A noble gas and cosmogenic radionuclide analysis of two ordinary chondrites from Almahata Sitta

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Abstract – We present the results of a noble gas (He, Ne, Ar) and cosmogenic radionuclide (^{10}Be, ^{26}Al, ^{36}Cl) analysis of two chondritic fragments (#A100, L4 and #25, H5) found in the Almahata Sitta strewn field in Sudan. We confirm their earlier attribution to the same fall as the ureilites dominating the strewn field, based on the following findings: 1) both chondrite samples indicate a pre-atmospheric radius of ~300 g cm^{-2}, consistent with the pre-atmospheric size of asteroid 2008 TC$_3$ that produced the Almahata Sitta strewn field, 2) both have, within error, a ^{21}Ne/^{26}Al based cosmic ray exposure age of ~20 Ma, identical to the reported ages of Almahata Sitta ureilites, 3) both exhibit hints of ureilitic Ar in the trapped component. We discuss a possible earlier irradiation phase for the two fragments of ~10-20 Ma, visible only in cosmogenic ^{38}Ar. We also discuss the ~3.8 Ga (^{4}He) and ~4.6 Ga (^{40}Ar) gas retention ages, measured in both chondritic fragments. These imply that the two chondrite fragments were incorporated into the ureilite host early in solar system evolution, and that the parent asteroid from which 2008 TC$_3$ is derived has not experienced a large break-up event in the last 3.8 Ga.

INTRODUCTION

The numerous meteorites found in the Almahata Sitta strewn-field are the first ones for which the small asteroid delivering them to Earth was observed in space. This asteroid, named 2008 TC$_3$, was detected by the Catalina Sky Survey on October 6th, 2008 to be on a collision course with Earth, and was determined to most resemble the spectroscopic class F of the Tholen taxonomy (Jenniskens et al., 2010, 2009; Tholen & Barucci, 1989). The light-curve allowed Scheirich et al. (2010) to reconstruct the shape and rotation period. The asteroid entered the atmosphere 20 hours after detection and broke up 37 km above ground in northern Sudan. A large, 30 x 7 km strewn-field was discovered near railway station 6 (Arabic*: Almahata Sitta*) by a search expedition from the University of Khartoum (Jenniskens et al., 2009; Shaddad et al., 2010), constituting, so to speak, the first "sample return mission" from a previously observed near-earth asteroid. More than 600 fragments with masses up to ~400 g and a total of ~10.7 kg have now been recovered (Shaddad et al., 2010). The majority of the meteorites have been classified as polymict anomalous ureilites (Jenniskens et al., 2010). About 20-30% of the recovered fragments are chondrites of several different types. The majority are enstatite chondrites (EL, EH); some ordinary chondrites (L, H) and one "unique" chondrite type (Horstmann et al., 2010) have also been recognized (Zolensky et al., 2010; Bischoff et al., 2010). Several arguments have been put forward to relate these chondrites to the fall of 2008 TC_3. Short-lived radionuclides have been found in several chondrite fragments (including ^{46}Sc, ^{54}Mn, and ^{57}Co with half-lives < 1 year; Bischoff et al., 2010). The chondrite fragments are fresh or only minimally affected by terrestrial alteration (Shaddad et al., 2010; Bischoff et al., 2010; Zolensky et al., 2010). A few of the ureilite fragments show multiple lithologies, indicating that they are part of a polymict breccia (Zolensky et al., 2010; Bischoff et al., 2010). Enstatite chondrites, which are relatively rare (making up only 1.6% of all observed falls; Grady, 2000), show a high abundance among Almahata Sitta non-ureilites and would require at least one recent EH- and one recent EL-chondrite fall within the strewn-field area, which is very unlikely (Bischoff et al., 2010). The size and the position of individual non-ureilite fragments within the strewn-field are consistent with those of ureilites (Shaddad et al., 2010). Sabbah et al. (2010) reported the detection of polycyclic aromatic hydrocarbons (PAHs) of ureilitic origin in some of the non-ureilite fragments. In this work, we determine the pre-atmospheric (host) meteoroid size and cosmic ray exposure (CRE) ages of two ordinary chondrite (L4, H5) fragments. If they are indeed related to asteroid 2008 TC_3, we expect the pre-atmospheric size and exposure age to be identical to the values reported for the Almahata Sitta ureilites (Welten et al., 2010).

Polymict ureilites with multiple xenoltihic lithologies (ordinary chondrites, R chondrites, angrites and carbonaceous chondrites; see Downes et al. 2008, Bischoff et al. 2010 and references therein for a discussion) have been identified before, but the specific mixture of abundant enstatite chondrites next to fewer ordinary chondrite clasts is so far unique to Almahata Sitta. Similar "xenoliths" are known from a variety of other meteorite types (Bischoff et al., 2002), and a few of them have been analyzed for their noble gas content to compare their CRE ages with the matrix in which they were found embedded. Several of these xenoliths show evidence of an additional earlier irradiation phase, prior to the one in which they were delivered to Earth (Schultz et al. 1972; Schultz & Signer 1977; Lorin & Pellas 1979; Bunch et al. 1979; Pedroni et al. 1988: Wieler et al. 1989). All these xenoliths are embedded in solar-gas-rich regolith breccias, derived from asteroidal regoliths close to the surface of an asteroid. A 2π irradiation (exposure to galactic cosmic rays (GCR) within the topmost ~1 m of the regolith) is the most likely explanation for any inferred pre-irradiation phase (Wieler et al., 1989). The xenoliths, or non-ureilite fragments of Almahata Sitta, are special in that the absence of solar wind derived noble gases in any fragment of the Almahata Sitta ureilites analyzed so far (Welten et al., 2010; Murty et al., 2010; Ott et al., 2010) suggests that Almahata Sitta was never part of the regolith of the ureilite parent body, but is likely derived from an interior part of a rubble pile asteroid. Our second goal thus is to investigate a possible pre-irradiation of the two Almahata Sitta chondrites, to determine if clasts in such fragmental or solar-gas-free breccias also show evidence of pre-exposure to cosmic rays.

The chondrite fragments of Almahata Sitta might also give us new insight into the history and evolution of the ureilites and the ureilite parent body (UPB). Ureilites have very low concentrations of U, Th, K (and thus of the long-lived radionuclides ^{235,238}U, ^{232}Th, ^{40}K), and high concentrations of primordial noble gases. The measurement of a radiogenic ^{4}He gas retention age is not possible, and the determination of a K-Ar age is challenging. Bogard and Garrison (1994) measured ^{40}A/^{39}Ar-ages in four different ureilites (Novo Urei, Kenna, PCA86502, and Haverö) and reported somewhat ambiguous ages of 3.3 to 4.1 Ga. These are in rough agreement with a ~3.8 Ga Sm-Nd age measured in the light rare earth element (LREE) component of four ureilites by Goodrich & Lugmair (1995). They are also roughly coincident with the proposed late heavy bombardment (LHB). The ^{26}Al and ^{53}Mn chronometers, on the other hand, indicate a very early formation of the

UPB (Goodrich et al., 2010). Other data point to a disruption at high temperature (1200 – 1300° C; Goodrich, 2004). But since the UPB would have had to be unlikely large (~lunar sized) to remain at this temperature until the LHB (Goodrich, 2004), it seems more likely that after an initial break-up, a (partially?) re-accreted UPB experienced a second break-up, or at least strong impact-related heating event, during the LHB.

