Orig Life Evol Biosph (2008) 38:5–21
DOI 10.1007/s11084-007-9110-5

Extraterrestrial Flux of Potentially Prebiotic C, N, and P to the Early Earth

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Received: 12 June 2007 / Accepted: 30 July 2007 /

Abstract With growing evidence for a heavy bombardment period ending 4–3.8 billion years ago, meteorites and comets may have been an important source of prebiotic carbon, nitrogen, and phosphorus on the early Earth. Life may have originated shortly after the late-heavy bombardment, when concentrations of organic compounds and reactive phosphorus were enough to "kick life into gear". This work quantifies the sources of potentially prebiotic, extraterrestrial C, N, and P and correlates these fluxes with a comparison to total Ir fluxes, and estimates the effect of atmosphere on the survival of material. We find (1) that carbonaceous chondrites were not a good source of organic compounds, but interplanetary dust particles provided a constant, steady flux of organic compounds to the surface of the Earth, (2) extraterrestrial metallic material was much more abundant on the early Earth, and delivered reactive P in the form of phosphide minerals to the Earth's surface, and (3) large impacts provided substantial local enrichments of potentially prebiotic reagents. These results help elucidate the potential role of extraterrestrial matter in the origin of life.

Keywords Meteorite flux · Prebiotic material · Cohenite · Schreibersite · Ammonia

Introduction

The detection of organic compounds in carbonaceous chondrites led many researchers to speculate that carbonaceous chondrites delivered important organics for the origin of life (e.g., Cooper et al. 2001; Strasdeit 2005; Mix et al. 2006). Quantitative calculations of the carbonaceous meteorite flux contradict this assertion, and suggest that the actual flux of carbon from these meteorites is miniscule relative to the flux of other extraterrestrial

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material (e.g., Anders 1989; Chyba and Sagan 1992). Nonetheless, delivery of prebiotic organic compounds by carbonaceous chondrites is a common theme encountered throughout astrobiology and consequently, many researchers have ignored the prebiotic potential of other extraterrestrial material. Iron meteorites and ordinary chondrites make up the majority of the mass flux and the numerical flux of meteorites respectively, and hence may have been more relevant to early Earth chemistry. The goal of this study is twofold: (1) to *clarify* the types of material that fall or fell to the surface of the Earth, and (2) to *quantify* the fluxes of prebiotic material globally and to localized regions under varied atmospheric conditions.

Extraterrestrial matter is broadly divisible into three groups by size: large impactors, meteorites, and interplanetary dust particles. The most massive impactors are infrequent catastrophic colliders and include comets and large asteroids. Meteorites are more common and strike the Earth several thousand times per year. Meteorites are the most well characterized extraterrestrial material due to the abundance of samples. Interplanetary dust particles (IDPs) are small (micrometer) grains originating from a variety of sources, and they constitute the majority of the yearly flux of extraterrestrial material. These three groups form a continuum. Large impactors fragment to produce massive meteorites, and many IDPs originate from the ablation of cometary and asteroid material.

We use carbonaceous chondrites and IDPs as proxies for cometary material in this study. The mineralogy and organic compounds present in Wild 2 are more similar to anhydrous IDPs than to any other material (e.g., Brownlee et al. 2006) and IDPs serve as an adequate proxy for the cometary flux.

Understanding the nature of carbon (C), nitrogen (N), and phosphorus (P) compounds in these groups of extraterrestrial matter in turn informs our understanding of the material available for chemical reactions on the surface of the early Earth. We focus on these three elements because they are the main limiting reagents in early biochemistry, due to the ubiquity of H and O as water and because the ratios of these three elements are fixed at 106:16:1 for C to N to P (Redfield 1958) in life today. The mineralogy of C, N, and P in meteorites is reviewed next with a special focus on phases relevant to the origin of life.

Ordinary chondrites and iron meteorites are the most abundant meteorites reaching the surface of the Earth today by number and by mass, respectively, and carbonaceous chondrites are used as proxies for IDP and cometary material. We omit other chondrite groups (i.e., enstatite, R, and K), stony-iron meteorites, and stony achondrites from our calculations. This is a simplification of the extraterrestrial flux, but these meteorites are a small portion of the total meteoritic flux based on our modern collection. Nonetheless, under some conditions these meteorites may have played important roles in the evolution of the terrestrial environment.

Carbon, Nitrogen, and Phosphorus Cosmochemistry

Characterizing the chemically reactive forms of the biogenic elements in extraterrestrial material is key to assessing its role in the origin of life. Some meteorite minerals are reactive on the surface of the Earth, like carbides, nitrides, and phosphides, whereas some are inert, like carbonates and phosphates. Some forms are soluble in water, like some simple organics, whereas others are insoluble, like macromolecular organic material. Soluble and/or reactive phases are the most relevant to the origin of life. The phases of C, N, and P in iron meteorites, ordinary chondrites, and carbonaceous chondrites are summarized in Table 1.

