IMPACT DELIVERY OF ORGANIC MOLECULES TO THE EARLY EARTH AND IMPLICATIONS FOR THE TERRESTRIAL ORIGINS OF LIFE

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A significant fraction of the Earth's volatile inventory may have been delivered by asteroidal (1) and cometary (2) impacts during the period of heavy bombardment. In addition to simple volatile molecules, ~3 mass % of C–type asteroids (3), and ~20 mass % of comets (4) is in the form of complex organics. This organic component has long led to speculation that impact delivery may also have provided the prebiotic compounds necessary to the terrestrial origins of life (5). The survival of organics in some such impacts is demonstrated by the carbonaceous chondrite meteorites (3). In addition, the correlation of a terrestrially–rare amino acid (α–amino isobutyric acid) with the Cretaceous–Tertiary boundary has been claimed as evidence that some fraction of extraterrestrial organics will survive even major impact events (6). However, a proper treatment of impactor/atmosphere interaction, surface collision, and resulting organic pyrolysis is required to determine whether more than a negligible amount of the total mass of organics present in asteroids and comets incident on Earth survived impact. Here we present the first results of such a comprehensive analysis.

The existence of complex terrestrial microorganisms by 3.5 Gyr ago (Ga), and arguments that impact frustration of the origin of life may have been insurmountable prior to ~4.2 Ga (7), suggest choosing the period 4.3 to 3.7 Ga to assess impact delivery of organics. Taking a 100 Myr cratering time constant, and using the observed Nectarian 30 to 300 km lunar cratering flux (8), a procedure described in (2) leads to an estimate that bodies with radii $\lesssim$30 km delivered $\sim 5 \times 10^{24}$ gm to Earth from 4.3 to 3.7 Ga. If C–type asteroids comprised $\sim$ 50% of these impactors (9), $\sim 10^{23}$ gm of organic molecules were incident on Earth at this time. Comets contributed a comparable quantity if they represented $\sim 5-10\%$ of the impactors. Basin–forming impactors may have delivered $\sim$ 10–100 times as much mass as these (2); however, this population is so poorly understood that we exclude it from our calculations.

A measure of the fraction of organics incident on Earth that must survive atmospheric entry and impact to be quantitatively significant for the terrestrial prebiotic inventory is given by estimates of photochemical production of organics in the Earth's primitive atmosphere. Such production rates are summarized by Stribling and Miller (10); their results give $\sim 10^{20} - 10^{21}$ gm HCN and H_2CO integrated over 600 Myr, assuming an atmosphere with $H_2/CO_2 \sim 1$. CO and CH_4 atmospheres give ~10 times higher yields, but are now often considered unlikely choices for the early Earth (11). Even $H_2/CO_2 \sim 1$ requires a volcanic H_2 source $\sim$ 100 times greater than at present (11); and HCN and H_2CO yields are expected to drop rapidly with decreasing H_2/CO_2 (10). Chemical processing of the atmosphere by impact shock heating does not appear to change the order of magnitude of the above results (12). Thus the survival of ~0.1-1% of incident organics could mean the terrestrial prebiotic inventory was dominated by an extraterrestrial source.

To investigate whether cometary organics are likely to survive atmospheric entry and impact, we examine detailed models of the relevant physical processes. Numerical simulations of ablation processes (13) imply that, at a velocity V=25 km sec^{-1}, substantial fractions of smaller icy impactors may be ablated (~20% of a 100 m radius comet). We assume that the organic material lost in this way is destroyed. However, larger impactors are essentially unchanged by their atmospheric passage.

If aerodynamic stresses($\sim \rho V^2 \sim$ 625 GPa) exceed the impactor strength, then catastrophic fragmentation may occur (14). These stresses are comparable to plausible strengths of porous ice and carbonaceous chondrite material. In fact, fragmentation of a carbonaceous chondrite has been confirmed (15). Under these conditions, enhanced aerobraking, due to greatly increaed surface area, may permit the incorporation of incident organics into the terrestrial inventory.

