EVIDENCE OF HIGH COSMIC DUST CONCENTRATIONS IN LATE PLEISTOCENE POLAR ICE (20,000 - 14,000 YEARS BP)

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Dust filtered from the lower portion of the Camp Century ice core (77°10′N, 61°08′W) has been analyzed for the presence of the cosmic dust indicators iridium and nickel using the neutron activation analysis technique. This study was carried out to test the hypothesis that the climatic change toward the end of the Last Ice Age was triggered by an incursion of nebular material into the Solar System. The analytical results are consistent with this hypothesis. Concentrations of Ir and Ni in the ice were one to two orders of magnitude higher during the latter portion of the Last Ice Age (19,700 - 14,200 years BP) as compared with current levels. Ir and Ni levels in 6 out of 8 samples suggest a total cosmic dust influx rate of about 0.5 - 3 $\times$ 10^7 tons/yr to the Earth's surface as compared with about 1 - 7 $\times$ 10^5 tons/yr for the current influx. Elemental concentrations in 6 of the 8 dust samples ranged from 6 - 96 ppb for Ir and < 60 to 3200 ppm for Ni. It is concluded that a major fraction of this invading dust would have been of submicron size in which case the concentration of light scattering particles would have been sufficient to significantly alter the light transmission properties of the Solar System and substantially affect the Earth's climate. These results mark the first time that cosmic dust deposition rates have been estimated for prehistoric times using the polar ice record.

INTRODUCTION

The Earth's sedimentary and glacial ice records preserve evidence indicating that during the Pleistocene Epoch the Earth's climate repeatedly underwent major changes ($\Delta T \sim 10°$ or more), often within the space of less than 100 years (Dansgaard *et al.*, 1972; Coope, 1977; Flohn, 1977; Woillard, 1979). LaViolette (1983a, 1983b, 1983c, 1985a) has suggested that such climatic variations are brought about as a result of recurrent incursions into the Solar System of submicron-sized light-scattering dust particles, these particles being vaporized from cometary material lying just outside of the heliopause (d $\sim$ 100 AU). He proposes that dust incursion events of this sort were responsible for causing the interstadials which coincided with the abrupt ending of the Last Ice Age about 10,000 - 13,000 years ago. The hypothesis of a dust invasion at the end of the Last Ice Age is testable. If the dust concentration in the interplanetary medium had increased as a result of such an incursion, then the rate of cosmic dust deposition on the Earth's surface should also have been higher, and consequently, evidence for this event could be detected in the Earth's polar record.

Polar ice is an ideal medium in which to assess past cosmic dust deposition rates. The ice caps preserve a record of the Earth's atmospheric composition dating as far back as the middle of the Last Ice Age and possibly even earlier. Glacial ice cores have the advantage over ocean and lake sediment cores in that they contain a relatively undisturbed record of deposited material. Also glacial ice cores permit the use of more closely spaced sampling time intervals allowing short term changes in cosmic dust deposition rate to be studied. Moreover, since the ratio of cosmic dust to terrestrial dust is much higher in glacial ice cores, concentrations of cosmic dust indicators such as Ir and Ni, are more likely to represent extraterrestrial contributions. Finally, cosmic dust deposition rates estimated from the Ir and Ni concentrations may in turn be stratigraphically correlated with a variety of other compositional data, such as measurements of the $^{18}O/^{16}O$ ratio (a climate indicator), NO^3 ion, and ^{10}Be (a cosmic ray activity indicator).

ANALYTICAL PROCEDURE AND RESULTS

Dust samples filtered from 8 sections of the Camp Century ice core spanning depths 1215 - 1279 meters, corresponding to 14,200 - 19,700 years BP, were analyzed by nondestructive neutron activation analysis (NAA) to determine their Ir and Ni contents. Ir and Ni are enriched in chondritic meteoritic material by 10^4 and 10^2 fold respectively, relative to most terrestrial crustal material. The ice core depths that were sampled are listed in column (2) of Table 1 and may be located in Figure 1 for comparison to the oxygen isotope and mineral dust concentration profiles for this core. The corresponding sample ages are listed in column (3). Columns (4) and (5) give the length of each ice core sample and the time span which it represents.

Three of the 8 tested samples (#3, #4, #6) were filtered by the author. The remaining five (#1, #2, #5, #7, #8) had been filtered in a previous study by Thompson (1975, 1977a, 1977b) subsequent to microparticle concentration analysis of the meltwater. The laboratory procedure which each investigator followed in preparing the filtrates is discussed elsewhere (LaViolette, 1983a; Thompson, 1977a). Both batches of dust samples were retained on 25 mm diameter Millipore® filters having a pore size of 0.45 microns. Sample filtrate dust weights and dust concentrations per liter of ice meltwater sample are listed in columns (6) and (7).