The chondritic fragments found in Almahata Sitta and other polymict ureilites, however, have much higher concentrations of U, Th, and K. It seems possible that these fragments have shared at least a large part of the thermal history of the second or third-generation ureilite parent asteroids (see Herrin et al. 2010 for a recent review of the ureilite history). If, for example, the ureilites were derived from the Hoffmeister family of asteroids, which experienced a catastrophic disruption 300±200 Ma ago (Nesvorný et al., 2005), as suggested as a possibility based on the orbital elements of 2008 TC_3 by Jenniskens et al. (2010), we expect to see this reflected in a re-setting of the gas retention age clocks at that time. A similar re-setting has been observed for many L chondrites (e.g. Bogard, 1995), which experienced a catastrophic breakup event ~470 Ma ago (Korochantseva et al., 2007) that similarly led to the formation of the Gefion family of asteroids (Nesvorný et al., 2009). Accordingly, a third important goal of the present work is the analysis of the radiogenic ^{4}He and ^{40}Ar content of the two chondrite fragments.

SAMPLES, METHODS AND RESULTS

Sample selection

We received two pieces of the Almahata Sitta fragments #A100 (2.36 g) and #25 (1.68 g). Fragment #A100 is a L4 chondrite with 11.4 g original mass, that was found on Dec 11th, 2009 on a follow-up expedition towards the low-mass end of the Almahata Sitta strewn field (Shaddad et al., 2010). Fragment #25 is a H5 chondrite that was found on Dec 30th, 2008, on the second Almahata Sitta search expedition, near the high-mass end of the strewn field. With a mass of 222 g, it is one of the very few recovered Almahata Sitta fragments with masses >200 g (Shaddad et al., 2010). Both fragments were about 70% covered by fusion crust and very fresh (unweathered) when found. No other lithologies were found in these fragments (Zolensky et al., 2010). For both pieces we received, a 0.25 g sample was separated for noble gas analysis, and the remaining mass was used for radionuclide analysis.

Noble gas analysis and component deconvolution

Samples #A100 and #25 each were divided, and each split was wrapped in aluminum foil and preheated in vacuum at 130 °C for ~24 hours to remove adsorbed atmospheric gases. He, Ne, and Ar were extracted by pyrolysis in a Mo crucible during a single extraction at a temperature of 1800 °C for ~30 minutes. A cryo-trap cooled with liquid nitrogen was used to separate Ar from He and Ne and to suppress interferences. Contributions from interfering species were always smaller than the ion counting error of the affected noble gas species. Blank corrections derived from these runs were typically ~1-2% of measured He, Ne and Ar. A more detailed description of the noble gas analysis can be found in Wieler et al. (1989).

The noble gas results are shown in Table 1. For the deconvolution of the trapped and cosmogenic noble gas components, we used the values for trapped and cosmogenic components given by Ott (2002) and Wieler (2002), respectively. The measured $^{20}Ne/^{22}Ne$ ratio of ~0.84-0.86 implies an almost entirely cosmogenic composition for Ne in both samples. From this, we conclude that ^{3}He is almost entirely cosmogenic in both samples. Using $(^{4}He/^{3}He)_{cos}$ = ~6 (Alexeev, 1998) we estimate that ~11% of the total ^{4}He is cosmogenic, the rest is assumed to be radiogenic. The

$^{36}Ar/^{38}Ar$ ratios of ~4.2 (#A100) and ~3.1 (#25) indicate a considerable amount of trapped Ar. For the deconvolution of Ar, we assume the cosmogenic and trapped end-members have a $^{36}Ar/^{38}Ar$ of 0.65 and 5.3, respectively. Corrections for trapped ^{38}Ar are 49-54% for #25 and 76-77% for #A100. Contributions from the decay of neutron-capture-produced ^{36}Cl ($^{36}Cl_{nc}$) to ^{36}Ar, as discussed later, are on the order of ~1% of total ^{36}Ar. These were subtracted before deconvolution. Only a minor amount (<0.1%) of ^{40}Ar can be of trapped/cosmogenic origin, and since both fragments are very fresh, we assume that they do not contain any trapped atmospheric Ar. We conclude that ^{40}Ar is entirely radiogenic.

Cosmogenic radionuclides and chemical analysis

For the analysis of the cosmogenic radionuclides ^{10}Be (half-life = 1.36 * 10^6 a), ^{26}Al (7.05 * 10^5 a), and ^{36}Cl (3.01 * 10^5 a), we separated the metal and stone fractions from both chondrites. The purified metal fraction was dissolved along with Be, Al, and Cl carrier in HNO_3, while the stone fraction was dissolved, in the presence of Be and Cl carrier, in HF/HNO_3. After dissolution, a small aliquot was taken for chemical analysis of major elements by atomic absorption spectrometry (Perkin Elmer AA3300), and of Th by ICP-MS (Thermo Electron X Series II, following procedures described in Friedrich et al., 2003). Beryllium, Al, and Cl were separated using procedures previously described in Welten et al. (2010). AMS measurements of ^{10}Be, ^{26}Al, and ^{36}Cl were performed at PRIME Lab, following procedures described previously by Sharma et al. (2000). After subtracting blank levels, we normalized the measured isotopic ratios to ^{10}Be, ^{26}Al, and ^{36}Cl AMS standards (Nishiizumi 2004; Nishiizumi et al., 2007; Sharma et al. 1990). The cosmogenic radionuclide results are given in Table 2. The quoted errors represent only 1σ uncertainties in the AMS measurements. Since the measured U concentration was very close to the background and the measured Th concentration is within error compatible with chondritic values, we use the chondritic U and Th concentrations given by Wasson and Kallemeyn (1988) for the calculation of a U, Th-He age.

DISCUSSION

Pre-atmospheric size and shielding depth

If the two chondrite fragments were delivered to Earth together with the Almahata Sitta ureilites, the pre-atmospheric radius derived from each of these fragments must be identical to the one derived from the Almahata Sitta ureilites. The pre-atmospheric radius of the meteoroid that delivered the Almahata Sitta ureilites (asteroid 2008 TC_3) is estimated to be ~300 g cm^{-2}, equivalent to a mass of 20,000-50,000 kg (Welten et al. 2010). One could argue though that two (or more) large strewn fields happen to overlap. However, fewer than ~10 meteoroids with pre-atmospheric masses >20,000 kg enter the Earth's atmosphere every year (Bland et al., 2006), and both ureilites and non-ureilites in the Almahata Sitta strewn-field are very fresh. Therefore, an accidental association of fragments from two (or more) strewn fields can essentially be excluded.

