and it is known that carbonaceous chondrites, which are thought to be the collision products of C-type asteroids, are consistently weaker than stony meteorites, of which the S-type asteroids are the putative parent bodies. It is somewhat disconcerting, therefore, that the interpretation by Dobrovolskis & Burns of the data requires C-type asteroids to be harder than S-type asteroids. The mass loss dM required to produce the observed braking is given by

$$d\omega/\omega \approx dM/M,$$

and the minimum in our V-shaped curves (figure 1) can only be accounted for if the intermediate-sized asteroids have lost *ca.* 50 % of their initial masses. It is questionable whether an asteroid could suffer such an extensive bombardment without suffering complete disruption and dispersion. Collisions in the asteroid belt occur at typical relative velocities of *ca.* 5 km s^{-1} and Davis *et al.* (1979) estimate that an asteroid of diameter 200 km would be disrupted by a single collision with another asteroid of diameter about 50 km or mass 0.02 M. Yet the angular momentum drain mechanism requires the total mass of the impact missiles to be of the same order as that of the target.

Dobrovolskis & Burns (1984) point out that their predicted curve assumes that the initial rotational rates of all asteroidal types were equal and that this is probably an unreasonable assumption. This has been emphasized by Dermott *et al.* (1984), who point out that the accretional theory of Harris (1979) which was adopted and modified by Dobrovolskis & Burns contains a factor of $2-q$ in the denominator of one of the major terms, where q is the asteroid size distribution index. Since q is *ca.* 1.82 (Dohnanyi 1970), a 5 % variation in q could result in a factor of two variation in the initial and the present rotation rates. In fact, since q may not be constant and may vary with both size range and asteroidal type, any small variation in q could possibly account completely for the observations.

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Discussion

J. F. James (*Department of Physics, University of Manchester, U.K.*). Have any calculations been done on the effect of radiation pressure on irregular asteroids, producing a sort of 'anemometer' effect and spinning them up?

C. D. Murray. Differential radiation forces can cause a spinning up of very small (under about 10 m) asteroids but such processes are unlikely to have accounted for any of the results we have presented. The effects of radiation forces on small particles have been summarized by Burns *et al.* (1979).

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T. Gold, F.R.S. (*Space Sciences Building, Cornell University, Ithaca, New York, U.S.A.*). On bodies that contain volatile substances the recoil from evaporation tends to be a much larger effect than radiation pressure.

J. R. Donnison (*University of London Goldsmiths' College, New Cross, London SE*14 6*NW, U.K.*). How easy does Dr Murray think it is to separate main belt asteroids into family and non-family asteroids? It has been suggested that only non-family main belt asteroids should be included in any statistical analysis of asteroid rotations. What is his opinion of this particular view?

C. D. Murray. Asteroid families are detected by a clustering of their proper elements. Currently the calculation of proper elements takes no account of the proximity to major resonances and therefore it seems likely that there are a number of catalogued asteroids which have yet to be identified as family members. There is strong evidence for this near the 2:1 Jovian resonance.

We have not made a deliberate attempt to exclude family members from our analysis. The results indicate that, on average, family members rotate faster than non-family members. This may reflect different collisional histories between the two groups.