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Accretion of Interplanetary Dust in Polar Ice

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Abstract. Measurements of helium isotopes in particles separated from polar ice demonstrate that extraterrestrial ^{3}He dominates the ^{3}He flux at the GISP2 (Greenland) and Vostok (Antarctica) ice core sites. Replicate measurements of late Holocene ice samples yield ^{3}He fluxes of $0.62 \pm 0.27 \times 10^{-12}$ cm^3 STP cm^{-2} ka^{-1} (GISP2) and $0.77 \pm 0.25 \times 10^{-12}$ cm^3 STP cm^{-2} ka^{-1} (Vostok), similar to results from marine sediments. These are the first detailed measurements of ^{3}He in particles from ice core samples, and they demonstrate the utility of the ice core record for evaluating the temporal history of the extraterrestrial dust flux. Results from Vostok samples from 1096-1403 m depth (75-97 ka B.P.) are similar to the late Holocene data, with the exception of two highly anomalous results from 1307 m. The latter probably indicate the presence of rare, large or gas-rich extraterrestrial particles.

Introduction

Accretion of extraterrestrial material to the earth is important to studies of the origin of the atmosphere and oceans, dynamics of dust in planetary systems, geochemical budgets, astronomical observations, and possibly terrestrial climate change [*Love and Brownlee*, 1993; *Muller and MacDonald*, 1995, 1997]. Marine sediments and polar ice provide an archive of the influx of extraterrestrial material in the form of interplanetary dust particles (IDPs) [*Parkin and Tilles*, 1968]. High levels of ^{3}He and other noble gas isotopes provide a unique signature of IDP in pelagic sediments [e.g., *Amari and Ozima*, 1988]. This signal can, in principle, be used to construct a record of extraterrestrial ^{3}He flux, and thereby derive a record of IDP accretion [*Farley and Patterson,* 1995; *Farley*, 1995; *Patterson and Farley*, 1998]. *Muller and MacDonald* [1995, 1997] highlighted the importance of these records by suggesting that the earth's 100 ka glacial-interglacial cycle might be driven by variations in the tilt of the orbital plane. Most other explanations of the 100 ka cycle rely on astronomically forced solar insolation changes [*Imbrie et al.*, 1993], and have difficulty explaining power in the 100 ka cycle. *Muller and MacDonald* [1995] suggested that variability in interplanetary dust abundance near the earth could link orbital inclination and climate. Several groups have searched marine sediment records for variations in IDP flux on 100 ka time scales, using ^{3}He as a proxy [*Farley and Patterson*, 1995; *Patterson and Farley*, 1998; *Marcantonio et al.*, 1996]. Results of these studies are equivocal. *Marcantonio et al.* [1996] argued for minimal IDP flux variations, while *Patterson and Farley* [1998] interpreted their data as evidence for 100 ka periodicity in IDP accretion.

The noble gas content of particles in polar ice cores may provide another record of IDP flux variations that would shed light on some of these issues, but prior to this study this potential has not been investigated in detail. There are a number of possible advantages of an ice core record of IDP flux. First, accumulation rates and time scales of deep polar ice cores are well known, allowing accurate flux calculations and comparison to other records. Second, ice core records contain a variety of climate proxies, including stable isotope and trace gas records, allowing examination of postulated links between IDP variability and climate change. Finally, the data presented here demonstrate that ^{3}He in ice core particulate matter is dominated by extraterrestrial helium.

Methods

Helium isotopes were measured in particles from GISP2 (central Greenland) and Vostok (central east Antarctica) ice core samples. GISP2 samples were from 132-138 m depth in the G2 core and are approximately 400-430 years old [*Meese et al.*, 1997]. Vostok samples were from the 110-111 m section of the BH-5 core and from selected depths between 1096 and 1404 m from the 5G deep core. The BH-5 samples were deposited about 3.8 ka B.P and the 5G samples were deposited between 75 and 97 ka B.P., using the time scale of *Sowers et al.* [1993].

