Space history of the High Possil and Strathmore meteorites from Ne and Ar isotopes

A. Carracedo1*, F.M. Stuart1, L. Di Nicola1 and J.W. Faithfull2
1 Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride G75 0QF, UK
2 Hunterian Museum & Art Gallery, University of Glasgow, 82 Hillhead Street, Glasgow G12 8QQ, UK
* Correspondence: ana.carracedoplumed@glasgow.ac.uk

Abstract: The High Possil and Strathmore L6 chondrites fell in Scotland in 1804 and 1917 respectively. Unravelling their cosmic-ray exposure (CRE) ages provides crucial information about when they were ejected from the parent body, how they were delivered to Earth and is ultimately important for understanding the dynamics of small bodies in the solar system. Here we use new measurements of the Ne and Ar isotopic composition to determine CRE ages of both meteorites. Duplicated cosmogenic 21Ne and 38Ar concentrations yield CRE ages of 44.6 ± 4.6 Ma for High Possil and 15.4 ± 1.3 Ma for Strathmore. These coincide with well-established peaks in the ejection record for the L6 chondrites. They yield 40Ar gas retention ages in excess of 3.15 Ga, which is consistent with both meteorites originating at depth within the parent body at the time of asteroidal break-up.

Thematic collection: This article is part of the Early Career Research collection available at: https://www.lyellcollection.org/cc/SJG-early-career-research

Received 25 January 2022; revised 6 May 2022; accepted 10 May 2022

The High Possil and Strathmore meteorites are two of the three meteorite falls recorded in Scotland (Bevan et al. 1985; Meteoritical Bulletin 110 (2021)). The fall of the High Possil (5 April 1804) meteorite was heard by the workers at Possil sandstone quarry (55° 4’ N, 4° 14’ W) and observed throughout Glasgow. The impact left a 38 cm diameter hole that filled with water leaving the meteorite fragments embedded into the soft sandy bedrock. Only two outer parts of the meteorite were recovered. Based on the reported dimensions from Prior and Hey (1923) the total weight of the meteorite was estimated to be 4.5 kg (Bevan et al. 1985 and references therein). The larger of the two recovered fragments was donated to the Hunterian Museum, University of Glasgow.

The Strathmore meteorite fell on 3 December 1917 around Coupar Angus and Blairgowrie. It consists of four stones totalling 13.2 kg. Three fragments were recovered in Perthshire, at Easter Essendy (56° 35’ N, 3° 15’ E) (two fragments: 9.911 and 0.021 kg), Carsie (1.085 kg) and Keithick (1.172 kg). One fragment was found at South Corston (1.066 kg) in Angus (Bevan et al. 1985). Detailed descriptions of the fall are available at https://www.nms.ac.uk/explore-our-collections/stories/natural-sciences/strathmore-meteorite/.

Both meteorites have petrographic, mineralogical and chemical compositions consistent with the L-group chondrites (McLintock and Ennos 1922; Bevan et al. 1985). They have abundant plagioclase feldspar which puts them in the petrologic type 6 of the Van Schmus and Wood (1967) classification. The L6 chondrites are characterized by low iron content and have been metamorphosed at P–T conditions sufficient to homogenize mineral chemical compositions. They likely originate in S-type asteroids. The level of silicate alteration due to shock-loading is variable, but not intense, suggesting that shock pressures were in the range of 10–25 GPa. Strathmore has a greater proportion of deformed grains than High Possil, consistent with shock loading to higher pressures (Bevan et al. 1985).

Cosmic-ray exposure (CRE) ages of meteorites provide fundamental constraints against which models for the origin and delivery of meteorites from the asteroid belt to Earth are tested (e.g. Nesvorny et al. 2009). Cosmogenic nuclides in meteorites are produced by nuclear interactions of high-energy galactic cosmic ray (GCR) protons from outside the solar system, and energetic solar cosmic ray (SCR) protons emitted by the Sun. Cosmogenic nuclide production rate is governed by the meteorite composition, the shape and size of the irradiated body and the position of the analysed sample within the parent body (Eugster 1988). L6 meteorites tend to originate from deep within their parent body so do not acquire a significant cosmogenic nuclide load prior to ejection into space. Consequently, the CRE age records the transit time of a small object from its parent body to Earth after parent body ejection.