Table 1 C, N, and P compounds in ordinary chondrites, carbonaceous chondrites, and iron meteorites

	Ordinary chondrites	Hydrous carbonaceous chondrites	Iron meteorites
Carbon	IOM and graphite. Little to no cohenite or soluble organics.[a]	Soluble organics, IOM, and carbonates. Carbonates are about 10% of the total C, and the ratio of soluble to insoluble material depends on the meteorite, but usually 10:90.[b,c]	Graphite, diamond, and cohenite, $(Fe,Ni)_3C$. Cohenite is most common in IAB and IIICD meteorites.[d]
Nitrogen	IOM or in graphite. Little to no nitrides or soluble N-organics.[a]	IOM and soluble organic fraction. Proportionate to the soluble/insoluble ratio.[b]	Ni-rich metal, and nitride minerals CrN or $(Fe,Ni)_4N$.[e,f]
Phosphorus	Phosphate minerals (apatite and other Ca-phosphates (>90%). Schreibersite, $(Fe,Ni)_3P$ (0–10%, dependent on type).[g]	Phosphates (>99%). Trace phosphonic acids (0.1 % total P). Rare P–S minerals. Few phosphides (<1%)[h,i]	Nearly all as $(Fe,Ni)_3P$. Rare phosphates, and other rare minor phosphides.[i]

IOM is insoluble organic matter

[a] Brearley and Jones (1998). [b] Pizzarello et al. (2006). [c] Cody and Alexander (2005). [d] Mittlefehldt et al. (1998). [e] Grady and Wright (2003). [f] Franchi et al. (1993). [g] Goreva and Lauretta (2004). [h] Pasek et al. (2004). [i] Pasek (2006).

Carbon Two forms are C have potential prebiotic utility: the soluble organic compounds and cohenite, $(Fe,Ni)_3C$. The organic chemistry of meteorites varies significantly with type (for a current overview of meteorite organics see Pizzarello et al. 2006). About half of carbonaceous chondrites have abundant organic C, and a majority of C in these meteorites is locked up in inaccessible, insoluble organic matter. The soluble C phase includes carboxylic acids, alcohols and polyols, amino acids, and aromatics. The Murchison meteorite is rich in soluble organic matter (≈30% of total C) and organic compounds in other carbonaceous chondrites are quite similar to Murchison, though total concentrations vary.

Cohenite is a common minor mineral in meteorites. Oparin (1938) originally suggested that cohenite was the primordial source of C for the origin of life based in part on historical reports of oil produced by the hydrolysis of cementite, Fe_3C, in steel (e.g., Mendeleyev 1891). Recent experiments demonstrate that hydrocarbons are produced by the corrosion of carbides (Oró 2002; Cataldo 2003), and these may be modified to form prebiotic reagents.

Nitrogen is a trace constituent of many meteorites, and was inaccessible for prebiotic chemistry when trapped in insoluble organic matter or in graphite. Reactive N compounds include the nitride minerals roaldite, $(Fe,Ni)_4N$, and carlsbergite, CrN, and N dissolved in the Ni-rich metal phase taenite. Nitrogen as nitrides corrodes in water to form NH_3 in solution (Smirnov et al. 2006). The soluble, organic material of meteorites includes amines, amides, and amino acids, and these could have been accessible for prebiotic syntheses.

Phosphorus has two distinct valence states in meteorites: +5 in phosphate minerals, and nominally 0 as an alloy in phosphide minerals. Meteoritic phosphates include apatite, whitlockite, and monazite, and several unusual phosphate minerals rarely found on Earth. Phosphates are a poor source of prebiotic P (Keefe and Miller 1995). Schreibersite, $(Fe,Ni)_3P$, is a common meteoritic phosphide mineral that corrodes in water to form a variety of reactive P compounds (Pasek and Lauretta 2005; Bryant and Kee 2006). Schreibersite forms reactive intermediates capable of phosphorylating organics, presumably through a radical reaction pathway (Pasek 2006; Pasek et al. 2007), and hence was an excellent source of prebiotic P on the early Earth.

Overview of Heavy Bombardment

Lunar impact age dates cluster at >3.8 Ga and suggest the impact rate was much higher than present, a time known as “heavy bombardment.” There are two interpretations of the heavy bombardment: one is that the impact dates record the tail-end of a gradual drop of impactors from ~4.4 Ga which continuously resurfaced the Moon and reset rock ages (Hartmann 2003), the other is that there was an intense late-heavy bombardment period (4.0–3.8 Ga) that followed a relatively quiescent pre-bombardment period (Ryder 2003). Neither interpretation has garnered incontrovertible proof, although the cataclysmic late-heavy bombardment has gained favor amongst both geochemists and dynamical theorists over the last decade.

The total flux of extraterrestrial material to the surface of the early earth is estimated as being between 2×10^{20} kg (Marty and Yokochi 2006) and 5×10^{22} kg (Owen 1998). The time scale over which this material fell to the surface of the earth is the primary area of disagreement between these two models. If the meteoritic flux was a gradual drop-off, then the available material from this increased flux was at most 10^3–10^4 times the current flux, as the total mass delivered is assumed to be evenly distributed through time. This higher flux would have operated on a much longer time scale than any cataclysmic bombardment. In contrast, the late-heavy bombardment reaches a higher peak flux ($\approx10^5$ times the present flux) for a shorter period of time, about 10–100 million years. We employ this larger estimate of the flux for the calculations that follow. The results from these calculations are thus upper limits to the maximum flux during the heavy bombardment, and the average flux on the early Earth may have ranged from 1 to 10^5 times the present day flux (Zahnle and Sleep 2006). These calculations represent a maximum estimate for the major beneficial aspect of increased extraterrestrial impact—the “seeding” of the Earth with potentially prebiotic chemicals.

