

Mass flux in the ancient Earth-Moon system and benign implications for the origin of life on Earth

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[1] The origin of life on Earth is commonly considered to have been negatively affected by intense impacting in the Hadean, with the potential for the repeated evaporation and sterilization of any ocean. The impact flux is based on scaling from the lunar crater density record, but that record has no tie to any absolute age determination for any identified stratigraphic unit older than ~ 3.9 Ga (Nectaris basin). The flux can be described in terms of mass accretion [Hartmann, 1980], and various independent means can be used to estimate the mass flux in different intervals. The critical interval is that between the end of essential crustal formation (~ 4.4 Ga) and the oldest mare times (~ 3.8 Ga). The masses of the basin-forming projectiles during Nectarian and early Imbrian times, when the last 15 of the ~ 45 identified impact basins formed, can be reasonably estimated as minima. These in sum provide a minimum of 2×10^{21} g for the mass flux to the Moon during those times. If the interval was 80 million years (Nectaris 3.90 Ga, Orientale 3.82 Ga), then the flux was $\sim 2 \times 10^{13}$ g/yr over this period. This is higher by more than an order of magnitude than a flux curve that declines continuously and uniformly from lunar accretion to the rate inferred for the older mare plains. This rate cannot be extrapolated back increasingly into pre-Nectarian times, because the Moon would have added masses far in excess of itself in post-crust-formation time. Thus this episode was a distinct and cataclysmic set of events. There are ~ 30 pre-Nectarian basins, and they were probably part of the same cataclysm (starting at ~ 4.0 Ga?) because the crust is fairly intact, the meteoritic contamination of the pre-Nectarian crust is very low, impact melt rocks older than 3.92 Ga are virtually unknown, and ancient volcanic and plutonic rocks have survived this interval. The accretionary flux from ~ 4.4 to ~ 4.0 Ga was comparatively benign. When scaled to Earth, even the late cataclysm does not produce ocean-evaporating, globally sterilizing events. The rooted concept that such events took place is based on the extrapolation of a nonexistent lunar record to the Hadean. The Earth from ~ 4.4 to ~ 3.8 Ga was comparatively peaceful, and the impacting itself could have been thermally and hydrothermally beneficial. The origin of life could have taken place at any time between 4.4 and 3.85 Ga, given the current impact constraints, and there is no justification for the claim that life originated (or reoriginated) as late as 3.85 Ga in response to the end of hostile impact conditions. **INDEX TERMS:** 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 5455 Planetology: Solid Surface Planets: Origin and evolution; 5470 Planetology: Solid Surface Planets: Surface materials and properties; 5499 Planetology: Solid Surface Planets: General or miscellaneous; **KEYWORDS:** Impacts, cataclysm, heavy bombardment, basins, accretion, life