Each sample filter paper was rolled up and inserted into a pre-cleaned high purity quartz irradiation vial. The vial was heated for a day in a vacuum oven (170° C, 0.5 atmos.) to carbonize the filter, and was then sealed shut under a vacuum. Three of the samples (#1, #5, #8) were irradiated in a nuclear reactor for 1000 hours at a flux of 6.8×10^{13} neutrons/cm²/sec and the remaining five were irradiated for 100 hours at a flux of 2.7×10^{13} neutrons/cm²/sec. After being irradiated, the contents of the vials were transferred into clean plastic polyvials and about one month later were counted to determine their content of Ir, Ni, and 13 other elements. The results of the other 13 elements are presented elsewhere (LaViolette, 1983a, 1985b). Uncertainties in determining the individual elemental weights in each sample were on the order of ±20%.

The concentrations of Ir and Ni per unit volume of ice that were found are listed in columns (8) and (10) of Table 1. Also, the concentrations of these two elements relative to the sample dust fraction are listed in columns (9) and (11). In 6 out of the 8 samples analyzed Ir concentrations were found to range from 6 ppb to 96 ppb, corresponding to enhancement factors above crustal abundance in the range 250 - 4000, where 0.024 ± 0.02 ppb is adopted as the crustal abundance value (Shaw *et al.*, 1976). Nickel concentrations for these same samples ranged from < 60 ppm to 3200 ppm, corresponding to enhancement factors of 0.6 to 33, for a crustal abundance value of 99 ppm (Ronov and Yaroshevsky, 1972).

Table 1
Concentration of iridium and nickel in 8 Wisconsin stage Camp Century ice core samples, together with projected cosmic dust deposition rates

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Samp. No.	Ice sample s	Ice sample t*	Ice sample Δs	Ice sample Δt*	Dust sample weight	Total dust concen.	Ir concentration in ice	Ir concentration in dust	Ni concentration in ice	Ni concentration in dust	Cosmic Dust deposition rates Ir based	Cosmic Dust deposition rates Ni based
	meters	years BP	cm	years	μg	μg/ℓ	pg/ℓ	ppb	μg/ℓ	ppm	μg/cm²/yr	μg/cm²/yr
1	1215.1	14,200	19.5	13	235 ± 50	3260 ± 700	54 ± 11	16.6 ± 3.3	0.53 ± 0.1	162 ± 32	4.0 ± 1.7	1.7 ± 0.7
2	1224.0	14,800	20	13	23 ± 5	525 ± 100	14.6 ± 3	28 ± 6	< 0.05	< 64	1.1 ± 0.5	< 0.16
3	1230.2	15,100	5	3	541 ± 7	3090 ± 40	< 0.9	< 0.3	< 0.13	< 41	< 0.06	< 0.4
4	1231.7	15,300	8	4.5	449 ± 7	2460 ± 40	17 ± 3	6.9 ± 0.1	0.26 ± 0.07	107 ± 2	1.3 ± 0.5	0.8 ± 0.4
5	1234.7	15,400	35	20	80 ± 25	1530 ± 500	85 ± 17	56 ± 18	1.5 ± 0.3	980 ± 325	6.0 ± 2.6	4.8 ± 2.1
6	1235.7	15,500	5	3	466 ± 7	2510 ± 40	< 1.0	< 0.4	< 0.09	< 36	< 0.07	< 0.3
7	1245.0	16,600	11	20	7 ± 1	345 ± 70	31 ± 6	96 ± 19	1.11 ± 0.2	3220 ± 640	2.2 ± 0.9	3.5 ± 1.7
8	1278.9	19,700	20	18	132 ± 26	3260 ± 700	20.5 ± 4	6.3 ± 1.3	0.64 ± 0.13	195 ± 39	1.5 ± 0.6	2.0 ± 0.9

*Sample age and sample time span estimates based on time depth relation given by LaViolette (1983a, Ch. 8). Ages are accurate to within ± 500 years.

