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1                                    Noble gases in Dome C micrometeorites -  
2                                    an attempt to disentangle asteroidal and cometary sources

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13  
14                                    **Abstract**

15                                    We have performed a comprehensive noble gas study, including the isotopes of krypton  
16                                    and xenon, on a set of micrometeorites (MMs) collected from surface snow at Dome C (DC)  
17                                    on the Antarctic plateau. He and Ne are generally dominated by a solar component, with  
18                                    lower <sup>4</sup>He concentrations and <sup>4</sup>He/<sup>20</sup>Ne ratios in crystalline (Xtal) compared to fine-grained  
19                                    carbonaceous (FgC) MMs. Concentrations of (surface-correlated) solar wind (SW) He and Ne  
20                                    in FgC MMs are at the high end of what has been seen in earlier work, whereas the  
21                                    abundances of (volume-correlated) Kr and Xe are similar to what has been found in previous  
22                                    studies of MMs. In most samples, isotopic ratios for Kr and Xe are in the usual range of Q-Kr  
23                                    and -Xe (the Q component is the dominating component in primitive macroscopic meteorites)  
24                                    and air. When quantifiable, cosmic ray exposure (CRE) ages based on cosmogenic <sup>21</sup>Ne and  
25                                    <sup>3</sup>He, in combination with the Poynting-Robertson effect, are broadly consistent with an origin  
26                                    of the MMs from the asteroid belt. An exception is an Xtal MM, which exhibits a cosmogenic  
27                                    <sup>21</sup>Ne concentration in agreement with an origin from beyond Saturn, consistent with a  
28                                    possible cometary origin. In addition, data for trapped noble gases in three (out of ten  
29                                    analyzed) DC MMs provide hints that these may be related to a cometary source. One sample,  
30                                    a fragment of a FgC MM, is of particular interest. This fragment exhibits a Xe composition,  
31                                    although with large analytical uncertainties, deficient in the heavy isotopes <sup>134</sup>Xe and <sup>136</sup>Xe.  
32                                    This is similar to the Xe isotopic pattern, probably related to cometary ice, measured by  
33                                    Rosetta in the coma of comet 67P/Churyumov-Gerasimenko. The same MM also has an  
34                                    unusually high <sup>36</sup>Ar/<sup>38</sup>Ar ratio, consistent with Rosetta's Ar measurement (in this case the  
35                                    latter having a large uncertainty). The other hints are for two MMs, of crystalline (Xtal) type,  
36                                    that show Ne similar to that found in laboratory analysis of refractory grains captured from  
37                                    comet 81P/Wild 2 by the Stardust mission. Additionally, a FgC/Xtal MM may contain excess  
38                                    <sup>3</sup>He, similar to what has been seen in some cluster interplanetary dust particles (cluster IDPs).

39  
40                                    Keywords: micrometeorites; noble gases; cosmic ray exposure; comets; asteroids

## 42 1. Introduction

43 The study of noble gases (and other volatiles) in micrometeorites is of interest for  
44 various reasons. One concerns the origin and evolution of the atmospheres of Earth and other  
45 inner solar system rocky planets, which is one of the outstanding questions in planetology. A  
46 variety of processes contributing the volatiles H, C, N and noble gases have been considered  
47 (e.g., Maurette et al., 2000; Trieloff et al., 2000; Pepin and Porcelli, 2002; Marty, 2012;  
48 Alexander et al., 2012; Albarède et al., 2013; Vogt et al., 2019; and references therein),  
49 including the possibility of accretion of volatile-rich materials by the forming planets. This  
50 infalling material may have been in form of planetesimals and/or interplanetary dust grains,  
51 from the outer asteroid belt, as well as cometary material from the outer solar system (Pepin,  
52 2006; Marty, 2012; Bradley et al., 2014). Recent models for the origin of Earth's atmosphere  
53 favor the contribution of a few percent of volatile-rich material, similar to carbonaceous  
54 chondrites, accounting for the bulk of the volatile inventory (Marty, 2012; Albarède et al.,  
55 2013), but the timing of such contribution is still a matter of debate. Some contribution from  
56 comets appears to be required based on recent analyses of volatiles in the coma of the Jupiter  
57 family comet (JFC) 67P/Churyumov-Gerasimenko (Marty et al., 2016, 2017).

58 Generally, one might expect that the contribution to the geochemical budget of the  
59 planets arising from infalling dust and planetesimals might be similar in composition to that  
60 from primitive meteorites. In fact, Marty (2012) proposes that the isotopic compositions of H,  
61 N, Ne and Ar of Earth's reservoirs can be explained by mixing of solar and chondritic end-  
62 members, with cometary contributions limited to a few percent. This was recently revisited  
63 with a model proposing an accretion of the Earth from enstatite-chondrite-like composition,  
64 with the need of later delivery of volatiles from an exogeneous source to account for the  
65 isotopic composition of the ocean water (Piani et al., 2020). However, "classical", i.e.  
66 macroscopic chondritic meteorites (i.e., with sizes in the range centimeter to meters) provide  
67 only a small contribution to the influx of extraterrestrial material to Earth, at least over the  
68 recent geological time scale. Instead, the dominant source of extraterrestrial material accreted  
69 by the Earth today is represented by micrometeorites (MMs) with sizes less than a mm (Love  
70 and Brownlee, 1993; Cremonese et al., 2012; Carrillo-Sánchez et al., 2020, Rojas et al., 2021).  
71 Such MMs can be recovered from polar ice and snow from Greenland and Antarctica  
72 (Maurette et al., 1991; Maurette et al., 2000; Taylor et al., 2000; Duprat et al., 2007; Rochette  
73 et al., 2008; Genge et al., 2018). Estimates for the present flux of micrometeorites before  
74 atmospheric entry are based on the study of hypervelocity impact craters on the Long  
75 Duration Exposure Facility (LDEF) spacecraft. From these, Love and Brownlee (1993)  
76 derived a total mass influx accreted by Earth of  $40 (\pm 20) \times 10^6$  kg per year, while a  
77 reevaluation of the LDEF data by Cremonese et al. (2012) suggests lower total mass influx  
78 rates, between  $7.4 (\pm 1.0)$  and  $4.2 (\pm 0.5) \times 10^6$  kg per year, the value depending on the  
79 assumed source - asteroidal or cometary. Estimates based on space observations and/or  
80 modelling have, among others, been published by Grün et al. (1985), Nesvorný et al. (2010)  
81 and, most recently, Carrillo-Sánchez et al. (2020). The latter yields a value of  $10.2 \times 10^6$  kg  
82 per year, and also provides estimates for fluxes to Mars of  $0.75 \times 10^6$  kg/year (surprisingly  
83 low in comparison to earlier estimates, e.g., Flynn, 1996) and for Venus of  $11.3 \times 10^6$  kg/year,  
84 respectively.

85 During their high velocity impact at Earth's atmosphere during entry, a portion of  
86 interplanetary particles is fully vaporized, while the remaining part survives as melted, partly  
87 melted and unmelted particles. Using Lidar observations of the vertical flux of mesospheric  
88 Na (originating from the vaporized part), Gardner et al. (2014) inferred an intermediate influx  
89 value (see this paper also for further estimates given in the literature). The fraction of the flux  
90 that survives as particles reaching Earth's surface has been measured in various collections,  
91 mainly from Antarctica. Values of  $\sim 1.6 \times 10^6$  kg were obtained from the amount of cosmic  
92 spherules recovered from the South Pole Water well (Taylor et al., 2012) and Transantarctic  
93 Mountains (Suttle and Folco, 2020), where the latter corresponds to an average over a  $\sim 10^6$   
94 year timescale. A measurement of the recent flux was performed at Dome C, using the  
95 collection from which the particles studied in this paper come from, by Rojas et al. (2021).  
96 The accurate control on the exposure parameter S (expressed in  $\text{m}^2$  times year) allowed to  
97 infer an annual flux of about  $5 \times 10^6$  kg, summing both melted (i.e. cosmic spherules) and un-  
98 melted (uMMs) particles (Rojas et al, 2021).

99 Carrillo-Sánchez et al. (2020) combined a chemical ablation model (CABMOD) with a  
100 Zodiacal Cloud Model (Zody), which also allowed to obtain separate predictions for the  
101 contributions from different sources: asteroidal, Jupiter-family comets (JFC) and Halley-type  
102 comets (HTC). In case of Earth (and Mars), their model predicts, in agreement with previous  
103 studies (Nesvorný et al., 2010), the dominant flux to be in form of unmelted MMs, and the  
104 dominant source to be comets, not only for the most fine-grained dust, but also in the size  
105 range of the MMs ( $\sim 200$   $\mu\text{m}$  diameter) that we studied in this work.

106 While MMs were initially mainly related to primitive CM-chondrite-like material based  
107 on mineralogical, chemical and isotopic studies, more diversity has become obvious as more  
108 micrometeorite collections were performed and extensively studied. A substantial fraction of  
109 the micrometeorite population (10 to 17%; Taylor et al., 2012; Cordier and Folco, 2014) may  
110 be similar to ordinary chondrites and related to asteroids (Genge, 2008; Cordier et al., 2011a;  
111 Suavet et al., 2011; van Ginneken et al., 2012; Imae et al., 2013; Noguchi et al., 2015; Shyam  
112 Prasad et al., 2018), while a smaller fraction (less than 6%) has been linked to differentiated  
113 asteroids such as the Vestoids (Taylor et al., 2007; Cordier et al., 2011b, 2012). There is also a  
114 specific family of MMs, the so-called ultra-carbonaceous micrometeorites (UCAMMs), that  
115 has a probable cometary origin. These particles, which have extremely high concentrations of  
116 carbon (Dartois et al., 2018), have been identified in collections from both Concordia Station  
117 (Dome C; Duprat et al., 2010) and Dome Fuji Station (Nakamura et al., 2005; Noguchi et al.,  
118 2015), and a cometary origin is inferred from their large deuterium excesses (Duprat et al.,  
119 2010) and the high nitrogen content of their organic matter (Dartois et al., 2013; Yabuta et al.,  
120 2017). Apparently, the diversity of micrometeorites is large, and selection effects may play a  
121 role in the assessment (Genge et al., 2020), since larger MMs are more easily found on Earth  
122 and easier to study. In any case, in the size range of the MMs that we have studied (Table 1),  
123 there should be a fair chance to encounter cometary (in particular, JFC) particles (Rojas et al,  
124 2021).

125 Based on an early set of data, Maurette et al. (2000) evaluated the possible contribution  
126 of micrometeorites to neon, organics, carbon dioxide, nitrogen and water on Earth and they

127 concluded that early accretion of primitive micrometeorites may have played a major role in  
128 the formation of the terrestrial atmosphere and oceans. In a more recent evaluation, Vogt et al.  
129 (2019) conclude that interplanetary particles (IDPs) and micrometeorites (MMs) may very  
130 well be an important source of Earth's neon (both interior and atmospheric). However, a  
131 crucial ingredient in these estimates is the pre-Archean micrometeorite flux that has to be  
132 extrapolated from the present-day flux with an uncertainty that is still a matter of debate.

133 Another aspect of noble gases in MMs is that they may possibly allow to distinguish  
134 between asteroidal and cometary sources, as the relative contribution of each source to dust  
135 entering the terrestrial atmosphere is still an open question. A difficulty, in this respect, is that  
136 Ne and He, in (unmelted) small particles that travelled through interplanetary space, are  
137 generally dominated by implanted solar wind components. This has been demonstrated in  
138 numerous studies, as, in fact, most studies of noble gases in MMs have concentrated on He  
139 and/or Ne only (see summary in Wieler, 2002a). Still, sometimes small excesses of  $^{21}\text{Ne}$  of  
140 cosmogenic origin have been observed, which allow, in combination with the Poynting-  
141 Robertson effect (Wyatt and Whipple, 1950) estimating a cosmic ray exposure age and  
142 inferring the place of origin. Using this approach, Trappitsch and Leya (2013) have re-  
143 examined the data available at the time and found three MMs that may have come from  
144 orbital distances far beyond the asteroidal belt, i.e. of possible cometary origin. This is,  
145 provided all cosmic ray exposure happened while the MMs were travelling as small particles.  
146 However, as the authors note, it is difficult to rule out that much or even most of the exposure  
147 occurred in a parent body regolith instead.

148 Less ambiguous would be signatures of trapped noble gas components. In case of an  
149 IDP ("Manchanito") the isotopic composition of Ne has been found to resemble Q-Ne (where  
150 Q is the major host phase of Ar, Kr and Xe – though not of Ne – in primitive meteorites).  
151 Since cometary Ne measured in samples returned by the Stardust mission (Marty et al., 2008)  
152 also resembles Q-Ne in composition, this has been taken as an indication for a cometary  
153 origin of this particle (Ogliore et al., 2020). Compared to He and Ne, the situation may be  
154 more favorable for the heavier noble gases, in particular Xe. There are clear differences  
155 between the composition of the trapped (i.e., non-radiogenic, non-cosmogenic) noble gas  
156 component in meteorites and the atmospheres of Earth and Mars, the solar wind and,  
157 apparently, also cometary noble gas. Compared to solar abundance ratios, trapped noble gases  
158 in primitive meteorites (the "planetary" component) are characterized by an elemental  
159 abundance pattern strongly favoring the heavy over the light noble gases. Similarly, in  
160 comparison to terrestrial and Martian atmospheres, marked differences appear, in particular in  
161 the Kr/Xe ratio and the isotopic composition of Xe (see, e.g., discussions in Ott and  
162 Begemann, 1985; Pepin, 1991; Owen et al., 1992; Owen and Bar-Nun, 1993; Owen, 2008;  
163 Ott, 2014; Ott et al., 2019). These differences cannot be explained by simple mixing of  
164 "planetary" and solar noble gases, unless some additional processing is invoked (e.g., Hébrard  
165 and Marty, 2014). Of particular interest here is the isotopic composition of Xe measured by  
166 the Rosetta spacecraft in the coma of JFC 67/P Churyumov-Gerasimenko (Marty et al., 2017),  
167 which is characterized by a unique pattern exhibiting a spectacular relative deficit of the two  
168 heaviest isotopes,  $^{134}\text{Xe}$  and  $^{136}\text{Xe}$ , by roughly 30 and 60 %, respectively, compared to  
169 common components. Identification in a MM would be an indication that it originated from a

170 parent body similar to 67/P-CG, more telling than the presence of Q-Ne, which appears also  
171 in primitive meteorites. Evidence for cometary Xe on the Moon may have been seen by  
172 Bekaert et al. (2017) and Pernet-Fisher et al. (2020), but the situation is complicated by the  
173 presence of contaminating (terrestrial) air and solar wind Xe. Modeling the Xe isotopic  
174 composition these authors measured in lunar anorthosites required, in addition to solar wind  
175 and air, a contribution from a component deficient in the heavy isotopes of Xe, such as in  
176 cometary (coma) Xe. While the origin of this Xe is not clear, one possibility is that it was  
177 introduced by micrometeorite impacts. Still, it is important to realize that Rosetta and Stardust  
178 sampled different types of cometary reservoirs, in addition to sampling different comets. Xe  
179 in the cometary coma measured by Rosetta corresponds to that carried in ices (maybe  
180 primarily the CO<sub>2</sub> fraction; Rubin et al., 2018), while Q-Ne was measured in solids captured  
181 from the cometary coma in the aerogel targets of the Stardust mission.

182 Previous studies of MMs including Ar and/or Kr and Xe are rare, see Marty et al. (2002,  
183 2005), Osawa and Nagao (2002a), Osawa et al. (2000, 2003a, b, 2010) and Okazaki et al.  
184 (2015). Among these, Osawa et al. (2003a, 2010) focused on cosmic spherules where noble  
185 gas abundances were close to blank level in most cases. For the isotopes of Kr and Xe, fairly  
186 precise data were obtained (in addition to data for He, Ne, Ar) by Sarda et al. (1991) on a  
187 single large (230 µg) micrometeorite. Other results for the isotopes of Kr and Xe are reported  
188 in Osawa et al. (2000) and Osawa and Nagao (2002a, b), whose data, however, do not include  
189 the isotopes lighter than <sup>82</sup>Kr and <sup>129</sup>Xe. More recently, a few micrometeorite analyses were  
190 included within an integrated study on Xe in Interplanetary Dust Particles by Spring (2014),  
191 using the Relax (Refrigerator Enhanced Laser Analyzer for Xenon) instrument at Manchester  
192 University (UK) (Gilmour et al., 1994; Crowther et al., 2008). Further results for Xe isotopes  
193 in a few large unmelted Antarctic Cap-Prudhomme micrometeorites (Maurette, 2006) were  
194 reported in an abstract by Olinger et al. (2013). In a previous study, we reported a full set of  
195 noble gas data in micrometeorites from the Transantarctic Mountains (Cordier et al., 2018;  
196 Baecker et al, 2018). These micrometeorites accumulated since about a million years ago  
197 (Rochette et al., 2008; Folco et al., 2008) and were relatively large (several hundred µm).  
198 Here we report new results on a set of recently fallen, i.e. recovered from surface snow, MMs  
199 from the Concordia collection (Duprat et al., 2007), with sizes of typically ~200 µm. We also  
200 include results for a single MM from Cap Prudhomme (Maurette et al., 1991; Kurat et al.,  
201 1994).

202

## 203 **2. Experimental Procedures**

### 204 **2.1. Dome C samples**

205 Except for the one MM from Cap Prudhomme (Kurat et al., 1994), the analyzed  
206 samples are part of the Concordia collection. They were collected at the Concordia station, a  
207 station jointly constructed by the French and Italian Polar Institutes, which is located at Dome  
208 C, about 3200 m above sea level on the Antarctic plateau, and about 1100 km from the coast  
209 of Adélie land. For details about the collection protocol see Duprat et al. (2007).

210           Before allocation for noble gas analysis, the MMs had been stored under vacuum  
211 conditions and had been handled in a clean room. During selection, the samples were  
212 observed under higher magnification (115 x) and sizes of the allocated specimens were  
213 determined using a stereo-microscope with a  $\mu\text{m}$ -scale as a reference. Roughly 1/3 of each (by  
214 volume) of a given MM was allocated for noble gas analysis at the Max-Planck-Institute for  
215 Chemistry (MPIC) in Mainz, while the remaining sample was kept at IJCLab (Orsay). The  
216 weights of the fragments for noble gas analysis were calculated using the approximate volume  
217 (assuming sphere or cone-head shape) and a density of  $\sim 2.1 \text{ g/cm}^3$ , as appropriate for CM and  
218 CI chondrites (Britt and Consolmagno, 2003). After selection and size measurements, the  
219 samples were deposited between two glass slides and transported to the MPIC.

220

221 Table 1. Dome C (DC) and Cap Prudhomme (CP) MMs analyzed for noble gases.

particle	fragment #*	size [ $\mu\text{m}$ ]	weight [ $\mu\text{g}$ ]	class <sup>§</sup>
<b>Dome C</b>				
DC 06_07_213	PL 09_20 3 (1)	97 x 91	~ 1.1	Xtal
DC 06_08_01	PL06_09A 1	110 x 92	~ 1.4	Xtal
DC 06_09_11	PL 07_01A 11	137 x 111	~ 1.3	FgC/Sc
DC 06_09_50	PL 07_02B 2	141 x 134	~ 3.3	FgC
DC 06_09_57	PL07_02B 9 (1)	74 x 36	~ 0.15	FgC
DC 06_09_57	PL07_02B 9 (2)	19 x 18	~ 0.01	FgC
DC 06_09_63	PL07_02C 3	198 x 141	~ 3.3	FgC/Xtal
DC 06_09_141	PL07_04C 9 (1)	84 x 79	~ 0.7	Xtal
DC 06_09_149	PL07_05A 5 (1)	85 x 60	~ 0.3	Xtal
DC 06_09_189	PL07_06A 9	93 x 92	~ 1.0	FgC/Sc
<b>Cap Prudhomme</b>				
CP 9-1-1994	PL 10-109-D9	252 x 188	~ 6.2	Sc

222 \*Material available for noble gas analysis often consisted of several fragments. Where not the  
 223 complete material was used, the fragment number is given in parentheses. The approximate  
 224 weight was calculated as described in the text.

225 <sup>§</sup>Xtal = crystalline; FgC = fine-grained carbonaceous; Sc = scoriaceous.

226

227 Table 1 gives basic information about the analyzed samples. The respective sample  
 228 name for each Dome C sample consists of the following combination: DC (Dome C) 06 (year  
 229 2006) 09 (number of the nylon filter where the particle was selected from) 247 (number of  
 230 particle). Each particle was fragmented in a dedicated glass holder labelled, e.g., PL07  
 231 (year)\_02B (glass holder) 7 (hole position). The Cap Prudhomme (CP) sample has a similar  
 232 code system. For the noble gas work, we concentrated on unmelted MMs since these are most  
 233 likely to have retained original noble gas signatures. The classification in Table 1 follows  
 234 Kurat et al. (1994), Engrand and Maurette (1998) and Genge et al. (2008): FgC = fine-grained  
 235 carbonaceous, Xtal =crystalline (consisting of coarse-grained anhydrous minerals). Only the  
 236 CP sample is scoriaceous, with two additional DC samples (DC 06\_09\_11 and DC  
 237 06\_09\_189) partly scoriaceous.

## 238 2.2. Noble gas analysis

239 Details of our procedures for noble gas analysis of MMs at MPIC, Mainz, are given in  
 240 our reports on MMs from the Transantarctic Mountains (Baecker et al., 2018; Cordier et al.  
 241 2018) and in the PhD thesis of B. Baecker (Baecker, 2014). In short, in view of the expected  
 242 low gas amounts, a newly dedicated system was set up at MPIC that differs from our  
 243 conventional systems (e.g., Schwenzer et al., 2007; Cartwright et al., 2014) primarily by two  
 244 features: a) Laser heating for gas extraction in order to minimize extraction blank; and b) a  
 245 high sensitivity Noblesse noble gas mass spectrometer (Nu Instruments) with multiple ion  
 246 counting (MIC; 8 channeltrons, plus a Faraday cup for larger signals) for simultaneous  
 247 isotope measurements, which maximizes the number of detected ions. This system requires



248 cross-calibration of the detectors and (minor) correction for cross talk, as described in  
249 Baecker et al. (2018).

250 Gas extraction was accomplished by heating with a 30 Watt CO<sub>2</sub> IR laser system (MIR  
251 10-30, New Wave Research), after which the released gases were cleaned using successive  
252 exposures to Zr-Al SAES getters. They were separated into He plus Ne, Ar, Kr and Xe  
253 fractions, respectively, using temperature-controlled activated charcoal, and sequentially  
254 admitted to the mass spectrometer for analysis. Full multi-ion collection (MIC) was used for  
255 Kr and Xe only, where, for Xe, we used a three-step measurement routine (Baecker, 2014;  
256 Baecker et al., 2018). In case of Ar, isotopes <sup>36</sup>Ar and <sup>38</sup>Ar were measured on the central  
257 channeltron (IC3), while <sup>40</sup>Ar was measured using the Faraday cup. Similarly, <sup>4</sup>He was mostly  
258 measured by Faraday detector, while the <sup>3</sup>He signal was detected on IC3. As for Ne, all  
259 isotopes of Ne as well as mass 18 (water, used for correction at <sup>20</sup>Ne) were measured using IC  
260 3. Masses 40 and 44, which were also used for interference correction, were measured by  
261 MIC using IC0 and IC6.

