

NOBLE GAS STUDIES OF LUNAR AND ENSTATITE METEORITES. J. Park^{1,2,3,4}, K. Nagao⁴, L. E. Nyquist⁵, G. F. Herzog², J. Choi⁴, J. M. Baek⁴, C. Park⁴, J. I. Lee⁴, M. J. Lee⁴, M. K. Weisberg^{1,3,6}, D. S. Ebel^{3,6}, B. D. Turrin⁷, A. Yamaguchi⁸, N. Shirai⁹ and M. Ebihara¹⁰. ¹Kingsborough Comm. Coll., Brooklyn, NY 11235, USA (jisun.park@kbcc.cuny.edu), ²Dept. Chem. & Chem. Biol., Rutgers Univ., Piscataway, NJ 08854, USA, ³Amer. Museum of Natural History (AMNH), NY, NY 10024, USA, ⁴Div. Polar Earth-System Sci., Korea Polar Res. Inst. (KOPRI), Incheon 21990, Korea, ⁵XI/NASA Johnson Space Center, Houston, TX 77058, ⁶Dept. Earth and Environmental Sci., Graduate Center, City Univ. New York, New York, USA, ⁷Dept. Earth Planet. Sci., Rutgers Univ., Piscataway, NJ 08854, USA, ⁸National Inst. of Polar Res., Tachikawa, Tokyo 190-0014, Japan, ⁹Tokyo Metropolitan Univ., Hachioji, Tokyo 192-0397, Japan, ¹⁰Waseda Univ., Shinjuku, Tokyo 169-8050, Japan.

Introduction: We assess, using noble gases, the controversial possibility that chemically reduced enstatite (E) chondrites, aubrites, Earth, and Moon represent material from the same nebular feeding zone. Numerical simulations of terrestrial planet accretion suggest extended feeding zones with about 60% of the Earth's mass deriving from heliocentric distances between ~0.5 and 1.5 A.U. [1,2]. Recent O-isotopic analyses show the average O-isotopic composition of E-meteorites and especially of aubrites to be very close to those of the Earth and Moon [e.g., 1-4]. Also, E-chondrites are the only chondrites with bulk Cr, Ti, Ni and Zn isotopic compositions similar to those of the Earth and the Moon [5-8]. Nevertheless, some authors question a potential relationship among E-meteorites, Earth, and Moon [9].

Here we report new noble gas studies of the lunar meteorites, Miller Range (MIL) 090034, 090036, and 090070 and compare them to earlier noble gas results for the E-meteorites Cumberland Falls and Peña Blanca Spring (aubrites), Qingzhen (EH3), Khairpur (EL6), and Happy Canyon and Ilafegh 009 (EL7) [10]. These lunar meteorites are well suited for this comparison. Hereafter we refer to them as MIL 34, MIL 36, and MIL 70, respectively.

Park et al. [11,12] presented $^{40}\text{Ar}/^{39}\text{Ar}$ ages for MIL

and 3540 ± 40 Ma, respectively [11,12]; additional consortium studies are ongoing [13-15]. Much older apparent $^{40}\text{Ar}/^{39}\text{Ar}$ ages (>4.6 Ga) also were observed for two bulk samples of MIL 36. Park et al. [12] suggested that it contains ^{40}Ar implanted from a "lunar atmosphere" during impact melting. Also, unlike MIL 34 and MIL 70, MIL 36 contains high concentrations of noble gases from the solar wind. On the basis of cosmogenic nuclide and petrologic data, Yamaguchi et al. [14] suggested that MIL 34 and MIL 70 were derived from a large crater, where MIL 70 was deeply buried in the impact melt sheet, while MIL 34 was located closer to the surface of the melt sheet. Further, compositional considerations [13] indicate that MIL 36 was derived from a KREEP-rich terrane.

Methods: Noble gases. All samples were preheated at 150 °C for 24 h to remove terrestrial contamination. The samples were degassed stepwise at temperatures of 500, 800, 1000, 1300 and 1800 °C for 30 minutes. He, Ne, Kr, Xe, and Ar were measured with a mass spectrometer, VG-5400, originally modified at the University of Tokyo and now at Korea Polar Research Institute (KOPRI) [16]. Sensitivities and mass discrimination correction factors were determined by measuring aliquots of atmospheric Ne, Ar, Kr, and Xe and, separately, standardized mixtures of ^3He and ^4He .

