Meteoritics & Planetary Science 43, Nr 3, 517–528 (2008)
Abstract available online at http://meteoritics.org

Noble gases in fossil micrometeorites and meteorites from 470 Myr old sediments from southern Sweden, and new evidence for the L-chondrite parent body breakup event

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(Received 02 May 2007; revision accepted 14 August 2007)

Abstract–We present noble gas analyses of sediment-dispersed extraterrestrial chromite grains recovered from ~470 Myr old sediments from two quarries (Hällekis and Thorsberg) and of relict chromites in a coeval fossil meteorite from the Gullhögen quarry, all located in southern Sweden. Both the sediment-dispersed grains and the meteorite Gullhögen 001 were generated in the L-chondrite parent body breakup about 470 Myr ago, which was also the event responsible for the abundant fossil meteorites previously found in the Thorsberg quarry. Trapped solar noble gases in the sediment-dispersed chromite grains have partly been retained during ~470 Myr of terrestrial residence and despite harsh chemical treatment in the laboratory. This shows that chromite is highly retentive for solar noble gases. The solar noble gases imply that a sizeable fraction of the sediment-dispersed chromite grains are micrometeorites or fragments thereof rather than remnants of larger meteorites. The grains in the oldest sediment beds were rapidly delivered to Earth likely by direct injection into an orbital resonance in the inner asteroid belt, whereas grains in younger sediments arrived by orbital decay due to Poynting-Robertson (P-R) drag. The fossil meteorite Gullhögen 001 has a low cosmic-ray exposure age of ~0.9 Myr, based on new He and Ne production rates in chromite determined experimentally. This age is comparable to the ages of the fossil meteorites from Thorsberg, providing additional evidence for very rapid transfer times of material after the L-chondrite parent body breakup.

INTRODUCTION

Schmitz et al. (1996) discovered a high concentration of fossil meteorites in a quarry of mid-Ordovician marine limestone in southern Sweden (Thorsberg quarry). Although the mineralogy of the meteorites has been altered during sediment diagenesis, the very resistant mineral chromite ($FeCr_2O_4$) preserved its original composition and allowed these meteorites to be classified as L (or LL) chondrites (Schmitz et al. 2001). Oxygen isotope data on chromites (Greenwood et al. 2007) as well as petrographic evidence (Bridges et al. 2007) further support the L-chondrite classification of these fossil meteorites. Chromite proved to be retentive for cosmogenic (and in one case also for solar) noble gases (Heck et al. 2003, 2004). Heck et al. (2004) showed that the transfer times of the fossil L chondrites from their parent body to Earth, measured by cosmogenic noble gases, were unusually short compared to the transfer times of modern ordinary chondrites—only between 0.1–1 Myr. Furthermore, ages increase with decreasing sediment age (Heck et al. 2004). The observed short transfer times are in agreement with dynamical models of debris produced in large asteroid collisions occurring close to important orbital resonances in the inner asteroid belt (Gladman et al. 1997; Zappalà et al. 1998; Nesvorný et al. 2007). The suite of fossil L chondrites is thought to have been produced in the breakup of the L-chondrite parent body (Schmitz et al. 2003; Heck et al. 2004). This event is well documented by a clustering of K-Ar gas retention ages around 500 Myr in recently fallen L chondrites, which also show signs of shock (Keil et al. 1994; Bogard 1995). A new study of Ar-Ar ages in L chondrites by Korochantseva et al. (2007) dates the L-chondrite parent body breakup event to 469.6 ± 5.4 Myr. This is consistent with the current age estimate of 467 ± 1.5 Myr for the middle

Table 1. Location and description of sediment or fossil meteorite samples from where relict chromite grains have been recovered.

Sample[a]	Quarry	Position	Description	Reference
Hällekis 5.50	Hällekis, at Kinnekulle (4 km NW of Thorsberg)	5.50 m above Arkeologen base	SEC grains, L-chondrite composition	–
Hällekis 3.57	Hällekis	3.57 m above Arkeologen base	SEC grains, L-chondrite composition	–
Gullhögen 001	Gullhögen, at Billingen Mountain (35 km SE of Thorsberg)	*Yangtzeplacognathus crassus* Conodont Zone; equivalent to the Tredje Karten and Sextummen beds in the Thorsberg quarry	Fossil meteorite, L chondrite ~1 cm diameter	Tassinari et al. 2004
Arkeologen	Thorsberg, at Kinnekulle	Upper part of Arkeologen bed	SEC grains, L-chondrite composition	Schmitz et al. 2003

[a] The samples are arranged according to time of deposition as determined by their stratigraphic position. Arkeologen samples are the oldest ones, while the SEC grains from the Hällekis quarry have been found in the youngest sediments. The samples are chromite grains extracted from fossil meteorites or directly from sedimentary rock. SEC grains = sediment-dispersed extraterrestrial chromite grains.

Ordovician sediments where the fossil meteorites were found (Gradstein et al. 2004). The high fossil meteorite density and their L-chondrite composition (Schmitz et al. 2001) in sediments of middle Ordovician age, their low exposure ages and the exposure age gradient, in accordance with theoretical predictions for a major asteroid breakup, confirm that the fossil meteorites are debris of the L-chondrite parent body breakup event near an important orbital resonance in the inner asteroid belt (Heck et al. 2004). It has been suggested that the L-chondrite parent body breakup was related to the generation of the Flora asteroid family (Nesvorný et al. 2002, 2007) upon the disruption of a 185 km large asteroid (Durda et al. 2007).

Since such an event should have produced a global increase in the flux of extraterrestrial material, it would be desirable to recover fossil meteorites from other locations in the same Ordovician stratigraphic sequences. The only fossil meteorite found to date in the same sediment beds at another location (Gullhögen quarry at Billingen, southern Sweden) proved also to be an L chondrite (Tassinari et al. 2004). In this work we present the cosmic-ray exposure age of this meteorite.

