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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 ⁴He concentrations and ⁴He/²⁰Ne 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 ²¹Ne and
25 ³He, 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 ²¹Ne 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 ¹³⁴Xe and ¹³⁶Xe.
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 ³⁶Ar/³⁸Ar 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 ³He, 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 10.2×10^6 kg
82 per year, and also provides estimates for fluxes to Mars of 0.75×10^6 kg/year (surprisingly
83 low in comparison to earlier estimates, e.g., Flynn, 1996) and for Venus of 11.3×10^6 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 m^2 times year) allowed to
97 infer an annual flux of about 5×10^6 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}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}Xe and ^{136}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 CO₂ 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 ⁸²Kr and ¹²⁹Xe. 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 μm -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 [μm]	weight [μg]	class [§]
Dome C				
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
Cap Prudhomme				
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 [§]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 CO₂ 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 ³⁶Ar and ³⁸Ar were measured on the central
257 channeltron (IC3), while ⁴⁰Ar was measured using the Faraday cup. Similarly, ⁴He was mostly
258 measured by Faraday detector, while the ³He signal was detected on IC3. As for Ne, all
259 isotopes of Ne as well as mass 18 (water, used for correction at ²⁰Ne) 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 cm³ STP,
265 approximately as follows: ³He: 2x10⁻¹⁵, ⁴He: 6x10⁻¹², ²⁰Ne: 4x10⁻¹³, ²²Ne: 7x10⁻¹⁴, ³⁶Ar: 4x10⁻
266 ¹³, ⁴⁰Ar: 1.0x10⁻¹⁰, ⁸⁴Kr: 1x10⁻¹⁴ and ¹³²Xe: 3x10⁻¹⁵.

267 Interference corrections were applied at mass 3 for interference from not fully resolved
268 HD/H₃, at the Ne isotopes for ¹H₂¹⁸O as well as doubly charged ⁴⁰Ar and CO₂, and at the Ar
269 isotopes ³⁶Ar and ³⁸Ar 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 ³He had been added resulting in ³He/⁴He ~5x10⁻⁴. 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 ⁴He and ²⁰Ne 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 ⁴He, but ³He was indistinguishable from
281 background. The data for those MMs, where both isotopes were detected, are displayed in
282 Fig. 1, a plot of ³He/⁴He in 10⁻⁴ units versus ⁴He in cm³ 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 Ogliore 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 ^4He 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 ^4He 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 ^3He 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).

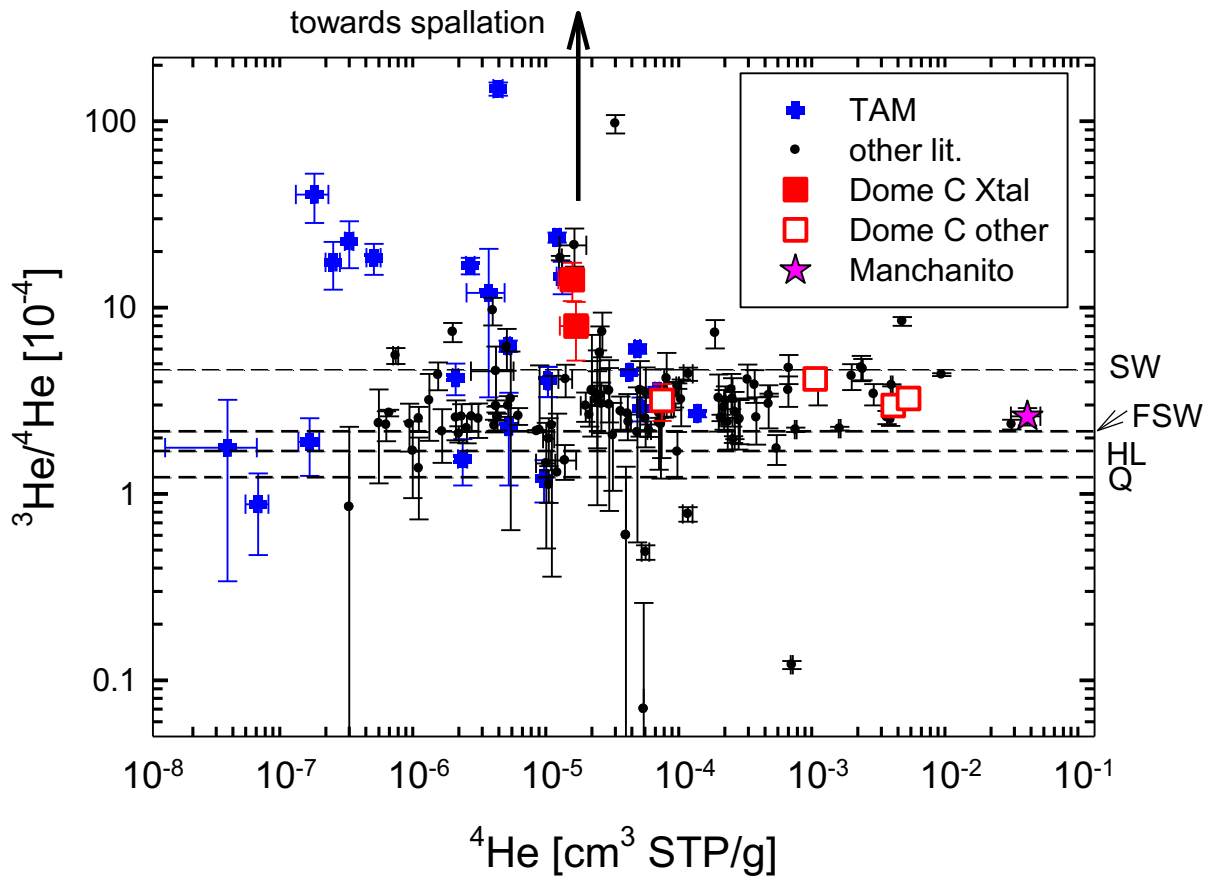
301 The results for Ne are presented in Table 3. For the two fragments from DC 06_09_57,
302 we obtained only upper limits, otherwise amounts of ^{22}Ne for the DC MMs range between ~ 5
303 $\times 10^{-13}$ cm^3 STP and $\sim 4 \times 10^{-12}$ cm^3 STP (concentrations between $\sim 3 \times 10^{-7}$ cm^3 STP/g and ~ 7
304 $\times 10^{-6}$ cm^3 STP/g). The scoriaceous MM from Cap Prudhomme is lower (2×10^{-13} cm^3 STP
305 and 3×10^{-8} 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 (1σ) are shown in parentheses and do not
 318 include errors in sample weight. Where upper limits are listed, these are 2σ . 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 #	^3He	^4He	^3He	^4He	$^3\text{He}/^4\text{He}$
		(10^{-14} cm ³ STP)	(10^{-12} cm ³ STP)	(10^{-8} cm ³ STP/g)	(10^{-6} cm ³ 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. ^4He concentration in $\text{cm}^3 \text{ STP/g}$ for
 325 Dome C micrometeorites. Error bars are 1σ . 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 ^3He or ^4He 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 $^3\text{He}/^4\text{He}$ (~ 0.2 ; e.g. Wieler, 2002b) than observed here, while
 338 $^3\text{He}/^4\text{He}$ in the terrestrial atmosphere (1.4×10^{-6}) is lower.