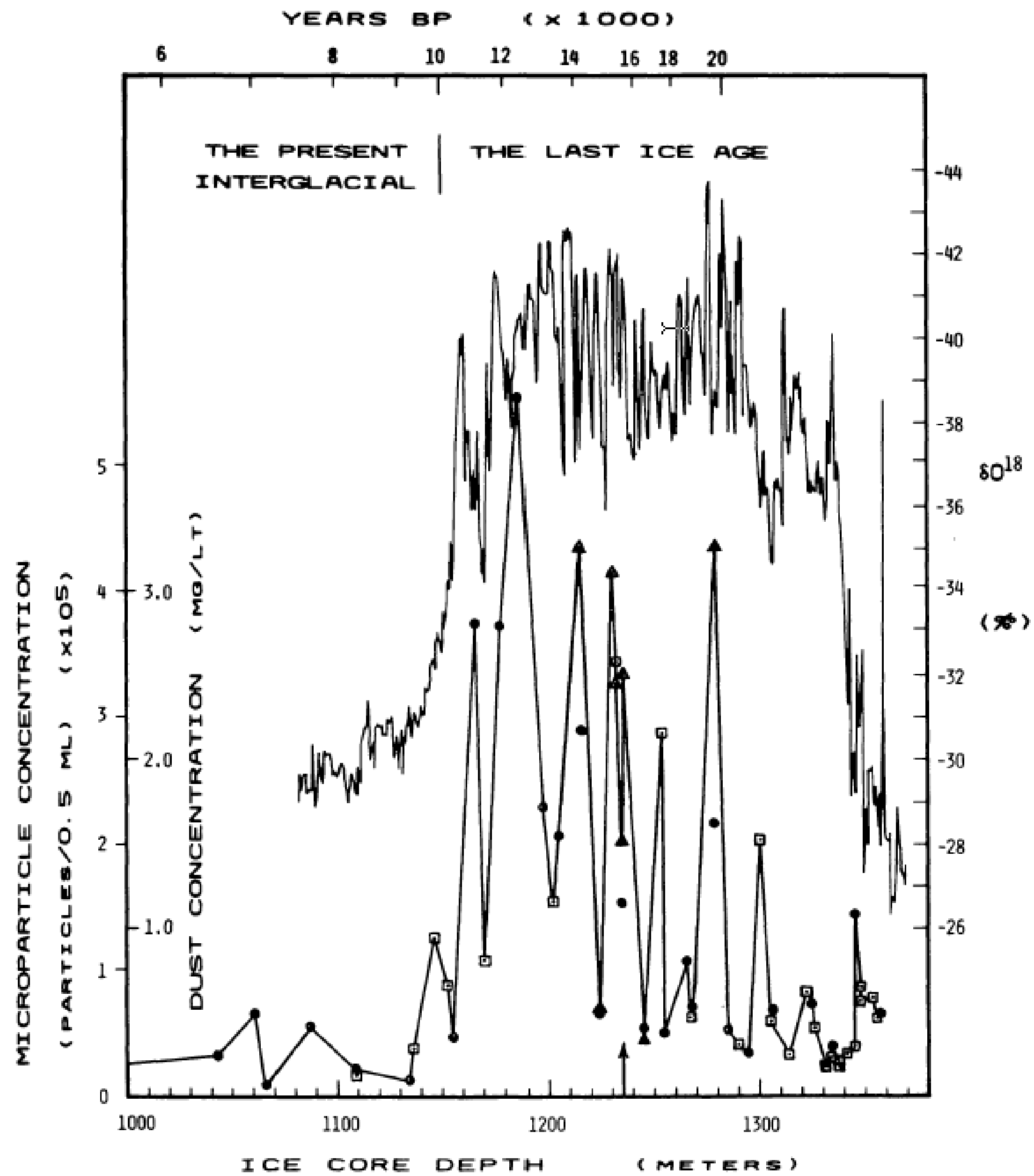

Fig. 1 The lower portion of the Camp Century ice core which spans the Last Ice Age. Upper curve: Oxygen isotope profile (Johnsen *et al.*, 1972); more negative $\delta^{18}O$ values indicate cooler climate and greater ice sheet extent. Lower curve: Mineral dust concentration profile synthesized from data of several sources: Circles: concentration of particles >0.62µ in diameter (Thompson, 1977a). Squares: dust weight concentrations (LaViolette, 1983a) estimated on the basis of Si and Al data of Cragin *et al.* (1977). Triangles: Dust weight concentrations derived for the 8 samples that were analyzed (LaViolette, 1983a). The time scale displayed along the top (LaViolette, 1983a) is roughly comparable to that published by Hammer *et al.* (1978).

[Note: The Camp Century ice core chronology has since been revised. See LaViolette 2003 for a revised plot.]

