STABILITY OF BINARY ASTEROIDS FORMED THROUGH FISSION. D.J. Scheeres, *U. Michigan, Ann Arbor (scheeres@umich.edu)*.

Introduction There are several proposed mechanisms for the formation of binary asteroids in the Near Earth Asteroid population. These include formation via an impact event, formation during a tidal rupturing event during a close planetary passage, and formation due to "fission" of an asteroid due to an increased spin rate resulting from either a close planetary passage or solar irradiation torquing (Ref. [1,2,3]). Each of these formation mechanisms will have implications for the resultant binary asteroid systems. In this paper we apply recent theoretical work on the stability of ideal binary asteroid systems to derive some constraints on binary asteroid systems produced by "fission" and their likely properties.

This current discussion only uses ideal shapes, such as spheres and ellipsoids, in order to make general observations. For real asteroid systems it is expected that local topography will play an extremely important role in constraining and controlling asteroid evolution.

Asteroid Fission We define asteroid fission to occur when the asteroid spin rate (angular momentum) is increased to the point where components of the body are no longer resting on each other, but instead have entered orbit about each other. A simple example is in order. Consider two spheres of equal density ρ, but different radii, resting on each other, the entire system rotating about its center of mass. First let one sphere have a non-zero radius and mass while the other is a material point resting on its surface (at the equator, we presume). Then if the system rotates faster than $\sqrt{4\pi G\rho/3}$ (where G is the gravitational constant) the two components will enter a mutual orbit and no longer rest on each other. If instead, the two spheres have equal radius and equal mass and rest on each other, then if the system rotates faster than $\sqrt{\pi G\rho/3}$ they will start to orbit each other. Obviously, the two equal sized masses will fission well before the material point will leave the surface. Each instance, however, should be viewed as an occurrence of asteroid fission.

There are two main mechanisms by which this increase can occur: spin-up by planetary flyby and spin-up by YORP. Repeated planetary flybys will, on average, cause asteroid rotation rates to increase, and could eventually lead to an asteroid having enough angular momentum to fission. A small asteroid that is being consistently spun-up by YORP torques would naturally arrive at a rotation rate that would lead to fissioning of the body into multiple parts, potentially occurring in several steps.

Basic Model For simplicity we will consider a binary system consisting of a sphere of radius R and an ellipsoid with semi axes $\alpha_1 \geq \alpha_2 \geq \alpha_3$. Due to the symmetry of the ellipsoid, the relative equilibria that can exist between these two bodies can be easily enumerated. We define the mass fraction of the system to be $\nu = M_s/(M_s + M_e)$, $0 \leq \nu \leq 1$, where M_s is the mass of the sphere and M_e is the mass of the ellipsoid. If the components have equal density, the radius of the sphere is $R = (\alpha_1\alpha_2\alpha_3)^{1/3}\left(\nu/(1-\nu)\right)^{1/3}$. We make no assumption about the relative size of the sphere and ellipsoid, and our discussion is relevant for the entire range of a small sphere and large ellipsoid to a large sphere and small ellipsoid.

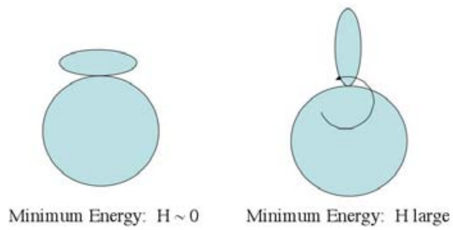
Minimum Energy Resting Configurations For a sphere and ellipsoid resting on each other and uniformly rotating, the sphere must be located along a principal axis of the ellipsoid and the system must be rotating about one of the principal axes of the ellipsoid. We will generally assume that the system will rotate about the maximum moment of inertia of the system, which reduces the possible configurations to be considered. If the sphere rests on the α_3 axis, the system will rotate about the α_3 axis or the α_2 axis, depending on the mass fraction and ellipsoid parameters. If the sphere rests on either the α_2 or α_1 axis the system rotates about the α_3 axis.

To formally compute the stability of these different configurations is difficult, however since we have identified a discreet set of equilibria, it is possible for us to delineate the minimum energy configuration that such a system can have. We then make the argument that, in the presence of perturbations such as planetary flybys and impacts, we expect the system to preferentially seek out these minimum energy configurations over time. Note, we tacitly assume that the system can energetically transition from one configuration state to another, however this is not necessarily true and should be investigated.

We consider the energy of different configurations at a constant value of angular momentum to find the minimum energy configuration. Then we studied how this minimum energy configuration changes as the angular momentum is increased. Assuming a value of system angular momentum, H, we can define the energy of the possible resting configurations. Then, as H increases from a small quantity we can identify the different configurations that result in a minimum energy.

At an angular momentum of $H = 0$ the minimum energy configuration has the sphere resting on the α_3 axis of the ellipsoid. This remains the minimum energy configuration when the system rotates slowly. Conversely, for large enough H (but less than the value for which fission occurs) the minimum energy configuration always consists of the sphere lying along the α_1 axis of the ellipsoid, the entire system rotating about the α_3 axis of the ellipsoid. This result holds for all values of ν, and has interesting implications.

