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Earth and Planetary Science Letters 130 (1995) 69–73

EPSL

Role of major terrestrial cratering events in dispersing life in the solar system

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Received 5 August 1994; accepted after revision 6 November 1994

Abstract

The larger and most energetic cratering events from comet and asteroid collisions with the Earth are probably associated with ejection of solid material faster than escape speeds every 100 Myr or so. Metre-sized boulders, we estimate, may have been ejected directly into Venus-crossing and perhaps Mars-crossing orbits from comet impacts at higher speeds and of larger mass, at least on 10 occasions in the last 3.5 Ga. Subsequent close encounters with Earth can also enable slower boulders to reach Mars-crossing orbits. Orbit perturbations from Mars and Jupiter would then have sent a fraction of the boulders to the outer planets and their icy satellite systems. In the so-called late bombardment epoch at 3.9 Ga, when primitive life was developing, ejection-causing impacts were much more frequent, at ~ 30 per 0.1 Ga, yielding an increased probability of distributing seeds of terrestrial biology to the outer regions of the solar system.

1. Introduction

Geological evidence suggests that life arose in the so-called late accretion stage of the planet as soon as the impact-dominated environment allowed. The earliest indirect evidence of life is in the form of an enhancement of ^{12}C relative to ^{13}C in the oldest sedimentary rocks [1,2], dated at about 3.9 Ga (1 Ga = 10^9 yr), when lunar crater data show that the late bombardment by asteroids and comets was still under way. This provokes the idea that life may have arisen even earlier, perhaps as soon as the Earth had acquired its atmosphere, and cometary fragments containing prebiotic matter were able to land intact at the surface. Here, we ask whether the violent impacts that characterised the late accretion phase, after life began, could have led to sizeable rocks (bolides) being expelled entirely from the Earth and reaching remote planetary and satellite surfaces with spores and other microscopic life forms intact. Transfer of biomaterial has been discussed by Melosh [3], his interest having been triggered by the discovery of SNC meteorites that originated on Mars. Melosh infers from spallation theory that an impacting asteroid could, in general, lead to the expulsion of boulders of typical sizes of about 1 m [3]. Such boulders that acquire speeds in excess of ~ 11 km s^{-1} would escape the Earth's gravity.

It is now generally believed that the early bombardment of the Earth by comets from ~ 4 Ga ago led to the acquisition of oceans and an atmosphere, which were necessary prerequisites

Elsevier Science B.V.
SSDI 0012-821X(94)00232-0

for life. The protracted period of violent bombardment that followed (4 Ga–3.8 Ga) has spawned the idea of 'impact frustration of life', although it may be that primitive life arose and survived despite the impacts. The progress and development of terrestrial life could, however, have been constrained by the continuing (if spasmodic) comet and asteroid bombardment, as well as by the widespread occurrence of seismic and volcanic activity that would have been prevalent at this time. During this period life may have arisen independently in diverse locations and natural selection would have favoured phenotypes resilient to extreme conditions. The development of taxonomic diversity, as seen in fossil archaea in the 3.5 Ga Apex cherts of northwestern Australia, had certainly arrived by the dawn of a quiescent period a few hundred million years later [4].

2. Impacts on the early Earth

The atmosphere of the early Earth is now thought to have been oxidising, so the old idea of complex, pre-biotic chemicals developing readily in ponds of organic soup, as suggested by Miller and Urey [5], appears far less probable. Indeed, Chyba and Sagan [6] have recently estimated that cometary impacts brought in a larger total quantity of certain pre-biotic compounds than would have formed under conditions prevailing in terrestrial ponds. Impacting material came not only from comets and meteorites, however. Fractions of 'recent' terrestrial meteorites have been identified as coming from the Moon and from Mars, these objects being thought to have been ejected into space via impacts on the parent bodies, and later to have been collected by the Earth. A similar process would also have occurred during the late planetary accretion phase, but with a greatly enhanced frequency. In this context we note that the material of the 'SNC' meteorites from Mars is largely unshocked, suggesting that these were surface rocks ejected on impact, probably accelerated by the mass of strongly shocked spall from deepest layers.

Similar ejecta arising from impacts on Earth would have to overcome a thicker atmosphere and stronger gravity. We follow earlier arguments [3,7] to estimate the minimum size of an impact crater for ejection to occur. On dimensional arguments, the impact energy has to suffice to vaporise the impactor (and some of the target) and to accelerate material to escape speeds in the presence of atmospheric resistance. From numerical simulations a factor 4 over the minimum is found to give ejection of most of the material:

$$mv^2 > 4m_*\left(v_{esc}^2 + 2H_{vap}\right) \tag{1}$$

where H_{vap} = the vaporisation energy per unit mass; v_{esc} = the escape velocity from the Earth; and m_* = the mass of atmosphere swept up with the ejecta.

