STABILITY OF A TERRESTRIAL MULTIPLE MOON SYSTEM. R. M. Canup[1], H. F. Levison[2] and G. R. Stewart[1], [1]LASP; University of Colorado, Boulder (canup@sargon.colorado.edu), [2]Southwest Research Institute, Boulder.

The currently favored theory of lunar origin is the giant-impact hypothesis. Recent work which has modeled accretional growth in impact-generated disks (Ida, Canup and Stewart 1997, *Nature* **389**; hereafter ICS97) has found that systems with two large moons are common outcomes. In this work we conduct a preliminary study of the stability of a terrestrial multiple moon system as it evolves due to mutual interactions (including mean-motion resonances) and tidal interaction with the Earth. We find that multiple moon configurations which form from impact-generated disks are typically unstable: these systems will likely evolve into a single moon state as the moons mutually collide or as the inner moonlet crashes into the Earth. In particular, our results indicate that all of the multiple moon systems produced in ICS97 are unstable for reasonable values of tidal parameterizations (Canup, Levison and Stewart, submitted).

A terrestrial satellite will orbitally evolve as it tidally interacts with the Earth. For a multiple moon system, the relative positions and masses of the moons determines whether their orbits will converge or diverge as a result of tidal evolution. Past works have assumed that a two-moon system which tidally converges to a separation of $\leq 3.5R_{hill}$ will destabilize, and that mutual collisions will lead to a single moon system (Canup and Esposito 1996, *Icarus* **119**). However, for tidally converging orbits, capture into mean-motion resonances is possible. Upon capture into resonance, moonlet eccentricities will increase as a result of the resonant interaction. Whether or not a stable, equilibrium eccentricity is reached depends on the relative influence of terrestrial vs. satellite tides, since the former generally act to increase eccentricities while the latter act to decrease eccentricities.

We utilize both numerical integrations (a modified version of the symplectic MVS integrator found in the SWIFT package) and analytical methods to track the evolution of multiple moon systems as they tidally evolve through mean motion resonances. Our general findings can be best categorized in terms of relative moonlet masses:

1) Massive inner moon/Small exterior debris

In this scenario, orbits are converging due to tides and capture into mean-motion resonances can occur for low enough eccentricities. However, we find that exterior eccentricity resonances are unstable over the whole range of plausible relative rates of satellite and terrestrial tidal dissipation. The assumption that a large inner moon will eventually overtake smaller exterior material as it tidally evolves outward is a good one.

2) Two-moons with $m_1 \gg m_2$

Here capture into resonances can again occur for low enough initial eccentricities, and equilibrium values of moonlet eccentricities in resonance are achieved for plausibly high rates of satellite dissipation. However, in this case resonances destabilize as the relative importance of satellite to planetary tides approaches its current value.

This configuration is predicted by one-third of the ICS97 simulations. In all of our integrations of the two-moon ICS97 cases (see for example Figures 1 and 2 below), we find that the inner moon rapidly crashes into Earth on a time scale of years due to its proximity to synchronous orbit for a terrestrial day of 5 hours. For a more rapidly spinning Earth (as would be appropriate for an initial giant impact event with twice the angular momentum of the current Earth-Moon system), the two-moon configuration could have persisted for some time and the eventual outcome may have been either a moonlet-moonlet collision or a moonlet-Earth collision.

3) Inner small material/Massive exterior body

In this case, orbits diverge due to tides and capture into resonance is precluded. This configuration is the one most likely to yield a stable, multiple moon system around the Earth. ICS97 do not predict this configuration from accretion in a smooth impact-generated, lunar-mass disk, since perturbations by the largest moon or moons which form are very effective at scattering inner small debris onto the Earth (ICS97). However, this conclusion could be affected by the presence of initially massive clumps prior to accretion in the disk (see Cameron and Canup 1998, *LPSC*).