For systems with $\nu \ll 1$, small particles will move from the polar regions to the long ends of the spinning ellipsoid as the angular momentum increases. For systems with $\nu \sim 1$, ellipsoidal rocks will move from resting on their minimum axis towards the sphere equator where they will stand on end, as the angular momentum increases. For any of these cases, if the rotation rate increases to the fission limit, the components would naturally separate and the system would transition smoothly into an equilibrium orbital configuration. The transitions between minimum energy states as angular momentum increases could be dramatic and could substantially change aspects of the asteroid's shape as it evolves.



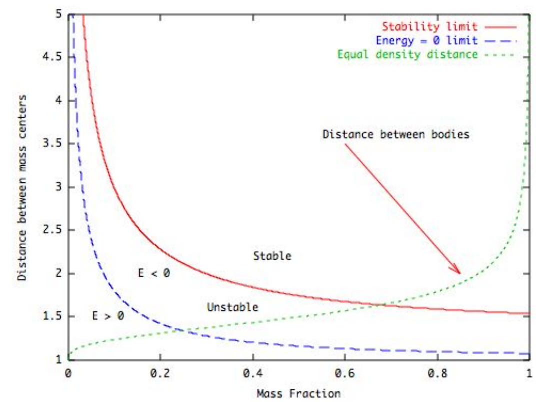
Stability of Relative Equilibria Now consider the stability of the system assuming that such fission has occurred, and that the asteroid is now formally an orbital binary (instead of a contact binary) with the sphere and ellipsoid orbiting about each other.

The formal stability of the relative equilibrium can be evaluated (Ref. [4]) and some specific results of these computations for two cases are shown in the figures. There is a clear stability transition as a function of mass fraction ν. For a fixed separation, for $\nu \ll 1$ the relative equilibrium are always unstable, meaning that small spheres lifted from the end of an ellipsoid will immediately be subject to an unstable environment. Thus they will drift (rapidly) from these locations in both radial and angular directions. At the other extreme, for $\nu \sim 1$, the relative equilibrium are completely stable, and correspond to stable synchronous rotation such as are found in nature. This implies that ellipsoidal rocks lifted off of a spinning sphere will enter a stable orbit, and will maintain this relative configuration. The subsequent evolution of the system due to continued perturbations are not considered here, but is a question of interest.

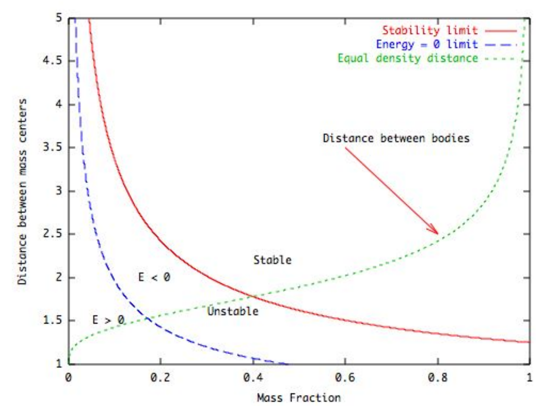
Stability of the resulting binary against mutual escape is more difficult to predict, however there are conditions for when this can and cannot occur. If the total system energy is negative then it is impossible for the binary system to evolve into an escaping system, barring transfer of energy and angular momentum from an external perturbation. If the system has a positive energy, then it is possible for a mutual escape to occur resulting from the orbital interactions between the sphere and ellipsoid. For small values of ν and sufficiently non-spheroidal ellipsoids we find that almost all binary systems will eventually disrupt under their own dynamics. It is important to note that any system which has a mutual escape will leave both bodies with rotation rates slower than they had previously (Ref. [5]), possibly halting the fission process for some time.

Systems formed by fission will retain the ability to reimpact each other, which becomes another mechanism for the evolution of an asteroid that has reached fission. If an unstable system is created and impact subsequently occurs, the secondary may become split into smaller components. The total system still retains the same amount of angular momentum, however this fracturing process releases additional potential energy that can allow the system to eject the smaller satellites (Ref. [6]), creating a runaway process that can effectively disperse and eliminate these particles from orbit about the body.

Conclusions We can draw a few conclusions from our observations. Asteroids with a strongly ellipsoidal shape cannot easily hold onto any secondary bodies that are fissioned off of them. If an elongate asteroid loses a significant fraction of its mass, it is also possible that the subsequent mutual escape of the system can leave the asteroid in a relatively slow rotation state. Asteroids with a spheroidal shape can more easily retain fissioned secondaries, allowing them to form long-term stable binary asteroid systems, whose orbital evolution may then follow more traditional dynamical evolutions. These observations are consistent with the data presented and discussions given in the binary asteroid survey paper by Pravec et al. (Ref. [7]). Finally, if an asteroidal body goes through a period of fast rotation, it may harbor evidence of this past through the presence of some surviving standing boulders on its surface.



Relative Equilibrium stability diagram for an ellipsoid with semi-axes 1x0.5x0.25



Relative Equilibrium stability diagram for an ellipsoid with semi-axes 1x0.9x0.8

References: [1] Merline et al. 2002, *Asteroids III*, 289-314. [2] Scheeres et al. 2002, *Asteroids III*, 527-544. [3] Bottke et al. 2002, *Asteroids III*, 395-408. [4] Scheeres 2006, *Celestial Mechanics* in press. [5] Scheeres 2002, *Icarus* 159(2): 271-283. [6] Scheeres 2004, *Celestial Mechanics* 69: 127-140. [7] Pravec et al., 2006, *Icarus* in press.