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Extra-terrestrial influx rates of cosmogenic isotopes and platinum group elements: Realizable geochemical effects

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Abstract—We present estimates of “realizable” influx of selected cosmogenic isotopes, ^{3}He, ^{10}Be, ^{26}Al, and ^{14}C, and platinum group elements, Ir, Os, and Re on the earth via influx of meteoroids. We define *realizable* as the particulate fraction of mass influx which is included in standard geochemical analyses of terrestrial sediments. This is the surviving mass fraction of size $<$ 0.5–1 cm, which gets mixed with terrestrial samples, and is analyzed in normal terrestrial assays of sediments. Larger surviving meteoroid fragments, of the order of cm to m or larger, obviously belong to the *non-realizable* flux category, since (i) their distribution in terrestrial samples would be very patchy, resulting in a highly variable density matrix, and (ii) they would also generally (except in wide-diameter cores) be excluded from sediment cores. We estimate the realizable influx of meteoritic particles, based on a recent model describing production of smaller size fragments arising during the atmospheric entry of meteoroids. Implicit in this work is the assumption that the secondary fragments are not subject to much heating and therefore most of the initial ^{3}He (and noble gases) would be preserved in the secondary fragments since after break-up they are not subjected to much heating. Under this assumption, production of small size fragments in the ablation process constitutes a “safe” landing mechanism for parts of the meteoroid. In this paper, we show that the meteoritic ablation/fragmentation process produces a significant flux of ^{3}He, platinum group metals, and cosmogenic ^{26}Al. In fact, measurements of these isotopes in ocean sediments should allow a reasonable estimate of temporal variations in the flux of meteoroids of 50 cm to 5 m radii, which produce most of the secondary fragments in the size range $<$1 cm.

We would like to state here that, as pointed out in our previous work, stratospheric collections would be biased towards collection of the primary incident extra-terrestrial particles, whereas terrestrial accumulations representing large (area × time) accumulations, as in the case of ocean sediments, would efficiently sample the fragmented particles. *Copyright © 2003 Elsevier Ltd*

1. INTRODUCTION

In their passage through the atmosphere, meteoritic bodies undergo appreciable mass-wastage due to ablationary processes causing vaporization, melting, and fragmentation. Recently, Lal and Jull (2002) considered in some detail the effect of this process in altering the population of small size particles, which are produced from fragmentation of meteoroids impacting the Earth. They showed that this leads to an appreciably larger flux of: (i) an enhanced population of secondary fragments in the size range, 10^{-4} to 10 cm, produced in the fragmentation of meteoroids of size ~ few hundred cm, and (ii) vaporized mass flux, both of which exceed the near-Earth mass influx due to meteoroids of mass, m, $10^{-11} < m < 10^{7}$ g (corresponding radius, r, $10^{-4} < r < 10^{2}$ cm). Secondary fragments of size $>$100 microns arising from fragmentation of meteoroids would mostly be deposited in the vicinity of the point of entry of the meteoroid, due to Stokes settling. Smaller particles ($\leq$5 microns), and the vaporized mass fraction would be expected to be removed from the stratosphere at midlatitudes, 40°–50° in zones of turbulence at the tropopause. After entry in the troposphere, they would most likely be preferentially deposited in high latitudes via wet precipitation. Their deposition in the ocean bottom would however be diffused due to transport in the surface waters by ocean currents. For details, reference is made to Lal and Jull (2002).

In this paper, we adopt the fragmentation model of Lal and Jull (2002). These authors adopted the time-averaged fluxes of extra-terrestrial matter in the size range of radii, r, $10^{-4} < r < 10^{4}$ cm, as summarized by Ceplecha (1992). Ceplecha (2001) has recently revised the flux of meteoroids of $>$10 m radius objects, basing on results from the Space Watch project. We also point out here that the integrated fluxes in the particle size range, 5×10^{-4} to 2.3×10^{-2} cm (10^{-9} to 10^{-4} g), as determined by Love and Brownlee (1993) from studies of particle impacts on Long Duration Exposure Facility (LDEF) are higher by a factor of ~3 than those based on the data summarized by Ceplecha (1992), and the fluxes estimated by Grün et al. (1985). The measurements of Love and Brownlee (1993) are real measurements, whereas the studies of Ceplecha (1992) and Grün et al. (1985) are flux models based on extrapolations of measurements made with different methods, each covering only a limited mass range and each having a variety of uncertainties in mass and flux calibrations. For convenience, however, in this paper we will adopt the number-mass fluxes as given by Ceplecha (1992), which were adopted by Lal and Jull (2002) in their fragmentation model calculations. We wish to point out here that irrespective of what extra-terrestrial flux model we use, the critical result is robust such that an appreciable mass flux results in secondary particles in the size range 10^{-4} to 10 cm. Secondary fragments that are not heated much

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subsequently in their transit through the atmosphere, should serve as carriers of organic matter, volatiles, and noble gases present in the meteoroids.

Although the long-term averaged particle fluxes of smaller particles are greatly enhanced, these particles would not be sampled efficiently in stratospheric collections, because they are produced in fragmentation of larger size objects whose impact rates are small. Thus, stratospheric collections would be biased towards collection of the primary incident extra-terrestrial particles, whereas terrestrial accumulations representing large (area × time) products, as in the case of ocean sediments, would efficiently sample the fragmented particles.

We present here model calculations of the expected influx rates of the radioactive nuclides: ^{3}He, ^{10}Be, ^{26}Al, and ^{14}C, and three platinum group elements via impact of meteoroids on the Earth, and discuss the implications of the results in the light of reported measurements of their extra-terrestrial accretion by the Earth. We conclude that bulk of ^{3}He found in terrestrial sediments arises from the fragmentation of the meteoroids in the atmosphere (Lal and Jull, 2002), which contributes to soft landing of ^{3}He present in meteoritic material, and also augments the *realizable flux* of ^{3}He by producing a large population of small particles. The term "realizable" refers to the particulate fraction of mass flux, which is included in standard geochemical analyses of terrestrial sediments. We cannot however exclude that some of the ^{3}He may also be carried with small interplanetary particles, which have been irradiated with solar wind. The fragmentation model augments the *realizable flux* of platinum group elements.