262 The DC samples were measured following the measurement of the TAM MMs (Baecker  
263 et al., 2018), at which time extraction blanks had become lower and more stable. Including  
264 interfering non-noble gas contributions at the respective masses, they were, in cm<sup>3</sup> STP,  
265 approximately as follows: <sup>3</sup>He: 2x10<sup>-15</sup>, <sup>4</sup>He: 6x10<sup>-12</sup>, <sup>20</sup>Ne: 4x10<sup>-13</sup>, <sup>22</sup>Ne: 7x10<sup>-14</sup>, <sup>36</sup>Ar: 4x10<sup>-</sup>  
266 <sup>13</sup>, <sup>40</sup>Ar: 1.0x10<sup>-10</sup>, <sup>84</sup>Kr: 1x10<sup>-14</sup> and <sup>132</sup>Xe: 3x10<sup>-15</sup>.

267 Interference corrections were applied at mass 3 for interference from not fully resolved  
268 HD/H<sub>3</sub>, at the Ne isotopes for <sup>1</sup>H<sub>2</sub><sup>18</sup>O as well as doubly charged <sup>40</sup>Ar and CO<sub>2</sub>, and at the Ar  
269 isotopes <sup>36</sup>Ar and <sup>38</sup>Ar for HCl and hydrocarbons. These corrections were generally minor.  
270 Sensitivity and instrumental mass discrimination were determined by intermittent analyses of  
271 a noble gas mixture (obtained from *Air Liquide*) with atmospheric isotopic composition, to  
272 which extra <sup>3</sup>He had been added resulting in <sup>3</sup>He/<sup>4</sup>He ~5x10<sup>-4</sup>. Errors in all the corrections are  
273 included in the reported (1σ) uncertainties.

274

## 275 **3. Results**

### 276 **3.1. Helium and neon**

277 The results for He and Ne are reported in Tables 2 and 3. Similar as in previous  
278 micrometeorite studies, the abundances of the major isotopes <sup>4</sup>He and <sup>20</sup>Ne are dominated by  
279 solar wind. No helium was detected in the two fragments of DC 06\_09\_57, while in two cases  
280 (DC 06\_09\_141 and DC 06\_09\_189) we found <sup>4</sup>He, but <sup>3</sup>He was indistinguishable from  
281 background. The data for those MMs, where both isotopes were detected, are displayed in  
282 Fig. 1, a plot of <sup>3</sup>He/<sup>4</sup>He in 10<sup>-4</sup> units versus <sup>4</sup>He in cm<sup>3</sup> STP/g, alongside with the results from  
283 previous studies and reference compositions (see figure caption for references). Separately  
284 shown are the data from our previous analyses of the (larger) TAM MMs (Baecker et al.,  
285 2018; Cordier et al., 2018) and the (smaller) IDP Manzanito of Oglione et al. (2020), which is  
286 of interest in the later discussion (chapter 4.5).

287 The isotopic ratios are broadly similar to previous studies, and also concentrations are  
288 within the range previously observed. Again, as noted before, solar wind He is present not  
289 only in unmelted MMs but also in such that have been partially molten (Sc = scoriaceous).  
290 Interestingly, there is a clear distinction between Dome C MMs that are classified as Xtal  
291 (crystalline) and others classified as FgC (= fine grained), FgC/Sc and FgC/Xtal. The highest  
292  $^4\text{He}$  concentrations are those of DC 06\_09\_189 (FgC/Sc) followed by DC 06\_09\_50 (FgC)  
293 and DC 06\_09\_63 (FgC/Xtal), which are among the highest reported so far. Not surprisingly,  
294 Xtal MMs with low  $^4\text{He}$  concentrations show high  $^3\text{He}/^4\text{He}$  ratios, distinctly higher than in all  
295 the trapped components shown, which is a clear indication for the presence of cosmogenic  
296  $^3\text{He}$  sited more retentively (volume-correlated) than solar wind He (surface-correlated).  
297 Conversely, the more gas-rich samples show  $^3\text{He}/^4\text{He}$  ratios similar to the trapped components  
298 expected to be present, and it is difficult to assess the presence of cosmogenic He in these  
299 cases. An exception may be FgC/Xtal DC 06\_09\_63, where the ratio is only slightly below  
300 that of unfractionated trapped solar wind (see chapters 3.4 and 4.4).

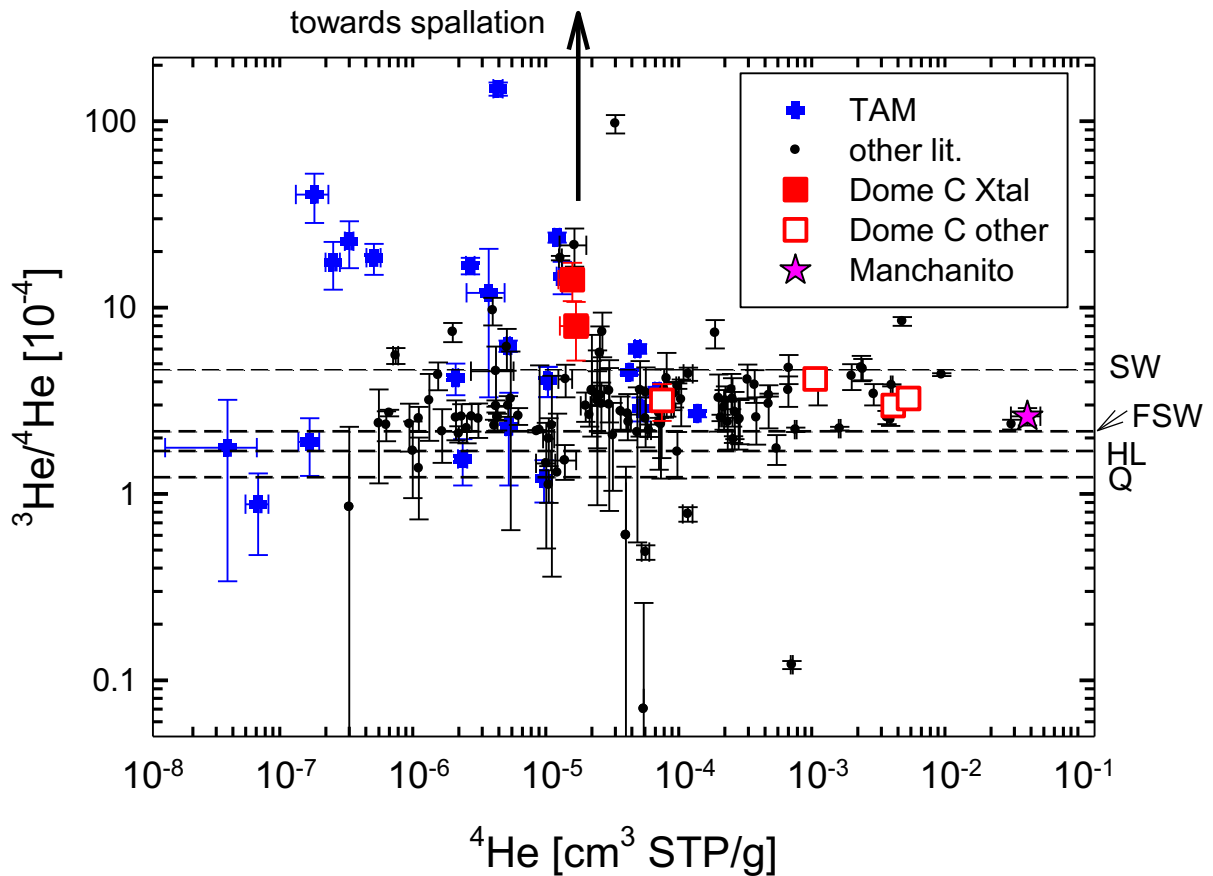
301 The results for Ne are presented in Table 3. For the two fragments from DC 06\_09\_57,  
302 we obtained only upper limits, otherwise amounts of  $^{22}\text{Ne}$  for the DC MMs range between  $\sim 5$   
303  $\times 10^{-13}$   $\text{cm}^3$  STP and  $\sim 4 \times 10^{-12}$   $\text{cm}^3$  STP (concentrations between  $\sim 3 \times 10^{-7}$   $\text{cm}^3$  STP/g and  $\sim 7$   
304  $\times 10^{-6}$   $\text{cm}^3$  STP/g). The scoriaceous MM from Cap Prudhomme is lower ( $2 \times 10^{-13}$   $\text{cm}^3$  STP  
305 and  $3 \times 10^{-8}$   $\text{cm}^3$  STP/g, resp.). Isotopic  $^{20}\text{Ne}/^{22}\text{Ne}$  ratios are  $>11$ , which clearly indicates  
306 substantial to dominant contributions from solar wind (SW and/or FSW). This is graphically  
307 shown in the three-isotope plot of Fig. 2. Fig. 2a compares our DC and CP data with previous  
308 results for MMs (see Figure Caption for references). Like for most of the previous studies, the  
309 data points plot roughly in the region between unfractionated solar wind (SW) and other  
310 trapped components with lower  $^{20}\text{Ne}/^{22}\text{Ne}$  (Ne-B, fractionated solar wind = FSW, Q, EA).  
311 Contributions from cosmogenic Ne are small and difficult to establish precisely, if at all  
312 (chapters 3.4 and 4.4). Again, this is typical for most MMs. Only in a few cases, in particular  
313 for the scoriaceous MMs with low concentrations of solar Ne in our earlier TAM MM study  
314 (Baecker et al., 2018; Cordier et al, 2018), a clear shift to higher  $^{21}\text{Ne}/^{22}\text{Ne}$  has been observed.

315

316 Table 2. He results for 10 different DC MM samples from 9 different MMs; as well as an additional  
 317 MM from Cap Prudhomme. Uncertainties in the last digits ( $1\sigma$ ) are shown in parentheses and do not  
 318 include errors in sample weight. Where upper limits are listed, these are  $2\sigma$ . For comparison, the  
 319 isotopic compositions of solar wind (SW), “fractionated solar wind” (FSW), Earth atmosphere (EA)  
 320 and the primordial components Q (P1) and HL are listed at the bottom.

Sample	particle #	$^3\text{He}$	$^4\text{He}$	$^3\text{He}$	$^4\text{He}$	$^3\text{He}/^4\text{He}$
		( $10^{-14}$ cm <sup>3</sup> STP)	( $10^{-12}$ cm <sup>3</sup> STP)	( $10^{-8}$ cm <sup>3</sup> STP/g)	( $10^{-6}$ cm <sup>3</sup> STP/g)	( $10^{-4}$ )
DC 06_07_213	PL 09_20 3 (1)	1.3 (3)	16.2 (3.9)	1.22 (28)	15.2 (3.7)	7.96 (2.76)
DC 06_08_01	PL06_09A 1	2.8 (3)	19.5 (3.9)	2.01 (27)	14.2 (3.0)	14.1 (3.3)
DC 06_09_11	PL 07_01A 11	2.8 (6)	86.7 (4.2)	2.13 (46)	67.1 (3.3)	3.18 (71)
DC 06_09_50	PL 07_02B 2	363 (15)	12150 (188)	109.9 (4.6)	3682 (57)	2.98 (12)
DC 06_09_57	PL07_02B 9 (1)	< 0.5	< 10	< 3.6	< 64	--
DC 06_09_57	PL07_02B 9 (2)	--	< 9	--	< 1141	--
DC 06_09_63	PL07_02C 3	131 (10)	3152 (57)	39.6 (2.9)	955 (17)	4.14 (30)
DC 06_09_141	PL07_04C 9 (1)	--	8.7 (4.3)	--	12.4 (6.1)	--
DC 06_09_149	PL07_05A 5 (1)	--	47.9 (4.3)	--	160 (14)	--
DC 06_09_189	PL07_06A 9	156 (3)	4799 (68)	156.3 (3.2)	4799 (68)	3.26 (9)
CP 9-1-1994	PL 10-109-D9	< 3.2	8.86 (5.67)	< 0.52	1.4 (9)	--
Component	References	$^3\text{He}/^4\text{He}$ ( $10^{-4}$ )				
SW	[1]	4.645 (8)				
"FSW"	[2], [3]	2.17 (5)				
Q (P1)	[4]	1.23 (2)				
EA	[5]	0.0140 (1)				
HL	[6]	1.70 (10)				

321 References: [1] Heber et al. (2012); [2] Benkert et al. (1993); [3] Wieler (2002a); [4] Busemann et al. (2000); [5] Ozima and Podosek  
 322 (2002); [6] Huss and Lewis (1994); Note: For more information regarding “FSW” see Wieler et al. (2007).



323

324 Figure 1. The ratio  ${}^3\text{He}/{}^4\text{He}$  in  $10^{-4}$  units is plotted vs.  ${}^4\text{He}$  concentration in  $\text{cm}^3$  STP/g for  
 325 Dome C micrometeorites. Error bars are  $1\sigma$ . Data from our previous work on TAM MMs  
 326 (Baecker et al., 2018; Cordier et al., 2018) are shown for comparison, as well as data for other  
 327 MMs from the literature (“other lit.”): Cap Prudhomme MMs extracted from ice, from Stuart  
 328 et al. (1999) and Marty et al. (2005); MMs extracted from snow at Dome Fuji (Osawa et al.,  
 329 2000; Osawa and Nagao, 2002a; Okazaki et al., 2015); MMs extracted from ice near the  
 330 Yamato Mountains (Osawa and Nagao, 2002b; Osawa et al. 2003b); a large MM from  
 331 Greenland (Sarda et al., 1991); and the partially melted “cosmic spherule M240410 from  
 332 Osawa et al. (2010). Otherwise, data for cosmic spherules are not included. Note also that this  
 333 plot is somewhat biased since MMs with either  ${}^3\text{He}$  or  ${}^4\text{He}$  below detection limit are not  
 334 included. For reference the  ${}^3\text{He}/{}^4\text{He}$  ratios of SW (Heber et al., 2012), “FSW” (Benkert et al.,  
 335 1993; Wieler et al., 2007), Q (Busemann et al., 2000) and the HL component observed in  
 336 meteoritic nanodiamond residues (Huss and Lewis, 1994) are shown. Spallation He is  
 337 characterized by much higher  ${}^3\text{He}/{}^4\text{He}$  ( $\sim 0.2$ ; e.g. Wieler, 2002b) than observed here, while  
 338  ${}^3\text{He}/{}^4\text{He}$  in the terrestrial atmosphere ( $1.4 \times 10^{-6}$ ) is lower.

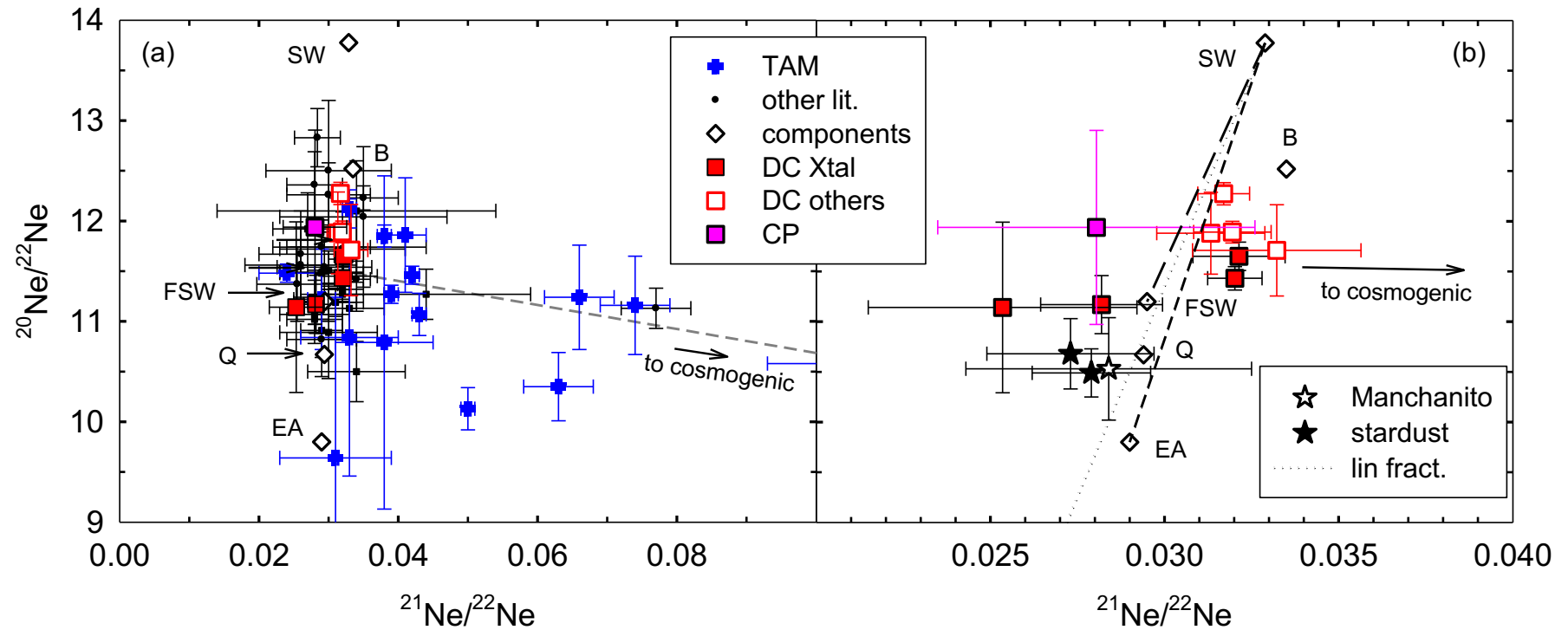
339

340 Table 3. Ne and Ar results for 10 different DC MM samples from 9 different MMs as well as an additional MM from Cap Prudhomme. Uncertainties  
 341 in the last digits ( $1\sigma$ ) are given in parentheses. Where upper limits are given, these are  $2\sigma$ . For comparison, the compositions of solar wind (SW),  
 342 “fractionated solar wind” (FSW), Earth atmosphere (EA) and the primordial components Q (P1) and HL are listed at the bottom.

sample	particle #	$^{22}\text{Ne}$ [ $10^{-12}$ cm $^3$ STP]	$^{22}\text{Ne}$ [ $10^{-8}$ cm $^3$ STP/g]	$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$	$^{36}\text{Ar}$ [ $10^{-12}$ cm $^3$ STP]	$^{36}\text{Ar}$ [ $10^{-8}$ cm $^3$ STP/g]	$^{40}\text{Ar}$ [ $10^{-6}$ cm $^3$ STP/g]	$^{38}\text{Ar}/^{36}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$
DC 06_07_213	PL 09_20 3 (1)	0.83 (3)	77.58 (7.76)	11.17 (29)	0.028 (2)	2.79 (34)	261 (32)	528 (65)	0.1841 (33)	202 (5)
DC 06_08_01	PL06_09A 1	3.22 (5)	234.9 (17.6)	11.43 (12)	0.032 (1)	2.61 (32)	190 (23)	37 (21)	0.2051 (38)	19.7 (10.8)
DC 06_09_11	PL 07_01A 11	0.52 (3)	40.62 (3.82)	11.71 (45)	0.033 (2)	2.14 (27)	165 (21)	178 (27)	0.1906 (41)	107 (9)
DC 06_09_50	PL 07_02B 2	3.89 (6)	117.8 (4.0)	12.27 (11)	0.032 (1)	19.7 (2.1)	596 (65)	181 (25)	0.1935 (23)	30.4 (2.6)
DC 06_09_57	PL07_02B 9 (1)	< 0.07	< 46.91	--	--	0.299 (132)	199 (88)	473 (22)	0.1726 (189)	237 (34)
DC 06_09_57	PL07_02B 9 (2)	< 0.07	< 771	--	--	2.98 (14)	37238 (1792)	76020 (4009)	0.1495 (39)	204 (4)
DC 06_09_63	PL07_02C 3	1.76 (10)	53.22 (3.56)	11.88 (41)	0.031 (2)	10.8 (4)	327 (14)	557 (30)	0.1830 (20)	170 (6)
DC 06_09_141	PL07_04C 9 (1)	0.22(2)	31.66 (5.69)	11.14 (85)	0.025 (4)	0.512 (132)	73.2 (18.8)	104 (31)	0.1731 (116)	142 (23)
DC 06_09_149	PL07_05A 5 (1)	2.06 (4)	688.0 (229.7)	11.65 (14)	0.032 (1)	8.64 (21)	2881 (70)	162 (108)	0.1863 (36)	5.62 (3.76)
DC 06_09_189	PL07_06A 9	3.09 (5)	309.1 (31.4)	11.89 (11)	0.032 (1)	14.6 (3)	1458 (31)	3177 (74)	0.1848 (36)	218 (2)
CP 9-1-1994	PL 10-109-D9	0.18 (3)	2.89 (52)	11.94 (97)	0.028 (5)	1.16 (5)	18.7 (8)	9.77 (72)	0.1719 (177)	52.1 (3.2)
component	references			$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$				$^{38}\text{Ar}/^{36}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$
SW	[1]			13.777 (10)	0.03289 (7)				0.183 (1)	
"FSW"	[2, 3]			11.2 (2)	0.0295 (5)				0.205 (2)	
Q (P1)	[4]			10.67 (2)	0.0294 (10)				0.187 (1)	
EA	[5, 6]			9.80	0.029				0.1885 (3)	298.56 (31)
HL	[7]			8.50 (6)	0.036 (1)				0.227 (3)	

343 References: [1] Heber et al. (2012); [2] Benkert et al. (1993); [3] Wieler (2002a); [4] Busemann et al. (2000), the  $^{20}\text{Ne}/^{22}\text{Ne}$  ratio is the mean for Q-Ne from Allende, Murchison,  
 344 Grosnaja and Chainpur; [5] Eberhardt et al. (1965); [6] Lee et al. (2006); [7] Huss and Lewis (1994); Note: For more information regarding “FSW” see Wieler et al. (2007).

345



346

347 **Figure 2:** Three isotope plots of  $^{20}\text{Ne}/^{22}\text{Ne}$  vs.  $^{21}\text{Ne}/^{22}\text{Ne}$ . Crystalline (Xtal) and other DC MMs are distinguished by different symbols. Error bars are  $1\sigma$ .  
 348 Plotted for reference are the trapped compositions SW (Heber et al., 2012), Ne-B (Black and Pepin, 1969), “FSW” (Benkert et al., 1993 and Wieler et al.,  
 349 2007), Q (P1) (Busemann et al., 2000), Earth atmosphere (EA) (Eberhardt et al., 1965), and HL (Huss and Lewis, 1994).

350 a) For comparison, MM data from Dome Fuji (Osawa et al., 2000; Osawa and Nagao 2002a; Okazaki et al. 2015) and from the Yamato ice field (Osawa  
 351 and Nagao, 2002b; Osawa et al., 2003b) are included, as well as such from our earlier report on MMs from the Transantarctic Mountains (TAM: separate  
 352 symbols; Baecker et al., 2018). In order not to clutter the diagram, only literature data with an error of less than 0.5 in the  $^{20}\text{Ne}/^{22}\text{Ne}$  ratio are shown. Some  
 353 scoriaceous TAM MMs fall outside the plotted range, shifted towards a cosmogenic composition.

