HIGH POROSITY AND COSMIC-RAY EXPOSURE AGE OF ASTEROID 2008 TC3 DERIVED FROM COSMOGENIC NUCLIDES.

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Introduction: On October 7, 2008, a small asteroid, 2008 TC3, exploded in the atmosphere at an altitude of 37 km above the Nubian Desert of northern Sudan. Several search expeditions yielded 300 meteorite fragments with a total mass of ~4 kg. The meteorite, known as Almahata Sitta, was classified as an anomalous polymict ureilite [1].

The pre-atmospheric size of Almahata Sitta was determined directly from observations of asteroid 2008 TC3 before impact, yielding a volume of 28±6 m^3 [2], corresponding to a radius of 1.88±0.12 m. However, the bulk density of the object is unknown, while the density of the recovered meteorites ranges widely, from 1.77 to 3.26 g/cm^3. In this work, we report the cosmogenic radionuclide noble gas concentrations, to constrain the pre-atmospheric mass (and density) of asteroid 2008 TC3 and determine its cosmic-ray exposure (CRE) age.

Experimental Methods: We received small chips of six Almahata Sitta fragments (#1, 4, 15, 36, 44, 47) for radionuclide measurements and four (#4, 36, 44, 47) for noble gas analysis. We dissolved 50-100 mg, along with 3-5 mg of Be and Cl, in concentrated HF/HNO_3. After dissolution, a small aliquot was taken for chemical analysis by atomic absorption spectrometry. We separated Be, Al and Cl using ion exchange and acetyl-acetone extraction techniques. AMS measurements of ^{10}Be and ^{36}Cl were performed at PRIME lab [3]. The concentrations and isotopic composition of light noble gases were measured in chips of 30-150 mg, following procedures described previously [4]. Results of the chemical, radionuclide and noble gas analysis are summarized in Table 1.

Radionculide results. The ^{10}Be concentrations of 19-24 dpm/kg are surprisingly high for a 4-meter object. The cosmogenic ^{36}Cl concentrations range from 3.6 to 15.3 dpm/kg, mainly due to variations in Fe (7.6-20.8 wt%) and Ca (0.9-5.8 wt%), the main targets elements for ^{36}Cl production (Fig. 1). When normalized to Fe and Ca, using $P(^{36}Cl)_{Ca} = 10{*}P(^{36}Cl)_{Fe}$, the results yield a relatively constant ^{36}Cl concentration of 20 ± 1 dpm/kg[Fe+10Ca]. To match the measured radionuclide concentrations with calculated depth profiles for a fixed radius of 1.88 m, we varied the density of the object from 1.0 to 2.3 g/cm^3 (which corresponds to chondritic objects with radii of 50 to 120 cm, i.e. 180-430 g/cm^2), using the chemical composition of individual samples (Table 1) and elemental production rates for chondrites with radii of 180-430 g/cm^2 [5].

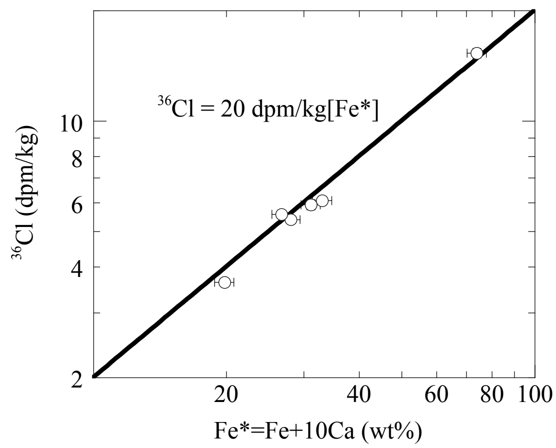

Figure 1. Correlation of ^{36}Cl concentrations in Almahata Sitta samples vs. chemical composition. The solid line represent a linear fit with a slope of 20 dpm/kg[Fe+10Ca].

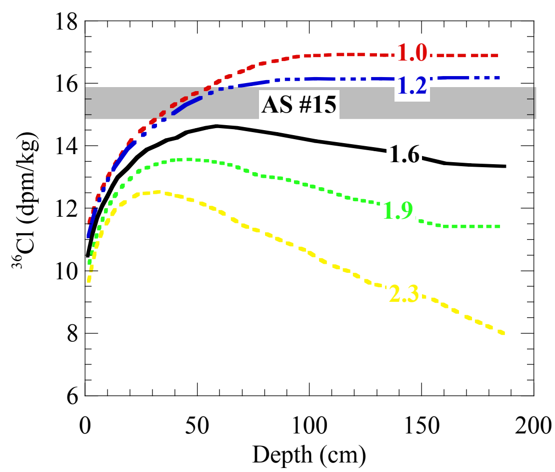

Figure 2. Comparison of measured ^{36}Cl concentrations in AS #15 (grey bars) with calculated depth profiles in objects with R=188 cm and density =1.0-2.3 g/cm^3.

Figure 2 shows that the high ^{36}Cl concentration in Almahata fragment #15 is only consistent with average meteoroid densities of 1.2-1.6 g/cm^3. The ^{36}Cl concentrations in other Almahata fragments yield similar densities, with a value of ~1.5 g/cm^3 yielding the best fit with both ^{10}Be and ^{36}Cl

concentrations. Assuming an average grain density of ~3.3 g/cm^3 for ureilites, the low bulk density thus implies that asteroid 2008 TC3 had a total porosity of ~50%. The bulk density of this small asteroid is lower than the measured densities of 1.77-3.26 g/cm^3 of the recovered meteorite fragments (Fig. 3). This high porosity of asteroid 2008 TC_3 is similar to - but more accurate than - the estimated porosity based on the atmospheric fragmentation of the asteroid as observed by Meteosat 8 [8].