2. METEOROID FRAGMENTATION MODEL

As mentioned earlier, we adopt the atmospheric fragmentation model of Lal and Jull (2002). Briefly, the model assumes that each meteoroid entering the atmosphere undergoes fragmentation as given by the break function, $g(r_0,r)$, describing the production of secondary fragments of radius in the fragmentation of a meteoroid:

$$g\ (r_0,\ r) = c \cdot r^{-a} \tag{1}$$

where c is a constant; α is slope in the differential spectrum of secondary particles. The break function, $g(r_0,r)$, describes the probability that a particle of initial radius, $r_{0,}$ will lead to a particle of radius, r on its entry through the atmosphere. The upper limit for the size of the fragmented particles is assumed to be $k_u r_0$, with $k_u = 0.5$. It is assumed that only particles of size greater than r_l ($>100\ \mu$) undergo fragmentation. Smaller particles are not heated much and escape melting and fragmentation. If we designate the initial differential number-radius distribution function of interplanetary objects impacting the Earth, as $n_0(r)$:

$$n_0(r) = \left[\frac{dn}{dr}\right]_{initial} = f(r_0) \tag{2}$$

the modified particle size distribution (after a single stage fragmentation in the atmosphere), and the combined number-radius distribution of primary particles of radius, $r < r_0$, and all secondary particles is given by:

$$n(r) = f(r_0)_{r_0<r_l} + \int_{r_l}^{\infty} f\ (r_0) \cdot g\ (r_0,\ r) \cdot dr_0 \tag{3}$$

With the requirement of mass balance, Lal and Jull (2002) show that the resulting size distribution of meteoritic particles, primary and secondary, in the atmosphere is given by:

$$n(r)|_{atm} = f\ (r)_{r_0<r_l} + m_f \cdot (4-\alpha) \cdot r^{-a} \cdot \int_{r}^{\infty} \frac{f\ (r_0) \cdot r_0{}^3}{[(k_u \cdot r_0)^{(4-\alpha)} - (r_{\min})^{(4-\alpha)}]}\, dr_0 \tag{4}$$

where m_f is the average mass fraction which survives during ablation; the rest is vaporized. The value of the slope, α in the break function, is estimated to lie between 4 and 5, based on studies of the observed population of shower and sporadic meteoroids, and the hypervelocity impact studies in the laboratory (see Lal and Jull, 2002).

The results of integration of Eqn. 4 with the plausible values: $\alpha = 4.1$, $m_f = 0.5$, $K_u = 0.5$ are shown in Figure 1, separately for differential number-radius, and mass fluxes in bins of mass interval, d ($\log_{10}$ (m)) = 1. As discussed earlier (Lal and Jull, 2000), the results are not very sensitive to the chosen value of α in the range 4–5. The flux units are per year$^-$ over the earth's surface; mass is expressed in grams, and radius in centimeters. The model results are near-straight lines since we assumed a constant value for $\alpha = 4.1$) in the break function (Eqn. 1). The wiggly lines represent the differential fluxes for the extra-terrestrial particles in near-Earth space based on data summarized by Ceplecha (1992).

The contribution to production of secondary particles depends on the slope in the differential number-radius spectrum of the primary meteoroid population. To be an effective producer of secondary fragments, the slope has to be much smaller than that in the break function, namely, $\alpha = 4.1$. Over the radius range, 1–5×10^2 cm, the slope in the primary dn/dr spectrum lies between 2 and 3 compared to slopes of (4–5) for most of the lower and higher radii, respectively (see Fig. 2 in Lal and Jull, 2002). The effect of fragmentation of meteoroids in this size range can be seen in Figure 2 where we have plotted the relative contributions to the production of secondary fragments, from fragmentation of meteoroids of different sizes during atmospheric ablation. Most of the secondary particles arise from fragmentation of meteoroids of 50 to 500 cm radius.

In Table 1, we present the near-Earth particle fluxes and the estimated long time-averaged atmospheric fluxes of extra-terrestrial particles, in bins of mass interval, d ($\log_{10}$m) = 3. To these fluxes must be added the total *vaporized mass flux*. The numbers in the last column of Table 1 differ somewhat from those in Lal and Jull (2002), since the present upper limit of integration in Eqn. 4 is larger, 10^4 cm. It should be noted here that since meteoroid fluxes are finite and small, especially for meteoroids of > 5–10 m radius, the efficiency of sampling secondary particles would depend on the product, collection area × time, represented by the collection. This point has been treated in detail by Lal and Jull (2002) who have