There are no cosmic ray irradiation models tailored to chondritic clasts embedded in a ureilitic host. Welten et al. (2010) interpreted the noble gas concentrations and cosmogenic radionuclide activities of Almahata Sitta ureilites using the Leya & Masarik (2009) model developed for carbonaceous chondrites, assuming a density of 2.25 g cm^{-3}. Due to the high carbon content (~2 wt %, A. Steele, unpublished) and the low density (Shaddad et al., 2010; Kohout et al., 2010) of the Almahata Sitta ureilites, this model may yield a better approximation to the flux density and energy distribution of secondary particles in ureilites than the ordinary chondrite model. Here, we use the noble gas and cosmogenic radionuclide production rates from each target element as calculated in the carbonaceous chondrite model by Leya & Masarik (2009). To calculate the total production rate for each cosmogenic species, we adopt the measured bulk concentration for the two fragments in Mg, Al, Ca, Mn, Fe and Ni, and average L, H chondrite composition for C, O, Na, and Si (Wasson and Kallemeyn, 1988), thereby simulating chondritic samples embedded in a carbonaceous chondrite matrix. .

The activity of ^{10}Be in the stone fraction relative to the ^{10}Be activity in the metal fraction (e.g., Welten et al., 2001; 2003) is an excellent indicator of pre-atmospheric size. Figure 1a shows a plot of the ^{10}Be activity in the stone fraction versus the ^{10}Be activity in the metal fraction of the two chondrite fragments. The ^{10}Be activities yield well-defined, usually non-intersecting curves for any meteoroid size (see Fig. 1a). To derive these curves, we use the LCS model by Masarik & Reedy (1994b) which has proven to be useful for large objects (Welten et al., 2003; Welten et al., 2011). The ^{10}Be activities in the stone and metal fractions of the two chondrite fragments plot within the modeled range for a ~300-400 g cm^{-2} object. This radius is indistinguishable to the ~300 g cm^{-2} pre-atmospheric radius determined for the Almahata Sitta ureilite fragments by Welten et al. (2010). The concentrations of cosmogenic ^{10}Be in the metal phase of #25 are ~30% lower than in #A100 (see table 2), indicating higher shielding for fragment #25. Based on ^{10}Be depth profiles for an object with a radius of ~300 g/cm^2, we derive shielding depths of 30-50 g cm^{-2} for #A100 and 80-150 g cm^{-2} for #25 (Figure 1b, 2c). The higher shielding of fragment #25 is also confirmed by a lower ^{22}Ne/^{21}Ne ratio (1.08 vs. 1.10 for #A100) and a lower ^{3}He/^{21}Ne ratio (3.55 vs. 3.85 for #A100), which both decrease monotonically with increasing shielding depth within the relevant shielding range (30-150 g cm^{-2}).

From ^{26}Al-data, a somewhat smaller pre-atmospheric size is derived, especially for #A100. We do not, however, consider the ^{26}Al results a reliable indicator of pre-atmospheric size in this instance. The ^{26}Al/^{10}Be ratios of 0.85±0.05 and 0.81±0.05 in the metal phase of #A100 and #25 are anomalously high. Typical ratios are 0.70±0.03 in irons and metal phases of chondrites and stony irons (Aylmer et al., 1988; Albrecht et al., 2000; Lavielle et al., 1999). The ^{36}Cl/^{10}Be ratio in the metal phase, and the ^{26}Al/^{10}Be ratio in the stone phase of both chondritic fragments are in the typical range for large chondrites (e.g., Welten et al., 2003). It seems likely that the high ^{26}Al-concentration in the metal phase is not related to the shielding conditions or a short CRE age, but rather to high P content (0.1 – 0.2 wt%) in the metal phase (a high S content can be excluded on the basis that troilite was leached in 0.2N HCl during sample preparation).

We estimate the amount of $^{36}Cl_{nc}$ by subtracting the activity of ^{36}Cl expected from spallation ($^{36}Cl_{sp}$) in the stone phase from the measured ^{36}Cl activity in the stone phase. Chlorine-36 from spallation is calculated as $^{36}Cl_{sp} = {}^{36}Cl_{(metal)} * [1.1 * Fe + a * Ca + b * K]$. Here, a is the production rate ratio of $^{36}Cl_{sp}$ produced from Ca relative to that from Fe, which can be estimated using the $^{10}Be_{(stone)}$ / $^{10}Be_{(metal)}$ ratio (resulting in a = 13.2 for #A100, 15.9 for #25), and b = 1.8*a, based on Welten et al. (2001). This results in $^{36}Cl_{nc}$ activities of 3.9 and 2.3 dpm/kg for #A100 and #25, respectively. Together with the shielding depths as calculated above, $^{36}Cl_{nc}$ can then be used to derive the Cl concentrations in the bulk samples, based on the model by Spergel et al. (1986). This results in a Cl concentration of 60-80 ppm for #A100, and 10-20 ppm for the H chondrite fragment #25. These are both within the range observed by Garrison et al. (2000). Since neutron-capture reactions are only important in objects with a large pre-atmospheric radius, the detection of $^{36}Cl_{nc}$ is a further confirmation that the precursor of the two chondrite fragments was a large object. Due to the relatively low amounts of $^{36}Cl_{nc}$ detected, corrections of the measured ^{36}Ar concentrations for contributions of ^{36}Ar from the decay of $^{36}Cl_{nc}$ are nearly negligible.

Cosmic ray exposure ages

Since the cosmogenic radionuclides ^{10}Be, ^{26}Al and ^{36}Cl show activities near equilibrium-values for moderately shielded ordinary chondrites, they can only provide a lower limit (> 5 Ma) of the CRE age. The CRE ages can be determined from the noble gas isotopes ^{3}He, ^{21}Ne, and ^{38}Ar. Each of these isotopes has contributions from non-cosmogenic and cosmogenic ($^{3}He_{cos}$, $^{21}Ne_{cos}$, $^{38}Ar_{cos}$) sources. The $^{3}He_{cos}$ and $^{21}Ne_{cos}$ concentrations in both chondritic fragments are similar or slightly higher than their counterparts in fragments from the ureilitic host (20 – 30 * 10^{-8} cm^3 STP/g and 6 – 8 * 10^{-8} cm^3 STP/g for $^{3}He_{cos}$ and $^{21}Ne_{cos}$, respectively, see Figure 2) (Welten et al., 2010). This similarity in concentrations suggests that the two chondrite fragments have been exposed for similar time spans as the ureilites, ~20 Ma (Welten et al., 2010).

To determine precise ^{21}Ne exposure ages of the two chondrite fragments, we first need to determine the ^{21}Ne production rate. The method developed by Eugster (1988) is not applicable for meteoroids of large (>50 cm radius) pre-atmospheric size (Leya & Masarik, 2009). Instead, we use the $^{21}Ne/^{26}Al$-production rate ratio, P(21)/P(26), which is almost insensitive to the size of the meteoroid and approaches a stable value for shielding depths >100 g cm^{-2} (e.g., Graf et al., 1990). The production rate ratio P(21)/P(26) for meteorites with ~300 g/cm^2 radius increases from ~0.0052 (in units of 10^{-8} cm^3 STP g^{-1} Ma^{-1} / dpm kg^{-1}) near the surface to 0.0057 for depths >100 g/cm^2 (Figure 3) for H chondrite chemistry. We adopt P(21)/P(26) ratios of 0.0054 for #A100 and 0.0057 for #25 (an error of 10% is added and propagated on all production rates), respectively. Taken together with the measured ^{26}Al-concentrations (Table 2), we obtain ^{21}Ne-production rates of 0.34 * 10^{-8} cm^3 STP g^{-1} Ma^{-1} and 0.31 * 10^{-8} cm^3 STP g^{-1} $Ma^{-1.}$ This results in CRE ages of 22±4 and 21±3 Ma for the two chondrite fragments #A100 and #25, respectively (Figure 2, table 3). These CRE ages are, within error, indistinguishable from the average CRE age of 19.5±2.5 Ma for the Almahata Sitta ureilites that was determined using the same $^{21}Ne/^{26}Al$ method (Welten et al., 2010). We conclude that the two chondrite fragments were indeed delivered to Earth within the same parent object as the Almahata Sitta ureilites, i.e., asteroid 2008 TC_3.