Cosmic dust deposition rates Φ_i were estimated from the Ir and Ni concentrations found in the ice by means of the following formula:

$$\Phi_i = \frac{c_i}{k_i} \cdot \alpha, \qquad (1)$$

where c_i is the concentration of Ir or Ni found in the ice, k_i is the fraction of Ir or Ni present in C1 chondrite meteoritic material (c_i/k_i being the concentration of cosmic dust in the ice), and α is the ice accumulation rate. It is assumed that at the time the dust samples were deposited the ice matrix was accumulating at about the same rate as it presently does at Camp Century, Greenland, i.e., $\alpha = 35 \pm 15$ cm H_2O per yr. The error range, $\pm$ 15, reflects the degree of uncertainty involved in projecting back in time the current ice accumulation rate.

The values adopted for k_i are 481 ppb for Ir and 1.10% for Ni (Anders and Ebihara, 1983), the assumption being that the Ir and Ni-bearing extraterrestrial dust component has a composition similar to C1 carbonaceous chondrite meteorite material. However, the majority of the extraterrestrial material entering the Earth's atmosphere comes not from meteorites, but from interplanetary dust particles which the Earth sweeps up in its passage through the zodiacal cloud and which are believed to be derived from comets (Millman, 1972; Dohnanyi, 1976; Fraundorf *et al.*, 1982). Golenetskii *et al.* (1981) have argued that cometary material is depleted in refractory elements such as Ir and Ni and enriched in volatiles, relative to C1 chondrite meteoritic material. Geochemical analysis performed on the residues of the 1908 Tunguska cometary explosion support this conclusion (Golenetskii *et al.*, 1977a, 1977b, 1978; Kolesnikov *et al.*, 1977). Also there is evidence that interplanetary dust is compositionally different from chondritic material. Although some cosmic dust particles collected from the stratosphere have been shown to have a C1 chondrite elemental signature (Ganapathy and Brownlee, 1979), there are also particles which are found to differ substantially from such a composition (Hemenway *et al.*, 1972; Hallgren and Hemenway, 1976; NASA, 1982; Mackinnon and Rietmeijer, 1984). However, it has been customary in past cosmic dust deposition rate studies (Barker and Anders, 1968; Crocket and Kuo, 1979) to assume a C1 chondrite composition for incoming dust, so this convention will be retained here. If anything, such an assumption should lead to an underestimate of the actual amount of cosmic dust present in the ice sample.[1]

[1]Another method sometimes used for estimating elemental deposition rates involves determining the amount of the element per unit cross-sectional area of the ice core and dividing this quantity by the number of accumulation years which the ice core sample represents, i.e., as given by the sample's span of vertical depth. However, for the Camp Century core this approach leads to erroneous results due to the fact that the ice core has become deformed as a result of plastic flow. Thus the 8 ice samples that were studied, which come from close to the bottom of the ice sheet (~ 100 - 160 meters above bedrock) have a characteristic depth-time correspondence of 0.6 to 1.8 cm H_2O per year, as compared with ~ 35 cm H_2O per year for ice near the top of the ice sheet (~ 1370 meters above bedrock), the latter essentially coinciding with the actual ice accumulation rate. Thus the ice from which the Wisconsin stage ice samples have been retrieved has been vertically deformed by a factor of about 20 - 60 fold. The concentration of dust in the ice does not change in the course of plastic deformation, except at melt zones. However, deformation does appreciably change the shape of the enclosing ice volume. Thus a one cm^2 cross-sectional area of ice core near the top of the ice sheet, becomes equivalent to a 20 - 60 cm^2 area near the bottom of the ice sheet. Since the ice flow dynamics for the Greenland ice sheet are not accurately known, it is difficult to devise the proper correction for such an effect. Thus it is best to follow the method summarized by formula (1) which utilizes deformation-independent quantities.

The cosmic dust deposition rate values derived using Eq. (1) are listed in columns (12) and (13) of Table 1 and have been plotted in Figure 2. The relatively close correspondence of the Ni and Ir-based cosmic dust deposition rate curves is consistent with these two elements being derived from C1 chondrite-like material. In 6 out of 8 samples, cosmic dust deposition rates are found to range from 1 - 6 $\times$ 10^{-6} g/cm^2/yr. This is about 10 - 60 times greater than the current polar cosmic dust deposition rate which is taken here to be 1.1 (+3, −1) $\times$ 10^{-7} g/cm^2/yr (upper dashed line in Fig. 1) and which is averaged from reported findings of nickel (McCorkell *et al.*, 1967; Hanappe *et al.*, 1968; Davidson *et al.*, 1981), iridium (Ganapathy, 1983), manganese-53 (Bibron *et al.*, 1974) and cosmic microsphere concentrations (Thiel and Schmidt, 1961; Langway, 1970) in polar firn and ice. The lower dashed line in Figure 2, representing a deposition rate of 1.8 $\times$ 10^{-8} g/cm^2/yr, is based on Ir concentrations recently measured in 75 year old ice from the South Pole (Ganapathy, 1983). If this lower value is adopted as a base line, then the 6 ice core samples indicate deposition rates that are 50 to 300 times higher than present rates!