Fossil meteorites are rare, even in the mid-Ordovician meteorite-enriched strata. Only in active quarries with workers trained for meteorite identification are systematic recoveries reported (Schmitz et al. 2001). Accidental finds, such as Österplana 001 (Nyström et al. 1988) and Gullhögen 001 (Tassinari et al. 2004) are very rare. A much more promising method is to look for relict meteoritic minerals in bulk sediment samples. By this approach, sediment-dispersed extraterrestrial chromite (SEC) grains (average grain size 80 to 100 µm) were found at various locations in southern Sweden in the same sediment beds as the fossil meteorites (Schmitz et al. 2003; Schmitz and Häggström 2006). It was suggested that these grains are remnants of disintegrated small meteorites 0.1 to 1 cm in diameter (Schmitz et al. 2003). However, here we will present evidence that at least some of the grains were submillimeter-sized micrometeorites or parts thereof in space. The relatively high abundance of the SEC grains and also the fossil meteorites suggests that the flux of extraterrestrial matter to Earth during the sediment deposition period in the Ordovician was about two orders of magnitude higher than today (Schmitz et al. 2003). SEM/EDS analyses indicated a chemical composition of the SEC grains that matches the composition of relict chromite grains from fossil meteorites and of chromites from modern L and LL chondrites (Schmitz et al. 2001; Schmitz and Häggström 2006). The characteristic composition of SEC grains are high Cr_2O_3 (~55–60 wt%), low Al_2O_3 (~5–8 wt%), and MgO (~1.5–4 wt%), and narrow ranges of V_2O_3 (0.6–0.9 wt%) and TiO_2 (~2.0–3.5 wt%) (see Fig. 4 and Table 2 in Schmitz and Häggström 2006).

Here we primarily present He and Ne data on selected SEC grains from different locations in southern Sweden. The purpose of these measurements was to elucidate relationships between these SEC grains and the fossil meteorites from the same sediment strata and to further constrain the origin and delivery mechanisms of the SEC grains.

In an auxiliary study, we determined cosmic-ray production rates of He and Ne in chromite (Heck et al. 2005). Due to a lack of measured cross section data for Cr, a major target element in chromite ($FeCr_2O_4$), production rates for cosmogenic ^{3}He and ^{21}Ne in chromite $P(^3\text{He}, ^{21}\text{Ne})$ used by Heck et al. (2004) were based on a model of nuclide production by cosmic-ray interactions (Leya et al. 2000). Here, we determined $P(^3\text{He}, ^{21}\text{Ne})$ in chromite directly, by comparing measured cosmogenic noble gas concentrations in chromite separates from ordinary chondrites with ^{3}He and ^{21}Ne from bulk meteorite samples, adjacent to those from which the chromites have been extracted.

SAMPLES AND EXPERIMENTAL

Chromite Grains

The orthoceratite limestone samples containing the extraterrestrial chromites are collected from different sediment beds in the Hällekis and Thorsberg quarries in southern Sweden (Table 1). The sediments formed in an epicontinental sea during the middle Ordovician about 470 Myr ago (see map, Fig. 1 in Schmitz et al. 2003; Lindström 1971). Sediment sample sizes range between 10–30 kg. Chromite grains larger than 63 µm (Fig. 1) were extracted by dissolving the limestone with hydrochloric and hydrofluoric acids as outlined in Schmitz et al. (2003). The maximum yields were ~3 SEC grains per kg of rock in the Arkeologen bed (Schmitz et al. 2003), leading to an accumulation density of about 3000 grains per m^2 during the formation interval of the Arkeologen bed. For this study, a subset of all the extracted chromite grains was selected randomly for noble gas analyses.

Relict chromite grains from the fossil meteorite Gullhögen 001 were extracted by HCl acid dissolution as described in Schmitz et al. (2001). Chromite grains from recent ordinary chondrites were extracted by HF acid dissolution.

Grains were selected under the light microscope and picked with a fine brush. To quantitatively determine the elemental composition with SEM/EDS as presented in Schmitz et al. (2001) and Schmitz and Häggström (2006), polished sections of chromite grains embedded in epoxy would need to be studied. However, polishing the grains would compromise the noble gas measurements. Therefore, unpolished samples were inspected with SEM/EDS to obtain a qualitative assessment of the chemical composition of the grains. Only grains with a composition consistent with the L- (or LL-) chondrite compositions of large numbers of extraterrestrial chromite grains studied earlier (see ranges cited in the Introduction) were considered to be extraterrestrial and chosen for further study. Previous quantitative analyses showed that in the sediments studied, SEC grains with L- (or LL-) chondrite compositions are about two orders of magnitude more abundant than the background population (Schmitz et al. 2003; Schmitz and Häggström 2006), making it unlikely that we sampled material from the extraterrestrial background flux, which can have a different composition. Batches of 4–6 relict chromite grains (average grain size 80–100 µm) from the same sample location were weighed with a microbalance to an accuracy of ~10%. Sample weights ranged between 4 and 8 µg. Two batches consisting of 5 and 6 single chromite grains (6 and 14 µg, respectively) from the fossil meteorite Gullhögen 001 were prepared for analyses. Nine batches of chromites from five recent meteorites in the same size range with a batch mass range of 4–23 µg were prepared. The five meteorites are ordinary chondrites of type L, LL, and H, with well-known, relatively high cosmic-ray exposure ages (~15–60 Myr) and average shielding, indicated by ^{22}Ne/^{21}Ne ≈ 1.11: Mt. Tazerzait (L5), Harleton (L6), Saint-Séverin (LL6), Eva (H5), and Hessle (H5).

To cope with the extremely low gas amounts expected in the chromites (as suggested by our previous study; Heck et al. 2004) we used an ultra-high-sensitivity mass spectrometer coupled to a low-blank extraction line and set up a tailored gas extraction and analysis procedure. The heart of the mass spectrometer is an inverse molecular drag pump (compressor) that concentrates the gas to be analyzed almost quantitatively into the small ionization volume of the ion source (Baur 1999). This results in a sensitivity about two orders of magnitude higher when compared to the same mass spectrometer equipped with a conventional ion source without a compressor (Baur 1999). Gases were extracted by complete melting of chromite samples for ~3–4 min with a CW Nd-YAG laser (1064 nm) in ultra-high vacuum (UHV). Exposure to a liquid-nitrogen-cooled trap and cooled activated charcoal traps, and to several types of chemical getters removes Ar, H_2O, and active gases from the sample gas. In order to minimize the production of doubly charged interfering species, such as Ar and CO_2, an electron acceleration voltage in the ion source of only 40 eV was used. ^{3}He can be resolved from HD, as the mass resolution of the instrument is ~650. Both He ions are detected simultaneously with an electron multiplier in ion counting mode (^{3}He) and with a Faraday cup (^{4}He). Because of the expected very small gas amounts, ion signals were monitored before and after sample gas admission. Sample signals were deduced as the difference of both signals extrapolated to gas admission time (Heck et al. 2007). The detection limits for these analyses of relict chromite grains were ~4–7 × 10^{-14} cm^3 STP ^{20}Ne and 0.9–14 × 10^{-13} cm^3 STP ^{4}He.