Cosmogenic ^{38}Ar: evidence for pre-irradiation?

While the determination of $^{38}Ar_{cos}$ in the ureilite fragments was not possible due to large contributions from trapped Ar and large variations in Ca content (Welten et al., 2010), this problem does not affect the two chondrite fragments. We report $^{38}Ar_{cos}$ concentrations of ~1 – 1.2 * 10^{-8} cm^3 STP/g for both fragments in Table 1 and Figure 2. The irradiation model by Leya & Masarik (2009) yields ^{38}Ar production rates of 3.1 * 10^{-10} cm^3 STP g^{-1} Ma^{-1} for #A100 and 3.7 * 10^{-10} cm^3 STP g^{-1} Ma^{-1} for #25, resulting in nominal ^{38}Ar CRE ages of 40±4 and 31±3 Ma, respectively. The ^{38}Ar ages of the two chondrite fragments are significantly larger than their $^{21}Ne/^{26}Al$-ages and the 19.5±2.5 Ma age of the Almahata Sitta ureilites.

If the measured $^{38}Ar_{cos}$ concentration had been acquired in only 19.5±2.5 Ma, it would require ^{38}Ar production rates significantly higher than any ^{38}Ar production rate (for any shielding and meteoroid size) predicted by the model by Leya & Masarik (2009). High production rates require Ca concentrations on the order of ~2.6% (vs. 0.98% measured) for #A100 and ~2.1% (vs. 1.16% measured) for #25. It is known that ~100 mg sized chondrite samples can have quite variable Ca concentrations. However, to find such high values simultaneously in both splits of both fragments seems very unlikely. Adopting average chondritic Ca values (from Wasson & Kallemeyn, 1988) lowers the nominal CRE age only to 34±3 and 28±2 Ma for the #A100 and #25 fragments, respectively. This age is still longer than the $^{21}Ne/^{26}Al$-age of the fragments or the Almahata Sitta ureilites. A loss of 30-50% of the $^{21}Ne_{cos}$ during the latest irradiation phase (as part of 2008 TC_3) can also be excluded since $^{3}He_{cos}/^{21}Ne_{cos}$, which would probably be fractionated more than $^{21}Ne_{cos}/^{38}Ar_{cos}$, is within 15% of the typical value expected for chondrites under the given shielding conditions. Finally, not correcting ^{36}Ar for the contribution of $^{36}Cl_{nc}$ would raise the $^{38}Ar_{cos}$ concentration by no more than 3%. It is possible that the high $^{38}Ar_{cos}$ concentrations reflect a longer total exposure to GCR than implied by the $^{21}Ne/^{26}Al$ data. Conceivably there was an earlier irradiation phase, followed by a loss of He and Ne (e.g., upon incorporation into the ureilitic matrix), prior to the last exposure to GCR as parts of 2008 TC_3.

Pre-irradiation of “xenoliths” in brecciated meteorites has been observed before (e.g. Schultz et al. 1972 in Weston; Schultz & Signer 1977 in St. Mesmin; Lorin & Pellas 1979 in Djermaia; Pedroni et al. 1988 in Kapoeta; Wieler et al. 1989 in Fayetteville). In most cases, this was attributed to 2π irradiation in an asteroidal regolith, which we can exclude for Almahata Sitta since it is not a solar-gas-rich regolith breccia (Welten et al., 2010; Murty et al., 2010; Ott et al., 2010; this work). Therefore, the two chondrite fragments were probably exposed to GCR in space (4π) before their incorporation into the ureilite host. The absolute time of pre-irradiation in space depends on their size, but the maximum production rate as individual objects (based on the Leya & Masarik (2009) model for ordinary chondrites) for #A100 is around ~$4.1 * 10^{-10}$ cm^3 STP g^{-1} Ma^{-1}, and ~$4.9 * 10^{-10}$ cm^3 STP g^{-1} Ma^{-1} for #25, resulting in minimum pre-irradiation CRE ages of 16±3 and 8±2 Ma for #A100 and #25, respectively. This is significantly longer than the collisional lifetime of 2-3 Ma for fragments of a few cm size (Farinella & Vokrouhlický, 1999). The two chondritic fragments are thus likely to be fragments of larger meteoroids that broke up upon impact or incorporation into the ureilite host.

Thermal history

Both chondrite fragments contain significant amounts of radiogenic ^{4}He and ^{40}Ar (table 1). Assuming a chondritic concentration in U and Th (13 ppb U and 43 ppb Th for the L chondrite, 12 ppb U and 42 ppb Th for the H chondrite, Wasson & Kallemeyn, 1988), the concentrations of the radiogenic noble gases yield average ^{4}He retention ages of 3.8 Ga for both chondrite fragments, or possibly up to 0.37 Ga longer if indeed ~15% of the He was lost at a late stage (e.g., the breakup of 2008 TC_3 in Earth's atmosphere), as discussed before (Figure 4). The lower figure corresponds roughly to the LHB period. The Ar-retention ages calculated from the measured bulk K concentration of 955 and 790 ppm for the #A100 and #25 fragment, respectively, are higher: 4.4 Ga for #A100 and 4.7 Ga for #25 (Figure 4). While simple U-Th-He and K-Ar retention ages are always somewhat ambiguous, we conclude that both chondrite fragments have not experienced a complete loss of radiogenic He and/or Ar for most of the history of the solar system. Also, given the significantly lower concentration of U, Th, and K in ureilites, it is not possible that these radiogenic noble gases were somehow inherited from the ureilite host asteroid. These observations imply that at least the ureilite parent body of which they were part never experienced a severe breakup event that reset the radiogenic clocks of all or most constituent materials, like e.g. the breakup event of the L chondrite parent body did for a significant fraction of the L chondrites. This also implies that asteroid 2008 TC_3 is not derived from the Hoffmeister family of asteroids, which experienced a catastrophic disruption 300±200 Ma ago (Nesvorný et al., 2005).