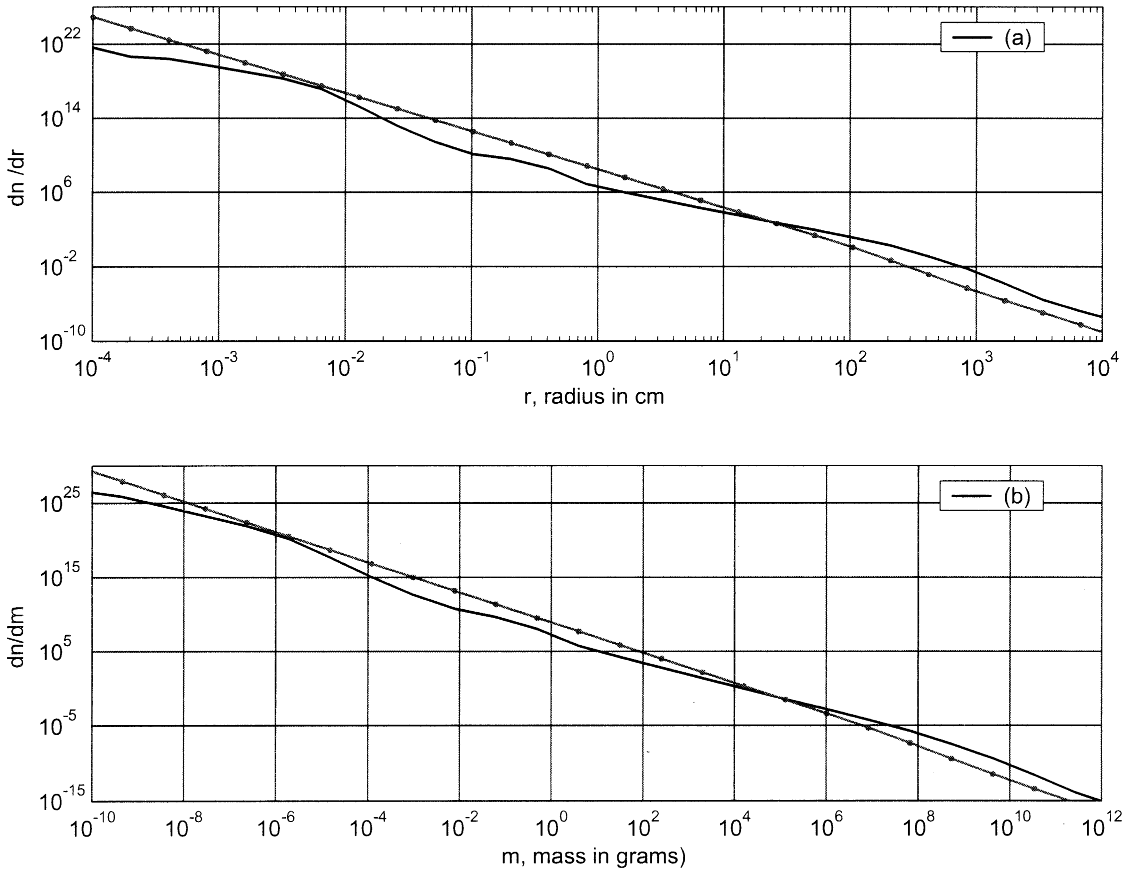

Fig. 1. Differential fluxes (per year on the earth) of extra-terrestrial particles in near-Earth space, based on observational data reviewed by Ceplecha (1992). The wiggly line in (a) gives the differential number of primary particles of radius, r, and that in (b) gives the differential number of primary particles of mass, m. The dotted lines in (a) and (b) give the corresponding fluxes of secondary particles produced in the atmosphere based on the fragmentation model of Lal and Jull (2002).

shown that in experiments based on studies of marine sediments, the product of "collection area and time" represented by the sample analyzed should be $\geq 10^3$, 10^5, and 10^8 (cm^2.y) respectively for efficiently sampling fragments produced by meteoroids of $>$ 10, 10^2, and $>10^3$ cm radii. *Long term-averaged fluxes* can only be obtained if the sample collector meets this condition.

The last row in Table 1 gives the mass of secondary fragments produced in the size fractions $10^{-4} < r < 10^{-1}$ and would contribute primarily to the *realizable flux* of extra-terrestrial matter in sediments. The realizable mass flux is seen to be appreciable, comparable to the total mass flux in the primary population for meteoroids of radii exceeding 100 cm.

3. ACCRETION FLUXES OF COSMOGENIC NUCLIDES AND PLATINUM GROUP ELEMENTS

We will now estimate the *long-term averaged fluxes* of galactic cosmic ray (GCR) produced ^{3}He and radionuclides, ^{10}Be, ^{26}Al, and ^{14}C, and platinum group elements, Ir, Os, and Re in the different size fractions in the secondary fragments.

3.1. GCR Produced Nuclides, ^{3}He, ^{10}Be, ^{26}Al, and ^{14}C

The problem of cosmogenic production of these nuclides has been dealt with extensively in the past. We adopt the most detailed recent calculations presented by Leya et al. (2000) who have given the nuclide production rates of ^{3}He, ^{10}Be, ^{26}Al, and ^{14}C by galactic cosmic radiation in stony meteorites of radii, 5, 10, 15, 25, 32, 40, 50, 100, and 120 cm. For larger radii meteorites, we assumed that the average production rate in the meteorite decreased exponentially with a mean value of 60 cm. In the case of ^{3}He, we added a uniform contribution of meteoritic (planetary) ^{3}He, which was estimated using a procedure suggested by K. Marti (private communication). The trapped xenon concentrations in meteorites have been determined by Marti (1967). Using the isotopic ratios, $^3\text{He}/^4\text{He} = 1.4 \pm 0.3 \times 10^{-4}$ and $^4\text{He}/^{132}\text{Xe} = 374 \pm 72$ as determined by Bussemann et al. (2000), we obtain the mean values of 3.7×10^{-10} cc STP and 1.0×10^{-10} cc STP for the planetary ^{3}He concentrations of carbonaceous chondrites (CC) and ordinary chondrites (Ch.), respectively.

In the case of the radionuclides, ^{10}Be, ^{26}Al, and ^{14}C, we assumed that their concentrations in meteorites were in secular equilibrium with production. In the case of ^{3}He, we assumed that the meteorites had an average exposure age of 10 my. We

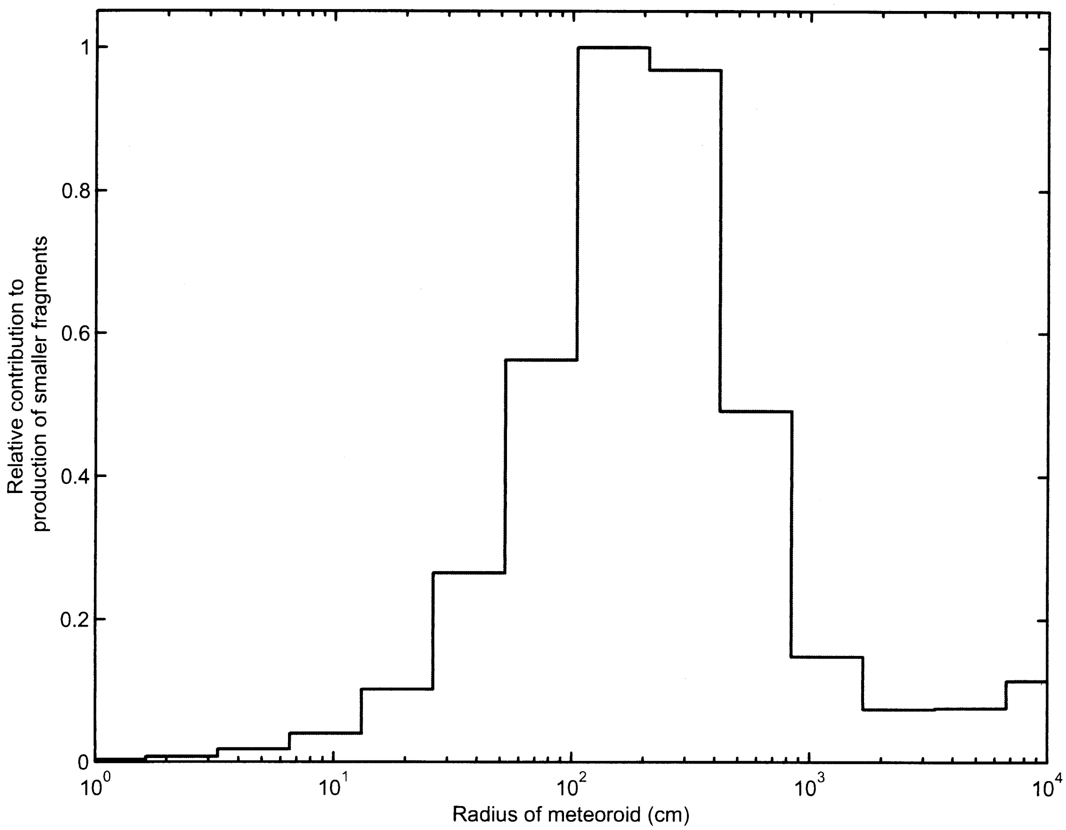

Fig. 2. Relative contributions to production of secondary fragments, from fragmentation of meteoroids of different sizes during atmospheric ablation, normalized to unity at the peak.

further assume that the nuclide concentrations of the fragments are given by the average concentration of the nuclide in the meteoroid fragmented.