Cosmogenic 21Ne and 38Ar are widely used to reconstruct the irradiation history of meteorites in space (Wieler 2002). Here we use new measurements of Ne and Ar isotopes to determine the concentration of the cosmogenic Ne and Ar in the High Possil and Strathmore L6 chondrites in order to estimate the pre-atmospheric size of the meteorites and to reconstruct the exposure time in space. The concentration of radiogenic 40Ar provides an insight into the thermal history of the parent body.
Samples and experimental techniques

In this study we report data on samples of the larger High Possil stone, provided by the Hunterian Museum, and the Keithick fragment of Strathmore, which was from the National Museum of Scotland collection. The specimens looked fresh under the binocular microscope and preserved fusion crust (Fig. 1). Chips (4.6 to 6.7 mg) were prised from the larger sample using tweezers taking care to avoid fusion crust. They were encapsulated in Pt packets, placed in recesses in a Cu pan then evacuated to ultra-high vacuum and baked for 12 h at c. 80°C to remove adsorbed atmospheric gases. The samples were degassed at c. 1300°C for 30 minutes using a 75 W 808 nm diode laser in apparatus identical to that described in Stuart et al. (1999). The gas released was purified by two SAES GP50 getters operated at 250°C and one at room temperature. Argon was trapped for 20 minutes on an activated charcoal-filled stainless-steel finger cooled to −196°C using liquid nitrogen. Neon was then trapped on activated charcoal in a cryostatic cold head at 30 K for 10 minutes; the unabsorbed He was pumped out then the Ne was released at 100 K prior to isotope analysis in static mode in a MAP-215-50 mass spectrometer (Williams et al. 2005). The Ar was subsequently released from the charcoal trap at room temperature and analysed using the same instrument.

System blanks were determined by heating an empty platinum tube to c. 1300°C. They never exceeded more than 0.2% of any isotope in the sample so blank corrections were not made. The sample packets were reheated and in all cases Ne and Ar concentrations did not exceed 1% of the gas released in the main step. Sensitivity and instrument mass discrimination are based on repeated measurements of an air standard. Neon isotopes have been corrected from isobaric interferences from H$_3$O$^+$, HF$^+$ and 40Ar$^{2+}$ at 20Ne$^+$, CO$_2$$^{+}$ at 22Ne$^+$ and 66Cu$^{3+}$ at 21Ne$^+$ following procedures in Codilean et al. (2008). Ne and Ar isotopes were determined in several splits of homogenized powder of the Millbillillie eucrite before and after these samples as a secondary check on mass spectrometer sensitivity and mass discrimination.

Results and discussion

Cosmogenic Ne and Ar

Neon isotopes were measured in three chips of High Possil and two chips of Strathmore (Table 1). The 20Ne/22Ne and 21Ne/22Ne ratios in each sample overlap within uncertainty (Fig. 2) and overlap the composition of cosmogenic Ne in chondrites (Eugster et al. 2007). This suggests that the contribution from atmospheric, solar or primordial Ne is negligible, and the Ne inventory is dominantly cosmogenic in origin.

Argon isotopes were measured in two aliquots of both meteorites (Table 2). 36Ar/38Ar of 0.88 ± 0.07 and 1.63 ± 0.33 for High Possil and Strathmore respectively are higher than the cosmogenic 36Ar/38Ar of L chondrites (c. 0.63; Wieler 2002). This is likely a consequence of the presence of significant contributions of solar wind and/or atmosphere-derived Ar, more so in the case of Strathmore. The low solar wind Ne and Ar content of L6 chondrites (Alexeev 2005) leads us to assume that the non-cosmogenic component is atmospheric in origin (36Ar/38Ar = 5.319) perhaps a consequence of incomplete degassing of adsorbed air prior to analysis. The correction for air-derived 38Ar is c. 5% in the case of High Possil and 14–28% for the two Strathmore splits. Variation in 40Ar/36Ar is also consistent with a minor atmospheric contribution. For the component deconvolution we did not consider the contribution of 36Ar generated by the decay of neutron-capture produced 36Cl. This will tend to increase the 36Ar/38Ar and reduce the cosmogenic 38Ar concentration (e.g. Huber et al. 2008).