Principal Component Analyses (PCA). PCA seems especially promising for investigating the sources of variations in the nine Xe isotope abundances observed during multi-step temperature extractions. A puzzling result of prior Xe isotopic investigations of lunar samples has been the apparent presence of a "trapped" component resembling terrestrial Xe in lunar anorthosites [17]. We applied PCA to 46 analyses of ^{130}Xe , ^{132}Xe , ^{134}Xe and ^{136}Xe data for the three MIL samples and six E-meteorite samples to identify trapped component(s) separately from other sources of noble gases. Radiogenic ^{129}Xe , cosmogenic ^{124}Xe , ^{126}Xe , and ^{128}Xe as well as ^{131}Xe (potentially influenced by neutron capture on ^{130}Ba) were ignored in the PCA to focus on parent body intrinsic Xe.

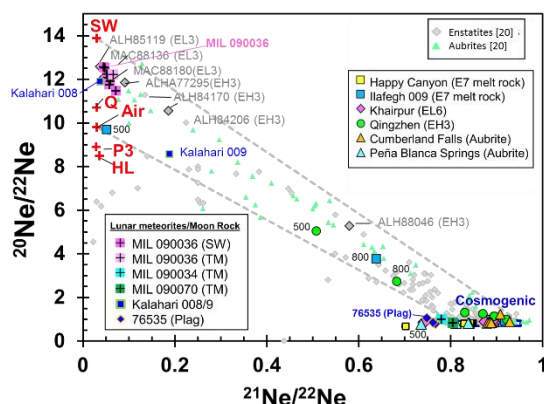


Fig. 1. Neon 3-isotope plot. Literature values from [10], [18], [19], [20].

34, MIL 36, and MIL 70 of 3500 ± 110 Ma, 3520 ± 30 Ma

Results and discussion: $^{21}\text{Ne}/^{22}\text{Ne}$ vs. $^{20}\text{Ne}/^{22}\text{Ne}$. Fig. 1 shows that neon in MIL 36 is dominated by solar wind, whereas neon in MIL 34 and MIL 70 is dominated by cosmogenic components. There is close agreement between results for MIL 34 and MIL 70 with data for plagioclase separated from lunar troctolite 76535 [18] as expected because of low MgO in plagioclase and comparatively low MgO of ~2.5% in these anorthositic lunar meteorites. CRE ages determined from the cosmogenic nuclides ^{21}Ne , ^{38}Ar , ^{78}Kr and ^{83}Kr of MIL 36 are ~100-120 Ma, while those of MIL 34 and MIL 70 are ~1-2 Ma [11, 12, this work]. The low CRE ages for MIL 34 and 70 are important to understanding the Xe isotopic data presented next.

$^{132,134,136}\text{Xe}/^{130}\text{Xe}$. To resolve the sources of isotopic variations it is helpful to choose a reference isotope whose budget is dominated by a single physical component. By using PCA, we found that considering ratios to ^{130}Xe was advantageous in resolving cosmogenic and fissionogenic $^{132,134,136}\text{Xe}$ from trapped Xe. This choice of ^{130}Xe as a reference isotope also follows the examples of Pepin et al. [21] and others (e.g., [22]).

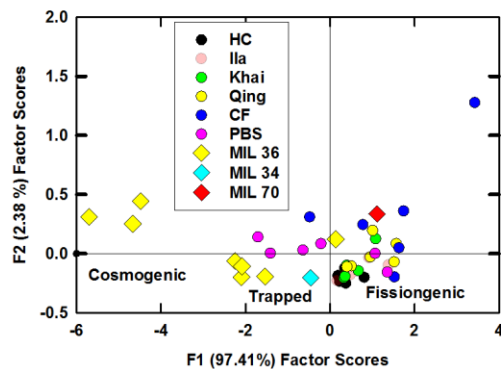


Fig. 2. PCA Biplot for $^{132,134,136}\text{Xe}/^{130}\text{Xe}$. HC = Happy Canyon, Ila = Ilafegh, Khai = Khairpur, Qing = Qingzhen, CF = Cumberland Falls, PBS = Peña Blanca Springs.