354 b) More detailed view of the DC MMs. Mixing lines SW-FSW and SW-EA, and the mass fractionation line (linear law) originating at the solar wind  
 355 composition (Heber et al., 2012) are shown for reference, furthermore the composition measured for the IDP Manchanito (Ogliore et al., 2020) and the  
 356 two more precise analyses of stardust track 41, aerogel cell C2044 (St-1 and Thera-2; Marty et al., 2008).

357 Fig. 2b shows the range between  $^{21}\text{Ne}/^{22}\text{Ne} = 0.02$  and  $0.04$  in more detail and  
358 concentrates on the samples of this study. Interestingly, as for He, there is a distinction  
359 between the MMs classified as Xtal and the others. The latter (i.e., the non-Xtal), together  
360 with two of the Xtal MMs, show higher  $^{20}\text{Ne}/^{22}\text{Ne}$  than the other two crystalline MMs.  
361 Compared to mixing lines between SW and FSW or EA, and also compared to compositions  
362 for (linearly) mass fractionated SW, these MMs show a small shift towards elevated  
363  $^{21}\text{Ne}/^{22}\text{Ne}$ , indicative of small cosmogenic contributions. On the other hand, Xtal DC  
364 06\_07\_213 and Xtal 06\_09\_141 (as well as, with large error, the CP MM) plot to the left of  
365 these lines. Their position is similar, although at somewhat higher  $^{20}\text{Ne}/^{22}\text{Ne}$ , to what has been  
366 observed for the IDP Manchanito (Ogliore et al., 2020) and in the two more precise analyses  
367 of cometary Ne in stardust track 41, aerogel cell C2044 (Marty et al., 2008). The significance  
368 of these observations will be discussed in chapter 4.5.

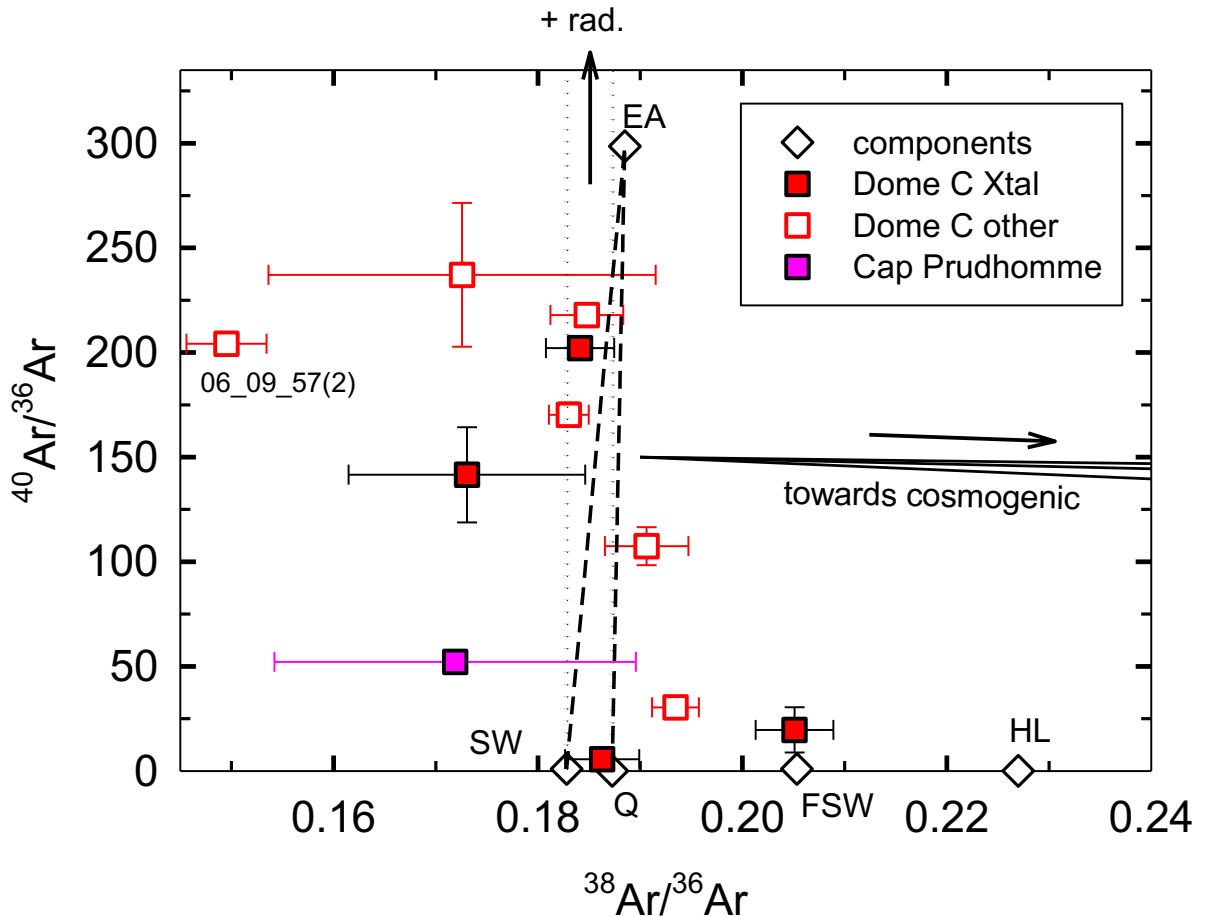
### 369 3.2. Argon

370 Results for Ar are given in Table 3 and depicted in a three-isotope plot of  $^{40}\text{Ar}/^{36}\text{Ar}$  vs.  
371  $^{38}\text{Ar}/^{36}\text{Ar}$  (Fig. 3). Except for the special case of DC 06\_09\_ (see below), all of our MMs contain  
372 substantial concentrations of  $^{36}\text{Ar}$  ( $\sim 7 \times 10^{-7}$  to  $\sim 3 \times 10^{-5}$  cm<sup>3</sup> STP/g), along with  $^{40}\text{Ar}/^{36}\text{Ar}$   
373 below the air ratio, thus clearly of extraterrestrial origin. Ratios of  $^{40}\text{Ar}/^{36}\text{Ar}$  range from  $\sim 6$   
374 (Xtal DC 06\_09\_149) up to  $\sim 218$  (Fg/Sc DC 06\_189). The former is also characterized by the  
375 highest concentration of (extraterrestrial)  $^{36}\text{Ar}$ , while the higher ratio for the latter may not be  
376 surprising, since it is partly scoriaceous, and because scoriaceous MMs are more likely to be  
377 contaminated by air Ar (Baecker et al., 2018).

378 Ratios of  $^{20}\text{Ne}/^{36}\text{Ar}$  are in the range 2 to 5, with the exception of DC 06\_08\_01 ( $\sim 14$ ).  
379 This is much lower than in the solar wind ( $\sim 42$ ; Heber et al., 2012; Vogel et al., 2009) and only  
380 the latter value is similar to what we have previously estimated for FSW ( $\sim 12$ ; Baecker et al.,  
381 2018; based on data from Benkert et al., 1993). It appears likely, therefore that for Ar, besides  
382 the solar wind contribution, there are also contributions from air and/or from primordial trapped  
383 components such as Q. However, the implied extent depends very much on how strongly  
384 fractionated the Ne/Ar ratio of the solar component is. This conclusion is borne out by the  
385 position of the data points in Fig. 3, where several (with small errors) in  $^{38}\text{Ar}/^{36}\text{Ar}$  plot close to  
386 the composition of SW, perhaps slightly shifted towards air/Q. A few are further enhanced in  
387 this ratio, in particular DC 06\_08\_01. Presence of cosmogenic  $^{38}\text{Ar}$  would offer an explanation,  
388 in principle, but this appears unlikely by comparison with the concentration of cosmogenic  $^{21}\text{Ne}$   
389 (chapter 3.4). Notably,  $^{38}\text{Ar}/^{36}\text{Ar}$  for this MM happens to agree with that of pure FSW.

390 There are four cases where  $^{38}\text{Ar}/^{36}\text{Ar}$  is lower than in SW, which has the lowest value  
391 among the reference compositions that are shown. Three of them have very large uncertainties  
392 and within  $1\sigma$  overlap with SW, so we do not take this as significant. The fourth case is the  
393 second specimen from DC 06\_09\_57 (labeled in Fig. 3), which we omitted in the discussion  
394 above. This sample has by far the highest nominal concentration of  $^{36}\text{Ar}$  of  $\sim 3.7 \times 10^{-4}$  cm<sup>3</sup>  
395 STP/g – note that this has been the smallest analyzed sample by far and that uncertainties in  
396 sample weight are not included in the errors given in Table 3. As it happens, the combination  
397 of  $^{38}\text{Ar}/^{36}\text{Ar}$  and  $^{40}\text{Ar}/^{36}\text{Ar}$  could also result from mass-fractionated air Ar (with, possibly, a  
398 small addition of radiogenic  $^{40}\text{Ar}$ ), but the mass fractionation would have to be enormous and

399 would have to favor the light isotopes, a very unusual situation. While one may also think of  
 400 overcorrection for blank or isobaric interferences as a reason, this is also unlikely since the  
 401 actual amount (rather than concentration) is not especially low in this sample. This is thus a  
 402 surprising result, and we note that the same sample appears also to be unique in Xe, and that  
 403 these two results might be related (chapter 4.5).



404  
 405 **Figure 3:** Three-isotope plot of  $^{40}\text{Ar}/^{36}\text{Ar}$  vs.  $^{38}\text{Ar}/^{36}\text{Ar}$  for, with  $1\sigma$  error bars, separately for  
 406 crystalline (Xtal) and "other" MMs. Plotted for reference are the compositions of SW (Heber et al.,  
 407 2012), "FSW" (Wieler, 2002a and Wieler et al., 2007), Q (P1) (Busemann et al., 2000), Earth  
 408 atmosphere (EA) (Lee et al., 2006), and HL (Huss and Lewis, 1994). The dotted lines indicate the  
 409 position of data points with SW-like and Q-like  $^{38}\text{Ar}/^{36}\text{Ar}$  and variable  $^{40}\text{Ar}/^{36}\text{Ar}$  due to addition of  
 410 radiogenic  $^{40}\text{Ar}$ , in order to guide the eye, while the dashed lines show the effects of mixing either  
 411 SW-Ar or Q-Ar with air. The solid lines trending to the right indicate the effect of mixing an  
 412 "arbitrary" (roughly in the center of the plot) composition with three types of cosmogenic Ar,  
 413 which, on the scale of the plot, are almost indistinguishable. From top to bottom these are:  
 414 cosmogenic Ar produced by GCR in MMs (Trappitsch and Leya, 2013); cosmogenic Ar as  
 415 typically found in meteorites (Wieler et al., 2002b); cosmogenic Ar produced in MMs by solar  
 416 cosmic rays characterized by a rigidity of 100 MV (Trappitsch and Leya, 2013). CM chondrite  
 417 chemical composition was assumed for the production in MMs. Ar in the coma of comet 67/P  
 418 Churyumov-Gerasimenko has a highly uncertain  $^{38}\text{Ar}/^{36}\text{Ar}$  ratio of  $0.185\pm 0.048$  (Rubin et al.,  
 419 2018), and a  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio has not been reported.

420

421



### 422 3.3. Krypton and Xenon

423 Tables 4 and 5 summarize the Kr and Xe results. Not listed are the rare isotopes  $^{78}\text{Kr}$ ,  
424  $^{124}\text{Xe}$  and  $^{126}\text{Xe}$ , for which no useful isotopic data were obtained. It is clear, though, that the  
425 abundances of these isotopes are low. As a consequence, there are no significant cosmogenic  
426 contributions that would make a noticeable effect on the ratios of the heavier, more abundant,  
427 isotopes. Kr and Xe were not detectable or indistinguishable from blank in two MMs: Xtal DC  
428 06\_09\_141 and the first (larger) of the DC 06\_09\_57 samples. Note that Spring (2014) also did  
429 not find detectable Xe in their analysis of another portion of DC 06\_09\_57. Additionally,  
430 krypton was not detectable in the scoriaceous Cap Prudhomme MM CP 9-1-1994.

431 Like in Ar, the second DC 06\_09\_57 sample is characterized by extremely high nominal  
432 concentrations of Kr and Xe. While this is the smallest analyzed sample by far - with associated  
433 large uncertainty in weight, which is not included in the nominal errors given in the tables - this  
434 hardly offers an explanation for the much higher nominal concentrations, by roughly two orders  
435 of magnitude in case of Kr (not counting DC 06-09\_189, which is only  $\sim 3$ x lower). Otherwise,  
436 Kr concentrations range between  $\sim 1$  and  $\sim 3 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$  ( $\sim 1$  to  $\sim 7 \times 10^{-14} \text{ cm}^3 \text{ STP}$ ).  
437 Measured amounts of  $^{132}\text{Xe}$  range from  $\sim 1 \times 10^{-15} \text{ cm}^3 \text{ STP}$  to  $\sim 2 \times 10^{-13} \text{ cm}^3 \text{ STP}$ , with  
438 concentrations mostly below  $10^{-8} \text{ cm}^3 \text{ STP/g}$ . The most notable exception, besides DC\_06\_189,  
439 is, again, the second fragment of DC 06\_09\_57. This is, while the first fragment of this MM,  
440 like the one analyzed by Spring (2014), was below detection limit.

441 Concerning isotopes of Kr, data scatter mostly around common trapped components (EA,  
442 Q, SW), but SW is unlikely to make significant contributions to either Kr or Xe in most cases,  
443 given the concentrations of the lighter elements and the relative abundances in the solar wind  
444 (see chapter 4.3). Uncertainties in measured isotopic compositions are large compared to  
445 diagnostic differences, anyway. The only possible exception is Xtal DC 06\_07\_213, which may  
446 show a slight mass fractionation effect. While otherwise this sample does not stand out, its  
447 position is similar in the three-isotope plots for Xe presented in Fig. 4, where the dotted and  
448 dashed lines show the effect of mass fractionation starting with the composition of Q-Xe and  
449 EA, respectively.

450 Isotopic ratios plotted in Fig. 4 are  $^{136}\text{Xe}/^{132}\text{Xe}$  on the ordinate vs.  $^{134}\text{Xe}/^{132}\text{Xe}$  (Fig. 4a)  
451 and  $^{130}\text{Xe}/^{132}\text{Xe}$  (Fig. 4b) on the abscissa. Xtal DC06\_09\_149 had the smallest measured  
452 amount of Xe and its isotopic data have extremely large uncertainties. The nominal values plot  
453 off scale. Reference compositions that are shown are SW, Q, EA (see Figure Caption for  
454 references). Two mixing lines are shown in each figure: one (solid black line trending upwards)  
455 between Q and HL-Xe, the Xe carried by presolar nanodiamond, and another between Q-Xe  
456 and Xe with the composition of cometary Xe (dashed dark cyan line), as inferred from  
457 measurements in the coma of comet 67P/Churyumov-Gerasimenko by Marty et al. (2017). The  
458 latter trends downwards.

459 Table 4. Kr results for DC micrometeorites (“DC”) and a single MM from Cap Prudhomme (“CP”). No data are reported for  
 460 the rare  $^{78}\text{Kr}$  isotope. Uncertainties in the last digits ( $1\sigma$ ) are given in parentheses, where the uncertainty in sample weight  
 461 is not included in the error of the concentration. For comparison, the compositions of solar wind (SW), Earth atmosphere  
 462 (EA) and the primordial components Q(P1) and HL are listed at the bottom.

sample	particle #	$^{84}\text{Kr}$ [ $10^{-14}$ cm <sup>3</sup> STP]	$^{84}\text{Kr}$ [ $10^{-8}$ cm <sup>3</sup> STP/g]	$^{80}\text{Kr}/^{84}\text{Kr}$	$^{82}\text{Kr}/^{84}\text{Kr}$	$^{83}\text{Kr}/^{84}\text{Kr}$	$^{86}\text{Kr}/^{84}\text{Kr}$
DC 06_07_213	PL 09_20 7 (3)	2.71 (60)	2.54 (56)	0.035 (5)	0.198 (17)	0.201 (12)	0.331 (20)
DC 06_08_01	PL06_09A 1	1.58 (60)	1.15 (43)	0.043 (8)	0.226 (27)	0.186 (18)	0.310 (27)
DC 06_09_11	PL 07_01A 11	1.18 (59)	0.91 (46)	0.038 (11)	0.274 (36)	0.209 (26)	0.312 (37)
DC 06_09_50	PL 07_02B 2	3.87 (61)	1.17 (19)	0.038 (4)	0.209 (12)	0.200 (9)	0.288 (13)
DC 06_09_57	PL07_02B 9 (1)	< 1.22	< 8.13	--	--	--	--
DC 06_09_57	PL07_02B 9 (2)	2.06 (52)	258 (65)	0.053 (7)	0.214 (23)	0.201 (18)	0.324 (30)
DC 06_09_63	PL07_02C 3	6.86 (77)	2.08 (23)	0.045 (3)	0.215 (8)	0.206 (7)	0.287 (10)
DC 06_09_141	PL07_04C 9 (1)	< 1.04	< 1.49	--	--	--	--
DC 06_09_149	PL07_05A 5 (1)	0.94 (51)	3.13 (1.71)	0.062 (13)	0.250 (38)	0.219 (27)	0.333 (44)
DC 06_09_189	PL07_06A 9	71.58 (3.19)	3.19 (38)	0.038 (1)	0.195 (7)	0.196 (6)	0.293 (8)
CP 9-1-1994	PL 10-109-D9	< 0.50	< 0.08	--	--	--	--
component	references			$^{80}\text{Kr}/^{84}\text{Kr}$	$^{82}\text{Kr}/^{84}\text{Kr}$	$^{83}\text{Kr}/^{84}\text{Kr}$	$^{86}\text{Kr}/^{84}\text{Kr}$
SW	[1]			0.0412 (2)	0.2054 (2)	0.2034 (2)	0.3012 (4)
Q (P1)	[2]			0.03937 (7)	0.2018 (2)	0.2018 (2)	0.3095 (5)
EA	[3]			0.039599 (20)	0.20217 (4)	0.2014 (2)	0.3052 (3)
HL	[4]			0.0305 (10)	$\equiv$ 0.1590	0.1989 (10)	0.3623 (18)

463 References: [1] Meshik et al. (2014); [2] Busemann et al. (2000); [3] Basford et al. (1973); [4] Huss and Lewis (1994) as re-calculated by  
 464 Busemann et al. (2000).

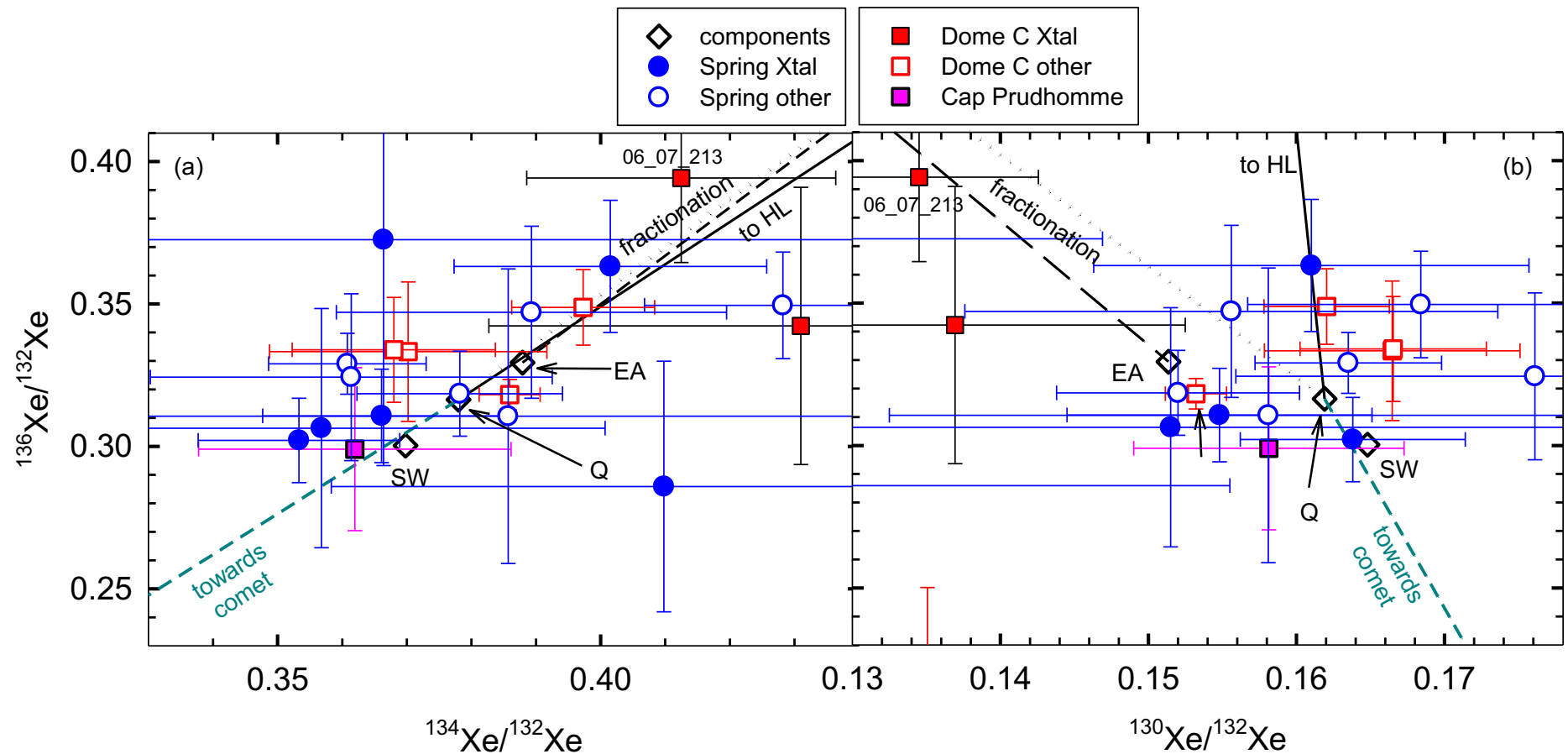
465

466 Table 5. Xe results for DC micrometeorites (“DC”) and a single MM from Cap Prudhomme (“CP”). No data are reported for the rare isotopes  $^{124}\text{Xe}$   
 467 and  $^{126}\text{Xe}$ . Uncertainties in the last digits ( $1\sigma$ ) are given in parentheses, where the uncertainty in sample weight is not included in the error of the  
 468 concentration. For comparison, the compositions of solar wind (SW), Earth atmosphere (EA) and the primordial components Q(P1) and HL are listed  
 469 at the bottom.

sample	particle #	$^{132}\text{Xe}$ [ $10^{-14}$ cm $^3$ ]	$^{132}\text{Xe}$ [ $10^{-8}$ cm $^3$ STP/g]	$^{128}\text{Xe}/^{132}\text{Xe}$	$^{129}\text{Xe}/^{132}\text{Xe}$	$^{130}\text{Xe}/^{132}\text{Xe}$	$^{131}\text{Xe}/^{132}\text{Xe}$	$^{134}\text{Xe}/^{132}\text{Xe}$	$^{136}\text{Xe}/^{132}\text{Xe}$
DC 06_07_213	PL 09_20 7 (3)	0.91 (19)	0.85 (18)	0.060 (11)	0.947 (47)	0.135 (8)	0.841 (46)	0.412 (24)	0.394 (30)
DC 06_08_01	PL06_09A 1	0.39 (18)	0.28 (13)	0.041 (23)	0.921 (78)	0.137 (16)	0.632 (75)	0.431 (48)	0.342 (49)
DC 06_09_11	PL 07_01A 11	1.01 (19)	0.78 (15)	0.083 (10)	1.033 (44)	0.166 (9)	0.783 (40)	0.370 (21)	0.333 (24)
DC 06_09_50	PL 07_02B 2	2.87 (25)	0.87 (7)	0.072 (5)	0.995 (23)	0.162 (4)	0.784 (19)	0.397 (11)	0.349 (13)
DC 06_09_57	PL07_02B 9 (1)	< 0.17	< 1.12	--	--	--	--	--	--
DC 06_09_57	PL07_02B 9 (2)	0.20 (8)	24.53 (10.21)	0.102 (64)	1.200 (139)	0.135 (48)	0.746 (157)	0.312 (78)	0.159 (91)
DC 06_09_63	PL07_02C 3	1.79 (26)	0.54 (8)	0.084 (8)	0.980 (31)	0.167 (6)	0.777 (29)	0.368 (16)	0.334 (18)
DC 06_09_141	PL07_04C 9 (1)	< 0.14	< 0.20	--	--	--	--	--	--
DC 06_09_149	PL07_05A 5 (1)	0.11 (8)	3.53 (27)	0.028 (112)	0.911 (210)	0.124 (86)	0.898 (254)	0.384 (134)	0.513 (182)
DC 06_09_189	PL07_06A 9	17.27 (26)	17.27 (26)	0.073 (2)	0.991 (14)	0.153 (2)	0.782 (9)	0.386 (5)	0.318 (5)
CP 9-1-1994	PL 10-109-D9	0.90 (6)	0.14 (1)	0.077 (10)	1.035 (46)	0.158 (9)	0.869 (41)	0.362 (24)	0.299 (29)
component	references			$^{128}\text{Xe}/^{132}\text{Xe}$	$^{129}\text{Xe}/^{132}\text{Xe}$	$^{130}\text{Xe}/^{132}\text{Xe}$	$^{131}\text{Xe}/^{132}\text{Xe}$	$^{134}\text{Xe}/^{132}\text{Xe}$	$^{136}\text{Xe}/^{132}\text{Xe}$
SW	[1]			0.0842 (2)	1.0405 (10)	0.1648 (3)	0.8256 (12)	0.3698 (6)	0.3003 (5)
Q (P1)	[2]			0.0822 (2)	1.042 (2)	0.1619 (3)	0.8185 (9)	0.3780 (11)	0.3164 (8)
EA	[3]			0.07136 (9)	0.9832 (12)	0.15136 (12)	0.7890 (11)	0.3879 (6)	0.3294 (4)
HL	[4]			0.0905 (6)	1.056 (2)	0.1542 (3)	0.8457 (13)	0.6356 (13)	$\equiv$ 0.6991

470 References: [1] Meshik et al. (2015); [2] Busemann et al. (2000); [3] Basford et al. (1973); [4] Huss and Lewis (1994) as re-calculated by Busemann et al. (2000)).