The results of the calculations based on the above estimates of nuclide concentrations are shown in Figure 3, and presented in Tables 2 and 3 in the same format as Table 1. The differences introduced due to differences in the planetary component of ^{3}He concentrations between carbonaceous (CC) and ordinary chondrites (Ch.) are small, and we ignore this difference. Essentially nearly all of the ^{3}He in the fragments is derived from GCR interactions.

3.2. Platinum Group Elements, Ir, Os, and Re

We adopt for the concentrations of these elements the meteoritic abundance values given by Anders and Grevesse (1989). Using the atomic abundances given by these authors, and values of 10.6% and 27.2%, respectively for the mean Si concentration (w/w) of carbonaceous (CC) and ordinary (Ch.) chondrites, we obtained the mean values of 0.48 (1.23), 0.49 (1.25), and 0.037 (0.094) ppm for Ir, Os, and Re, respectively; the first value is for CC, the second within parenthesis is for Ch. meteorites. These values agree fairly well with the mean concentrations of Ir, Os, and Re in CC (Ch.) meteorites as given by

Table 1. Near-Earth, and the estimated long time-averaged fluxes of extra-terrestrial particles due to atmospheric fragmentation, in bins of d ($\log_{10}$r) = 1, and d ($\log_{10}$m) = 3.

Size range (cm)	Mass range (g)	Near-Earth mass flux (Ceplecha, 1992) (g/y)	Estimated flux of fragmented particles to the earth (g/y)
$10^{-4} < r < 10^{-3}$	$10^{-11} < m < 10^{-8}$	1.1×10^8	1.4×10^{10}
$10^{-3} < r < 10^{-2}$	$10^{-8} < m < 10^{-5}$	2.6×10^9	1.1×10^{10}
$10^{-2} < r < 10^{-1}$	$10^{-5} < m < 10^{-2}$	4.9×10^8	8.2×10^9
$10^{-1} < r < 1$	$10^{-2} < m < 10$	1.1×10^8	6.5×10^9
$10^0 < r < 10^1$	$10^1 < m < 10^4$	3.9×10^8	5.1×10^9
$10^1 < r < 10^2$	$10^4 < m < 10^7$	8.5×10^9	3.8×10^9
$10^2 < r < 10^3$	$10^7 < m < 10^{10}$	5.9×10^{10}	1.5×10^9
$10^{-4} < r < 10^{-1}$	$10^{-11} < m < 10^{-2}$	3.2×10^9	3.3×10^{10}

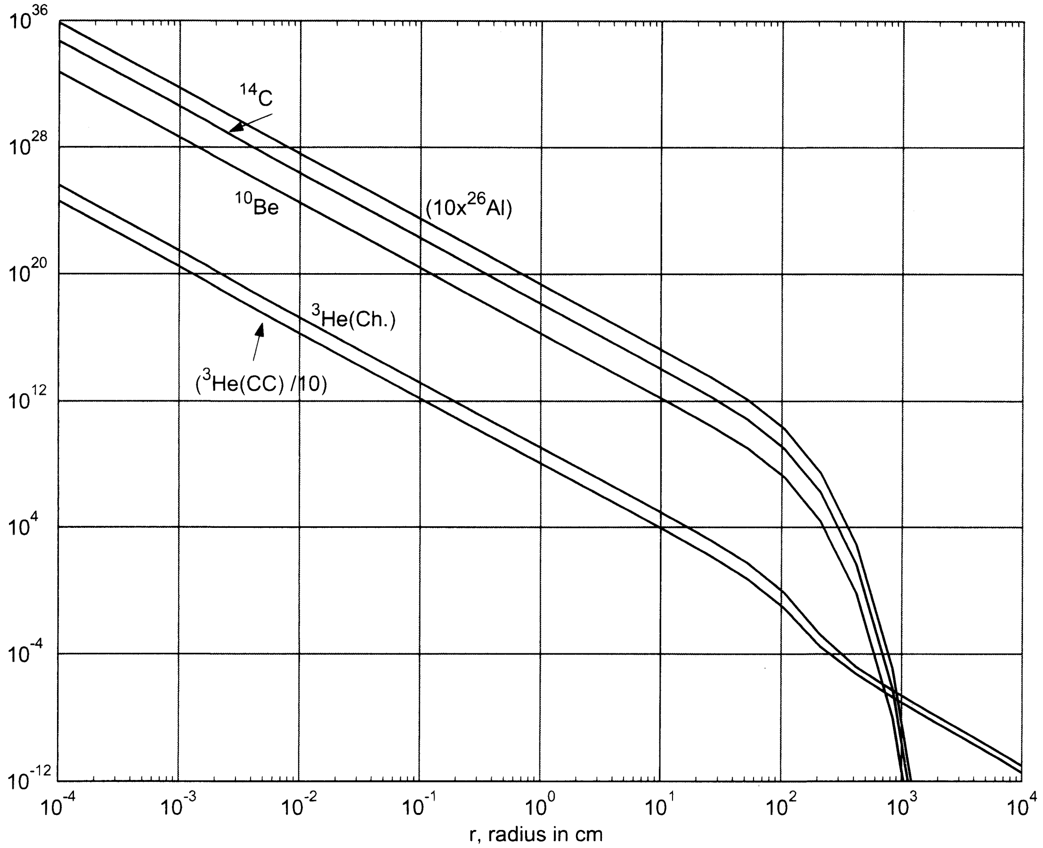

Fig. 3. Estimated differential concentrations of isotopes in the secondary fragments of different radii are plotted as a function of radius, based on the fragmentation model of Lal and Jull (2002). The curve-marked ^{3}He represent average contributions from carbonaceous (CC) and ordinary (Ch.) chondrites. ^{3}He concentrations are given in units of 10^{-8} cc/g. Other differential concentration (atoms/g) curves are for the isotopes, ^{14}C, ^{26}Al, and ^{10}Be, produced by the galactic cosmic radiation in ordinary chondrites, based on calculations of nuclide production rates by Leya et al. (2000). The ^{3}He curve for CC meteorites is divided by 10, and that for ^{26}Al is multiplied by 10 for clarity.