Ice samples were cut on a band saw and weighed. Particles were extracted by melting at room temperature in a glass filtration funnel in a class 100 clean hood. Meltwater was vacuum filtered through 0.45 or 0.2 micron pure silver filters (Osmonics-Poretics). The filters were rinsed with ethanol, folded, and placed in aluminum foil boats. Helium was extracted by melting the particles, filter, and foil boat in an ultra-high vacuum furnace with a tantalum crucible. Helium was purified and the isotopes measured using static noble gas mass spectrometry; the mass spectrometer and procedures used are described by *Kurz et al.* [1996]. Blanks were between 4 and 6 x 10^{-11} cm^3 STP ^{4}He with approximately atmospheric ^{3}He/^{4}He ratios, and represent small corrections to ^{4}He and ^{3}He. The ultimate detection limit of the system is approximately 2 x 10^{-16} cm^3 STP ^{3}He (5000 atoms); the smallest samples discussed here are approximately 20 times larger than this detection limit. All helium concentrations are reported in units of cm^3 STP g^{-1} ice.

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Table 1. Helium Isotope Data for > 0.45 Micron Particles Filtered From Ice Samples.

Sample Depth (m)	Age^1 (ka)	Wgt. Ice (g)	^{4}He (10^{-12} cm^3 g^{-1} ice)	^{3}He/^{4}He (R/R$_a$)	^{3}He (10^{-18} cm^3 g^{-1} ice)	Ice Accum.^{2} (g cm^{-2} a^{-1})	^{3}He Flux (10^{-12}cm^3 cm^{-2} ka^{-1})
GISP 2 (Greenland)							
132.7-133.1	0.40	1092.70	0.77 ± 0.02	42.83 ± 0.28	45.47 ± 0.96	22.4	1.02 ± 0.02
133.6-133.7	0.41	338.50	0.99 ± 0.02	8.75 ± 0.25	12.01 ± 0.42	22.4	0.27 ± 0.01
134.2-134.3	0.41	800.60	4.26 ± 0.09	7.31 ± 0.06	43.09 ± 0.93	22.4	0.97 ± 0.02
137.2-137.7a^5	0.43	751.75	0.59 ± 0.01	15.70 ± 0.25	12.73 ± 0.32	22.4	0.29 ± 0.01
137.2-137.7b^5	0.43	938.88	0.82 ± 0.02	28.58 ± 0.28	32.55 ± 0.73	22.4	0.73 ± 0.02
137.54-138.18	0.42	1186.23	0.86 ± 0.02	16.17 ± 0.18	19.15 ± 0.50	22.4	0.43 ± 0.01
137.54-138.18^3	0.42	1186.23	0.30 ± 0.01	0.96 ± 0.19	0.39 ± 0.08		
						Mean ± 2σ:	0.62 ± 0.27
Vostok (Antarctica)^4							
110.0-110.19a^5	3.80	259.69	1.82 ± 0.04	173.51 ± 0.92	437.02 ± 9.04	2.0	0 87 ± 0 02
110.0-110.19b^5	3.80	280.35	2.22 ± 0.04	174.11 ± 0.78	535.39 ± 10.97	2.0	1 07 ± 0 02
110.19-110.38	3 80	265.96	1.33 ± 0.03	139.07 ± 1.14	255.16 ± 5 51	2.0	0 51 ± 0 01
110.38-110.48a^5	3.80	145.15	1.01 ± 0.02	159.05 ± 1.72	223.08 ± 5.07	2.0	0.45 ± 0.01
110.38-110.48b^5	3.80	139.50	2.22 ± 0.04	152.21 ± 1.05	466.61 ± 9.87	2.0	0.93 ± 0.02
						Mean ± 2σ:	0.77±0.25
1096.0	75.26	154.73	5.16 ± 0.01	109.98 ± 0.56	785.88 ± 16.22	1.2	0.97 ± 0.02
1145.0	77.99	168.92	3.15 ± 0.06	143.79 ± 0.80	626.62 ± 13.02	1.5	0.92± 0.02
1220.0	84.04	152.03	2.37 ± 0.05	156.14 ± 1.04	510.77 ± 10.73	1.5	0.75 ± 0.02
1261.0	87.56	158.99	3.60 ± 0.07	116.14 ± 0.71	578.09 ± 12.10	1.4	0.80 ± 0.02
1265.0	87.89	215.93	2.39 ± 0.05	90.85 ± 0.60	300.99 ± 6.34	1.3	0.40 ± 0.01
1285.0	89.14	254.01	3.00 ± 0.06	159.23 ± 0.67	660.49 ± 13.50	1.4	0.91 ± 0.02
1303.3	89.94	176.94	2.85 ± 0.06	128.74 ± 0.88	508.51 ± 10.75	1.5	0.76 ± 0.02
1307.0a^5	90.08	67.44	46.34 ± 0.93	200.05 ± 0.86	12829.29 ± 262.45	1.4	17.88 ± 0.37
1307.0b^5	90.08	100.98	1.60 ± 0.03	102.38 ± 0.98	227.18 ± 5.04	1.4	0.32 ± 0 01
1307 0c^5	90.08	94.16	37.28 ± 0.75	193.13 ± 0.92	9963.83 ± 204.85	1.4	13.89 ± 0.29
1316.6a^5	90.87	105.46	1.44 ± 0.03	163.28 ± 1.69	325.71 ± 7.33	1.6	0 52 ± 0.01
1316.6b^5	90.87	106.24	1.44 ± 0.03	173.75 ± 1 77	346.75 ± 7 78	1 6	0 55 ± 0.01
1321.0	91.28	271.70	2.22 ± 0.04	147.82 ± 0 74	453.21 ± 9.34	1.4	0 65 ± 0.01
1333.0	92.39	221.45	2.26 ± 0.05	136.33 ± 0 76	426 69 ± 8 86	1.4	0.62 ± 0.01
1341 0	92.99	119.85	8.17 ± 0.16	149.61 ± 0.72	691.59 ± 34.79	1.5	2 47 ± 0 05
1346 0	93.36	207.50	5.60 ± 0 11	194.93 ± 0.77	1512.07 ± 30.83	1.5	2.21 ± 0 05
1403.6	97.30	106.56	5.80 ± 0.12	101.04 ± 0.65	811.55 ± 17.04	1.6	1 27 ± 0.03