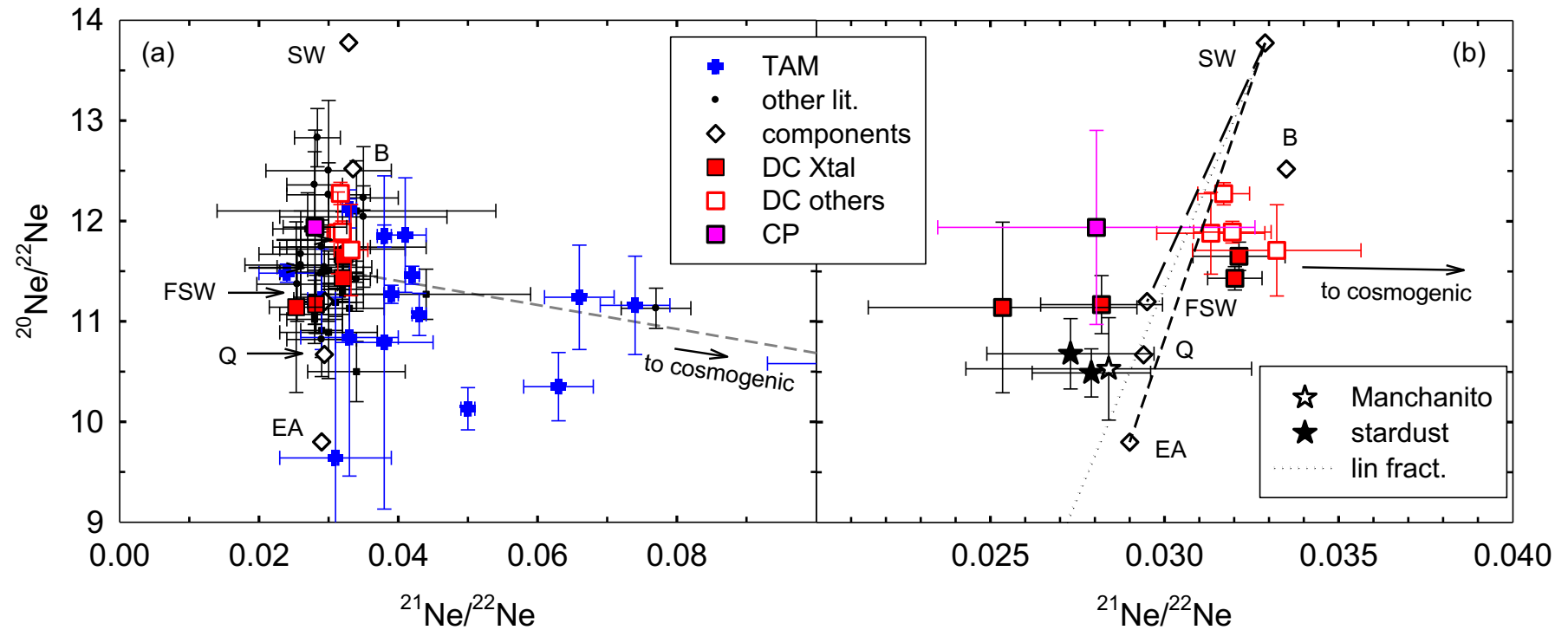
339

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 (1σ) are given in parentheses. Where upper limits are given, these are 2σ . 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}Ne [10^{-12} cm 3 STP]	^{22}Ne [10^{-8} cm 3 STP/g]	$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$	^{36}Ar [10^{-12} cm 3 STP]	^{36}Ar [10^{-8} cm 3 STP/g]	^{40}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 1σ .
 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.

