COSMIC-RAY EXPOSURE HISTORY AND PREATMOSPHERIC SIZE OF THE MIFFLIN L5 CHONDRITE FALL. K. C. Welten[1] , M. M. M. Meier[2], M. W. Caffee[3], M. Laubenstein[4], P. R. Heck[5], R. Wieler[2] and K. Nishiizumi[1], [1]Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA (kcwelten@ssl.berkeley.edu), [2]Department of Earth Sciences, ETH Zürich, CH-8092 Zürich, Switzerland, [3]Department of Physics, Purdue University, West Lafayette, IN 47907, USA, [4]Laboratori Nazionali del Gran Sasso, I.N.F.N., S.S. 17/bis km 18+910, I-67100, Assergi (AQ), Italy, [5]Robert A. Pritzker Center for Meteoritics and Polar Studies, Dept. of Geology, The Field Museum, 1400 South Lake Shore Drive, Chicago, IL 60605, USA.

Introduction: On April 14, 2010, a bright fireball was seen in parts of Wisconsin, Iowa, and Illinois, and was captured by a camera on the roof of the University of Wisconsin-Madison. More than 70 stones with a total mass of >3.5 kg were recovered in the area near Mifflin Township, Wisconsin, within a few weeks after the fall. The meteorite, Mifflin, is an L5 chondrite, showing a brecciated texture with light clasts in a dark matrix [1]. To determine the pre-atmospheric size and cosmic-ray exposure (CRE) age of Mifflin, we measured cosmogenic radionuclides and noble gases in the Mifflin chondrite.

Experimental methods: We used a Mifflin specimen (Me 5109) of ~48 g in mass, which is partially covered by fusion crust. The concentrations of short-lived cosmogenic radionuclides, as well as ^{26}Al (half-life = 7.05x10^5 yr) and natural radioactivity in a 44.3 g fragment, were measured using non-destructive gamma-ray spectroscopy [2] at the underground laboratories, Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Radionuclide activities given in Table 1 were corrected to the time of fall.

A piece of ~1.2 g was used for the analysis of cosmogenic ^{10}Be (half-life =1.36x10^6 yr), ^{26}Al and ^{36}Cl (3.01 x10^5 yr). After separating the metal and stone fraction, we dissolved ~42 mg of metal and ~120 mg of stone, along with carrier solution. After dissolution, a small aliquot was taken for chemical analysis by atomic absorption spectroscopy. We separated Be, Al and Cl using procedures described previously [3] and measure the concentrations of ^{10}Be, ^{26}Al and ^{36}Cl by accelerator mass spectrometry (AMS) at Purdue University [4]. The results are normalized to AMS standards [5-7]. The metal phase yields ^{10}Be = 4.8 ± 0.1 dpm/kg and ^{36}Cl = 22.1 ± 0.7 dpm/kg, while other measurements are in progress.

For noble gas analysis at ETH Zürich, we split a piece of ~0.35 g into four subsamples with different amounts of light and dark lithologies. Three of the subsamples contain some fusion crust, the fourth aliquot contains none. The concentrations and isotopic composition of light noble gases were measured in four chips, following procedures described previously [8]. Results are given in Table 2.

Results and Discussion: The presence of very short-lived cosmogenic radionuclides in Mifflin are consistent with a recent fall, while their absolute concentrations are a function of shielding as well as solar modulation of the galactic cosmic-ray flux [9]. The relatively high ^{22}Na/^{26}Al activity ratio of 2.2 ± 0.2 is in agreement with what is expected for this fall during a long period of low solar activity [9].

Pre-atmospheric size. The concentration of cosmogenic ^{60}Co, which is predominantly produced by neutron-capture, indicates a pre-atmospheric radius of ≥25 cm [10]. Comparison of the ^{10}Be concentration with model calculations indicate irradiation at a depth of ~20 cm in an object with a radius of ~45 cm, similar to Knyahinya [11]. This size is consistent with the diameter of ~1 m derived from the fireball observations [1]. However, the ^{26}Al concentration is lower than the expected value of ~70 dpm/kg for a depth of ~20 cm with a radius of 45 cm [12]. In addition, the low ^{60}Co concentration also indicates a lower shielding depth. Although this discrepancy is not well understood, it could be due to a nonspherical shape of the meteoroid, leading to lower secondary neutron fluxes.

Cosmogenic noble gases. The ^{20}Ne/^{22}Ne ratios of 0.83-0.85 indicate that neon is purely cosmogenic, and shows no evidence of solar neon in any of the samples. The elevated ^{36}Ar/^{38}Ar ratios of 1.5-1.8 indicate a small trapped Ar component, either planetary and/or atmospheric origin. We calculated the cosmogenic ^{38}Ar concentrations assuming ^{36}Ar/^{38}Ar ratios of 5.32 for the trapped and 0.65 for the cosmogenic Ar components. The ^{3}He concentrations in the samples with fusion crust are 19-37% lower than in the sample without fusion crust, suggesting that ^{3}He in these samples was lost during atmospheric ablation, yielding low ^{3}He/^{21}Ne ratios of 2.7-3.3 compared to a ^{3}He/^{21}Ne ratio of 3.9 for the fusion-crust free sample. We note that the ^{21}Ne concentrations in these three samples are 5-10% lower than in the crust-free sample, while cosmogenic ^{38}Ar concentrations are 1-7% lower (Table 2). We therefore use only sample #4 for CRE age calculations.

