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The violent environment of the origin of life: Progress and uncertainties*

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Abstract—Dating of terrestrial fossils and returned lunar samples reveals that the origin of life on Earth occurred not in a quiescent, peaceful environment, but rather in a violent, impact-ridden one. This realization has important consequences. On the one hand, sufficiently large and fast impactors can erode planetary atmospheres, and the very largest of these may have sterilized the surface of the Earth. In this regard, deep-sea hydrothermal vents become especially interesting for the history of early life, as they provide an environment protected against all but the greatest impact devastation. At the same time, impactors would have been delivering key biogenic elements (such as carbon and nitrogen) to Earth's surface, and (with much greater difficulty) intact organic molecules as well. Estimates of the various sources of prebiotic organics suggest that the heavy bombardment either produced or delivered quantities of organics comparable to those produced by other energy sources. However, substantial uncertainties exist. After reviewing the current understanding of the role of the heavy bombardment in the origins of life, a number of remaining key uncertainties are considered, and attempts are made to both quantify their magnitude and point to means of resolving them.

INTRODUCTION

BOTH MICROSCOPIC FOSSILS and fossil stromatolites (macroscopic structures formed by sediment-trapping algae) require life to have originated on Earth prior to 3.5 thousand million years (Gyr) ago (SCHOPF and WALTER, 1983; WALTER, 1983). Controversial evidence for biologically mediated carbon isotope fractionation suggests that life may already have existed by 3.8 Gyr ago (SCHIDLOWSKI, 1988). The terrestrial origin of life must have therefore coincided with the last stages of the heavy bombardment of the inner Solar System, during which those planetesimals remaining from planetary accretion were largely swept up or scattered.

This bombardment is known primarily from samples returned from the Moon (BVSP, 1981). These data are shown in Fig. 1. Here, the abscissa shows the age of a given surface, determined by the radioactive dating of lunar samples. For each surface, the total number of craters larger than a certain diameter (in this case, larger than 4 km) is then found by crater counting, and the result expressed in terms of a crater density (numbers of craters per km^2). As Fig. 1 makes evident, the early bombardment declined in intensity (roughly exponentially) through two to three orders of magnitude, dropping to its present comparatively low level by about 3.5 Gyr ago.

Similarities in plots of crater frequency as a function of crater diameter for the Moon, Mars, and Mercury have been interpreted to imply that all these worlds were bombarded by the same population of objects in early Solar System history (STROM, 1987). It seems certain that the early Earth (and Venus) were also subject to this bombardment, even though subsequent geological activity on these planets has obliterated its most obvious traces. (A signature of the heavy bombardment on ancient Earth may remain in the abundances of the highly siderophile elements in the terrestrial mantle, however; see CHOU, 1978, and CHYBA, 1991a). The cratering experienced by the Moon may therefore be scaled to that expected on Earth, taking into account the latter's larger surface area and gravitational cross sections. Such scaling leads to a number of remarkable conclusions.

IMPACT FRUSTRATION OF LIFE'S ORIGINS

The largest lunar impact feature identified with confidence is the South Pole–Aitken basin on the lunar far side, with a diameter $\gtrsim$2200 km (BELTON et al., 1992). The largest nearside basin, Mare Imbrium, has a diameter of 1160 km. Such giant basins correspond to impacting asteroids or comets with masses in the range $\sim 10^{18}$–10^{19} kg ($\sim$50–150 km in radius). Since the Earth's gravitational cross section for typical Earth-crossing asteroid velocities is some twenty-four times that of the Moon, Earth must have collected many more such large objects than did the Moon. In fact, statistically speaking, Earth should have been struck by about seventeen objects larger than the South Pole–Aitken impactor (CHYBA, 1991a). We are therefore in the frustrating position of knowing that early Earth must have suffered many such enormously destructive events but being required to rely on small-number statistical extrapolations from the Moon to estimate their frequency. Yet the absence of a comprehensive geological record of ancient Earth leaves us no choice: Knowledge of the early Earth, at least in this regard, requires extrapolation from our knowledge of the Moon and nearby planets.