The noble gas data alone are not sufficient to determine the pre-atmospheric size of the meteorite and so determine the
sample depth. The empirical correlation of Bhandari et al. (1980) facilitates the determination of the pre-atmospheric mass and radius although it is only valid for samples that are from the interior of the meteorites where the variations of Ne ratios are relatively small. The relatively high $^{21}\text{Ne}/^{22}\text{Ne}$ of High Possil (0.87) and Strathmore (0.91), in combination with the cosmogenic $^{20}\text{Ne}/^{22}\text{Ne}$ ratio, is consistent with only a few centimetres of shielding (Garrison et al. 1995) and legitimizes the use of the empirical correlation between the cosmogenic $^{22}\text{Ne}/^{21}\text{Ne}$ and the pre-atmospheric mass of the meteorite developed by Bhandari et al. (1980). Using the average density for L-chondrites of 3.35 g cm$^{-3}$ (Britt and Consolmagno 2003), we calculate pre-atmospheric radii of 14 and 19 cm for High Possil and Strathmore respectively (Table 3). The recovered masses for High Possil and Strathmore (4.5 and 13 kg, respectively; Bevan et al. 1985) suggest mass loss of around 89 and 87% during atmospheric entry. This is in line with the typical mass ablation for L-chondrites (Bhandari et al. 1980; Alexeev 2004). In this case the pre-atmospheric masses are c. 40 and 100 kg for High Possil and Strathmore, respectively.

As the pre-atmospheric radii of both meteorites was less than 65 cm we can apply the calculation method of Dalcher et al. (2013) to determine the CRE ages of both meteorites. This uses the empirical correlations between the cosmogenic $^{21}\text{Ne}$ ($^{21}\text{Ne}_{\text{cos}}$) and $^{38}\text{Ar}$ ($^{38}\text{Ar}_{\text{cos}}$) production rates and the ($^{22}\text{Ne}/^{21}\text{Ne}$)$_{\text{cos}}$ ratio as a shielding indicator. From the measured ($^{22}\text{Ne}/^{21}\text{Ne}$)$_{\text{cos}}$ (Table 1) we obtain $^{21}\text{Ne}$ production rates of 0.28 and 0.39 $\times 10^{-8}$ cm$^3$STP g$^{-1}$ Ma$^{-1}$ for High Possil and Strathmore, respectively. This leads to average CRE ages of 4.9 and 5.1 Ma for High Possil and Strathmore, respectively.

Table 1. Measured Ne concentrations and isotope ratios, and calculated cosmogenic Ne concentrations, in bulk samples of the High Possil and Strathmore L6 chondrites

| Sample         | Mass* (mg) | $^{20}\text{Ne}$ | 1σ | $^{21}\text{Ne}_{\text{cos}}$ | 1σ | $^{20}\text{Ne}/^{22}\text{Ne}$ | 1σ | $^{21}\text{Ne}/^{22}\text{Ne}$ | 1σ |
|----------------|------------|------------------|----|-------------------------------|----|-------------------------------|----|-------------------------------|----|
| High Possil #1 | 4.6        | 10.50            | 0.85| 10.80                         | 1.60| 0.835                         | 0.049| 0.862                         | 0.064 |
| High Possil #2 | 6.3        | 11.56            | 0.96| 11.94                         | 1.74| 0.836                         | 0.049| 0.866                         | 0.064 |
| High Possil #3 | 6.4        | 10.97            | 0.89| 11.43                         | 1.64| 0.831                         | 0.049| 0.870                         | 0.064 |
| Average        | 6.4        | 11.01            | 0.43| 11.39                         | 0.47| 0.834                         | 0.002| 0.866                         | 0.003 |
| Strathmore #1  | 6.7        | 5.69             | 0.48| 6.15                          | 0.90| 0.833                         | 0.049| 0.903                         | 0.067 |
| Strathmore #2  | 6.6        | 5.94             | 0.48| 6.35                          | 0.93| 0.816                         | 0.048| 0.924                         | 0.068 |
| Average        | 6.6        | 5.82             | 0.12| 6.25                          | 0.10| 0.825                         | 0.009| 0.914                         | 0.011 |

*Sample mass in mg.
†Concentrations in $10^{-8}$ cm$^3$STP g$^{-1}$.

