DYNAMICAL CAUSE OF THE LATE HEAVY BOMBARDMENT. R. Malhotra, Lunar and Planetary Laboratory, The University of Arizona, 1629 E. University Blvd. Tucson AZ 85721. renu@lpl.arizona.edu.

Introduction: The crater record on the Moon and the terrestrial planets shows that the old impactor population associated with the Late Heavy Bombardment (LHB), ~ 3.9 Ga, had a size distribution nearly identical with that of the main asteroid belt, strongly suggesting that the LHB impactors were main belt asteroids (MBAs) ejected from the asteroid belt in a size-independent manner [2]. We discuss some implications of this result for the dynamical mechanism that caused the LHB.

First, we note that the size distribution of the present-day Near Earth Asteroids (NEAs) is relatively more abundant in smaller asteroids compared with the main asteroid belt [1]. Current understanding of these differences in the size distributions of NEAs and MBAs is that NEAs derive from the MBAs via a combination of non-gravitational effects (such as the Yarkovsky effect [3]) which cause asteroids to drift into the Kirkwood Gaps, whence gravitational resonances eject them into planet-crossing orbits; because the first part of this process – non-gravitational orbital drift – is size-dependent (smaller asteroids have larger rates of Yarkovsky drift), the NEA population is relatively more abundant in smaller asteroids compared to its source population of MBAs [4].

The near-coincidence of the size distribution of the LHB impactors and the MBAs suggests that the timescale of the ejection mechanism that launched MBAs into the LHB impactor population was short enough that non-gravitational processes were ineffective in altering the size distribution of the impactors from that of its source, the MBAs. This means that the ejection mechanism involved gravitational resonances alone, without the help of any size-dependent processes. The only known manner in which this can be accomplished in the early history of the solar system is by causing the locations of gravitational resonances to drift (sweep) across a significant range of asteroidal semimajor axis on a short timescale.

Duration of the LHB: The small differences between the size distribution of the MBAs and the LHB projectiles still need to be determined from the available data and modelling. We note here that these differences could have two causes: (A) a second, less dominant, population of impactors of a size distribution distinct from that of the MBAs, or (B) the finite (but relatively short) duration of the dynamical process that launched the MBAs into the inner solar system; the finite duration would allow the Yarkovsky effect (or other size-dependent process) to contribute a larger abundance of the smaller MBAs to the LHB projectile population. Thus, it may be possible to constrain the duration of the LHB by studying the small differences between the MBA size distribution and the LHB projectile size distribution.

Planet migration link to LHB: In an independent line of study over the past decade, it has come to be widely accepted that the outer planets (Jupiter–Neptune) underwent a significant amount of orbital migration in their early history; evidence for this is found in the orbital distribution of Kuiper Belt objects [5–9]. The timescale of the migration has been roughly constrained to 10^6–10^8 years, also by consideration of the KBO orbital distribution [10]. However, the epoch of the giant planet orbital migration has been difficult to constrain based on outer solar system dynamics. Now, given the new insights into the origin of the LHB impactors which require resonance sweeping of the asteroid belt, it is conceivable that the LHB was caused by the same giant planet migration that has been linked to the orbital structure of the Kuiper Belt: in particular, the migration of Jupiter and Saturn would naturally result in a sweeping of mean motion and secular resonances in the asteroid belt. By making this link, and by recalling the cosmochemical evidence that the LHB occurred ~ 3.8–4.0 Ga [11], we can time the giant planet migration to that same epoch. The implications of this argument must be considered carefully.

The migration of the giant planets owes to the ejection of residual planetesimals that remained for some time after planet formation was nearly completed in the outer solar system. The nearly-solar composition of Jupiter, somewhat less so of Saturn, and much less so of Uranus and Neptune, has long suggested a planet-accretion timescale that was short for Jupiter and Saturn (nearly contemporaneous with the Sun, as astronomical evidence suggests that the lifetimes of protostellar disks of sun-like stars are only $\sim 10^7$ yr [12]), but considerably longer for Uranus and Neptune. The accretion of Uranus and Neptune has long been a major challenge for planet formation theory. Classical calculations based on planetesimal accretion have yielded accretion times for these planets in excess of the age of the solar system [13]; however, a recent calculation that includes an improved assessment of the effects of dynamical friction in a planetesimal disk yields Uranus and Neptune accretion time $\sim O(10^7)$ yr at heliocentric distance 20–30 AU [14]. Both these estimates are quite approximate, of course. It is possible, perhaps even plausible, that the LHB epoch, $\sim 600 \pm 100$ Myr after the birth of the Sun, provides the timing of the migration of the giant planets, which in turn was triggered by the near-completion of the formation of Uranus and Neptune. (The accretion of Neptune to nearly its final mass is required in order for these planets to be effective in perturbing the distant residual planetesimal mass that was available in the primordial Kuiper Belt and that served to fuel the planetary migration process.) I.e., the accretion time for Uranus and Neptune was ~ 600 Myr.

The late formation of Uranus and Neptune in the above scenario has been previously suggested in ref. [8]. In an alternative scenario, proposed in ref. [15], Uranus and Neptune form contemporaneously with, and in close proximity to, Jupiter and Saturn; the orbital migration of the planets proceeds slowly for ~ 600 Myr, at which epoch Jupiter and Saturn pass through a mutual 2:1 mean motion resonance; this resonance passage causes excitation of Jupiter and Saturn's orbital eccentricities and a short phase of strongly chaotic orbits of Uranus and Neptune which is eventually damped by residual planetesimals; the

LHB is caused by orbital instabilities in the asteroid belt that ensue due to the perturbations of the giant planets during and subsequent to the Jupiter-Saturn 2:1 resonance passage. The details of both scenarios remain to be elucidated and evaluated critically.

A test of the resonance sweeping hypothesis: One prediction of the resonance sweeping of the asteroid belt as a cause of the LHB is as follows. The main asteroid belt is known to have a significant gradient in composition as measured by spectroscopic colors, and we can roughly define three zones: an inner belt, the middle belt and the outer belt. One of the strongest resonances for the delivery of asteroids to the inner solar system at the present epoch is the secular resonance, ν_6, which defines the observed inner edge of the main asteroid belt. We consider that this resonance may have been the most efficient and dominant in ejecting asteroids from the main asteroid belt if resonance sweeping caused the LHB. The location of this resonance is most sensitive to the orbit of Saturn. We have calculated the ν_6 resonance location as a function of the orbital semimajor axis of Saturn. We find that the provenance of the LHB impactors would be related to the magnitude of Saturn's orbital migration: a small, ~ 1 AU outward migration would cause the ν_6 to sweep through only the inner belt and the LHB impactors would be dominated by inner belt members; a migration of $\sim$ 1–2 AU would yield LHB impactors from the middle as well as the inner belt; an outward migration of Saturn by more than ~ 2 AU would be required to produce ν_6-ejected impactors from the entire main asteroid belt.

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