[1] Ages for GISP2 from Meese et al. [1997]; ages from Vostok from SPECMAP time scale of Sowers et al [1993]. [2] GISP2· Cuffey and Clow [1997], Vostok: Sowers et al. (1993). [3] 0.2-0.45 m size fraction. [4] Depths for below 111.0 m are top depths of samples spanning 10-15 cm [5] Replicates for Holocene GISP2 and Vostok samples were prepared by cutting core sections longitudinally. Replicates of deep Vostok samples were made on unoriented variable sized pieces from 10-15 cm intervals.

Blank measurements on unused filters and procedural blanks using deionized, filtered water were indistinguishable from furnace line blanks. As a test of filtration efficiency and yield one sample was filtered first through a 0.45 micron filter and then through a 0.2 micron filter. The quantity of ^{3}He trapped on the 0.2 micron filter was less than 2% of the total trapped by the two filters (Table 1), indicating that the 0.45 micron filters effectively trap most of the particulate ^{3}He. This is consistent with predictions of the size distribution of He-retaining IDPs [*Farley et al.*, 1997], which suggest that the majority of IDP-borne ^{3}He is carried in particles with diameters greater than 1 micron. A greater quantity of ^{4}He passed through the larger filter (~26% of the total; Table 1) suggesting that some ^{4}He is carried in smaller particles, probably terrestrial dust.

Results

The ^{4}He content of the GISP2 samples ranges from 0.30 to 4.26 x 10^{-12} cm^3 STP g^{-1} ice (Table 1). ^{4}He concentrations of the Vostok samples are higher, reflecting the lower ice accumulation rates at Vostok. Although Holocene accumulation rates at the GISP2 site are ~ 10 times higher than at Vostok (Table 1), the mean ^{4}He concentration of the GISP2 samples is roughly half of the mean for the Holocene Vostok samples. This probably reflects the relative proximity and abundance of terrestrial dust sources at the GISP2 site, although differences in the age, composition, or particle size of the dust may also contribute. ^{3}He/^{4}He ratios for GISP2 samples are between 7.3 and 42.8 R$_a$ (R$_a$ is the atmospheric ^{3}He/^{4}He ratio, 1.384 x 10^{-6}). Vostok ratios are higher, between 91 and 200 R$_a$ (Table 1). Estimates of the ^{3}He/^{4}He ratio for IDPs range from 173 R$_a$ [*Nier and Schlutter*, 1992] for stratospheric particles to 310 R$_a$ for the solar wind [*Geiss et al.*, 1971]. The high ^{3}He/^{4}He ratios for ice core samples indicate that virtually all of the ^{3}He they contain is extraterrestrial. Using a two component mixing model [e.g., *Patterson and Farley*, 1998] the fraction ^{3}He$_{et}$/^{3}He$_{total}$ is greater than 99.8% for Greenland samples and >99.99% for Antarctic samples. This calculation assumes that ^{3}He$_{et}$/^{3}He$_{total}$ =(^{4}He/^{3}He$_{obs}$-^{4}He/^{3}He$_{crust}$)/(^{4}He/^{3}H$_{et}$-^{4}He/^{3}He$_{crust}$), ^{3}He/^{4}He$_{et}$= 290 R$_a$, and ^{3}He/^{4}He$_{crust}$=0.015 R$_a$. The crustal ratio may be as high as 0.33 R$_a$ [*Marcantonio et al.*, 1998]. However, even using this ratio ^{3}He in Vostok samples is > 99.7 % extraterrestrial and ^{3}He in Greenland samples is > 98.0% extraterrestrial.