Table 2. Measured Ar concentrations and isotope ratios, and calculated cosmogenic Ne concentrations, in bulk samples of the High Possil and Strathmore L6 chondrites

| Sample         | $^{40}\text{Ar}$ | 1σ | $^{36}\text{Ar}$ | 1σ | $^{36}\text{Ar}/^{38}\text{Ar}$ | 1σ | $^{38}\text{Ar}_{\text{cos}}$ | 1σ |
|----------------|------------------|----|-----------------|----|-------------------------------|----|-----------------------------|----|
| High Possil #2 | 4016             | 6  | 1.71            | 0.10| 0.90                         | 0.07| 1.81                        | 0.02 |
| High Possil #3 | 5406             | 4  | 1.83            | 0.11| 0.87                         | 0.07| 2.00                        | 0.02 |
| Average        | 4711             | 695| 1.77            | 0.06| 0.88                         | 0.01| 1.90                        | 0.09 |
| Strathmore #1  | 3814             | 1  | 1.69            | 0.10| 1.30                         | 0.11| 1.12                        | 0.01 |
| Strathmore #2  | 3246             | 2  | 1.86            | 0.11| 1.95                         | 0.16| 0.69                        | 0.01 |
| Average        | 3530             | 284| 1.78            | 0.09| 1.63                         | 0.33| 0.90                        | 0.21 |

*Concentrations in $10^{-8}$ cm$^3$STP g$^{-1}$.

Fig. 2. Neon isotope data from the analysis of bulk material from High Possil (filled diamonds) and Strathmore (open diamonds) L6 chondrites. Solar wind (SW) Ne is taken from Geiss et al. (2004), P3 and HL endmembers are from Huss and Lewis (1994) and the Ne-Q is from Wieler et al. (1992). Mixing lines between air and galactic cosmic ray (GCR; full line) and solar cosmic ray (SCR; dashed line) produced Ne isotope compositions are taken from Garrison et al. (1995). The theoretical shielding line (dotted line) is taken from Hohenberg et al. (1978).
Concentrations reported in Table 2.

Bevan et al. (1985). The radii are calculated using the average density for L-chondrites of 3.35 g cm\(^{-3}\) (Britt and Consolmagno 2003) and the % of mass ablation uses the recovered masses (\(M_0\)) reported by Bevan et al. (1985).

### Table 3. Pre-atmospheric mass (\(M_0\)) and radius (\(R_0\)) of High Possil and Strathmore L6 chondrites, calculated using the empirical correlation of Bhandari et al. (1980)

| Sample | \(2^{21}\)Ne | \(d\) | \(M_0\) (Kg) | \(R_0\) (cm) | \(M_e\) (Kg) | % Ablation |
|--------|-------------|------|-------------|-------------|-------------|------------|
| High Possil | 1.155 | 0.004 | 40 | 14 | 4.5 | 89% |
| Strathmore | 1.095 | 0.013 | 100 | 19 | 13 | 87% |

The radii are calculated using the average density for L-chondrites of 3.35 g cm\(^{-3}\) (Britt and Consolmagno 2003) and the % of mass ablation uses the recovered masses (\(M_0\)) reported by Bevan et al. (1985).

### Table 4. Cosmogenic production rates of \(2^{21}\)Ne (\(P(21\text{Ne})\)) and \(38\text{Ar}\) (\(P(38\text{Ar})\)) (10\(^{-8}\) cm\(^{-3}\)STP g\(^{-1}\) Ma\(^{-1}\)) are calculated using the correlation of Dalcher et al. (2013) and the \(\sigma\) ratio for High Possil and Strathmore L6 chondrites

| Sample | \(P(21\text{Ne})\) | \(\sigma\) | \(T_{\text{CRE}}\) (21Ne) | \(\sigma\) | \(P(38\text{Ar})\) | \(\sigma\) | \(T_{\text{CRE}}\) (38Ar) | \(\sigma\) | \(T_{\text{ret}}\) (40Ar) | \(\sigma\) |
|--------|-----------------|------|-----------------|------|-----------------|------|-----------------|------|-----------------|------|
| High Possil #1 | 0.269 | 0.027 | 20.14 | 0.04 | 40.14 | 0.04 | 40.14 | 0.04 | 40.14 | 0.04 |
| High Possil #2 | 0.277 | 0.028 | 43.05 | 0.04 | 4.305 | 0.04 | 4.305 | 0.04 | 4.305 | 0.04 |
| High Possil #3 | 0.286 | 0.029 | 40.01 | 0.04 | 4.001 | 0.04 | 4.001 | 0.04 | 4.001 | 0.04 |

The CRE ages (\(T_{\text{ret}}\) (Ma)) are calculated using the \(2^{21}\)Ne and \(38\text{Ar}\) concentrations from Tables 1 and 2. The \(40\text{Ar}\) retention ages (\(T_{\text{ret}}\) (Ma)) are calculated using the measured \(40\text{Ar}\) concentrations reported in Table 2.

