MASS FLUX DURING THE ANCIENT LUNAR BOMBARDMENT: THE CATACLYSM.

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Introduction: The lunar cratering record is generally shown as a function of crater density against time (e.g., [1,2]). The curve shows crater densities back to ~4.5 Ga, but there are no surfaces older than the Nectaris basin that have both a crater density and an absolute age determination. 2/3 of the basins are older than Nectaris, and thus this part of a crater density curve is entirely conjectural in its chronology.

The impact flux does not have to be in crater density terms. Mass flux was used by Hartmann [3] and is a better parameter to examine the ancient flux. Using this parameter, segments of the flux curve can be derived or constrained independently of crater densities, not all using the same methods. These can be used to evaluate the impacting record of the Moon. The present-day mass flux and that over the last million years or so can be evaluated reasonably well from spacecraft and from lunar and terrestrial observational data. Absolute dating, crater density counts, and regolith properties of lunar mare surfaces allow reasonable estimates to be made back to about 3.8 Ga. The mass flux for lunar accretion at ~4.5 Ga can be constrained. For these eras, the mass flux constraints are not particularly controversial ([3], Fig. 1). Here, I address how mass flux between crustal formation and the end of the basin-forming era at ~ 3.8 Ga can shed light on the impact history of the Earth-Moon system.

Ancient lunar stratigraphy and chronology: The ancient lunar stratigraphic record is based on the multi-ring impact basins, of which there are ~45 recognized [2,4]. They are arranged relatively by mutual superposition relationships and superposed crater densities. The youngest ~1/3 of the basins are either of the Nectarian Period (11 basins) or the younger Early Imbrian Epoch (3 basins). The age of Nectaris has been derived from absolute ages of lunar impact melt fragments that are interpreted as ejecta from, and therefore older or equal in age to, Nectaris. The age so-derived is close to 3.90 Ga, arguably 3.92 Ga. Virtually all authors agree with this 3.9 Ga age within a few tens of millions of years. Fragments from the Luna 20 mission suggest that Crisium is 3.89 Ga, and the Apollo 17 poikilitic boulders provide compelling evidence for a 3.89 Ga age for Serenitatis. Ages of impact melts at the Apollo 14 and 15 landing sites and of superposed volcanic rocks at the Apollo 15 site constrain the age of Imbrium to be 3.85 ± 0.02 Ga. Only two basins postdate Imbrium: Schrödinger and Orientale. They must be older than 3.80 Ga, and may be almost as old as Imbrium. In any case, 11 basins formed between ~3.85 and 3.90 Ga.

Mass accretion rate in the Early Imbrian Epoch (Imbrium -Orientale) and the Nectarian Period (Nectaris-Imbrium): Crater densities and chronology can be used to evaluate the flux in these times [2]. However, the amount of mass colliding with the Moon in the Nectarian-Early Imbrian can be estimated independently of absolute time, by considering the projectile masses. These can be estimated from how big a basin is, how much energy it took to produce, and how that energy relates to projectile mass, velocity, and energy partition during the event [4]. None of these are well-known, and some factors require scaling form better-known, smaller scale events. An important factor is the size of the transient cavity. The Imbrium projectile mass has been generally estimated as ~ 2×10^{21} g, and that for the Orientale projectile ~ 1.5×10^{21} g, although other estimates are generally larger. Transient crater estimates from [4], high velocities of 20 km/sec, and the scaling relationship of [5]) produce conservative masses of ~8×10^{20} g and ~4×10^{20} g for the Imbrium and Orientale projectiles, respectively. The mass of the 15 Nectarian and Early Imbrian basin projectiles is then ~ 10^{21}g as a conservative low estimate (~ 5×10^{21} g or even ~ 10^{22} g might be considered more reasonable). The mass of the corresponding small crater-producing projectiles would be comparatively minor if the distribution were biased towards larger projectiles, as most commonly inferred.

Adding time constraints, if the combined Nectarian-Early Imbrian period lasted 80 Ma, then the average mass flux was ~ 1.25×10^{13} g/y. This is a little higher than the accretion estimated from crater density, not surprising if the mass distribution is biased towards larger objects. *A mass flux of ~ 1.25×10^{13} g/y cannot be on a curve that is any reasonable smooth continuous decline from initial lunar accretion*. It is more than an order of magnitude above the uniform high level even proposed by [3], and three orders above the extrapolation back for the more recent heliocentric primitive chondritic flux. It cannot be considered a minor "spike", because it includes the last 1/3 of impact basins, not just one or two events.

If, in contrast, this Nectarian-Early Imbrian period were as long as 300 Ma (Nectaris at 4.12 Ga, Orientale at 3.82 Ga), the average mass collision rate of ~ 3×10^{12} g/y would still be almost an order of magnitude or more above the [3] curve for that period (Fig. 1). Even this cannot be considered a mere "spike", but is a profound set of events, not related to Earth or Moon accretion, nor to a later "normal" heliocentric flux. Increasing the size of the projectiles, e.g., by assuming larger transient cavities or slower impactors, increases the discrepancy between the Nectarian-Early Imbrian and the "background" fluxes.