Treating the 6 GISP2 samples as replicates, the mean ^{3}He concentration is 28 ± 12 x 10^{-18} cm^3 STP g^{-1} ice (all means reported as ± 2 x standard error). For the five Vostok Holocene samples the mean ^{3}He content is 384 ± 123 x 10^{-18} cm^3 STP g^{-1}. The GISP2 samples span an age range of about 40 years. If there were variability in IDP flux to the ice surface on decadal or shorter time scales [suggested by *Kayser et al.*, 1998] this uncertainty estimate would be a maximum. There also could be scatter in the results due to seasonal variations in snowfall. The average annual snow accumulation rate at the site is approximately 22 cm/yr, but summer/fall accumulation is slightly greater (~10-20%) than winter/spring accumulation [*Shuman et al.*, 1995]. Although the season of deposition is unknown, the samples are at least 10 cm thick (Table 1) and therefore represent approximately 50% or more of annual snowfall. Given the small seasonal variations at this site this issue is probably not significant. The uncertainty for the Vostok replicates is 32 % of the mean (Table 1), and these samples represent deposition over ~ 25 years.

Duplicate ^{3}He measurements at 1316 m at Vostok (Table 1) yield better agreement, within 6.4 % of the mean (Table 1). Given the consistency of this duplicate measurement, results for triplicate measurements of the 1307 m sample (Table 1) are difficult to interpret. One replicate had a concentration of 227 ± 5 x 10^{-18} cm^3 STP g^{-1}, similar, though slightly lower than, relatively low values found in the two samples below this depth (Table 1). The ^{3}He content of the other two replicates of this sample are extremely high, 12,829 ± 263 and 9,964 ± 205 x 10^{-18} cm^3 STP g^{-1}, ~ 10 times higher than the mean for all other Vostok samples. These samples also had 5-20 times more ^{4}He than the others (Table 1). The origin of these high concentrations is unclear but may result from sampling relatively rare gas-rich or large IDPs [*Patterson and Farley*, 1998]. ^{3}He/^{4}He ratios for these two replicates are 200 and 193 R_a, the highest in the data set, supporting this conclusion. These high ^{3}He/^{4}He ratios are similar to those obtained for individual IDPs [Nier and Schlutter, 1992], illustrating that extraterrestrial helium dominates the particulate matter helium budget. The occurrence of these two highest concentrations in our data set at the same depth level is curious, and unlikely if particles are randomly distributed. This may indicate that there were temporal variations in the size distribution of ^{3}He-bearing extraterrestrial particles.

Discussion

The number of IDPs in a sample is proportional to sample size and inversely proportional to accumulation rate. Following *Farley et al.* [1997] the total accumulation of ice or sediment in a sample can be described by the ratio of the sample mass to accumulation rate, or "area-time product" (AT). Larger values of AT are preferable to reduce statistical effects related to the small number of IDPs in typical samples (*Farley et al.*, 1997). The mean AT for GISP2 samples discussed here is 0.004 m^{2}a, and for Vostok samples the mean AT is 0.01 m^{2}a. For comparison, most marine sediment ^{3}He data comes from sediments with AT values of 0.02 to 0.5 m^{2}a [*Farley and Patterson*, 1995; 1997; *Marcantonio et al.*, 1996; *Patterson and Farley*, 1998]. Uncertainty in multiple replicates of marine sediments from ODP Site 806 with AT of 0.125 m^{2}a ranges from 15-185% (one standard deviation) with the more extreme values driven primarily by one or two anomalously high concentrations [*Patterson and Farley*, 1998].

