The Bombardment History of the Moon and the Origin of Life on Earth

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Abstract**—Life on Earth probably evolved between the Moon-forming impact ~ 4.5 billion years ago and the earliest evidence for life on Earth ~ 3.8 billion years ago. Whether the heavy bombardment of the Earth during this period frustrated or promoted the origin of life is uncertain. However, estimates of the extent and importance of the role of bombardment could be improved if we had better contraints on the time-dependence of the bombardment, and specifically on whether there was a spike in the bombardment rate ~ 3.85 billion years ago. We review the evidence in the on-going debate about the existence and extent of such a spike, or late heavy bombardment (LHB). We briefly summarize our analysis of the crater counts in the oldest lunar basins and explain why our analysis does not support the LHB hypothesis. We also describe how corrections for saturation effects, undetected old basins and the assumption of constant impact rates made in our analysis, all have the effect of making the case against the LHB more robust.**

I. PLANETARY ACCRETION → EARLY BOMBARDMENT → LATE BOMBARDMENT? → LIFE

The Sun, like other stars, formed during the collapse of an over-dense clump in a molecular cloud in the plane of the Galaxy. This collapse and the concomittant formation of an accretion disk took about $10^5 - 10^6$ years as the Sun went through the earliest T-Tauri stages of star formation: FU-Orionis, strong-lined T-Tauri, classical T-Tauri, then weak lined T-Tauri stage (e.g. Hartmann 2000, Gaidos 2005, Zahnle et al 2007).

Cosmochemists date the origin of the Solar System by the age of the oldest, most refractory solids found in meteorites: calcium-aluminium rich inclusions $t_o = 4.56745 +/- 0.00035$ billion years ago, “Ga” (Amelin et al 2009). In the early stages of star formation, dissipation due to magnetic turbulence and viscosity in the mid-plane of the dusty proto-planetary disk, leads to gravitational clumping and the formation of planetesimals. A few tens of Moon-to-Mars-sized planetesimals, or planetary embryos, form within the interval $10^5 - 10^6$ From $10^7 - 10^8$ years these planetary embryos scatter and collide as the most massive begin to dominate the distribution during a period of oligarchic growth (Kokubo & Ida 1998, Thommes, Duncan & Levison, 2003, Chambers 2004, Raymond 2004, Kokubo 2007, Armitage 2007). This picture is based on numerical simulations and is supported by the ~ 3 Myr timescale for the disappearance of near-infrared excesses seen in the spectra of young stars (Mamajek 2004, Hillenbrand 2006). This disappearance of the near-IR excess traces the dissipation of the inner gaseous and debris disk for the < 1.5 AU region where terrestrial planets are thought to form around solar mass stars. Cosmochemical evidence based on the composition of the Earth and other bodies in the Solar System supports these models and observations. Thus, current evidence suggests that the Earth and the other rocky planets formed by accretion from the dust, planetesimals and planetary embryos in a proto-planetary disk during a ~ 90 million year period from ~ 4.57 Ga to ~ 4.48 Ga.