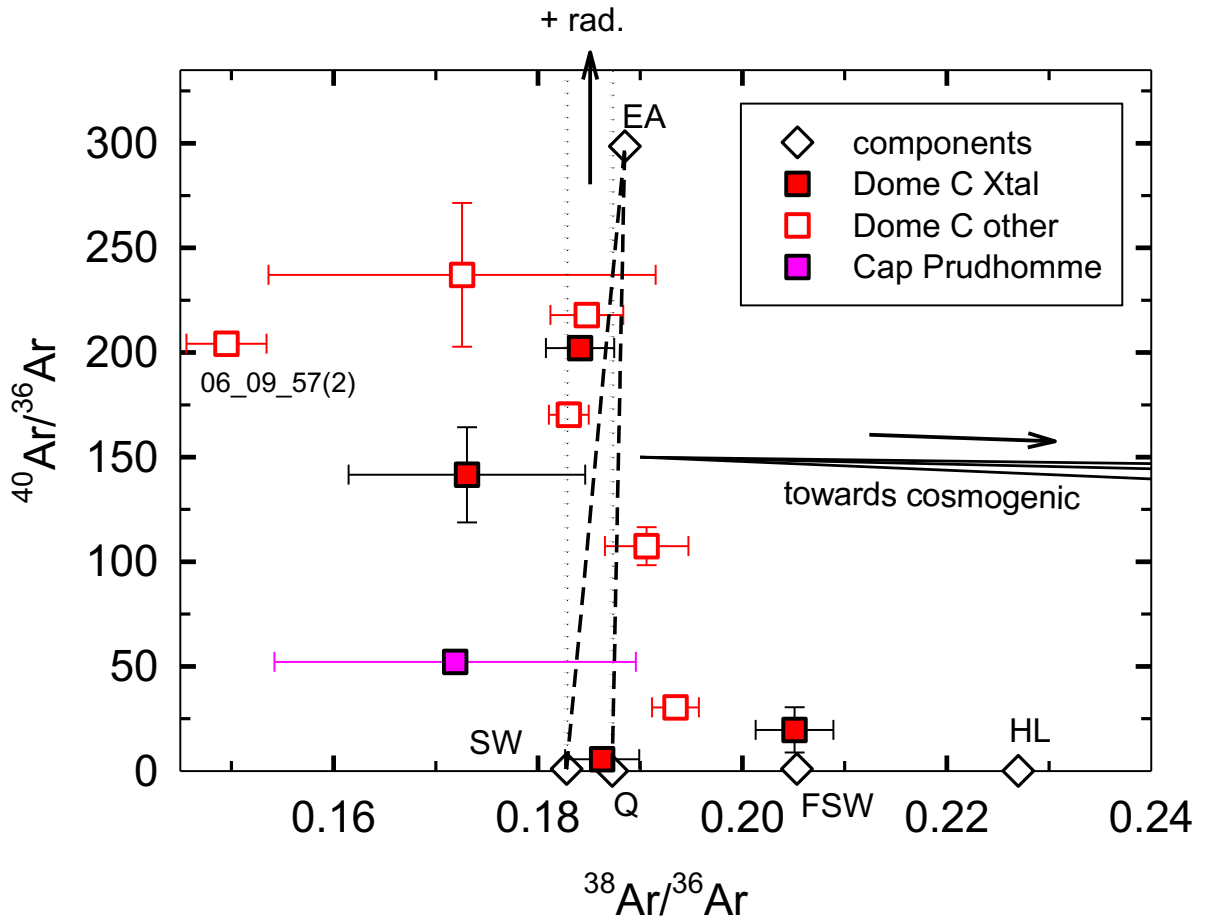
369 3.2. Argon

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}Ar ($\sim 7 \times 10^{-7}$ to $\sim 3 \times 10^{-5}$ cm³ 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 ~ 6
374 (Xtal DC 06_09_149) up to ~ 218 (Fg/Sc DC 06_189). The former is also characterized by the
375 highest concentration of (extraterrestrial) ^{36}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 (~ 14).
379 This is much lower than in the solar wind (~ 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 (~ 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}Ar would offer an explanation,
388 in principle, but this appears unlikely by comparison with the concentration of cosmogenic ^{21}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 1σ 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}Ar of $\sim 3.7 \times 10^{-4}$ cm³
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}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 1σ 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}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 ± 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 ⁷⁸Kr,
424 ¹²⁴Xe and ¹²⁶Xe, 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 ~3x lower). Otherwise,
436 Kr concentrations range between ~1 and ~3 x 10⁻⁸ cm³ STP/g (~1 to ~7 x 10⁻¹⁴ cm³ STP).
437 Measured amounts of ¹³²Xe range from ~1 x 10⁻¹⁵ cm³ STP to ~2 x 10⁻¹³ cm³ STP, with
438 concentrations mostly below 10⁻⁸ cm³ 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 ¹³⁶Xe/¹³²Xe on the ordinate vs. ¹³⁴Xe/¹³²Xe (Fig. 4a)
451 and ¹³⁰Xe/¹³²Xe (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}Kr isotope. Uncertainties in the last digits (1σ) 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}Kr [10^{-14} cm ³ STP]	^{84}Kr [10^{-8} cm ³ 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).