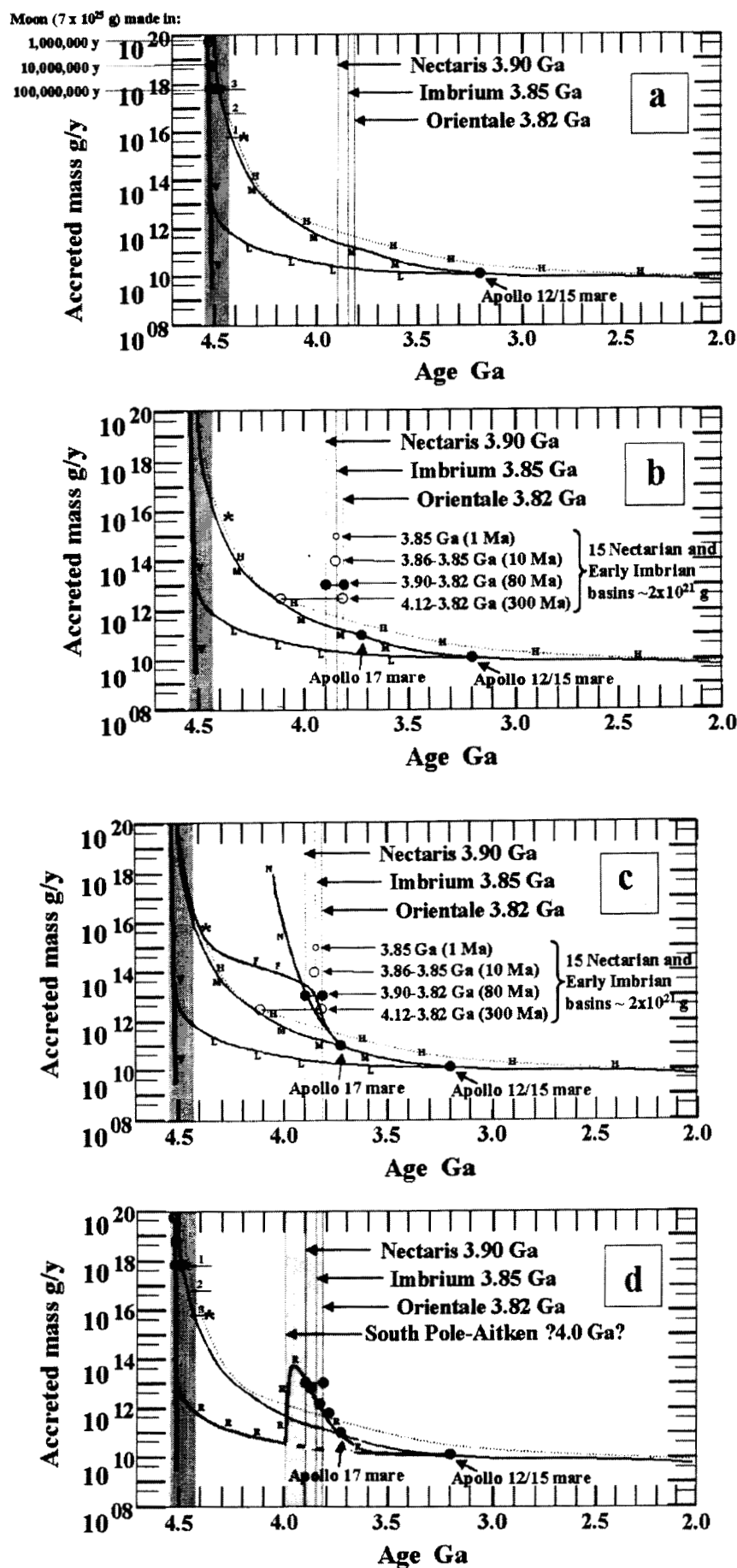
1. Introduction

[2] Over the last two decades there have been several studies of the impact environment on Earth during the time relevant for the origin and earliest evolution of life, that is, prior to the deposition of the oldest known water-lain sediments in Greenland at ~ 3.85 Ga [Nutman *et al.*, 1997, 2000]. These sediments contain carbon isotopic evidence

for the existence of life [Mojzsis *et al.*, 1996; Mojzsis and Harrison, 2000]. While both the age of the sediments and the evidence for the life in them have been disputed [e.g., Appel and Moorbath, 1999; Moorbath *et al.*, 1997; Myers and Crowley, 2000], the possibility that life existed on Earth by 3.85 Ga is now an important consideration in the origin of life.

[3] The assessment of ancient impact environments for the Earth includes the effects both of individual events and of the flux. In particular, these studies have addressed the potential for repeated oceanic evaporation and sterilization [Maher and Stevenson, 1988; Oberbeck and Fogleman, 1989, 1990; Sleep *et al.*, 1989; Zahnle and Sleep, 1997;

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helms, 1987; Spudis, 1993]. They are arranged stratigraphically by mutual superposition relationships and superposed crater densities (Figure 3). The accepted stratigraphic division using the Orientale, Imbrium, and Nectaris basins is historical and functional but not fundamental. The youngest $\sim 1/3$ of the recognized basins are either of the Nectarian Period (11 basins) or the Early Imbrian Epoch (3 basins).

[14] No specific basins or surfaces older than Nectaris have any known relationship with lunar sample chronological data. The age of Nectaris has been derived from absolute ages of lunar impact melt fragments in samples at the Apollo 16 landing site that are interpreted as ejecta from Nectaris [e.g., James, 1981; Spudis, 1984, 1993], assuming that the fragments either are from the basin or are older than the basin. The age derived is close to 3.90 Ga, arguably ~ 3.92 Ga. Stöffler *et al.* [1985] suggested an age as young as 3.85 Ga, but that is not consistent with the precise age of 3.893 Ga for the stratigraphically younger Serenitatis basin [Dalrymple and Ryder, 1996]. Hiesinger *et al.* [2000] continue to espouse an age for Nectaris of 4.1 Ga, without geological or radiogenic arguments. Virtually all authors presently agree with the ~ 3.90 Ga age within a few tens of millions of years, although the ramifications of such a young age have been generally overlooked. There remains some possibility that the geological arguments are in error and that Nectaris is at least somewhat older than ~ 3.9 Ga, and this will be considered in the arguments below.

[15] Age determinations of impact melt fragments from the Luna 20 mission suggest that Crisium is 3.89 Ga [Swindle *et al.*, 1991], although this is a rather less certain

assignment because of the limited sampling and poor geological context of any individual fragment. The very strong inference that Serenitatis is 3.89 Ga is derived from impact melt boulders at the Apollo 17 landing site [Dalrymple and Ryder, 1996], and it is geologically unlikely that these boulders are younger than Serenitatis. Although Haskin *et al.* [1998] made a case for the Imbrium origin of these melt materials, that is not consistent with their radiogenic age or their physical expression at the Apollo 17 landing site.

[16] Ages of inferred Imbrium and pre-Imbrium event impact melts at the Apollo 14 and 15 sites and of KREEP volcanic rocks superposed on Imbrium at the Apollo 15 site constrain the age of Imbrium to be 3.85 ± 0.2 Ga [Wilhelms, 1987; Spudis, 1993; Dalrymple and Ryder, 1993; Ryder, 1994] although there is no certainty that any particular melt that was created in the Imbrium impact has been identified. Only two basin events postdate Imbrium: Schrödinger and Orientale. Crater densities [Neukum and Ivanov, 1994; Hartmann *et al.*, 1981] show that these basins are older than the oldest exposed mare lava plains, and correlations among lava plains and sample ages demonstrate that they must be older than 3.80 Ga; they may be almost as old as Imbrium. This age uncertainty will be considered in the arguments below.

