Tumbling Asteroids

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Submitted as a Note to ***Icarus***

July 31, 1993
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ABSTRACT

Burns and Safronov (*Mon. Not. R. Astron. Soc. 16S,* 403-411, 1973) estimated the damping timescale of rotational wobble for asteroids, and concluded that all asteroid rotations then known should be damped to a state of principal-axis rotation about the axis of maximum moment of inertia, I have re-examined this question in the light of some more recently determined case.s of very slow rotation rates, and find that for several asteroids, the damping timescale is expected to be considerably longer than the age of the solar system, implying that these objects may very well exhibit non-principal axis rotation: wobble, or in extreme cases, the appearance of "tumbling" in space. Perhaps most notable in this group is the asteroid 4179 Toutatis. Both radar observations (Ostro, personal communication) and lightcurve observations (Barucci, Spencer, personal communications) suggest that Toutatis may indeed be in a more complex state of rotational motion than simple principal axis rotation 1 mention several other examples of objects which might be expected to be in similar states, and a couple examples of lightcurve observations of such objects that appear to support that conclusion.

Most of our knowledge regarding the rotation states of asteroids comes from photometric lightcurves. To date periods have been determined for more than 600 objects. For about 100 of these, the lightcurves are sufficiently detailed and cover enough cycles to support the conclusion that the rotation is constant about the axis of maximum moment of inertia. That is, the lightcurve is strictly periodic with a single rotation frequency (plus harmonics), except for variations attributable to changing aspect of illumination and viewing. Since it is generally believed that the rotational motion is the result of collisional processes, and among smaller asteroids involves catastrophic disruptions from larger parent bodies, one would expect that original spin states involved large amplitude wobbles, resulting in a complex "tumbling" type of motion, such as appears to be the case for the nucleus of Comet P/Halley (Peale and Lissauer 1989; Belton 1991). Burns and Safronov (1973) examined the rate of dissipation of rotational energy as a result the stress-strain within an asteroid which arises from non-principal axis rotation Such motion is exactly analogous to the Earth's Chandler Wobble, and as with the Earth, is damped due to stress-strain hysteresis within the body. They derive the following expression for the time scale τ of damping of the wobble to a state of principal axis rotation:

$$\tau \sim \mu Q/(\rho K_3^2 r^2 \omega^3),$$

where μ 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), p is the bulk density of the body, K_3^2 is a numerical factor relating to the irregularity of the body 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 ω is the angular frequency of rotation, Burns and Safronov compute damping timescales for 4 example asteroids, obtaining timescales ranging from ~10^5 years to ~10^8 years, Thus they concluded that probably all observed asteroids are in a state of damped rotational motion,

At the time that they made their analysis, the longest rotation period "known" (McAdoo and Burns 1973) was 18.813 hours (for 5321 Herculina; that reported value subsequently turned out to be wrong), so in the context of all rotations known then, their conclusion was quite irrefutable, even allowing for a generous range of uncertainty of the parameters involved, most notably μQ. It is clear however, due to the factors $r^2\omega^3$, the damping, time could be very long for small asteroids with very long rotation periods, This was pointed out by McAdoo and Burns (1974), but promptly forgotten by most cver~'one, myself included.

At the urging of S, J. Ostro (personal communicant ion), I reconsidered the timescales of wobble damping for the now much larger data set of asteroid rotations, which include several examples of many-day rotation periods, The case in point was the asteroid 4179 Toutatis, which was imaged on many days with radar by Ostro and his collaborators, and was observed photoelectrically very extensively over two months from December 1992 through January 1993 (Barucci, Spencer, persona] communications). Preliminary examination of both the radar and optical data indicate that Toutatis is a very irregular object with a very long rotation "period", and suggest that Toutatis' rotational motion is more complex than simple principal axis rotation A quick substitution of the physical parameters appropriate for Toutatis (rotation period ~7.5 days, r ~2 km, K_3^2 ~ 0.05), and adopting Burns' and