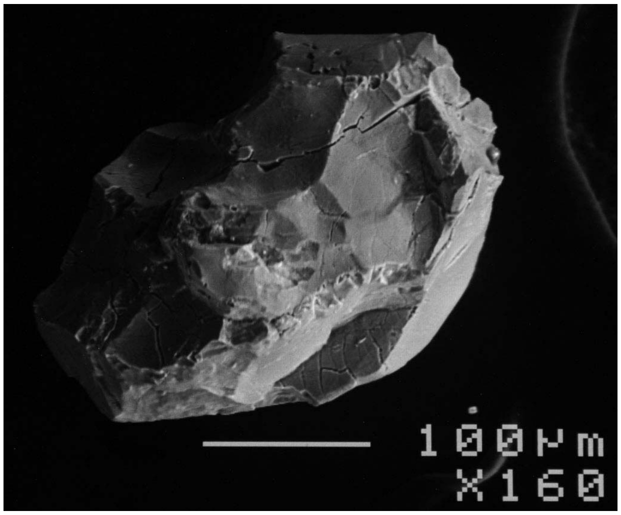

Fig. 1. SEM image of a well-preserved relict meteoritic chromite grain (Hällekis quarry, Sweden). Although chromite is one of the most resistant mineral phases in ordinary chondrites, different stages of alteration can be observed by inspecting surface morphology and ZnO content. The preservation state is also a measure of ^{3}He retentivity (Heck et al. 2004).

Bulk Meteorite Samples

The larger gas amounts expected in bulk meteorite samples did not require the use of the ultra-high-sensitivity

Table 2. Helium and neon concentrations and isotopic ratios of batches of relict chromite grains[a] extracted from a fossil meteorite, of sediment-dispersed extraterrestrial chromite grains and of chromites extracted from modern ordinary chondrites.

Sample[b]	Mass (µg)	^{3}He (10^{-8} cm^3/g)	^{4}He (10^{-5} cm^3/g)	^{20}Ne (10^{-8} cm^3/g)	^{21}Ne (10^{-8} cm^3/g)	^{22}Ne (10^{-8} cm^3/g)	^{3}He/^{4}He (10^{-5})	^{20}Ne/^{22}Ne	^{4}He/^{22}Ne
Chromites from fossil meteorites									
Gull 001-1	6.0	0.851 ± 0.087	2.95 ± 0.30	4.55 ± 0.49	0.0648 ± 0.0042	0.560 ± 0.064	28.8 ± 0.6	8.12 ± 0.53	5280 ± 290
Gull 001-2	14	1.16 ± 0.12	4.26 ± 0.43	4.46 ± 0.45	0.0857 ± 0.0026	0.560 ± 0.057	27.3 ± 0.4	7.95 ± 0.15	7590 ± 130
Sediment-dispersed extraterrestrial chromite grains									
Ark 1-1	5.0	125 ± 13	552 ± 55		23.5 ± 2.4	771 ± 77	22.7 ± 0.03		716 ± 2
Ark 1-2	4.0	117 ± 12	649 ± 65		20.9 ± 2.1	682 ± 68	18.1 ± 0.03		952 ± 3
Ark 2	8.0	101 ± 10	488 ± 49		19.8 ± 2.0	652 ± 65	20.6 ± 0.03		749 ± 2
H-Kis 3.57-1	4.5	29.3 ± 2.9	136 ± 14	5750 ± 580	14.9 ± 1.5	489 ± 49	21.6 ± 0.09	11.8 ± 0.05	278 ± 1
H-Kis 3.57-2	6.0	182 ± 18	739 ± 74		26.0 ± 2.6	861 ± 86	24.7 ± 0.04		859 ± 3
H-Kis 5.50-1	4.0	132 ± 13	515 ± 52		27.7 ± 2.8	905 ± 91	25.6 ± 0.05		570 ± 2
H-Kis 5.50-2	7.0	51.3 ± 5.1	222 ± 22		25.7 ± 2.6	844 ± 84	23.1 ± 0.05		263 ± 1
H-Kis 5.50-4	7.0	223 ± 22	942 ± 94			1700 ± 170	23.6 ± 0.03		555 ± 2
Chromites from modern ordinary chondrites									
Mt.T-1	18	119 ± 24	0.96 ± 0.19	5.3 ± 1.1	4.38 ± 0.88	5.1 ± 1.0	12,405 ± 70	1.04 ± 0.01	180 ± 2
Mt.T-2	23	95 ± 19	0.93 ± 0.19	4.71 ± 0.95	3.52 ± 0.70	4.14 ± 0.83	10,288 ± 44	1.14 ± 0.01	197 ± 2
St.S-1	18	22.6 ± 4.5	0.52 ± 0.11	1.98 ± 0.41	0.53 ± 0.11	0.79 ± 0.16	4318 ± 58	2.50 ± 0.08	265 ± 8
St.S-2	17	24.5 ± 4.9	0.45 ± 0.09	2.67 ± 0.56	0.64 ± 0.13	0.98 ± 0.20	5500 ± 62	2.71 ± 0.08	167 ± 5
Eva-1	17	129 ± 26	1.34 ± 0.27	4.9 ± 1.0	4.56 ± 0.91	5. 5 ± 1.1	9596 ± 45	0.90 ± 0.02	273 ± 6
Eva-2	11	110 ± 22	0.91 ± 0.18	16.8 ± 3.4	3.95 ± 0.79	6.2 ± 1.2	12,085 ± 130	2.72 ± 0.03	54 ± 1
Hes	4	98 ± 20	10.1 ± 2.0	11.5 ± 2.4	3.54 ± 0.71	5.2 ± 1.0	964.6 ± 2.9	2.21 ± 0.05	880 ± 19
Har-1	12	70 ± 14	0.62 ± 0.13	3.99 ± 0.82	2.22 ± 0.45	2.82 ± 0.57	11,248 ± 151	1.41 ± 0.04	156 ± 5
Har-2	5	67 ± 13	0.73 ± 0.15	10.4 ± 2.2	2.08 ± 0.42	3.65 ± 0.73	9167 ± 237	2.85 ± 0.09	70 ± 3
Solar wind and air isotopic ratios[c]									
Solar wind							43.0 ± 2.5	13.7 ± 0.3	7810 ± 70
Air							0.14 ± 0.001	9.80 ± 0.08	3.1 ± 0.2

[a] Uncertainties (2σ) include weighing errors, ion statistics, and blank corrections.

[b] Gull = Gullhögen 001; Ark = Arkeologen; H-Kis = Hällekis; Hes = Hessle; Mt.T. = Mount Tazerzait; St.S. = Saint-Séverin.

[c] Solar wind (Geiss et al. 2004) and air (Eberhardt et al. 1965; Mamyrin et al. 1970) compositions are given for comparison.