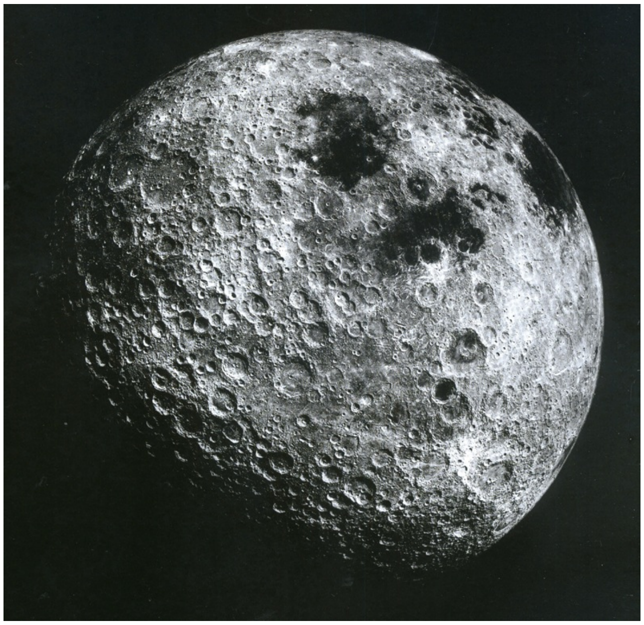

Fig. 1. The density of craters on the surface of a body in the Solar System is a proxy for the age of the surface. The heavily cratered highlands of the Moon are older than the lunar mare which have a lower crater density. We use the crater density within the largest lunar basins to obtain their relative ages. When combined with the absolute ages of a few large basins, we reconstruct an estimate of the integral of the bombardment rate as a function of time (Fig. 3). Image: NASA Apollo 16 metric camera frame AS16-M-3025.

The impact that formed the Moon 90 ± 20 Myr after t_o or $t_{Moon} = 4.48 \pm 0.02$ Ga (Halliday 2008) is generally recognized (somewhat arbitrarily) as either the end of the accretion of the Earth, or the beginning of the early heavy bombardment. This giant impact is widely considered to have given rise to the ejection of enough mass into orbit to form a ring of debris that subsequently accreted into the Moon beyond the Roche limit (Cameron 1991, Canup & Asphaug 2001, Canup 2004, Armitage 2007).

The gravitational energy and heat of accretion resulted in a magma ocean on the newly-formed Moon that cooled quickly and crystallized to form the early lunar crust containing ferroan noritic anorthosite dated at 4.46 ± 0.04 Ga (Norman et al 2003). With a crust in place, the Moon became a palimpsest or bombardometer, capable of recording and, at least partially, preserving large impacts for billions of years.

A. Earliest Life on Earth

Evidence for anything during the first billion years of Earth's history is sparse and controversial. Thus, the evidence for the earliest life on Earth is, unsurprisingly, controversial. Mojzsis et al (1996) and McKeegan et al (2007) interpret isotopic fractionation of carbon 12 and 13 in rocks from Akila Island, Greenland as evidence of life before ~ 3.83 Ga. van Zuilun et al (2002), Lepland et al (2005) and Nutman & Friend (2007) challenge this interpretation. Rosing (1999) finds light carbon isotopic evidence for life before ~ 3.7 Ga. The presence of 3.8 Ga banded iron formations in Isua, Greenland, may be related to microbial oxidation of ferrous iron (Konhauser et al 2002). Evidence for the oldest putative microfossils at ~ 3.46 Ga (Schopf and Packer 1987) has also been challenged (Brazier et al 2004), while the biogenic interpretation of ~ 3.5 Ga old stromatilites (Walter et al 1980, Allwood et al 2006) seems fairly secure.

It is important to realize that terrestrial life got started before these dates. How much earlier is uncertain, but since the record is sparse, life could have originated substantially earlier, possibly not long after the Moon-forming impact. Summarizing these uncertainties Lineweaver & Davis (2005) estimate that life has been on Earth for $4.0^{+0.4}_{-0.2}$ Ga. This time interval, from 4.4 to 3.8 Ga, was also a time of heavy and rapidly decreasing (not necessarily monotonically decreasing) bombardment of the Earth. This temporal overlap has led to speculations about possible links between meteoritic bombardment, early earth environments, and the origin of life (Brack 2008, Furukawa 2009, Pasek 2007, 2008). What role, if any, did large impacts play in frustrating or promoting the origin of life?

4.4 Ga the Moon was ~ 10 times closer. Therefore tides were ~ 1000 times larger. Instead of 2 meter tides every 12 hours, there were 2 kilometer tides every 6 hours. There was no oxygen in the atmosphere and no UV-absorbing ozone. The consensus seems to be that the moon-forming impact was large enough to sterilize the Earth. Whether subsequent smaller impacts had that ability is more controversial (Sleep et al 1989, Ryder 2002, 2003, Abramov and Mojzsis 2008a, 2008b).