![Fig. 3. Calculated CRE ages for High Possil (filled symbols) and Strathmore (open symbols) L6 chondrites based on cosmogenic \(2^{21}\)Ne (diamonds) and \(38\text{Ar}\) (circles). The average ages (continuous lines) and standard deviation (dashed lines) are calculated using the five ages determined for High Possil and three ages of Strathmore. The oldest Strathmore CRE age (grey circle) is not included in the mean exposure age calculation.](image)

The CRE ages of 41.1 ± 1.4 and 16.1 ± 0.9 Ma (Table 4). Applying the \((2^{21}\text{Ne})/2^{21}\text{Ne}_{\text{cos}}\) to the calculation of the \(38\text{Ar}\) production rate we obtain production rates of 0.038 and 0.047 \(\times 10^{-8}\) cm\(^{-3}\)STP g\(^{-1}\) Ma\(^{-1}\) for High Possil and Strathmore, respectively. This produces CRE ages of 49.9 ± 1.9 for High Possil and 24.9 ± 2.5 to 13.8 ± 1.4 Ma for Strathmore (Table 4).

In the case of High Possil the five CRE ages agree within 1σ uncertainty and yield an average age of 44.6 ± 4.6 (Fig. 3). This overlaps the large c. 40 Ma peak in CRE ages of L6 chondrites that indicate a major collisional event on the L-chondrite parent body (Wieler 2002; Herzog and Caffee 2014).

The 21Ne and 38Ar CRE ages of the two High Possil splits are 3467 and 3935 Ma, and for Strathmore are 3389 and 3145 Ma (1σ uncertainties are 20% predicated on the uncertainty in the assumed K content). More precise K concentration data are required in order to distinguish whether the two meteorites have different gas retention ages. In any case, both meteorites have high gas retention ages that imply they were not close to the surface of the parental body when the asteroidal break-up event occurred at 470 Ma (e.g. Swindle and Kring 2008; Terfelt and Schmitz 2021).

### Conclusions

The K–Ar gas retention age of chondrites records the time since the meteorite experienced a thermal event causing leakage and provides an indication of the position of the meteorite within the parent body. Radiogenic 40Ar concentrations can be combined with previously published K concentrations to determine the Ar retention age. Bevan et al. (1985) reported K concentrations of 1000 and 1200 ppm for High Possil and Strathmore, respectively. These values are slightly higher than the average for L-chondrites of 858 ppm (Kallemeyn et al. 1989). Using a K concentration of 1000 ± 200 ppm and the measured 40Ar concentration (Table 2) the gas retention ages of the two High Possil splits are 3467 and 3935 Ma, and for Strathmore are 3389 and 3145 Ma (1σ uncertainties are 20% predicated on the uncertainty in the assumed K content). More precise K concentration data are required in order to distinguish whether the two meteorites have different gas retention ages. In any case, both meteorites have high gas retention ages that imply they were not close to the surface of the parental body when the asteroidal break-up event occurred at 470 Ma (e.g. Swindle and Kring 2008; Terfelt and Schmitz 2021).

Radiogenic 40Ar

The K–Ar gas retention age of chondrites records the time since the meteorite experienced a thermal event causing leakage and provides an indication of the position of the meteorite within the parent body. Radiogenic 40Ar concentrations can be combined with previously published K concentrations to determine the Ar retention age. Bevan et al. (1985) reported K concentrations of 1000 and 1200 ppm for High Possil and Strathmore, respectively. These values are slightly higher than the average for L-chondrites of 858 ppm (Kallemeyn et al. 1989). Using a K concentration of 1000 ± 200 ppm and the measured 40Ar concentration (Table 2) the gas retention ages of the two High Possil splits are 3467 and 3935 Ma, and for Strathmore are 3389 and 3145 Ma (1σ uncertainties are 20% predicated on the uncertainty in the assumed K content). More precise K concentration data are required in order to distinguish whether the two meteorites have different gas retention ages. In any case, both meteorites have high gas retention ages that imply they were not close to the surface of the parental body when the asteroidal break-up event occurred at 470 Ma (e.g. Swindle and Kring 2008; Terfelt and Schmitz 2021).
Acknowledgements This project was part of AC’s PhD. We would like to thank Peter Davidson from the National Museum of Scotland for donating a piece of Strathmore meteorite. We would also like to thank the reviewers and the editor for their thoughtful comments and effort to improve our manuscript.