Table 3. Concentrations of cosmogenic ^{3}He and ^{21}Ne, and cosmic-ray exposure ages (T_3, T_{21}) determined in bulk meteorites (averaged values) and relict chromite grains from the fossil L chondrite Gullhögen 001 (Gull)[a].

Sample	$^3He_{cos}$ (10^{-8} cm^3 g^{-1})	$^{21}Ne_{cos}$ (10^{-8} cm^3 g^{-1})	T_3 (Myr)	T_{21} (Myr)
Mt. Tazerzait	93.4 ± 9.5	21.1 ± 2.2	61 ± 6	58 ± 6
Saint-Séverin	20.2 ± 2.05	3.71 ± 0.38	16 ± 2	16 ± 2
Eva	72.7 ± 7.3	15.6 ± 1.6	54 ± 5	54 ± 5
Hessle	105 ± 10.6	19.4 ± 2.0	66 ± 7	47 ± 5
Harleton[b]	70.5 ± 7.5	14.4 ± 1.4	44 ± 4	42 ± 4
Gull 001-1	0.847 ± 0.087	0.0513 ± 0.0066	0.43 ± 0.06	0.73 ± 0.12
Gull 001-2	1.15 ± 0.12	0.0725 ± 0.0077	0.58 ± 0.08	1.03 ± 0.15

[a] Errors are given as 1σ and include weighing uncertainties, ion statistics, and blanks.

[b] Helium and neon data of Harleton are the average values published in the compilation by Schultz and Franke (2004).

mass spectrometer used for chromites. Therefore, we used a mass spectrometer equipped with a conventional (Baur-Signer) ion source (Baur 1980) and without a compressor. Average blanks for this instrument for ^{4}He and ^{20}Ne were ~4.5×10^{-12} cm^3 STP and ~1.1×10^{-13} cm^3 STP (Vogel 2003; Vogel et al. 2003).

We measured helium and neon isotopes in ~100 mg bulk samples of four of the five recent ordinary chondrites mentioned above. The bulk data of the ordinary chondrite Harleton given in Table 3 are from the data compilation of Schultz and Franke (2004). Gases from the ~100 mg bulk meteorite samples were extracted in a furnace by total fusion at $T \approx 2000$ K in UHV and subsequently cleaned using liquid-nitrogen-cooled activated charcoal traps and hot metal alloy getters (Zr-V-Fe, Zr-Al, Zr-Ti). Ionization was achieved by impact with 45 eV electrons. This electron energy minimizes the amount of doubly charged ^{40}Ar, which interferes with ^{20}Ne$^+$. He and Ne isotopes as well as ion signals needed for interference corrections were measured. The mass resolution of the instrument ($M/\Delta M \approx 550$) allows ^{3}He and ^{20}Ne to be separated from HD and $H_2{}^{18}O$, respectively. Ion detection was done using alternately an electron multiplier in counting mode and a Faraday cup.

Gas concentrations of the bulk meteorite samples were corrected by subtracting blank signals (determined by melting empty aluminum foil wrapping) and correcting for remaining interferences. Ion signals in both spectrometers were calibrated using an artificial gas mixture, whose amounts are believed to be known to be better than 3%. We assume the ^{3}He amount in the meteorite samples to be entirely cosmogenic. Cosmogenic ^{21}Ne for bulk meteorite samples has been corrected for atmospheric Ne (<1.5% of total ^{21}Ne).

RESULTS

Cosmogenic Noble Gas Production Rates in Chromite

Concentrations of cosmogenic ^{3}He and ^{21}Ne in chromites from five modern ordinary chondrites are given in Table 2. Aliquot measurements always agree within 2σ analytical error. We calculated cosmic-ray exposure ages (CRE) for the five chondrites using bulk meteorite noble gas data shown in Table 3 and elemental production rates of ^{3}He and ^{21}Ne taken from Leya et al. (2000). We assume a typical meteorite radius of 25 cm and a sample position of about 10 cm below the surface. In Fig. 2, the measured concentrations in chromite grains versus the adopted CRE of the meteorites correlate with each other. The slope of the best linear fit forced through the origin gives the production rates of ^{3}He and ^{21}Ne, respectively (Table 4).

Our new ^{21}Ne production rate, $P(^{21}Ne) = (7.04 \pm 0.65) \times 10^{-10}$ STP g^{-1} Myr^{-1}, falls in the range of previously used values (see Table 4). These measurements confirm the exposure age range found for fossil meteorites by Heck et al. (2004). The new ^{3}He production rate, $P(^3He) = (1.99 \pm 0.17) \times 10^{-8}$ STP g^{-1} Myr^{-1}, is ~50% higher than the value used by Heck et al. (2004). This difference is of no concern for the former work, however, because diffusive ^{3}He losses from the chromites of fossil meteorites had forced us to rely exclusively on ^{21}Ne exposure ages anyway. In the following, we adopt both the new $P(^{21}Ne)$ and $P(^3He)$ values.

The Fossil Meteorite Gullhögen 001

Noble gas concentrations measured in chromites from the fossil meteorite Gullhögen 001 are given in Table 2. Two batches of relict chromite grains from this meteorite contained cosmogenic noble gases in comparable concentrations as chromites from the suite of fossil meteorites found at the nearby Thorsberg quarry (Table 2). The exposure age T_{21} of Gullhögen 001 of about 0.7–1.0 Myr (Table 3) is unusually low compared to typical values for recent meteorite falls but is similar to the CRE of the Thorsberg meteorites (Table 3; Fig. 3). The values based on cosmogenic ^{3}He (T_3) are below the range of T_{21}. This indicates He loss, as observed for other fossil meteorites (Heck et al. 2004), and T_3 is therefore dismissed.