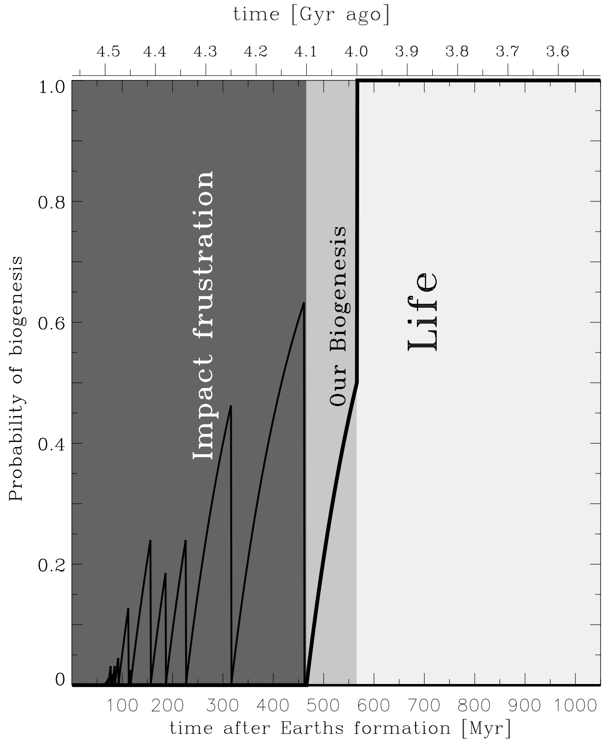

Fig. 2. After the sterilizing impact that formed the Moon about 90 ± 20 Myr after the formation of the solar system (Halliday 2008), a heavy but decreasing and stochastic bombardment lasted for a few hundred million years probably frustrated the origin of life on Earth. Eventually, the molecular evolution that led to life as we know it, was able to squeeze through the thermal bottlenecks produced by impacts (however see Abraomov & Mojzsis 2008a,b). Figure from Davies & Lineweaver 2005.

Because of the larger gravitational focusing of the Earth as well as the resultant increased velocity of Earth impactors Hartmann et al (2000) estimated that the Earth experienced ~ 10 impacts by objects more massive than any that struck the Moon. Byrne (2007) sees evidence for an early lunar near-side megabasin ($D \sim 6000$ km) from an impactor large enough to sterilize the Earth (Sleep et al 1989, Sleep & Zahnle 1998). Putting these results together implies that ~ 10 impacts could have frustrated biogenesis on the early Earth. Maher & Stevenson (1988), Sleep et al (1989), Zahnle & Sleep (1997) Sleep and Zahnle (1998) and Davies & Lineweaver (2005) have explored the impact frustration of life and conclude that life could have originated, been wiped out, originated again and been wiped out repeatedly (~ 10 times?) during the ~ 600 Myr period after the Moon-forming impact (see Fig. 2).

As an added possible complication Arrhenius & Lepland (2000) suggest that the bombardment history of the Moon was so local that it does not necessarily represent the bombardment history of the Earth. However, evidence linking the lunar and terrestrial bombardment rates may be forthcoming (e.g. Trail et al 2007).

II. The Late Heavy Bombardment Hypothesis

A. *Impact breccias*

Absolute age determinations of the largest lunar basins by dating impact breccias returned by Apollo missions in the late 60's and early 70's found dates that clustered around 3.7-3.9 billion years ago. These dates led to the hypothesis of the late heavy bombardment – a spike in the lunar bombardment mass flux during this period (Tera et al 1974). Subsequent work has confirmed this clustering (e.g. Dalrymple & Ryder 1993, Norman et al 2006). However, impact breccias may be biased by their collection on the near-side equatorial regions which may be unrepresentative of the entire Moon in being dominated by a small number of the largest, most recent near-side impact basins.

B. *Glass spherules*

Instead of dating macroscopic rocks (impact breccias) one can also date microscopic glass spherules in the lunar soil. Ar-Ar dating of Apollo 12 and 14 regolith glass spherules shows no pronounced clustering between $3.7 - 4.0$ Ga (Culler et al 2000, Levine et al 2005). Rather, Culler et al (2000) Fig. 2 indicates a broad peak near 3 Ga and both papers show peaks during the most recent 0.4 Ga. The disagreement between the impact breccia dates and the glass spherule dates is difficult to explain. Perhaps glass spherule dates trace the flux of smaller impactors while impact breccia dates trace the flux of larger impactors. Or perhaps glass spherule dates are less biased by astronaut rock selection. In either case, the glass spherule dates do not confirm or provide support for the LHB hypothesis.