471



472  
 473 **Figure 4.** Three-isotope plots of  $^{136}\text{Xe}/^{132}\text{Xe}$  vs.  $^{134}\text{Xe}/^{132}\text{Xe}$  (a) and vs.  $^{130}\text{Xe}/^{132}\text{Xe}$  (b). Data points for crystalline and other MM samples are shown  
 474 separately. Error bars are  $1\sigma$ . DC 06\_09\_149 with very large uncertainties is not shown, while DC 06\_09\_57 (2) is off scale and discussed separately  
 475 (chapter 4.5). Plotted for comparison are the compositions of air (Basford et al., 1973), Q-Xe (Busemann et al., 2000) and Xe-HL (Huss and Lewis,  
 476 1994; as recalculated by Busemann et al., 2000). Data from Spring (2014) obtained for MMs from Dome C and Cap Prudhomme are also included.  
 477 The dotted and the dashed lines show the trend expected for mass fractionation starting from Q and air composition, respectively, while the solid line  
 478 is the mixing line between Q and HL-Xe. The dashed dark cyan lines are mixing lines between Q-Xe and Xe as reported for the coma of comet  
 479 67P/Churyumov-Gerasimenko by Marty et al. (2017).

480 Besides our own results, we have included in Fig. 4 data from Spring (2014), who  
481 obtained data for Xe in the same MMs from Dome C analyzed here. Like our data, the Spring  
482 data are distinguished in Fig. 4 between MMs classified as Xtal and others. Good agreement is  
483 observed between her and the two data sets, but the uncertainties are large in both cases, due to  
484 the small gas amounts analyzed. The Spring (2014) data do not include DC 06\_09\_57, since  
485 Xe was not above extraction blank level. Again, this is in agreement with our result for the  
486 larger fragment we analyzed from this MM. The smaller fragment that we analyzed, however,  
487 turned out different, having strange Ar isotopes (chapter 3.2), with very high abundances of Ar  
488 and Kr, and comparably high Xe abundance. Concerning isotopes of Xe, this fragment is also  
489 unique, with very low  $^{134}\text{Xe}/^{132}\text{Xe}$  and  $^{136}\text{Xe}/^{132}\text{Xe}$ . It plots off scale in Fig. 4, and we will return  
490 to this observation below (chapter 4.5).

### 491 **3.4. Cosmogenic noble gases**

492 Contributions from cosmogenic noble gases in meteorites are commonly observed as  
493 excesses of  $^{21}\text{Ne}$ ,  $^3\text{He}$  and, less frequently,  $^{38}\text{Ar}$ . Such excesses are clearly visible only in few  
494 of our MMs. This contrasts with the situation in the TAM MMs of Baecker et al. (2018), but  
495 is similar to the majority of MMs analyzed in other previous studies (Dome Fuji and Yamato:  
496 Osawa et al., 2000, 2003; Osawa and Nagao, 2002a, 2002b; Okazaki et al., 2015), the reason  
497 being the high abundances of solar wind noble gases. For Ne, this is obvious in Fig. 2, where  
498 Fig. 2a shows a comparison with the previous data, and Fig. 2b shows in more detail that our  
499 data points plot close to trapped compositions that one might expect to be present: mixtures of  
500 solar wind proper (SW; Heber et al., 2012) with fractionated solar wind (FSW; Benkert et al.,  
501 1993), Q (Ott, 2014) and Earth atmosphere, or simply mass fractionated solar wind (the dotted  
502 line).

503 Obviously, the data points to the left of the lines in Fig. 2b show no evidence of  
504 cosmogenic Ne. Six others plot to the right, and we list in Table 6 the inferred concentrations  
505 of cosmogenic  $^{21}\text{Ne}$ , together with the concentrations of trapped  $^{20}\text{Ne}$ . We list two sets of  
506 values obtained by using two different reference trapped compositions. However, as also  
507 obvious in Fig. 2b, differences between the two approaches are small compared to the  
508 analytical errors. In one approach, following Baecker et al. (2018) to whom we refer for more  
509 detail, the numbers were obtained from a 3-component deconvolution: a cosmogenic  
510 endmember (with negligible influence of the exact choice), and two “trapped” endmembers,  
511 namely “fractionated solar wind” Ne (FSW; Benkert et al., 1993) and solar-wind Ne (SW;  
512 Heber et al., 2012), as given in Table 3. The other approach, which was also used by, e.g.,  
513 Schmitz et al. (2019) in their study of fossil MMs, was simply considering the excess  $^{21}\text{Ne}$   
514 over the composition of (linearly) mass fractionated solar wind. Uncertainties of the reference  
515 compositions were taken into account in calculating the listed uncertainties. Two additional  
516 entries in Table 6 are upper limits for the two samples from DC 06\_09\_57, corresponding to  
517 the actually measured amounts of  $^{21}\text{Ne}$ .

518

519 **Table 6.** Concentrations of cosmogenic  $^3\text{He}$ ,  $^{21}\text{Ne}$  as well as “cosmogenic”  $^{38}\text{Ar}$  and  
520 concentration of trapped  $^{20}\text{Ne}$ . Units are  $10^{-8} \text{ cm}^3 \text{ STP/g}$ , errors ( $1\sigma$ ) are in parentheses. The  
521 cosmogenic abundances are sensitive to assumptions about the composition of the trapped  
522 components, and two different sets have been used for both Ne and He, as described in the  
523 text. In case of cosmogenic  $^{21}\text{Ne}$ , the upper values are those obtained from 3-component  
524 resolution, while the lower values correspond to excesses over the linearly fitted SW mass  
525 fractionation line. For cosmogenic  $^3\text{He}$ , the upper values are those obtained from an assumed  
526 SW/FSW mixing ratio for the trapped component derived from the Ne data, while the lower  
527 values assume a constant  $3 \times 10^{-4}$  for trapped  $^3\text{He}/^4\text{He}$ . In case of DC 06:09\_57 the listed upper  
528 limits ( $2\sigma$ ) correspond to total measured abundances instead. The case for the nominally high  
529 abundance of cosmogenic  $^3\text{He}$  in DC 06\_09\_189 is marginal and listed in italics and small  
530 print. Evidence for “cosmogenic”  $^{38}\text{Ar}$  (calculated for the two cases with high  $^{38}\text{Ar}/^{36}\text{Ar}$  in  
531 Fig. 3, following Baecker et al., 2018) is also marginal and the values are listed in italics and  
532 small print as well.

sample	particle #	$^{21}\text{Ne}_{\text{cos}}$	$^{20}\text{Ne}_{\text{tr}}$	$^3\text{He}_{\text{cos}}$	$^{38}\text{Ar}_{\text{cos}}$
DC 06_07_213	PL 09_20 3 (1)	--	867 (90)	0.90 (24) 0.77 (24)	--
DC 06_08_01	PL06_09A 1	0.53 (18) 0.41 (15)	2684 (51)	1.67 (24) 1.54 (24)	< 4.4
DC 06_09_11	PL 07_01A 11	0.13 (7) 0.11 (7)	475 (31)	0.30 (51) 0.12 (47)	--
DC 06_09_50	PL 07_02B 2	0.09 (4) 0.06 (3)	1445 (25)	< 4.28 < 16.66	2.5 (2.2)
DC 06_09_57	PL07_02B 9 (1)	< 1.00	< 251	< 3.62	--
DC 06_09_57	PL07_02B 9 (2)	< 12.66	< 5146	--	--
DC 06_09_63	PL07_02C 3	0.05 (4) 0.03 (4)	632 (43)	12.48 (4.35) 10.92 (2.92)	--
DC 06_09_141	PL07_04C 9 (1)	--	353 (47)	--	--
DC 06_09_149	PL07_05A 5 (1)	1.44 (67) 1.13 (62)	8014 (188)	--	--
DC 06_09_189	PL07_06A 9	0.49 (21) 0.36 (18)	3675 (73)	<i>19.23 (6.75)</i> <i>12.30 (10.40)</i>	--
CP 9-1-1994	PL 10-109-D9	--	35 (7)	< 0.45	--

533  
534 For cosmogenic  $^3\text{He}$ , except for two Xtal MMs (DC 06\_07\_213 and DC 06\_08\_01)  
535 which clearly plot at higher  $^3\text{He}/^4\text{He}$  than all trapped compositions (Fig. 1), results (or, for that  
536 matter, the mere evidence for presence of cosmogenic  $^3\text{He}$ ) depend sensitively on the choice  
537 for the trapped ratio. Again, we list the results for two cases: in one case, again following  
538 Baecker et al. (2018), we chose a composition for trapped  $^3\text{He}/^4\text{He}$  assuming the same mixing  
539 ratio (and nominal uncertainties) between SW and FSW for He as inferred for Ne. Since in  
540 some cases, notably DC 06\_09\_63 and DC 06\_09\_189, the so obtained results appeared  
541 unrealistic, and, since, in Fig. 1,  $^3\text{He}/^4\text{He}$  for high ( $>10^{-4} \text{ cm}^3 \text{ STP/g}$ )  $^4\text{He}$  concentrations  
542 seems to level off at  $\sim 3 \times 10^{-4}$ , we used this value for the trapped component in the alternative  
543 approach. An error of  $0.2 \times 10^{-4}$  in this ratio was propagated in this case. For the cosmogenic  
544 component, we used  $^3\text{He}/^4\text{He} = 0.20 \pm 0.05$  in both cases, but, as in Ne, the exact choice of the  
545 cosmogenic composition has essentially no influence in the calculation of its abundance. With

546 the alternative assumption for the composition of the trapped component, the nominally high  
547 cosmogenic  $^3\text{He}$  abundance in DC 06\_09\_189 becomes a marginal case, but the abundance in  
548 DC 06\_09\_63 remains high. We note that the measured ratio in this MM is still below the  
549 ratio for unfractionated SW and so, in principle, the possibility remains that this cosmogenic  
550  $^3\text{He}$  is not real. By comparison with other MMs it appears unlikely, however, to have such a  
551 high trapped  $^3\text{He}/^4\text{He}$  ratio (see also chapter 4.4).

552 As for  $^{38}\text{Ar}$ , there are two MMs that clearly show enhanced  $^{38}\text{Ar}/^{36}\text{Ar}$  relative to SW,  
553 “planetary” (Q) and air: DC 06\_08\_01 (Xtal) and DC 06\_09\_50 (FgC). The high ratios may,  
554 in principle, be explained by addition of cosmogenic Ar. We have therefore calculated  
555 nominal abundances of cosmogenic  $^{38}\text{Ar}$  using the approach of Baecker et al. (2018), where  
556 contributions to trapped Ar from SW, FSW and planetary Ar are estimated from the SW/FSW  
557 mixing ratio at Ne and the Ne/Ar ratio of the different components. The values are listed in  
558 Table 6, but obviously, cosmogenic contributions are difficult to ascertain even in these two  
559 cases. We will not consider cosmogenic  $^{38}\text{Ar}$  in chapter 4.4.

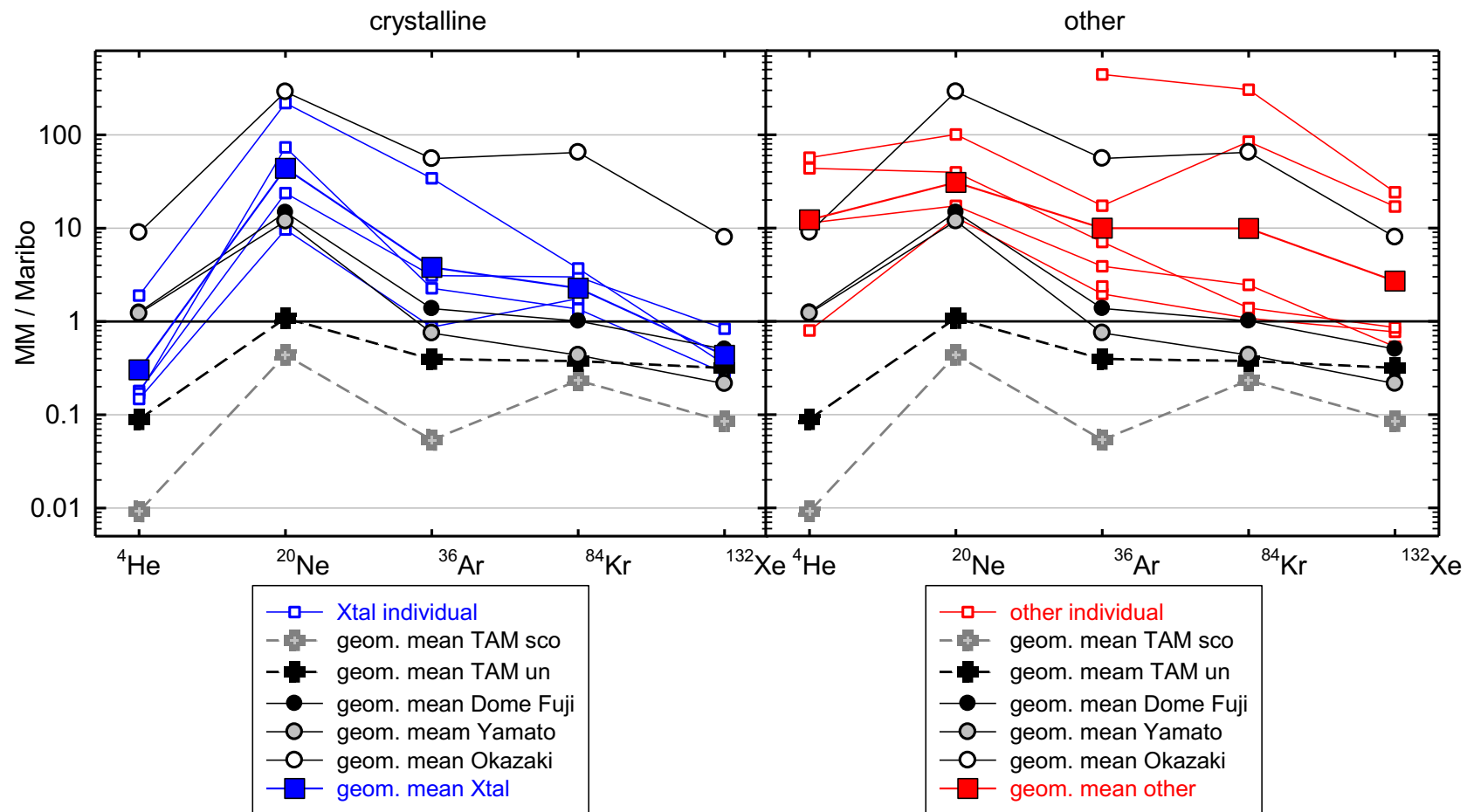
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## 561 **4. Discussion**

### 562 **4.1. Noble gas general pattern**

563 We will concentrate on the MMs from Dome C in this discussion. The single particle  
564 from Cap Prudhomme, although being of larger size, is scoriaceous rather than primitive and  
565 has low noble gas abundances and, therefore, does not add information.

566 As common in meteorites with implanted solar wind, the light noble gases He and Ne of  
567 the MMs from Dome C analyzed in this work are dominated by the trapped solar wind  
568 component, while for heavy Kr and Xe a trapped “planetary” component (Ott, 2014) accounts  
569 for most of the inventory. Argon generally represents a mixed case. Here we present a short  
570 general overview of abundances, while in the following sections (4.2 and 4.3), we will discuss  
571 the individual cases in more detail. We show an overview of the trapped noble gas abundances  
572 in Figure 5 (crystalline MMs, left; others, right). The concentrations of the major isotopes are  
573 plotted, and, since MMs have often been compared to CM meteorites (Kurat et al., 1994;  
574 Engrand and Maurette, 1998), we normalized them to the concentrations in CM meteorites,  
575 where we considered CM Maribo #2 as reported in Haack et al. (2012) as representative, as we  
576 did in Baecker et al. (2018). Again, the possible, but probably small, radiogenic contributions  
577 to  $^4\text{He}$  are ignored. Shown are the individual specimens as well as the geometric means for the  
578 two populations. For comparison, we also show the geometric means for the TAM MMs of  
579 Baecker et al. (2018) and for the Antarctic MMs collected at Dome Fuji and in the Yamato  
580 Mountain area as reported by Osawa et al. (2000), Osawa and Nagao (2002a, b) and Osawa et  
581 al. (2003b). Data on another suite of Dome Fuji samples analyzed by Okazaki et al. (2015) are  
582 shown separately, while, for the geometric mean of TAM MMs, we distinguish between  
583 scoriaceous and unmelted MMs.



584

585 Figure 5. Noble gas concentrations in DC MMs, normalized to CM Maribo #2 (Haack et al., 2012). Shown are the individual specimens  
 586 as well as the geometric means for the two populations (Xtal and “other”) separately. For comparison we also show the geometric means  
 587 for the TAM MMs of Baecker et al. (2018) and for Antarctic MMs collected at Dome Fuji and in the Yamato Mountain (Osawa et al.,  
 588 2000; Osawa and Nagao, 2002a, b; Osawa et al., 2003b). Data the Dome Fuji samples of Okazaki et al. (2015) are shown separately, while  
 589 for the geometric mean of TAM MMs we distinguish between scoriaceous and unmelted MMs.



590 Several features are apparent. First, the scoriaceous MMs show, by far, the lowest noble  
591 gas concentrations. This is to be expected given the higher temperature experienced by  
592 scoriaceous (partly melted) micrometeorites during atmospheric entry, resulting in more severe  
593 gas loss. Nevertheless, concentrations also in the unmelted TAM MMs are lower than in the  
594 other MMs, in particular for He and Ne. The larger sizes of the TAM MMs (~600  $\mu\text{m}$  on  
595 average; Baecker et al., 2018) compared to the Dome Fuji and Yamato Mountain MMs as well  
596 as our DC MMs, and the correspondingly lower surface to volume ratio of TAM MMs may  
597 have played a role, since He and Ne are predominantly of solar wind origin and thus surface-  
598 correlated (implantation depth  $< 0.1 \mu\text{m}$ ). Second, in accordance with such an interpretation,  
599 on average the concentrations of (volume-correlated) Xe in the unmelted TAM MMs are not  
600 too different from those of the Dome Fuji and Yamato Mountains MMs of Osawa et al. (2000,  
601 2003b) and Osawa and Nagao (2002a, b), as well as the reference CM meteorite, for that matter.  
602 This similarity holds also in comparison with the majority of our DC MMs, although at least  
603 two of the latter show significantly higher concentrations, raising the mean for our DC samples  
604 above those reference abundances.