This study highlights the importance of several factors which predispose a terrestrial system to a single moon state. First is the rapid rate of orbital evolution of satellites due to tidal interaction with the Earth. Even for solid body tidal Q values ($Q \approx 100$'s), a protomoon which forms close to the Earth evolves out to $20R_\oplus$ (a typical outer limit for an impact-generated debris cloud; Cameron and Benz 1991) in only 10^7 - 10^8 years. In contrast, tidal evolution rates around gas planets are $10^3 - 10^4$ times slower. Second, terrestrial Q values are within an order-of-magnitude of likely tidal Q values for orbiting satellites. This means that the plausible range of ``A values"--the relative role of satellite to planetary tides in affecting satellite eccentricity evolution—extends only up to about $A<20$, with a current value of about $A=0.5$ to 1. For a satellite orbiting a gaseous planet, $A \approx 1000$. In a terrestrial system, planetary tides thus play an important role in increasing satellite eccentricities, which acts to destabilize resonances and to increase mutual collisions. Finally, the large mass-ratio of the Moon to the Earth, coupled with lunar formation from a central, impact-generated disk, may insure that small inner disk material inside the Roche radius is effectively scattered onto the Earth (ICS97).

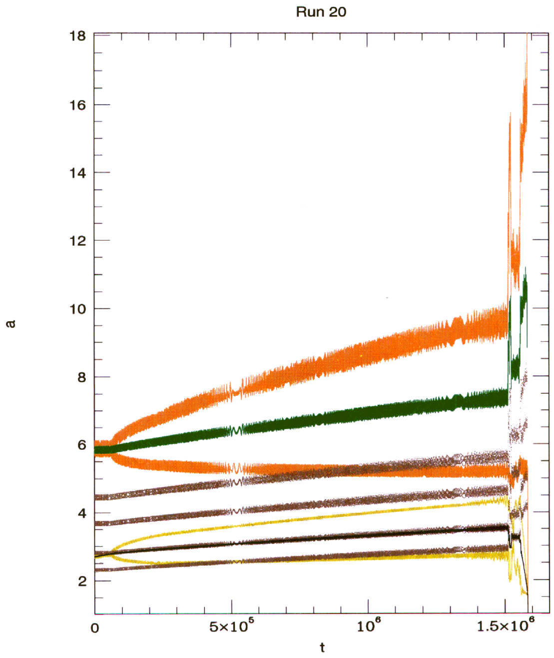

Figure 1: The black and green curves are a_1 and a_2 respectively, while the yellow and orange curves show periapse and apoapse at each time step. The brown curves indicate the location of the 3:2, 2:1, 3:1 and 4:1 mean-motion resonances. The y-axis is in Earth radii; the x-axis is (t(sec)/808). The plot shows the numerical integration of the evolution of a two-moonlet case from ICS97 (their Run 13). A terrestrial day of 5 hours was assumed. Here the two moons are captured into the 3:1-e_1e_2 resonance until about t=1.5x10^6 (about 40 years). After a brief period of capture in the 4:1, perigee of the inner moon falls within synchronous orbit and its orbit then circularizes and falls into the Earth.

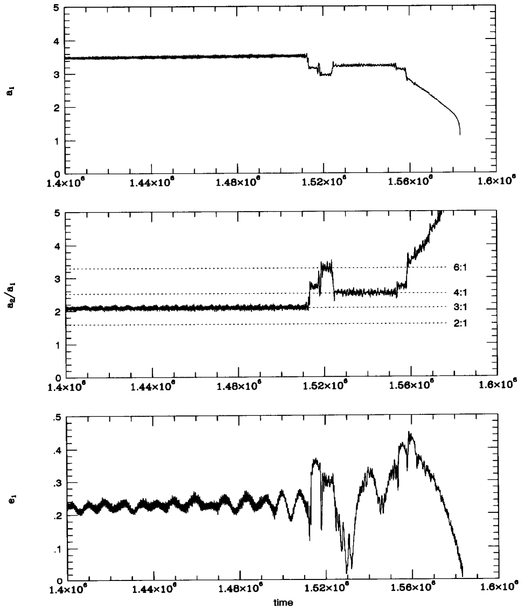

Figure 2: The relevant quantities for the inner moon from the simulation shown in Figure 1. The top figure is semi-major axis, the middle figure is the ratio of the orbital radii of the outer to the inner moon, and the bottom figure is the eccentricity of the inner moon.