What does the lunar cratering record tell us of the environment of early Earth? Extrapolations of the kind just described imply that Earth was struck by $>10^4$ objects as large or larger than comet Halley (Halley is equivalent in volume to a sphere about 5 km in radius). Objects of this size are in the approximate size range necessary to cause impact erosion of the terrestrial atmosphere (MELOSH and VICKERY, 1989),

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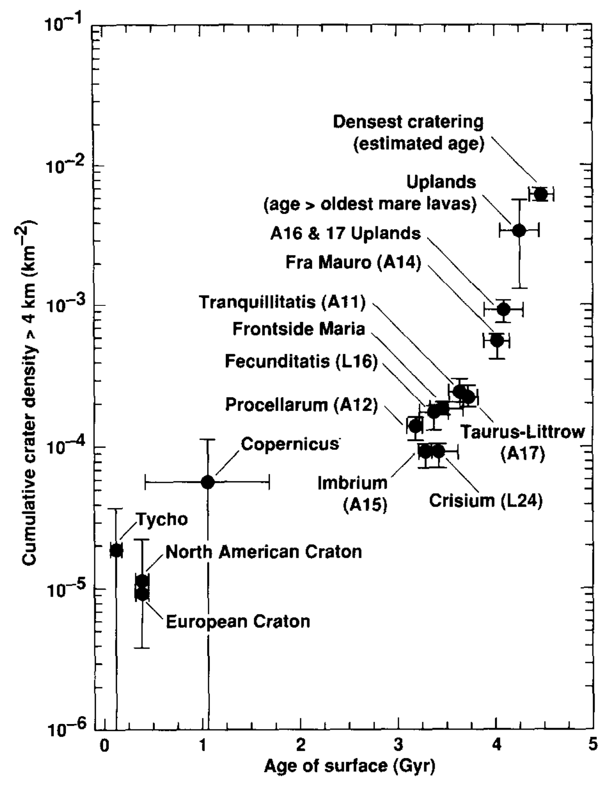

FIG. 1. Cumulative lunar crater density (for craters with diameters greater than 4 km) as a function of surface age. Parenthetical labels refer to US *Apollo* or Soviet *Luna* sample return missions. After BVSP (1981).

provided they have sufficiently high velocities (around 25 km s^{-1}). Nearly all asteroidal-type objects would have struck Earth at velocities below this, but something like half of short-period comet collisions would have been sufficiently fast to erode the atmosphere (CHYBA, 1990). The Earth could have easily lost a contemporary atmosphere's worth of atmospheric gases in this way, but this result is strongly dependent on still poorly constrained parameters, especially the exact size and velocity distributions of early impactors (CHYBA, 1991a).

More dramatically, it appears likely that prior to ~3.8 Gyr ago, Earth was struck several times by objects with impact energies sufficient to vaporize the entire terrestrial ocean. As shown by SLEEP et al. (1989), such gargantuan impacts result in the formation of a 100 bar globe-encircling rock vapor atmosphere, which persists for several months before cooling sufficiently to condense out. During this time, the entire ocean is evaporated, leading to a runaway greenhouse effect that holds Earth's surface temperatures to ~2,000 K for thousands of years. Such impacts would effectively heat-sterilize the Earth to a depth of some hundreds of meters. Whether this is equivalent to sterilizing the Earth depends on whether life originated and had time to evolve into protected niches at depths sufficient to be insensitive to the surface heating (and otherwise not fatally influenced by altered surface conditions). Were the origins of life still ongoing at the time of such a giant impact, it seems likely that the result would be to reset the clock for life's origins; therefore, there may have been several "impact frustrations" (MAHER and STEVENSON, 1988; OBERBECK and FOGLEMAN, 1989) of the origins of life. (If this scenario is correct, terrestrial life today might be quite different if that final terrestrial impact had missed; "we" might then be the descendants of an earlier, perhaps very different, origin of life.) These recent quantitative results support early post-*Apollo* suggestions that the origin of life on Earth would have had at most several hundred million years between the time of the end of impact devastation and the oldest known fossil record (SAGAN, 1974).

In addition to the few most devastating, ocean-evaporating impacts, Earth would sustain nearly five times more impacts sufficiently energetic to evaporate the ocean's ~200 m thick photic zone. In this kind of milder catastrophe, adverse terrestrial surface conditions would persist for only some 300 y after impact (SLEEP et al., 1989). The outlook of such an impact for obligate photosynthetic organisms would be grim (though some fraction might survive through downward mixing in the boiling ocean). Moreover, statistically speaking, it is likely that a photic-zone-destroying impact would occur subsequent to the final ocean-evaporating impact so that the last catastrophe life on early Earth would have faced was a destruction of the photic zone. All else being equal, this favors the origins of life in the deep oceans, possibly at hydrothermal vents (CORLISS et al., 1981; BAROSS and HOFFMAN, 1985). However, there are arguments that the highest-temperature vents would preferentially destroy, not synthesize, relevant prebiotic molecules (MILLER and BADA, 1988, 1989; BADA, 1991).

