ORBITAL EVOLUTION OF THE MOON AND THE LUNAR CATACLYSM. Matija Ćuk, Harvard University, Department of Earth and Planetary Sciences, 20 Oxford St, Cambridge, MA 02138; cuk@eps.harvard.edu

Introduction: The concept of Lunar Cataclysm (and sometimes synonymous Late Heavy Bombardment) originated from the the study of lunar samples collected by Apollo missions [1]. Despite many new lines of evidence, the best data we have on the LC/LHB is still that from Earth's Moon [2]. There has even been skepticism if the LC/LHB even happened outside the Earth-Moon system [3]. In any case, the question of there being a connection between the Moon's complex orbital evolution and the Cataclysm is legitimate given that the timescales involved are similar. Also it is interesting to see what consequences for the lunar orbit would result from different scenarios of LC/LHB.

Multiple Moons of Earth: In principle, the Moon-forming impact could have resulted in multiple satellites [4], in which case their subsequent orbital evolution would have been rather complex. A lunar-only cataclysm all but requires some sort of late instability in a terrestrial multiple-moon system. Canup et al. [5] studied evolution of such systems using both analytical and numerical methods, and found that smaller satellites always get trapped in eccentricity-type mean-motion resonances. Orbital evolution in these resonances invariably leads to extremely high eccentricities and relatively rapid instability. Therefore [5] concluded that a terrestrial multiple-moon system could have lasted for less than million years, with the clear implication that they were not the cause of the Cataclysm.

Our own more recent research mostly confirms results of [5]. We integrated a full three-dimensional system with solar perturbations, and found that the moons often tend to become trapped in inclination-type, rather than eccentricity-type mean-motion resonances (this applies to the 1:3 resonance, among others). Despite this difference, the system always encounter instability rather fast, after the smaller moon attains first large inclination and then also large eccentricity.

While the results so far on the stability of such systems are quite discouraging, there are reasons to assume that there might be some aspects of the problem that have been overlooked. In particular, the curious configuration of Pluto's three-satellite system contradicts our present models of multiple-moon doom [6,7], so the long-lived other moons of Earth cannot be completely dismissed until we better understand Pluto's system.

Lunar Trojans: Few years ago my collaborators and myself [8] suggested that lunar Trojans could be very long-lived, escaping only when the Moon reaches the distance of 38 Earth radii, which is plausibly synchronous with the LC/LHB. However, our initial numerical simulations failed to take into account variations of Earth's orbital eccentricity (crucial for the strength of resonances involving the Sun) as well as the Trojan's own gravity, which is also crucial for the outcome of resonance crossings. Our final conclusion is that a Trojan massive enough to cause the LC/LHB could not have survived the evolution all the way to 38 Earth radii, but would have likely escaped when Moon was at about 27 Earth radii, which likely happened within the first 100 Myr of the system's history.

Planet V and the Lunar Orbit: One of the recent theories of the LC/LHB involves a quasi-stable fifth terrestrial planet between Mars and the asteroid belt [9]. After destabilizing the asteroid belt for 100-200 Myr, this 'Planet V' meets its end similar to an NEA, with solar or planetary collision and ejection all being possible. During its final scattering phase, Planet V should have had close encounters with the Earth-Moon system. Using a simple Monte-Carlo approach where many sets of such encounters are integrated with a Burisch-Stoer integrator we conclude that a Mars-sized Planet V would have likely excited lunar eccentricity beyond values compatible with the present state. On the other hand, a lunar-sized Planet V can be reconciled with the present lunar orbit. Interestingly, inclination is relatively more resistant to such encounters, requiring at least a Mars-sized interloper to account for the present value of 5.5 degrees. Therefore Planet V is unlikely to be the source of the Moon's inclination, but a similar encounter in the early Solar System is still a possibility (as first suggested by [10]). Interestingly, despite large mass involved in the 'Nice model' of the LC/LHB [11], Earth-Moon system is relatively unaffected, as rogue TNOs spend very little time among inner planets, as they are all times dynamically coupled to Jupiter (unlike what is expected of Planet V).

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