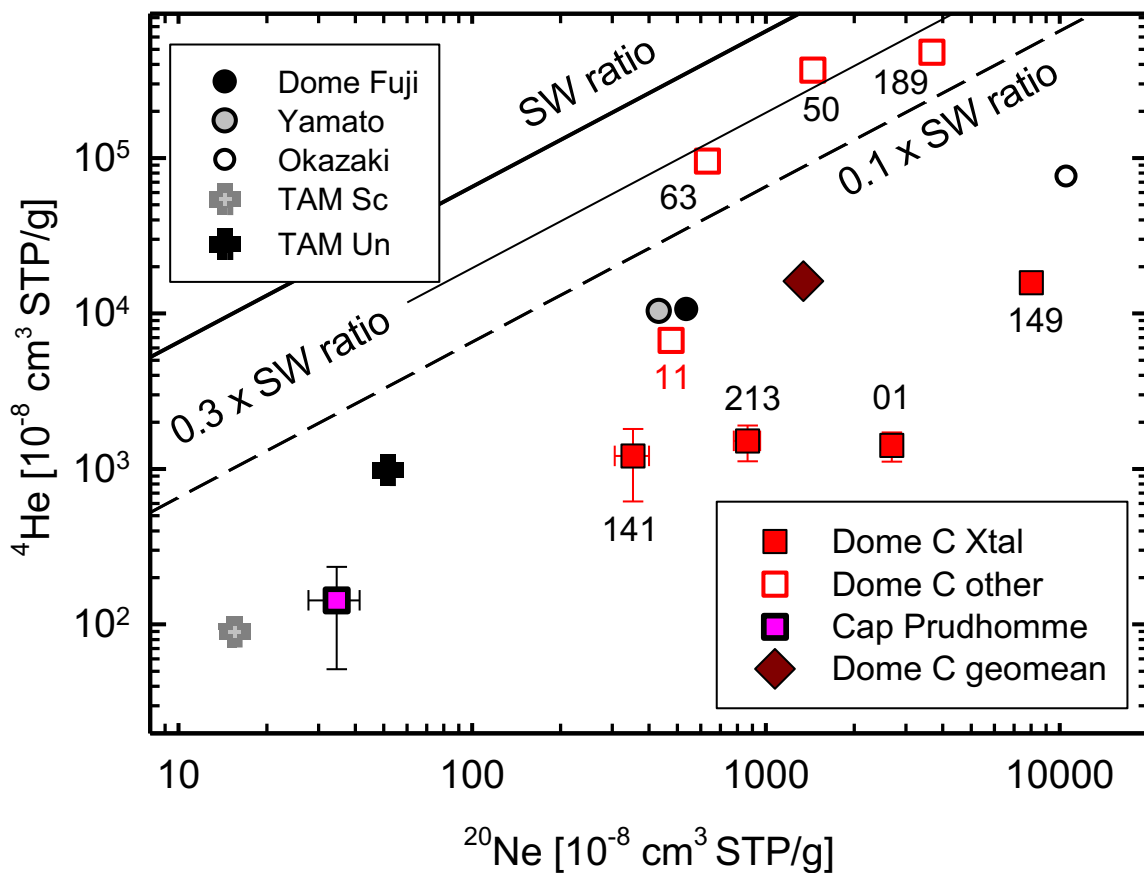
605 Third, the average concentrations reported by Okazaki et al. (2015) for MMs recovered  
606 from surface snow near Dome Fuji are one to two orders of magnitude higher than the others  
607 reported previously, but are roughly matched by some of our DC MMs. The similarity between  
608 the two sets of data is striking and most probably related to the collection method. Our Dome  
609 C and the Dome Fuji particles of Okazaki et al. (2015) were collected using the same protocol,  
610 which is gentle and rapid melting of surface snow (Duprat et al., 2007; Okazaki et al., 2015).  
611 This protocol is specific to these 2 collections, where the particles were trapped in snow at  
612 temperatures far below  $0 \text{ }^\circ\text{C}$  before being extracted from their host matrix (the snow) rapidly  
613 (within hours). In contrast, MMs from other collections were trapped in a matrix (ice,  
614 sediments...) that experienced much larger temperature variations and mechanical stress. In  
615 particular, most MMs from the other collections experienced repeated contact with liquid water,  
616 in particular during thawing/freezing cycles at the surface of ice fields, whereas the MMs from  
617 Dome C and the Dome Fuji samples of Okazaki et al. (2015) experienced only limited contact  
618 with liquid water, for a few hours during their extraction (note that this is also different for the  
619 samples extracted from snow at Mount Fuji; Osawa et al., 2000; Osawa and Nagao, 2002a).  
620 The striking difference in the noble gas concentrations between MMs obtained by different  
621 collection methods suggests that part of the noble gases initially present in dust in interplanetary  
622 space is hosted by a phase that may be subject to leaching by water.

623 Another interesting feature is the depletion of Xe relative to Kr and the reference CM  
624 meteorite ratio (roughly that in phase Q, the major carrier of heavy noble gases in primitive  
625 meteorites; Ott, 2014). We have argued previously that this may a sign for contamination by  
626 (terrestrial) air, which has an  $^{84}\text{Kr}/^{132}\text{Xe}$  ratio of  $\sim 28$ , much higher than the primitive noble gas  
627 component in carbonaceous chondrites ( $\sim 1$ ). We will come back to this later (chapter 4.3).

## 628 **4.2. Solar wind gases: Helium and Neon**

629 The solar wind origin of the noble gases He and Ne is highlighted in Figure 6, which is  
630 a plot of trapped  $^4\text{He}$  vs.  $^{20}\text{Ne}$  abundances for those AMMs, where both could be measured  
631 (Tables 2, 3 and 6). Minor corrections for cosmogenic contributions have been applied but are

632 negligible. Any radiogenic  $^4\text{He}$  present is still included, however. Compared to the  $^4\text{He}/^{20}\text{Ne}$   
 633 ratio of 656 determined for present-day solar wind (Heber et al., 2009), which defines the  
 634 solid line in Figure 6, all data points are shifted down / to the right, i.e. have lower  $^4\text{He}/^{20}\text{Ne}$ .  
 635 As noted before (chapter 4.1; and Baecker et al., 2018), unmelted MMs have higher  
 636 concentrations of solar wind gases than partially melted (scoriaceous) ones, and the  
 637 concentrations roughly scale with size, a consequence of the fact that they are surface-  
 638 correlated. This is also apparent in that MM DC 06\_09\_11, which is partly scoriaceous  
 639 (FgC/Sc), has lower concentrations and lower  $^4\text{He}/^{20}\text{Ne}$  than the “purely FgC” MMs.  
 640 However, we do not observe this for the other FgC/Sc MM DC 06\_09\_189, which has the  
 641 highest concentrations of  $^4\text{He}$  and  $^{20}\text{Ne}$  in our sample set.



642

643 **Figure 6:** Concentrations of  $^4\text{He}$  plotted vs. concentrations of trapped  $^{20}\text{Ne}$ . The individual  
 644 data points for our DC MMs are labeled with the last digits of the sample name (Table 1). We  
 645 also show the geometric means for our DC MMs as well as for the results of previous studies  
 646 of MMs from Dome Fuji, the Yamato Mountains area and the Transantarctic Mountains.  
 647 References: Osawa et al. (2000, 2003b), Osawa and Nagao (2002a, b), Baecker et al. (2018).  
 648 The Dome Fuji value from the Okazaki et al. (2015) study is shown separately, and the TAM  
 649 MMs are distinguished between Unmelted (Un) and scoriaceous (Sc). The lines correspond to  
 650 the solar wind  $^4\text{He}/^{20}\text{Ne}$  ratio (Heber et al., 2009), as well as 0.3x and 0.1x the solar wind  
 651 ratio.

652 A new feature, not apparent from previous work, is the difference between MMs that  
653 are crystalline (Xtal) and those that are fine-grained carbonaceous (FgC). While both cover  
654 about the same range in concentrations of Ne, the Xtal ones have significantly lower  $^4\text{He}$  and  
655 thus much lower  $^4\text{He}/^{20}\text{Ne}$ , by almost two orders of magnitude – geometric means are  $\sim 1.6$  vs.  
656  $\sim 170$ , ignoring partly scoriaceous DC 06\_09\_11. Previous noble gas studies have mostly  
657 distinguished between, on one hand, unmelted (often simply called MM; e.g., Osawa et al.,  
658 2003) and, on the other, scoriaceous MMs and completely melted cosmic spherules, thus  
659 missing the apparent difference between Xtal and FgC unmelted MMs.

660 Compared to previous works, the mean  $^4\text{He}$  and  $^{20}\text{Ne}$  concentrations for our Dome C  
661 MMs as well as the MMs of Okazaki et al. (2015) are higher, but plot roughly along a line  
662 parallel to the solar wind line, i.e. they all have, on average, similar  $^4\text{He}/^{20}\text{Ne}$  ratios, of  $\sim 20$ ,  
663 i.e.  $\sim 0.03$  times the SW ratio. On the other hand, our samples clearly defined as FgC MMs,  
664 show roughly ten times higher ratios of  $\sim 0.3 \times \text{SW}$ , as do some in the earlier studies (Osawa  
665 and Nagao, 2002a; Osawa et al., 2000, 2003b; see also Fig. 2 in Okazaki et al., 2015). The  
666 fact that, in all studies so far, the average  $^4\text{He}/^{20}\text{Ne}$  is about the same suggests that, in all these  
667 studies, the mix of fine-grained carbonaceous and crystalline MMs was fairly similar.

668 Interestingly,  $^4\text{He}/^{20}\text{Ne}$  ratios observed in IDPs (Nier and Schlutter, 1990; Pepin et al.,  
669 2000) more or less cover the same range as those observed for unmelted MMs. We have  
670 argued earlier (Baecker et al., 2018), based on comparison not only with IDPs, but also with  
671 lunar soil samples and grains returned from asteroid Itokawa (Nagao et al., 2011), that ratios  
672 such as those observed in MMs DC 06\_09\_50, 06\_09\_63 and 06\_09\_189 may be common  
673 (characteristic) for the pre-terrestrial ratio in MMs. Even though lower than in solar wind  
674 proper, such ratios are therefore not necessarily indicative of loss during passage through the  
675 terrestrial atmosphere. Differences in absolute concentrations (of both He and Ne) may then  
676 be related to size (via the surface/volume ratio), fractional loss of the outermost  $\sim 0.05$  nm,  
677 where the solar wind gases reside, and - in cases where not the whole MM was used for noble  
678 gas analysis - the unknown fraction of surface present in the sample actually used for the  
679 noble gas work (Baecker et al., 2018).

680 As for the difference in average  $^4\text{He}$  contents and  $^4\text{He}/^{20}\text{Ne}$  ratios between Xtal and FgC  
681 MMs, it appears likely that this was established during atmospheric entry heating. The  
682 apparent loss of He by one to two orders of magnitude suggested by Fig. 6 is similar to that  
683 found by Furi et al. (2013) in their series 1 experiment for two-second heating to  $1350^\circ\text{C}$  of  
684 grains of the Orgueil (CI) meteorite, used for simulation of entry heating. After this, the grains  
685 were still characterized as fine-grained, non-vesicular (Toppani et al., 2001). We note,  
686 however, that in this case Furi et al. (2013) also observed significant loss of Ne (some 80 %),  
687 while for our crystalline MMs there is no indication for Ne loss (Fig. 6). We also note that the  
688 results of Furi et al. (2013) are compromised by large variations in the abundances of the  
689 starting material used for heating and that there is no information on the abundance before  
690 heating in the individual samples. In any case, the differences between the Xtal and other  
691 grains of our study indicate that, besides the temperature reached during atmospheric entry,  
692 the mineralogical makeup of the MM also determines the degree of loss of solar wind He. As  
693 a consequence, the temperature dependence of  $^4\text{He}$  release during analysis (Nier and

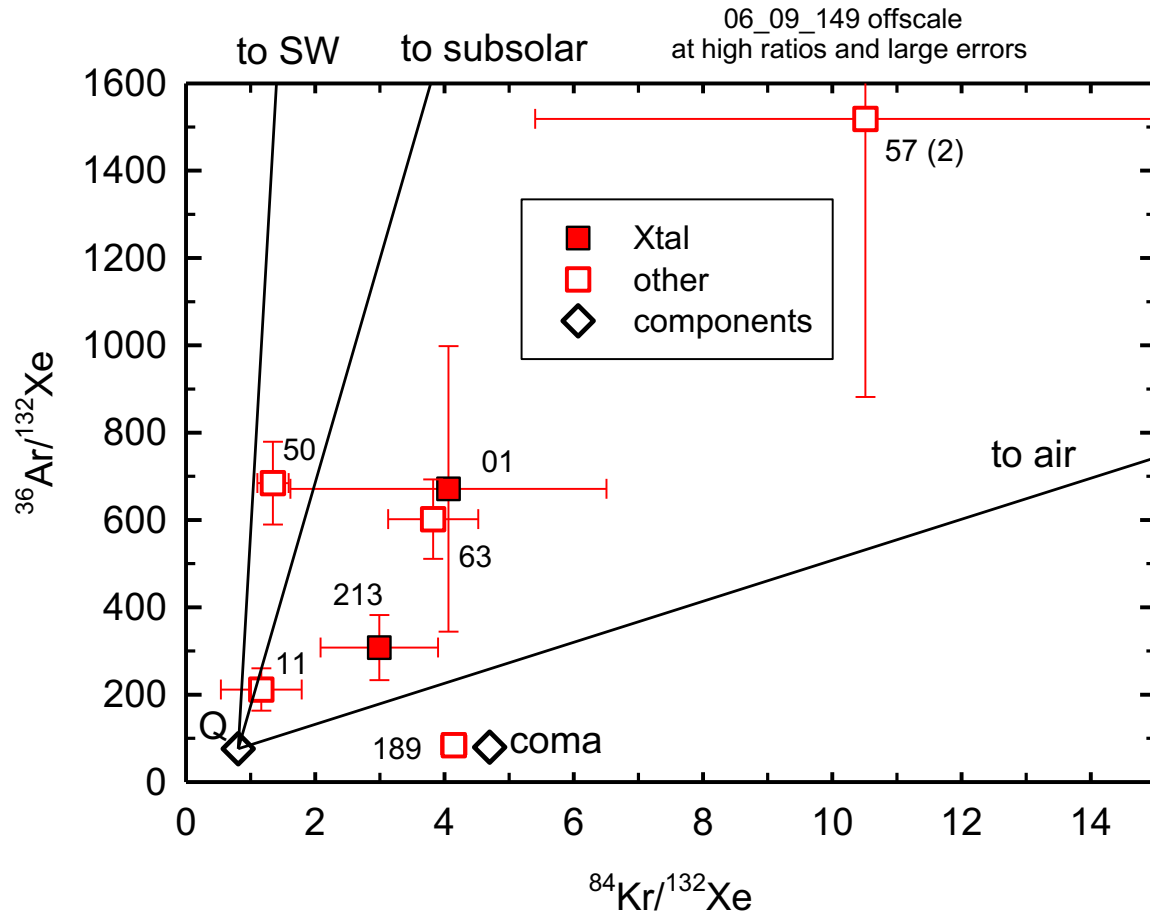
694 Schlutter, 1993; Okazaki et al., 2015) alone may not be a reliable measure for determining the  
695 degree of heating experienced by a MM during atmospheric entry.

696 While in this work on MMs from Dome C we concentrated on unmelted MMs, it useful  
697 to keep in mind that even in scoriaceous MMs some solar wind Ne has been retained. Preferred  
698 orientation during atmospheric entry that resulted in a small fraction of surface to remain intact  
699 may be a possible explanation, but it cannot be excluded that some amount of solar wind gas  
700 might have been acquired by subunits of the MMs during residence in an asteroidal regolith  
701 prior to assembly and ejection. This could then reside in the MM's interior (Baecker et al.,  
702 2018) rather than close to the surface.

### 703 **4.3. Heavy noble gases: Argon, krypton and xenon**

704 The case of krypton and xenon is distinct from that of He and Ne since they can be  
705 expected to be primarily of the “planetary” type (Ott, 2014) and volume- rather than surface-  
706 sited. The case of Ar is more complicated and differs from that of our TAM samples (Baecker  
707 et al., 2018), since the DC MMs have significantly higher solar wind gases concentrations  
708 (chapter 4.2; Figs. 5 and 6).

709 The difference is also obvious in a plot of  $^{36}\text{Ar}/^{132}\text{Xe}$  vs.  $^{84}\text{Kr}/^{132}\text{Xe}$  (Fig. 7) where the  
710 high  $^{36}\text{Ar}/^{132}\text{Xe}$  ratios in all MMs, with the exception 06\_09\_189, can only be explained by  
711 the contribution of solar components. As an example, treating the measured compositions as a  
712 3-component mixture of solar wind, Q and air (all unfractionated), for DC 06\_09\_63 the  
713 contribution to  $^{36}\text{Ar}$  of SW is 65% (vs. 24% from air and 11% from Q). For DC 06\_09\_11, as  
714 another example, the corresponding values are 57% (SW), 7% (air) and 35% (Q).



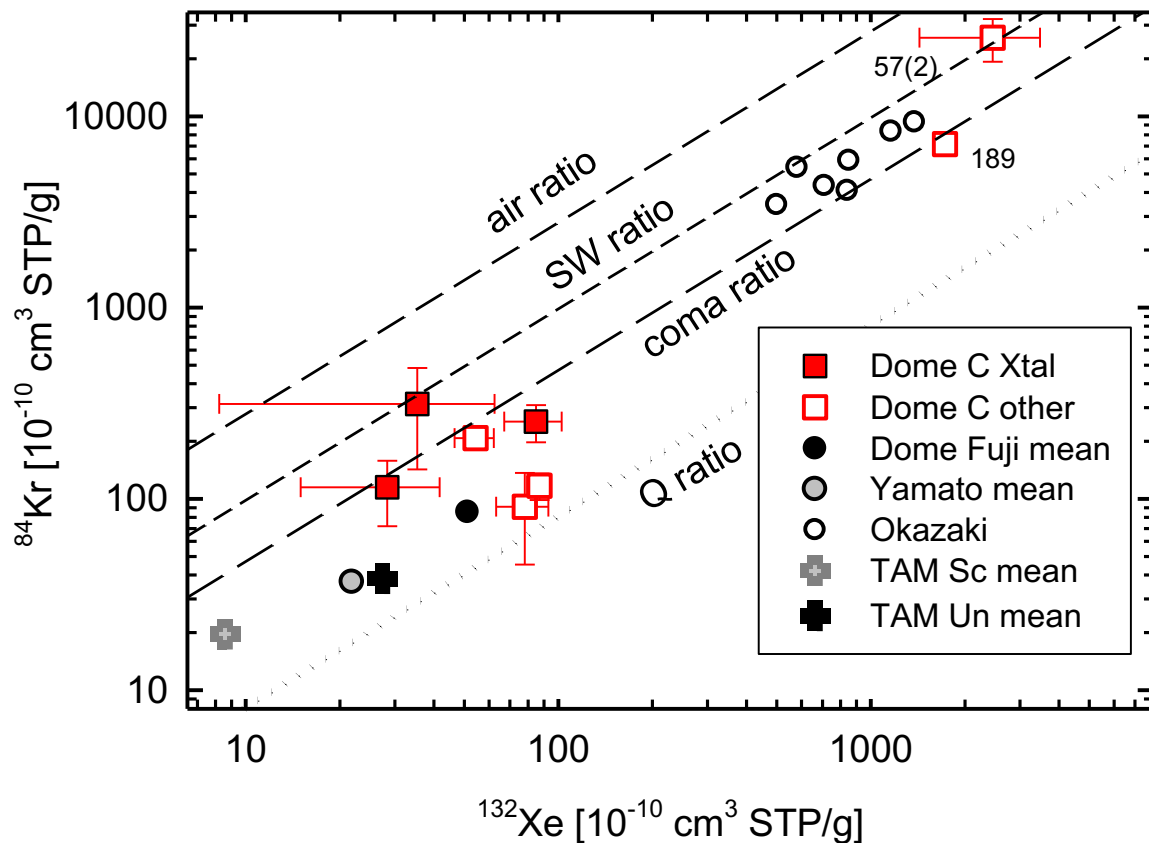
715

716 Figure 7. Plot of  $^{36}\text{Ar}/^{132}\text{Xe}$  vs.  $^{84}\text{Kr}/^{132}\text{Xe}$ . The data points are labeled with the last digits of  
 717 the sample names (Table 1); DC\_06\_09\_149 plots off scale. The composition of Q  
 718 (Busemann et al., 2000; Ott, 2014) and of gases in the corona of comet Churyumov-  
 719 Gerasimenko (Rubin et al., 2018) are shown for reference, as well as mixing lines between Q  
 720 and solar wind (Vogel et al., 2011), subsolar gas (Ott, 2014) and air.

721 On the other hand, it is also obvious, in particular from DC 06\_09\_11, that a component  
 722 similar to Q, with low ratios, is needed as well. For Xe, in the three-component mixing model  
 723 discussed above, Q is always the dominant component, accounting for 88 and 98% in the two  
 724 examples. As a result, the Xe isotopic compositions discussed in chapters 3.3 and below in  
 725 chapter 4.5, are essentially those of the non-solar component(s). For Kr, the situation is often  
 726 not so clear-cut, but from the 3-component exercise it still follows that the SW contribution is  
 727 comparably small (usually <10%). Of course, the simple 3-component assumption used in the  
 728 estimates above is somewhat naive, with some of the components being possibly elementally  
 729 fractionated compared to their normal composition, and with gases that have Ar/Kr/Xe ratios  
 730 like in the coma of comet Churyumov-Gerasimenko (Rubin et al., 2018) as a possible  
 731 alternative (to air) or as an additional component. Still, the exercise provides some clues.  
 732 Interestingly, but possibly just by coincidence, the position of DC 09\_06\_189 is identical to  
 733 that of the coma composition. This special MM, which is fine-grained carbonaceous (FgC),  
 734 but also partially scoriaceous, does not require a contribution from solar wind Ar (nor Kr or  
 735 Xe, for that matter), which contrasts with the fact that it has the highest abundances of (solar)  
 736 He and Ne (Fig. 6) and a  $^{20}\text{Ne}/^{36}\text{Ar}$  ratio very much like the others (Table 3).

737 With SW contributions to Kr probably small (<10%), it makes sense to examine the  
 738 results for further details (i.e., including concentrations) in the Kr-Xe system alone, which we  
 739 are doing in Fig. 8. Two of our grains stand out: DC 06\_09\_189 and the smaller sample from  
 740 DC 06\_09\_57. Their concentrations are much higher than those of the Xtal MMs and also in  
 741 comparison to the other MMs counted among “others”. Two of the latter are close in  
 742  $^{84}\text{Kr}/^{132}\text{Xe}$  to the ratio in the Q component, indicating little contribution from other  
 743 components. Overall, these grains have concentrations similar to the MMs from Dome Fuji  
 744 analyzed by Osawa et al. (2000) and Osawa and Nagao (2002a), which in turn are similar to  
 745 the most primitive macroscopic meteorites (types 2 and 1). Their concentrations are higher  
 746 than those of MMs from the Yamato region (Osawa and Nagao, 2002b; Osawa et al. 2003)  
 747 and from the Transantarctic Mountains (Baecker et al., 2018). There is a clear gap in Fig. 8  
 748 between these and the much higher concentrations found in the Dome Fuji samples of  
 749 Okazaki et al. (2015). Compared to latter, DC 06\_09\_189 is at the upper end and DC  
 750 06\_09\_57(2) even higher. As discussed above in section 4.1, this striking difference may be  
 751 related to the specific collection protocol used for the Dome Fuji samples of Okazaki et al.  
 752 (2015) and our Dome C samples only, and suggests that this specific Kr and Xe component  
 753 may be hosted by a phase sensitive to repeated episodes of leaching by water. Interestingly,  
 754 the Ar/Kr/Xe ratio of DC 06\_09\_189 almost perfectly matches Ar/Kr/Xe in the coma of  
 755 comet Churyumov-Gerasimenko (Figs. 7, 8). We will come back to this in section 4.5.