The globally integrated cosmic dust deposition rate during the Last Ice Age may be conservatively estimated to be 0.5 - 3 $\times$ 10^7 tons/yr as compared with 1 - 7 $\times$ 10^5 tons/yr for the current deposition rate (upper and lower estimates). These globally integrated values may have to be increased by a factor of 2 - 3 if upper atmospheric circulation tends to concentrate cosmic dust toward the mid latitudes (Brocas and Picciotto, 1967). It would also be necessary to increase these estimates if the accreted interplanetary dust was depleted in iridium or nickel relative to concentrations found in chondritic material. For example such an upward adjustment may be warranted for sample #5 which contains an unusually high concentration of tin and of other low melting point elements of apparently extraterrestrial origin (LaViolette, 1983c, 1985b).

DISCUSSION

Comparison to Ocean Core Measurements

This is the first time that the polar ice record has been utilized to determine the deposition rate of extraterrestrial material on the Earth's surface for prehistoric times. Previously, cosmic dust deposition rates in polar ice had been determined only for samples spanning the past 700 years. Based on determinations of platinum group metal concentrations in deep-sea sediments, Barker and Anders (1968) have estimated the long term average influx rate of extraterrestrial material to be about 8±4 $\times$ 10^4 tons for the past 10^5 years. Their results appear to be low compared with the Wisconsin stage cosmic dust deposition rates reported here. One possibility is that the ocean sediment core depths which they sampled do not span the same time period as the ice core samples studied here, hence their sampling may have missed this event. Another possibility is that the core sedimentation rates which they adopt are too low. By comparison, Crocket and Kuo (1979) report relatively high Ir deposition rates in a well-dated core from the Caribbean (P6304-9). If the Ir which they find is entirely cosmic in origin, then a cosmic dust deposition rate of 1.7 $\times$ 10^{-6} g/cm^2/yr ($\sim$ 8 $\times$ 10^6 tons/yr) is projected, in agreement with the high deposition rates reported here.

