ON THE SHAPES AND SPINS OF "RUBBLE PILE" ASTEROIDS.

A. W. Harris[1], E. G. Fahnestock[2], and P. Pravec[3], [1]Space Science Institute, [2]Univ. of Michigan, [3]Ondrejov Observatory

Introduction: We examine the shape of a "rubble pile" asteroid as it slowly gains angular momentum by YORP torque, to the point where "landsliding" occurs. We find that it evolves to a "top" shape with constant angle of repose from the equator up to mid-latitude. A similar calculation for a non-spinning, extremely elongate rubble pile body suggests that it should collapse into the rough shape of a prolate ellipsoid of about 2.5:1 axis ratio. We also investigate the tidal effects of a binary system with a "top shape" primary spinning at near the critical limit for stability. We find that very close to the stability limit, the tide from the secondary can actually levitate loose debris from the surface and re-deposit it, in a process we call “tidal saltation”, such that angular momentum is transferred from the primary spin to the satellite orbit, thus maintaining the equilibrium of near-critical spin as YORP continues to add angular momentum to the system.

Rubble pile constraints on shapes: Beginning with an initial spherical shape, we find that when spin rate is about 90% of the critical rate at which gravity is cancelled by centrifugal force at the equator, “landsliding” will occur, transporting matter from mid-latitudes toward the equator. Adding angular momentum to the limit, where gravity and centrifugal force balance at the equator after slumping has occurred so that the angle of repose remains at about the maximum allowed (~40°), the quasi-equilibrium shape becomes like a top, or in particular essentially that observed for the near-critically spinning binary NEA (66391) 1999 KW4 [1], as shown in Figure 1.

We have used the same program to investigate the maximum extreme of figures of non-spinning (or slowly spinning, such that spin forces are negligible) rubble pile asteroids. We start from a 5:1 prolate ellipsoid, for which the angle of repose in some latitude range exceeds the critical value. Thus, “landsliding” occurs toward the equator, but not all the way to the equator, until a figure is reached where the angle of repose is everywhere less than the critical value. Figure 2 is a plot of some of the results. In a totally free solution where the figure relaxes to maximum slope everywhere, a curious bi-lobed shape results, which seems unphysical but does resemble some “contact binary” figures seen among elongate asteroids. A more constrained solution very closely resembles a 2.8:1 prolate ellipsoid, which is the maximum that starts out with no slopes exceeding the angle of repose.

We ran one further simulation, starting from an oblate spheroid, to see how flattened an asteroid could be before slumping would occur. The result was about 5:1 polar flattening of an oblate spheroid.

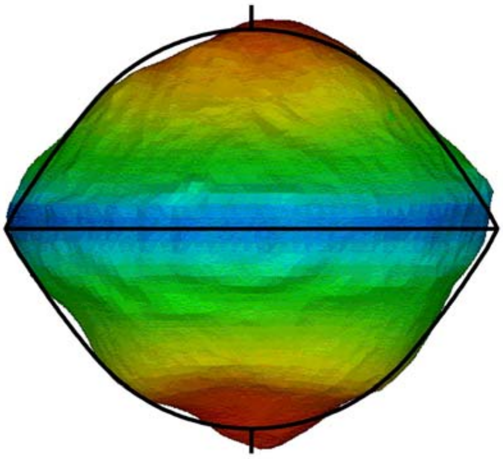

Figure 1. Constant-slope figure for critical slope of 37° compared to shape of (66391) 1999 KW4 (shape profile from [1]).

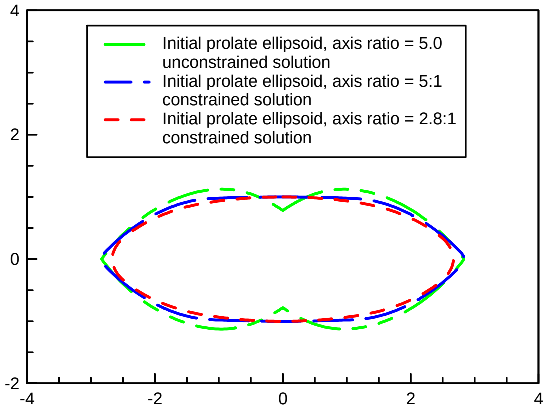

Figure 2. Constant-slope figures of prolate, non-rotating bodies.

These “static” results illustrate just how extreme a figure can be in terms of deviation from a fluid equilibrium figure before mass flow (landsliding) will occur. We conclude from this that modeling shapes of small bodies as fluid equilibrium figures, and in particular inferring bulk densities corresponding to minimum deviation from fluid equilibrium, is a useless exercise for small bodies.