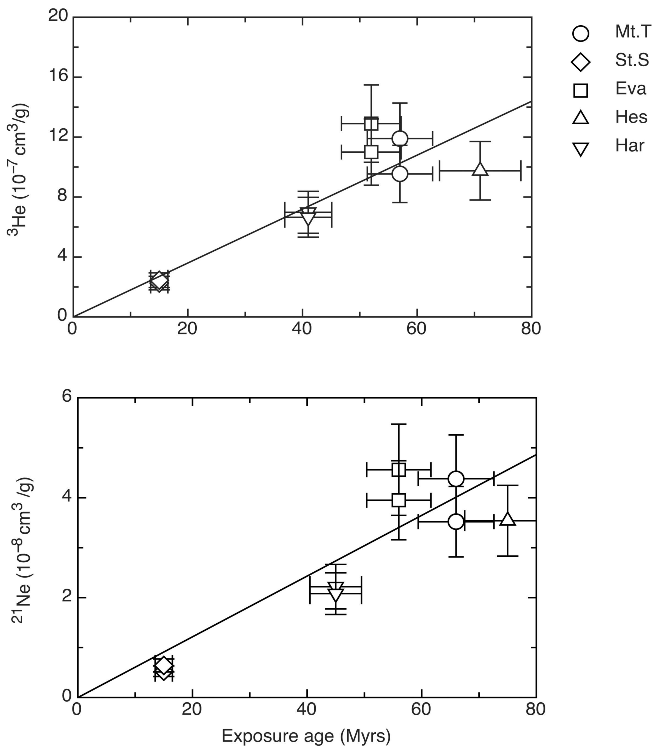

Fig. 2. Measured cosmogenic ^{3}He- and ^{21}Ne concentrations in meteoritic chromite separates plotted against average exposure ages calculated from measured ^{3}He and ^{21}Ne data for bulk meteorites (see the Cosmogenic Noble Gas Production Rates in Chromite section). The slope of the best linear fit forced through the origin gives the production rates shown in Table 4. Error bars are 2σ.

Sediment-Dispersed Extraterrestrial Chromite Grains

The SEC grains contained very high concentrations of trapped solar He and Ne (Table 2). This is surprising, since we suspected that the SEC grains might be relicts of disintegrated meteorites and solar gases in meteorites are quite rare (see the Solar Noble Gases section). The trapped noble gases provide interesting clues about the provenance of chromites. Because of the very high trapped gas amounts, ^{20}Ne could only be measured in one sample. In the other grains, ^{20}Ne gas amounts were above the detection threshold of the ion counter (>1 MHz) and the system was not programmed to switch to the Faraday-cup detector. This one grain (H-Kis 3.57-1) has a ^{20}Ne/^{22}Ne ratio of 11.8, in the range of (fractionated) solar wind Ne. Also, the ^{3}He/^{4}He ratio of all grain batches is close to fractionated solar wind composition (formerly known as "SEP-He;" Grimberg et al. 2006). As discussed below, the solar noble gases indicate that the SEC grains came to Earth as small particles. The element ratios ^{4}He/^{22}Ne lie between the atmospheric (3.1) and the solar (~9000) value, indicating partial loss of solar gases, as is also observed for recent interplanetary dust particles (IDPs) (Kehm et al. 2002).

Table 4. Comparison of experimentally determined ^{3}He and ^{21}Ne production rates in chromites based on measured bulk meteorite data and measured noble gas concentrations in chromites.

	Production rates[a] for chromites based on measured bulk data	Production rates[a] for chromites based on predictions[b] using model[c]
$P(^3He)$ 10^{-8} STP g^{-1} Myr^{-1}	1.99 ± 0.17	1.23 ± 0.49
$P(^{21}Ne)$ 10^{-10} STP g^{-1} Myr^{-1}	7.04 ± 0.65	4.7–7.2

[a] Values for ^{21}Ne in the last column vary mainly due to variable Mg concentrations (a major target element for cosmogenic Ne production) in relict chromite grains from fossil meteorites.
[b] Heck et al. (2004).
[c] Leya et al. (2000).

DISCUSSION

Gullhögen 001

The remarkably short exposure age of the Gullhögen 001 meteorite is comparable to the unusually young ages of the suite of fossil meteorites found in the Ordovician sediments of southern Sweden. Gullhögen 001 has been recovered from sediments belonging to the *Yangtzeplacognathus crassus* Conodont Zone in the Gullhögen quarry (Tassinari et al. 2004). The same conodont zone encompasses the fossil meteorite-bearing Tredje Karten and Sextummen sediment beds in the Thorsberg quarry. The ^{21}Ne-exposure age of Gullhögen 001 (T_{21} = 0.88 ± 0.10 Myr) is similar to the one of fossil meteorite Österplana 042 alias Tredje Karten 002 (T_{21} = 0.83 ± 0.12 Myr) from Thorsberg (Heck et al. 2004). Exposure ages of the Sextummen meteorites recovered from the same conodont zone (but below Tredje Karten) are ~0.2 to 0.4 Myr lower. The exposure age of Gullhögen 001 thus fits smoothly into the age gradient determined from fossil meteorites of the Thorsberg quarry (Fig. 3) using conodont stratigraphy to date the sediments.

The low exposure age of Gullhögen 001 and its consistency with the exposure age distribution of the Thorsberg meteorites corroborates that Gullhögen 001 is related to the fossil meteorites found at Thorsberg and strongly suggests that the Ordovician sediments in the Gullhögen quarry also contain many meteorites from the L-chondrite parent body breakup event ~470 Myr ago.

Sediment-Dispersed Extraterrestrial Chromite Grains

Solar Noble Gases

Rather surprisingly, the SEC grains are rich in solar gases. This prevents the determination of cosmic-ray exposure ages of the grains, because ^{21}Ne/^{22}Ne ratios are too close to solar values to reliably deduce any excess of