If the mass flux curve from late mare times through the Nectarian-Early Imbrian period (of the chronology in Fig. 1) is extrapolated back in time, it produces a mass equivalent to the entire Moon at ~4.1 Ga. As the Moon was formed and differentiated at a much earlier time, this flux increase cannot be so extrapolated back. Instead, the curve has to either flatten or decrease. Either solution requires that the Nectarian-Early Imbrian is a fundamentally different impact regime (or part of such a regime) from that both preceding it and postdating it.

Mass accretion rate in pre-Nectarian times: Indirect methods have to be used to evaluate accretion during the pre-Nectarian period. The projectile mass for the 30 basins was roughly twice that of the Nectarian-Early Imbrian. There are three endmember flux possibilities: 1) these basins, or at least some of them, were an early but integral part of the Nectarian/Early Imbrian cataclysm, with ages in the 3.90 to ~ 4.0 Ga range. 2) these basins formed roughly uniformly in time between crustal completion (at 4.4 Ga) and 3.9 Ga. 3) these basins all formed very early after crustal formation, and all substantially predate Nectaris.

There is no fundamental difference between pre-Nectarian and later basins, thus no suggestion of any hiatus in impacting prior to Nectaris, or of any flux change coincident with Nectaris. Meteoritic siderophile abundances in ancient highlands units such as Nectaris and Imbrium ejecta itself are low (much less than 1% chondritic equivalent). They suggest a post-crustal production flux averaging ~ 10^{11} g/yr - 10^{12} g/yr, depending on what depth they represent, unless the impactites are largely lost instead of accreting. Spectral evidence for an essentially intact lunar crust is consistent with a low average flux in pre-Nectarian times, with only the upper few kilometers churned. Such would be consistent with that derived from the observable highland crater population. Given the virtual absence of impact melt breccias older than 3.92 Ga among samples, yet the presence of ancient mare-like basalts among pre-Nectarian age rocks, then it seems most likely that most of these pre-Nectarian basins do not pre-date Nectaris itself by more than a few tens of millions of years. Thus the basin-forming period constitutes a cataclysm.

An alternative is that the basin-forming era projectiles eroded the Moon to the same extent as they accreted to it, or it did not accrete at all. The Moon would then have a crust that was well-mixed, destroyed, and eroded by the impacts. This is not the case; a reasonably intact crust has existed for 4.4 Ga. If non-accretional, erosional basin-scale bombardment had taken place, it would represent a most unusual impacting population in the inner solar system.

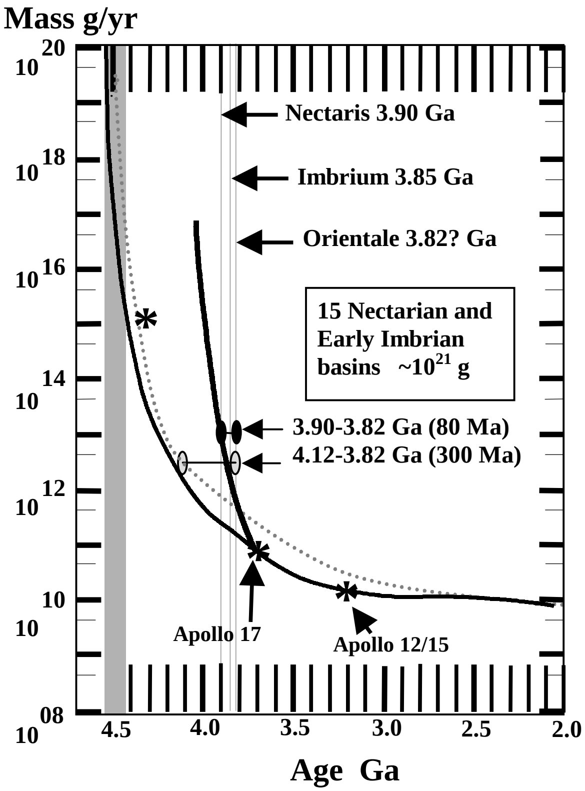

Fig. 1. Mass flux to the Moon. The asterixes mark reasonably well-constrained points from sample and current records (after 3.8 Ga) and the origin of the Moon itself (pre-crustal formation ~ 4.4 Ga, gray band). The dotted line is the flux assessed by Hartmann [3], and the solid line the "background" curve inferred here. The heavy solid line is the flux based on the Nectarian-Early Imbrian projectile masses. Extrapolated back, it produces Moon-masses at about 4.1 Ga, much too late to be reasonable. Thus, though it exists, it cannot be continued back in reality.

Scaling the lunar cataclysm to the Earth shows that the impacting was of insufficient intensity to evaporate oceans and sterilize Earth after ~ 4.35 Ga.

References: [1] Neukum G. and Ivanov B.A. (1994) in Hazards Due to Comets, Univ. Arizona Press, 359-416. [2] Stöffler D. and Ryder G. (in press) Space Science Reviews. [3] Hartmann W.K. (1980) Proc. Conf. Lunar High. Crust, 155-171. [4] Spudis P.D. The Geology of Multi-Ring Impact Basins, Cambridge Univ. Press, 263 pp. [5] Holsapple K.A. (1993) Ann. Rev. Earth Planet. Sci. 21, 333-373.