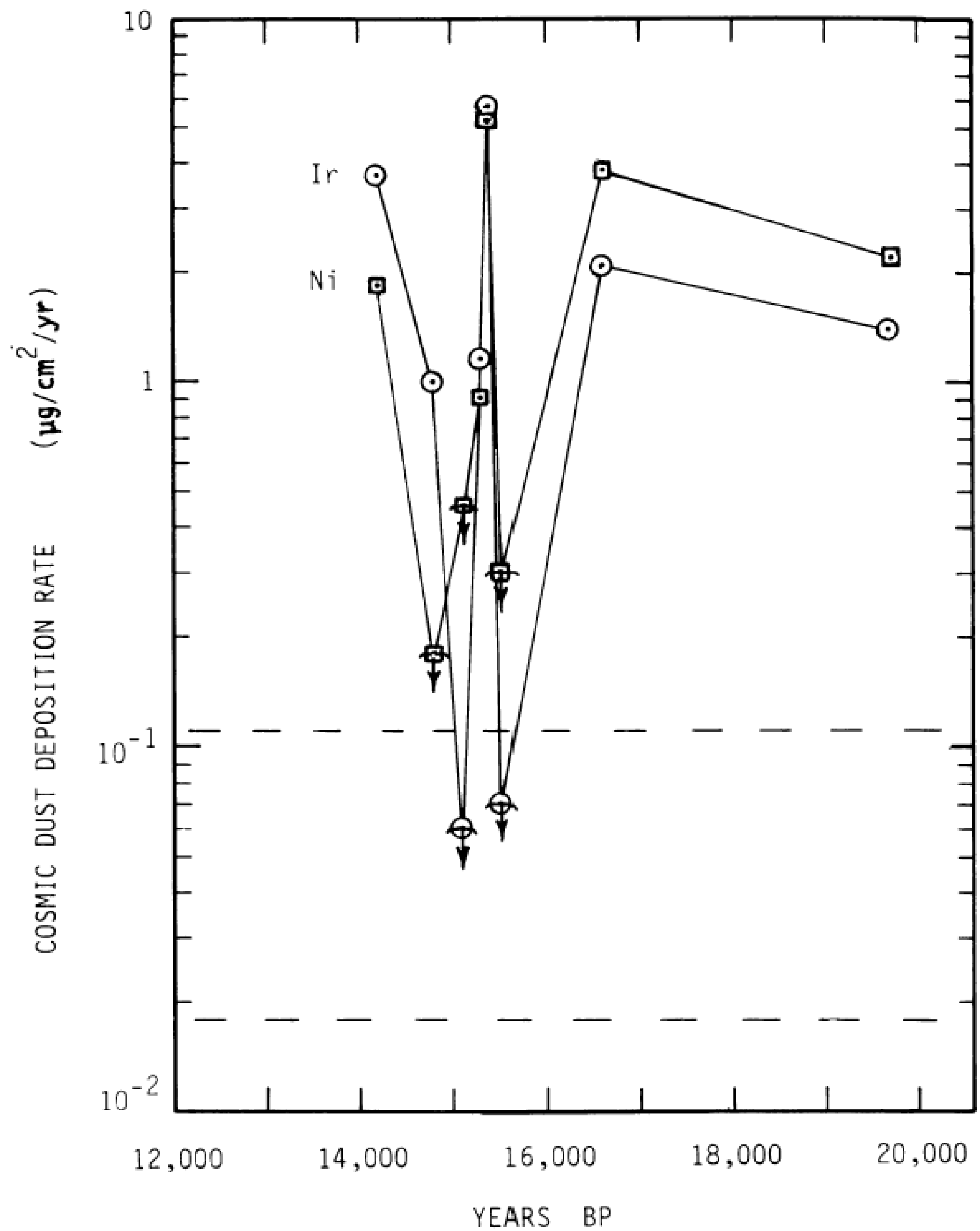

Fig.2 **Cosmic dust deposition rates at Camp Century, Greenland for the period 20,000 - 14,000 years BP determined on the basis of iridium and nickel concentrations found in glacial ice. Arrows pointing downward indicate upper limit determinations. Horizontal dashed lines represent the range of present average deposition rates.**

[Note (2005): The Camp Century ice core chronology has since been revised. With the new chronology, these samples span the period 35,300 to 73,100 years B.P. Their dates left to right are respectively: 35,300, 41,300, 46,200, 47,700, 50,300, 50,700, 54,600, and 73,100 years B.P. See LaViolette 2003 for revised dates.]

Sample Contamination Unlikely

Because of the unusual nature of the reported findings, it is advisable to consider whether the high Ir and Ni values could have been due to sample contamination. It is known that the Camp Century ice core was drilled using a diesel oil and antifreeze mixture. Thus, some amount of particulate material present in this drilling fluid would most likely have adhered to the outer surface of the ice core. Also, some amount of external contamination would have been acquired as a result of sample handling. Thus, in processing the ice samples, precautions were taken to melt off the outer 0.2 - 0.7 cm of each ice sample by rinsing with triple distilled filtered water. This would have removed the majority of any external dust contamination which may have lodged in microscopic surface cracks in the ice during drilling and storage. Since the ice samples were unfractured at the time of processing it is unlikely that any contaminants would have penetrated the ice surface to any great depth. In addition, the melting and filtration of the samples was carried out under exceptionally clean and dust-free laboratory conditions (Thompson, 1977a; LaViolette, 1983a).

But even if some amount of dust had succeeded in entering the samples it is unlikely that this would have contributed much to the Ir content of the ice. For example, most terrestrial dust sources contain less than 0.3 ppb of Ir. Thus, even if as much as 3% of the sample dust weights were to include environmental dust, the Ir content found in the 6 Ir-bearing samples would have been made to increase by no more than 0.01% - 0.15%.

The low risk of contamination from precious metals is born out by the results of the study by Boutron *et al.* (1984). A block of prehistoric blue ice collected from a coastal ablation area in east Antarctica was analyzed for its content of various elements, and variations of elemental concentrations as a function of radial depth into the ice sample were determined. It was found that gold was among the elements for which there was no evidence of surface contamination. On the other hand, in an earlier study of the same block of ice Pb was found to increase by 1000 fold from the ice sample interior to its surface (Boutron and Patterson, 1983). The difference in these results is understandable. Relative to concentrations in Antarctic blue ice, gold is *depleted* by a factor of 10^3 - 10^4 in typical environmental dust sources, whereas lead is *enriched* by a factor of 10^5, e.g., in urban areas (Huntzicker *et al.*, 1975). As a further check on the adequacy of using deep ice core samples for assessing ancient deposition rates of precious metals, an investigation is presently being planned in which ice samples from the Camp Century deep ice core will be analyzed so as to determine how Ir, Ni, and other elements vary as a function of depth below the sample's outer surface.