Author contributions AC: data curation (lead), formal analysis (lead), investigation (lead), methodology (lead), writing – original draft (lead); FMS: project administration (lead), supervision (lead), writing – review & editing (equal); LDN: formal analysis (supporting), methodology (supporting), writing – review & editing (equal); JWF: resources (supporting), writing – review & editing (supporting)

Funding This project was part of AC’s PhD and was supported by the Natural Environment Research Council and Scottish Universities Environmental Research Centre (SUECRC)

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability All data generated or analysed during this study are included in this published article.

Scientific editing by Martin Kirkbride

References

Alexeev, V.A. 2004. Meteorite ablation evaluated from the data on the density of cosmic-ray tracks. Solar System Research, 38, 194–202, https://doi.org/10.1023/B:SOLR.0000030859.48114.3e

Alexeev, V.A. 2005. The history of ordinary chondrites from the data on stable isotopes of noble gases (a review). Solar System Research, 39, 124–149, https://doi.org/10.1007/s11208-005-0028-z

Bevan, A.W.R., Hutchison, R., Easton, A.J., Durant, G.P. and Farrow, C.M. 1985. High Possil and Strathmore – a study of two L6 chondrites. Meteoritics, 20, 491–501, https://doi.org/10.1111/j.1945-5100.1985.tb00045.x

Bhandari, N., Lal, D., Rajan, R.S., Arnold, J.R., Marti, K. and Moore, C.B. 1980. Atmospheric ablation in meteorites: a study based on cosmic ray tracks and neon isotopes. Nuclear Tracks, 4, 211–262, https://doi.org/10.1016/0191-278X(80)90037-2

Britt, D.T. and Consolmagno, G.J.S. 2003. Stony meteorite porosities and densities: a review of the data through 2001. Meteoritics & Planetary Science, 38, 1161–1180, https://doi.org/10.1111/j.1945-5100.2003.tb00305.x

Codilean, A.T., Bishop, P., Stuart, F.M., Hoey, T.B., Fabel, D. and Freeman, S.P. 2008. Single-grain cosmogenic $^{21}$Ne concentrations in fluvial sediments reveal spatially variable erosion rates. Geology, 36, 159–162, https://doi.org/10.1130/G24360A.1

Dalcher, N., Caffee, M.W., Nishizumi, K., Welten, K.C., Vogel, N., Wieler, R. and Leca, I. 2013. Calibration of cosmogenic noble gas production in ordinary chondrites based on $^{18}$Cl–$^{36}$Ar ages. Part 1: refined production rates for cosmogenic $^{21}$Ne and $^{39}$Ar. Meteoritics & Planetary Science, 48, 1841–1862, https://doi.org/10.1111/maps.12203

Eugster, O. 1988. Cosmic-ray production rates for $^6$He, $^{12}$C, $^{24}$Ne, $^{35}$Ar, $^{36}$Ar, $^{38}$Ar, and $^{39}$Ar in chondrites based on $^{39}$Ar–$^{40}$Ar exposure ages. Geochimica et Cosmochimica Acta, 52, 1649–1662, https://doi.org/10.1016/0016-7037(88)90233-5

Eugster, O., Lorenzetti, S., Krähenbühl, U. and Marti, K. 2007. Comparison of cosmic-ray exposure ages and trapped noble gases in chondrule and matrix samples of ordinary, enstatite, and carbonaceous chondrites. Meteoritics & Planetary Science, 42, 1351–1371, https://doi.org/10.1111/j.1945-5100.2007.tb00579.x

Garrison, D.H., Rao, M.N. and Bogard, D.D. 1995. Solar-proton-produced neon in shergottite meteorites and implications for their origin. Meteoritics, 30, 738–747, https://doi.org/10.1111/j.1945-5100.1995.tb01172.x

Geiss, J., Bühler, F., Cerutti, H., Eberhardt, P., Filleux, C.H., Meister, J. and Signer, P. 2004. The Apollo SWC experiment: results, conclusions, consequences. Space Science Reviews, 110, 307–335, https://doi.org/10.1023/B:SPAC.0000024309.54649.40