The majority of the heavy bombardment impactors likely originated in the asteroid belt based on siderophile trace element analysis of lunar melts (Kring and Cohen 2002), the continental crust (Schmidt et al. 2005), old terrestrial rocks (Schoenberg et al. 2002), and on dynamical models (Strom et al. 2005). We assume that the composition of the meteorite flux today is similar to the flux of meteorites in the past for the calculations that follow. Asteroidal bodies had differentiated and cooled by 3.9 ± 0.1 Ga (e.g., Cook et al. 2004), so a metal/silicate flux ratio similar to the current flux is not unreasonable.

Methods

The yearly flux of C, N, and P compounds is determined for IDPs, meteorites, and large impactors. We consider only material that reaches the surface of the Earth and do not consider material that burns in the atmosphere. These fluxes are then placed in the historical context of the heavy bombardment to estimate fluxes for this time period. The values used for C, N, and P abundance calculations, and reasonable maxima and minima are presented in Table 2. For these calculations we assume the heavy bombardment reached a maximum flux of 10^5 times the present day flux. We also track the total flux of Ir to verify these flux calculations are consistent with the Earth's total crustal Ir abundance, and estimate the effect of a thick atmosphere on total flux.

For each estimate of mass flux described below, potentially prebiotic C, N, and P delivery are estimated by the simple equation:

$$F_X = M_F \times X_E \times k \tag{1}$$

where F_X is the flux of a given element for each group under study, M_F is the yearly mass flux of a given extraterrestrial material group, X_E is the abundance of the element of interest, and k is a factor determining potentially prebiotic varieties of the element (i.e., soluble C fraction, percent P as phosphide).

Table 2 Values used for calculations, and reasonable maxima and minima

	Reasonable average	Minima	Maxima	Reference
Chondrites				
Carbon (wt%, CC)	2.2% (CM)	2.0% (CR)	3.45% (CI)	1
Fraction of meteorites with soluble C, N (CC)	50%	64% (number fraction Antarctic)	34% (mass fraction Antarctic)	TW
Soluble C (CC)	10%	1% (like the Tagish Lake meteorite)	30% (like Murchison)	2
Carbon in OC (ppm)	2,500 (L)	2,100 (H)	3,100 (LL)	1
Phosphorus in CC,OC (ppm)	1,000			1
Reactive or soluble phosphorus CC,OC (ppm)	10	1 (as phosphonic acids)	100 (some OCs)	3, 4, 5
Soluble nitrogen (ppm, CC)	10			1, 6
Iridium, CC (ppm)	0.5			1
Iridium, OC (ppm)	0.60			1
Iron Meteorites				
Phosphorus (wt%)	0.52%	0.04 (IVA)	2 (IIG)	TW
Carbon as carbide (ppm)	140	10 (IVA)	200 (max Irons)	TW
Iridium (ppm)	5			TW
Nitrogen (ppm)	30 (ave.)	0.4 (IVB)	85.5 (some IABs)	6, 7
IDPs				
Mass flux of IDPs (kg/year)	3×10^7			8
Fraction hydrous carbonaceous	27.5%			9
Carbon in carbonaceous (wt%)	8%	6%	10%	10
Phosphorus in IDPs (wt%)	0.3%	0.1%	0.7%	10
Phosphorus as phosphide	1% (like CC)	0% (hydrous IDPs)	10% (highest of OC)	TW
Maximum Bombardment Flux	$10^5\times$			

TW is this work. *OC* is ordinary chondrites, *CC* is carbonaceous chondrites. *CM*, *CR*, and *CI* are individual classes of carbonaceous chondrites. *IVA*, *IVB*, *IAB* and *IIG* are iron meteorite classes. References refer to: *1* Lodders and Fegley 1997, *2* Pizzarello et al. 2006. *3* Cooper et al. 1992. *4* Pasek et al. 2004. *5* Goreva and Lauretta 2004. *6* Grady and Wright 2003. *7* Franchi et al. 1993. *8* Love and Brownlee 1993. *9* Rietmeijer 1998. *10* Thomas et al. 1993

Meteorite Flux Calculations

We first establish mass vs number relations for meteorites. Meteorites provide direct constraints on the nature of large impactors and they are important contributors to the total flux of extraterrestrial material. Specifically we use the results here to constrain the fluxes of iron meteorites, ordinary and carbonaceous chondrites, and relate these three meteorite groups to estimated heavy bombardment fluxes.

Meteorite mass flux calculations are dependent on the data set used. There are three collections upon which to build such a data set: global meteorite finds, global meteorite falls, and Antarctic finds. Global meteorite finds have a significant human bias where the untrained frequently collect the most unusual rocks, resulting in the over-collection of meteorites with no terrestrial counterparts. This data set provides significant information on meteorite subgroup classification. Much of the human bias is eliminated by examining only meteorites observed to fall, and since falls are recorded globally, there is no regional bias. The primary source of error in this set is that only larger, cohesive falls are recovered, whereas small masses are difficult to collect. The collecting of meteorites in Antarctica is systematic and has recovered meteorites of all sizes and types. However, this collection is regional in scope, and paired meteorites and strewn fields are difficult to recognize due to geomorphologic processes which separate paired individuals. Additionally, geomorphologic sorting processes may limit the number of large meteorites collected. We use data from all three collections to describe the nature of the meteoritic material that has fallen to Earth in this study.