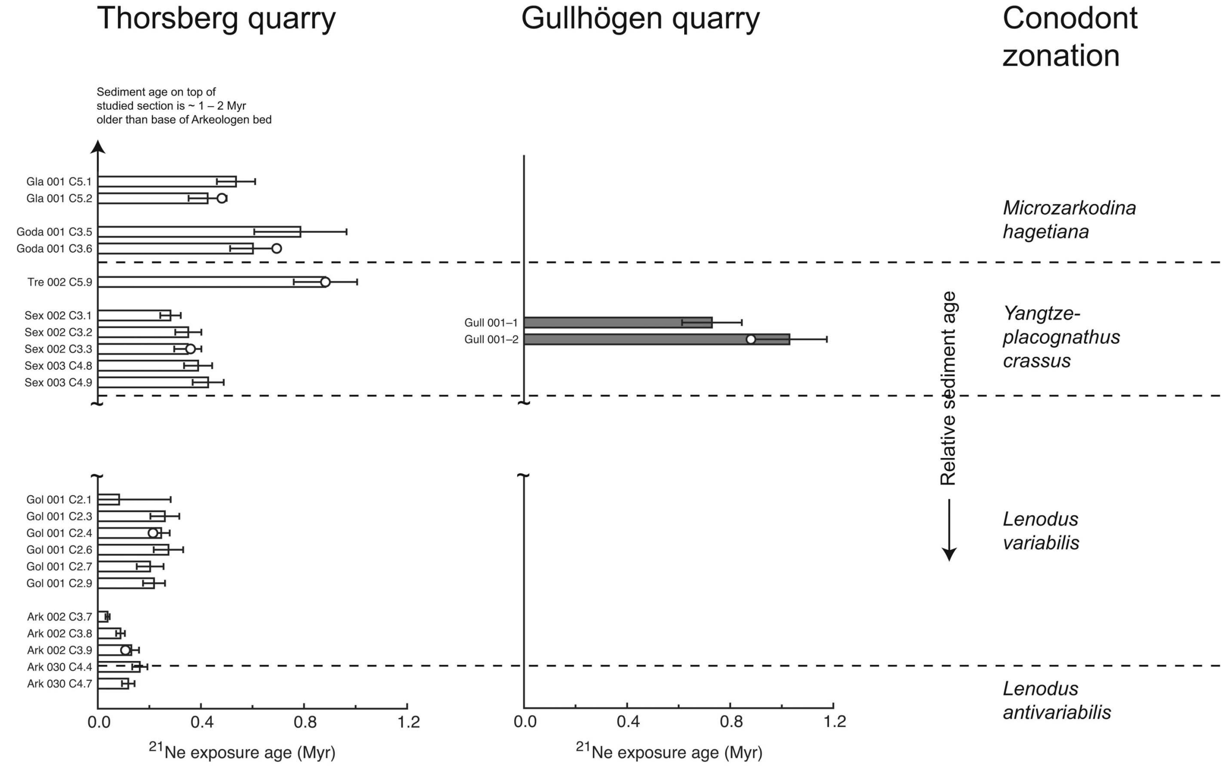

Fig. 3. ^{21}Ne cosmic ray exposure ages for two samples of relict chromite grains from the fossil meteorite Gullhögen 001 found in the Gullhögen quarry at Billingen mountain (shaded bars). Also shown are exposure ages based on previously published data for chromites from fossil meteorites from the Thorsberg quarry (empty bars, Heck et al. 2004), now determined with the new ^{21}Ne production rate given here. The sediments where Gull 001 has been found belong to the *Yangtzeplacognatus crassus* Conodont Zone which encompasses the Tredje Karten and Sextummen beds at Thorsberg, as indicated in the figure. The total deposition time of the sediments studied at Thorsberg was ~1–2 Myr, estimated from conodont biochronology and average sedimentation rates (Schmitz et al. 1996, 2001; Jianhua 1998). Error bars are 1σ, and include weighing uncertainties, ion statistics, and blanks. Open circles are averaged ^{21}Ne exposure ages of all analyses from the same quarry bed. Ages of Gla 001 may be too low due to an unusually large preatmospheric size or moderate losses of cosmogenic Ne (Heck et al. 2004). Ark = Arkeologen; Gol = Golvsten; Gla = Glaskarten; Sex = Sextummen; Tre = Tredje Karten; Gull = Gullhögen; Goda = Goda Lagret.

cosmogenic ^{21}Ne. In a future study, cosmogenic ^{21}Ne may be detected by analyzing chromites whose outermost solar-gas-bearing layers had been etched off, such that only the cosmic-ray-induced He and Ne component would remain. However, the solar noble gases by themselves tell an interesting story.

At least part of the surface of at least one grain from each batch of 4–6 grains must once have been exposed to the solar wind. Since solar wind ions penetrate only a few ten nanometers into solid matter, solar-gas-rich grains thus had to be exposed to free space. This may have happened when the chromite grains were (parts of) small individual particles in interplanetary space, as is observed for IDPs and micrometeorites (see below). Alternatively, the chromite grains could originate from macroscopic solar-gas-rich meteorites, i.e., compacted dust from asteroid surface layers. In this case, solar noble gases would have been implanted while the chromite grains resided at the immediate asteroid surface (Suess et al. 1964). The second possibility can be excluded for two reasons. First, solar-gas-rich L chondrites are rare—comprising only about 3% of all L chondrites (Bischoff and Schultz 2004). Thus, the probability that all 8 analyzed SEC grain batches from different sediment beds contain at least one grain from the solar gas-rich population is less than 10^{-6}. Second, the range of solar ^{22}Ne concentrations in gas-rich L chondrites of ~(10–150) × 10^{-8} cm^3/g (Schultz and Franke 2004) is clearly lower than the range of ^{22}Ne concentrations found in the chromites (Fig. 4), although the chromites have a larger grain size and thus a lower surface-to-volume area than meteoritic matrix grains. We therefore conclude that a sizeable fraction—if not most—of the chromite grains came to Earth as small (ø 63 to ~300 μm), gas-rich particles and at least partially retained solar gases during atmospheric entry, ~470 Myr residence in marine sediments and the harsh chemical treatment applied to isolate the grains in the laboratory.

Schmitz et al. (2003) suggested that the SEC grains mostly stemmed from disintegrated meteorites of about 0.1–1 cm size. In view of the presence of solar He and Ne in many SEC grains, this estimate needs to be partly revised. At least one out of 4–6 chromite grains must have been either an individual ~100 micron-sized chromite IDP or must be from a grain assemblage small enough that each chromite had a good