Taking m_* as the total mass lying above a tangent plane at the point of impact [7] is too conservative. Large impacts blast upwards through the entire atmosphere and, if the crater dimension substantially exceeds the atmosphere scale height, m_* is the mass lying directly above the crater area [3]. With appropriate scaling [6], this translates to a crater diameter that must exceed a critical value, D_*, given by:

$$D > D_* = 100(v/20\,\mathrm{km\,s^{-1}})^{-0.3}\mathrm{km} \tag{2}$$

This includes a factor 1.65 by which the final crater diameter is larger than the initial transient crater [3]. We note that the median Earth-impact speeds of asteroids and comets are $v = 17$ and 23 km/s, respectively [8]. From studies of lunar craters, the cumulative number of comet and asteroid impact craters integrated over the Earth's surface up to a diameter, D, at time t can be expressed as:

$$N(D,t) = \left[At + K(\exp(t/t_B) - 1)\right](D/D_*)^{-1.8} \tag{3}$$

where A and K are constants and t_B is a timescale which is either 0.144 Ga or 0.22 Ga, according to two possible fits to the cratering data [8]. If $D_* = 100$ km, the corresponding values are $A = 129$, 99 $\mathrm{Ga^{-1}}$ and $K = 2.97 \times 10^{-9}$, 4.53×10^{-5}, when the impact rates are corrected for the greater mass of the Earth (compared to the moon) and t is measured in Ga. From Eq. (3)

it is easily calculated that the impact rates $\mathrm{d}N/\mathrm{d}t$ at $t = 4.0$–3.9 Ga are typically 100 times higher than at the present time $t = 0$.

It may be that only the higher velocity impacts give sufficient amounts of escaping solid ejecta. Spallation theory gives ejecta speeds decreasing steeply with distance from the impactor; $v_{ej} \simeq v(a/r)^{2.87}$ for distances exceeding impactor radius a, but Melosh [3] uses an observational figure $v_{ej} \simeq 0.35 v_{esc}$ that includes subsequent acceleration. On this basis only the 15% of comet impacts with velocities exceeding $v_* = 30$ km/s give substantial amounts of escaping solid ejecta.

Whether these comets or asteroids, ≥ 10 km in size, land in the sea or on dry land seems unimportant [9]: the water is blasted aside and fast ejecta emerge before it returns. However, there is a tendency for ejecta to be more focused and slower from sea impacts, analogous to the SL9 impacts on Jupiter.

We see that the frequency of impacts producing craters with $v > v_*$ and $D > D_*$ at the present epoch is $A = 15$–20/Ga. This agrees roughly with the frequency of biological extinction spurts in the geological record, including the famous K/T boundary, which is attributed to a comet impact. That boundary is plausibly connected with the 180 km diameter crater at Chicxulub (Yucatan), which resulted from an impact sufficiently powerful to blast off a part of the atmosphere and also leave a high load of dust in the upper atmosphere, with consequent climatic perturbations that may have contributed to species extinction [10–13]. It is possible that the Melosh argument leads to too optimistic an estimate and that D_* is, say, 3 times larger for significant ejection to space. However, Eq. (3) still implies $A = 3$–4/Ga; so 10 or so ejection events must surely have occurred throughout the quiescent period (< 3.5 Ga) of terrestrial life, and about 30 ejection events per 0.1 Ga at 3.9 Ga.

3. Fate of rocks escaping the Earth

With ejection speed $v > v_{esc}$ as in (1), some dust and debris from larger impacts must escape into interplanetary space. However, most would remain around 1 AU from the sun, where they have a chance of re-accretion by the Earth and Moon. The cross-section for accretion is:

$$\pi d_o^2 = \pi R^2 \left(1 + v_{esc}^2/u^2\right) \tag{4}$$

where u = the initial excess velocity over the escape speed; and R = the radius of the Earth. In comparison, the cross-section for a strong perturbation by a velocity increment, ΔV, is larger, with impact parameter, d, given by:

$$d^2/d_o^2 = v_{esc}^4 \left\{4 - (\Delta V/u)^2\right\} / \left\{4 \Delta V^2 \left(u^2 + v_{esc}^2\right)\right\} \tag{5}$$

with $\Delta V < 2u$.

To reach Mars or Venus requires $\Delta V > 5.5$ and 2.6 km/s, respectively. The maximum Earth ΔV given by (5) is $2u$, so most debris ($u < 3$ km/s) would need successive scatterings to reach the outer solar system planets and satellites; even reaching Mars may have a low probability per individual object or bolide. Alternatively, an impact may be so energetic that debris could, indeed, reach Mars or Venus in a single shot; this can be estimated by replacing v_{esc} in (1) by v_{esc} + 5.4 or 2.6 km/s, respectively, implying slightly larger crater sizes and lower frequencies by factors of 0.65 and 0.8, respectively, using the D dependence of Eq. (3). Moreover, the fraction of ejecta from surface material close to the impactor (at 10–30% of impactor radius) has higher speeds — up to 0.85 v_{obs} [3] — and could transit directly to Mars.