We collected data for mass vs number relationship from the MetBase Meteorite Data Retrieval Software (2005). This data set provides classification and mass data for both falls and finds (including Antarctic finds) and is current through 2004. Fall and Antarctic meteorites were divided into ordinary chondrites, carbonaceous chondrites, and iron meteorites. Data was sorted in cumulative log–log plots by determining the number (N) of meteorites with a mass greater than a given mass (M) for each meteorite group. Meteorites with masses >1,000 kg were omitted from this portion of the study.

The flux of meteorites with a mass >0.02 kg is estimated to be 159 per million square kilometers per year, with an error range of a factor of two. This fall rate is consistent with camera observations (Bland et al. 1996). The global flux of meteorites > 0.02 kg is ≈80,000 falls per year. About 8,400 meteorites were recovered from Antarctica as of 2004 with masses greater than 0.02 kg. The log–log plots were adjusted by increasing the y-intercept of derived Antarctic find lines by a factor of 9 (0.95 log units) to produce yearly meteorite fluxes for masses in the range of 0.02 to 100 kg, and using the slopes of fall meteorites for masses above 100 kg, with slopes set to intersect the Antarctic lines at 100 kg.

We use the abundances of Willis (1980) to calculate the mass of P, C, and Ir in iron meteorites. The weighted average percent of P, C, and Ir in iron meteorites is calculated from the amount of P, C, and Ir in various iron meteorite groups over the total number of iron meteorites (Table 3). Using Table 3 we calculate 0.52 wt% of P, 140 ppm of C, and 5 ppm for Ir for an average iron meteorite.

Large Impactor Flux Calculations

For mass fluxes of large impactor material, that is material >1,000 kg that may form craters and falls less often than one time per year, we used the piecewise log N vs log M profiles from Bland and Artemieva (2006). Large falls were much more frequent on the early Earth,

Table 3 Average elemental abundances of P, C, and Ir in iron meteorites by class

Class	Number	P wt%	C wt%	Ir ppm
IAB	117	0.21	0.01	2.7
IC	11	0.43		0.38
IIAB	78	1	0.003	10
IIC	8	0.53	0.004	6.4
IID	17	0.98		9.9
IIE	15	0		4.1
IIF	5	0.26	0.0008	6.2
IIG	5	2		0.15
IIIAB	224	0.7	0.01	4.1
IIICD	31	0.21	0.014	2.70
IIIE	13	0.56		4.10
IIIF	9	0.22		3.2
IVA	61	0.1	0.02	1.9
IVB	12	0.2	0.004	22.0

Data from Mitthlefeldt et al. (1998), Willis (1980), and Sugiura (1998).

The number of each class of meteorite in our collection is also given.

and one of Bland and Artemieva's (2006) important results is that iron meteorite falls dominate (>95%) the mass range 10^3–10^9 kg. Stony chondritic impactors dominate for masses greater than 10^{10} kg, forming craters but delivering little mass to the surface of the Earth.

The Bland and Artemieva (2006) model relationships are primarily used for calculations of flux during the heavy bombardment. We modified the Bland and Artemieva (2006) piecewise log N vs log M functions by adding 0.42 (a factor of 2.67) to the y-intercept of each line to be consistent with the Bland et al. (1996) yearly flux. For masses less than 1,000 kg, we employed the relationships determined in the prior section. The mass flux during heavy bombardment was determined by taking these modified log N vs log M relationships and increasing the y-intercept by 5, an increase by a factor of 10^5, our maximum estimate of the factor of increase of flux during the late heavy bombardment. We calculate the total mass of meteorites 0.02–10^9 kg by the relationship:

$$Mass = \sum_{M=0.02kg}^{10^9} M_n \times (N(M_n) - N(M_{n+1})) \times \sqrt{1.05} \tag{2}$$

where M_n is the mass of interest, and M_{n+1} is the next larger mass of interest. M_{n+1} is larger than M_n by a factor of 1.05, and $\sqrt{1.05}$ corrects for the average mass of the meteorites between M_n and M_{n+1}. N is the number of meteorites with mass M. Meteorites in the mass range 10^3–10^9 are assumed to be iron meteorites.

IDP Flux

The mass flux of IDP material was calculated by Love and Brownlee (1993) to be 3×10^7 kg/year. We use this value for the calculations that follow. Potentially prebiotic C, N, and P are assumed to be only in hydrous, carbonaceous IDPs, analogous to carbonaceous chondrites. Carbides, nitrides, and phosphides may be present in IDPs, but the very nature of this material makes it difficult to determine. Hence the estimates presented below are probably underestimates of the prebiotic contribution by IDPs.

Effect of Atmosphere

The density and composition of the atmosphere of the early Earth are unclear, but suggestions range from reducing and approximately as dense as the current atmosphere (Tian et al. 2005), to neutral with a high surface pressure of CO_2 (Walker et al. 1981). Changing the atmospheric density influences calculations of the delivery of extraterrestrial material to the surface of the Earth, as a denser atmosphere increases aerobraking of falling material, increases the ablation of material, provides an increased chance of fragmentation, and increases the area over which fragments fall. The composition of the atmosphere does not significantly affect meteor entry beyond changing the density profile of the atmosphere through which the material falls, as the extraterrestrial material does not have enough time to react with the atmosphere during fall.