C. *Lunar meteorites*

Lunar meteorites that have fallen on the Earth probably come from all over the lunar surface and therefore, as a group, should not be biased geographically. The dates of lunar meteorite impact-melt clasts (Cohen et al 2000) are distributed in age quite broadly and show little pronounced clustering between $3.7 - 4.0$ Ga. Few are older than ~ 4 Ga. Cohen et al (2000) interprets this as support for the LHB. Kring (2008) writes: "The dearth of impact ages > 4 Ga among lunar meteorites and within the Apollo and Luna collections implies that all of the basins including those in the Pre-Nectarian Period were produced in the same narrow window of time 3.84-4.05 Ga."

However, an alternative interpretation of the lunar meteorite dates is that 1) their most important feature is the absence of a pronounced peak between $3.7 - 4.0$ Ga (consistent with glass spherule dates), and therefore they do not support the LHB. 2) the relative dearth of lunar meteorite ages older than ~ 4 Ga can also be explained by a selection effect associated with the preferential burial of the oldest surfaces (Chapman et al 2007). That is, just as on Earth where the oldest surfaces have been largely buried, incompletely "gardened" or obliterated, the oldest surfaces on the Moon may also be largely buried. Evidence for a heavier bombardment earlier than 4 Ga would then be largely buried. The lunar meteorites were preferentially flung off from the top 1 or 2 km's of the lunar surface and do not sample very efficiently deeply buried (5 or 10 kms) older surfaces. The thickness of the lunar megaregolith may be 10's of kilometers (Wilhelms 1987, Heiken et al 2001). Gardening implies hoeing or plowing which brings buried material to the surface. It suggests a level of upheaval that might not allow burial to remove all traces of an old surface. Chapman et al (2007) point to this issue as the most important one in trying to explain the dearth of early evidence. Although impact "gardening" keeps some fraction of older material near the lunar surface, the average age of material is older as you go deeper. More work needs to be done to quantify ejecta blanket burial, and the incomplete impact "gardening" of the lunar surface. If burial is important enough, it would explain the dearth of evidence from the current surface, for a heavy, pre-4 Ga bombardment (however see Norman et al 2007 for impact breccia dated at 4.2 Ga).

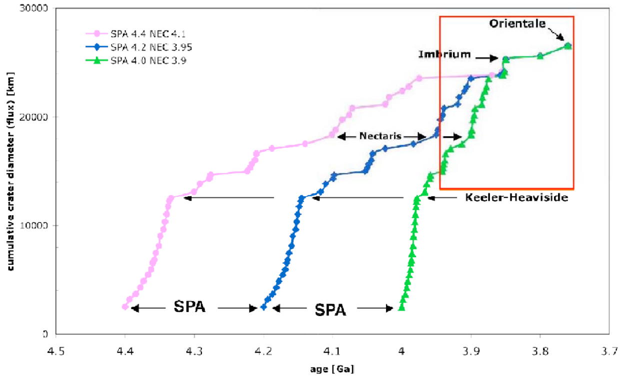

Fig. 3. Cumulative diameter of lunar basins. Crater densities within the basins are used to assign relative ages to the basins. The ages of Orientale and Imbrium are used to give an absolute calibration to the relative ages of the youngest basins. The plausible range of the absolute ages of South Pole Aitken (SPA) and Nectaris are expressed by the three assumptions that produce the three different curves plotted. The y-axis is the cumulative basin diameter of the largest lunar basins ($D > 300$ km) as a function of their age. Cumulative crater diameter is a proxy for accreted mass (Cintala & Grieve 1998). As shown in Fig. 4, these curves are the integral of the impact rate or the mass accretion rate. Thus, the steepest positive slopes of these cumulative curves tell us where the impact rate is the highest. If there were a spike in the impact rate at $\sim 3.85 \pm 0.1$ Ga (see boxed area), these curves would be steepest in that time frame. If we accept the Imbrium and Orientale dates (also used to argue for the LHB hypothesis) then the slope from 3.85 to 3.75 Ga is the flattest (and most reliable) part of this plot, and excludes any spike at that time. *The steepest part of the plot is the earliest part.* Young ages for Nectaris and SPA can steepen the entire plot but do not change the relative steepness (which is a measure of the relative impact rate). If Nectaris and Keeler-Heaviside are young and SPA is very old (a scenario not shown here) then this plot would not significantly undermine the LHB hypothesis.