4. Crater Density and Mass Accretion

[17] In part of the following, mass accretion is derived from the crater density, which is reduced to a standard

Figure 4. (opposite) Constrained and hypothesized accretionary mass flux against time for lunar stratigraphy older than 2.0 Ga. The gray band at the left of each diagram reflects lunar formation, differentiation, and essential crust formation, completed at ~ 4.42 Ga. The vertical lines show the inferred ages for the Orientale, Imbrium, and Nectaris basins, from combined geological and geochronological data; these are subject to some debate. The other lines are hypothetical or constrained flux curves and are identified and discussed in the text. The large dots reflect mass flux at a point in time (or over a range in time when joined by a horizontal line) determined from crater densities and regolith characteristics (Apollo 12, 15, and 17 mare) and from inferred projectile masses (Nectarian–Early Imbrian basins). In Figure 4a, constraints from lunar accretion include the size of the Moon, isotopic evidence on how fast the Moon formed, and isotopic evidence on when the bulk of the crust had formed. Modern understanding of the accretion of the Moon suggests very fast formation of the Moon (such as a flux line V) and then a decline in the rate. This geocentric flux is succeeded by the heliocentric flux. For a flux line drawn through the asterisk from anywhere near the origin of the Moon, mass equivalent to 20–30% of the lunar crust would have been added after crustal formation, and this is not consistent with observations. A constant rate at the level of the asterisk for 100 million years (short horizontal line 1) would have added 10% crustal equivalent, also not consistent with observations. Hartmann's [1980] curve is drawn as H and produces too much accretion postcrustal formation. Curve M is barely acceptable but, as seen in Figure 4b, requires the flux at ~ 3.7 Ga to be part of the normal decline. Curves of lower flux are more likely, and even very low flux curve L is possible. Figure 4b is as Figure 4a, but with lunar and crustal formation detail omitted and constraints for early mare times and the Nectarian–Early Imbrian added as large dots. The constrained projectile mass accreted during the Nectarian–Early Imbrian interval is shown as four alternative fluxes, depending on how long this interval was. The one most consistent with currently understood chronology is shown as the black dots, with a range of 80 million years. During this basin-forming episode the flux was more than an order of magnitude greater at a minimum than any potential "background" flux from continually and uniformly declining impacting, such as Hartmann's [1980]. Figure 4c shows hypothetical flux curves projected into the pre-Nectarian. The curve derived for the Nectarian–Early Imbrian–Apollo 17 mare plains cannot be extrapolated increasingly back in time; by 4.1 Ga the rate would be such as to add a Moon mass in 100 million years, yet this is well after crust formation. A sinusoidal curve such as F is the minimum needed to avoid adding huge amounts of material to the crust and to have the flux curve lie below and to the left of the asterisk. Figure 4d contains the interpretation of the actual flux (R) preferred in this paper, showing a cataclysmic impact episode that includes all the observed basins, preceded by a long period of relative impact quiescence. The curve does not have to be so extremely low in the period 4.4–4.0 Ga but is consistent with what we know of lunar petrology, chronology, meteoritic siderophile element abundances, and crustal structural preservation. The cataclysm might have been a little more prolonged, with South Pole–Aitken at ~ 4.1 Ga.

size-distribution curve [e.g., *Neukum and Ivanov*, 1994]. Unrecognized deviations from that standard curve will cause errors in estimated mass accretion, but there is considerable evidence that the standard curve applies reasonably from the present day back to the end of the heavy bombardment period at least [e.g., *Neukum and Ivanov*, 1994; *Hartmann*, 1995]. This standard curve perhaps does not apply to the basin-forming era [e.g., *Wetherill*, 1981], but in this paper, for that era, mass accretion is referred to as a minimum independently derived from the basin-forming impactors, and so it is not crucial to the argument that the standard distribution prevails. If it does not, of course, then there is no reason to tie the basin-forming episode in any way to "normal" bombardment.

5. Mass Accretion Rate: Origin of Moon and Crustal Formation

[18] The Moon has a mass of $\sim 7.35 \times 10^{25}$ g. Most workers now accept (if hesitantly) that it formed from a geocentric debris ring of nonchondritic material from the mantles of the Earth and a protoplanet that collided obliquely with it [*Cameron*, 2000; *Canup and Asphaug*, 2001] and not from the heliocentric population from which the Earth was accreting. Isotopic and dynamical constraints show that most of the Moon formed early (certainly by 4.50 Ga [*Halliday et al.*, 2000; *Wiechert et al.*, 2002]) and rapidly (perhaps on the order of years [*Canup and Agnor*, 2000]). The flux of geocentric impactors is likely to have rapidly dropped below that of the heliocentric population that was forming the Earth.

[19] Lunar samples show that the Moon had formed, melted, cooled, and differentiated to produce abundant crustal rocks (ferroan anorthosites) by ~ 4.42 Ga [*Snyder et al.*, 2000; *Carlson and Lugmair*, 1988]. At least 99% of the Moon had accreted by this time, shown as the gray box in Figure 4a; 1% mass added to the Moon after this time would be an ultramafic mass equivalent to a 6 km thick layer of solid rock. Various formational flux possibilities are shown in Figure 4a. The flux has to lie to the left of and below the asterisk; otherwise, too much mass is added to the moon to be compatible with observations of the crust. If the flux curve passed through the asterisk, then at least 2–3% of lunar mass (~ 12 – 18 km rock equivalent) would have been added to the Moon in the period 4.45–4.35 Ga. The horizontal lines 1, 2, and 3 show continuous rates in this 100 million year interval that would have increased lunar mass by 1% (10% of crust equivalent), 10% (the entire crust equivalent), and 100%, respectively, over the same period.

