The Inner Solar System Cataclysm, the Origin of Life, and the Return to the Moon

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Summary: There has long been debate over the early cratering history of the lunar surface. While some argue that the data are consistent with a steady decline of impact rate, others interpret the data as indicating a cataclysmic bombardment of the Moon at around 3.9 Gyr (the lunar cataclysm or late heavy bombardment). Evidence now suggests that this cataclysm affected the entire inner Solar System. The cataclysm occurs at a time just before the earliest evidence of life on Earth, and could have had important implications for the origin and early history of life. The cataclysm leads to much lower impact rates on the early Earth than the steady decline model, opening up the possibility that life could have started very early. Alternatively the cataclysmic bombardment may itself have played a role in the origin of life, through delivery of organics to the Earth, creation of temporary environments, or transferring material between planets.

Keywords: The Moon, Impacts, Cataclysm, Heavy Bombardment, Origin of Life.

Introduction

The Moon has the most pristine planetary surface in the Solar System, and provides our best-preserved record of the history of the early Solar System. The samples returned by the Apollo and Luna missions have made it possible to provide precise dates for impact events on the Moon and thus provide a calibration of cratering rates that currently provides our only way of dating other solar-system surfaces. However, there remains considerable uncertainty about the early impact history of the Moon. A preponderance of impact melt dates around 3.9 Gyr has led to the suggestion that there was a cataclysmic bombardment, or spike of impact rates on the Moon, at this time [1,2]. This is known as the 'lunar cataclysm' or 'late heavy bombardment'. Others have argued that the data are consistent with a steady decline of impact rates with time [3,4]. The latter argue that the records of earlier impacts may have been erased by subsequent events and that the limited coverage of the Moon's surface by Apollo and Luna (limited to the equatorial near-side), has led to a record biased by a few events such as the Imbrium basin impact.

To remove this selection effect, an analysis of lunar meteorites was carried out [5] showing similar evidence for a cataclysm from meteorites presumably originating over the whole lunar surface. Evidence has also been found that the cataclysm extended to other inner Solar System objects. The only sample of ancient Mars we have, the Martian meteorite ALH84001 (other Martian meteorites are much younger) shows an Ar-Ar age indicating a shock event at 3.92 Gyr [6] coincident with the lunar cataclysm. Evidence for the impact cataclysm is also reported in ordinary meteorites [7]. Recently, depth profiling of Hadean zircons from Western Australia [8] has shown in four out of six zircons, overgrowths with ages of 3.94-3.97 Gyr, with no further overgrowths between this and the zircon core age (>4.2 Gyr in some cases). This provides evidence for the same cataclysmic bombardment having occurred on the Earth.

While this inner Solar System cataclysm remains controversial it clearly has important implications for the early history of the Earth and the Solar System as a whole. Important questions are:

- What could have caused the cataclysm?
- What effect did it have on Earth and particularly on the early history of life?

The Cause of the Cataclysm

A recent study [9] has shown that the population of impactors responsible for the cataclysm was different from that of subsequent impacts. The size distribution of craters in the lunar highlands and old Mars plains is different from that in younger surfaces. The older craters are consistent with the size distribution of main-belt asteroids. The younger craters similarly match the size distribution of near-Earth asteroids. The difference in the size distribution of main-belt and near-Earth asteroids can be understood as due to the operation of the Yarkovsky effect [10] that causes smaller bodies to preferentially migrate into near-Earth space.

Proposed mechanisms for the cataclysm, include the collisional break-up of a large main belt asteroid [11], the loss of a fifth terrestrial planet outside the orbit of Mars [12,13], or events triggered by the formation of Uranus and Neptune [14,15]. However, there are problems with all these mechanisms. The asteroid break-up mechanism requires much more massive asteroids than those currently in the main belt. The fifth terrestrial planet mechanism is difficult to reconcile with the current state of the inner Solar System. It tends to lead to loss of other planets, and leaves the remaining planets with higher orbital eccentricities than observed today. The formation of Uranus and Neptune would have to occur at a very late time to account for the cataclysm.

A new model [16,17] explains the cataclysm as the result of the readjustment of the orbits of the giant planets in the outer Solar System. On this model the Solar System would have originally formed with Saturn at an orbital period less than half that of Jupiter, and with Uranus and Neptune at substantially lower orbital radii than at present. Interaction with a disk of planetesimals would cause migration of the orbits until Saturn and Jupiter crossed their 1:2 mean motion orbital resonance. The resonance crossing would have caused the orbits to become eccentric, and interactions between the planets would lead to the planets rapidly migrating to their current heliocentric distances and eccentricities. The process would lave have led to a massive delivery of planetesimals to the inner Solar System, and to disruption of the asteroid belt. The model can account for a number of features of the cataclysm and the Solar System that are otherwise difficult to explain.

- It explains the ~700 Myr delay between the formation of the Solar System and the cataclysm. This is the time that the orbits of Jupiter and Saturn take to reach the mean motion resonance.
- It explains the eccentricity of the giant planet orbits, when they would be expected to form with coplanar circular orbits.
- It explains the location of the orbits of Uranus and Neptune. It would be hard to form giant planets directly at this location because there would be insufficient material to accrete a planetary core.