Lodders and Fegley (1998), 0.47 (1.1), 0.49 (1.2), and 0.038 (0.073) ppm, respectively. The results of calculations are presented in Table 4 in the same format as Tables 1, 2, and 3.

4. DISCUSSION

4.1. ^{3}He

Results of our model calculations are presented in Figure 3 and in Table 2. Ablation during atmospheric entry leads to heating and fragmentation of meteoroids, with significant mass wastage. Except for primary particles smaller than 100 μm, which are not heated appreciably during atmospheric entry (Farley et al., 1997), others suffer intensive heating and fragmentation. Before proceeding further, we must note that very little is known about the survival efficiency of larger size fragmentation debris, and in particular about the survival of volatiles like He (Don Brownlee, private communication). For particles to survive atmospheric entry, the parent particles have

Table 2. Estimated long time-averaged fluxes of GCR produced ^{3}He due to fragmentation of carbonaceous (CC) and ordinary (Ch.) meteoroids in the atmosphere, in bins of d ($\log_{10}$r) = 1, and d ($\log_{10}$m) = 3.

		Estimated average ^{3}He fluxes via fragments produced in the atmosphere	
Size range (cm)	Mass range (g)	^{3}He(CC) × 10^{-15} cc/(cm^2 · y)	^{3}He(Ch.) × 10^{-15} cc/(cm^2 · y)
$10^{-4} < r < 10^{-3}$	$10^{-11} < m < 10^{-8}$	1.2×10^{-1}	1.2×10^{-1}
$10^{-3} < r < 10^{-2}$	$10^{-8} < m < 10^{-5}$	8.4×10^{-2}	8.3×10^{-2}
$10^{-2} < r < 10^{-1}$	$10^{-5} < m < 10^{-2}$	5.9×10^{-2}	5.8×10^{-2}
$10^{-1} < r < 1$	$10^{-2} < m < 10$	4.7×10^{-2}	4.6×10^{-2}
$10^{0} < r < 10^{1}$	$10^{1} < m < 10^{4}$	3.7×10^{-2}	3.6×10^{-2}
$10^{1} < r < 10^{2}$	$10^{4} < m < 10^{7}$	2.2×10^{-2}	2.1×10^{-2}
$10^{2} < r < 10^{3}$	$10^{7} < m < 10^{10}$	9.0×10^{-4}	8.0×10^{-4}
$10^{-4} < r < 10^{-1}$	$10^{-11} < m < 10^{-2}$	2.7×10^{-1}	2.6×10^{-1}

Table 3. Estimated long time-averaged fluxes of GCR produced ^{10}Be, ^{26}Al and ^{14}C due to fragmentation of meteoroids in the atmosphere, in bins of d ($\log_{10}$r) = 1, and d ($\log_{10}$m) = 3.

		Estimated average nuclide fluxes via fragments produced in the atmosphere (atoms/cm^2 · year)		
Size range (cm)	Mass range (g)	^{10}Be	^{26}Al	^{14}C
$10^{-4} < r < 10^{-8}$	$10^{-11} < m < 10^{-8}$	16	23.4	1.7×10^{-1}
$10^{-3} < r < 10^{-2}$	$10^{-8} < m < 10^{-5}$	10.6	16.5	1.3×10^{-1}
$10^{-2} < r < 10^{-1}$	$10^{-5} < m < 10^{-2}$	7.3	12.1	9.7×10^{-2}
$10^{-1} < r < 1$	$10^{-2} < m < 10$	5.8	9.6	7.7×10^{-2}
$10^{0} < r < 10^{2}$	$10^{4} < m < 10^{7}$	4.6	7.6	6.1×10^{-2}
$10^{1} < r < 10^{2}$	$10^{4} < m < 10^{7}$	2.7	4.5	3.8×10^{-2}
$10^{2} < r < 10^{3}$	$10^{7} < m < 10^{10}$	9.8×10^{-2}	1.8×10^{-1}	1.5×10^{-3}
$10^{-4} < r < 10^{-1}$	$10^{-11} < m < 10^{-2}$	3.4×10^{1}	5.2×10^{1}	4.0×10^{-1}

to fragment near 100 km altitude, and then decelerate to low velocities. Brownlee states: “Most meteoroids fragment at high speed. If they fragment at high speed and ‘lower than IDP [interplanetary dust particles] deceleration altitudes’ then the generated particles are exposed to severe heating. The frictional power density generated by a small particle at a given speed varies directly as the ambient air density, which decreases by a factor of ten every 15 km change in altitude. Typically larger bodies fragment below the altitude where IDPs decelerate and thus their debris should be much more strongly heated.”

Realizing our present lack of understanding of the survival efficiency of particles and the volatiles in the fragmentation process, we have proceeded in this paper with the working hypothesis that particles of radius, 10^{-4} to 10^{-1} cm (10^{-11} g $< m < 10^{-2}$ g) are fairly well preserved. We also assume that most of the ^{3}He should be well preserved in the secondary fragments in this size range. The mass of secondary fragments, $10^{-4} < r < 10^{-1}$ ($10^{-11} < m < 10^{-2}$), is appreciable, 3.3×10^{10} g/(year. Earth) (Table 1). This component, deriving from the interior solid parts of the meteoroids, should be well preserved in sediments, and constitutes what we call the realizable extra-terrestrial flux for ^{3}He. The corresponding ^{3}He flux values for CC and Ch. meteoroids (Table 2) are 0.27×10^{-15} cc/(cm^2. y) and 0.26×10^{-15} cc/(cm^2. y), respectively. This is a significant flux, being comparable to the measured ^{3}He in sediments (as discussed below), and would not be expected to be there had it not been for the fact that these fragments soft landed, in the sense they are assumed not to be heated much after production in the fragmentation process.