We quantify the effect of a change of atmospheric density on falling material by solving a system of equations to determine the final mass and velocity of a meteor just prior to impact with the Earth's surface [equations 1, 2, and 4 of Bland and Artemieva (2006) and detailed fully in Melosh (1989), and Chyba et al. (1993)] for a 1 bar air atmosphere, and a 10 bar CO_2-dominated atmosphere. We perform these calculations for both iron and stony meteors over the mass range 10^{-4} to 10^{8} kg, and assume that these bodies are perfectly spherical, and begin our calculations with entry into the atmosphere at 200 km above the surface of the Earth. We also estimate the likelihood of fragmentation, and determine the spreading velocities of fragments. For these calculations we use values assumed in Bland and Artemieva (2006), and assumed hydrostatic equilibrium in the atmosphere. We then compared the results from the 10 bar CO_2 atmosphere to the results from air.

Results

The calculated mass flux for meteorites and IDPs and the associated fluxes of potentially prebiotic C, N, and P, and of total Ir are shown in Table 4. Fluxes of biogenic elements during the heavy bombardment are also summarized in Table 4. Interplanetary dust particles were the major source of extraterrestrial organics and large iron meteorites were the major source of extraterrestrial reactive P during the heavy bombardment. Changing the density of the atmosphere did not significantly influence the survivability of the smallest material (IDPs) or the largest material (large meteorites), hence only results for the late heavy bombardment using the modern atmosphere are reported.

Meteorite Log–Log Plots

The log *M* vs log *N* relationships are presented in Table 5 and Fig. 1. These data reveal compositional biases in the collection of meteorites. For iron meteorites and ordinary chondrites, fall meteorites slopes are larger (less negative) than Antarctic find meteorite slopes over equivalent mass ranges. For the low mass meteorites this is attributed to the greater ease of collecting small meteorites in Antarctica than collection of small meteorites after a meteorite fall. Conversely, large meteorites may be underrepresented in blue ice fields. Most meteorites collected from Antarctica are collected on from

Table 4 Total mass flux in kilogram per year of extraterrestrial material, potentially prebiotic reagents, and iridium, sorted by class

Class	Flux	C	N	P	Ir
CC	600	0.5	0.03	0.006	0.0003
OC	30,000	~0	~0	0.3	0.018
Iron	13,000	2	0.4	70	0.075
IDPs	3×10^{7}	5×10^{4}	800	900	15
LHB					
Iron	3×10^{10}	5×10^{6}	10^{6}	10^{8}	10^{5}
CC	8×10^{7}	10^{5}	5×10^{3}	1000	40
OC	3×10^{9}	0	0	3×10^{4}	2×10^{3}
IDPs	3×10^{12}	5×10^{9}	10^{8}	10^{8}	10^{6}

As before, *CC* is carbonaceous chondrites, *OC* is ordinary chondrites, *Iron* is iron meteorites, and *IDPs* are interplanetary dust particles. Fluxes during the Late Heavy Bombardment (LHB) are given as at the bottom of the table. Errors for present day flux are a factor of 4 for total flux, and a factor of 30 for LHB. Carbon and nitrogen are in soluble organic compounds for carbonaceous chondrites and IDPs, and in carbides and nitrides for iron meteorites. Phosphorus is in phosphides and phosphonic acids for carbonaceous chondrites and IDPs, and in phosphides for ordinary chondrites and iron meteorites.

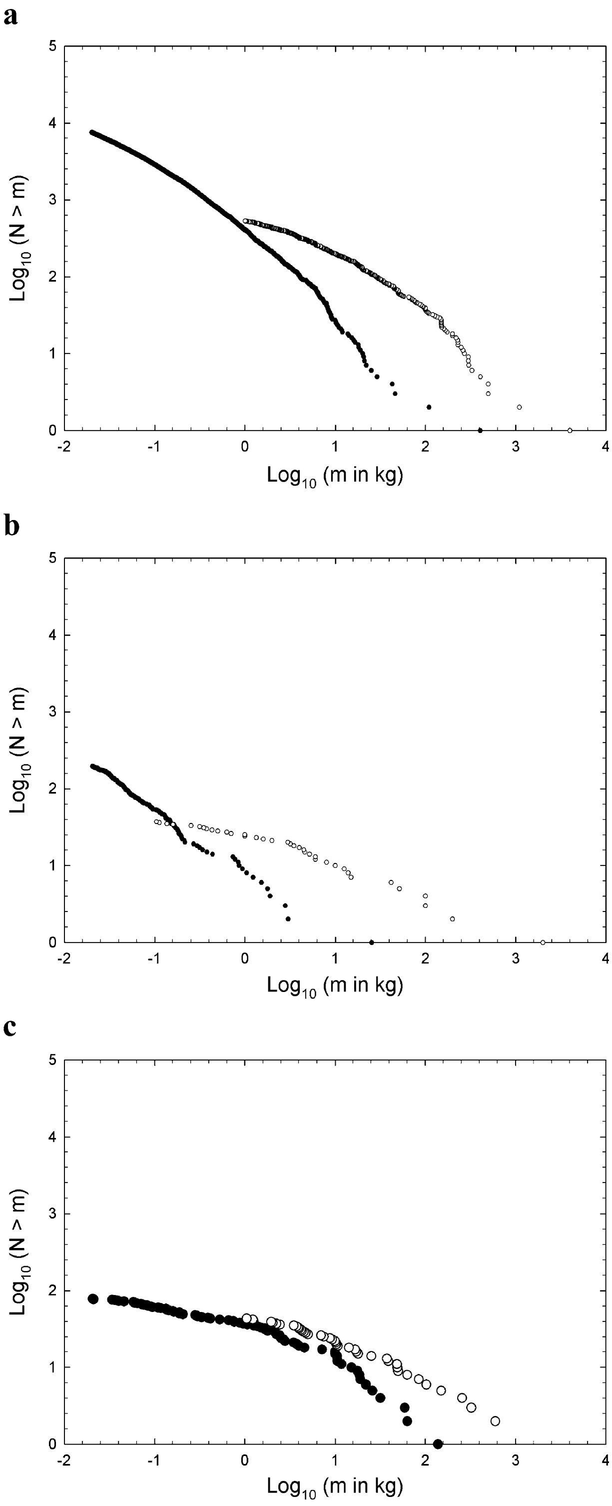
evaporative blue ice fields and are small ordinary chondrites. Large, massive meteorites are less buoyant in ice and may never reach the surface for collection. An analogous phenomenon is active in the Omani desert wherein massive iron meteorites sink in the sand, resulting in the under-collection of large, metallic meteorites (Al-Kathiri et al. 2006). For this reason we employed fall mass vs number relations for the high mass meteorites (>100 kg).