[20] If the Moon formed in a few years ($\sim 10^{24}$ g/yr) or even millions of years ($\sim 10^{19}$ g/yr), then the geocentric accretional rate had probably declined to much less than 7.5×10^{15} g/yr by 4.45 Ga (the curve might be almost vertical; Figure 4a, line V). The contemporaneous heliocentric flux is not well-constrained. The curve shown by *Hartmann* [1980] (Figure 4a, line H) accretes $\sim 1\%$ of the Moon after crustal formation at 4.42 Ga and indeed $\sim 2\%$ in the period from 4.45 to 4.40 Ga, essentially after crustal formation, demonstrating that his curve is at too high a rate at this time and therefore later. Such a mass

collision rate would churn and thoroughly mix this original crust, whether or not impactor materials accreted or were lost. Almost the entire crust would show a 20% admixture of late added material (either ultramafic or siderophile-bearing or both) if it were generally accreted, but that does not appear in the lunar crustal record.

[21] The actual curve must lie somewhere below that of curve H. Line M (Figure 4a) would be a maximum smoothed curve, assuming that the flux during the earliest preserved mare times (Apollo 17 mare plains; see below) was part of a continual decline. The much lower curve, L, is equally possible, if extreme, if it was not.

6. Mass Accretion Rate: Current and Last 100 Myr

[22] The current rate of lunar accretion, mainly from heliocentric, primitive chondritic material, can be estimated in several ways. *Love and Brownlee* [1993] measured small particles ($< 10^{-4}$ g) in the vicinity of the Earth and obtained an accretion rate (to the Earth) of $40 \pm 20 \times 10^9$ g/yr and estimated a rate double that for the total infall, including larger particles. Such an estimate is consistent with those derived from isotopic and geochemical measurements (e.g., Ir and Os in pelagic sediments [*Kyte and Wasson*, 1986; *Peucker-Ehrenbrink and Ravizza*, 2000]) that cover a range up to the last 100 million years or so and broadly consistent with the terrestrial cratering record in the Phanerozoic [*Grieve*, 1998]. With scaling for the gravitational cross section of the Moon and its lower surface area, this corresponds to a present-day lunar flux on the order of 4×10^9 g/yr [e.g., *Hartmann*, 1980]. This is consistent with estimates based on lunar microcrater densities and exposure ages on rocks over the last few tens million of years as well as crater densities on the ejecta of reliably dated young craters on the Moon such as North Ray crater at the Apollo 16 landing site [*Hörz et al.*, 1975].

7. Mass Accretion Rate ~ 3.1 – 3.4 Billion Years Ago

[23] The youngest mare lava plains sampled were at the Apollo 12, Luna 24, Apollo 15, and Luna 16 landing sites (surface eruptions 3.1, 3.2, 3.3, and 3.4 Ga, respectively [*Wilhelms*, 1987; *Stöffler and Ryder*, 2001]). The crater densities on these surfaces are similar to each other (within uncertainties) and most consistent with a cratering rate over the last 3.4 Gyr that has been on average similar to that of the last ~ 100 million years [*Neukum and Ivanov*, 1994; *Wilhelms*, 1987]. It is not known how constant the rate has been, and various lines of evidence suggest that it has varied some [e.g., *Ryder et al.*, 1991; *Wilhelms*, 1987; *Culler et al.*, 2000].

[24] The regolith at the Apollo 12 landing site is typically ~ 5 m thick, and its Ir content averages ~ 8 ppb (1.6% chondritic equivalent), at least near the surface. (Unless otherwise specified, data sources for meteoritic siderophile elements in regoliths in this paper are from *Heiken et al.* [1991]). This is a primitive chondritic component, for example, C1 [*Morgan et al.*, 1977]. Assuming that this average abundance extends through

Table 1. Summary of Lunar Chronology and Inferred Absolute Ages

Stratigraphy	Dated Surface	Age, Ga	Crater Density (1 km), $\times 10^{-3}/\text{km}^2$	Average Crater Density Production During Interval	Production Rate per Million Years During Interval	Production Rate Comparing A12/15 to Present	Production Rate as Mass per Year, g/yr
Crustal completion		4.42					
Pre-Nectarian			(3.60 \pm 110)	>200 \pm 100	>0.38 \pm 0.20	>370	1.4×10^{12}
	Nectarian basin	3.90	120 \pm 40				
Nectarian				83 \pm 30	1.7 \pm 0.5	1650	6.6×10^{12}
	Imbrium basin	3.85	37 \pm 7				
Early Imbrian				15 \pm 5	0.5 \pm 0.2	485	1.9×10^{12}
	(Orientale basin)	3.82	22 (?)				
	(oldest mare basalts)	3.80	20 (?)	12 \pm 5	0.17 \pm 0.05	165	6.6×10^{11}
	Apollo 17 mare		10 \pm 3				
Late Imbrian	Apollo 11 mare	3.58	6.4 \pm 2	6.7 \pm 2	0.019 \pm 0.005	18	7.2×10^{10}
	Luna 16 mare	3.40	3.3 \pm 1				
	Apollo 15 mare	3.30	3.2 \pm 1				
	Luna 24 mare	3.20	3.0 \pm 1				
	Apollo 12 mare	3.15	3.6 \pm 1				
Eratosthenian				3.3 \pm 1	0.0010 \pm 0.003	1	4×10^9
Copernican							
	present day	0.00	0				3×10^9

the regolith and that the history is typical of the whole Moon's impact record over this time interval, the average accretion rate of chondritic material to the Moon has been ~ 3 or 4×10^9 g/yr, within uncertainty of the present-day estimate. This is a minimum, in that some of the flux may have been lost after impact volatilization rather than accreted. Most of this accreted material is from the micrometeoroid flux, which may not adequately reflect the materials added by larger projectiles (which might sample a different population with different dynamic lifetime), although the general gardening process will tend to mix these in. A similar flux value is derived from Apollo 15 data. The regolith thicknesses at the Luna sites are unknown (their Ir contents are similar to those at the Apollo 12 and 15 landing sites). An assumption of a mass accretion flux similar to, and no more than a factor of 2 or 3 higher than, the current rate (i.e., $\sim 10^{10}$ g/yr) at 3.1–3.4 Ga with an average of $\sim 4 \times 10^9$ g/y (Table 1; Figure 4a) is most consistent with the crater density and regolith physical and chemical properties.