756



757 Figure 8. Plot of  $^{84}\text{Kr}$  vs.  $^{132}\text{Xe}$  concentrations. DC 06\_09\_189 and DC 06\_09\_57(2) with the  
 758

759 highest abundances are labeled. For comparison geometric means from previous studies on  
760 MMs from Mount Fuji, the Yamato Mountains and the Transantarctic Mountains (TAM) are  
761 shown (Osawa et al., 2000, 2003b; Osawa and Nagao, 2002a, b; Baecker et al. 2018). The  
762 Dome Fuji MMs of Okazaki et al. (2015) are shown as individual data points and are not  
763 included in the Dome Fuji mean, while the TAM MMs are distinguished between Unmelted  
764 (Un) and scoriaceous (Sc). The various lines correspond to the  $^{84}\text{Kr}/^{132}\text{Xe}$  ratio in air, SW, the  
765 coma of comet Churyumov-Gerasimenko and Q. References as in Figure 7.

#### 766 4.4. Cosmic ray exposure (CRE) and provenance

767 Cosmic ray exposure ages are commonly calculated from the overabundance of isotopes  
768 that are much rarer in trapped components than the other isotopes of the same element, but are  
769 produced by cosmic ray interaction in roughly equal amounts, such as  $^3\text{He}$ ,  $^{21}\text{Ne}$  and  $^{38}\text{Ar}$ .  
770 Their concentrations – calculated as described in chapter 3.4 - are listed in Table 6. The  
771 favored approach is usually that using  $^{21}\text{Ne}$ , because this isotope is less susceptible to loss  
772 than  $^3\text{He}$  and less sensitive to variations in chemical composition than  $^{38}\text{Ar}$ . The problem in  
773 using  $^{21}\text{Ne}$  with MMs (as well as IDPs, for that matter) is the high abundance of solar wind  
774 Ne (and solar wind He, for the case of  $^3\text{He}$ ). Shifts to the right in the Ne three-isotope plot of  
775 Fig. 2 indicative of cosmogenic  $^{21}\text{Ne}$  are therefore small and often zero within  $2\sigma$ . This is  
776 different from the situation in our TAM MMs (Fig. 2), which have generally much lower  
777 concentrations of solar wind noble gases (Baecker et al., 2018). It is similar, however, to the  
778 situation for MMs from the Yamato Mountains and Dome Fuji (Osawa and Nagao, 2002a,  
779 2002b; Osawa et al., 2000, 2003): no cosmogenic Ne was detected in the Yamato Mountains  
780 MMs, and only 10% of the Dome Fuji MMs showed detectable  $^{21}\text{Ne}$  excesses (Osawa et al.,  
781 2003), mostly such with high  $^{20}\text{Ne}/^4\text{He}$  ratios (see their Fig. 5).

782 From the nominal amounts of cosmogenic  $^{21}\text{Ne}$  (Table 6; chapter 3.4), we have  
783 calculated nominal cosmic ray exposure ages and inferred places of origin by considering the  
784 Poynting-Robertson effect of small particles spiraling towards the Sun (Wyatt and Whipple,  
785 1950; Trappitsch and Leya, 2013). The calculations, the results of which are listed in Table 7,  
786 were obtained using the Trappitsch and Leya (2013) cosmic ray production rates, with updates.  
787 Two values are listed in each case, corresponding to the two approaches for defining the  
788 trapped composition used in Table 6 and described in chapter 3.4. We have done the same  
789 using  $^3\text{He}$  (also two sets of values corresponding to the two values in Table 6). For this, we  
790 corrected  $^3\text{He}$  assuming recoil losses of 32% (including losses of directly produced  $^3\text{He}$  and  
791 the larger losses of  $^3\text{H}$  produced as a precursor), which seems roughly appropriate for particles  
792 in the studied size range (Ott et al., 2009; Trappitsch and Leya, 2016). No values are given for  
793 the cases ( $^{21}\text{Ne}$  in DC 06\_07\_213;  $^3\text{He}$  in DC 06\_09\_50 and DC 06\_09\_149) that result in  
794 negative nominal values (see also chapter 4.5). Note also that, apart from the analytical and  
795 production rate uncertainties, the action of the Poynting-Robertson effect may be more  
796 complicated than in this simple approach, in particular in case of non-spherical and / or fluffy  
797 particles (Kimura et al., 2002). Moreover, the approach considers only the Poynting-  
798 Robertson effect and not others that may affect the orbit of a particle.

799 The most convincing case is that of DC 06\_08\_01, which results in a CRE age of  $\sim 2$  Ma  
800 and a place of origin of  $\sim 4$  au, i.e. well in the asteroid belt. Notably,  $^3\text{He}$  gives consistent  
801 results, indicating that any loss of cosmogenic  $^3\text{He}$  has been small. Interestingly, this is an

802 Xtal MM characterized by low concentration of solar wind He, relative to solar wind Ne  
803 (chapter 4.2; Fig. 5). On the one hand, the relatively low background of solar wind He leads to  
804 a relatively high  $^3\text{He}/^4\text{He}$  ratio of  $\sim 14 \times 10^{-4}$  (Table 2) and thus allows identifying rather  
805 clearly the abundance of cosmogenic  $^3\text{He}$  (Fig. 2). On the other hand, low  $^4\text{He}$  with high  $^3\text{He}$   
806 also demonstrates the different loss behavior of surface-sited solar wind vs. cosmogenic He  
807 contained in the bulk of the MM. Consistent results from  $^{21}\text{Ne}$  and  $^3\text{He}$  are also obtained for  
808 Fg/Sc DC 06\_09\_11, however with a very short inferred exposure age of only  $\sim 0.2$  Ma with  
809 an origin at  $\sim 1.5$  au. Ages from  $^{21}\text{Ne}$  are also short for DC 06\_09\_50 and DC 06\_09\_63,  
810 while DC 06\_09\_189 (Fg/Sc) is similar to DC 06\_08\_01, i.e. compatible with an origin in the  
811 asteroid belt. The same is true for the other case of “safe” cosmogenic  $^3\text{He}$ , DC\_06\_07\_213  
812 (Fig. 1), with an inferred CRE age of  $\sim 1$  Ma, and coming from  $\sim 3$  au. No  $^{21}\text{Ne}$  age could be  
813 obtained for this MM, however. Finally, a rather long cosmic ray exposure from  $^{21}\text{Ne}$  is  
814 indicated for DC 06\_09\_149, which has the smallest analytical uncertainty and is clearly  
815 offset from the trapped composition lines in Fig. 2. The nominal age of  $\sim 15$  Ma, still with  
816 comparably large uncertainty, suggests an origin at a much larger distance, possibly beyond  
817 Saturn, thus from a cometary source. This age (like all the other nominal ages) rests on the  
818 assumption that the cosmic ray exposure took place during travel as a small particle.  
819 However, it cannot be ruled out that much (or even most) cosmogenic  $^{21}\text{Ne}$  production took  
820 place in the parent body regolith instead (Trappitsch and Leya, 2013). For GCR production in  
821 a well-mixed regolith the  $^{21}\text{Ne}$  production rate has been estimated as  $0.11 \times 10^{-8}$  cm<sup>3</sup> STP per  
822 gram and Ma (Trappitsch and Leya, 2013), which in case of DC 06\_09\_149 would mean an  
823 exposure roughly 100 to 150 Ma.

824



825 Table 7. Nominal cosmic ray exposure (CRE) ages and implied places of origin (distance  
826 from the sun) of Dome C MMs. These have been calculated following Trappitsch and Leya  
827 (2013) from the interplay between cosmic ray production and action of the Poynting-  
828 Robertson effect. The approach assumes  $^{21}\text{Ne}$  and  $^3\text{He}$  excesses over abundances in common  
829 trapped components are due to cosmic ray production, as described in the text and listed in  
830 Table 6, with an assumed 32% recoil loss of cosmogenic  $^3\text{He}$  (see text). For production by  
831 solar cosmic rays updated production rates for a rigidity of 100 MV have been used. Chemical  
832 abundances used for the calculation are CM chondritic. Column 2 gives the type of MM  
833 (Table 1). In the calculations masses for the complete MMs three times those of the analyzed  
834 specimens were assumed, with correspondingly larger sizes. Values in italics / small print are  
835 suspicious and the observed effects may require an explanation other than cosmic ray  
836 exposure, as discussed in the text (chapter 4.4).

sample	type	$T_{21}$ (Ma)	$r_{21}$ (au)	$T_3$ (Ma)	$r_3$ (au)
DC 06_07_213	Xtal	--	--	1.1 (-0.3, +0.3) 0.9 (-0.3, +0.3)	3.3 (-0.4, +0.4) 3.0 (-0.5, +0.4)
DC 06_08_01	Xtal	2.52 (-1.42, +1.94) 1.50 (-0.89, +1.31)	4.64 (-1.50, +1.46) 3.63 (-1.18, +1.26)	2.1 (-0.3, +0.3) 2.0 (-0.3, +0.3)	4.3 (-0.3, +0.3) 4.1 (-0.3, +0.3)
DC 06_09_11	FgC/Sc	0.20 (-0.13, +0.19) 0.15 (-0.11, +0.18)	1.62 (-0.37, +0.44) 1.50 (-0.34, +0.43)	0.3 (-0.3, +0.7) 0.1 (-0.1, +0.6)	1.9 (-0.9, +1.1) 1.4 (-0.4, +1.2)
DC 06_09_50	FgC	0.11 (-0.06, +0.06) 0.07 (-0.04, +0.04)	1.28 (-0.14, +0.14) 1.17 (-0.09, +0.11)	--	--
DC 06_09_63	FgC/Xtal	0.05 (-0.04, +0.06) 0.03 (-0.03, +0.05)	1.14 (-0.12, +0.14) 1.08 (-0.08, +0.13)	<i>16.8 (-5.9, +6.0)</i> <i>14.7 (-4.0, +4.0)</i>	<i>10.2 (-2.0, +1.7)</i> <i>9.5 (-1.4, +1.2)</i>
DC_06_09_149	Xtal	17.2 (-10.3, +10.8) 12.3 (-8.9, +9.9)	14.6 (-5.3, +4.0) 12.4 (-5.8, +4.2)	--	--
DC 06_09_189	FgC/Sc	2.41 (-1.62, +2.35) 1.30 (-0.95, +1.62)	4.78 (-1.93, +1.87) 3.57 (-1.54, +1.67)	<i>26.1 (-9.2, +9.3)</i> <i>16.6 (-14.2, +14.2)</i>	<i>15.5 (-3.0, +2.4)</i> <i>12.3 (-7.5, +4.5)</i>

837

838 There are several additional results that are difficult to understand (or to accept, for that  
839 matter). As for  $^3\text{He}$  ages, these concern DC 06\_09\_63 and DC 06\_09\_189. The latter can be  
840 easily explained, though, and will disappear if we allow for a slightly higher  $^3\text{He}/^4\text{He}$  ratio for  
841 the trapped component ( $>3.26 \times 10^{-4}$  instead of  $(2.85 \pm 0.12) \times 10^{-4}$  and  $(3.00 \pm 0.20) \times 10^{-4}$  in  
842 the two approaches will do). DC 06\_09\_63 is not as easily explained away. Although the  
843 measured  $^3\text{He}/^4\text{He}$  of  $(4.14 \pm 0.30) \times 10^{-4}$  is lower than the ratio in the SW proper, it is still  
844 much higher than in the FSW component and the mixing approach (alternative 1) suggests a  
845 trapped ratio of  $(2.83 \pm 0.40) \times 10^{-4}$ . It is also much higher than in the MMs with the highest  
846 SW concentration, where the influence of the cosmogenic component must be suppressed.  
847 The lack of equivalent amounts of cosmogenic Ne suggests a non-cosmogenic origin for the  
848  $^3\text{He}$  (if real), and similarly excesses of  $^3\text{He}$  not easily attributed to cosmic ray production have  
849 been found in some IDPs (Nier and Schlutter, 1993; Pepin et al., 2000, 2001). The more  
850 distinct excesses in these studies, with measured  $^3\text{He}/^4\text{He}$  often clearly above the SW value,  
851 would require unreasonably long CRE times of between 50 Ma and  $>10$  Ga, and are, as in our

852 case, characterized by lack of corresponding excesses of cosmogenic  $^{21}\text{Ne}$ . At this time, we  
853 cannot add further to the extensive discussions of possible alternative explanations by Pepin et  
854 al. (2000, 2001), but none of them seems totally convincing.

#### 855 **4.5. Cometary origins (?)**

856 The smaller IDPs collected in the stratosphere most probably have a cometary origin, in  
857 particular for the chondritic porous (CP) subtype (e.g., Bradley, 2005; Ishii et al., 2008;  
858 Messenger et al., 2003; Busemann et al., 2009). In contrast, micrometeorites recovered from  
859 ice and snow, from traps, or fossil have generally been regarded as of asteroidal origin and as  
860 largely related to common meteorites (Kurat et al., 1994; Genge et al., 1997, 2020; Taylor et  
861 al., 2012; Cordier and Folco, 2014; Noguchi et al., 2015; Shyam Prasad et al., 2018),  
862 including differentiated ones (Taylor et al., 2007; Cordier et al., 2012). The large deuterium  
863 excesses (Duprat et al., 2010) and the high nitrogen content of their organic matter (Dartois et  
864 al., 2013; Yabuta et al., 2017) is suggestive of a cometary origin for the ultra-carbonaceous  
865 MMs, but otherwise the question whether at least some MMs are cometary has loomed large  
866 from the start of MM studies (e.g., Noguchi et al., 2015). Still, the modelling by Nesvorný et  
867 al. (2010), see also Carrillo-Sánchez et al. (2020) and (Rojas et al, 2021), suggests that a  
868 significant part of the cosmic dust reaching Earth in the size range of the MMs may derive  
869 from Jupiter Family Comets (JFC).

870 Noble gases can contribute in this matter, in different ways. Particles from asteroidal  
871 and cometary sources may have, on average, different entry velocities when encountering  
872 Earth, and, in the study of IDPs, Nier and Schlutter (1990, 1993) tried to use the release  
873 profile of solar wind He as a measure. In principle, a similar approach might be applicable to  
874 MMs, however, as we have shown in chapter 4.1, also the mineralogical makeup plays a role  
875 for the observed He abundance: Xtal MMs in our collection have much lower  $^4\text{He}$  abundances  
876 and  $^4\text{He}/^{20}\text{Ne}$  ratios than FgC MMs. While we have not studied the release pattern in this  
877 work, presumably it is also different between the two types, which, if not taken into account,  
878 tends to obscure the entry effect. Still, it may be a useful approach in future work.

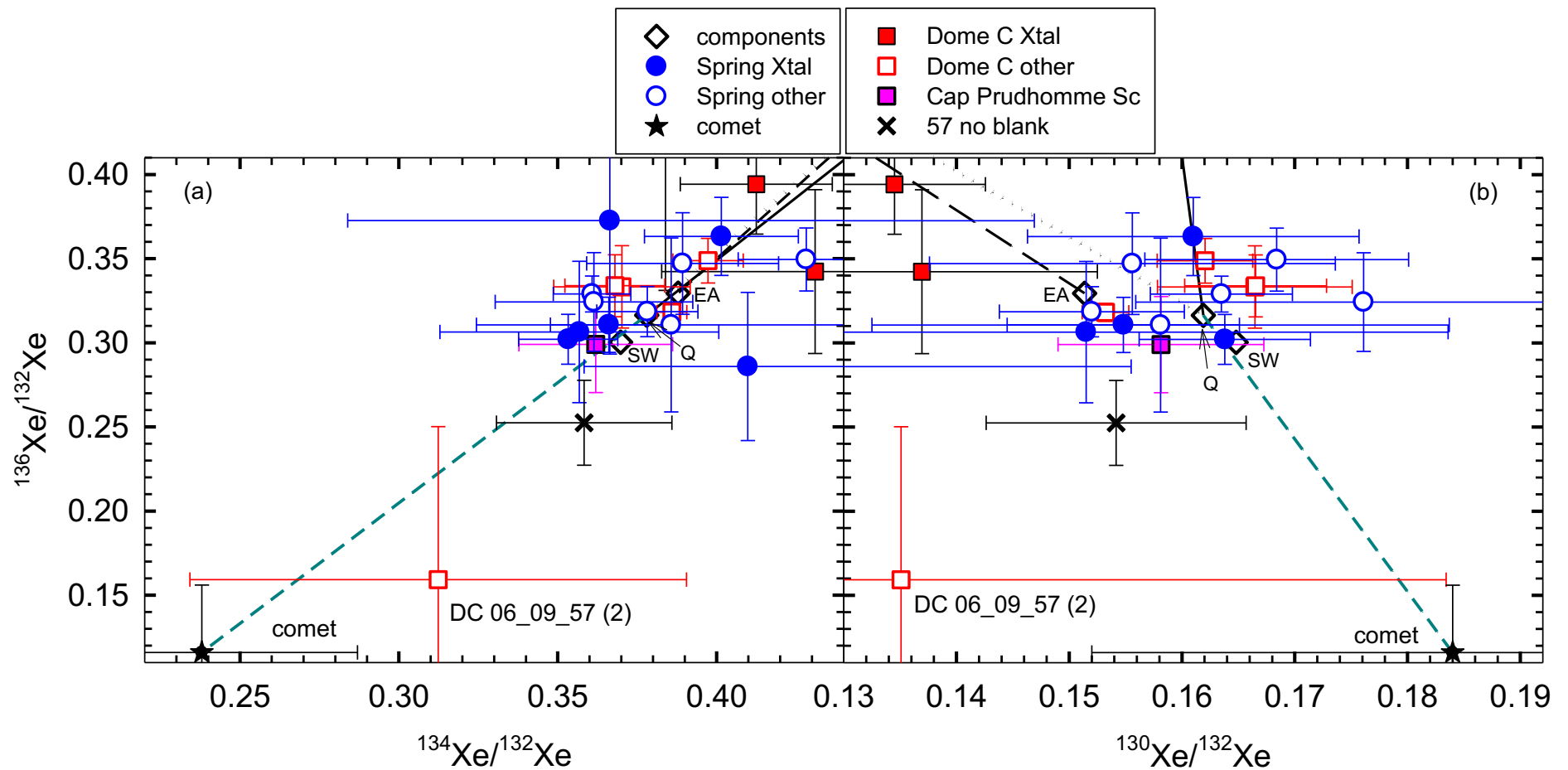
879 Another approach can be based on differences in cosmic ray exposure. In our case, and  
880 presumably in all cases involving primitive small particles, this is analytically challenging  
881 because of the large abundances of solar wind gas, with only minor and barely (if at all)  
882 detectable excesses of cosmogenic  $^3\text{He}$  and  $^{21}\text{Ne}$ , with the added problem that cosmogenic  
883 gases (like the trapped gases) may have been lost during atmospheric entry (e.g., Füre et al.,  
884 2013; Baecker et al., 2018). In our data set, nominal CRE ages that we were able to obtain are  
885 all consistent with an asteroidal source, with the possible exception of DC 06\_09\_149 and the  
886 exception of the possible excess  $^3\text{He}$  in DC 06\_09\_63 (chapter 4.4). They do not, however,  
887 rule out a cometary origin, as once ejected from their parent body, cometary dust particles are  
888 subject to non-gravitational forces that affect their initial velocities and trajectories and may  
889 result in orbits close to those expected from asteroidal dust.

890 A third approach can be based on the search for signatures in the trapped noble gas  
891 components that have been found in *bona fide* cometary materials. There are two sets of data  
892 that we can relate to in this approach, which have sampled different comets (though both

893 Jupiter Family) and different cometary reservoirs: the mass spectrometer onboard the Rosetta  
894 mission measured the composition of noble gases in the coma of comet 67P/Churyumov-  
895 Gerasimenko (Marty et al., 2017; Rubin et al., 2018), while He and Ne abundances were  
896 measured in the laboratory in solids captured from the coma of 81P/Wild 2 in aerogel and  
897 returned to Earth (Marty et al., 2008). The former presumably measured gases that were  
898 trapped in ices (maybe primarily CO<sub>2</sub> ice; Rubin et al., 2018), while the latter analysis was of  
899 solid particles, probably high-temperature igneous grains (Marty et al., 2008).

900 In fact, we do find some similarities between the observed signatures, which, however,  
901 are suggestive only. Two of our MMs show similarities to features observed in the coma of  
902 67P/Churyumov-Gerasimenko. For one, the elemental abundance ratios <sup>36</sup>Ar/<sup>132</sup>Xe and  
903 <sup>84</sup>Kr/<sup>132</sup>Xe for DC 06\_09\_189 (Figs. 7 and 8) are almost identical to what has been inferred  
904 for the bulk abundance ratios of the coma gases (Rubin et al., 2018). Given that a substantial  
905 fraction of <sup>36</sup>Ar is probably from solar wind, this must appear to be fortuitous, at least as far as  
906 <sup>36</sup>Ar/<sup>132</sup>Xe is concerned. One might also expect some elemental fractionation between noble  
907 gases trapped in ice vs. other, more refractory, solids.

908 More telling than elemental ratios are isotopic ratios, and the second similarity is in the  
909 isotopic composition of Xe and of Ar. Xe as measured in the coma of Churyumov-  
910 Gerasimenko (Marty et al., 2017) is highly diagnostic, i.e. characterized by huge depletions of  
911 the two heaviest isotopes, <sup>134</sup>Xe and <sup>136</sup>Xe, when compared to other Solar System reservoirs.  
912 A hint for a contribution from such a component is seen in the Xe pattern of the small MM  
913 fraction DC 06\_09\_57(2) shown in Fig. 4, and in a more extended version in Fig. 9. But this  
914 case has been analytically challenging, with an amount of <sup>132</sup>Xe of only ~2x10<sup>-15</sup> cm<sup>3</sup> STP  
915 (some 50,000 atoms) after blank correction (<sup>136</sup>Xe: ~8600 atoms), and where the blank  
916 contributed about half of the measured <sup>132</sup>Xe (2/3 in case of <sup>136</sup>Xe). To illustrate the point, we  
917 show in Fig. 9 also the ratios as measured, before blank subtraction. In essence, while  
918 suggestive, the measurement errors, both from the MM and Rosetta, are too large for a firm  
919 conclusion. It is intriguing, though, that in the same MM sample we also measured highly  
920 unusual Ar, with <sup>38</sup>Ar/<sup>36</sup>Ar = 0.1495 ± 0.039, significantly lower than in any other well-  
921 defined trapped Ar component (chapter 3.2). The corresponding <sup>36</sup>Ar/<sup>38</sup>Ar ratio of 6.69 ± 0.17  
922 agrees within uncertainties with the coma <sup>36</sup>Ar/<sup>38</sup>Ar ratio of 5.4 ± 1.4 reported by Rubin et al.  
923 (2018), however, in this case, the large error of the comet measurement prevents any firm  
924 conclusion. In addition, the Ar/Xe and Kr/Xe ratios for DC 06\_09\_57(2) are significantly  
925 larger than reported for coma gas (Fig. 7), so strong elemental fractionation would be  
926 required.



927

928 Figure 9. Same as Figure 4, but with scale expanded to include DC 06\_09\_57(2) and the composition measured in the coma of comet Churyumov-  
 929 Gerasimenko (Marty et al., 2017). Also shown is the measured value for DC 06\_09\_57(2), without extraction blank subtracted (“57 no blank”).