It has been suggested on the basis of molecular phylogeny studies (e.g., WOESE, 1987) that archaebacteria are the most "primitive" of extant organisms and that the ancestral archaebacterium was a thermophile growing near the temperatures of boiling water. This is sometimes taken mistakenly as strong evidence for an origin of life at hydrothermal vents. In fact, it is consistent both with such an origin and with a kind of post-origin "bottleneck" during which only those organisms that had evolved into deep-sea niches survived. The hostile nature of Earth's surface during the heavy bombardment is the obvious candidate for the creation of such a bottleneck.

STOCKING THE PREBIOTIC INVENTORY WITH EXOGENOUS ORGANICS

If the heavy bombardment devastated early Earth, it may also have had effects beneficial to the origin of life. "Impacts giveth and impacts taketh away," to take the observation of MCKINNON (1989) about cometary impacts only slightly out of context. There seems to be no question that the early impact environment had this Janus-like nature. [Janus was the Roman solar deity who was the doorkeeper of heaven and patron of beginnings and ends (BULLFINCH 1979). He had two faces, one for the rising, and one for the setting Sun.] At the same time that big impactors were devastating (and at times globally sterilizing) Earth's surface, some of them would have been delivering volatile elements and, much less effectively, organic molecules useful for the origin of life.

While large, fast-moving impactors were eroding the terrestrial atmosphere, their smaller or slower-moving compatriots were successfully delivering water, carbon, nitrogen, and other volatiles. Combining data for terrestrial collision velocities of contemporary Earth-crossing comets and asteroids with data on these objects' elemental compositions, it appears that the competition between impact delivery of new volatiles and impact erosion of those already present strongly favored the net accumulation of planetary oceans by the larger worlds of the inner Solar System (CHYBA, 1990). Indeed, these kinds of estimates are consistent with Earth receiving the bulk of its surface volatiles in this manner (CHYBA, 1991a).

Delivering intact organic molecules to early Earth is more difficult. The idea that early, organic-rich planetesimals may have played a role in the origin of life goes back at least to the beginning of this century (CHAMBERLIN and CHAMBERLIN, 1908). In 1961, J. Oró (ORÓ, 1961) suggested, on the basis of spectroscopic observations of carbon- and nitrogen-containing radicals in cometary comae, that comets may have played a similar role. This suggestion attracted renewed interest with the in-situ discovery of organic-rich grains in the coma of comet Halley (JESSBERGER and KISSEL, 1991, and references therein). Comets may be as much as 25% organic by mass (CHYBA et al., 1990). We have long known that carbonaceous meteorites, and by implication C-type asteroids, are several percent organic by mass (WILKENING, 1978, and references therein).

The problem comes in envisioning ways to deliver these organics to the surface of the Earth intact. Of course, there is no difficulty in the nondestructive delivery of organic molecules to Earth in objects as small as meteorites. The bulk of the mass in potential terrestrial impactors, however, is concentrated in much larger bodies. For extraterrestrial material to have had a substantial influence on prebiotic chemistry, it seems that this reservoir must somehow be tapped. Yet even objects as small as 100 m in radius cannot be sufficiently decelerated by the Earth's present atmosphere for organic inclusions to survive the ensuing impact. Only in hypothetical, dense (~ 10 bar CO_2) early atmospheres could ~ 100 m comets be sufficiently decelerated so that an appreciable fraction of their organics would survive impact (CHYBA et al., 1990).

However, interplanetary dust shed from evaporating comets and colliding asteroids might have provided an important source of prebiotic organics. ANDERS (1989) has estimated the flux of intact organic matter reaching the contemporary Earth in interplanetary dust particles (IDPs). (IDPs appear to be typically $\sim 10\%$ organic by mass; see GIBSON, 1992; and references therein); particles below about 100 μm in radius are sufficiently gently decelerated during atmospheric entry to deliver their organics to Earth more or less intact.) Earth is currently accreting $\sim 3 \times 10^5$ kg yr^{-1} of intact organics in this way (ANDERS, 1989). Scaling this flux back through the heavy bombardment is wrought with uncertainty, but this procedure seems no more dangerous than similar assumptions routinely made in the origins of life field, e.g., the assumption that the lightning energy discharge rate of early Earth was the same as that of contemporary Earth (MILLER and UREY, 1959; CHYBA and SAGAN, 1991). Simply scaling with the population of impactors implied by the lunar cratering record suggests Earth was accreting $\sim 6 \times 10^7$ kg yr^{-1} in IDP organics 4 Gyr ago (CHYBA and SAGAN, 1992).