Table 5 Linear regression fits for meteorite classes by mass range

	A	B	R^2	Mass range
Falls				
Ordinary chondrites	−2.2328	6.283	0.9378	>150
	−0.8199	3.193	0.9958	15–150
	−0.4501	2.7794	0.9812	<15
Carbonaceous chondrites	−0.9858	2.3155	0.9253	>40
	−0.6507	1.5926	0.9655	2–40
	−0.1768	1.3935	0.9775	<2
Iron meteorites	−0.8117	2.3352	0.9791	>40
	−0.4026	1.6896	0.9759	4–40
	−0.1517	1.5934	0.92	<4
Antarctic Finds				
Ordinary chondrites	−0.8888	2.1513	0.893	>15
	−1.7818	3.2361	0.9836	6–15
	−0.7574	2.6934	0.9872	<6
Carbonaceous chondrites	−0.8533	0.9327	0.9929	All
Iron meteorites	−0.9885	2.1297	0.9828	>10
	−0.4214	1.574	0.947	1–10
	−0.2295	1.5769	0.982	<1

The relationship between mass (*M* in kg) and number (*N*) of meteorites with a mass >*M* is equal to $\mathrm{Log}_{10}N = A\,\mathrm{Log}_{10}M + B$.

Fig. 1 Log mass–log number relationships between **a** ordinary chondrites, **b** carbonaceous chondrites, and **c** iron meteorites. *Open circles* are fall meteorites, *filled circles* are Antarctic meteorites



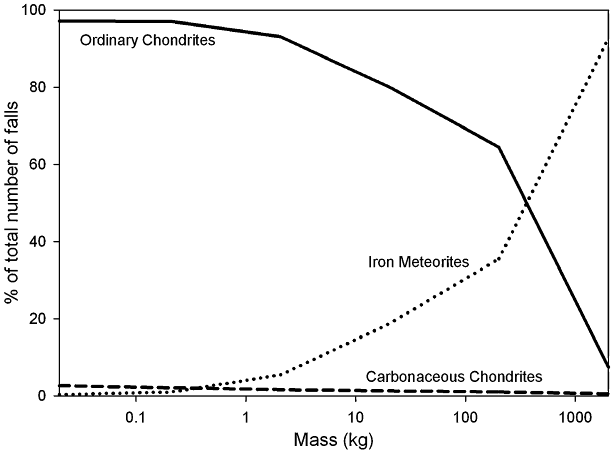


Fig. 2 Dominant meteorite type by mass

Ordinary chondrites are the dominant meteorite fall for masses less than ~300 kg, and iron meteorites become dominant above this mass (Fig. 2). Carbonaceous chondrites are never a major constituent of the total meteorite flux reaching the Earth.

Regional Fluxes of Prebiotic Material

IDPs bring in more reactive C, N, and P than any other extraterrestrial material. However, this mass is dispersed throughout the surface of the Earth (511×10^6 km^2), so the current flux of soluble C material is 0.1 g/km^2 (10 kg during heavy bombardment) and P is 20 μg/km^2 (0.2 g during heavy bombardment). Meteorites deliver much more C and P to a much smaller region.

Carbonaceous chondrite meteorites and stony meteorites are much more friable than iron meteorites and usually fragment significantly before impact. As a result, these meteorites typically deliver less material to a larger area, diluting the delivery of prebiotic reagents significantly. As an example, the largest iron meteorite fall in modern history was the Sikhote–Alin 1947 fall which delivered a total mass of 23,000 kg of material to an area ~0.7 km^2. Comparatively, the largest ordinary chondrite fall (Jilin) delivered 4,000 kg to an area ~500 km^2, the largest carbonaceous chondrite fall (Allende) delivered 2,000 kg to an area ~150 km^2, and the largest carbonaceous chondrite fall with abundant organics (Murchison) delivered 100 kg to an area ~15 km^2 (Grady 2000).