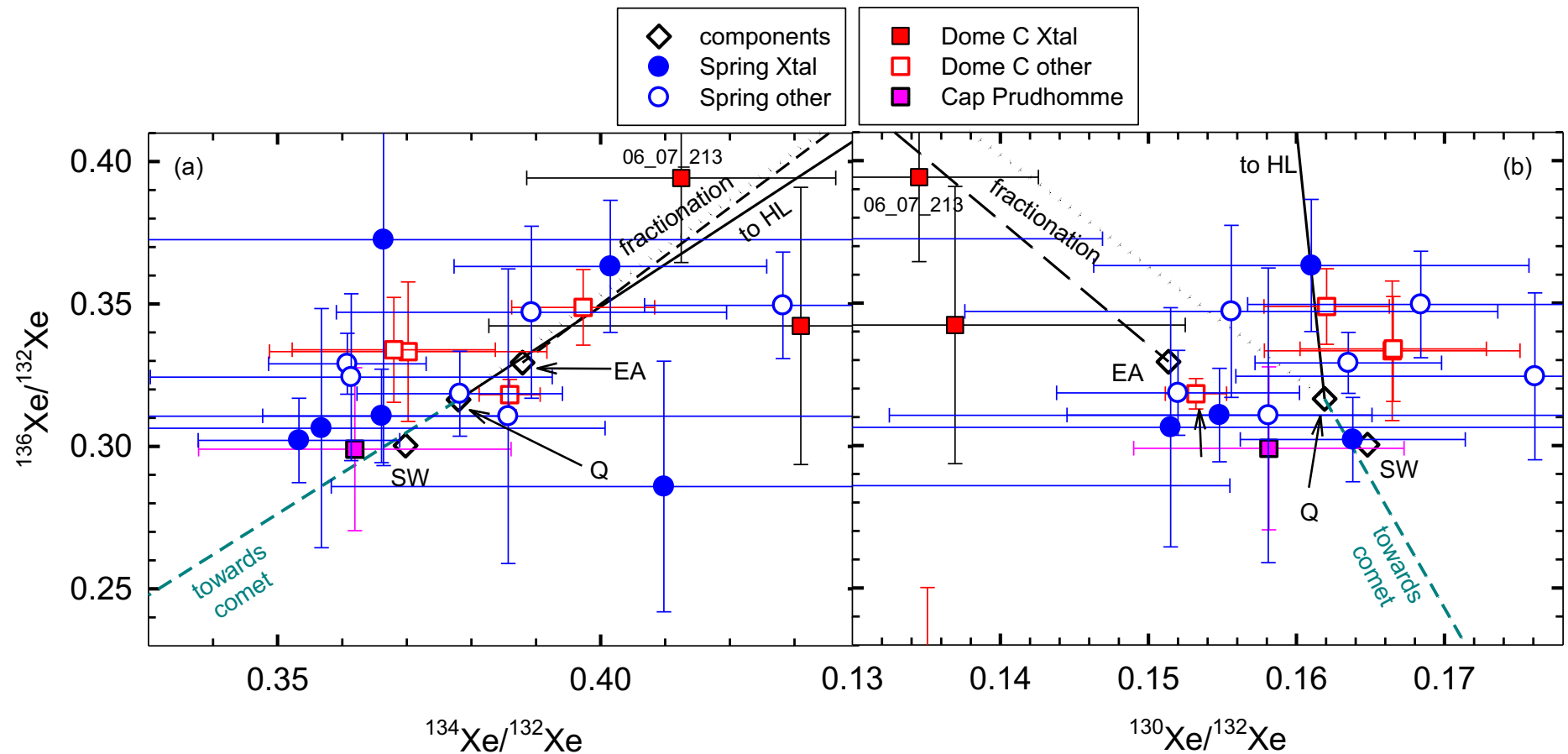
465

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}Xe
467 and ^{126}Xe . Uncertainties in the last digits (1σ) 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}Xe [10^{-14} cm 3]	^{132}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 1σ . 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}Ne , ^3He and, less frequently, ^{38}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}Ne , together with the concentrations of trapped ^{20}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}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}Ne .

518

519 **Table 6.** Concentrations of cosmogenic ^3He , ^{21}Ne as well as “cosmogenic” ^{38}Ar and
520 concentration of trapped ^{20}Ne . Units are $10^{-8} \text{ cm}^3 \text{ STP/g}$, errors (1σ) 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}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 ^3He , 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 3×10^{-4} for trapped $^3\text{He}/^4\text{He}$. In case of DC 06:09_57 the listed upper
528 limits (2σ) correspond to total measured abundances instead. The case for the nominally high
529 abundance of cosmogenic ^3He in DC 06_09_189 is marginal and listed in italics and small
530 print. Evidence for “cosmogenic” ^{38}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 ^3He , 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 ^3He) 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 ($>10^{-4} \text{ cm}^3 \text{ STP/g}$) ^4He 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 0.2×10^{-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 ^3He 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 ^3He 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}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}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}Ar in chapter 4.4.