How does such an exogenous source of organics compare with other, endogenous sources that would also have been operating at that time? A careful, though inevitably incomplete, attempt to draw up a "balance sheet" for the origins of life yields a number of insights (CHYBA and SAGAN, 1992). (Such an attempt represents an updating of the original work by MILLER and UREY, 1959 in this area.) Most importantly, it appears that which sources of prebiotic organics were quantitatively dominant depends strongly on the composition of the early terrestrial atmosphere.

In the event of an early reducing atmosphere, shock synthesis of organics (due to shock production by meteors traversing the atmosphere and post-impact vapor plumes from larger objects colliding with the Earth) are a dominant mechanism. Organic synthesis by ultraviolet light may, in turn, have dominated shock production, especially if a long-wavelength ultraviolet absorber such as H_2S were supplied to the atmosphere at a rate sufficient for synthesis to have been limited by ultraviolet flux, rather than reactant abundance (CHYBA and SAGAN, 1992).

However, it is currently thought that the once-favored reducing atmosphere was not the atmosphere of early Earth. It seems more likely that early Earth had an atmosphere rich in carbon dioxide and nitrogen, an intermediate oxidation state atmosphere (WALKER 1986). In this kind of atmosphere, it is much harder to synthesize organic molecules (STRIBLING and MILLER, 1987). The change from reducing to intermediate oxidation state atmospheres for early Earth is more than just a change in some scientific fashion. Whether early volcanic gases contained carbon in the form of methane (CH_4) or carbon dioxide (CO_2) depended on whether metallic iron remained in the Earth's mantle or whether it had already sunk down to the core. It was once thought that core formation took place slowly, so that carbon could be outgassed as CH_4 for hundreds of millions of years. However, there is now evidence from uranium-lead isotopes, the simplest interpretation of which is that core formation was essentially complete by 4.4 Gyr ago, almost immediately after Earth accreted (NEWSOM and SIMS, 1991). Under these conditions, Earth would have had an intermediate oxidation state atmosphere (MASON, 1991, and references therein). [However, the role impacts may have played in the oxidation state of the early atmosphere is only just starting to be examined. KASTING (1990) has argued that impacts during the first few hundred million years of Earth history may have maintained atmospheric CO/CO_2 ratios greater than unity; impacts of large iron-rich asteroids may also have produced pulses of highly reduced gases (COMMITTEE ON PLANETARY BIOLOGY AND CHEMICAL EVOLUTION, 1990; KASTING, 1990) through equilibration of vaporized iron and elemental hydrogen, carbon, nitrogen, and sulfur.]

In an early intermediate oxidation state atmosphere, atmospheric shocks were probably of little importance for direct organic production. For $[H_2]/[CO_2]$ ratios of ~ 0.1, net organic production was a factor of ~ 500 lower than for reducing atmospheres, with delivery of intact exogenous organics in IDPs and ultraviolet production being the most important sources. At still lower $[H_2]/[CO_2]$ ratios, IDPs may have been the dominant source of prebiotic organics on the early Earth. Therefore, the heavy bombardment of the early inner Solar System appears to have been a significant source of prebiotic organics for early Earth, either by shock-production in reducing atmospheres, or by delivery on IDPs in intermediate oxidation state atmospheres (CHYBA and SAGAN, 1992).

KEY UNCERTAINTIES

The question of the contribution of exogenous organics to the Earth's prebiotic inventory has haunted speculations on the origins of life for nearly a century. Until recently, however, most work in this field typically went little further than noting that comets seemed to be organic-rich, organics were needed for the origins of life, and comets fell on the early Earth, so maybe they were important. Indeed, some work has continued to imply that one simply needs to estimate the total organic content of all infalling planetesimals and take this as the exogenous contribution to the origins of life. Such plausibility arguments, while valuable, are no longer sufficient: Substantial progress may be made, first in ruling out the importance of certain potential mechanisms for a wide range of early Earth conditions and, second, in quantifying (within broad uncertainties) the possible contribution of those mechanisms that remain plausible. In particular, the organics in those impactors too large to be substantially aerobraked or to airburst, representing the vast bulk of the potential exogenous source, should have been pyrolyzed on impact and therefore (barring the invocation of dense early atmospheres, or novel, as-yet unquantified mechanisms) did not substantially contribute to the origins of life on Earth (CHYBA et al., 1990).