In the previous section, we have proposed that an earlier irradiation phase might have produced cosmogenic noble gases in the two chondritic fragments, of which only $^{38}Ar_{cos}$ remains. The putative event that led to the loss of He, Ne can not have been more recent than 3.8 Ga according to the U, Th-He age measured in both fragments. The pre-irradiation phase and thus presumably also the incorporation of the chondrite fragments into the ureilite host must have taken place ≥3.8 Ga ago, at or before the time of the LHB. Since some ureilites have Ar-Ar-ages (Bogard & Garrison, 1994) similar to the LHB, and/or show a Sm-Nd-isochron of ~3.8 Ga (Goodrich & Lugmair, 1995), it seems likely that the (second-generation, or re-assembled) ureilite parent body experienced a major disruption around the time of the LHB. The ureilitic fragments of this breakup event later reassembled into (third-generation) asteroids (Goodrich et al., 2004; Jenniskens et al., 2010; Herrin et al., 2010), thereby incorporating some non-ureilitic fragments (like the L and H chondrites analyzed here), which were perhaps themselves dislodged by impacts on their respective parent bodies during the LHB. These non-ureilitic fragments may thus represent a snap-shot of the formation environment of the asteroids which later became the parent bodies of the ureilites delivered to Earth today (Jenniskens et al., 2010; Bischoff et al., 2010; Gayon-Markt et al., 2011).

A trapped ureilitic Ar component?

Both chondrite samples contain trapped ^{36}Ar in concentrations that are surprisingly large for equilibrated chondrites (~22.6 * 10^{-8} cm^3 STP/g for #A100 and 6.5*10^{-8} cm^3 STP/g for #25). Carbon-rich separates from ureilites have high concentrations of ^{36}Ar, of up to ~80,000 * 10^{-8} cm^3 STP g^{-1} (Göbel et al., 1978). Bulk Almahata Sitta ureilite samples contain up to 1390 * 10^{-8} cm^3 STP g^{-1} trapped ^{36}Ar (Welten et al., 2010). We thus explore the possibility that the trapped ^{36}Ar found in the two chondritic fragments is of ureilitic, i.e., Almahata Sitta host origin.

A significant contribution of ^{36}Ar from the decay of neutron-capture ^{36}Cl can be excluded, since 2 – 4 dpm/kg $^{36}Cl_{nc}$ only yield 1 – 1.7 * 10^{-9} cm^3 STP/g over a ~20 Ma exposure age. This represents only about 1-2% of the total ^{36}Ar (or up to double this amount when taking a pre-irradiation phase under similar shielding conditions into account).

An atmospheric origin of the ^{36}Ar would, by proportional addition of atmospheric ^{40}Ar, also require a significant reduction of the ~4.6 Ga K-Ar gas retention ages, making them shorter than the U,Th-He ages. The atmospheric and radiogenic ^{40}Ar would then also fortuitously add up to a total ~4.6 Ga retention age, for both fragments. We thus conclude that a large atmospheric contribution is unlikely.

In the compilation of Schultz & Franke (2004) we found only one out of 77 listed L4 chondrite samples (from 28 different meteorites) with measured He, Ne and Ar concentrations that has a higher trapped ^{36}Ar concentration than the #A100 fragment. This meteorite, though, is a solar-gas-rich regolith-breccia ($^{20}Ne/^{22}Ne$ > 10, $^{20}Ne/^{36}Ar$ > 10). Likewise, only 14 out of 435 listed H5 samples (from 257 different meteorites) with measured He, Ne, and Ar concentrations have higher trapped ^{36}Ar concentrations than the average of the two splits of the #25 fragment. Six of these meteorites are solar-gas-rich regolith breccias, and the remaining meteorites all have an atmosphere-like $^{20}Ne/^{36}Ar$ > 0.2. The trapped $^{20}Ne/^{36}Ar$ ratios of ~0.01 – 0.02 for both Almahata Sitta chondrite fragments are, however, an order of magnitude lower than this.

Many ordinary chondrites contain trapped noble gases of phase Q, which has a $^{20}Ne/^{36}Ar$ ratio of ~0.04 (Busemann et al., 2000), within a factor of 2 of the trapped $^{20}Ne/^{36}Ar$ ratio in the two Almahata Sitta chondrite fragments. However, none of the meteorites from the compilation by Schultz & Franke (2004) contained similarly high concentrations of ^{36}Ar of phase Q origin. A possible alternative to a phase Q origin is a "ureilitic" origin.

Göbel et al. (1978) identified a distinct "ureilitic" noble gas elemental abundance pattern in carbon-rich separates of three ureilites. This pattern is similar to the phase Q pattern observed in many carbonaceous and ordinary chondrites (e.g., Busemann et al., 2000), but has higher $^{36}Ar/^{84}Kr$ and $^{36}Ar/^{132}Xe$ ratios (Rai et al., 2003) and lower $^{4}He/^{36}Ar$ and $^{20}Ne/^{36}Ar$ ratios (Ott, 2002), i.e., it is rich in ^{36}Ar, compared to other components. A ureilitic, i.e., Almahata Sitta ureilite origin for the measured non-cosmogenic ^{36}Ar may be a viable explanation. Since we have only analyzed bulk samples in a single temperature step, we can only speculate about the carrier of this ureilitic component within the chondritic samples. In ureilites, the carbon-rich vein material is extremely rich in trapped ^{36}Ar (Göbel et al., 1978) and it was shown by Fukunaga et al. (1987) that diamonds are the main carriers of the ureilitic component. It is conceivable that some of that material was mobilized and deposited on or within the chondrite samples over their long, >3.8 Ga, residence time in the ureilitic host matrix. The detection of polycyclic aromatic hydrocarbons (PAHs) of ureilitic origin in fragment #25 by Sabbah et al. (2010) led these authors to a similar conclusion.

In any case, if the trapped ^{36}Ar in the chondrite fragments indeed derives from a ureilite source (irrespective of the nature of the carrier phase), this is yet another strong argument that the Almahata Sitta chondrite and ureilite fragments were once part of the same asteroid.

CONCLUSIONS

Based on an analysis of noble gases (He, Ne, Ar) and cosmogenic radionuclides (^{10}Be, ^{26}Al, ^{36}Cl) of two chondrite fragments (#A100, L4 and #25, H5) found in the Almahata Sitta strewn-field, we can make the following five conclusions:

The two chondrite fragments derive from a meteoroid with a pre-atmospheric radius of ~300 g cm^{-2}, i.e. within error identical to the size of asteroid 2008 TC_3 that produced the Almahata Sitta strewn-field. Shielding depths of 30 – 50 g cm^{-2} and 100 – 150 g cm^{-2} are calculated for the L4 and H5 fragment, respectively. Although the concentrations of neutron-capture ^{36}Cl are relatively low (2-4 dpm/kg) they are consistent with a large pre-atmospheric size for the precursor meteoroid, thus providing an independent confirmation.

The cosmic-ray exposure ages of the two fragments, as measured with the ^{21}Ne/^{26}Al method, are 22±4 and 21±3 Ma for the L4 and H5 fragment, respectively. This is, within error, identical to the ^{21}Ne/^{26}Al-based cosmic ray exposure age of 19.5±2.5 determined for the ureilites by Welten et al. (2010), independently confirming that the ordinary chondrite fragments were delivered to Earth within the same object as the Almahata Sitta ureilites, i.e., asteroid 2008 TC_3.

For $^{38}Ar_{cos}$, a longer cosmic ray exposure age of 40±4 and 31±3 Ma is calculated. This can be interpreted as an additional irradiation phase (followed by loss of He and Ne) of at least 16±3 and 8±2 Ma for the L4 and H5 fragment, respectively, when assuming 4π irradiation in space before incorporation of the fragments into the ureilite host.