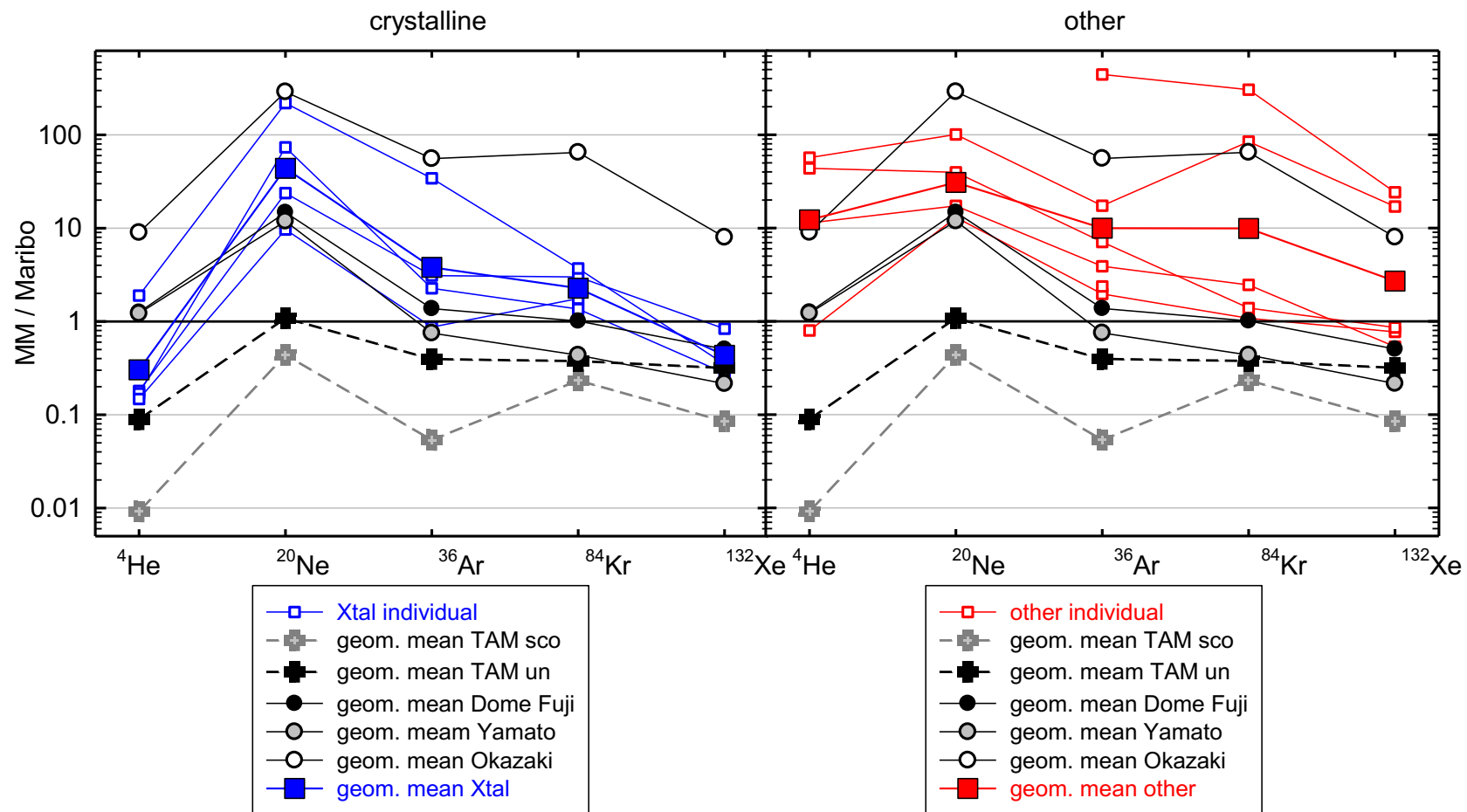
560

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 ^4He 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 μm 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.