Herzog, G.F. and Caffee, M.W. 2014. Cosmic-ray exposure ages of meteorites. In: Davies, A.M. (ed.) Meteorites and Cosmochemical Processes, 1, 419–454, https://ui.adsabs.harvard.edu/abs/2014mcnp.book..419H

Hohenberg, C.M., Marti, K., Podoles, F.A., Reddy, R.C. and Sherk, J.R. 1978. Comparisons between observed and predicted cosmogenic noble gases in lunar samples. In: Lunar and Planetary Science Conference Proceedings, Lunar Planetary Institute Provided by the NASA Astrophysics Data System, 9, 2311–2344

Huber, L., Gnos, E. et al. 2008. The complex exposure history of the Jiddat al Haraisa 073 L-chondrite shower. Meteorites & Planetary Science, 43, 1691–1708, https://doi.org/10.1111/j.1945-5100.2008.tb00637.x

Huss, G.R. and Lewis, R.S. 1994. Noble gases in presolar diamonds I: three distinct components and their implications for diamond origins. Meteoritics, 29, 791–810, https://doi.org/10.1111/j.1945-5100.1994.tb01994.x

Kallemeyn, G.W., Rubin, A.E., Wang, D. and Wasson, J.T. 1994. Ordinary chondrites: bulk compositions, classification, lithophile-element fractions and composition-petrographic type relationships. Geochimica et Cosmochimica Acta, 53, 2747–2767, https://doi.org/10.1016/0016-7037(94)90146-4

McLintock, W.F.P. and Ennos, F.R. 1922. On the structure and composition of the Strathmore meteorite. Mineralogical Magazine and Journal of the Mineralogical Society, 19, 323–329, https://doi.org/10.1180/minmag.1922.2019.98.02

Meteorite Bulletin, 110 (2021), https://www.lpi.usra.edu/meteor/about.php

Nesvorny, D., Vokrouhlicky, D., Morbidelli, A. and Bottke, W.F. 2009. Asteroidal source of L-chondrite meteorites. Icarus, 200, 698–701, https://doi.org/10.1016/j.icarus.2008.12.016

Prior, G.T. and Hey, M.H. 1923. Catalogue of Meteorites. British Museum, London.

Stuart, F.M., Harrop, P.J., Knott, S. and Turner, G. 1999. Laser extraction of helium isotopes from Antarctic micrometeorites: source of He and implications for the flux of extraterrestrial $^{3}He$ to Earth. Geochimica Cosmochimica Acta, 93, 2653–2665, https://doi.org/10.1016/S0016-7037(99)00161-1

Swindle, T.D. and Kring, D.A. 2008. Chronological evidence for the late heavy bombardment in ordinary chondrite meteorites. In: Workshop on the Early Solar System Impact Bombardment, 19–20 November 2008, Houston, Texas, 1439, 59–60, https://www.lpi.usra.edu/lpi/contribution_docs/LPI-001439.pdf

Terfel, F. and Schmitz, B. 2021. Asteroid break-ups and meteorite delivery to Earth: the past 500 million years. Proceedings of the National Academy of Sciences, 118, https://doi.org/10.1073/pnas.200977118

Van Schmus, W.R. and Wood, J.A. 1967. A chemical-petrological classification for the chondritic meteorites. Geochimica et Cosmochimica Acta, 31, 747–765, https://doi.org/10.1016/0016-7037(67)90030-9

Wieler, R. 2002. Cosmic-ray-produced noble gases in meteorites. Reviews in Mineralogy and Geochemistry, 47, 125–170, https://doi.org/10.2138/rmg.2002.47.5

Wieler, R., Anders, E., Baur, H., Lewis, R.S. and Signer, P. 1992. Characterisation of Q-gases and other noble gas components in the Murchison meteorite. Geochimica et Cosmochimica Acta, 56, 2907–2921, https://doi.org/10.1016/0016-7037(92)90367-R

Williams, A.J., Stuart, F.M., Day, S.J. and Phillips, W.M. 2005. Using pyroxcene microphenocrystals to determine cosmogenic $^{3}He$ concentrations in old volcanic rocks: an example of landscape development in central Gran Canaria. Quaternary Science Reviews, 24, 211–222, https://doi.org/10.1016/j.quascirev.2004.07.004