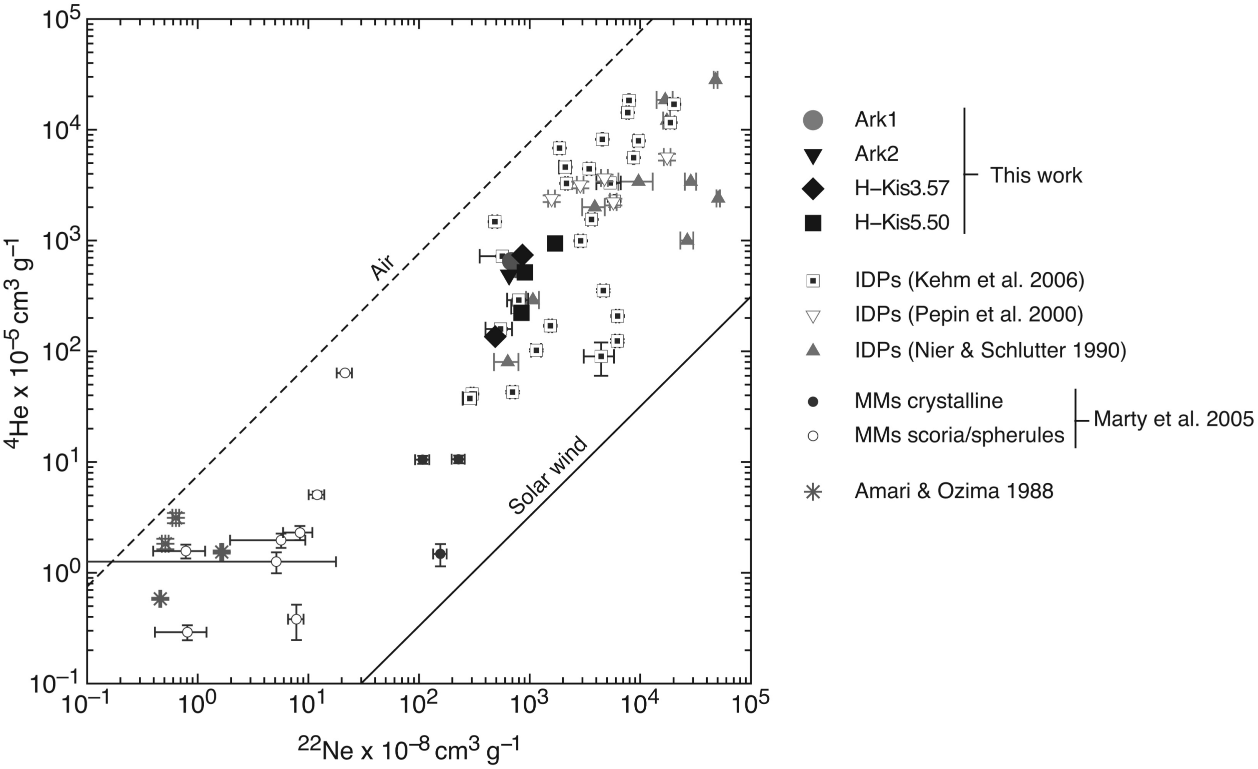

Fig. 4. Comparison of Ne and He concentrations in Ordovician sediment-dispersed chromite grains with values for IDPs and micrometeorites from other studies. The chromite grains have higher concentrations than more recent micrometeorites (Marty et al. 2005). At the lower end are data from magnetically separated bulk fractions from Quaternary Pacific deep-sea sediments by Amari and Ozima (1988) and cosmic spherules recovered from ice (Marty et al. 2005). At the higher end are stratospheric IDPs (references given in legend). Air (Eberhardt et al. 1965) and solar wind (Geiss et al. 2004) compositions are given as straight lines. Errors are 1σ (not shown if smaller than symbols).

chance to have part of its surface exposed to free space. The second option may be more likely, because individual chromite grains in meteorites rarely are much larger than 100 microns, hence fragments of such grains should mostly be smaller than what is observed in the sediment record. However, the solar noble gases strongly suggest that a sizeable fraction of the chromite grains came to Earth in particles not exceeding a few hundred micrometers. Future noble gas analyses on individual SEC grains (rather than batches of 4–6 grains) should further constrain the fraction of grains arriving as small particles.

Since both IDPs captured in the stratosphere and micrometeorites collected on the Earth's surface, mostly contain noble gases implanted from the solar wind (e.g., Rajan et al. 1977; Amari and Ozima 1988; Olinger et al. 1990; Nier and Schlutter 1990; Kehm et al. 2002, 2006; Pepin et al. 2000; Marty et al. 2005), we compare gas concentrations in our SEC grains with data from micrometeorites and IDPs from other studies (see Fig. 4).

^{22}Ne and ^{4}He concentrations of the SEC grains range from about 500 to 1700 10^{-8} cm^3/g and from about 140 to 950 10^{-8} cm^3/g, respectively. This is comparable with the lower range of concentrations found in stratospheric IDPs, and mostly higher than noble gas concentrations found in recent micrometeorites recovered from terrestrial ice and the sea floor (Fig. 4). Our least gas-rich chromites have comparable Ne concentrations as the most gas-rich micrometeorites from Greenland analyzed by Olinger et al. (1990).

Assuming equal irradiation times or saturation, surface-implanted solar noble gas concentrations should inversely correlate with grain size. The much lower gas concentrations of the larger micrometeorites cannot be explained by their smaller surface-to-volume ratio alone, but are mainly a result of gas loss due to higher peak temperatures during atmospheric entry, which is more important for larger particles (Love and Brownlee 1991, 1994; Nier and Schlutter 1990). The high noble gas concentrations in some stratospheric IDPs compared to those of the SEC grains are again probably largely the result of size-dependent gas losses during atmospheric entry heating (Love and Brownlee 1991, 1994) because IDPs are mostly smaller than the SEC grains. Stratospheric IDPs are also spared from terrestrial alteration effects. They therefore may retain a higher fraction of solar noble gases than micrometeorites found on Earth's surface.

The dust grains were exposed to the solar wind between 1 and 2 AU. Assuming present-day solar wind flux, measured gas concentrations yield nominal solar wind exposure ages of between months and years only, much lower than dynamical lifetime estimates of up to 1 Ma (see the following section). This is another argument for a considerable noble gas loss.

However, the fact that we have detected (surface-implanted) solar noble gases in ~470 Myr old chromite grains indicates that the mineral chromite is very retentive for solar gases, similar to lunar ilmenite (Signer et al. 1977). Experimental studies of artificially irradiated ilmenite ($FeTiO_3$) have demonstrated the high retentivity of solar gases in ilmenite compared to olivine (Futagami et al. 1993). A comparable study on chromite is lacking and would be desirable.

Dynamical Constraints on the Lifetime of Dust from the L-Chondrite Parent Body Breakup

The fact that the SEC grains were delivered to Earth as small particles, subjected to non-gravitational forces, and hence possibly had different delivery times compared to larger meteorites, raises the question of whether we should indeed expect to find high concentrations of SEC grains in the same strata where large fossil meteorites are abundant. In this study solar noble gas-rich SEC grains were found in sediments of the Arkeologen bed throughout strata spanning up to 5.5 m above the Arkeologen bed, representing a time span of at least 2 Myr. The base of the Arkeologen bed contains fossil meteorites which had arrived on Earth just about one to two hundred thousand years after having been generated in the L-chondrite parent body breakup (Heck et al. 2004). Such a fast delivery for meteorites is expected if the asteroid collision occurred close to a major orbital resonance in the inner asteroid belt (Gladman et al. 1997; Zappalà et al. 1998; Nesvorný et al. 2007). Two of the most important resonances are the 3:1 orbital resonance with Jupiter at about 2.5 AU and the ν_6 resonance with Saturn and Jupiter. The position of the latter is a function of orbital inclination (2 AU for orbits in the plane of the ecliptic and 2.5 AU for orbits with ~20 degrees inclination; Farinella et al. 1993). It is likely that these two resonances played a major role in the delivery of asteroidal material to Earth. The delivery of material after breakup of the Flora family parent body through the ν_6-resonance has been modeled recently (Nesvorný et al. 2007). This model can explain the short exposure ages of the fossil meteorites from Thorsberg.

