LUNAR ACCRETION FROM DISKS PRODUCED BY NON-CANONICAL IMPACTS. J. Salmon[1] and R. M. Canup[1], [1]Southwest Research Institute, Planetary Science Directorate, 1050 Walnut Street - Suite 300, Boulder, CO, 80302, USA (julien@boulder.swri.edu)

Introduction: The Earth's Moon is thought to have formed from a circum-terrestrial disk generated from the debris of a giant impact on the Earth. In the "canonical case", a Mars-sized impactor is involved, forming a disk composed mostly of impactor material (e.g. [1,2]). Given that the impactor likely had a composition different from that of the Earth, this is at odds with the identical isotopic compositions of the Earth's mantle and the Moon. Pahlevan & Stevenson [3] suggested that material exchange between the disk's and Earth's atmospheres could modify the composition of the disk to match that of the silicate Earth, resulting in compositional equilibration in $O(100)$ years. Recent modeling of the Moon's accretion from the disk shows accretion timescales compatible with that required for equilibration to occur [4]. It might, however, be difficult for equilibration to occur without simultaneously depleting the disk of its mass [5]. In addition, in these models a substantial portion of the Moon forms rapidly after the impact from material placed into distant orbits [4], and at least this portion appears unlikely to equilibrate with the Earth.

Recently, new types of impacts involving larger impactors [6] or high-velocity impacts on a fast-rotating Earth [7] have been proposed. These "non-canonical" impacts produce disks with a composition nearly identical to that of the Earth, potentially removing the need for equilibration. However, the post-impact system in these impacts has a large excess of angular momentum. The evection resonance between the Earth, Moon and Sun is then invoked as a mechanism capable of reducing the Earth-Moon system's angular momentum by a factor of two or more to make it compatible with its current value [7].

We have identified two possible issues with non-canonical impacts: 1) they produce more compact disks than in the canonical case, with most of their mass located inside the Roche limit, $a_R = 2.9\ R_\oplus$. Recent studies of the accretion of the Moon from the protolunar disk have shown that incorporation of material inside a_R is rather inefficient [4], and so whether these more compact disk can produce a Moon-size object is unclear. 2) the required prolonged capture of the Moon into the evection resonance (occurring at ~ $7R_\oplus$) appears to occur over a rather narrow range of parameters. Prior work [7] assumed that the Moon formed at $1.3a_R$, while [4] find that the Moon forms substantially farther away, around $2.1a_R$ (or at about $6R_\oplus$).

We are here performing numerical simulations of the accretion of the Moon from non-canonical disks in order to assess whether a Moon-size object can be formed and to determine the likely range of the Moon's orbital parameters following its accretion.

Model: The model in [4] represents the protolunar disk by a uniform fluid disk inside a_R, and a collection of individual particles tracked with the *N*-body code SyMBA [8] beyond a_R. As inner disk material spreads beyond the Roche limit, mass and angular momentum are removed from the inner disk and added to the *N*-body portion of the simulation in the form of a new "spawned" moonlet.

We have here expanded this model to include effects of the Earth's oblateness (which is very large for non-canonical impacts due to the short, 2 to 3-hr post-impact rotation period of the Earth) and the gravitational potential of the Roche-interior disk. Both the Earth's J_2 and the inner disk cause precession of the orbits of moonlets as they accrete outside the Roche limit. Such precession shifts the positions of mean motion resonances between the moonlets, making the states of a given commensurability more well-separated.

Initial parameters: For our initial disks we used parameters derived from the results of [6] and [7]. We use total disk masses ranging from 1.75 to $3.25M_L$ (M_L is the mass of the Moon), with 60 to 90% of the disk mass initially inside a_R. For the outer disk, we use outer edges ranging from 3.5 to 4.5 $R_\oplus$ to represent compact disks. The disk's total specific angular momentum ranges from 0.86 to 0.92 $\sqrt{a_R G M_\oplus}$ (G is the gravitational constant), which is significantly lower than the values typical of canonical disks [4].

Results: We find overall accretion dynamics similar to that observed with canonical disks [4]. Figure1 shows the mass of the largest body (solid line) and the fraction of its mass derived from the inner disk (dashed), for a sample simulation. As in canonical cases, the Moon forms in 3 consecutive steps, accreting first the material from the outer disk in less than a year, and subsequently material from the inner disk in a protracted final accretion phase that lasts over 100 years as inner disk material viscously spreads outward.