Safronov's values of all the other parameters, yields a timescale of -1.5 x10^{12} years. Thus one should *expect* that Toutatis' rotational motion is not simple, even if it is as old as the age of the solar system. Considering that asteroids only a few kilometers in diameter arc expected to have a collisional lifetimes of only a small fraction of the age of the solar system (probably <10^8 years), it is even mote likely that Toutatis' rotational wobble is undamped,

Following the realization that there arc now cases where the wobble damping time is expected to be long compared to the ages of the asteroids, 1 re-evaluated the above equation in greater detail, using more current estimates for the other parameters. I chose p = 2.0 and $\mu Q \approx$ S x 10'[2], based on estimates of these parameters for Phobos, the only small body in the relevant size range for which we have estimates of these properties. The estimate of μQ for Phobos is based on the observed eccentricity of its orbit about Mars, and a plausible past orbital history under tidal evolution (Yoder 1982). Burns and Safronov chose a value of $\mu Q \approx 3 \times 10^{14}$, which would be appropriate for a solid, non-porous rock, and is likely too high, but was appropriately chosen to obtain a firm upper limit in their work. Peale and Lissauer (1989) suggest that $\mu \approx$ 10'0 and $Q \leq 100$ might be appropriate for Comet Halley. Thus I conclude that μQ probably lies within a factor of 10 of the assumed value of 5 x 10^{12}, and certainly wit hin a factor of 100. The uncertainty in p probably dots not exceed a factor of 1.5, so the error budget is dominated by μQ. Even the range of values possible of K_3^2, from 0.01 to 0.1, is hardly significant compared to the uncertainty in μQ. Thus in the relation below, I have adopted a uniform value of 0.03, even though one could in principle estimate values for each individual asteroid based on lightcurve amplitude, Using these constants, I derive the following relationship between rotation period P in hours, diameter D in km, and damping timescale τ in billions of years:

$$P \approx 17\, D^{2/3} \tau^{1/3}.$$

The uncertainty in the constant is about a factor of 2,5, combining the uncertainties in all of the other parameters; that is, $P \approx (7\text{-}40)\, D^{2/3} \tau^{1/3}$.

in Figure J, I have plotted solutions to the above relation for three values of τ on a plot of measured asteroid rotation rates vs., diameters. It has generally been claimed that most of the present asteroids, especially those smaller than 100-200 km in diameter, arc not primordial, but rather arc the products of catastrophic disruptions. Such an event should "rc.set" the rotation state of the fragments, and especially induce large wobble amplitudes. Recent estimates of the collision energy threshold for catastrophic disruption as a function of size of the target body (Housen *et al.* 1991) imply that the expected "age" of a 50 km asteroid may be – 10^8 years, and objects a few km in diameter may survive only 10^7 years, Thus in the figure, any object that falls below even the topmost line plotted should be considered a candidate for non-principal axis rotation, and those below the bottom line arc almost certain to be in a state of large amplitude wobble, or "tumbling".

I have identified in the figure all of the objects that have estimated $\tau \leq 1$ b.y. Note that the four objects, 3102 1981 QA, 4179 Toutatis, 1220 Crocus, and 288 Glauke, arc most extreme, having damping timescales much longer than the age of the solar system. As I have already noted, the observational data on Toutatis is at least consistent with, if not requiring, tumbling motion A major point of this note is to encourage observers to evaluate the available data in the light of this prospect, Of the other three objects, it can be said that the existing data arc insufficient to demonstrate non-principal axis rotation, but arc not inconsistent with that possibility (see Harris *et al.* 1992 for the lightcurve of 3 102; Binzel 1985 for 1220; and Harris 1983 for 288). Moving up to the asteroids with τ -- 4,5 b.y., 887 Alinda was observed extensively during two apparitions, in 1969/70 and 1973/74, by Dunlap and Taylor (1979), but again the overlap in coverage was inadequate to make any definite statement about the presence or absence of wobble. The other two objects, 1689 Floris-Jan and 3288 Seleucus (1982 DV), arc the best candidates for demonstrated wobble motion among these objects, The lightcurve of 1689 was first presented by Schober *et al.* (1982). in that paper, it was briefly noted that the observations from "1'able Mountain Observatory ('I'M()) were not fully consistent with those from CTIO and ESO. In a short rediscussion of the TMO observations, Harris and Young (1 989) noted that the discrepancy amounted to as much as 0.15 magnitude, even allowing for possible phase angle effects between the t imc of the CTIO and ESO observat ions and the TMO observat ions approximately two weeks later. We said then, "WC have reexamined our data, restandardized the comparison stars, and tried to fit all of the data with other periods. None of our efforts have resolved the problem." While it is