The expected statistical distribution of results for the Holocene Vostok samples (mean AT=0.01 m^{2}a) was modeled using the method of *Farley et al.* [1997]. (We focus on these samples because they are most likely to yield statistically meaningful results). We employed the predicted size distribution and flux of IDPs that were heated to less than 600°C upon atmospheric entry (and therefore retained ^{3}He) from that study. A Monte Carlo method was used to calculate the expected distribution of relative ^{3}He content with respect to the global mean value, assuming that the ^{3}He concentrations are correlated with particle surface area [*Farley et al.*, 1997], generating a synthetic distribution of 2000 points. The distribution has a mean value close to the global mean, but a standard deviation of over 100%, reflecting the statistically small numbers of IDPs in samples with low AT values. We then created 1000 model samples of n=5 for comparison with the Vostok results by repeatedly selecting randomly from the 2000 points.

Although data are limited at this point, the implied agreement of our replicates appears to be better than predicted by the model treatment. The probability of obtaining an uncertainty of 32% in a sample of n=5 for AT=0.01 m^{2}a is slightly less than 15% based on the model. Although more data are required to characterize the statistics of extraterrestrial ^{3}He in ice core samples one explanation for the difference between the replicate results and the model prediction is that the IDP size distribution used in the model is inaccurate. For example, the number flux of small particles (10 micron and less) could be underestimated; this is a plausible hypothesis because the IDP size distribution is not well known for small particles. Fragmentation of particles during atmospheric entry or in the ice is another possible explanation [*Peucker-Ehrenbrink and Ravizza*, 2000]. Future analysis of size-fractionated samples may shed light on this issue.

The accumulation rate at the GISP2 site was 22.4 g cm^{-2} yr^{-1} in the depth range of the samples analyzed [*Cuffey and Clow*, 1997]. ^{3}He fluxes were calculated assuming that $^3\mathrm{He}_{\mathrm{flux}}={}^3\mathrm{He}_{\mathrm{conc}} * b$, where b is accumulation rate. At Vostok accumulation rates were based on the accumulation-temperature relationship [*Sowers et al.*, 1993] (Table 1). Resulting fluxes are 0.62 ± 0.27 x 10^{-12} cm^3 STP cm^{-2} ka^{-1} for GISP2 and 0.77 ± 0.25 x 10^{-12} cm^3 STP cm^{-2} ka^{-1} for Vostok. These results are similar to previous estimates of the extraterrestrial ^{3}He flux to marine sediments over the past 200 ka (Figure 1) [*Patterson and Farley*, 1998; *Marcantonio et al.*, 1996, 1999]. ^{3}He fluxes at Vostok in the 1096.0-1403.6 m depth interval (Figure 2) are between 0.32-2.47 x 10^{-12} cm^3 STP cm^{-2} ka^{-1} (excluding the anomalous data for two of three replicate measurements of the 1307 m sample). The mean flux in this interval is 0.94 ± 0.32 x 10^{-12} cm^3 STP cm^{-2} ka^{-1}. The latter value