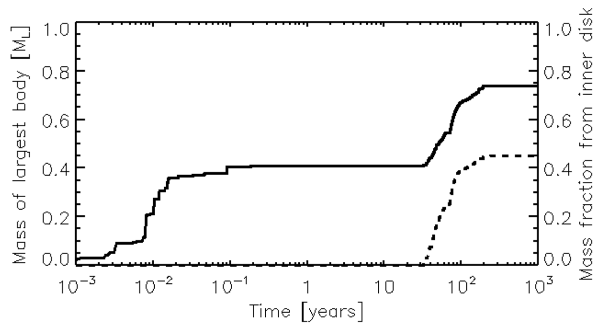

Figure 1: Mass of the largest moon in the simulation (solid line) and fraction of its mass derived from the Roche-interior disk (dashed line) shown vs. time.

Figure 2 (upper) shows the semi-major axis of the largest Moon from Fig. 1. The bottom panel shows the semi-major axis of the 2nd largest body in this simulation at any given time, so that multiple bodies are represented in the plot. The 2nd largest body is often scattered, resulting in large semi-major axis values. The red lines represent the Moon's 2:1 and 3:1 Mean Motion Resonances (MMR). Capture of a single body into the 3:1 MMR occurs at about 200 yr. Figure 3 shows the accompanying evolution of the Moon's eccentricity.

We find that forming a Moon-sized object requires an initial disk mass ~$3M_L$. Such massive disks are produced in some of the impact simulations of [6].

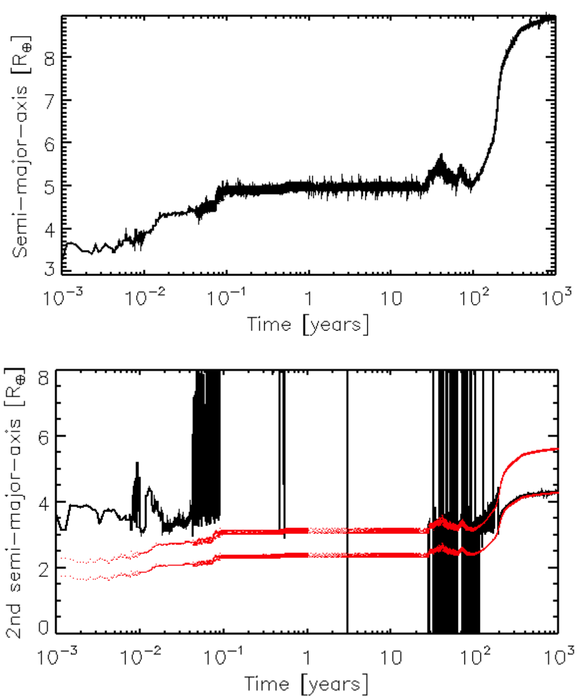

Figure 2: Evolution of the Moon's semi-major axis (top) and of the semi-major axis of the 2nd largest body in the simulation at each time (bottom panel). The red lines are the Moon's 2:1 (upper) and 3:1 (lower) Mean Motion Resonances.

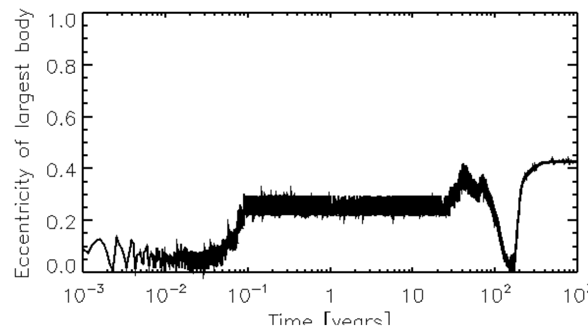

Figure 3: Eccentricity of the Moon. Around 100 yr, the eccentricity of the Moon decreases as it accretes material. Then an inner object is captured into its inner 3:1 MMR at about 200 yr, and its eccentricity increases.

The main difference from canonical cases is that in non-canonical disks, we find more frequent and protracted capture of objects formed at the Roche limit into MMRs with the outer largest Moon. The smaller inner object is typically captured into the MMR after it is spawned from the inner disk as its orbit expands due to resonant interactions with the disk. The latter cause its orbit to converge on that of the Moon, whose orbit is distant enough that its strong MMRs no longer fall within the disk. Capture results in a transfer of angular momentum from the disk to the Moon, whose orbit expands to beyond $8R_\oplus$ in this case. The Moon's eccentricity is also resonantly driven to high values, typically $O(0.1)$. Such orbital parameters may compromise capture into the evection resonance, since the Moon may cross the resonance as it is still accreting material and with a substantial orbital eccentricity. This should be evaluated further with models that include the effects of planet and satellite tides.

Our model assumes that outer disk material may be approximated as a condensate disk. Cooling to this state may require several years or more. The simulations here would then approximate the disk's evolution starting after this time post-impact, with a key caveat that there could be important evolution of the disk's properties in the interim period [9].

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