Fits to the Lunar Impact Record

One uncertainty that is fundamental to most attempts to quantify the importance of various heavy-bombardment contributions to the prebiotic organic inventory is the choice one makes of analytical fit to the lunar cratering record. There are a number of important uncertainties in attempting to pursue such models. While these uncertainties are now sometimes explicitly acknowledged in the literature, they have often been disregarded, with different authors making particular choices without acknowledgment of alternative possibilities. But as discussed by CHYBA (1990), different fits to the lunar cratering record lead to estimates of terrestrial mass accretion as a function of time varying by a factor ~800 at 4.4 Gyr ago, the time at which the discrepancies are greatest. There it was argued that the most extreme (the highest) of these results (that employed by MAHER and STEVENSON, 1988; see also OBERBECK and FOGLEMAN, 1989) could possibly be ruled out on the grounds of its implications for the terrestrial water inventory. This argument is far from decisive, however, because one may always take the view that the heavy bombardment impactors were simply extremely water-poor. A superior method would be to pursue the approach of SLEEP et al. (1989), who used lunar regolith siderophile abundances to estimate meteoritic infall subsequent to the formation of the lunar crust.

CHYBA (1991a) found that one particular fit to the lunar cratering record, subsequent to ~4.4 Gyr ago, was in good agreement with both lunar and terrestrial geochemical requirements. The terrestrial mantle siderophile abundances appear to reduce the uncertainty in the upper limit in total accreted post-core formation mass to a factor of ~4, with most of this uncertainty stemming from the possibility of whole-mantle mixing. Note that the geochemical constraint provides only a constraint on the integral over time of the heavy bombardment flux (and, rigorously, only an upper limit to this integral; some or even most of the highly siderophile elements found in the mantle could, e.g., be left over from core formation). Therefore, while it certainly may be used to rule out those flux models whose integrals exceed the geochemically derived value, it cannot speak to the details of the time rate of change of the bombarding flux. But it does seem to rule out a 70 m.y. half-life fit to the cratering record (MAHER and STEVENSON, 1988; OBERBECK and FOGLEMAN, 1989). Remaining simple analytical fits in the literature consistent with that record (MELOSH and VICKERY, 1989; CHYBA 1990) differ at 4.4 Gyr by a factor of ~4. Numerical experiments I have performed suggest that a much broader range of constant half-life fits is not consistent with the cratering data.

More sophisticated, variable half-life fits (GRINSPOON, 1988) need to be pursued, however. Since the geochemical constraint is an integral constraint and the cratering data are so sparse, a more elaborate fit with a varying decay "half-life" can certainly not be excluded. To the contrary, some version of the latter is almost certain to prove ultimately correct. Fitting any single decay "constant" to the cratering flux is a procrustean exercise, as the bombardment flux cannot have actually decayed at a constant rate, but must rather have made a transition from rapidly swept-up objects in Earth-like orbits to objects from comparatively long-lived, slowly decaying orbits (WETHERILL, 1977; HARTMANN, 1980). Integrated over time, however, all fits must deliver no more than the same upper limit of mass to Earth.

Finally, it must be noted that the entire interpretation of the heavy bombardment as representing exponentially decaying remnants of planetary formation is questioned by those arguing for a lunar cataclysm (e.g., RYDER, 1990). Were a cataclysm to prove to be the correct interpretation of the lunar cratering record, results given here for terrestrial conditions ~4 Gyr should remain largely unchanged as the lunar data are relatively plentiful back to about this date. Conclusions based on attempts to scale the impactor flux back in time beyond ~4 Gyr ago, however, would be greatly in doubt.

Recently RAMA MURTHY (1991) obtained a much-improved fit to terrestrial excess siderophile mantle abundances by considering an equilibrium core-mantle differentiation at 3000–3500 K. While this approach results in mantle abundances that closely match the observed values for all but the highly siderophile elements (Ru, Rh, Pd, Re, Os, Ir, Pt, and Au; RAMA MURTHY, 1991, explicitly considers only three of these), it fails to reproduce these eight elements' CI relative abundance ratios without an appeal to additional mechanisms. Relative to CI abundances, the highly siderophile elements are present in the mantle at $\sim 10^{-2}$–10^{-1} times the other siderophiles. In the usual picture (CHOU, 1978; NEWSOM and SIMS, 1991), the heavy bombardment delivers the highly siderophile elements in CI abundances and therefore makes little impact on the absolute or relative abundances of the remaining mantle siderophiles, i.e., those which the model of RAMA MURTHY (1991) is best able to explain. In any case, the abundances of highly siderophile elements in the mantle remains useful as an upper limit on the post-core formation input from the heavy bombardment.