III. Analysis of Crater Densities in the Largest Lunar Basins

We have described our analysis of crater densities in the largest lunar basins in Norman & Lineweaver (2008) and Lineweaver & Norman (2008). Following Wilhelms (1987) we were able to use crater densities ($D > 20$ km) inside the largest lunar basins ($D > 300$ km) to establish the relative ages of lunar basins. We pinned the relative age

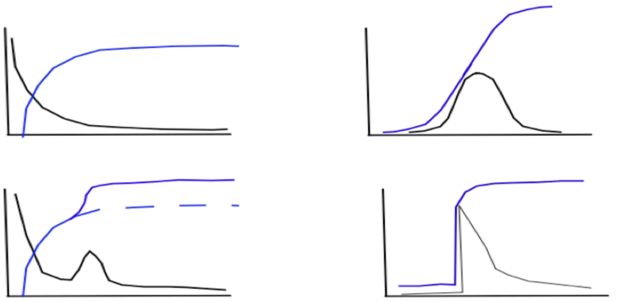

Fig. 4. Decreasing bombardment rates and monotonically increasing cumulative mass. In these four plots, let the x-axis be time, from the origin of the Moon, until today. Let the y-axis for the black curves be the impact rate (either diameter of impacts per unit time dD/dt, or mass accreted per unit time, dM/dt). Let the monotonically increasing blue curves be the cumulative diameter of the basins on the Moon, D(t) which is a proxy for the cumulative mass deposited $M(t)$. That is $D(t) = \int_{t=0}^{t} \frac{dD}{dt} dt$ or $M(t) = \int_{t=0}^{t} \frac{dM}{dt} dt$ where $\frac{dD(t)}{dt} \propto \frac{dM(t)}{dt}$. Consider the exponentially falling impact rate in the upper left (black curve). The resulting cumulative mass (blue curve) increases rapidly in the beginning and then levels off because the bombardment rate is so low at late times. Since the largest impacts are the rarest (and the largest contributors to the total mass) small number statistics for these largest objects will produce the largest variability – producing spikes and troughs in the impact rate around some overall average that is declining. Consider the case of a late heavy bombardment hypothesized to be a $\sim$ 100 Myr spike in the impact rate centred about 3.85 billion years ago (shown in the lower left panel). Such a spike would increase the slope of the blue cumulative mass curve and lead to a higher normalization. The dashed line shows the cumulative curve without a spike. For context, the upper right panel shows a gaussian impact rate and the blue shows the cumulative mass (i.e. the integral of a gaussian). If the spike has a very sudden onset (lower right panel), the cumulative curve is very steep. These curves provide the context for understanding the cumulative diameters of lunar basins as a function of time, shown in Fig. 3

scale to absolute ages using the ages of Orientale, Imbrium ($t_{Orientale} = 3.75$ Ga, $t_{Imbrium} = 3.85$ Ga) and plausible age ranges for Nectaris and South Pole Aitken (SPA) $(t_{SPA}, t_{Nec}) = (4.4, 4.1), (4.2, 3.95)$ or $(4.0, 3.9)$ Ga. Our main result is shown in Fig. 3. Figure 4 provides a conceptual context for interpreting Fig. 3.

A. Corrections

Wilhelms (1987, p 157) discusses the incompleteness of the number of oldest basins. He writes: “Procellarum, South Pole Aitken, and at least 14 now-obliterated basins formed between crustal solidification and the oldest of the 28 pre-Nectarian basins”In Fig. 3, there are 16 basins between SPA and Keeler-Heaviside. The oldest of the 28 pre-Nectarian basins is Al-Khwarizmi/King and it is the second point from the left (the leftmost point is SPA). Wilhelms’ estimate means that we probably should add at least 14 basins between SPA and Al-Khwarizmi/King. Adding 14 basins to this part of the plot steepens the initial part of the curve substantially and creates much stronger support for the idea that the steepest part of the curve (and therefore the time of heaviest bombardment) occurs before the hypothesized LHB whose time frame is indicated by the box in the upper right (3.8 ± 0.1 Ga) of Fig. 3.