Using typical chondritic U, Th, and measured K concentrations we derive U, Th-He ages of 3.8 Ga, and a K-Ar age of 4.4 Ga and 4.7 Ga for the L4 and H5 fragment, respectively. These results also indicate that the ureilite parent body (bodies?), in contrast e.g., to the L chondrite parent body, did not experience a catastrophic disruption resulting in the loss of radiogenic He, Ar during the last 3.8 Ga.

The trapped Ar content of the two samples is large for equilibrated chondrites. This could be the result of the admixture of small amounts of Ar-carrying phases of ureilitic origin into (or onto) the chondritic fragments, providing another link between the Almahata Sitta chondrite and ureilite fragments.

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FIGURE CAPTIONS

Figure 1: Beryllium-10 in stone vs. metal fraction, and resulting shielding depths

a) Beryllium-10 concentrations in dpm/kg measured in the stone vs. metal fraction of the two Almahata Sitta chondrites (#25, H5, and #A100, L4), plotted together with the modeled concentrations based on the LCS model for chondrites by Masarik & Reedy (1994a) for three different meteoroid sizes (solid lines: 440 g cm^{-2}, long-dashed lines: 370 g cm^{-2}, short-dashed lines: 290 g cm^{-2}) of different chemistry (grey: H; black: L). The meteoroid size for the Almahata Sitta ureilites is ~300 g cm^{-2} (Welten et al., 2010). Errors are 1σ. Beryllium-10 in the metal phase (in dpm/kg) vs. shielding depth is shown in panel b) for L, and panel c) H chondrite chemistry. From the concentrations of ^{10}Be in the two chondrite samples, shielding depths of 30-50 g cm^{-2} and 100-150 g cm^{-2} were derived for #A100 (b) and #25 (c), respectively.

Figure 2: Concentrations of cosmogenic He, Ne for Almahata Sitta samples

The concentration of cosmogenic ^{3}He (white), ^{21}Ne (light grey), and ^{38}Ar (dark grey) from the four sub-samples of the two chondrite fragments (top), and from four ureilite fragments of Almahata Sitta (from Welten et al. 2010), and the cosmic ray exposure ages (bottom) for ^{21}Ne (light grey) and ^{38}Ar (dark grey). Note that the concentrations for ^{3}He and ^{38}Ar have been scaled with a factor of 0.3 and 8, respectively, to make the depiction more readable. No cosmogenic ^{38}Ar concentration for the ureilite samples was given in Welten et al. 2010. See Shaddad et al. (2010) for more information on the sample/fragment numbers.

Figure 3: $^{21}Ne/^{26}Al$ production rate ratio

Calculated production rate ratio of $^{21}Ne/^{26}Al$ in an H-chondrite (fragment #25) embedded in a carbonaceous-chondrite like matrix and , based on the irradiation model by Leya & Masarik (2009), for a meteoroid of 345 g cm^{-2} total shielding. Note that the production rate ratio is nearly insensitive to shielding (~10% change over 200 g cm^{-2} shielding).

Figure 4: ^{4}He, ^{40}Ar gas retention ages

Radiogenic retention ages in Ga for ^{4}He and ^{40}Ar in all four sub-samples. The black columns represent the U,Th-He gas-retention age resulting from a chondritic U concentration, with the upper error bar accounting for a 15% He-loss. The grey columns represent the K-Ar age.