Impactor Composition

A critical uncertainty in evaluating the organic influx to the early Earth is the question of the fraction of the heavy bombardment composed of organic-rich bodies (comets and carbonaceous chondrites). None of the data currently available decisively, or even very persuasively, resolves this question (CHYBA, 1987; CHYBA, 1991a). (On the other hand, only a fraction of the heavy bombardment on Earth need have been cometary for the bulk of the terrestrial oceans to derive from a cometary source.) The fraction of the heavy bombardment composed of comets or carbonaceous asteroids is ultimately a free parameter. This uncertainty remains and is fundamental.

In recent work on the prebiotic contribution of meteorites and IDPs, we have simply extrapolated into the past their current organic fraction (CHYBA and SAGAN, 1992). The contribution of meteorites is so negligible that there seems little point in discussing the associated uncertainties. Interplanetary dust particles, however, are potentially the most important source of intact exogenous organics on the early Earth, so it is valuable to examine uncertainties in their contribution in some detail.

Interplanetary Dust Particles

CHYBA and SAGAN (1992), following ANDERS (1989), estimated the contribution of IDPs to the early terrestrial inventory via three key assumptions. The first was that the organic composition of IDPs in the past was that of IDPs today. The second was that the IDP number-mass distribution in the past was the same as that of IDPs today. The third was that IDP flux through time scaled like the lunar cratering record. Each of these assumptions is the most "natural" to make, but each is an assumption based on ignorance. Let us examine each in turn.

ANDERS (1989) cites evidence that the current influx of IDPs is ~10% organic by mass. This is a value midway between what one might expect for cometary and carbonaceous chondritic particles; whether comets or asteroids are the primary source of IDPs remains unclear (BROWNLEE, 1985; SANFORD and BRADLEY, 1989). As typical IDP survival lifetimes in the inner solar system due to collisions and Poynting-Robertson drag are only $\sim 10^4$–10^5 yr (GRÜN et al., 1985; BROWNLEE, 1985), the present organic fraction of IDPs cannot be used to say what was typical far in the past. This question may well turn on past relative abundances of comets, organic-rich asteroids, and organic-poor objects.

The bulk of the mass in the current population of IDPs peaks around 10^{-6}–10^{-4} g, a result that is now widely accepted in the IDP literature (HUGHES, 1978; KYTE and WASSON, 1986; ANDERS, 1989; FLYNN and MCKAY, 1990). However, as the existence of this mass peak sometimes causes confusion, it may be worthwhile to review briefly the reasons for its existence.

A plot of global IDP mass influx per mass interval (in which the mass peak around 10^{-5} g is apparent) derives immediately (HUGHES 1978) from the data for IDP cumulative number flux vs. mass (see, for example, DOHNANYI, 1972, 1978; HUGHES 1978). The latter curve is of the following form (HUGHES, 1978):

$$N(m) \propto m^{1-q}, \qquad (1)$$

where $N(m)$ is the cumulative flux of IDPs with mass greater than m, and q is the mass index. Over the mass range 10^{-13}–10 g, this curve is well known from a combination of spacecraft, radio, and photographic data (DOHNANYI, 1972, 1978; HUGHES 1978; GRÜN et al. 1985). The curve may be extended up to 10^6 g by observations of meteorite fireballs (DOHNANYI 1972; HUGHES 1978) and to higher masses by observations of Earth-crossing asteroids and the lunar impact record (KYTE and WASSON, 1986).

Uncertainties in IDP absolute cumulative fluxes are about one order of magnitude (HUGHES, 1978). At particle masses below about 10^{-6} g, $q \approx 1.6$; between 10^{-6} g and 10^{-4} g, q passes through the value 2 and then climbs to nearly 3 by 10 g (HUGHES, 1978, and references therein). This slope change is important when considering global IDP mass influx per mass interval. This distribution is given by integrating Eqn. 1 over mass, giving a mass flux proportional to m^{2-q}. On a log-log scale, the slope of this curve changes from positive to negative as q passes through 2; there is therefore a peak in the IDP mass input where this transition occurs (around 10^{-5} g).

If one simply extended the power-law distribution of larger impactors down below ~10 g, the mass influx predicted for IDPs would be five to six orders of magnitude smaller than it is in fact observed to be. Should the change in q from 1.6 to 3 over the relevant mass range be expected to have persisted in time? In the absence of an understanding of the origins of IDPs, this question cannot be answered a priori. A constraint, however, is placed by lunar and terrestrial siderophile abundances.