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not possible to offer a quantitative model for the rotational motion of Floris-Jan from the existing lightcurves, I now believe that these lightcurves are sufficient to contradict a model based on principal axis rotation, and to infer a more complex rotation state. Finally, most of the lightcurves of 3288 Seleucus have not been published. Dcbchognc *et al.* (1983) present one lightcurve of 31/2 hours durat ion from which they infer a period >16 hours and an amplitude >0.4 msg. in a preliminary anal)·sis, mentioned by Dcbchognc *et al.* I estimated a period of-75 hours and an amplitude of-1 .0. More detailed analysis now in progress is consistent with that result in general, but I am unable to fit all of the data to a unique period, much as was the case with Floris-Jan. The TM(J data set is extensive enough that it maybe possible to demonstrate conclusively non-principal axis rotation for this object.

It should be mentioned that comet P/Halley is the most widely accepted example of "tumbling" rotational motion, and has reopened dynamical interest in this topic (e.g., Peale and Lissauer 1989, Belton 1991), As those authors note, the damping timescale for P/Halley is probably short compared to the age of the solar system (Peale and Lissauer suggest <10^8 years), but jet activity appears sufficient to maintain the tumbling state. It is possible that some of the near-Earth asteroids mentioned above may be extinct comet nuclei. If so, then their present I otat ional slates may have been established even more recently than suggested by collisional lifetimes.

Of the objects discussed above, all except 887 Alinda and 1689 Floris-Jan have lightcurve amplitudes of -1 magnitude. The other two have amplitudes of--0.4 magnitude, For the objects of largest amplitude, the wobble frequency should be comparable to the rotation frequency, and the objects should appear to "tumble" irregularly, like the motion proposed for the nucleus of P/Halley. Because the value of K_3^2 appropriate for highly irregular bodies is about a factor of 2 larger than the mean value used in computing τ in Fig. 1, the damping timescales for these objects should be reduced by a similar factor from that read off the plot. For the two less irregular *bodies,* K_3^2 should be somewhat less than the mean value used, so their estimated damping timescales should be increased by a similar factor. Also, the wobble periods for these bodies should be several times longer than the spin periods, so their lightcurves should appear more nearly periodic from one cycle to the next, but should show modulation on a timescale of several cycles.

In summary, it appears that we now' have lightcurve observations of several objects that are small enough and rotating slowly enough that non-principal axis rotation, or "tumbling", should be expected. Some of those observat ions are even suggestive of such motion, Observers should be mindful of this possibility when analyzing observations of small slowly rotating asteroids, and should follow up with extensive observations of such objects to try to confirm (his behavior.

ACKNOWLEDGMENTS

I thank Steven J. Ostro for suggesting repeatedly to me that something is funny with Toutatis, thus motivating me to reexamine the possibility of non-principal axis rotation, and also for sharing with me his preliminary results on the size and spin state of Toutatis. This work was supported at the Jet Propulsion Laboratory, California 1 nst itute of Technology, under contract from NASA,