FIGURES

Figure 1

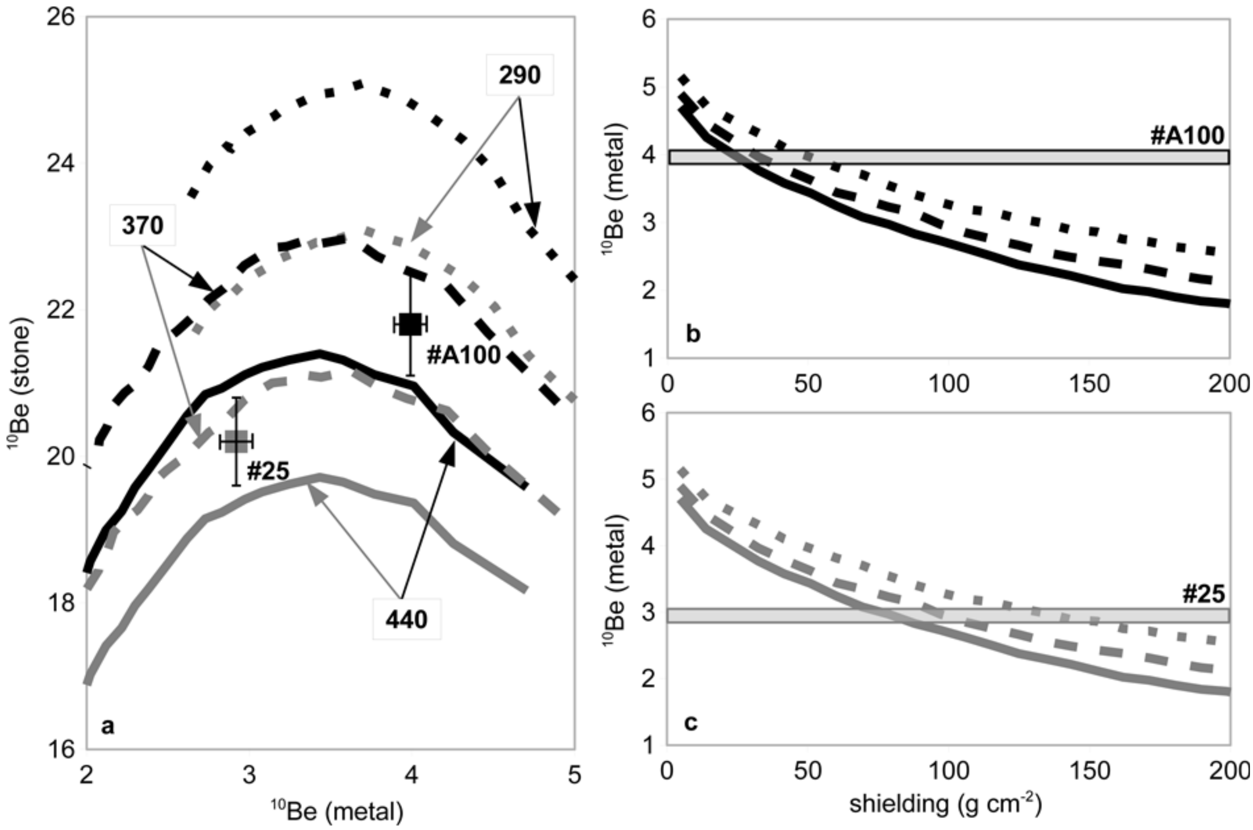
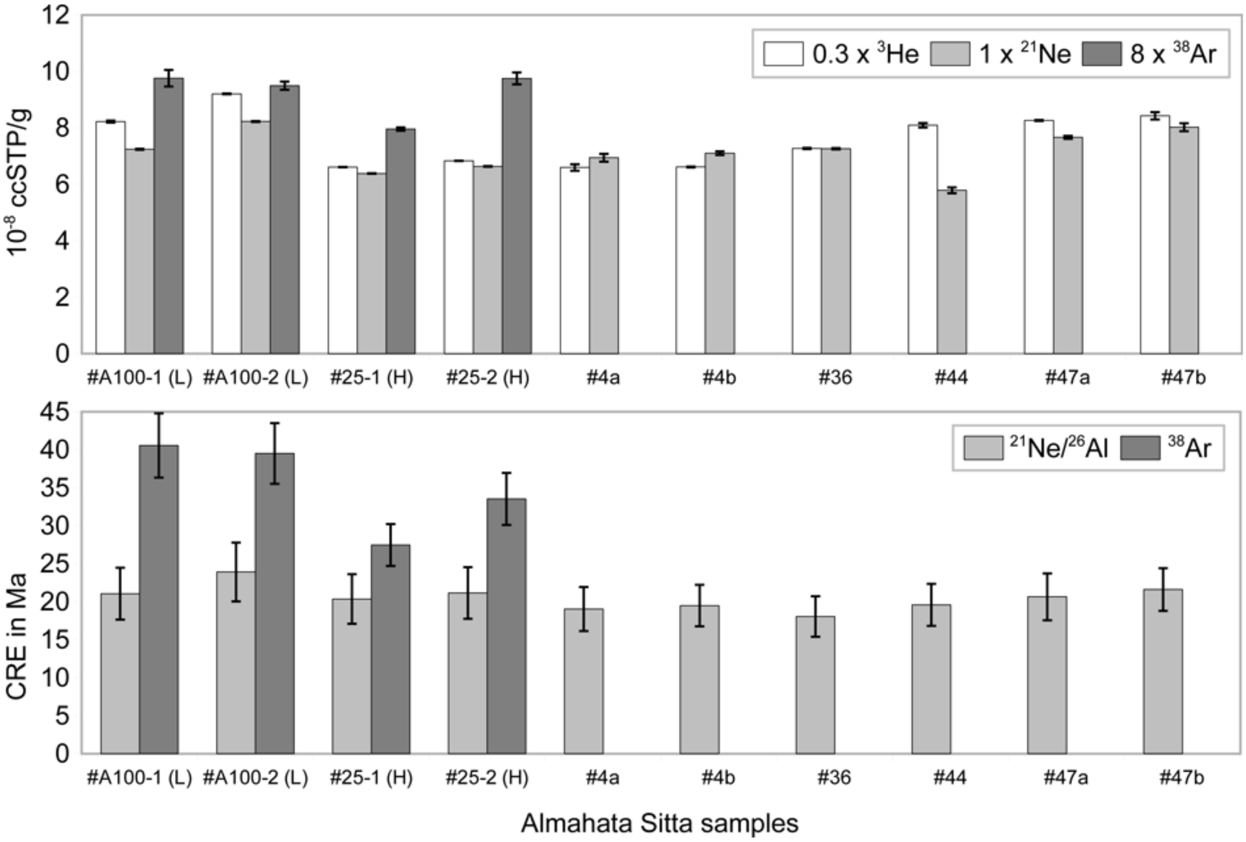
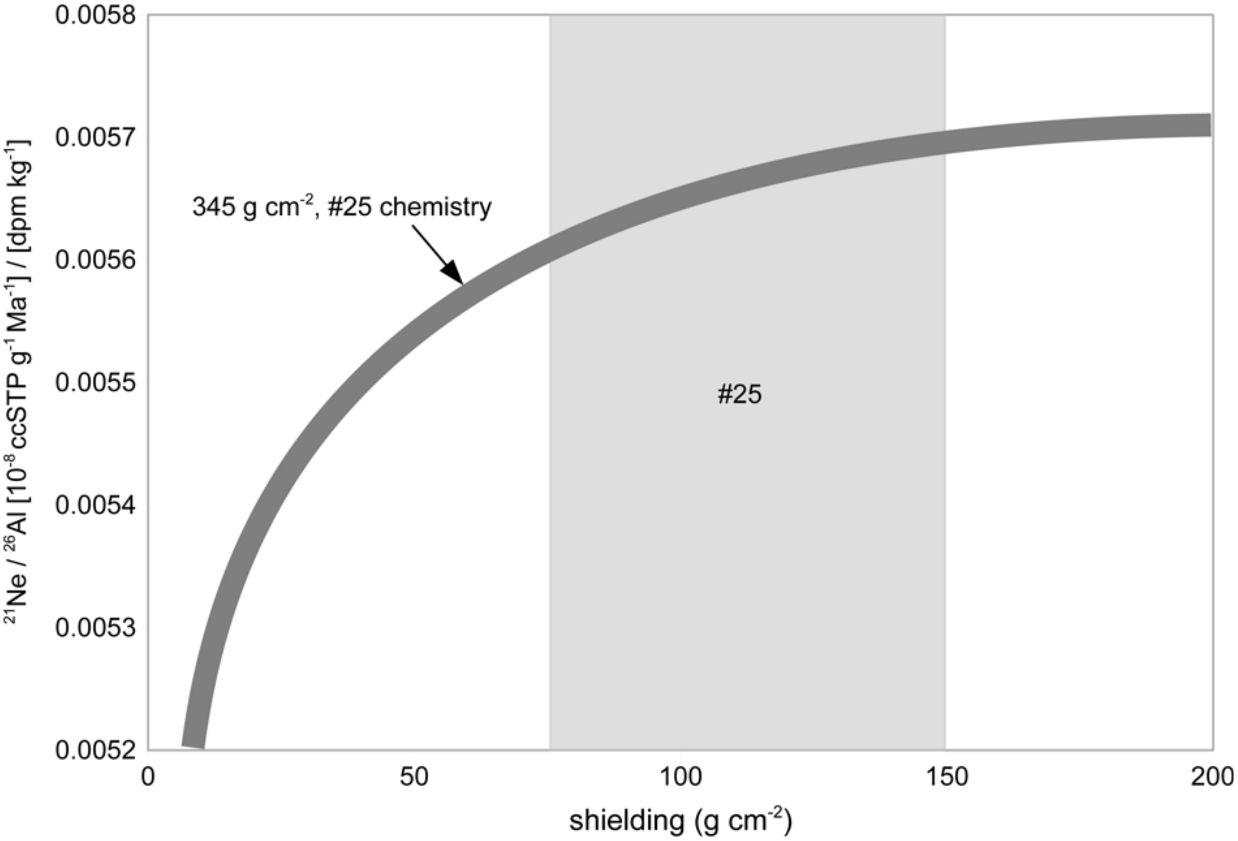