The current terrestrial mass influx from IDPs found by HUGHES (1978) on the basis of meteor observations is in excellent agreement with accretion rates inferred from terrestrial and lunar data. In the case of the Earth, these data are based on siderophile abundances found in deep-sea sediments. These observations have now been extended from the past million years [BARKER and ANDERS, 1968; these authors' estimate of sedimentation rate should be corrected (see KYTE and WASSON, 1986) by the results of KU et al., 1968] to the period between 33 and 67 m.y. ago (KYTE and WASSON, 1986). Similarly, the current net accretion of siderophiles from IDPs is consistent with the micrometeorite component in the lunar regolith (DOHNANYI, 1971; ANDERS et al., 1973). Results from three *Apollo* missions for mare soils vary by only 25% (ANDERS et al., 1973); the present net IDP mass flux therefore appears to have been remarkably constant over the past 3.5 Gyr. (These results have been summarized in tabular form by CHYBA and SAGAN, 1992.)

Because these data take the form of an integral over the IDP size distribution, they cannot be used to prove that the current shape of the IDP flux curve has remained unchanging through time. Moreover, there is no empirical evidence for or against the claim that, prior to 3.5 Gyr ago, the IDP population would have increased proportionally to the cratering flux. If IDPs are the product of cometary evaporation or of asteroid-asteroid collisions, one would expect their number roughly to scale linearly, or as the square, respectively, of the number of such objects in the inner Solar System. This is by no means certain, however, especially because a reliable model must also take loss mechanisms into account (CHYBA and SAGAN, 1992). A safe lower limit for the IDP flux on Earth prior to 3.5 Gyr would seem to be a simple extension of the current flux back into the past. At 4 Gyr ago, the time of relevance to the origins of life, this introduces an uncertainty of about two orders of magnitude into the relevant IDP mass flux.

Finally, one difficulty that, so far, has received little attention is whether IDP atmospheric deceleration is really gentle enough for molecules of evident prebiotic interest to survive. (It is also unknown, and this must not be forgotten, whether IDPs actually contain such molecules or whether the bulk of their organic material is in, presumably, less-interesting kerogen-like heteropolymers.) Models predict cometary IDPs to be typically heated to around 900 K for several seconds during atmospheric entry (FLYNN, 1989). A naive application of thermal decomposition rates for amino acids (CHYBA et al., 1990) suggests these molecules would survive around 800 K for 1 s, but these rates are of dubious relevance to degradation of amino acids in a mineral matrix. [However, it is of interest that the alanine decarboxylation half-life seems to be the same whether performed in aqueous or solid phase (BADA, 1991), suggesting the aqueous phase results may be more broadly applicable than has sometimes been suggested (CHYBA, 1991b).] A need for further laboratory experiments in this area is clear.

Impactor Velocities and Maximum Masses

The total mass $M(t)$ delivered to Earth subsequent to some time t, calculated from the lunar cratering record, depends upon a "typical" impactor velocity v and the mass $m_{\max}$ of the largest impactor used in the calculation. In recent work (CHYBA 1991a), this dependence was found to be

$$M(t) \sim v^{-1.7} m_{max}^{0.46}. \qquad (2)$$

Different choices of crater scaling relationships (see, e.g., BAILEY, 1991) typically vary the exponents in Eqn. 2 by up to several tenths.

Letting the uncertainty for lunar impact velocity range from that appropriate to the slowest plausible impactors (residual Earth-crossers), with $v_\infty \approx 8$ km s^{-1} (WETHERILL, 1977) to SP comets, with $v_\infty \approx 20$ km s^{-1} (CHYBA, 1991a), introduces an uncertainty of a factor of ~4 in $M(t)$. Treating this error and that introduced by different fits to the cratering record as independent, the net error introduced by these uncertainties together is around a factor of 6.

There are also great uncertainties in the largest object that struck the Earth subsequent to 4.4 Gyr ago; as emphasized here in the preceding text, the mass of this object can only be evaluated, at present, via the statistics of small numbers. However, this question is a red herring for the question of the exogenous contribution to the prebiotic inventory. Consider the various exogenous sources that potentially contribute to the terrestrial prebiotic inventory. The contributions of airbursts and comet impact survival employ values of maximum-mass impactors many orders of magnitude smaller than the largest impactors striking the Earth. The contributions of IDPs and meteorites make no reference to $m_{\max}$ at all. The choice of the latter is irrelevant to all these results.