These higher energy cratering impacts would have ejected rocks of the SNC type of 1 m in size [3], with cracks harbouring bacterial spores, and thrown even larger amounts of dirt and sediments containing viable bacteria out into space. Heat sterilization depends on separation from the gaseous fireball. The ejecta and fireball burst through the atmosphere in a second, then the expanding hot gas accelerates. With contact times of a few seconds to 1 min, thermal sterilization would occur from depths of 1 mm to 1 cm [3]. Most of the escaping material is initially in Earth-crossing orbits, with a finite probability of being accreted by the Earth or the Moon. By equation (5), the cross-section for a large perturbation, $\Delta V = u$ for $u = 0.2–0.3 v_{esc}$, is 10–20 times that for accretion. Taking randomness of perturbation direction into account, roughly 10% are re-accreted and 90% would receive successive gravitational kicks that would expel them into Venus- and Mars-crossing orbits. Steel [14] has made sample calculations of terrestrial planet accretion rates; in comparison with orbit diffusion via successive perturbations in the inner solar system it would appear that Venus accretes some 1% and Mars 10 times less. Some end up in the Sun, but the majority are kicked further out.

4. Survivability of trapped cells

For an object in a Mars- or Venus-crossing orbit, the mean timescale for planetary accretion may be estimated as $\sim 10^7$ yr [14]. Survivability of any life for this length of time in the solar environment will depend on the size of the harbouring bolide, as well as the proximity of resident bacteria/bacterial spores to the surface. It is known that bacteria, even in a vegetative state, can survive high doses of ionizing radiation, upwards of a megarad [15,16]. Many desiccated species can survive vacuum conditions, and indeed spores tend to be hardier at far subzero temperatures [17]. A thickness of bolide material of less than 1 cm would suffice to protect interior microorganisms from lethal doses of solar X-rays and protons at typical energies ~ 100 MeV [18]. With overlying material of 1 g/cm^2, megarad doses of ionising radiation are delivered in 10^5 yr, in which time some 1% or so of the orbiting bolides would be accreted by Mars and Venus.

Survivability of microorganisms at blast-off and landing also imposes constraints. Surface layers of the bolide would be ablated, due to atmospheric heating, at both ends of a journey but microbes buried within objects would be expected to remain cool and viable in a high fraction of cases. In this context, it is relevant to note that the SNC meteorites show rather little evidence for shock alteration of their structure. The larger impacting bolides that strike either rock or ocean surfaces at speeds much in excess of 10 km/s would be mostly vaporised. On the other hand, meteorite fragments are often found that have maintained cold interiors. It appears that fracturing of rocky bolides produces a cloud of debris with increased surface area that can be decelerated to low speeds, due to atmospheric friction [19]; some interior fragments can thus land relatively unscathed on satellites and planets endowed with atmospheres. For the case of airless, icy satellites with low escape speeds (e.g., 2 km/s for Europa of Jupiter's system, or 0.2 km/s for Saturn's Enceladus) survival would appear quite probable for bolides that strike the surface in overtaking collisions at low relative speed. The ice fractures and spalls under 100 bar pressures, well below Melosh's (1988; [3]) estimate of 10^3 bar pressure limit, which would be reached by only a fraction of the impactor before it shatters. Bolide fragments containing viable biomaterial can thus become buried in ices at the surface.

5. Conclusion

The mass of escaping ejecta from the presumed 10 km comet that caused the 180 km Chicxulub crater, with a radius of roughly 10 km and 1 m deep, amounted to ~ 300 Mm^3, of which one third may have been rock and 10% higher-speed ejecta that could have transited directly to Mars. It may haven taken 10 Ma to impact Mars but, following the arguments of section 3, the probability is not 'exceedingly low' [3] but 0.1–1%.

The survival and replication of microorganisms once they are released at destination would depend on the local conditions that prevail. Although viability on the present-day Martian surface is problematical, Earth-to-Mars transfers of life were feasible during an earlier 'wet' phase of the planet, prior to 3.5 Ga ago [20]. The Martian atmosphere was also denser at that epoch, with several bars of CO_2, thus serving to decelerate meteorites, as on the present-day Earth. Since the reverse transfer can occur in a similar manner, early life evolution of the two planets may well have been linked. The transfer of life-bearing material to the icy satellites of Saturn and Jupiter and beyond is, of course, less probable. However, given the range of impact/dynamical situations that would have arisen over a billion year period in the Earth's early history, it would seem quite conceivable that terrestrial life forms have reached the remotest icy satellites of the solar system, including Triton and Pluto. The icy satellites are of particular interest because some are thought to have possessed — and may indeed still possess — liquid H_2O interiors. At early epochs, when such water was only some 100 m below the surface and surface cracking arose via tidal flexure or bolide impacts, the transported microbes (and spores) would have reached the interior oceans. Wherever the ambient conditions permitted, such life might have taken root, and even survive to the present day. *[UC]*

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