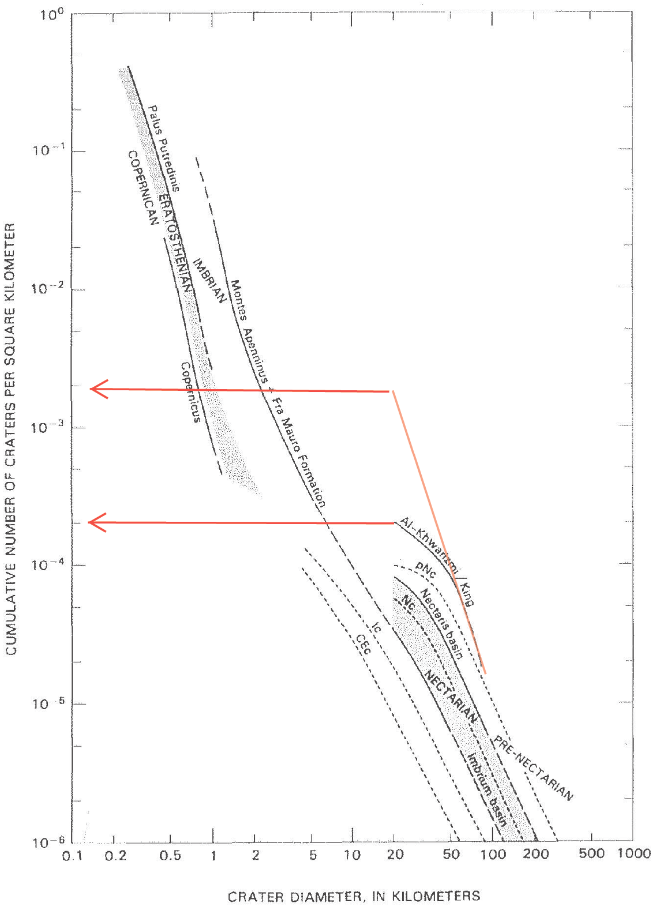

Fig. 5. Crater densities inside the oldest basins are underestimates since, with increasing basin age, saturation effects become more important. For example, in this plot modified from Wilhelms 1987, we expect the cumulative crater counts of the very old Al-Khwarizmi/King basin to increase along the nearly vertical slope of the red line – as we compute the cumulative number of craters within Al-Khwarizmi (starting with the largest ones with $D \sim 250$ km and then including progressively smaller ones) the number goes up, but instead of following the red line (which leads to a cumulative number of a few times 10^{-3} as indicated by the upper red arrow) it bends over for crater diameters less than about 80 km and leads to a cumulative number about an order of magnitude smaller (horizontal red arrow).. This is because small craters are more easily obliterated by subsequent impacts. For the old Al-Khwarizmi/King crator, this saturation effect can lower the crater density (= cumulative number of craters of $D > 20$ km) by a factor of approximately ten (shown by the difference in the y-axis values indicated by the upper and lower horizontal arrows). When a constant bombardment rate between SPA and Nectaris is used to convert crater densities to absolute time, the effect of not correcting for this saturation is to make the earliest part of Fig. 3 less steep. Thus, if we had corrected for this effect, (while conditioning on one of the three SPA ages considered here) the computed absolute ages of the oldest basins would be closer to the age of SPA, which would produce an even steeper curve between SPA and Keeler-Heaviside than we have already.

SPA is so obliterated that it is plausibly and probably the case that many impacts half the size of SPA and of the same age would not have been detected. It is uncertain whether Wilhelms (1987) is including these in his “at least 14 now obliterated basins”.