On the other hand, calculations of atmospheric erosion, volatile delivery, and possible post-impact recombination of organics does rely on the value chosen for $m_{\max}$. The uncertainty in $m_{\max}$ for the Moon lies somewhere between the masses of the Imbrium and "Procellarum" objects. [The latter may well not have existed (SPUDIS, 1988), but we include this putative largest lunar basin here in order to maximize our stated error.] This range in basin sizes, 1160–3200 km, introduces a range of error in $m_{\max}$ of a factor $(3200/1160)^{3.4} \approx 30$ since impactor mass varies with post-collapse crater diameter D as $\sim D^{3.4}$. This in turn introduces an error into our estimates of mass flux of a factor $\sim(30)^{0.46} \approx 5$. Combining uncertainties in fits to the cratering record, velocities, and $m_{\max}$ then gives an overall uncertainty in $M(t)$ of a factor ~8, or about one order of magnitude in either direction. It is unwise, and too easy, to lose sight of this uncertainty as one paints images of the early Earth.

Impact Synthesis

GILVARRY and HOCHSTIM (1963) suggested that shock waves from meteoroids traversing the terrestrial atmosphere may have synthesized organics on early Earth. It was first demonstrated in 1970 by BAR-NUN et al. (1970) that shock heating of reducing gas mixtures in the laboratory yielded amino acids. If the atmosphere of early Earth was, in fact, reducing, meteors and post-impact vapor plumes may have been the dominant source of prebiotic organics. However, there remains the absolutely fundamental uncertainty in the oxidation state of the early terrestrial atmosphere. Atmospheric shock production of organics was likely of little quantitative importance in the absence of a reducing atmosphere (CHYBA and SAGAN, 1992).

In addition, there is the question of the importance of post-impact recombination by the material of the projectile itself. Unfortunately, as detailed elsewhere, results of laboratory experiments relevant to this question are, so far, problematic (CHYBA and SAGAN, 1992). Experiments in which target material (such as meteorite samples) are entirely, not just partially, vaporized, in the presence of reducing, intermediate, and oxidizing background atmospheres could be quite informative. It is possible that this mechanism was a major source of prebiotic organics on the early Earth.

Uncertainties in Endogenous Organic Production

To put the uncertainties just detailed into context, it may be valuable to consider the magnitude of some uncertainties typical in estimates of the endogenous contribution to the prebiotic organic inventory. One measure of these uncertainties is the result that recent estimates of energy dissipation by lightning and coronal discharge suggest that for the past forty years, the origins of life community has been overestimating the importance of these sources by one to two orders of magnitude (CHYBA and SAGAN, 1991). Even now, a number of key quantities are inferred from a very limited number of observations, suggesting that the possible contemporary error may remain comparably large. In addition, however, there remains a potentially grave and virtually unquantifiable source of error in these results: One can do no better, at present, than assume that the rate of electrical discharges on the early Earth equalled that of the Earth today.

Similar uncertainties exist for the second key early energy source, ultraviolet light. The evolution of ultraviolet luminosity of G class stars is poorly understood (Zahnle and Walker, 1982). However, this evolution appears to increase ultraviolet fluxes at 4 Gyr ago by about an order of magnitude over those of the present-day Sun (Chyba and Sagan, 1992; this effect coexists with the decrease in overall solar luminosity as one goes back in time). The quantitative implications of decreasing ultraviolet luminosity with time of the main-sequence Sun had not been considered previously by the origins of life community.

Finally, there are undoubtedly other mechanisms for the terrestrial production of organics that have not yet been well quantified. One such example, potentially of great importance, would be the production of organics by Fischer-Tropsch-like reactions involving volcanic gases and fresh-fractured surfaces of xenoliths and basalts (Tingle et al., 1990, 1991). This proposal is all the more intriguing as it would not require an early reducing atmosphere.

In summary, it can be seen that order-of-magnitude uncertainties are typical in the origins of life field. Worse, some uncertainties are, at present, nearly impossible to quantify. This does not mean we have learned nothing from the past thirty years of research. It does mean key facts about the primordial terrestrial environment remain poorly understood. (Most importantly, the oxidation state of the early atmosphere remains poorly constrained. This uncertainty is so central that its implications have had to be confronted at nearly every step throughout the preceding discussion.) But this, after all, is exactly the contribution that planetary science can make to our understanding of the origins of life. In the absence of an extant terrestrial record, we must look outward for knowledge of conditions on the early Earth.

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