PRE-ENTRY SIZE AND COSMIC HISTORY OF THE ANNAMA METEORITE.

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Introduction. A bright fireball was instrumentally observed by the Finnish Fireball Network on April 19, 2014. During a 5-day search campaign, two meteorites of 120 and 48 g (referred to as Annama I and II) were found only a few hundred meters from the predicted landing site in the remote Kola Peninsula (Russia) close to the Finnish border [1]. The meteorites were classified as H5 chondrite and were named Annama (MetBull 104). Based on the fireball observations, the pre-entry mass was estimated to be 472 kg with meteoroid spherical radius of 30-35 cm [1].

Methods: Noble gas (He, Ne, Ar) analysis in ETH Zurich was done on a fragment from Annama I using a furnace extraction method most recently described in detail by [2], in a single temperature step to ~1700°C, with Ar measured separately from He and Ne. Long-lived radionuclides were measured by accelerator mass spectrometry at Purdue's PRIME Lab on a 50 mg sample from Annama I that was taken within a few mm from the sample used for noble gas analysis. The radionuclide separations and measurements were done following procedures described in [3]. Short-lived radionuclides were measured at Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare, Italy on Annama II meteorite using gamma-ray spectroscopy within five months after the fall.

Results and discussion: The He, Ne, Ar content of Annama I can be fully described as a mixture of cosmogenic and radiogenic gases – trapped noble gases (e.g., solar wind) are absent, except for a minor Ar component. The measured $^{22}Ne/^{21}Ne$ ratio of 1.06 is compatible with a meteoroid radius of at least 65 cm and a shielding depth of about 45 cm, according to cosmogenic nuclide production models [4]. Since this is significantly larger than the 30-35 cm radius of the Annama meteoroid [1], this could suggest that Annama experienced a complex exposure history, with a first stage irradiation in a larger parent body. Under the shielding conditions indicated above, the ^{3}He, ^{21}Ne, and ^{38}Ar exposure ages are 28, 34 and 27 Ma, respectively. Our preferred value is 30 ±4 Ma, which should however be considered to be a lower limit given the possibility of a complex exposure history. The U, Th-He age of Annama is 2.7 Ga, and the K-Ar age is 3.8 Ga, assuming average chondritic U, Th, and K abundances [5].

Measured radionuclide concentration in the Annama I stone fraction are 22.3 ±0.3 dpm/kg for ^{10}Be, 89 ±3 dpm/kg for ^{26}Al and 9.8 ±0.2 dpm/kg for ^{36}Cl. The ^{10}Be and ^{26}Al concentrations in the stone fraction correspond to bulk values of 18.6 ±0.4 and 72 ±3 dpm/kg, respectively. The ^{26}Al concentration is within error consistent with calculated production rates in the center of objects with radii of 40-50 cm [4], i.e. slight larger than the size estimated from the fireball observations [1]. The ^{10}Be concentration is ~10% lower than expected for such shielding conditions, which could indicate a recent break-up event 3-5 Ma ago. Such a scenario seems consistent with the noble gas data, which indicate higher shielding conditions than inferred from the radionuclides and fireball observations. The ^{36}Cl concentration indicates a small contribution (~3 dpm/kg) of neutron-capture produced ^{36}Cl, consistent with the pre-atmospheric radius of >30 cm.

Short-lived radionuclides detected in Annama II are ^{26}Al, ^{7}Be, ^{22}Na, ^{57}Co, ^{58}Co, ^{56}Co, ^{60}Co, ^{54}Mn, ^{46}Sc, and ^{44}Ti. Comparing the ^{26}Al concentration (54.3 ±4.6 dpm/kg) to those obtained on Annama I (72 ±3 dpm/kg) one can infer that Annama II came from a shallower depth in the meteoroid than Annama I. This also seems consistent with the low ^{60}Co activity in Annama II, which indicates a depth of <5 cm in an object with R >30 cm. Finally, the $^{22}Na/^{26}Al$ ratio of 1.7 ±0.2 in Annama II is a bit higher than would be expected for its fall date in April 2014, i.e., at the maximum of a relatively weak solar cycle #24.

Conclusions: Annama is not part of the prominent "7-8 Ma" peak in the exposure age histograms of the H-chondrites [6]. Instead, its exposure age is within uncertainty of a smaller peak at ~33 Ma. The combination of noble gases and radionuclides seem to indicate a complex exposure history, although it is not well constrained. The results from short-lived radionuclides are compatible with a pre-entry radius of 30-40 cm. However, Annama must have been part of a larger body (radius >65 cm) for a large part of its cosmic-ray exposure history.

References: [1] Trigo-Rodríguez J. M. et al. 2015. *MNRAS* 449:2119-2127. [2] Meier M. M. M. et al. 2016. *Meteoritics & Planetary Science*, submitted. [3] Welten K. C. et al. 2011. *Meteoritics & Planetary Science* 46: 177-198. [4] Leya I. and Masarik J. 2009. *Meteoritics & Planetary Science* 44:1061–1086. [5] Wasson J. T. and Kallemeyn G. W. 1988, *Royal Society of London Philosophical Transactions Series A* 325:535–544. [6] Marti K. and Graf T. 1992. *Annual Reviews of Earth & Planetary Science* 20:221-243.