CRE age. The cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar concentrations in sample #4 yield an average CRE age of 16.5 Myr, based on production rates from [13], corresponding to a $^{22}Ne/^{21}Ne$ ratio of ~1.05. These production rates are probably too high, since the production rate formalism of Eugster does not hold up for $^{22}Ne/^{21}Ne$ ratios <1.08. More realistic production rates [in units of 10^{-8} cm^3 STP g^{-1} Myr^{-1}] of 0.35 for ^{21}Ne and 0.041 for ^{38}Ar, corresponding to a depth of 20 cm in an object with R~45 cm [14], yield a CRE age of 19-20 Myr. However, it is not clear what caused the low $^{22}Ne/^{21}Ne$ ratio in Mifflin. For a shielding depth of ~20 cm in an object with R~45 cm, we expect a $^{22}Ne/^{21}Ne$ ratio of ~1.08 [12,14]. A possible explanation for the low $^{22}Ne/^{21}Ne$ ratio in Mifflin is that it experienced a complex exposure history with a first-stage exposure at much higher shielding. In this scenario, the first stage must have occurred >5 Myr ago, since the radionuclide concentrations, which reflect shielding conditions for the last 5 Myr, are consistent with a radius of 45 cm. However, there is no additional evidence for a complex exposure history. For example, although we cannot exclude the possibility that Mifflin contains neutron-capture ^{36}Ar, based on the elevated $^{36}Ar/^{38}Ar$ ratios of 1.5-1.8, this seems unlikely, since the presence of neutron-capture ^{36}Ar leads to overcorrection of trapped Ar and thus to unusually high cosmogenic $^{21}Ne/^{38}Ar$ ratios [e.g., 3]. In contrast, the cosmogenic $^{21}Ne/^{38}Ar$ ratio of ~8 in Mifflin is consistent with typical ratios for medium-sized chondrites [12,14]. Additional measurements of ^{21}Ne and ^{10}Be or ^{26}Al in other Mifflin meteorite fragments are needed to verify whether or not this meteorite had a complex exposure history.

Thermal history. Taking into account the U and Th contents of 12 ± 1 and 46 ± 4 ppb, measured by gamma-ray spectroscopy, the radiogenic ^4He concentration of 190 ± 30 x 10^{-8} cm^3 STP/g yields a U,Th-He age of 0.65 ± 0.10 Gyr. Mifflin thus falls in the large group of L-chondrites with short gas retention ages. A plot of ^{40}Ar versus trapped ^{36}Ar yields a slope of 85 and an intercept of ^{40}Ar = 990 x 10^{-8} cm^3 STP/g, suggesting that ~30% of trapped Ar is atmospheric. The measured K content of 760 ± 80 ppm yields a K-Ar age of 1.8 ± 0.1 Gyr, indicating incomplete degassing of ^{40}Ar during the large breakup event 470 Myr ago.

Conclusions: The concentrations of short-lived and long-lived radionuclides indicate irradiation at a depth of ~20 cm in an object with a radius of ~45 cm. This radius is consistent with a diameter of ~1 m derived from the fireball observations. The cosmogenic noble gas concentrations yield a CRE age of ~20 Myr, although the low $^{22}Ne/^{21}Ne$ ratio of ~1.05 suggests that Mifflin may have experienced a complex exposure history with a first stage under high shielding conditions, but no firm evidence of this complex exposure has been found yet. Although Mifflin shows the light-dark structure typical of regolith breccias, it does not contain solar gases.

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Table 1. Activity concentration (corrected to the time of fall) of cosmogenic radionuclides (in dpm kg^{-1}) in the 44.3 g specimen of the Mifflin L5 chondrite measured by non-destructive gamma-ray spectroscopy. Errors are 1σ uncertainties.

Nuclide	^{48}V	^{51}Cr	^{7}Be	^{46}Sc	^{56}Co	^{58}Co	^{57}Co	^{54}Mn	^{22}Na	^{60}Co	^{26}Al
half-life	16.0 d	27.7 d	53.1 d	83.8 d	77.3 d	70.9 d	271.8 d	312.3 d	2.60 y	5.27 y	$7.05x10^5$ y
Activity	18±2	63±10	98±11	10±1	8±1	12±1	16±2	117±12	109±11	11±1	50±5

Table 2. Noble gas concentrations[1] (in 10^{-8} cc STP/g) and CRE ages (in Myr) based on cosmogenic ^3He (T3), ^{21}Ne (T21), and ^{38}Ar (T38) concentrations in light and dark samples of the Mifflin L5 chondrite fall and production rates from [12].

ID - lithology	^3He	^4He	$^{20}Ne/^{22}Ne$	^{21}Ne	^{22}Ne	$^{22}Ne/^{21}Ne_c$	^{38}Ar	^{40}Ar	$^{36}Ar/^{38}Ar$	$^{38}Ar_c$	T3	T21	T38
#1 light +dark*	22.85	357	0.838	6.81	7.16	1.051	1.10	1128	1.78	0.83	14.0	15.1	16.6
#2 dark*	19.50	312	0.848	6.46	6.84	1.056	1.06	1067	1.81	0.79	11.9	14.9	15.9
#3 light*	17.74	253	0.846	6.44	6.76	1.048	1.06	1139	1.62	0.84	10.8	14.1	16.7
#4 dark	28.16	374	0.827	7.20	7.54	1.048	1.05	1045	1.51	0.85	17.2	15.6	16.8

[1]Uncertainties are 2-4% for concentrations and 0.5-1% for isotopic ratios. *These samples contain some fusion crust.