Figure 2



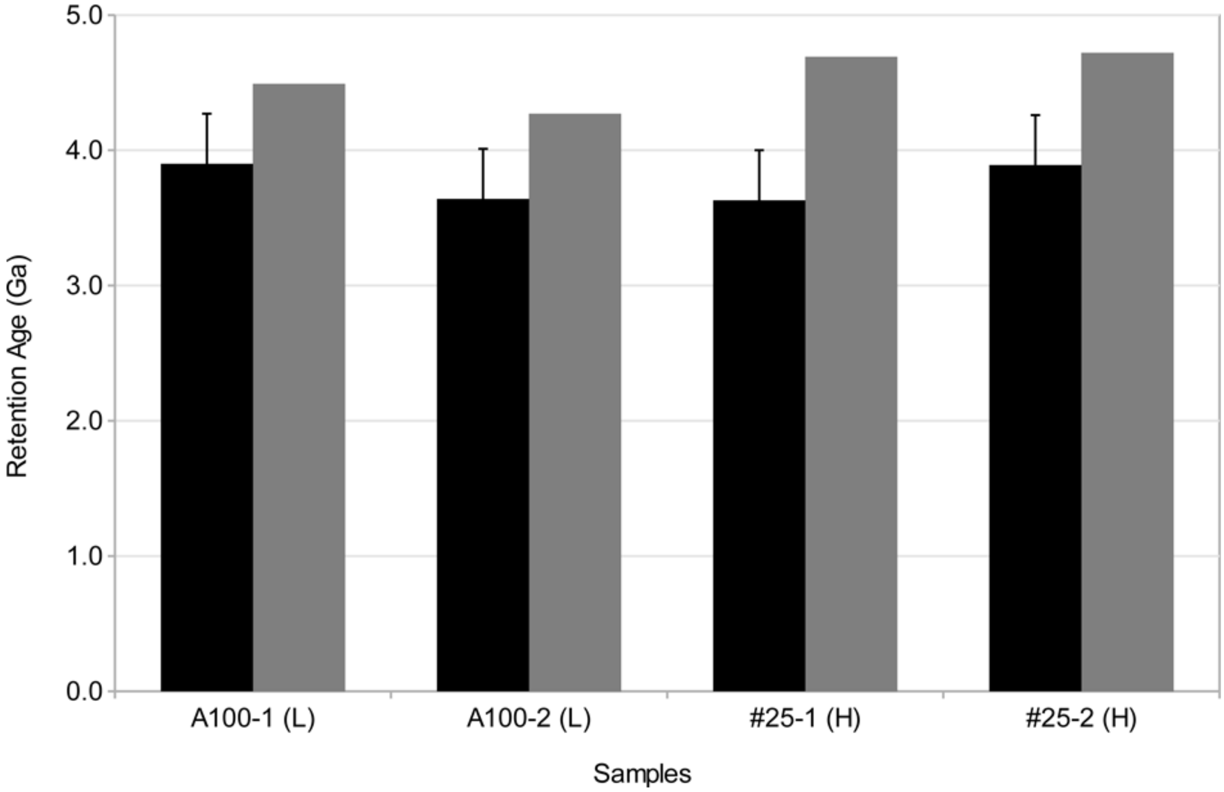
0.3 x ^{3}He
1 x ^{21}Ne
8 x ^{38}Ar
10^{-8} ccSTP/g
12
10
8
6
4
2
0
#A100-1 (L)
#A100-2 (L)
#25-1 (H)
#25-2 (H)
#4a
#4b
#36
#44
#47a
#47b
^{21}Ne/^{26}Al
^{38}Ar
CRE in Ma
45
40
35
30
25
20
15
10
5
0
#A100-1 (L)
#A100-2 (L)
#25-1 (H)
#25-2 (H)
#4a
#4b
#36
#44
#47a
#47b
Almahata Sitta samples

Figure 3



0.0058
0.0057
0.0056
0.0055
0.0054
0.0053
0.0052
^{21}Ne / ^{26}Al [10^{-8} ccSTP g^{-1} Ma^{-1}] / [dpm kg^{-1}]
345 g cm^{-2}, #25 chemistry
#25
0
50
100
150
200
shielding (g cm^{-2})

Figure 4


5.0
4.0
3.0
2.0
1.0
0.0
Retention Age (Ga)
A100-1 (L)
A100-2 (L)
#25-1 (H)
#25-2 (H)
Samples

TABLES

Table 1: Noble gas results of Almahata Sitta chondrites

	#A100-1	**#A100-2**	**#25-1**	**#25-2**
Type	L4 chondrite		H5 chondrite	
Mass (mg)	162.3	65.84	183.2	67.80
Measured concentrations (10^{-8} cm^3 STP/g)				
^{4}He	1821	1671	1494	1663
^{22}Ne	7.98	9.03	6.90	7.14
^{36}Ar	23.1	21.6	6.01	8.48
Measured isotopic ratios				
^{3}He/^{4}He	0.0155	0.0188	0.0152	0.0141
^{20}Ne/^{22}Ne	0.856	0.863	0.842	0.845
^{21}Ne/^{22}Ne	0.907	0.911	0.924	0.928
^{36}Ar/^{38}Ar	4.26	4.22	2.99	3.18
^{40}Ar/^{36}Ar	350	332	1250	896
Cosmogenic concentrations (10^{-8} cm^3 STP/g)				
^{3}He$_{cos}$	27.4	30.7	22.0	22.8
^{21}Ne$_{cos}$	7.24	8.22	6.38	6.63
^{38}Ar$_{cos}$	1.26	1.22	1.02	1.24
Radiogenic concentrations (10^{-8} cm^3 STP/g)				
^{4}He$_{rad}$	1650	1480	1360	1520
^{40}Ar$_{rad}$ = ^{40}Ar$_{meas}$	8094	7167	7480	7593

Ion counting errors, uncertainty of the blanks and of sample mass are about ~0.1%. The uncertainty of mass spectrometer sensitivity is <1% for ratios and <5% for concentrations.

Table 2: Major element composition and cosmogenic radionuclide activities

	#A100-metal	#A100-stone	#A100 bulk	#25-metal	#25-stone	#25 bulk
Mass (mg)	44.3	123.5	-	77.2	133.0	-
Major element composition, in wt%						
Mg	0.08	16.5	15.2	0.01	17.8	14.6
Al	-	1.19	1.09	-	1.13	0.93
Ca	-	1.07	0.98	-	1.42	1.16
Mn	-	0.26	0.24	-	0.28	0.23
Fe	85	16.1	21.6	88	13.6	27.0
Co	0.68	-	0.05	0.43	-	0.08
Ni	12.2	0.32	1.27	10.3	0.17	2.0
ppm						
K	-	1034	955	-	970	790
Th	-	42	39	-	36	30
Cosmogenic radionuclide activities, in dpm/kg						
^{10}Be	3.99±0.10	21.8±0.70	20.5±0.6	2.92±0.10	20.2±0.60	17.1±0.5
^{26}Al	3.38±0.20	68.7±2.6	63.7±2.4	2.37±0.12	66.7±2.9	55.0±2.4
^{36}Cl	19.4±0.5	10.5±0.2	11.2±0.2	14.4±0.4	8.1±0.2	9.2±0.2
$^{36}Cl_{nc}$	3.9±0.9			2.3±0.8		

Table 3: Cosmic Ray Exposure and Gas Retention Ages (in Ma)

Fragment	T21/26	T38	$T38_{pre-exp}$	R4 (chond)	R40 (meas)
#A100, average	22±4	40±4	>16±3	3770	4380
#25, average	21±3	31±3	>8±2	3760	4710