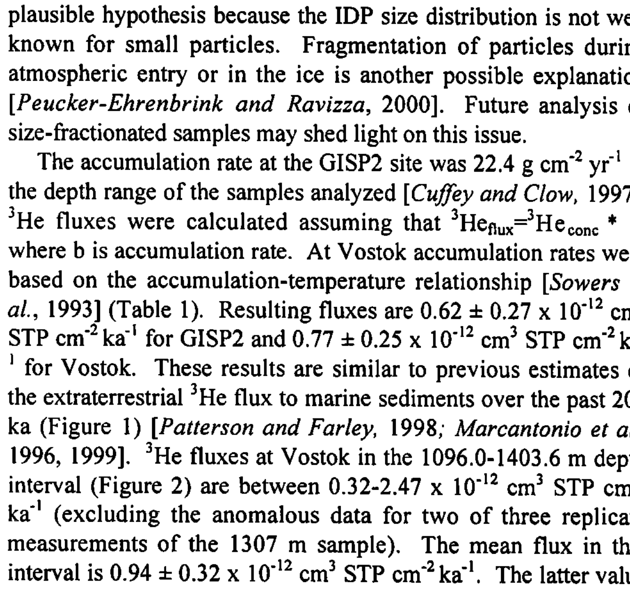

Figure 1. Comparison of ice core data presented here with recent estimates of the extraterrestrial ^{3}He flux. 1 = this paper. 2 = Average for last 200 ka from *Marcantonio et al.* [1996]. 3 = Average for last 20 ka from *Marcantonio et al.* [1998]. 4= average for the past 114 ka from *Patterson and Farley* [1998]. 5 = average for the last 200 ka from *Marcantonio et al.* [1999].

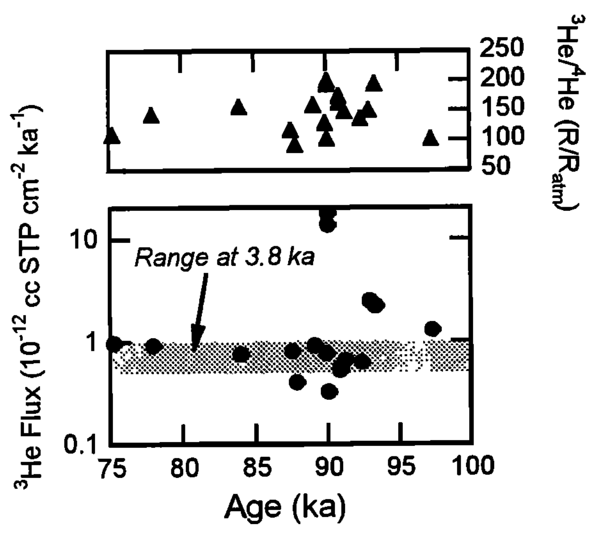

Figure 2. ^{3}He fluxes and ^{3}He/^{4}He ratios from Vostok, 1096-1404 m. Gray bar shows range of fluxes from replicate measurements of late Holocene Vostok samples. High values at ~ 90 ka are for two of three replicates for the 1307 m sample and may be due to rare, large or gas rich IDPs.

is also similar to recent estimates spanning the last 200 ka (Figure 1). However, there is no significant difference between the mean of all of the Holocene results (GISP2 and Vostok, n=11) and glacial results (Vostok, n=15) at the 95% confidence interval (two-tailed students t-test, t=1.240, outliers at 1307 m neglected). The overall mean flux for the data set, (neglecting the outliers at 1307 m) is 0.83 ± 0.20 x 10^{-12} cm^3 STP cm^{-2} ka^{-1}. This value may be more appropriate for comparison to marine sediment data which are averaged over long time periods by strip sampling [e. g., *Patterson and Farley, 1998*]. There is also apparent temporal variability in the Vostok results for the samples deposited between 75 and 97 ka (Figure 2). Apart from the highly anomalous results from the sample at 1307 m, the Vostok results indicate an apparent variability in the ^{3}He flux of a factor of almost 4 on time scales of a few thousand years (Figure 2). Apparent fluxes between 97 and 93 ka are 1.27 - 2.47 x 10^{-12} cm^3 STP cm^{-2} ka^{-1}. In the subsequent period between 92 and 84 ka fluxes ranged from 0.32 - 0.91 cm^3 STP cm^{-2} ka^{-1}, and then returned to higher values between 0.92 and 0.97 x 10^{-12} cm^3 STP cm^{-2} ka^{-1} by 78 ka.). Such rapid changes not appear in marine sediment data, but bioturbation and sampling techniques smooth the marine record to varying degrees, while ice cores should preserve a higher resolution record of flux variations.

There are a number of possible reasons for the apparent temporal ^{3}He flux variations in the Vostok core. First, they may reflect the statistics of small IDP populations. Second, there may be terrestrial factors that affect the IDP content of polar ice. For example, variations in wind velocity might change the size distribution of deposited IDPs. Finally, the ^{3}He flux variability may reflect changes in the dynamics of interplanetary dust production, transport, or accretion. This latter possibility is intriguing, as it implies that ice core samples could be used to examine IDP flux variations over the past ~ 400 ka.

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