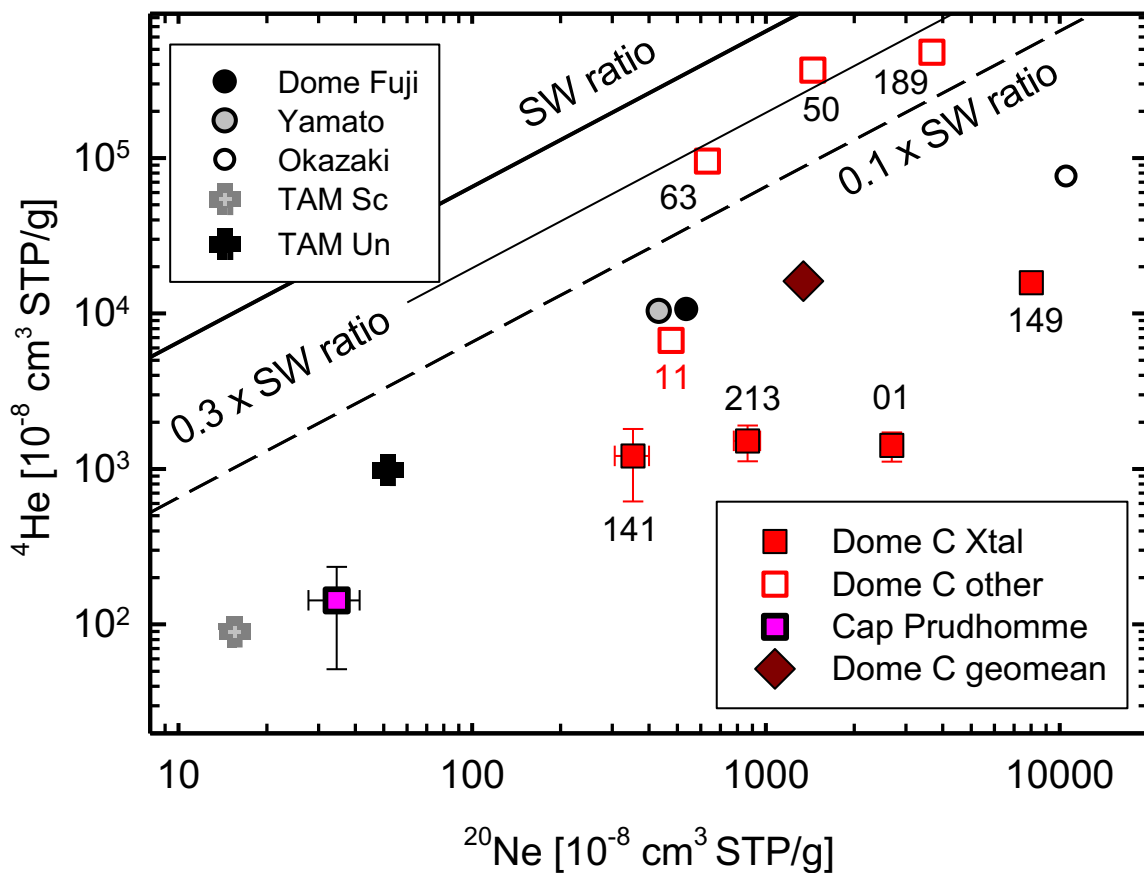
605 Third, the average concentrations reported by Okazaki et al. (2015) for MMs recovered
606 from surface snow near Dome Fuji are one to two orders of magnitude higher than the others
607 reported previously, but are roughly matched by some of our DC MMs. The similarity between
608 the two sets of data 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 ~ 28 , much higher than the primitive noble gas
627 component in carbonaceous chondrites (~ 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 ^4He vs. ^{20}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 ^4He 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 ^4He and ^{20}Ne in our sample set.



642

643 **Figure 6:** Concentrations of ^4He plotted vs. concentrations of trapped ^{20}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 ^4He and
655 thus much lower $^4\text{He}/^{20}\text{Ne}$, by almost two orders of magnitude – geometric means are ~ 1.6 vs.
656 ~ 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 ^4He and ^{20}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 ~ 20 ,
663 i.e. ~ 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 $\sim 0.3x$ 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 ~ 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 ^4He 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°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 ^4He release during analysis (Nier and

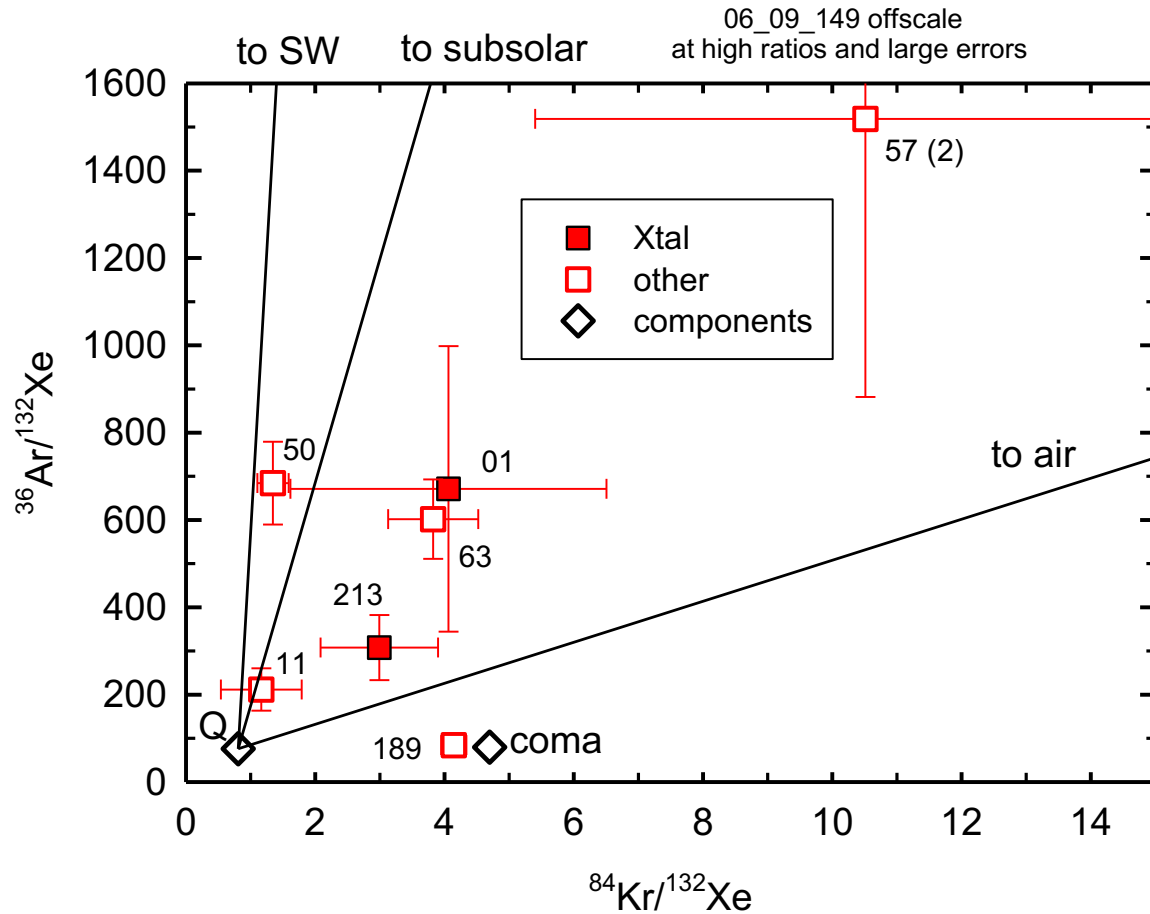
694 Schlutter, 1993; Okazaki et al., 2015) alone may not be a reliable measure for determining the
695 degree of heating experienced by a MM during atmospheric entry.