Tidal saltation and equilibrium spin of asynchronous binary asteroids: The asynchronous binary NEA 1999 KW4 is remarkable in that the spin of the primary is indeed almost exactly at the critical limit defined by our shape study above, suggesting that the spin is regulated by some dynamical process as the YORP effect continues to add angular momentum to the system. Classical tidal friction is too slow, but we suggest a variation of solid state tidal friction, where the tide from the satellite may actually levitate loose material around the equator, leading to much enhanced energy loss and momentum transfer. We adopt the parameters

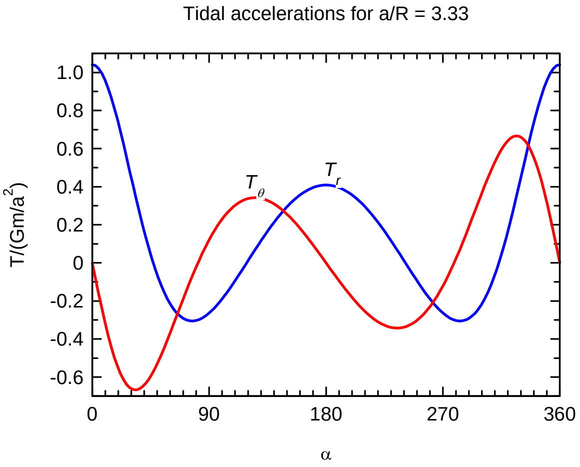

Figure 3. Radial and tangential tidal accelerations at the equator of the primary scaled appropriately for the separation of the (66391) 1999 KW4 binary.

of the binary 1999 KW4 for convenience, and because they are well determined, but the shape and critical spin of this system is very common among asynchronous binaries, suggesting that this process is common among such systems. Figure 3 is a plot of the radial and tangential tidal accelerations at the equator as a function of angle α from the sub-satellite longitude. Note that the tide is considerably different from just a second harmonic of the angle, due to the closeness of the satellite.

In numerical calculations of the motion of a regolith particle at the equator, we find that levitation and motion along the equator starts to occur when the radial tidal acceleration is close to the same as the differential acceleration, gravity minus centrifugal acceleration. Figure 4 is a plot of the motion as seen standing on the surface of the primary. Slight motion starts to occur even when the maximum radial tide is 0.9 of the differential acceleration from gravity and spin, and becomes substantial when that ratio is just 1.0. Figure 5 is a plot of the particle motion in the frame of reference of the satellite, where it can be seen that the maximum levitation, leading to tidal torque transfer, is at a substantial angle, around 45°, which would be the maximum dissipation lag angle for a classical tide. Thus, we expect that this process is very much more powerful than tidal friction and may serve to regulate the spin of the primary. Unlike classical tidal friction, which is not very sensitive to the spin rate of the primary, this process is very sharply tuned to the spin rate of the primary, and in fact shuts off completely when the spin rate is only a percent or less below the critical rate (as is the case for 1999 KW4). Thus, we do not expect the primary to slow down much below the critical rate over time, but instead remain just under the critical spin rate.

The results reported here are still preliminary. Papers are submitted [2] or about to be submitted [3] reporting the work in greater detail.

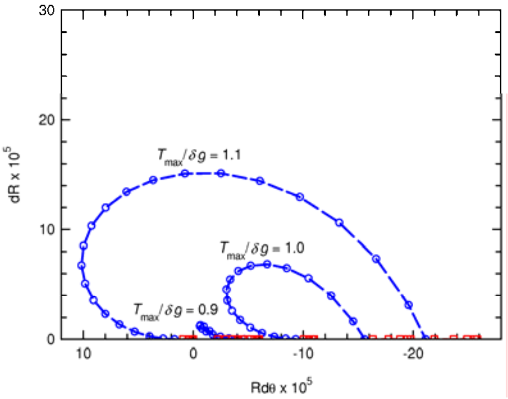

Figure 4. Motion of a particle on the equator of a near-critically spinning sphere. See text for description.

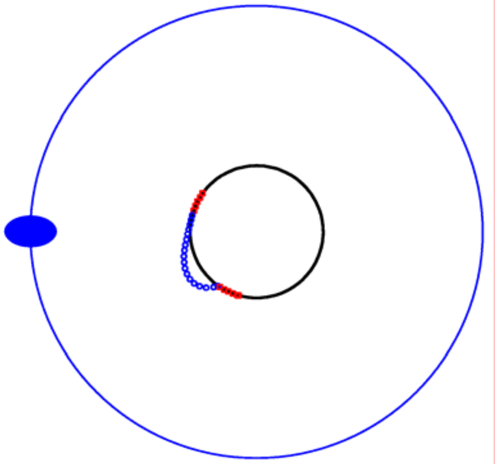

Figure 5. Motion as seen in coordinates rotating with the satellite. Radial height exaggerated 3000 times. Only the path for $T_{max}/\delta = 1.0$ is shown.

References: [1] Scheeres D. J. et al. (2004) *Science 314*, 1280-1283. [2] E. G. Fahnestock, E. J., and Scheeres, D. J. (submitted), *Icarus*. [3] Harris A. W. et al. (to be submitted) *Icarus*.