8. Mass Accretion Rate ~ 3.4 –3.75 Billion Years Ago

[25] Crater densities on the mare plains at the Apollo 11 landing site (3.58 Ga) and the Apollo 17 landing site (3.75 Ga) are higher than on the Apollo 12 and 15 mare plains by factors of ~ 2 and ~ 3 , respectively [Neukum

and Ivanov, 1994; Wilhelms, 1987]. Thus the cratering and mass accretion rate from 3.4 to 3.75 Ga was on average $\sim 18\times$ higher than the post-A12/15 average, thus $\sim 7.2 \times 10^{10}$ g/yr (Table 1; Figure 4b). The Ir contents of the Apollo 11 and Apollo 17 mare soils are actually somewhat lower than those of the Apollo 12 and 15 landing sites (5–6 ppb rather than 7–8 ppb). This is generally consistent with the thicker soils (~ 2 – $3\times$ as thick at the Apollo 17 ALSPEP/LM locations) developed at these older sites, assuming a uniform depth distribution of Ir. However, it might actually indicate that much of this older impacting population was not delivering as much Ir per unit mass impacting as was the younger, chondritic meteoritic material. The Apollo 11 component at least, while dominantly probably a C1 component, is comparatively depleted in volatiles compared with refractory siderophiles [Morgan et al., 1977], and thus the older component might represent, or at least include, a different population of impactors.

9. Mass Accretion Rate in the Earliest Late Imbrian Epoch (Orientale-A17 Mare Plains)

[26] Crater densities are available for the Orientale ejecta and for the oldest mare plains [Neukum and Ivanov, 1994; Wilhelms, 1987; Hartmann et al., 1981], but absolute ages are not available for either. The oldest mare plains are inferably older than 3.80 Ga. Their crater densities are a factor of 2 higher than the Apollo 17 mare basalts, and mare

Table 2. Nectarian–Early Imbrian Basin Sizes and Inferred Projectile Masses^a

Basin	Main Rim Diameter, k	Transient Cavity Diameter, k	Projectile Mass, g	Age, Ga
Orientele	930	582 ± 77	4 × 10 ²⁰	3.82?
Schrödinger	320	290 ± 72	3 × 10 ¹⁹	
Imbrium	1160	685 ± 88	8 × 10 ²⁰	3.85
Bailly	300	280 ± 46	3 × 10 ¹⁹	
Sikorsky-Rittenhouse	310	285 ± 45	3 × 10 ¹⁹	
Herzsprung	570	408 ± 58	1 × 10 ²⁰	
Serenitatis	920	572 ± 76	4 × 10 ²⁰	3.89
Crisium	740	488 ± 67	2 × 10 ²⁰	3.89
Humorum	425	340 ± 51	6 × 10 ¹⁹	
Humboldtianum	650	445 ± 63	1 × 10 ²⁰	
Mendeleev	365	311 ± 49	4 × 10 ¹⁹	
Korolev	440	347 ± 52	6 × 10 ¹⁹	
Moscoviense	420	337 ± 51	5 × 10 ¹⁹	
Mendel-Rydberg	420	337 ± 51	5 × 10 ¹⁹	
Nectaris	860	544 ± 73	3 × 10 ²⁰	3.90/3.92
Sum			2.65 × 10 ²¹	

^aMain rim diameters and transient cavity calculation method are from *Spudis* [1993]. Projectile mass derivation assuming 20 km/s impact velocity is from *Holsapple* [1993, and references therein].

basalt fragments from the Apollo 11 and Apollo 17 mare plains are older than 3.80 Ga [e.g., *Papike et al.*, 1998]. Orientele ejecta has crater densities that are slightly greater than these oldest mare plains, and a consistent age for Orientele is 3.82 Ga or possibly even older. The average cratering flux during this 70 Myr period (3.82 – 3.75 Ga) would then have been ~165× the post-Apollo 12/15 average, or ~6.6 × 10¹¹ g/yr (Table 1; Figure 4b).

10. Mass Accretion Rate in the Early Imbrian Epoch (Imbrium-Orientele) and Nectarian Period (Nectaris-Imbrium)

10.1. Crater Densities, Ages, and Regolith Characteristics

[27] Crater densities on the Imbrium and Nectaris ejecta are ~10× and ~22×, respectively, those on the Apollo 12 and 15 landing sites [*Neukum and Ivanov*, 1994; *Wilhelms*, 1987; *Hartmann et al.*, 1981] (Table 1). The significance of these for mass flux depends on the ages of these basins. Adopting the ages in Figure 3 and Table 2, the cratering flux average ~485× the post-A12/15 average during Early Imbrian times (~4× as many in ~30 million years) and ~1650× during Nectarian times (~25× as many in 50 million years). These correspond with mass accretion rates derived from cratering correlations of ~1.9 × 10¹² and ~6.6 × 10¹² g/yr, respectively (Table 1). The regolith developed on the Fra Mauro may reflect such a post-Imbrium accretion: it contains ~13 ppb Ir and might be as much as 35 m thick. If so, it would reflect the appropriate 10× post-A12/15 crater density. Such a calculation presumes (or, alternatively, requires) a negligible pre-Imbrium siderophile component.