Another improvement to Fig. 3 can be made by iterating between the initial average bombardment rates used in our analysis (see Norman & Lineweaver 2008), the associated absolute ages (which determine how steep the curve is) and then back to a new estimate of the bombardment rates, which then would yield new absolute ages. Although such an analysis is beyond the scope of this paper, it is straight-forward to estimate that the steepest parts of the curves in Fig. 3 would produce the highest new estimates of the bombardment rates, which would shorten the time interval between Keeler-Heaviside and SPA, which would then steepen the curve in this time interval, and thus be in conflict with the relatively low bombardment rate at t_{SPA} in Fig. 6.

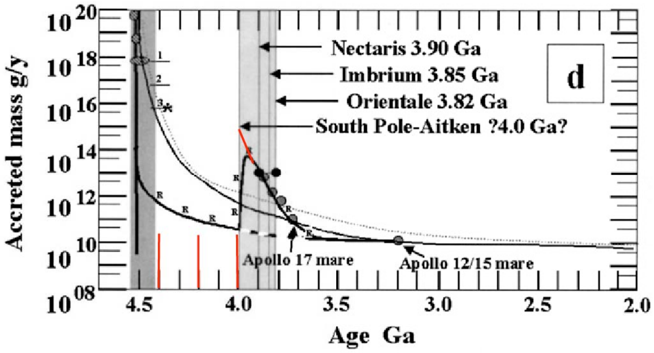

Fig. 6. Ryder's (2002) preferred model of the LHB, adapted from his Fig. 4d which he described as a "cataclysmic impact episode that includes all the observed basins, preceded by a long period of relative impact quiescence. The curve does not have to be so extremely low in the period 4.4 - 4.0 Ga..." Ryder's cataclysm occurs at $t_{LHB} = 3.9 \pm 0.1$. Three vertical red lines in the lower left indicate the 4.2 ± 0.2 Ga estimate of the age of SPA used in the three models in Figure 3. Ryder has assumed that the age of SPA is 4.0. Even if we assume Ryder's $t_{SPA} = 4.0$ Ga, Fig. 3 indicates that there is no increase in the impact rate after t_{SPA} (as postulated by Ryder) since the slope of the cumulative curve is steepest at t_{SPA} and does not steepen appreciably after t_{SPA}, which is required by Ryder's model. This is true independent of the value of t_{SPA}. In the $t_{SPA} = 4.0$ Ga model, Fig. 3 suggests that if we accept the decrease in the impact rate from 3.9 to 3.7, then the data suggests that the earlier impact rate is even higher shown by the diagonal red line....which is strongly inconsistent with the pre-Nectarian part of Ryder's model.

IV. FIGURE 3 AND RYDER'S LHB MODEL

Ryder (2002, 2003) was a leading advocate of the LHB. His preferred model is shown in Fig. 6. There are minor differences between our analysis and his. He assumes $(t_{Orientale}, t_{Imbrium}) = (3.82.3.85)$ Ga while we use $(3.75, 3.85)$ Ga. Even if we accept a young age of 3.90 Ga for Nectaris, there is 80 Myrs and 12 basins between $t_{Orientale}$ and $t_{Nectaris}$. There are at least 30 (+ 14) pre-Nectarian basins. Thus, the 80 Myr time interval between 3.90 and 3.82 Ga contains $1/4 - 1/5$ of the impacts $(12/56 \sim 1/4 - 1/5)$ in the time interval between $t_{Orientale}$ and t_{SPA}. Thus, using the average impact rate between $t_{Orientale}$ and t_{SPA}, the pre-Nectarian impacts would occupy 240 or 320 Myr before 3.90 Ga, which would then extend the beginning of the spike of the LHB to $4.14 - 4.21$ Ga. When a "spike" lasts ~ 400 Myr, it looses its spikiness.