A large iron impactor (10^{10} kg) could form a crater with a diameter of about 5 km, with an area of 16 km^2. Assuming ~5% of the P survives the collision with Earth as schreibersite, this would amount to ≈100,000 kg of reactive P per square kilometer. This local flux is the equivalent of 1 million year's worth of reactive P from the fall of IDPs during the late-heavy bombardment. Such substantial enrichments would have been commonplace during this time period, with several of these craters forming every 100 years. The minimum and maximum regional extraterrestrial fluxes of the biogenic elements C, N, and P are summarized as Table 6.

Table 6 Regional minimum and maximum fluxes during the late heavy bombardment

Element	Minimum flux (kg/km^2)	Maximum flux (kg/km^2)
C	10	3×10^3
N	0.2	500
P	3×10^{-4}	10^5

The minimum flux is calculated from the total global flux of prebiotic reagents from IDPs divided by the surface area of the Earth. The maximum flux is calculated from amount of prebiotic reagents that a 10^{10} kg iron meteorite impactor delivers divided by the area of its associated crater (~16 km^2).

The flux per square kilometer of specific organic compounds from IDPs may be determined from the following relationship:

$$[X] = \frac{W_{Murchison} \times M_{IDP} \times LHB_{Flux} \times P_C \times S \times R_C}{511 \times 10^6 km^2} \tag{3}$$

Where $W_{\mathrm{Murchison}}$ is the weight of a specific component [X] of interest in parts per million in the meteorite Murchison, M_{IDP} is the present mass flux of IDPs in kilograms per year, $\mathrm{LHB}_{\mathrm{Flux}}$ is the increase of flux during the heavy bombardment, P_C is the percent of IDPs that are hydrous and carbonaceous, S is the fraction of organics that are soluble relative to Murchison (≈10%/30%), R_C is the total ratio of carbon in carbonaceous IDPs to the total carbon in Murchison (8%/2.2%), and 511×10^6 km^2 is the surface area of the Earth. Using values from Table 2, this is equivalent to:

$$[X] = \frac{W_{Murchison}}{500} \frac{kg}{ppm \times year \times km^2} \tag{4}$$

Current estimated abundances of organics in the meteorite Murchison are in Pizzarello et al. (2006), and references therein.

Flux of Iridium

The total flux of Ir through the last 4 billion years is estimated as:

$$\mathrm{Ir} = F_{LHB} \times t_{LHB} + F_{Ir} \times \left(4 \times 10^9 - t_{LHB}\right) \tag{5}$$

where F_{LHB} is the flux of iridium during the late heavy bombardment, t_{LHB} is the time length of the late-heavy bombardment, and F_{Ir} is the current flux of iridium. Estimates for the length of time of the late-heavy bombardment range from 10 to 100 million years. This corresponds to a total flux of 10^{13}–10^{14} kg of Ir in the last 4 Ga, comparable to the present bulk crustal Ir of $\approx2\times10^{13}$ kg (Taylor and McLennan 1985). Equivalently, we estimate the amount of time that the flux was ~10^5 times the present day flux at less than 20 million years.

Effect of Atmosphere

An increase in the surface pressure of the atmosphere by a factor of 10 has a minimal effect on the smallest material (<1–10 μg, like IDPs), as these particles lose heat more efficiently through radiative cooling than ablation (e.g., Murad 2001). Conversely, large impactors (>10^6–10^7 kg) are minimally aerobraked by the atmosphere, and hence material delivered

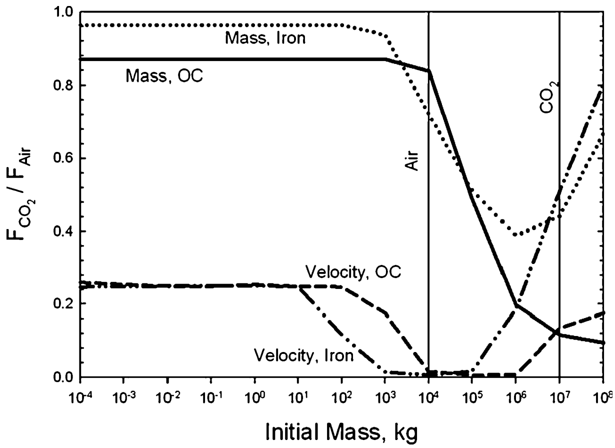


Fig. 3 Ratios of masses and velocities of meteors at the surface of the Earth for a 10 bar CO_2-atmosphere and a 1 bar air atmosphere. The initial entry mass is given and the initial velocity is assumed to be 18 km/s. Also shown is the estimated survivability limit for a single fragment in air and in the 10 bar CO_2 atmosphere

by these bodies is not significantly affected by surface density. Since these two groups of material deliver most of the prebiotic compounds to the surface of the Earth, the results presented in Table 4 are increased by the change in atmosphere by only a factor of ~2, primarily due to the increased survival of moderately large meteors.

The surface density of the atmosphere has the largest effect on bodies in the size range of 10^4–10^7 kg (Fig. 3). In air, stony meteors, i.e. ordinary chondrites and carbonaceous chondrites lose 90 to 98% of their mass on entry, respectively, and iron meteors lose about 70%. In a 10 bar CO_2-dominated atmosphere, these mass losses increase by 1–2% as a result of increased ablation. Stone meteors with entry masses <10,000 kg are slowed to terminal velocity in air, whereas a 10 bar CO_2 atmosphere slows stony meteors with masses <10^7 kg to terminal velocity. Iron meteors with entry masses <1,000 and <10^6 kg are slowed to terminal velocity in air and 10 bar CO_2 atmosphere respectively. These values are for single pieces. Single pieces that are not slowed by the atmosphere sufficiently strike the surface of the Earth with enough energy to be completely vaporized, and these energies correspond to velocities just prior to impact of between 2 and 6 km/s. A thick atmosphere reduces the likelihood of complete vaporization, and hence, increases the delivery of larger material for the mass range between 10^4 and 10^7 kg. These estimates ignore fragmentation, which can increase the survivability of meteors by dispersing energy through ablation and aerobraking.