10.2. Basin Impactor Sizes and Masses

[28] The amount of mass colliding with the Moon during the Nectarian–Early Imbrian period can be estimated in another way independent of any absolute time. Projectile masses for a basin-forming event 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. None of these are well known, and some factors require scaling from better-known, smaller-scale impacts. An important factor is the size of the transient cavity [*Spudis*, 1993]. The Imbrium projectile mass has been generally estimated as ~2 × 10²¹ g and that for the Orientele projectile as ~1.5 × 10²¹ g [*Zahnle and Sleep*, 1997; *Baldwin*, 1981; *Wetherill*, 1981] although other estimates are generally larger. I use the transient crater estimates and calculation method from *Spudis* [1993] and assume high velocities of 20 km/s, well above the lunar escape velocity of 2.4 km/s, though less than the velocities of comets. Higher velocities correspond with smaller impactors, hence mass accretion. *Zahnle and Sleep* [1997] suggested an average collision velocity on the Moon in the appropriate period of 13 km/s. Applying the scaling relationship of *Holsapple* [1993], I obtain conservative masses of ~8 × 10²⁰ g and ~4 × 10²⁰ g for the Imbrium and Orientele projectiles, respectively (Table 2). The entire mass of the 15 Nectarian and Early Imbrian basin projectiles is then ~2 × 10²¹ g as a very conservative low estimate (~5 × 10²¹ g or even ~10²² g might be considered more reasonable). The mass of the corresponding small crater-producing projectiles would be comparatively minor if the mass distribution were biased toward larger projectiles, as most commonly inferred [*Wilhelms*, 1987; *Hartmann et al.*, 1981; *Hartmann*, 1995].

[29] The time-independent mass was, of course, added within some time interval; thus the flux depends on the length of that interval. If the combined Nectarian–Early Imbrian period lasted 80 million years (e.g., Nectaris 3.90 Ga, Orientele 3.82 Ga), then the average mass flux was ~2 × 10¹³ g/yr (Figure 4b, black dots), somewhat higher than that. This is higher than the accretion estimated from crater density, not surprising if the mass distribution is biased toward larger objects. A mass flux of ~2 × 10¹³ g/yr cannot be on a curve that is on any reasonable smooth continuous decline from initial lunar accretion (Figure 4b). It is more than an order of magnitude above even the uniform high level proposed by *Hartmann* [1980] and three orders above the extrapolation back in time for the more recent heliocentric primitive chondritic flux. It cannot be

considered a minor “spike,” because it includes the last 1/3 of all known impact basins, not just one or two events. It is even possible, with the absolute age constraints, that the combined Nectarian–Early Imbrian set of events took place in as little as 30 million years, from 3.89 to 3.86 Ga, with an average minimum mass accretion of $\sim 6 \times 10^{13}$ g/yr (Figure 4b).

[30] If, in contrast, this Nectarian–Early Imbrian period were as long as 300 million years (Nectaris at 4.12 Ga, Orientale at 3.82 Ga; Figure 4b), the average mass collision rate of $\sim 6 \times 10^{12}$ g/yr would still be almost an order of magnitude or more above the *Hartmann* [1980] curve for that period. Even this lower rate over 300 million years cannot be considered a mere spike imposed on the *Hartmann* [1980] curve. Instead, this period contains a profound set of events, not related directly to either Earth or Moon accretion or to a later “normal” heliocentric flux. Increasing the estimated size of the projectiles, for example, by assuming larger transient cavities or slower impactors, increases the discrepancy between the Nectarian–Early Imbrian flux and the “background” flux.

11. Mass Accretion in Pre-Nectarian Times

11.1. Hypothetical Extrapolation From Post-Nectaris Time Into Pre-Nectaris Time

[31] If the mass flux curve from late mare times through the Nectarian–Early Imbrian period (of the chronology in Figure 3, 80 million years) is extrapolated increasingly back in time, it produces a mass equivalent to the entire Moon in the interval after 4.1 Ga (Figure 4c, line N). However, the Moon was formed and differentiated at a much earlier time, so this flux increase cannot be so extrapolated back. Instead, the curve has to either flatten (e.g., Figure 4c, line F) or decrease. Either solution requires that the Nectarian–Early Imbrian had a fundamentally different impact regime from that both preceding it and postdating it. Calculations using logarithmic flux decay rather than exponential decay [*Holman and Wisdom*, 1993; *Evans and Tabachnik*, 1999] do not change that requirement; logarithmic decay would be a fundamentally distinct regime.

[32] If Nectaris is as old as 4.3 Ga, then it is just possible that flux extrapolation would not produce a hypothetical oversized Moon. However, there is neither evidence nor likelihood that Nectaris is so old. If it were, we would expect to find impact melt rocks at the Apollo 16 landing site with ages approaching 4.3 Ga, but none older than ~ 3.92 Ga have been reported [e.g., *Dalrymple et al.*, 2001].