Effects on Earth

The occurrence of the cataclysm at ~3.9 Gyr is just before the earliest evidence of life on Earth. Stromatolites [18,19] and microfossils [20,21] are found in rocks of about 3.5 Gyr age in Western Australia, and suggest that life was well established at this time. Carbon isotope ratios indicative of life, in rocks from Greenland [22], may push the record back to more than 3.8 Gyr although this is more controversial [23]. If the high impact rate at 3.9 Gyr is part of a steady decline in impacts, this could leave very little time for to get started. This rapid appearance of life on Earth has been used as the basis of statistical arguments that life may be common in the Universe [24], or may have an extraterrestrial origin [25].

It has been estimated [26] that an impact of an asteroid of mass 1.3 x 10^{20}kg (about 440km in diameter) would completely evaporate the Earth's oceans destroying any life. An asteroid of 1.1 x 10^{19}kg (about 190km in diameter) would be sufficient to evaporate the photic zone (the upper 200m of the ocean where photosynthesis would be possible). The mass of the impactors responsible for the Orientale and Imbrium basins on the Moon are estimated to be 1.4 x 10^{18} and 2 x 10^{18}kg [26]. This corresponds to asteroid diameters ~100km. On a steady decline model it is therefore highly likely that the Earth was hit by one or more of these sterilising impactors in the period before 3.9 Gyr [27]. This leads to the scenario of "impact frustration" of the origin of life [28] where impacts of large objects limit the origin (or re-origin) of life to near the end of the bombardment.

On the cataclysm hypothesis, however, the peak of the bombardment occurs at about 3.9 Gyr. The largest impactors on the Moon at this time are the ~100km objects responsible for the maria basins. While the larger size of the Earth, means that statistically it is likely to be hit by somewhat larger objects at this time, it is unlikely that any of these would be the 50-100 times more massive objects required to sterilize the planet, and quite possible that no impacts large enough to sterilize the photic zone occurred. On the cataclysm hypothesis then the environment would be relatively benign [29] and life could well have survived through the cataclysm period. As there is evidence from analysis of Hadean zircons that oceans and continents were present on Earth as far back as 4.4 Gyr [30, 31], life could have originated at any time back to 4.4 Gyr ago. With good evidence for life only being found at 3.5 Gyr, the time available for the emergence of life is ~0.9 Gyr, and life's appearance may not be as rapid as some previous studies have assumed [24, 25].

Analysis of the "tree of life" derived from ribosomal RNA has led to the suggestion that the common ancestor of all life was a hyperthermophile (an organism adapted to very high temperatures) [32]. This could indicate that life began in a high temperature environment, but an alternative interpretation is that the impacts during the cataclysm could provide a high-temperature bottleneck [33] through which only hyperthermophiles survived. Yet another hypothesis is that of "thermoreduction" [34, 35] in which the prokaryotes are a more streamlined form of life that evolved from a eukaryote-like ancestor to cope with the stresses of high temperatures. Again, the cataclysm could provide the high temperature conditions needed for this to occur.

An alternative view of the importance of the cataclysm might be that the cataclysm played a direct role in the origin of life itself. This could have happened in a number of ways. The bombardment of impactors could have brought organic material to Earth [36, 37] that provided the building blocks for the origin of life. It could have brought a key component needed for life such as molecules with a preferred handedness [38, 39] needed to account for the homochirality of biological molecules. The impacts could have created temporary environments, such as hydrothermal systems, that were important for the development of early life [40].

Another way in which the cataclysm could have been involved in the appearance of life on Earth is through the transfer of life between planets. In this model life originated on another planet, most probably Mars, and was transferred to Earth carried in rocks ejected during impacts [25, 41]. Such transfer of life between planets would be most likely to occur during the cataclysm.

The Return to the Moon

Determining the precise impact history is therefore fundamental to a number of key issues in understanding the early history of our Solar System, and of life on Earth. We need to determine whether the impact history is described by the cataclysm or steady decline model or something more complex. Determining the width and shape of the cataclysm spike could help us to distinguish between different models of the cataclysm. And we would like to have a better understanding of what effect the cataclysm might have had on Earth.

The answers to all these questions could be found on the Moon. We need to go back to the Moon and finish the job that was started by Apollo. NASAs new "Vision for Space Exploration", as well as other lunar exploration programs by other countries will provide the opportunity to do this. By collecting and accurately dating a much wider range of lunar samples we should be able to definitively tie down the early impact history of the Moon. The new NASA Exploration Systems Architecture will provide the ability to go anywhere on the Moon, including the polar regions and the far-side.

We may also be able to use the Moon to learn more about the Earth's history. It is estimated that the lunar regolith should contain 7ppm of material transferred from Earth [42], mostly during the cataclysm. If we can find and study this material it could help to fill in a part of Earth's history totally missing from the geological record on our own planet. It may also provide the missing clues to the origin of life on our own planet.

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