Several measurements have recently been reported of ^{3}He concentrations in sediments. Farley and Patterson (1995) reported estimated ^{3}He fluxes of 0.5–1.75×10^{-15} cc ^{3}He/(cm^2. y) in sediments from the mid-Atlantic Ridge, during 250–400 ky B. P. Similar concentrations, $1.1 \pm 0.4 \times 10^{-15}$ cc ^{3}He/(cm^2. y) are reported by Marcantonio et al. (1996, 1999) in Equatorial Indian and Pacific Ocean cores, over the past 200 ky. Brook et al. (2000) reported measurements of ^{3}He concentrations in Greenland ice core from the Summit. They measured ^{3}He fluxes of $0.62 \pm 0.27 \times 10^{-15}$ cc ^{3}He/(cm^2. y) for ~400-yr-old ice. Earlier measurements by Sowers et al. (1993) for the Vostok ice core yielded fluxes of $0.77 \pm 0.25 \times 10^{-15}$ cc ^{3}He/(cm^2. y) for ice samples of age ~3.8 ky B. P. and 75–97 ky B. P. These depositional fluxes, averaging to $\sim 1.0 \times 10^{-15}$ cc ^{3}He/(cm^2. y), should be compared with the mean value of 0.29×10^{-15} cc/(cm^2. y), obtained from the model calculations presented in this paper for the GCR produced ^{3}He.

So far, we did not consider the possibility of influx of solar wind ^{3}He via small particles, which escape heating in the atmosphere. Measurements by Nier and Schlutter (1992) and Pepin et al. (2000) show that stratospheric cosmic dust particles (termed interplanetary dust particles, IDPs) often contain high amounts of helium with high ^{3}He/^{4}He ratios, and the ^{3}He concentrations are appreciable. The masses of the particles studied by Pepin et al. (2000) lie in the range 0.2–30 ng. There is apparent size dependence, with larger particles having smaller ^{3}He concentrations. IDPs of ~1 ng mass have 10^{-5} to 10^{-3} cc ^{3}He/g, whereas the particles of 5–50 ng have ~ 10^{-7} to 10^{-5} cc ^{3}He/g. Taking the mass fluxes of primary extra-terrestrial particles in the size range $< 10^{-2}$ cm (Table 1), and assuming an average ^{3}He concentration of 10^{-7} cc ^{3}He/g, we

Table 4. Estimated long time-averaged extra-terrestrial fluxes of three platinum group elements due to fragmentation of meteoroids in the atmosphere, in bins of d ($\log_{10}$r) = 1, and d ($\log_{10}$m) = 3.

		Fluxes via fragments produced in the atmosphere (g/cm^2 · my)					
Size range (cm)	Mass range (g)	Ir (CC)	Ir (Ch.)	Os (CC)	Os (Ch.)	Re (CC)	Re (Ch.)
$10^{-4} < r < 10^{-3}$	$10^{-11} < m < 10^{-8}$	1.4×10^{-9}	3.5×10^{-9}	1.4×10^{-9}	3.5×10^{-8}	1.0×10^{-10}	2.6×10^{-10}
$10^{-3} < r < 10^{-2}$	$10^{-8} < m < 10^{-5}$	1.0×10^{-9}	2.6×10^{-9}	1.0×10^{-9}	2.6×10^{-9}	7.7×10^{-11}	2.0×10^{-10}
$10^{-2} < r < 10^{-1}$	$10^{-5} < m < 10^{-2}$	7.7×10^{-10}	2.0×10^{-9}	7.8×10^{-10}	2.0×10^{-9}	5.8×10^{-11}	1.5×10^{-10}
$10^{-1} < r < 10^{0}$	$10^{-2} < m < 10^{1}$	6.1×10^{-10}	1.6×10^{-9}	6.2×10^{-10}	1.6×10^{-9}	4.6×10^{-11}	1.2×10^{-10}
$10^{0} < r < 10^{1}$	$10^{1} < m < 10^{4}$	4.9×10^{-10}	1.2×10^{-9}	4.9×10^{-10}	1.3×10^{-9}	3.7×10^{-11}	9.4×10^{-11}
$10^{1} < r < 10^{2}$	$10^{4} < m < 10^{7}$	3.6×10^{-10}	9.4×10^{-10}	3.7×10^{-10}	9.3×10^{-10}	2.7×10^{-11}	7.0×10^{-11}
$10^{2} < r < 10^{3}$	$10^{7} < m < 10^{10}$	1.4×10^{-10}	3.5×10^{-10}	1.4×10^{-10}	3.6×10^{-10}	1.1×10^{-11}	2.7×10^{-11}
$10^{-4} < r < 10^{-1}$	$10^{-11} < m < 10^{-2}$	3.1×10^{-9}	8.0×10^{-9}	3.2×10^{-9}	8.1×10^{-9}	2.4×10^{-10}	6.1×10^{-10}

obtain a value of 5×10^{-15} cc ^{3}He/(cm^2. y) for the flux of ^{3}He via IDPs. However, this must be treated as an upper limit because ^{3}He in the IDPs may not be preserved in sediments. The IDPs are known to be fluffy and amorphous (as a result of radiation damage due to implantation of solar wind and solar flare ions). Consequently, the ^{3}He carried by the IDPs may be lost quickly in sediments by chemical action. Because of the lack of our understanding of the behavior of IDPs in sediments, it is therefore difficult to reach any conclusions at the present moment about the role of IDPs in contributing to the ^{3}He content of the sediments. This question can possibly be answered by subjecting IDPs to seawater.

4.2. ^{10}Be, ^{26}Al, and ^{14}C

Based on the GCR production rates as given by Leya et al. (2000), the influx rates of ^{10}Be, ^{26}Al, and ^{14}C via fragmented particles are given in Figure 3 and Table 3. The last row in Table 3 gives their realizable contributions (for the size range 10^{-4}–10^{-1} cm) in sediments. The volatilized fraction of ^{10}Be, ^{26}Al would be removed to sediments in short time periods $<$1000 yr. The volatilized ^{14}C will mix with the atmospheric carbon dioxide; only a small fraction of this would be removed to the ocean sediments since the residence time of carbon in the oceans is ~50,000 yr. Therefore, only in the case of ^{10}Be and ^{26}Al are their fluxes to sediments twice the values given in the last row of Table 3; the value for ^{14}C is not affected by the volatilized fraction. The global atmospheric production rates of ^{10}Be, ^{26}Al, and ^{14}C are 1.4×10^6, 4.4×10^3, and 7.9×10^7 atoms/(cm^2.s), respectively (Lal and Peters, 1967). The meteoritic contributions for ^{10}Be and ^{14}C are thus smaller by 4 and 8 orders of magnitude than their production in the Earth's atmosphere, respectively. (Nevertheless, we have presented these figures because in planets with small atmospheres, or of composition unfavorable to production of ^{10}Be and ^{14}C, the meteoritic contributions may become significant). In the case of ^{26}Al, however, the meteoritic contribution is not small; the value in Table 3 is ~2.3% of the cosmogenic production in the Earth's atmosphere. At such levels, one may expect to observe high pulses in sediments associated with enhanced fluxes of meteoroids during certain epochs in the past. (We would like to note here that in the case of ^{26}Al, the contribution to its extra-terrestrial flux due to production in IDPs by solar flare accelerated energetic particles is estimated to be at least an order of magnitude smaller than that due to galactic cosmic ray produced ^{26}Al in large meteoroids.)