According to Ryder (2002) there are several other pieces of evidence in favor of the LHB. One is that with a lunar crust "fairly intact" by 4.46 (based on ferroan noritic anorthosite dates of Norman et al 2003) and assuming SPA of 4.0 Ga, there do not seem to be any more impact melt rocks older than 3.92. This is strange since we know from Fig. 3 that there were more large impacts before Nectaris than afterwards. Burial (or not complete gardening) is probably the answer. Although the vertical structure of the lunar regolith and megareolith is poorly known, studies of the geological cross-sections of the Apollo landing sites suggest (Heiken et al 2001) that a thick layer (many hundreds of meters? or several kilometers?) of pre-Nectarian debris has buried (and early impacts have obliterated) many or most of the earliest basins. Burial also solves the problems that Ryder raises regarding the lack of meteoritic material from a 4.4 to 3.8 Ga heavy bombardment and the lack of pre-Nectarian impact melts. Chapman et al (2007) suggest that more work needs to be done to model burial to be more confident in this scenario.

Although an age of 4.46 Ga is obtained for the oldest ferroan anorthosites /crustal formation (Norman et al 2003), this does not necessarily imply that the Moon became an all-impact-preserving bombardometer after 4.46 Ga. It is plausible that for much of the surface of the Moon, an on-going bombardment broke through the crust, was a source of local heating that prevented the crust from maintaining the structural features required to hold a recognizable impact crater for 4 Ga. Ferroan anorthosite (early lunar crust) is found in scattered fragments, not as an intact sheet at the surface over large areas of the Moon that would necessarily hold recognizable basin walls (Hawke et al 2003).

Ryder raises the question, where is the impact melt from the many pre-Nectarian basins? A possible solution is that these basins haven't been sampled by near-side equatorial Apollo missions and/or they have been buried by subsequent impact ejecta.

Ryder (2002, 2003) has argued that the impact rate responsible for the basins in the 100 Myr interval 3.85 ± 0.05, is too high to be extrapolated back to the origin of the Moon without exceeding the total mass of the Moon. Any bombardment rate must pass beneath the asterisk labeled "3" in Fig. 6. This mass flux argument may be flawed if, for the largest impacts (which are supposed to contribute most of the mass) an increasingly large portion of the impactor mass is not accreted.

Ryder favors a young age for SPA, 4 Ga and suggests that the pre-Nectarian 28 (+ 14 Wilhelms 1987) are all part of the LHB. However, his excess mass flux estimate depends strongly on a young age for SPA. Even if we accept an age of 4.0 Ga for SPA, the steepest part of the curve in Fig. 3 is between 4.0 and 3.95 Ga which pre-dates the age range usually given for the LHB. Ryder's preferred model for the LHB (Fig. 6) depends on an early ($\sim$ 4 Ga) date for SPA. However, the fact that the steepest part of the curve in Fig. 3 is the earliest part, suggests that, within the timeframe sampled by pre-Nectarian basins, the impact rate kept getting higher into the past. In other words, Fig. 3, even in the $t_{SPA} = 4$ Ga case, supports the diagonal red line superimposed on Fig.

6. In order to have a "spike" or a "cataclysm" one must have some evidence of a decrease in the impact rate before t_{SPA}. We do not see evidence for this in our analysis. If we do not accept Ryder's preferred age for SPA of ~ 4 Ga, then the LHB "spike" begins to look much less like an outlier (after a relatively quiescent period) and more like a spikey general decrease in the accretion/impact rate between 4.4 and 3.8 Ga.

A single important observation that will have the most impact in constraining the early bombardment history of the Moon and Earth will be the dating of SPA.

V. CONCLUSION

Our preliminary analysis of the ages (given current uncertainties) and cumulative impact diameter of lunar basins (Fig. 3) does not support the late heavy bombardment. Our analysis does not indicate a pronounced spike in the bombardment rate at 3.85 ± 0.10 Ga. Corrections to our analysis to compensate for saturation effects in the oldest craters, the inclusion of an estimated ~ 14 pre-Al Khwarizmi/King obliterated basins to the analysis and an iterative approach to determining the impact rate, all support the idea that the highest impact rate pre-dates the LHB date of 3.85 ± 0.1. The decrease in the number of lunar meteorites with ages older than ~ 4 Ga is probably best explained as a selection effect of lunar meteorites (and glass spherules) sampling the current surface of the Moon, not the largely buried, older than 4 Ga surface. The evidence for a pre-SPA or pre-4 Ga heavy bombardment has been buried by its own, and subsequent impact blankets.

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