930

931 The signatures discussed above are likely those of the “icy” cometary component, but,  
932 in the MMs, we are dealing with more refractory solids. So, if a connection to our MMs  
933 actually exists, there must have been some equilibration between noble gases in cometary ice  
934 and cometary solids. Less surprising might be to find, in grains of cometary origin, the  
935 signature that has been observed in grains returned by the Stardust mission. The diagnostic  
936 feature here is the isotopic composition of Ne, which resembles Ne in the Q phase of  
937 chondritic meteorites (Marty et al., 2008). In fact, the same signature appears to have been  
938 seen recently in a refractory IDP, Manchanito (Ogliore et al., 2020), for which also other  
939 properties point toward a cometary origin. Data for this IDP, as well as the Stardust grain  
940 data, are plotted together with our MM data in the Ne three-isotope plot of Fig. 2b. Obviously,  
941 two of our Xtal grains, DC 06\_07\_213 and DC 06\_09\_141 (both with relatively low  $^{20}\text{Ne}$   
942 abundance), plot at a similar position, albeit at slightly higher  $^{20}\text{Ne}/^{22}\text{Ne}$ , probably due to  
943 contribution from SW Ne. Presence of Q as a trapped noble gas component is certainly  
944 consistent with the Xe isotopic composition we observe, not only in these, but also most other  
945 MMs (Fig. 4; chapter 3.3). but the  $^{20}\text{Ne}/^{132}\text{Xe}$  ratio for these MMs is on the order of 1000 or  
946 higher, i.e. much higher than the ratio of 3 found for Q gas in carbonaceous chondrites  
947 (Busemann et al., 2000; Ott, 2014). Thus it is unlikely to be hosted by the Q phase as known  
948 from macroscopic meteorites that come from asteroids. It is also opposite the direction  
949 expected in case of partial loss of Q-phase noble gases. Obviously, although the analytical  
950 errors do not allow to firmly equate the observed composition with that of Q-Ne, the same  
951 holds for the Manchanito particle and Stardust grain data. Having data for Xe (or the complete  
952 noble gas spectrum) in Manchanito and Stardust grains would have been useful in this  
953 context. Still, the similarity between the data is intriguing, and with the Stardust grains  
954 undoubtedly cometary, the two MMs and the Manchanito IDP may very well carry cometary  
955 signatures.

956

## 957 **5. Summary - Conclusions**

958 We have performed a complete noble gas study on fragments from ten Antarctic  
959 micrometeorites (AMMs) collected at Dome C, including the isotopes of Kr and Xe, which  
960 have been largely missing in previous noble gas studies of micrometeorites. Additional data  
961 obtained on a scoriaceous MM from Cap Prudhomme do not provide much information. In  
962 the Dome C MMs, He and Ne are dominated by a solar component, with lower  $^4\text{He}$   
963 concentrations and  $^4\text{He}/^{20}\text{Ne}$  ratios in crystalline (Xtal) compared to fine-grained  
964 carbonaceous (FgC) MMs. The latter fall in the high range of solar wind noble gas  
965 concentrations seen in earlier work, which may be related to the collection method (gentle and  
966 rapid melting of surface snow) and indicate existence of a noble gas host phase in MMs that  
967 may be affected by exposure to liquid water. The abundances of (volume-correlated) heavier  
968 gases are similar to what was found in previous studies of MMs. For this reason, solar wind is  
969 also an important part of Ar and may make also a noticeable contribution to Kr in some cases,  
970 however not to Xe.

971 Xe isotopic ratios are generally in between the composition dominating in primitive  
972 macroscopic meteorites (Q component) and air, but, in most cases, uncertainties are too large

973 for strong conclusions. Because of the high abundances of SW He and Ne, cosmogenic  
974 contributions are difficult to resolve. Nevertheless, when resolvable, cosmic ray exposure  
975 ages based on cosmogenic  $^{21}\text{Ne}$  in combination with the Poynting-Robertson effect are  
976 consistent with an origin from the asteroid belt in most cases. The same is true for the rarer  
977 cases where we could also derive CRE ages from  $^3\text{He}$ . One of the MMs (of FgC/Xtal variety)  
978 shows a  $^3\text{He}$  excess similar to what has been seen in some cluster IDPs.

979 There are hints that some of our (non-representative sample of DC) MMs may relate to  
980 a cometary source, but uncertainties are too large for a firm conclusion. These include

- 981 • A Xtal MM, for which the abundance of cosmogenic  $^{21}\text{Ne}$  suggests it may  
982 originate from beyond the orbit of Saturn.
- 983 • A small specimen taken from a FgC MM that may contain Xe deficient in the  
984 heavy isotopes  $^{134}\text{Xe}$  and  $^{136}\text{Xe}$ , like in the Xe component identified in the coma  
985 of comet 67P/Churyumov-Gerasimenko, where it is probably derived from  
986 cometary ice. The same MM has a precisely measured highly unusual  $^{36}\text{Ar}/^{38}\text{Ar}$   
987 ratio of  $\sim 6.7$ , consistent with the measurement of coma Ar ( $^{36}\text{Ar}/^{38}\text{Ar} = 5.4 \pm$   
988  $1.4$ ). In this case, the large error of the coma measurement is an obstacle for a  
989 firm conclusion.
- 990 • Two MMs of Xtal type, with low SW contributions, that show Ne similar to  
991 what has been found in laboratory analysis of refractory grains captured from  
992 the coma of comet 81P/Wild 2 by the Stardust mission, and also more recently  
993 in the IDP Manchanito, where this was considered as suggesting a cometary  
994 origin., While trapped Ne with such a composition is also characteristic of the Q  
995 component found in macroscopic meteorites, a connection to Q-Ne (and thus a  
996 chondritic parent body) is unlikely because the Ne/Xe ratio (not obtained in the  
997 Stardust and Manchanito analyses) differs by orders of magnitude.

998

## 999 **Declaration of Competing Interest**

1000 The authors declare no competing interests.

1001

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1011

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1013 **References:**

- 1014 Albarede F., Ballhaus C., Blichert-Toft J., Lee C.-T., Marty B., Moynier F. and Yin Q.-Z.  
1015 (2013) Asteroidal impacts and the origin of terrestrial and lunar volatiles. *Icarus* **222**,  
1016 44-52. <https://doi.org/10.1016/j.icarus.2012.10.026>.
- 1017 Alexander C. M. O'D., Bowden R., Fogel M. L., Howard K. T., Herd C. D. K. and Nittler L.  
1018 R. (2012) The provenances of asteroids, and their contributions to the volatile  
1019 inventories of the terrestrial planets. *Science* **337**, 721-723.  
1020 <https://doi.org/10.1126/science.1223474>.
- 1021 Baecker B. (2014) Primordial and other noble gases in micrometeorites. PhD Thesis,  
1022 University of Heidelberg, Germany, 362 p.
- 1023 Baecker B., Ott U., Cordier C., Folco L., Trierloff M., van Ginneken M. and Rochette P.  
1024 (2018) Noble gases in micrometeorites from the Transantarctic Mountains. *Geochim.*  
1025 *Cosmochim. Acta* **242**, 266-297. <https://doi.org/10.1016/j.gca.2018.08.02>.
- 1026 Basford J. R., Dragon J. C., Pepin R. O., Coscio Jr. M. R. and Murthy V. R. (1973) Krypton  
1027 and xenon in lunar fines. *Proc. 4th Lunar Sci. Conf. (Suppl. 4, Geochim. Cosmochim*  
1028 *Acta)*, 1915-1955.
- 1029 Bekaert D. V., Avice G., Marty B., Henderson B. and Gudipati, M. S. (2017) Stepwise  
1030 heating of lunar anorthosites 60025, 60215, 65315 possibly reveals an indigenous noble  
1031 gas component on the Moon. *Geochim. Cosmochim. Acta* **218**, 114-131.  
1032 <https://doi.org/10.1016/j.gca.2017.08.041>.
- 1033 Benkert J.-P., Baur H., Signer P. and Wieler R. (1993) He, Ne, and Ar from the solar wind  
1034 and solar energetic particles in lunar ilmenites and pyroxenes. *J. Geophys. Res.* **98**,  
1035 13,147-13,162. <https://doi.org/10.1029/93JE01460>.
- 1036 Bradley J. P. (2005) Interplanetary dust particles. In: Davis, A.M. (Ed.), *Treatise in Geo-*  
1037 *chemistry*, vol.1. Elsevier–Pergamon, Amsterdam, pp.689-711.
- 1038 Bradley J. P., Ishii H. A., Gillis-Davis J. J., Ciston J., Nielsen M. H., Bechtel H. A. and  
1039 Martin M. C. (2014) Detection of solar-wind produced water in irradiated rims on  
1040 silicate minerals. *Proc. Natl. Acad. Sci.* **111**, 1732-1735.  
1041 <https://doi.org/10.1073/pnas.1320115111>.
- 1042 Britt D. and Consolmagno G. (2003 ) Stony meteorite porosities and densities: A review of  
1043 the data through 2001. *Meteoritics & Planetary Science* **38**, 1161-1180.  
1044 <https://doi.org/10.1111/j.1945-5100.2003.tb00305.x>.
- 1045 Busemann H., Baur H. and Wieler R. (2000) Primordial noble gases in “phase Q” in  
1046 carbonaceous and ordinary chondrites studied by closed system stepped etching.  
1047 *Meteorit. Planet. Sci.* **35**, 949-973. <https://doi.org/10.1111/j.1945-5100.2000.tb01485.x>.
- 1048 Busemann H., Nguyen A. N., Cody G. D., Hoppe P., Kilcoyne A. L. D., Stroud R. M., Zega  
1049 T. J. and Nittler L. R. (2009) Ultra-primitive interplanetary dust particles from the



- 1050 comet 26P/Grigg–Skjellerup dust stream collection. *Earth Planet. Sci. Lett.* **288**, 44–57.  
1051 <https://doi.org/10.1016/j.epsl.2009.09.007>.
- 1052 Carillo-Sánchez J. D., Gómez-Martin H. C., Bones D. L., Nesvorný D., Pokorný P., Benna  
1053 M., Flynn G. J. and Plane J.M.C. (2020) Cosmic dust fluxes in the atmospheres of  
1054 Earth, Mars, and Venus. *Icarus* **335**, #113395.  
1055 <https://doi.org/10.1016/j.icarus.2019.113395>.
- 1056 Cartwright J. A., Ott U., Herrmann S. and Agee C. B. (2014) Modern atmospheric signatures  
1057 in 4.4 Ga Martian meteorite NWA 7034. *Earth Planet. Sci. Lett.* **400**, 77-87.  
1058 <https://doi.org/10.1016/j.epsl.2014.05.008>.
- 1059 Cordier C. and Folco L. (2014) Oxygen isotopes in cosmic spherules and the composition of  
1060 the near Earth interplanetary dust complex. *Geochim. Cosmochim. Acta* **146**, 18-26.  
1061 <https://doi.org/10.1016/j.gca.2014.09.038>.
- 1062 Cordier C., Folco L., Suavet C., Sonzogni C. and Rochette P. (2011a) Major, trace element  
1063 and oxygen isotope study of glass cosmic spherules of chondritic composition: The  
1064 record of their source material and atmospheric entry heating. *Geochim. Cosmochim.*  
1065 *Acta* **75**, 5203-5218. <https://doi.org/10.1016/j.gca.2011.06.014>.
- 1066 Cordier C., Folco L. and Taylor S. (2011b) Vestoid cosmic spherules from the South Pole  
1067 Water Well and Transantarctic Mountains (Antarctica): A major and trace element  
1068 study. *Geochim. Cosmochim. Acta* **75**, 1199-1215.  
1069 <https://doi.org/10.1016/j.gca.2010.11.024>.
- 1070 Cordier C., Suavet C., Folco L., Rochette P. and Sonzogni C. (2012) HED-like cosmic  
1071 spherules from the Transantarctic Mountains, Antarctica: Major and trace element  
1072 abundances and oxygen isotopic compositions. *Geochim. Cosmochim. Acta* **77**, 515-  
1073 529. <https://doi.org/10.1016/j.gca.2011.10.021>.
- 1074 Cordier C., Baecker B., Ott U., Folco L. and Trieloff M. (2018) A new type of oxidized and  
1075 pre-irradiated micrometeorite. *Geochim. Cosmochim. Acta* **233**, 135-158.  
1076 <https://doi.org/10.1016/j.gca.2018.04.010>.
- 1077 Cremonese G., Borin P., Martellato E., Marzari F. and Bruno M. (2012) New calibration of  
1078 the micrometeoroid flux on Earth. *Astrophys. J. Lett.* **749**, L40.  
1079 <https://doi.org/10.1088/2041-8205/749/2/L40>.
- 1080 Crowther S., Mohapatra R. K., Turner G., Blagburn D., Kehm K., and Gilmour J. D. (2008)  
1081 Characteristics and applications of RELAX, an ultrasensitive resonance ionization mass  
1082 spectrometer for xenon. *J. Anal. At. Spectrom.* **23**, 938-947.  
1083 <https://doi.10.1039/B802899K>.
- 1084 Dartois E., Engrand C., Brunetto R., Duprat J., Pino T., Quirico E., Remusat L., Bardin N.,  
1085 Briani G., Mostefaoui S., Morinaud G., Crane B., Szwec N., Delauche L., Jamme F.,  
1086 Sandt Ch. and Dumas P. (2013) UltraCarbonaceous Antarctic micrometeorites,  
1087 probing the Solar System beyond the nitrogen snow-line. *Icarus* **224**, 243-252.  
1088 <https://doi.org/10.1016/j.icarus.2013.03.002>.

- 1089 Dartois E., Engrand C., Duprat J., Godard M., Charon E., Delauche L., Sandt C. and  
 1090 Borondics F. (2018) Dome C ultracarbonaceous Antarctic micrometeorites. Infrared and  
 1091 Raman fingerprints. *Astron. Astrophys.* **609**, A65. [https://doi.org/10.1051/0004-](https://doi.org/10.1051/0004-6361/201731322)  
 1092 [6361/201731322](https://doi.org/10.1051/0004-6361/201731322).
- 1093 Duprat J., Engrand C., Maurette M., Kurat G., Gounelle M. and Hammer C. (2007)  
 1094 Micrometeorites from central Antarctic snow: The CONCORDIA collection. *Adv.Space*  
 1095 *Res.* **39**, 605-611. <https://doi.org/10.1016/j.asr.2006.05.029>.
- 1096 Duprat J., Dobricâ E., Engrand C., Aléon J., Marrocchi Y., Mostefaoui S., Meibom A.,  
 1097 Leroux H., Rouzaud J.-N. and Gounelle M. (2010) Extreme Deuterium excesses in  
 1098 ultracarbonaceous micrometeorites from Central Antarctic snow. *Science* **328**, 742-  
 1099 745. <https://doi.org/10.1126/science.1184832>.
- 1100 Eberhardt P., Eugster O., and Marti K. (1965) A redetermination of the isotopic composition  
 1101 of atmospheric neon. *Z. Naturforsch.* **20a**, 623-624. [https://doi.org/10.1515/zna-1965-](https://doi.org/10.1515/zna-1965-0420)  
 1102 [0420](https://doi.org/10.1515/zna-1965-0420).
- 1103 Engrand C. and Maurette M. (1998) Carbonaceous micrometeorites from Antarctica.  
 1104 *Meteorit. Planet. Sci.* **33**, 565-580. <https://doi.org/10.1111/j.1945-5100.1998.tb01665.x>.
- 1105 Flynn G. J. (1996) The delivery of organic matter from asteroids and comets to the early  
 1106 surface of Mars. *Earth, Moon, and Planets* **72**, 469-474.  
 1107 <https://doi.org/10.1007/BF00117551>.
- 1108 Folco L., Rochette P., Perchiazzi N., D'Orazio M., Laurenzi M. A. and Tiepolo M. (2008)  
 1109 Microtektites from Victoria Land Transantarctic Mountains. *Geology* **36**, 291-294.  
 1110 <https://doi.org/10.1130/G24528A.1>.
- 1111 Füri E., Aléon-Toppani A., Marty B., Libourel G. and Zimmermann L. (2013) Effects of  
 1112 atmospheric entry heating on the noble gas and nitrogen content of micrometeorites.  
 1113 *Earth Planet. Sci. Lett.* **377-378**, 1-12. <https://doi.org/10.1016/j.epsl.2013.07.031>.
- 1114 Gardner C. S., Liu A. Z., Marsh D. R., Feng W. and Plane J. M. C. (2014) Inferring the  
 1115 global cosmic dust influx to the Earth's atmosphere from lidar observations of the  
 1116 vertical flux of mesospheric Na. *J. Geophys. Res. Space Physics* **119**, 7870–7879.
- 1117 Genge M. J. (2008) Micrometeorites and their implications for meteors. *Earth, Moon, and*  
 1118 *Planets* **102**, 525-535. <https://doi.org/10.1007/s11038-007-9185-z>.
- 1119 Genge M. J., Grady M. M. and Hutchison R. (1997) The textures and compositions of fine-  
 1120 grained Antarctic micrometeorites: Implications for comparison with meteorites.  
 1121 *Geochim. Cosmochim. Acta* **61**, 5149-5162. [https://doi.org/10.1016/S0016-](https://doi.org/10.1016/S0016-7037(97)00308-6)  
 1122 [7037\(97\)00308-6](https://doi.org/10.1016/S0016-7037(97)00308-6).
- 1123 Genge M. J., Engrand C., Gounelle M. and Taylor S. (2008) The classification of  
 1124 micrometeorites. *Meteorit. Planet. Sci.* **43**, 497-515. [https://doi.org/10.1111/j.1945-](https://doi.org/10.1111/j.1945-5100.2008.tb00668.x)  
 1125 [5100.2008.tb00668.x](https://doi.org/10.1111/j.1945-5100.2008.tb00668.x)

- 1126 Genge, M. J., van Ginneken M., Suttle M. D. and Harvey R.P. (2018) Accumulation  
1127 mechanisms of micrometeorites in an ancient supraglacial moraine at Larkman  
1128 Nunatak, Antarctica. *Meteorit. Planet. Sci.* **53**, 2051-2066.  
1129 <https://doi.org/10.1111/maps.13107>.
- 1130 Genge M. J., Van Ginneken M. and Suttle M. D. (2020) Micrometeorites: Insights into the  
1131 flux, sources and atmospheric entry of extraterrestrial dust at Earth. *Planetary and Space  
1132 Science* **187**, #104900. <https://doi.org/10.1016/j.pss.2020.104900>.
- 1133 Gilmour J. D., Lyon I. C., Johnston W. A. and Turner G. (1994) RELAX: An ultrasensitive,  
1134 resonance ionization mass spectrometer for xenon. *Rev. Sci. Instr.* **65**, 617-625.  
1135 <https://doi.org/10.1063/1.1145127>.
- 1136 Grün E., Zook H. A., Fechtig H. and Giese R. H. (1985) Collisional balance of the meteoritic  
1137 complex. *Icarus* **62**, 244–272. [https://doi.org/10.1016/0019-1035\(85\)90121-6](https://doi.org/10.1016/0019-1035(85)90121-6).
- 1138 Haack H., Grau T., Bischoff A., Horstmann M., Wasson J. T., Sørensen A., Laubenstein M.,  
1139 Ott U., Palme H., Gellissen M., Greenwood R. C., Pearson V. K., Franchi I. A., Gabelica  
1140 Z. and Schmitt-Kopplin P. (2012) Maribo-A new CM fall from Denmark. *Meteorit.  
1141 Planet. Sci.* **47**, 30–50. <https://doi.org/10.1111/j.1945-5100.2011.01311.x>.
- 1142 Heber V. S., Wieler R., Baur H., Olinger C., Friedmann T. A. and Burnett D. S. (2009) Noble  
1143 gas composition of the solar wind as collected by the Genesis mission. *Geochim.  
1144 Cosmochim. Acta* **73**, 7414-7432. <https://doi.org/10.1016/j.gca.2009.09.013>.
- 1145 Heber V. S., Baur H., Bochsler P., McKeegan K. D., Neugebauer M., Reisenfeld D. B.,  
1146 Wieler R. and Wiens R. C. (2012) Isotopic Mass Fractionation of Solar Wind: Evidence  
1147 from fast and slow Solar Wind collected by the Genesis mission. *Astrophys. J.* **759**, 121.  
1148 <https://doi.org/10.1088/0004-637X/759/2/121>.
- 1149 Hébrard E. and Marty B. (2014) Coupled noble gas-hydrocarbon evolution of the early Earth  
1150 atmosphere upon solar UV irradiation. *Earth Planet. Sci. Lett.* **385**, 40-48.  
1151 <https://doi.org/10.1016/j.epsl.2013.10.022>.
- 1152 Huss G. R. and Lewis R. S. (1994) Noble gases in presolar diamonds I: Three distinct  
1153 components and their implications for diamond origins. *Meteoritics* **29**, 791-810.  
1154 <https://doi.org/10.1111/j.1945-5100.1994.tb01094.x>.
- 1155 Imae N., Taylor S. and Iwata N. (2013) Micrometeorite precursors: Clues from the  
1156 mineralogy and petrology of their relict minerals. *Geochim. Cosmochim. Acta* **100**, 116-  
1157 157. <https://doi.org/10.1016/j.gca.2012.09.052>.
- 1158 Ishii H. A., Bradley J. P., Dai Z. R., Chi M., Kearsley A. T., Burchell M. J., Browning N. D.,  
1159 and Molster F. (2008) Comparison of comet 81P/Wild 2 dust with interplanetary dust  
1160 from comets. *Science* **319**, 447–450. <https://doi.org/10.1126/science.1150683>.
- 1161 Kimura, H., Okamoto, H. and Mukai, T. (2002) Radiation pressure and the Poynting-  
1162 Robertson effect for fluffy dust particles. *Icarus* **157**, 349–361.  
1163 <https://doi.org/10.1006/icar.2002.6849>.