4.3. Platinum Group Elements

Sufficiently representative terrestrial flux estimates are available in the case of Ir (Kyte and Wasson, 1986; Kyte et al., 1993). This is however not the case for Os and Re, although Peuker-Ehrenbrink and Ravizza (2000) used a model to obtain reasonable fluxes based on Os. In the case of Os, the results of Lee et al. (2003) show that it may not be an easy task to estimate its globally representative flux to the sediments, since Os is preferentially precipitated in reducing coastal regions. We will therefore only confine ourselves to a discussion of the modeled Ir fluxes in relation to its measured fluxes in sediments.

Kyte et al. (1993) measured Ir in several sections of a long piston core (LL4-GPC3) from the central North Pacific and obtained a time series of the flux of Ir since the late Cretaceous. They obtained values lying between 10–17 ng/(cm^2.my) for six epochs covering the time range 1.8–66.4 my, and a value of 30 ng/(cm^2.my) for the Pleistocene (0–1.8 my). In an earlier paper, Kyte and Wasson (1986) measured a mean iridium flux of 13 ng/(cm^2.my) in a long sediment core section from the same Pacific core covering the time period 33 to 67 my. These fluxes have to be corrected for terrestrial Ir contributions, estimated to lie between 1 ng/(cm^2.my) from eolian deposition, and 7 ng/(cm^2.my) from authigenic deposition. Thus, over the past 60 my, the deposition rate of extra-terrestrial Ir seems to range from 5 to 25 ng/(cm^2.my), with an uncertainty of ±4 ng/(cm^2.my).

We obtained values of 3 and 8 ng/(cm^2.my) for the Ir fluxes from secondary fragments in the size range, $10^{-4} < r < 10^{-1}$ cm arising from CC and Ch. meteorites respectively (Table 4). To this we must add the amount expected to be deposited globally from vaporization of meteorites during ablation. Taking a value of 50% as the volatilized mass fraction (Lal and Jull, 2002), we obtain a value of 3.55×10^{10} for the flux of the vaporized mass (/yr. Earth). This corresponds to additional Ir depositional fluxes of 3.0 and 7.4 ng/(cm^2.my) for CC and Ch. meteoroids, respectively. The total Ir flux therefore lies between 6 and 15.4 ng/(cm^2.my), which is in good agreement with the value of (5–25) ± 4 ng/(cm^2.my), based on Kyte et al. (1993) and Kyte and Wasson (1986), discussed above.

5. CONCLUSIONS

We have presented results of model calculations of *realizable* influx of galactic cosmic ray produced nuclides, ^{3}He, ^{10}Be, ^{26}Al, and ^{14}C due to fragmentation of meteoroids during their passage through the atmosphere. Two unique features of this model are that: (1) it results in soft landing of GCR produced ^{3}He in the secondary fragments arising from a breakup of the meteoroid, and (2) it distributes the larger mass meteoroids as small particles on the Earth, making it possible to efficiently detect extra-terrestrial flux in terrestrial deposits. One way to state this is that the break-up makes the influx of large meteoroids *realizable*, in that the material is dispersed throughout the sediments. In fact, it is now recognized that virtually all stony meteorites are irregular unmolten atmospheric fragmentation debris of larger bodies (Brownlee, private communication; Engrand and Maurette, 1998; Taylor and Lever, 2001).

Model fluxes of ^{3}He and Ir due to fragmentation seem to explain their measured depositional fluxes satisfactorily. The two cases differ substantially in their modes of deposition via meteoroids. In the case of Ir, about half of its flux comes from the vapor produced during volatilization of meteoroids, and therefore an agreement with its observed depositional flux does not constitute a test for the validity or otherwise of the fragmentation model proposed by Lal and Jull (2002). The validity of this model is put to stringent test in the case of ^{3}He, since in this case, it predicts significant survival of GCR produced ^{3}He via production of secondary fragments which are not heated appreciably in the atmosphere; note that the ablated vapor component does not contribute to ^{3}He in the sediments. The break-up model predicts ^{3}He fluxes which are lower by a factor of ~3 compared to the observed depositional fluxes of ^{3}He in sediments and in ice, as discussed in Section 4. This is not a serious discrepancy, considering present uncertainties in the meteorite fluxes, and in the model parameters. We must also stress here that the yield of secondary fragments is quite critically dependent on the slopes in the differential number-radius spectra of the primary meteoroid population. If we are underestimating the yield of secondary fragments by a factor of ~3 (needed to explain the discrepancy in the depositional flux of ^{3}He), this would raise the predicted value for Ir only by a factor of 2, since our model predicts ~50% deposition due to vaporization of meteoroids. However, as mentioned in the previous section, the explanation of the discrepancy may lie in the additional contribution from solar wind implanted ^{3}He in particles of radii smaller than 100 μm, which are not expected to be heated much during entry in the atmosphere. At the present time, one of the important questions is: what fraction of ^{3}He measured in sediments (Farley and Patterson, 1995; Marcantonio et al., 1996) is contributed from IDPs? It is quite likely that these particles, being fluffy and amorphous, may in fact lose most of their ^{3}He during their residence in the corrosive sediments. An insight into the retention of solar ^{3}He in micrometeorite particles of 50 to 400 μm recovered from Antarctic ice was obtained by Stuart et al. (1999) from laser extraction experiments. The degree of corrosion and therefore the loss of solar ^{3}He from micrometeorites in ocean sediments may be much more severe! This hypothesis, however, needs to be tested.