PCA (XLSTAT®) applied to the three sets of $^{132,134,136}\text{Xe}/^{130}\text{Xe}$ data showed that 97.41% of the data could be represented by the first Principal Component F1 (Fig. 2). For an alternative representation of the four isotopes ($^{130,134,136}\text{Xe}/^{132}\text{Xe}$) only 77.65% of the data can be represented by F1. In Fig. 2, the MIL 34 and MIL 70 data overlaps those of the E-meteorites.

We choose the ^{130}Xe normalization for further interpretations. Fig. 3 shows $^{134,136}\text{Xe}/^{130}\text{Xe}$ data for the Miller Range meteorites compared to similar data for E-meteorites [10]. A cosmogenic trend line is defined for MIL 36. A fissionogenic trend line for Cumberland Falls intersects (star) the MIL 36 trend near the Solar Wind (SW) composition. Data for Peña Blanca Springs show a nearly continuous linear trend intersecting the MIL 36 trend (star) slightly to the right of the Q com

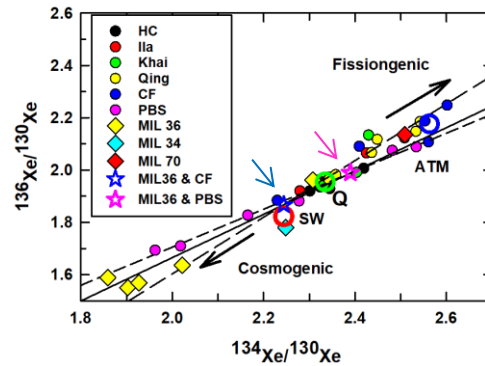


Fig. 3. $^{136}\text{Xe}/^{130}\text{Xe}$ vs. $^{134}\text{Xe}/^{130}\text{Xe}$ for lunar and enstatite meteorites near Solar Wind (SW), Q [23], and terrestrial atmosphere compositions (ATM). See Fig. 2 caption for labels. The most cosmogenic data for MIL 36 and most fissionogenic data for CF are not shown. Intersections for regression lines are shown by open stars color-coded to the corresponding data, trapped compositions by open circles.

position. Data for MIL 34 and MIL 70 span a region of the diagram near Q [23] and overlap much of the E-meteorite data.

Conclusions: Our Xe isotopic data for the Miller Range meteorites do not support earlier suggestions of an “Earth-like” composition for “lunar Xe”, but rather a Q-like composition. There is a good correspondence between the composition of trapped noble gases in these lunar and E-meteorites, but additional analyses of both are needed and planned.

References: [1] Clayton R. N. et al. (1984) *JGR*, 89, C245-C249. [2] Weisberg M. K. & Kimura M. (2012) *Chem. Erde*, 72, 101-115. [3] Keil K. (2010) *Chem. Erde* 70, 295-317. [4] Rubin A. E. (2015) *Chem. Erde*, 75, 1-28. [5] Greber N. D. & Dauphas N. (2017) *LPS* 48, Abstract #2837. [6] Javoy M. et al. (2010) *EPSL* 293, 259-268. [7] Mougél B. et al. (2018) *PSL* 481, 1-8. [8] Moynier F. et al. (2011) *GCA* 75, 297-307. [9] Fitoussi C. & Bourdon B. (2012) *Science* 335, 1477-1480. [10] Park J. et al. (2018) *LPS* 49, Abstract #1914. [11] Park J. et al. (2013) *LPS* 44, Abstract #2576. [12] Park J. et al. (2015) *MetSoc* 78, Abstract #5237. [13] Shirai N. et al. (2012) *LPS* 43, Abstract #2003. [14] Yamaguchi A. et al. (2013) *Goldschmidt*, Abstract #2539. [15] Nyquist L. E. et al. (2016) *LPS* 47, Abstract #1521. [16] Nagao K., et al. (2016) *MetSoc* 79, Abstract #6109. [17] Niedermann S. & Eugster O. (1992) *GCA* 56, 493-509. [18] Lugmair G. W. et al. (1976) *PLSC* 7, 2009-2033. [19] Sokol A. K. et al. (2008) *GCA* 72, 4845-4873. [20] Schultz L. & Franke L. (2004) *MAPS* 39, 1889-1890. [21] Pepin R. O. et al. (1975) *PLSC* 6, 2027-2055. [22] Kaiser W. A. et al. (1974) *LPI*, 57-60. [23] Ott U. (2014) *Chem. Erde* 74, 519-544.