[33] An alternative explanation for the lack of total lunar mass added is that the older basin-forming era projectiles did indeed collide with the Moon, but they eroded it to about the same extent as they accreted to it, or it did not accrete at all but instead volatilized and entirely escaped the Moon. The Moon would then have a crust that was well-mixed, destroyed, and eroded by the impacts. Remote sensing and sample evidence show that this is not the case and that a reasonably intact lunar crust has existed for 4.4 Gyr. If this sort of nonaccretional, erosional bombardment had taken place, it would nonetheless represent a most unusual impacting population in the inner solar system.

11.2. Empirical Lunar Crustal Record of Impacts, Ages, and Meteoritic Siderophile Element Abundances in Pre-Nectarian Time

[34] Indirect methods have to be used to evaluate accretion during pre-Nectarian times, during which ~ 30 impact basins were formed. The total projectile mass for these basins was roughly twice that of the Nectarian–Early Imbrian (the size distribution is similar), although South Pole–Aitken itself, the largest and stratigraphically oldest recognized impact basin, was probably produced by a projectile a few to several times more massive than that of Imbrium. The more ancient and large Procellarum basin cannot (yet) be shown to be of impact origin. There are three end-member flux possibilities. First, these older basins, or at least some of them, could have been the earliest but nonetheless integral part of the Nectarian–Early Imbrian cataclysm, with ages in the 3.90 to ~ 4.0 or 4.1 Ga range. Second, these older basins could have formed roughly uniformly in time between crustal completion at ~ 4.4 Ga and Nectaris formation at ~ 3.9 Ga, be unrelated to the Nectarian–Early Imbrian cataclysmic phase, and indeed represent a tail end of background heliocentric accretion. Third, these basins could have all formed very early after lunar crustal formation, and all substantially predate Nectaris.

[35] The Nectaris basin was arbitrarily chosen as a stratigraphic divide (it happens to be appropriately mappable from Earth). There is no fundamental geological 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. This, in turn, suggests that the second and third possibilities, which require some change coincident with the Nectaris event, are not likely.

[36] It has long been known that there is a dearth of impact melt rock samples from the lunar crust with crystallization (hence impact) ages in excess of ~ 3.92 Ga [e.g., *Turner*, 1977; *Hartmann*, 1980; *Ryder*, 1990]. Many rocks of different kinds have been affected in some way by impact heating in the period ~ 3.8 – 3.9 Ga [*Tera et al.*, 1974]. More recent attempts to find older, pre-Nectarian samples, such as would be predicted to occur at the Apollo 16 site, have failed to identify older impact melts of any composition [e.g., *Swindle et al.*, 1991; *Dalrymple and Ryder*, 1993, 1996; *Cohen et al.*, 2000; *Dalrymple et al.*, 2001].

[37] Feldspathic granulitic impactites, which also have an impact origin (in many cases a multiple impact history), provide information on the early history of the lunar crust. Nearly all of these formed in feldspathic KREEP-poor or KREEP-free crust, and all are contaminated with meteoritic siderophile elements. For some the clast-matrix textures demonstrate an impact-produced assemblage followed by thermal metamorphism, whereas others have been inferred to be of impact melt origin [e.g., *Cushing et al.*, 1999]. Their thermal metamorphism suggests that they were heated near to the surface and formed in small craters (<90 km diameter) rather than basins [*Cushing et al.*, 1999]. Quite possibly, the metamorphism took place in the central uplift of such craters [*Gibson et al.*, 2001]. Nearly all of these feldspathic granulitic impactites have heating ages in the 3.8–3.9 Ga range. But a few do have older ages, for example, 78155, 4.22 Ga [*Turner and Cadogan*, 1975] and 78527, 4.15 Ga [*Dalrymple and Ryder*, 1996]. Thus these granulites provide

evidence for some impacting during this deep Hadean interval, as expected, but not evidence for a continually resetting, destructive, basin-forming impact era. The presence of ancient mare-like volcanic rocks among pre-Nectarian age samples [e.g., *Dasch et al.*, 1987; *Papike et al.*, 1998] is also most consistent with the concept that most of the pre-Nectarian basins do not predate Nectaris itself by more than a few tens of millions of years.

[38] Meteoritic siderophile abundances in ancient highlands rocks inferred to be Nectaris and Imbrium ejecta itself are low and much less than 1% chondritic equivalent [Ryder, 1999]. Much of this component is cryptic in the feldspathic granulites, and little is in the ferroan anorthosite and feldspathic aphanitic melt component that dominates these ancient rocks, such as assemblages in the feldspathic fragmental breccias at the Apollo 14 Cone crater and the Apollo 16 North Ray crater. A lunar crust continuously impacted at the Nectarian–Early Imbrian rate for 500 million years would contain a considerable meteoritic siderophile component. The low abundances actually present suggest a postcrustal production flux averaging $\sim 10^{11}$ – 10^{12} g/yr, depending on what depth they represent, again, unless the impactites were largely lost instead of accreting. Spectral evidence for an essentially intact lunar crust [e.g., *Bussey and Spudis*, 2000; *Tompkins and Pieters*, 1999] 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 [Hörz et al., 1976].