We have also presented model calculations for extra-terrestrial influx of cosmogenic nuclides, ^{10}Be, ^{26}Al, and ^{14}C. The contributions from break-up of meteoroids are insignificant for ^{10}Be and ^{14}C, which are produced efficiently in the atmosphere from N and O. The meteoroid flux constitutes about 2% on the average of the terrestrial inventory of ^{26}Al, which is produced primarily in cosmic ray interactions with atmospheric Ar, whose concentration is 0.9% (v/v). One may therefore expect to observe high ^{26}Al concentration pulses in sediments during periods of enhanced fluxes of meteoroids in the past. We wish to point out here that in the case of planets with thin atmospheres, meteoroid contribution would be expected to be important for the three nuclides: ^{10}Be, ^{26}Al, and ^{14}C.

Interestingly, the meteoroid model presented here predicts that: (i) the population of IDPs sampled in the stratosphere would mostly be the primary interplanetary dust particles, but that (ii) the extra-terrestrial particles in the size range 0.1 mm to 1 cm found in ice cores and in sediments would primarily be the secondary fragments produced in ablation/break-up of incident meteoroids of radii 50 cm to 5 m. These facts and the expected fluxes of isotopes and platinum group elements should allow stringent testing of the fragmentation model of Lal and Jull (2002).

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REFERENCES

Anders E. and Grevesse N. (1989) Abundance of the elements: Meteoritic and solar. *Geochim. Cosmochim. Acta* **53,** 197–214.

Brook E. J., Kurz M. D., and Curtice J. (2000) Accretion of interplanetary dust in polar ice. *Geophys. Res. Lett.* **27,** 3145–3148.

Bussemann H., Baur H., and Wieler R. (2000) Primordial noble gases in "phase Q" in carbonaceous and ordinary chondrites studied by closed-system stepped etching. *Meteoritics Planet. Sci.* **35,** 949–973.

Ceplecha Z. (1992) Influx of interplanetary bodies onto Earth. *Astron. Astrophys.* **263,** 361–366.

Ceplecha Z. (2001) The meteoroidal influx to the Earth. In *Collisional Processes in the Solar System* (eds. M. Ya. Markov and H. Rickman), pp. 35–50. Kluwer Academic Publishers.

Engrand C. and Maurette M. (1998) Carbonaceous meteorites from Antarctica. *Metoritics and Planet. Sci.* **33,** 565–580.

Farley K. A. and Patterson D. B. (1995) A 100-kyr periodicity in the flux of extra-terrestrial ^{3}He to the sea floor. *Nature* **378,** 600–603.

Grun E., Zook H. A., Fechtig H., and Giese R. H. (1985) Collisional balance of the meteoritic complex. *Icarus* **62,** 244–272.

Kyte F. and Wasson J. T. (1986) Accretion rate of extra-terrestrial matter: Iridium deposited 33 to 67 million years ago. *Science* **232,** 1225–1229.

Kyte F. T., Leinen M., Heath R. G., and Zhou L. (1993) Cenozoic sedimentation history of the North Pacific: Inferences from the elemental geochemistry of core LL44-GPC3. *Geochim. Cosmochim. Acta* **57,** 1719–1740.

Lal D, Peters B (1967) Cosmic ray produced radioactivity on the earth. *Handbuch der Physik.* Springer-Verlag, Berlin. **46/2,** 551–612.

Lal D. and Jull A. J. T. (2002) Atmospheric cosmic dust fluxes in the size range 10^{-4} to 10 centimeters. *Astrophys. J.* **576,** 1090–1097.

Lee C. T., Wasserburg G. J. and Kyte F. (2003). Platinum-group elements (PGE) and rhenium in marinesediments across the Createous-Tertiary boundary: Constraints on Re-PGE transport in the marine environment. *Geochim. Cosmochim. Acta* **67,** 655–670.

Leya I., Lange H., Neumann S., Wieler R., and Michel R. (2000) The production of cosmogenic nuclides in stony meteoroids by galactic cosmic ray particles. *Meteoritics Planet. Sci.* **35,** 259–286.

Lodders K. and Fegley B., Jr.. (1998) *The Planetary Scientist's Companion.* Oxford University Press, 371 pp.

Love S. G. and Brownlee D. E. (1993) A direct measurement of the terrestrial mass accretion rate of cosmic dust. *Science* **262,** 550–553.

Marcantonio F., Anderson R. F., Stute M., Kumar N., Schlosser P., and Mix A. (1996) Extra-terrestrial ^{3}He as a tracer of marine sediment transport and accumulation. *Nature* **383,** 705–707.

Marcantonio F., Turekian K. K., Higgins S., Anderson R. F., Stute M., and Schlosser P. (1999) The accretion rate of extra-terrestrial ^{3}He based on oceanic ^{230}Th flux and the relation to Os isotope variation over the past 200,000 years in an Indian ocean core. *Earth Planet. Sci. Lett.* **170,** 157–168.

Marti K. (1967) Trapped xenon and the classification of chondrites. *Earth Planet. Sci. Lett.* **2,** 193–196.

Nier A. O. and Schlutter D. J. (1992) Extraction of helium from individual interplanetary dust particles by step heating. *Meteoritics* **27,** 166–173.

Pepin R. O., Palma R. L., and Schlutter D. J. (2000) Noble gases in interplanetary dust particles, I: The excess helium-3 problem and estimates of the relative fluxes of solar wind and solar energetic particles in interplanetary space. *Meteoritics Planet. Sci.* **35,** 495–504.

Peuker-Ehrenbrink B. and Ravizza G. (2000) The effects of sampling artifacts on cosmic dust flux estimates: A reevaluation of nonvolatile tracers (Os, Ir). *Geochim. Cosmochim. Acta* **64,** 1965–1970.

Sowers T., Bender M., Labeyne L., Martinson D., Jouzel J., Raynaud D., Pichon J. J., and Korotkevich J. S. (1993) A 135,000 year Vostok-SPECMAP common temporal framework. *Paleoceanography* **8,** 737–766.

Stuart F. M., Harrop P. J., Knott S., and Turner G. (1999) Laser extraction of helium isotopes from Antarctic micrometeorites: Source of He and implications for the flux of extra-terrestrial ^{3}He to Earth. *Geochim. Cosmochim. Acta* **63,** 2653–2665.

Taylor S. and Lever J. H. (2001) Seeking unbiased collections of modern and ancient micrometeorites. In *Accretion of Extraterrestrial Matter Throughout Earth's History* (eds. B. Peucker-Ehrenbrink and B. Schmitz), pp. 205–219. Kluwer Academic/Plenum, New York.