We can assume that the transfer times from the asteroid belt to Earth for dust particles injected into a resonance are similar to those of larger meteoroid-sized objects. However, the lifetime of dust particles in interplanetary space also depends on several other factors. Poynting-Robertson (P-R) light drag is of particular importance in delivering particles <500 µm from the asteroid belt to the inner solar system (Dermott et al. 2002). Solar wind drag would work in the same direction as P-R drag, but can be neglected for the size range of particles discussed here (Burns et al. 1979). The cratering record of the Long Duration Exposure Facility (LDEF) satellite experiment (Love and Brownlee 1993) suggests that large dust particles in the size range of ~100 to 200 µm with a peak at 140 µm dominate the dust population at the Earth's orbit at 1 AU, comparable to the average grain-size of our SEC grains (ø 80–100 µm). The reason for this is the relatively long lifetime of these large particles, which increases the time span where their orbits are modified by gravitational resonances of giant planets and gravitational scattering by terrestrial planets (Dermott et al. 2002).

Characteristic orbital decay times determined by P-R drag are proportional to particle grain size. Assuming perfectly light-absorbing particles and circular initial orbits, P-R lifetimes (in years) can be estimated by the following equation (Burns et al. 1979):

$$T_{PR} = 400 \times R^2/\beta \qquad (1)$$

R is the heliocentric distance in AU and β the ratio between solar radiation pressure to gravity, given by:

$$\beta = 0.57 \times Q_{PR}/(\rho \times s) \qquad (2)$$

where Q_{PR} is ~1 for particles larger than a few µm radius, ρ is the density in g/cm^3, and s the grain radius in µm. For ~100 µm sized chromite grains released at 2–2.5 AU (the location of the 3:1 and ν_6 resonances) this yields P-R decay times of 0.6–1 Myr.

The rough estimate of T_{PR} is comparable with the upper range of delivery times of the fossil meteorites from Thorsberg (Heck et al. 2004). Therefore, we may conclude that the first collisional dust that arrived on Earth took the path through the orbital resonances like the meteorites. Dust arriving later was not exclusively delivered by the resonance fast track but was partly also delivered to Earth by orbital decay due to P-R drag. As a consequence of the P-R lifetimes, it may seem that we should not expect to find 100 µm-sized dust from the L-chondrite parent body disruption event in sediments younger than ~1 Myr relative to the Arkeologen beds, where the first collisional debris were deposited, which reached the Earth within about 0.1 Myr. However, we have to keep in mind that the extraterrestrial contribution to the sedimentary record after a large asteroid collision depends on the nature of the event and the collisional cascade produced by it. There could be several second, third, or higher generation particles produced by collisions among larger bodies several Myr after the destruction of the parent body. These particles would reach Earth some time after the first wave of debris had arrived. Hence, collisional debris (dust and larger meteorite-sized fragments) can be expected in sediments conceivably younger than 1 Myr relative to Arkeologen (W. F. Bottke, personal communication), such as the 11 SEC grains found in the Hällekis quarry 8.5 m above Arkeologen described by Schmitz and Häggström (2006), whose abundances (0.4 grains per kg) represent a substantial enrichment relative to the background occurrence of SEC grains (0–0.01 grains per kg) but already a depletion relative to the SEC-rich Arkeologen beds (~3 grains per kg; see

Table 1 in Schmitz and Häggström 2006). We also note that the collisional lifetime of dust in the μg-mass range is higher than for larger dust particles in the mg mass range (Grün et al. 1985). This implies that larger dust was destroyed by collisions and generates more small dust particles, whose lifetime is determined primarily by the mechanisms described above. This is an additional argument that the SEC grains were small (~100 μm) meteoroids.

Dynamical models not only give constraints on the delivery times of collisional dust but also on its flux. Davis et al. (1979) postulated that major collisions among asteroids produce large amounts of dust along with much larger collisional fragments. More recent model calculations by Dermott et al. (2002) predict a disruption of a large rubble-pile asteroid to produce such a large amount of dust that Earth's extraterrestrial mass-accretion rate would be increased by two orders of magnitude over the average background. Their model prediction is matched by the high flux estimate for the Ordovician based on distributions of SEC grains (Schmitz et al. 2003).

CONCLUSIONS

1. New cosmogenic helium and neon production rates in chromite (P_3 = 1.99 ± 0.17 10^{-8} STP g^{-1} Myr^{-1}; P_{21} = 7.04 ± 0.65 10^{-10} STP g^{-1} Myr^{-1}) have been determined experimentally. They are similar to previously used values, confirming the low cosmic-ray exposure ages of fossil meteorites (~0.1–1 Myr) found in Ordovician sediments in southern Sweden.
2. The meteorite Gullhögen 001 has a very low cosmic-ray exposure age of ~0.9 Myr, which falls in line with the ages of other fossil L chondrites recovered from the same sediment strata at other locations in southern Sweden. This meteorite is most likely also a fragment of the major asteroid collision which disrupted the L-chondrite parent body ~470 Myr ago.
3. At least about one out of 4–6 sediment-dispersed extraterrestrial chromite grains found in Ordovician sediments in southern Sweden is rich in solar gases. These were trapped from the solar wind while the respective grains were exposed in space either as individual chromite IDPs or parts of slightly larger micrometeorites. They had been generated in the L-chondrite parent body breakup event.
4. The solar noble gases in chromites have partially been lost, as indicated, e.g., by $^4He/^{22}Ne$ ratios considerably below solar values. Nevertheless, it is remarkable that the solar gases in the chromite grains partly survived the atmospheric entry heating, the 470 Myr residence on Earth, and the harsh chemical treatment in the laboratory upon recovery from sediment. Chromite may be equally well retentive for solar noble gases than ilmenite in the lunar regolith. The solar gas concentrations are comparable to those in the most gas-rich micrometeorites from Greenland melt-water lakes and to gas-poor stratospheric IDPs.
5. Noble gases produced by galactic cosmic rays were not detectable in the sediment-dispersed extraterrestrial chromite grains due to copious amounts of solar noble gases. For cosmic-ray exposure age dating, it is only possible to use sediment-dispersed grains originating from interior parts of larger meteorites or grains from which the solar noble gases have been removed, e.g., by surface etching, prior to analysis.
6. The sediment-dispersed extraterrestrial chromite grains arrived rapidly on Earth via two mechanisms: (1) by fast delivery after injection into a major resonance in the inner asteroid belt and (2) by orbital decay mainly due to the Poynting-Robertson drag.

Acknowledgments–We thank Bill Bottke for helpful discussions and Mario Tassinari for participation in the fossil meteorite search project. This project has been partly funded by ETH Zürich and by the Swedish Research Council. Field work was funded by the National Geographic Society. We thank Karl Kehm for valuable comments and discussions.

Editorial Handling—Dr. Marc Caffee

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