12. Ancient Impact History of the Moon

[39] The mass accretion constraints combined with those from geochronology and geochemistry are consistent with a basin-era flux as drawn in Figure 4d (curve R), with all the basins, including South Pole–Aitken, at less <4.0 Ga. This is consistent with the inference that at least nine of the Nectarian basins were formed in a very short interval of perhaps 3.89–3.90 Gyr (Table 2). Postulating older ages for basins requires some valid explanation for the absence of more ancient impact melts in the sample collections. So far this has not been forthcoming, and the elimination of old impact melt ages by shock heat resetting [Hartmann, 1980; Hartmann et al., 2000] would have the related effect of turning the bulk of the lunar highlands into impact melt, categorically not the case. The limited range of impact melt ages cannot be assigned to the biased sampling of a single event, such as Imbrium, because the melt rocks represent a wide diversity of geological environments, chemical compositions, targets, projectiles, and distinct ages [Wilhelms, 1987; Swindle et al., 1991; Dalrymple and Ryder, 1993, 1996; Ryder, 1994; M. D. Norman et al., Targeting the impactors: Signatures of highly siderophile elements in lunar impact melts from Serenitatis, submitted to *Earth and Planetary Science Letters*, 2001]. For example, the poikilitic boulders sampled extensively at the Apollo 17 landing site are inconsistent with an Imbrium origin, either directly or indirectly, given the physical characteristics of the rocks and the units from which they must have been derived, more than 1000 km from the Imbrium target. The melt rocks found in the North Ray crater samples, from beneath the Cayley at the Apollo 16

landing site, as well as the coarser poikilitic impact melt rocks from the Cayley plains are geologically improbable as being of Imbrium melt origin. The Apollo 16 poikilitic impact melt rocks might have been delivered during the Imbrium event.

[40] The lunar highlands crust as a whole is isostatically compensated, yet the impact basins show thinned crust and a lack of compensation; even the oldest, largest basin, South Pole–Aitken, is not completely compensated [Neumann et al., 1996]. This lack of compensation is consistent with an age for the basins rather younger than the crust itself, after the Moon had cooled somewhat. Finally, there is evidence from nonlunar meteorites for a preponderance of reset ages in the same ~ 4.0 – 3.8 Ga period [Bogard, 1995]. This inference of a lunar bombardment history is directly testable with a sample return from the Moon, for instance, focused on determining the ages of Orientale and South Pole–Aitken [e.g., *Duke et al.*, 2000].

13. Terrestrial Hadean Impact Environment and Benign Implications for the Origin of Life on Earth

[41] The implications of the lunar record for the terrestrial record inferred in this paper are straightforward: the bombardment of the Earth in the later Hadean was not as intense cumulatively or even in the very latest heavy bombardment interval (~ 3.8 – 3.9 Ga) as many authors have supposed. The Earth was not continually subject to ocean-evaporating, Earth-sterilizing conditions for 500 million years.

[42] The terrestrial impact record for the Hadean is obtained by scaling from that for the Moon. If the scenario of Figure 4d reasonably represents the lunar record, it implies that the Earth went through a similar but scaled up cataclysmic set of events in the period ~ 4.0 to 3.80 Ga, preceeded by a comparatively quiet period in which the impact levels of the cataclysm were not exceeded after ~ 4.4 Ga or perhaps 4.3 Ga. This record has not yet been recognized from the Earth itself, and indeed events as late as 3.85 Ga have not yet been identified [Ryder et al., 2000; Koeberl et al., 2000; Anbar et al., 2001; Mojzsis and Ryder, 2001]. During the cataclysm the Earth would have undergone events of an order of magnitude larger than that of the Moon, and many more of them. According to Zahnle and Sleep [1997], hundreds of objects like the Imbrium and Orientale impactors must have struck the Earth during the basin-forming era. Nonetheless, an Imbrium-sized impactor scaled to terrestrial collision energy had only 1% of the energy needed to evaporate Earth's oceans, assuming an ocean mass similar to today's and that 25% of the energy of such an impact was partitioned into the ocean [Zahnle and Sleep, 1997] (a model assumption of unknown validity). Such an impact would have vaporized only the upper few tens of meters of ocean by heating from above by an atmosphere of hot silicate. Even impacts orders of magnitude larger would have been far from sufficient, boiling off a few hundred meters. Ocean-vaporizing impacts were considered rare after 4.4 Ga in the estimation of Zahnle and Sleep [1997]; the lunar record suggests that they may have been absent.

[43] Life is unlikely to have arisen in such an exposed environment as a surficial aqueous one, and there is cer-

tainly no evidence that it arose in one. Instead, life may have first formed in a hydrothermal system, consistent with evidence that the most primitive lifeforms were thermophilic or hyperthermophilic, with photosynthesis and its necessary near-surface environment a rather later development. Thus early life may have been comparatively oblivious of nonglobally evaporating/sterilizing impact events. Impacts during the Nectarian–Early Imbrian cataclysm on Earth would have had several positive effects, apart from the generally acknowledged introduction of possible organic nutrients to the Earth: Impact set up numerous hydrothermal systems in a wide variety of styles and environments, potentially beneficial to life [e.g., Ryder, 1991, 2000; Kring, 2000], and cumulatively added energy that warmed up the ocean in general. An impact capable of sterilizing the Earth's oceans did not necessarily occur after ~4.35 Ga.

[44] Life on Earth might have originated during this comparatively quiet period from 4.35 to 4.0 Ga, or it might have required the arrival of the late cataclysm to provide the appropriate environment. Without further information on the life-forming process, both should be considered valid possibilities. There were oceans on the Earth at 4.4 Ga (although we do not know that they were continuously in existence from then until 3.85 Ga) [Wilde *et al.*, 2001; Mojzsis *et al.*, 2001], so invoking any specific time for life's origin between 4.4 and 3.85 Ga is compatible with the terrestrial record. However, the common claim that life emerged quickly after the last sterilizing impact has no basis in the Earth's impact record as extrapolated and scaled from that of the Moon. The time frame is as yet unknown.

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