The likelihood of meteor fragmentation is roughly proportional to the amount of time it takes a meteor to fall. Thus in a 10 bar CO_2 atmosphere, meteors are more likely to fragment into small pieces. Additionally, these meteor fragments have higher spreading velocities in a denser atmosphere (Passey and Melosh 1980), which increases the size of strewn fields. We estimate that in a 10 bar atmosphere, the area of meteorite strewn fields increases by about a factor of 7.

Discussion

The differences between the slopes of the fall collection and the Antarctic find collection are due primarily to collecting procedures and geomorphological processes. Our results are consistent with the calculations of Harvey and Cassidy (1989), Halliday et al. (1989), Cassidy and Harvey (1991), Huss (1991), and Ikeda and Kimura (1992). The mass vs number slopes for meteorites ranges from −0.75 to −0.85 in these studies, consistent with the ordinary chondrite slope calculations presented in Table 5, albeit with less resolution than the present study.

Iron meteorites dominate the high-mass meteorites. Previous approximations of total mass flux by meteorite type (e.g., Cassidy and Harvey 1991; Huss 1991) frequently omit large impactors, and result in an overestimate of ordinary chondritic material flux. However, large impactor estimates (e.g., Bland and Artemieva 2003, 2006) support the dominance of metallic material for large masses, in agreement with the small crater record (Paillou et al. 2004).

If the atmosphere on the early Earth was significantly denser than our present day atmosphere, the flux of meteorites in the 10^3–10^6 kg range increases significantly. This increase is counterbalanced in part by an increased mass loss through ablation, and results in a slight overall increase in the total flux of moderate-size meteorites, primarily irons and ordinary chondrites. The regional delivery of material is decreased slightly as well, due to the increased size of meteorite strewnfields.

Our results agree with prior studies (e.g., Anders 1989; Chyba and Sagan 1992) that carbonaceous meteorites were not a significant source of soluble carbon to the surface of the Earth. During the late-heavy bombardment, a biomass would have fallen to the Earth every few hundred thousand years. This number differs from the value of 10 million years of Whittet (1997) due to our assumption of a late-heavy bombardment period vs the gradual drop off used by Whittet (1997) and Chyba and Sagan (1992). This study also agrees with the Ir fluxes calculated by Kyte and Wasson (1986), and is consistent with the current Ir concentration of the Earth's crust. No previous study has quantified the flux of P or N to the surface of the Earth.

Implications for the Origin of Life

The biochemical process of glycolysis takes place with organic and phosphorus concentrations on the order of 10^{-3} to 10^{-5} M. This concentration range is typical for many biochemical processes (Nelson and Cox 2005 and refs. therein). Hence, the origin of life likely required concentrations equal to or above these concentrations.

The expected fluxes of C, N, and P to the ocean during the late-heavy bombardment to be 10^{-10}, 10^{-11}, and 10^{-11} M/year, respectively, assuming present day ocean mass. At steady state, the concentration of these species would be:

$$[X] = \frac{F_X \times t_{1/2}}{\ln 2} \tag{6}$$

where F_X is the flux of material X per year, and $t_{1/2}$ is the chemical half life of the material. Assuming a fairly long half life of ~10^4 years for most of these compounds, the steady state concentration of these species may be as high as 10^{-5}, 10^{-7}, and 10^{-7} M. With more reasonable half lives of ~100 years, these numbers decrease by a factor of 10. The ocean is a poor place for the concentration of prebiotic reagents due to this dilution effect.

Cratering by large impactors may have provided an excellent environment on the early Earth for the concentration of prebiotic reagents. With regional fluxes from meteorites reaching thousands of kilograms of reactive prebiotic reagents per square kilometer, these zones would have provided an effective geomorphologic zone wherein the concentration of prebiotic reagents could have reached steady state concentrations appropriate for the origin of life. The prebiotic chemicals in these regions would have been supplemented post-impact by both exogenous and endogenous compounds, continually renewing the reactive reagents that may have served as precursors to the origin of life.

Conclusions

We have quantified the fluxes of several extraterrestrial materials, and have provided our assumptions so that our calculated fluxes may be refined as future work provides better constraints.

Life may have originated shortly after the end of the heavy bombardment period, and the earliest evidence of life follows the putative late-heavy bombardment event by a few hundred million years (Schopf and Packer 1987; Mojzsis et al. 1996; Papineau et al. 2005). The extraterrestrial delivery of prebiotic reagents was dominated by two classes of material on the early Earth: a steady state flux of prebiotic reagents from IDPs dispersed across the surface of the Earth, and the stochastic delivery are substantial quantities of prebiotic reagents from large impactors to localized regions.

Acknowledgements Pasek was supported by a Bessey–LaPlace NAI center fellowship and a NAI Postdoctoral Fellowship. Early drafts of this MS benefited from comments by Ron Fevig and Virginia Pasek. Discussions with Brian Jackson and an anonymous reviewer further strengthened this MS.

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