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}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).



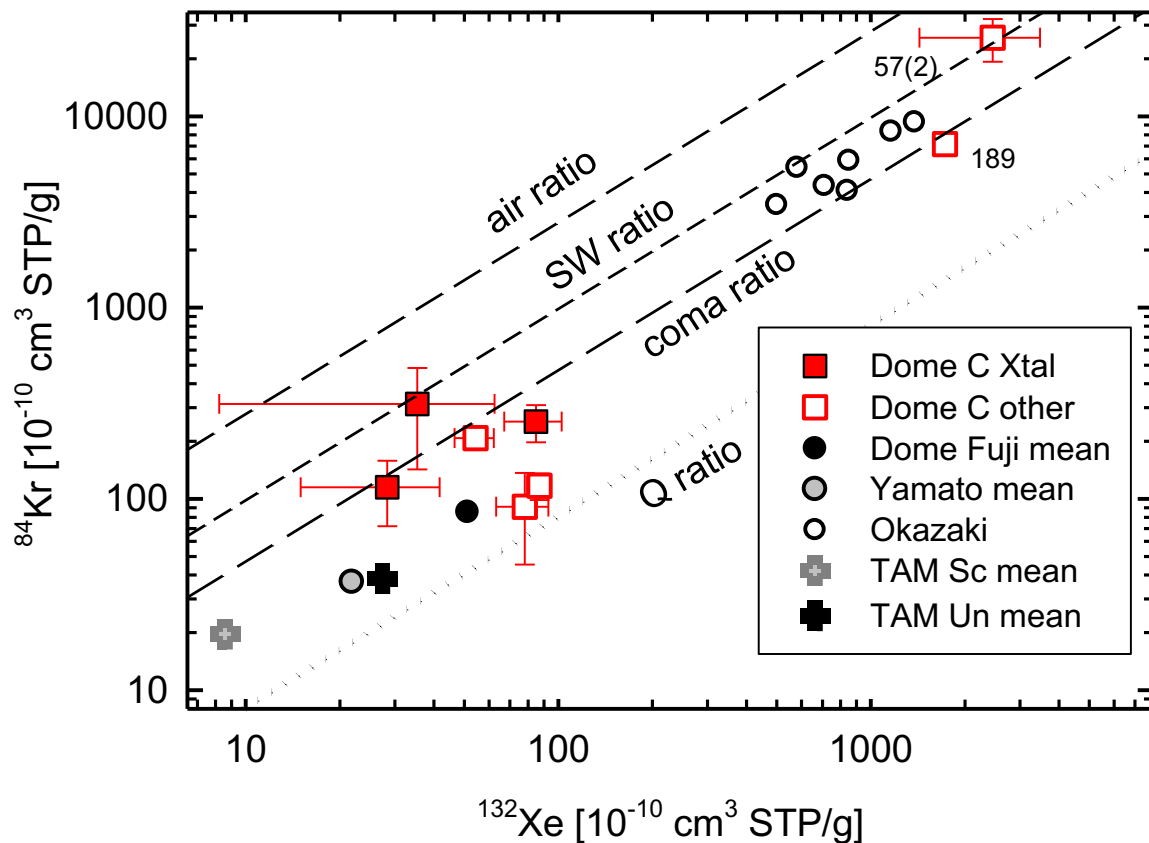
715

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}Kr vs. ^{132}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 ^3He , ^{21}Ne and ^{38}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}Ne , because this isotope is less susceptible to loss
772 than ^3He and less sensitive to variations in chemical composition than ^{38}Ar . The problem in
773 using ^{21}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 ^3He). Shifts to the right in the Ne three-isotope plot of
775 Fig. 2 indicative of cosmogenic ^{21}Ne are therefore small and often zero within 2σ . 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}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}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 ^3He (also two sets of values corresponding to the two values in Table 6). For this, we
790 corrected ^3He assuming recoil losses of 32% (including losses of directly produced ^3He and
791 the larger losses of ^3H 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}Ne in DC 06_07_213; ^3He 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 ~ 2 Ma
800 and a place of origin of ~ 4 au, i.e. well in the asteroid belt. Notably, ^3He gives consistent
801 results, indicating that any loss of cosmogenic ^3He 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 ^3He (Fig. 2). On the other hand, low ^4He with high ^3He
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}Ne and ^3He are also obtained for
808 Fg/Sc DC 06_09_11, however with a very short inferred exposure age of only ~ 0.2 Ma with
809 an origin at ~ 1.5 au. Ages from ^{21}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 ^3He , DC_06_07_213
812 (Fig. 1), with an inferred CRE age of ~ 1 Ma, and coming from ~ 3 au. No ^{21}Ne age could be
813 obtained for this MM, however. Finally, a rather long cosmic ray exposure from ^{21}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 ~ 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}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}Ne production rate has been estimated as 0.11×10^{-8} cm³ 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}Ne and ^3He 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 ^3He (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 ^3He 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 ^3He (if real), and similarly excesses of ^3He 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}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 ^4He 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.