- 1164 Kurat G., Koeberl C., Presper T., Brandstätter F. and Maurette M. (1994) Petrology and  
 1165 geochemistry of Antarctic micrometeorites. *Geochim. Cosmochim. Acta* **58**, 3879-3904.  
 1166 [https://doi.org/10.1016/0016-7037\(94\)90369-7](https://doi.org/10.1016/0016-7037(94)90369-7)
- 1167 Lee J. Y., Marti K., Severinghaus J. P., Kawamura K., Yoo H. S., Lee J. B. and Kim J. S.  
 1168 (2006) A redetermination of the isotopic abundances of atmospheric Ar. *Geochim.*  
 1169 *Cosmochim. Acta* **70**, 4507-4512. <https://doi.org/10.1016/j.gca.2006.06.1563>.
- 1170 Love S. G and Brownlee D. E. (1993) A direct measurement of the terrestrial mass accretion  
 1171 rate of cosmic dust. *Science* **262**, 550-553.  
 1172 <https://doi.org/10.1126/science.262.5133.550>.
- 1173 Marty B. (2012) The origins and concentrations of water, carbon, nitrogen and noble gases  
 1174 on Earth. *Earth Planet. Sci. Lett.* **313-314**, 56-66.  
 1175 <https://doi.org/10.1016/j.epsl.2011.10.040>.
- 1176 Marty B., Matrajt G., Zimmermann L., Engrand C. and Duprat J. (2002) Nitrogen and noble  
 1177 gas isotopes in Antarctic micrometeorites. *Lunar Planet. Sci.* **33**, abstract #1578.
- 1178 Marty B., Robert P. and Zimmermann L. (2005) Nitrogen and noble gases in  
 1179 micrometeorites. *Meteorit. Planet. Sci.* **40**, 881-894. <https://doi.org/10.1111/j.1945-5100.2005.tb00161.x>.
- 1181 Marty B., Palma R. L., Pepin R. O., Zimmermann L., Schlutter D. J., Burnard P. G., Westphal  
 1182 A. J., Snead C. J., Bajt S., Becker R. H. and Simones J. E. (2008) Helium and neon  
 1183 abundances and compositions in cometary matter. *Science* **319**, 75-78.  
 1184 <https://doi.org/10.1126/science.1148001>.
- 1185 Marty B., Avice G., Sano Y., Altwegg K., Balsiger H., Hässig M., Morbidelli A., Mousis O.  
 1186 and Rubin M. (2016) Origins of volatile elements (H, C, N, noble gases) on Earth and  
 1187 Mars in light of recent results from the ROSETTA cometary mission. *Earth Planet. Sci.*  
 1188 *Lett.* **441**, 91-102. <https://doi.org/10.1016/j.epsl.2016.02.031>.
- 1189 Marty B., Altwegg K., Balsiger H., Bar-Nun A., Bekaert D. V., Berthelier J.-J., Bieler A.,  
 1190 Briois C., Calmonte U., Combi M., De Keyser J., Fiethe B., Fuselier S. A., Gasc S.,  
 1191 Gombosi T. I., Hansen K. C., Hässig M., Jäckel A., Kopp E., Korth A., Le Roy L., Mall  
 1192 U., Mousis O., Owen T., Rème H., Rubin M., Sémon T., Tzou C.-Y., Waite J. H. and  
 1193 Wurz P. (2017) Xenon isotopes in 67P/Churyumov-Gerasimenko show that comets  
 1194 contributed to Earth's atmosphere. *Science* **356**, 1069-1072.  
 1195 <https://doi.org/10.1126/science.aal3496>.
- 1196 Maurette M. (2006) *Micrometeorites and the Mysteries of Our Origins*. Springer-Verlag,  
 1197 Berlin Heidelberg, New York, 330 pp..
- 1198 Maurette M., Olinger C., Christophe Michel-Levy M., Kurat G., Pourchet M., Brandstätter F.  
 1199 and Bourot-Denise M. (1991) A collection of diverse micrometeorites recovered from  
 1200 100 tonnes of Antarctic blue ice. *Nature* **351**, 44-47. <https://doi.org/10.1038/351044a0>.

- 1201 Maurette M., Duprat J., Engrand C., Gounelle M., Kurat G., Matrajt G. and Toppani A.  
1202 (2000) Accretion of neon, organics, CO<sub>2</sub>, nitrogen and water from large interplanetary  
1203 dust particles on the early Earth. *Planet. Space Sci.* **48**, 1117-1137.  
1204 [https://doi.org/10.1016/S0032-0633\(00\)00086-6](https://doi.org/10.1016/S0032-0633(00)00086-6).
- 1205 Meshik A., Hohenberg C., Pravdivtseva O. and Burnett D. (2014) Heavy noble gases in solar  
1206 wind delivered by Genesis mission. *Geochim. Cosmochim. Acta* **127**, 326-347.  
1207 <https://doi.org/10.1016/j.gca.2013.11.030>.
- 1208 Meshik A. P., Pravdivtseva O. V., Hohenberg C. M. and Burnett D. S. (2015) Refined  
1209 composition of solar wind xenon delivered by Genesis: Implication for primitive  
1210 terrestrial xenon. *Lunar Planet Sci.* **46**, #2640 (abstract).
- 1211 Messenger S., Keller L. P., Stadermann F. J., Walker R. M. and Zinner E. (2003) Samples of  
1212 stars beyond the solar system: silicate grains in interplanetary dust. *Science* **300**, 105–  
1213 108. <https://doi.org/10.1126/science.1080576>.
- 1214 Nagao K., Okazaki R., Nakamura T., Miura Y. N., Osawa T., Bajo K.-i., Matsuda S., Ebihara  
1215 M., Ireland T. R., Kitajima F., Naraoka H., Noguchi T., Tsuchiyama A., Yurimoto H.,  
1216 Zolensky M. E., Uesugi M., Shirai K., Abe M., Yada T., Ishibashi Y., Fujimura A.,  
1217 Mukai T., Ueno M., Okada T., Yoshikawa M. and Kawaguchi J. (2011) Irradiation  
1218 history of Itokawa regolith material deduced from noble gases in the Hayabusa samples.  
1219 *Science* **333**, 1128-1131. <https://doi.org/10.1126/science.1207785>.
- 1220 Nakamura T., Noguchi T., Ozono Y., Osawa T. and Nagao K. (2005) Mineralogy of  
1221 ultracarbonaceous large micrometeorites. *68th Annu. Meteorit. Soc. Meeting*, abstract  
1222 #5046.
- 1223 Nesvorný D., Jenniskens P., Levison H. F., Bottke W. F., Vokrouhlický D. and Gounelle M.  
1224 (2010) Cometary origin of the Zodiacal Cloud and carbonaceous micrometeorites.  
1225 Implications for hot debris disks. *Astrophys. Journ.* **713**, 816-836.  
1226 <https://doi.org/10.1088/0004-637X/713/2/816>.
- 1227 Nier A. O. and Schlutter D. J. (1990) Helium and neon isotopes in stratospheric particles.  
1228 *Meteoritics* **25**, 263–267. <https://doi.org/10.1111/j.1945-5100.1990.tb00710.x>.
- 1229 Nier A. O. and Schlutter D. J. (1993) The thermal history of interplanetary dust particles  
1230 collected in the Earth's stratosphere. *Meteoritics* **28**, 675-681.  
1231 <https://doi.org/10.1111/j.1945-5100.1993.tb00639.x>.
- 1232 Noguchi T., Ohashi N., Tsujimoto S., Mitsunari T., Bradley J. P., Nakamura T., Toh S.,  
1233 Stephan T., Iwatag N., and Imae N. (2015) Cometary dust in Antarctic ice and snow:  
1234 Past and present chondritic porous micrometeorites preserved on the Earth's surface.  
1235 *Earth Planet. Sci. Lett.* **410**, 1-11. <https://doi.org/10.1016/j.epsl.2014.11.012>.
- 1236 Ogliore R. C., Palma R. L., Stodolna, J., Nagashima K., Pepin R. O., Schlutter D. J.,  
1237 Gainsforth Z., Westphal A. J. and Huss G. R. (2020) Q-Gases in a late-forming  
1238 refractory interplanetary dust particle: A link to comet Wild 2. *Geochim. Cosmochim.*  
1239 *Acta* **271**, 116-131. <https://doi.org/10.1016/j.gca.2019.11.033>.

- 1240 Okazaki R., Noguchi T., Tsujimoto S.-i., Tobimatsu Y., Nakamura T., Ebihara M., Itoh S.,  
1241 Nagahara H., Tachibana S., Terada K. and Yabuta H. (2015) Mineralogy and noble gas  
1242 isotopes of micrometeorites collected from Antarctic snow. *Earth, Planets and Space* **67**,  
1243 90. <https://doi.org/10.1186/s40623-015-0261-8>.
- 1244 Olinger C. T., Maurette M., Das J. P. and Meshik A. (2013) Noble gas contents of unmelted  
1245 Cap-Prudhomme “Giant Micrometeorites”. *Lunar Planet. Sci.* **44**, abstract #2278.
- 1246 Osawa T. and Nagao K. (2002a) Noble gas compositions of Antarctic micrometeorites  
1247 collected at the Dome Fuji station in 1996 and 1997. *Meteorit. Planet. Sci.* **37**, 911–936.  
1248 <https://doi.org/10.1111/j.1945-5100.2002.tb00867.x>.
- 1249 Osawa T. and Nagao K. (2002b) On low noble gas concentrations in Antarctic  
1250 micrometeorites collected from Kuwagata Nunatak in the Yamato meteorite ice field.  
1251 *Antarct. Meteorite Res.* **15**, 165-177.
- 1252 Osawa T., Nagao K., Nakamura T. and Takaoka N. (2000) Noble gas measurement in  
1253 individual micrometeorites using laser gas-extraction system. *Antarct. Meteorite Res.* **13**,  
1254 322-341.
- 1255 Osawa T., Nagao K., Noguchi T., Nakazawa A. and Mikada J. I. (2003a) Remnant  
1256 extraterrestrial noble gases in Antarctic cosmic spherules. *Antarct. Meteorite Res.* **16**,  
1257 196-219.
- 1258 Osawa T., Nakamura T. and Nagao K. (2003b) Noble gas isotopes and mineral assemblages  
1259 of Antarctic micrometeorites collected at the meteorite ice field around the Yamato  
1260 Mountains. *Meteorit. Planet. Sci.* **38**, 1627–1640. [https://doi.org/10.1111/j.1945-  
1261 5100.2003.tb00005.x](https://doi.org/10.1111/j.1945-5100.2003.tb00005.x).
- 1262 Osawa T., Yamamoto Y., Noguchi T., Iose A. and Nagao K. (2010) Interior textures,  
1263 chemical compositions, and noble gas signatures of Antarctic cosmic spherules: Possible  
1264 sources of spherules with long exposure ages. *Meteorit. Planet. Sci.* **45**, 1320-1339.  
1265 <https://doi.org/10.1111/j.1945-5100.2010.01093.x>.
- 1266 Ott U. (2014) Planetary and pre-solar noble gases in meteorites. *Chemie der Erde –*  
1267 *Geochem.* **74**, 519-544. <https://doi.org/10.1016/j.chemer.2014.01.003>.
- 1268 Ott U. and Begemann F. (1985) Are all the Martian meteorites from Mars? *Nature* **317**, 509-  
1269 512. <https://doi.org/10.1038/317509a0>.
- 1270 Ott U., Heck P. R., Gyngard F., Wieler R., Wrobel F., Amari S. and Zinner E. (2009) He and  
1271 Ne ages of large presolar silicon carbide grains: Solving the recoil problem. *Pub.*  
1272 *Astronom. Soc. Australia* **26**, 297–302. <https://doi:10.1071/AS08039>.
- 1273 Ott U., Swindle T. D. and Schwenger S. P. (2019) Noble gases in Martian meteorites:  
1274 Budget, sources, sinks, and processes, In: *Volatiles in the Martian Crust* (ed. J. Filiberto  
1275 and S.P. Schwenger), 35-70, Elsevier.

- 1276 Owen T. (2008) The contributions of comets to planets, atmospheres, and life: Insights from  
 1277 Cassini-Huygens, Galileo, Giotto and inner planet missions. *Space Sci. Rev.* **138**, 301-  
 1278 316. <https://doi.org/10.1007/s11214-008-9306-7>.
- 1279 Owen T. and Bar-Nun A. (1993) Noble gases in atmospheres. *Nature* **361**, 693-694.
- 1280 Owen T., Bar-Nun A. and Kleinfeld I. (1992) Possible cometary origin of heavy noble gases  
 1281 in the atmospheres of Venus, Earth and Mars. *Nature* **358**, 43-46.  
 1282 <https://doi.org/10.1038/358043a0>.
- 1283 Ozima M. and Podosek F. A. (2002) Noble Gas Geochemistry. Cambridge University Press,  
 1284 Cambridge, New York, Oakleigh, Madrid, Cape Town. 286 pp..
- 1285 Pepin R. O. (1991) On the origin and early evolution of terrestrial planet atmospheres and  
 1286 meteoritic volatiles. *Icarus* **92**, 2-79. [https://doi.org/10.1016/0019-1035\(91\)90036-S](https://doi.org/10.1016/0019-1035(91)90036-S).
- 1287 Pepin R. O. (2006) Atmospheres on the terrestrial planets: Clues to origin and evolution.  
 1288 *Earth Planet. Sci. Lett.* **252**, 1-14. <https://doi.org/10.1016/j.epsl.2006.09.014>.
- 1289 Pepin R. O. and Porcelli D. (2002) Origin of noble gases in the terrestrial planets. In: *Noble*  
 1290 *Gases in Geochemistry and Cosmochemistry* (eds. D. Porcelli, C. J. Ballentine and R.  
 1291 Wieler). *Rev. Min. Geochem.* **47**, 191-246. <https://doi.org/10.2138/rmg.2002.47.7>.
- 1292 Pepin R. O., Palma R. L. and Schlutter D. J. (2000) Noble gases in interplanetary dust  
 1293 particles, I: The excess helium-3 problem and estimates of the relative fluxes of solar  
 1294 wind and solar energetic particles in interplanetary space. *Meteorit. Planet. Sci.* **35**, 495-  
 1295 504. <https://doi.org/10.1111/j.1945-5100.2000.tb01431.x>.
- 1296 Pepin R. O., Palma R. L. and Schlutter D. J. (2001) Noble gases in interplanetary dust  
 1297 particles, II: Excess helium-3 in cluster particles and modeling constraints on  
 1298 interplanetary dust particle exposure to cosmic-ray irradiation. *Meteorit. Planet. Sci.* **36**,  
 1299 1515-1534. <https://doi.org/10.1111/j.1945-5100.2001.tb01843.x>.
- 1300 Pernet-Fisher J. F., Joy K. H. and Gilmour J. D. (2020) Identifying primitive noble gas  
 1301 components in lunar ferroan anorthosites. *Icarus* **352**, 113977.  
 1302 <https://doi.org/10.1016/j.icarus.2020.113977>.
- 1303 Piani L., Marrocchi Y., Rigaudier T., Vacher L. G., Thomassin D. and Marty B. (2020)  
 1304 Earth's water may have been inherited from material similar to enstatite chondrite  
 1305 meteorites. *Science* **369**, 1110-1113. <https://doi.org/10.1126/science.aba1948>.
- 1306 Rochette P., Folco L., Suavet C., van Ginneken M., Gattacceca J., Perchiazzi N., Braucher R.  
 1307 and Harvey R. P. (2008) Micrometeorites from the Transantarctic Mountains. *Proc.*  
 1308 *National Acad. Sci.* **105**, 18206-18211. <https://doi.org/10.1073/pnas.0806049105>.
- 1309 Rojas J., Duprat J., Engrand C., Dartois E., Delauche L., Godard M., Gounelle M., Carrillo-  
 1310 Sánchez J. D., Pokorný P. and Plane J. M. C. (2021) The micrometeorite flux at Dome  
 1311 C (Antarctica), monitoring the accretion of extraterrestrial dust on Earth. *Earth Planet.*  
 1312 *Sci. Lett.* **560**, # 116794. <https://doi.org/10.1016/j.epsl.2021.116794>.

- 1313 Rubin M., Altwegg K., Balsiger H., Bar-Nun A., Berthelier J.-J., Briois C., Calmonte U.,  
1314 Combi M., De Keyser J., Fiethe B., Fuselier S. A., Gasc S., Gombosi T. I., Hansen K.  
1315 C., Kopp E., Korth A., Laufer D., Le Roy L., Mall U., Marty B., Mousis O., Owen T.,  
1316 Rème H., Sémon T., Tzou C.-Y., Waite J. H. and Wurz P. (2018) Krypton isotopes and  
1317 noble gas abundances in the coma of 67/PChuryumov-Gerasimenko. *Science Advances*  
1318 **4**, eaar6297. <https://doi.org/10.1126/sciadv.aar6297>.
- 1319 Sarda Ph., Staudacher Th. and Allègre C. J. (1991) Complete rare gas study of a very large  
1320 unmelted cosmic dust particle from Greenland. *Lunar Planet. Sci.* **22**, 1165-1166  
1321 (abstract).
- 1322 Schmitz B., Feist R., Meier M. M. M., Martin E., Heck P. R., Lenaz D., Topa D., Busemann  
1323 H., Maden C., Plant A. A. and Terfelt F. (2019) The micrometeorite flux to Earth  
1324 during the Frasnian–Famennian transition reconstructed in the Coumiac GSSP section,  
1325 France. *Earth Planet. Sci. Lett.* **522**, 234-243.  
1326 <https://doi.org/10.1016/j.epsl.2019.06.025>.
- 1327 Schwenzer S. P., Herrmann S., Mohapatra R. K. and Ott U. (2007) Noble gases in mineral  
1328 separates from three shergottites: Shergotty, Zagami, and EETA79001. *Meteorit.*  
1329 *Planet. Sci.* **42**, 387-412. <https://doi.org/10.1111/j.1945-5100.2007.tb00241.x>.
- 1330 Shyam Prasad M., Rudraswami N. G., de Araujo A. A. and Khedekar V. D. (2018)  
1331 Characterisation, sources and flux of unmelted micrometeorites on Earth during the last  
1332 ~50,000 Years. *Scientific Reports* **8**, 8887. <https://doi.org/10.1038/s41598-018-27158-x>.
- 1333 Spring N. H. (2014) Investigating the Origin and Distribution of Primordial Noble Gases and  
1334 Volatiles in Asteroids and Comets: A Comparative Study of Interplanetary Dust Particles  
1335 (IDPs), Antarctic Micrometeorites (AMMs) and Carbonaceous Chondrites. PhD Thesis.  
1336 *University of Manchester, United Kingdom*, 178 p.
- 1337 Stuart F., Harrop P. J., Knott S., and Turner G. (1999) Laser extraction of helium isotopes  
1338 from Antarctic micrometeorites: Source of He and implications for the flux of  
1339 extraterrestrial <sup>3</sup>He to earth. *Geochim. Cosmochim. Acta* **63**, 2653-2665.  
1340 [https://doi.org/10.1016/S0016-7037\(99\)00161-1](https://doi.org/10.1016/S0016-7037(99)00161-1).
- 1341 Suavet C., Cordier C., Rochette P., Folco L., Gattacceca J., Sonzogni C. and Dampffoffer D.  
1342 (2011) Ordinary chondrite-related giant (> 800µm) cosmic spherules from the  
1343 Transantarctic Mountains, Antarctica. *Geochim. Cosmochim. Acta* **75**, 6200-6210.  
1344 <https://doi.org/10.1016/j.gca.2011.07.034>.
- 1345 Suttle, M. D. and Folco L. (2020) The extraterrestrial dust flux: Size distribution and mass  
1346 contribution estimates inferred from the TransantarcticMountains (TAM)  
1347 micrometeorite collection. *Journal of Geophysical Research: Planets* **125**,  
1348 e2019JE006241. <https://doi.org/10.1029/2019JE006241>.
- 1349 Taylor S., Lever J. H. and Harvey R. P. (2000) Numbers, types, and compositions of an  
1350 unbiased collection of cosmic spherules. *Meteorit. Planet. Sci.* **35**, 651-666.  
1351 <https://doi.org/10.1111/j.1945-5100.2000.tb01450.x>.



- 1352 Taylor S., Herzog G. F. and Delaney J. S. (2007) Crumbs from the crust of Vesta:  
1353 Achondritic cosmic spherules from the South Pole water well. *Meteorit. Planet. Sci.*  
1354 **42**, 223-233. <https://doi.org/10.1111/j.1945-5100.2007.tb00229.x>.
- 1355 Taylor S., Matrajt G. and Guan Y. (2012) Fine-grained precursors dominate the  
1356 micrometeorite flux. *Meteorit. Planet. Sci.* **47**, 550-564. <https://doi.org/10.1111/j.1945-5100.2011.01292.x>.  
1357
- 1358 Toppani A., Libourel G., Engrand C. and Maurette M. (2001) Experimental simulation of  
1359 atmospheric entry of micrometeorites. *Meteorit. Planet. Sci.* **36**, 1377-1396.  
1360 <https://doi.org/10.1111/j.1945-5100.2001.tb01831.x>.
- 1361 Trappitsch R. and Leya I. (2013) Cosmogenic production rates and recoil loss effects in  
1362 micrometeorites and interplanetary dust particles. *Meteorit. Planet. Sci.* **48**, 195-210.  
1363 <https://doi.org/10.1111/maps.12051>.
- 1364 Trappitsch R. and Leya I. (2016) Production and recoil loss of cosmogenic nuclides in  
1365 presolar grains. *Astrophys. J.* **823**, 12. <https://doi.org/10.3847/0004-637X/823/1/12>.
- 1366 Trieloff M., Kunz J., Clague D. A., Harrison D. and Allègre C. J. (2000) The nature of  
1367 pristine noble gases in mantle plumes. *Science* **288**, 1036-1038.  
1368 <https://doi.org/10.1126/science.288.5468.1036>.
- 1369 van Ginneken M., Folco L., Cordier C. and Rochette P. (2012) Chondritic micrometeorites  
1370 from the Transantarctic Mountains. *Meteorit. Planet. Sci.* **47**, 228-247.  
1371 <https://doi.org/10.1111/j.1945-5100.2011.01322.x>.
- 1372 Vogel N., Heber V. S., Baur H., Burnett D. S. and Wieler R. (2011) Argon, krypton, and  
1373 xenon in the bulk solar wind as collected by the Genesis mission. *Geochim. Cosmochim.*  
1374 *Acta*, **75**, 3057-3071. <https://doi.org/10.1016/j.gca.2011.02.039>.
- 1375 Vogt M., Hopp J., Gail H.-P., Ott U. and Trieloff M. (2019) Acquisition of terrestrial neon  
1376 during accretion – A mixture of solar wind and planetary components. *Geochim.*  
1377 *Cosmochim. Acta* **264**, 141-164. <https://doi.org/10.1016/j.gca.2019.08.016>.
- 1378 Wieler R. (2002a) Noble gases in the Solar System. In: *Noble Gases in Geochemistry and*  
1379 *Cosmochemistry* (eds. D. Porcelli, C. J. Ballentine and R. Wieler). *Rev. Min. Geochem.*  
1380 **47**, 21-70. <https://doi.org/10.2138/rmg.2002.47.2>.
- 1381 Wieler R. (2002b) Cosmic-ray-produced noble gases in meteorites. In: *Noble Gases in*  
1382 *Geochemistry and Cosmochemistry* (eds. D. Porcelli, C. J. Ballentine and R. Wieler).  
1383 *Rev. Min. Geochem.* **47**, 125-170. <https://doi.org/10.2138/rmg.2002.47.5>.
- 1384 Wieler R., Grimberg A. and Heber V. S. (2007) Consequences of the non-existence of the  
1385 “SEP” component for noble gas geo- and cosmochemistry. *Chem. Geol.* **244**, 382-390.  
1386 <https://doi.org/10.1016/j.chemgeo.2007.06.026>.
- 1387 Wyatt S. P. and Whipple F. L. (1950) The Poynting-Robertson effect on meteor orbits.  
1388 *Astrophys. Journ.* **111**, 134-141. <https://doi.org/10.1086/145244>.

1389 Yabuta, H., Noguchi T., Itoh S., Nakamura T., Miyake A., Tsujimoto S., Ohashi N.,  
1390 Sakamoto N., Hashiguchi M., Abe K.-i., Okubo A., Kilcoyne A. L. D., Tachibana S.,  
1391 Okazaki R., Terada K., Ebihara M. and Nagahara H. (2017) Formation of an  
1392 ultracarbonaceous Antarctic micrometeorite through minimal aqueous alteration in a  
1393 small porous icy body. *Geochim. Cosmochim. Acta* **214**, 172-190.  
1394 <https://doi.org/10.1016/j.gca.2017.06.047>.