Another source of contamination that was considered was the NaCl solution that had been added to some of the samples. Prior to filtering his meltwater samples, Thompson had added to them a small amount of a 2% NaCl solution to facilitate microparticle counting. This solution was made from analytically pure NaCl dissolved in filtered distilled water. So to rule out the possibility that the salt solution may have contaminated the samples, NAA was performed on a quantity of analytical grade NaCl. Since its Ir content was found to be less than 0.2 ppb, any potential contribution to the samples was determined to be insignificant. The microparticle counting process itself was also ruled out as a potential source of Ir and Ni.

The most likely source of contamination, if any, was determined to be the filter papers themselves. The Ir content in blank Millipore® filters irradiated with the samples was determined to be $< 8 \times 10^{-14}$ g for Thompson's batch of filter papers and $< 4 \times$

10^{-14} g for the batch that the author used, giving filter contributions ranging from < 2% to < 12% in the 6 samples where Ir was detected. Hence the potential contribution was judged to be insignificant. Nickel concentrations in the filter blanks, however, were relatively high: $8 \pm 4 \times 10^{-9}$ g in Thompson's batch of filters and $2 \pm 1 \times 10^{-8}$ in the batch used by the author. Thus, due to filter background, it was possible to give only upper limit concentrations for three samples (#2, #3, and #6). In the remaining 5 samples the filter contribution was subtracted. The ratio of the filter Ni weight contribution to the sample Ni weight (after filter subtraction) ranged from 3.6% for sample #5 to 17% for sample #7 and was 50% for sample #4. It is expected that by using another brand of filter paper, such as Nucleopore®, in future studies, it should be possible to reduce the filter paper contribution by an order of magnitude.

Volcanism Ruled Out

It is also worth considering whether the high levels of Ir found in Wisconsin stage polar ice could be due to the presence of iridium-bearing volcanic material. For example, recently Zoller *et al.* (1983) reported the detection of high concentrations of Ir in aerosol emissions from the Kilauea volcano in Hawaii. They estimate that between 10 - 40 grams of Ir per day were released in the January 1983 eruption (Zoller, personal communication, 1983). The closest active volcano to Camp Century, Greenland that could be a potential iridium emitter is Hekla in Iceland which is located ~ 1700 km to the southeast. However, even if this volcano matched the Ir output of the Kilauea eruption and continued with this output every day, it would only come to about 10^3 g Ir/yr. As an upper limit case, suppose that this material became dispersed evenly over a 1700 km radius region surrounding the volcano. The Ir deposition rate at Camp Century would then have been only ~ 10^{-14} g/cm²/yr. A more realistic atmospheric dispersion model would give a rate much lower than this. By comparison, the Ir levels observed in Camp Century ice over the 5500 year period that was sampled ranged as high as $0.5 - 3 \times 10^{-12}$ g/cm²/yr, or about 2 orders of magnitude higher.

It is also important to note that Thompson (1977b) estimates that volcanic material makes up less than 5% of the dust present in Late Wisconsin ice from Camp Century. Thus if volcanism were to explain the high Ir levels, Ir concentrations in the range of up to 2 ppm or more would have had to be present in the volcanic emissions. Although platinum group metals have been found at high concentrations in certain types of igneous rocks, e.g., up to 740 ppb in dunite and 290 ppb in peridotite (Rankama and Sahama, 1950, p. 691), such abundances would be unlikely for Hekla.

Planetesimal Impacts Ruled Out

Planetesimal impacts with the Earth (Alvarez *et al.*, 1980; Clube and Napier, 1982) and close encounters with cometary tails (Hoyle and Wickramasinghe, 1978; Butler and Hoyle, 1979) may also be ruled out as the source of the iridium in the Late Wisconsin stage ice. The problem is that such events would not be expected to occur frequently enough to account for the observed Ir concentrations. For example, dust from the impact of an asteroid or comet would remain airborne for less than a year (Pollack *et al.*, 1983), equivalent to less than one centimeter of ice in the Wisconsin section of the Camp Century ice core. For 6 out of 8 glacial ice samples to register high cosmic dust deposition rates ($1 - 6 \times 10^{-6}$ g/cm²/yr, each sample spanning about 15 - 20 years), 200 - 500 meter diameter bodies (10^{14} - 10^{15} grams) would have had to impact the Earth as frequently as once every 20 years. Or bodies the size of the Tunguska object ($\sim 10^{13}$ g) would have had to impact at least once a year. Such a high impact frequency for objects of this size seems highly improbable.