In addition, we investigate the likelihood of survival of organics upon impact. A numerical simulation using the smoothed particle hydrodynamic method (16) indicates that temperatures $\sim 10^3 - 10^4$ K are reached in impacts of a 1 km radius comet at 25 km sec^{-1}. The lower end of this temperature range is near the upper limit that can be withstood by organic molecules on timescales comparable to that of the impact (~0.5 sec). Most organic material in carbonaceous chondrites is in the form of high-molecular weight, intractable polymer (3). As an analogue to such material in asteroids and comets, we use a similar organic material (3), terrestrial kerogens. Kinetic parameters from pyrolysis experiments with types I and II kerogens (17) indicate that such material can survive no more than $\sim 10^{-2}$ sec^{-1} at 1000 K. However, ~50% of the resulting kerogen pyrolysate is composed of *n*-alkanes up to $\sim C_{30}$, as well as such aromatics as benzene, toluene, and *m,p*-xylene (18, and A. Burnham, *pers. comm.*). To understand the ultimate fate of kerogen-like organics in the impactor, we must therefore examine the fate of short-chain hydrocarbons and simple aromatics (and their O- and N- analogues). Kinetic parameters derived from shock-tube pyrolysis of such compounds at temperatures over the range 1000–2000 K (19) show that these basic organic units will survive ~1000 K for as long as 5–10 minutes.

Preliminary simulations indicate that, for cometary impacts onto rock, the survival of even the kerogen pyrolysates is unlikely. However, organic survivability may increase significantly in the (more likely) case of cometary impacts into an ocean, as well as carbonaceous chondrite–rock impacts. This is because the partition of collisional energy into the impactor increases with decreasing impactor-to-target density ratios (20). Our simulations show that the least-shocked parts of the impactor are promptly ejected (Fig. 1), so that the organics most likely to survive the initial collision are also likely to be expelled from the vicinity of the impact without further heating.

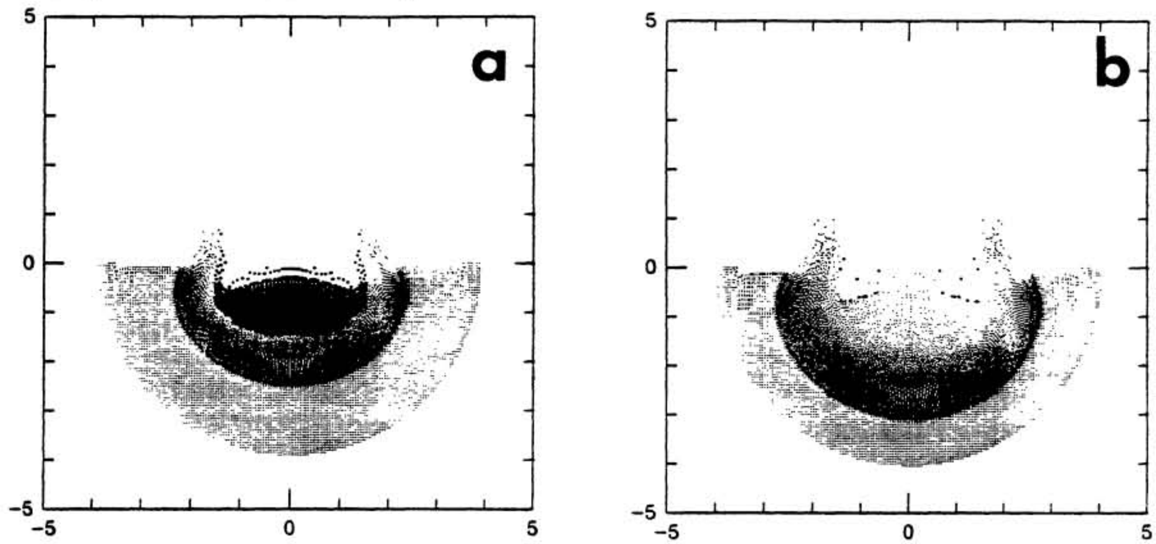

Fig. 1. (a) Simulation of 25 km sec^{-1} impact (heavy points represent impactor); and (b) for the same time, location of least-heated fraction of impactor (heavy points). Coordinates are in km.

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