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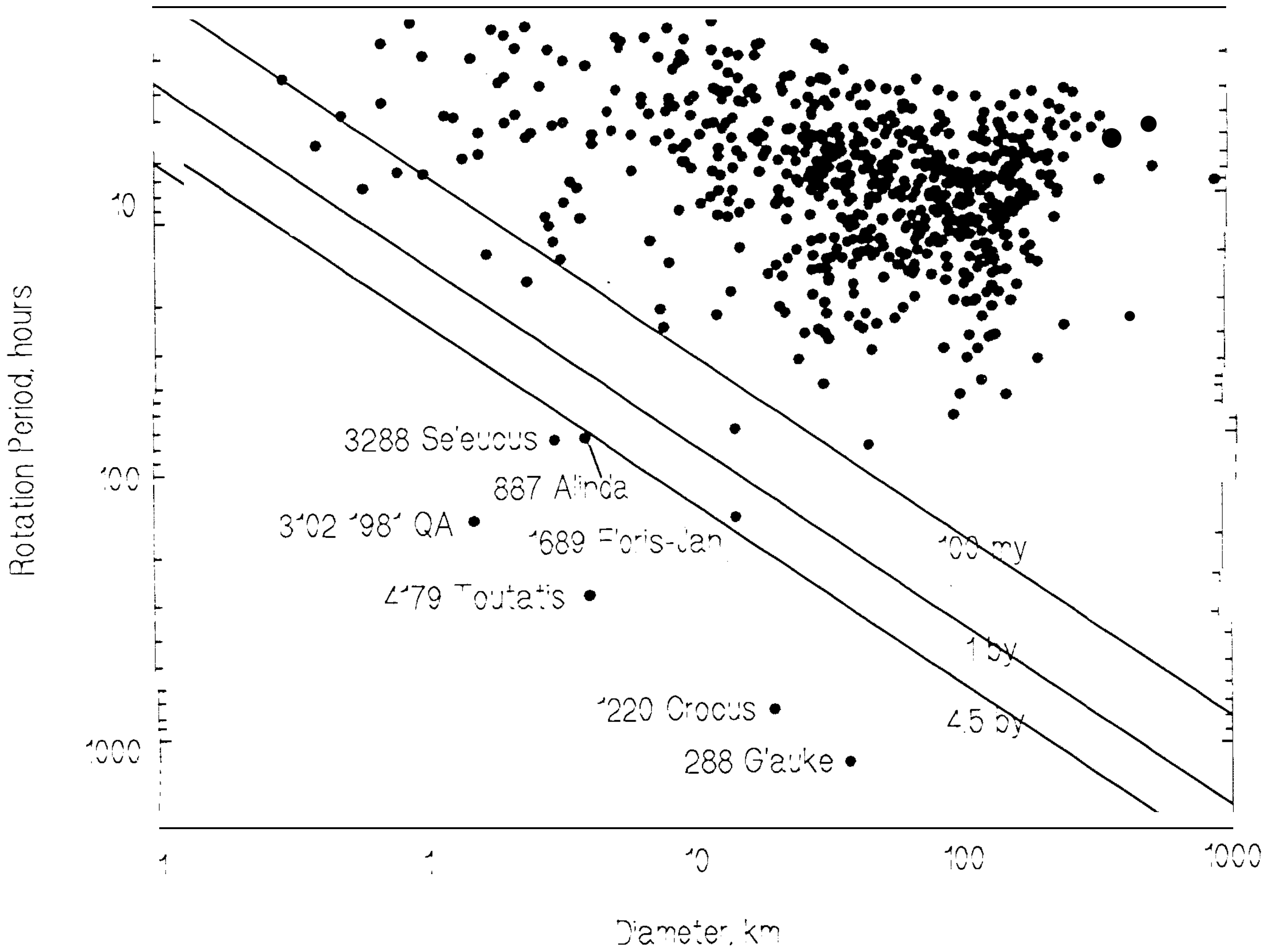
FIGURE CAPTION

1, Rotation period vs. diameter for 632 asteroids, Also plotted arc lines of constant damping timescale τ of non-principal axis rotational motion (wobble). Several small and slowly rotating asteroids fall well below even the line corresponding to the age of the solar system, thus those objects should be *expected 10* exhibit non-principal axis rotation Since all such objects also have large amplitudes of variation, the wobble periods should be comparable to their spin periods, and thus should appear to "tumble" in a complex fashion.


Rotation Period, hours
10
100
1000
3288 Seleucus
887 Alinda
1689 Floris-Jan
4179 Toutatis
1220 Crocus
288 Glauke
100 my
1 by
4.5 by
1
10
100
1000
Diameter, km