Also, if such a bombardment were maintained over a period of 5500 years, the period spanned by this study, and if the objects were meteoritic in nature, at least 100 impact craters greater than 4 kilometers in diameter should have been produced. But there is no geological evidence of young impact craters occurring in such great numbers. Moreover there is also no evidence that Wisconsin stage ice contains elevated levels of meteorite or planetesimal ablation products. For example, the occurrence of cosmic microspheres remains relatively constant throughout both the Camp Century and Byrd Station ice cores (Thompson, 1977b). The lack of ablation products is also inconsistent with the short-period-comet — break-up scenario proposed by Clube and Napier (1984); see LaViolette (1985b).

Elevated Interplanetary Dust Concentrations

The high cosmic dust deposition rates indicated by the present study are best interpreted as resulting from elevated space concentrations of nebular material in the interplanetary environment. The mass concentration ρ_0 that this cosmic dust would have had in the local interplanetary environment may be estimated with the following relation:

$$\rho_0 = \frac{4\,\Phi}{v[1 + (v_0/v)^2]}\,, \tag{2}$$

where Φ is the value of the cosmic dust deposition rate, the coefficient 4 is the ratio of the Earth's surface area to its cross-sectional area, the coefficient $v_0 = 11.1$ km/sec is the Earth's escape velocity, and v is the relative velocity of the Earth with respect to the nebular material. Assuming that the nebular material falls freely toward the Sun, it would attain a relative velocity of 40 km/sec in the Earth's vicinity. Consequently, for Φ in the range 1 - 6 $\times 10^{-6}$ g/cm^2/yr, a local dust concentration of 0.3 - 1.8 $\times 10^{-19}$ g/cm^3 is estimated for the period 20,000 - 14,000 years BP. This may be compared with the present local interplanetary dust concentration of 0.5 - 3 $\times 10^{-21}$ g/cm^3 estimated from the upper and lower limiting values given in Figure 2 (dashed lines). The recently discovered dust ring lying within the Solar System between the orbits of Mars and Jupiter (Low *et al.*, 1984), and which is believed to be no more than a few tens of thousands of years old, may have been formed during the proposed nebular incursion episode.

Climatic Effects

Elevated interplanetary dust concentrations could have substantially affected the Earth's climate by altering the light transmission properties of the Solar System. The magnitude of this effect would have depended on several factors such as the size of the dust particles, their optical properties, the amount of cometary ice they may have been associated with, and their spatial distribution around the Sun. Currently, most of the mass of the zodiacal cloud is contributed by particles having a diameter of about 300μ. However, particles this large are rarely found in Camp Century ice. Almost all of the dust particles have diameters less than 30 microns with the majority being less than a few microns in size (Thompson, 1977a, p. 12). A small size for Late Wisconsin interplanetary dust particles is consistent with an incursion of nebular material vaporized from cometary debris. For example, dust particle sizes on the order of 0.2μ have been observed in cometary tails (O'Dell, 1971) and in interstellar space (Hoyle and Wickramasinghe, 1969).

It is estimated that interplanetary dust particles having a diameter of 0.4μ, optical properties similar to iron grains, and a local interplanetary mass density of 1.5×10^{-19} g/cm^3 would produce optical depths of 0.3 between the Earth and Sun, 0.1 in the outer portion of the Solar System, and 1.0 in the Earth's upper atmosphere (LaViolette, 1985b). Optical depths this large would have significantly altered the spectrum and intensity of solar radiation reaching the Earth and changed the light transmission properties of the Earth's upper atmosphere. It is expected that such conditions would have tended to warm the Earth's atmosphere and fostered the production of temperature inversions, particularly in the polar regions (LaViolette, 1983a, 1985b). Depending on their magnitude, these effects could have produced conditions favoring either rapid glacial advance or rapid glacial recession.

CONCLUSION

It is concluded that on five occasions during the interval 20,000 - 14,000 years BP, cosmic dust mass concentrations in the Solar System rose by one and two orders of magnitude above present day levels. Moreover if the particles found in these ice core samples are indicative of the particle size distribution which prevailed in the interplanetary medium at that time, then it may be concluded that the space number density of submicron sized particles must have increased by a factor of 10^5 or more. During these times the light transmission properties of the Solar System environment would have been significantly altered resulting in major adverse effects to the Earth's climate. Thus it is quite possible that these dust congestion episodes were responsible for the abrupt climatic variations which occurred toward the end of the Last Ice Age.

A more detailed stratigraphic analysis of the polar ice record should be undertaken in the near future to gain a better understanding of past variations in the rate of cosmic dust influx and to investigate whether such variations are indeed closely correlated with climatic change.

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