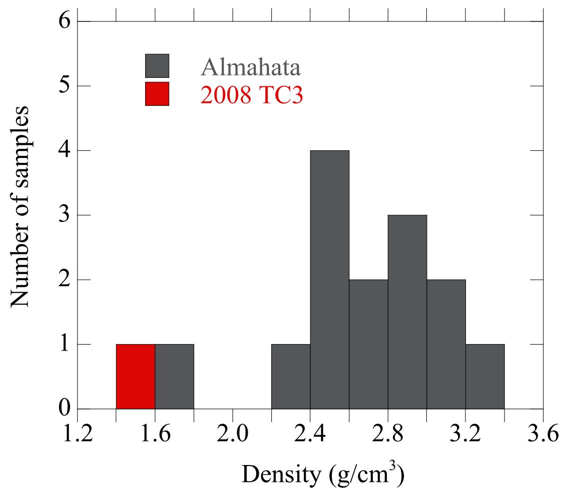

Figure 3. Bulk density of asteroid 2008 TC_3 (red) in comparison with measured densities of individual meteorite fragments (grey) from the Almahata Sitta strewnfield.

Noble gases and CRE age. Concentrations of cosmogenic ^{3}He and ^{21}Ne are relatively constant at 22-28 and 5.8-7.8, respectively. The shielding-sensitive $(^{22}Ne/^{21}Ne)_{cos}$ ratio is also quite constant (around 1.05-1.06) in all samples except sample #44. This sample has a higher value of ~1.10, indicating that it had been closer to the pre-atmospheric surface than the others. We calculated production rates as a function of ^{22}Ne/^{21}Ne, after taking into account that the ^{22}Ne/^{21}Ne ratios in ureilites are systematically ~2% lower than in L-chondrites [7,8]. We used chemical correction factors for each individual sample, since the major element concentrations in the Almahata Sitta ureilite vary significantly from sample to sample (Table 1). Calculated ^{3}He and ^{21}Ne production rates (in units of 10^{-8} cm^3 STP/g/Myr) range from 1.68-1.72 (^{3}He) and 0.38-0.54 (^{21}Ne). These values yield average ^{3}He and ^{21}Ne ages of 14.9±1.8 Myr and 14.5±0.9 Myr, respectively. Similar ages of 12-14 Myr are reported for two fragments measured by Ott [9]. The average age of ~15 Myr is in the range of typical ureilite ages of 1-50 Myr [8].

Conclusions. The relatively high concentrations of cosmogenic ^{10}Be and ^{36}Cl in six fragments of the Almahata Sitta ureilite strewnfield indicate that they came from an object with a radius of 260-300 g/cm^2. Given the pre-atmospheric radius of Almahata Sitta of ~1.9 m as determined from direct observations of asteroid 2008 TC3 before its impact on Earth, this constrains its bulk density to 1.5 ± 0.1 g/cm^3 and its porosity to 55 ± 5 %.

With the reflectance spectrum of 2008 TC3 being consistent with F-class asteroids, the discovery of the surviving meteorite fragments of Almahata Sitta firmly links polymict ureilites to F-class objects, which are mainly found at a semi-major axis of ~2.45 AU, near the 3:1 mean motion resonance with Jupiter. The cosmogenic ^{3}He and ^{21}Ne concentrations in four Almahata Sitta fragments yield a consistent CRE age of ~15 Myr. This age represents the transfer time of asteroid 2008 TC3 from an F-type parent body in the asteroid belt to Earth [10].

Acknowledgments. This work was supported by NASA grant NNG06GF22G, the Planetary Astronomy program and the Swiss National Science Foundation.

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Table 1. Concentrations of major elements (in wt%) and cosmogenic ^{10}Be and ^{36}Cl (in dpm/kg) and ^{3}He, ^{21}Ne (in 10^{-8} cm^3 STP/g) and cosmogenic ^{22}Ne/^{21}Ne ratio in Almahata Sitta ureilite samples.

Sample	Mg	Al	Ca	Mn	Fe	Ni	^{10}Be	^{36}Cl	^{36}Cl*	^3He_c	$^{21}Ne_c$	$(^{22}Ne/^{21}Ne)_c$
#1	19.6	0.16	0.92	0.28	20.8	0.37	19.0±0.4	5.9±0.2	19.7±0.6	–	–	–
#4	20.9	0.29	1.72	0.38	9.7	0.05	22.5±0.9	5.4±0.1	20.0±0.4	22.0	7.01	1.058
#15	17.0	0.43	5.75	0.32	15.2	0.14	19.6±0.4	15.3±0.5	21.1±0.6	–	–	–
#36	23.7	0.17	1.12	0.31	7.6	0.03	21.9±0.4	3.6±0.1	19.4±0.5	24.2	7.25	1.062
#44	19.5	0.28	1.73	0.30	14.6	0.16	21.4±0.4	6.1±0.1	19.1±0.4	27.0	5.78	1.098
#47	20.1	0.14	1.05	0.28	15.1	0.17	24.1±0.9	5.6±0.1	21.8±0.5	27.8	7.83	1.045

*normalized to Fe+10Ca