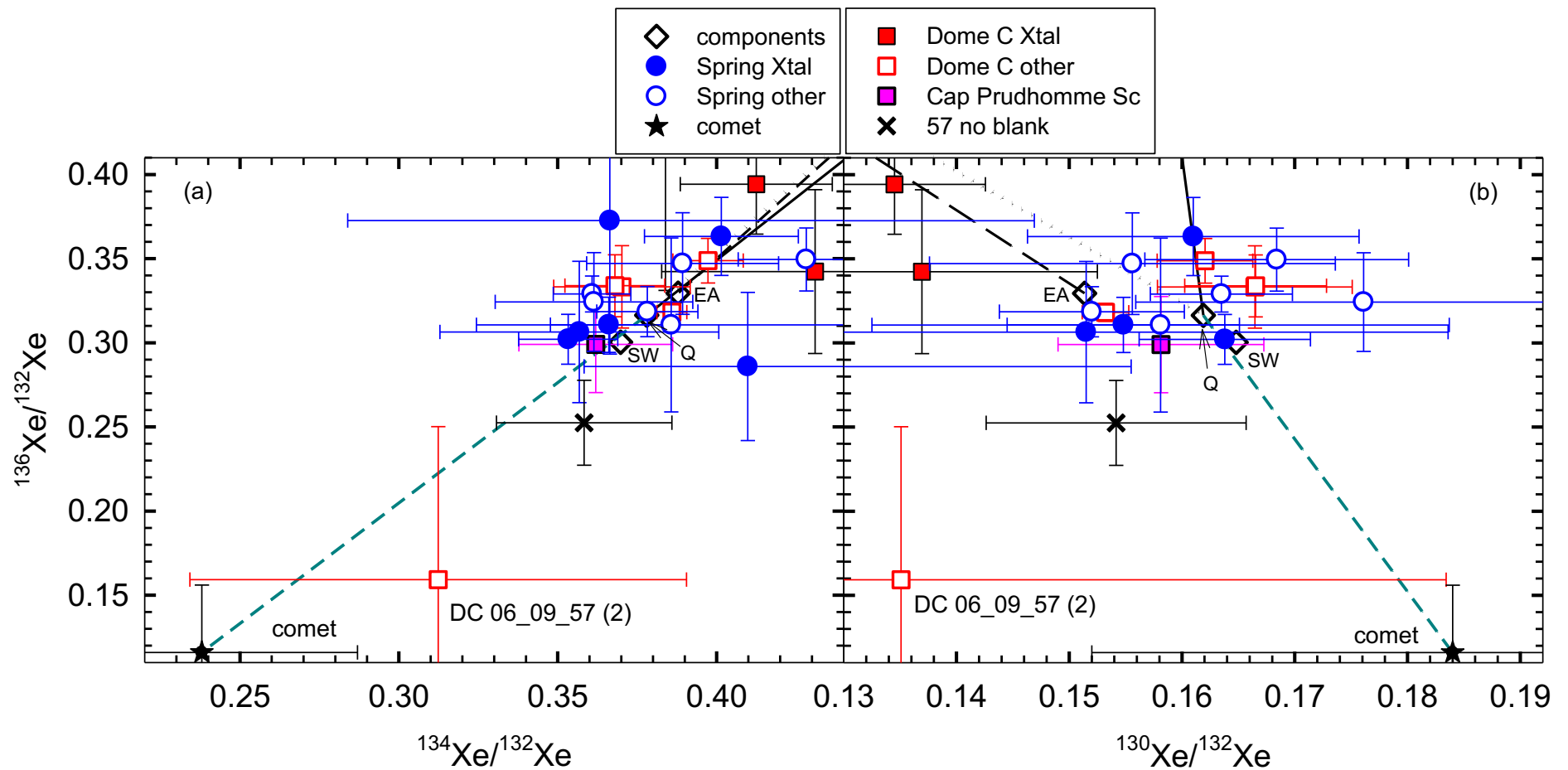
879 Another approach can be based on differences in cosmic ray exposure. In our case, and
880 presumably in all cases involving primitive small particles, this is analytically challenging
881 because of the large abundances of solar wind gas, with only minor and barely (if at all)
882 detectable excesses of cosmogenic ^3He and ^{21}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 ^3He 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 CO₂ 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 ³⁶Ar/¹³²Xe and
903 ⁸⁴Kr/¹³²Xe 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 ³⁶Ar is probably from solar wind, this must appear to be fortuitous, at least as far as
906 ³⁶Ar/¹³²Xe 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, ¹³⁴Xe and ¹³⁶Xe, 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 ¹³²Xe of only ~2x10⁻¹⁵ cm³ STP
915 (some 50,000 atoms) after blank correction (¹³⁶Xe: ~8600 atoms), and where the blank
916 contributed about half of the measured ¹³²Xe (2/3 in case of ¹³⁶Xe). 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 ³⁸Ar/³⁶Ar = 0.1495 ± 0.039, significantly lower than in any other well-
921 defined trapped Ar component (chapter 3.2). The corresponding ³⁶Ar/³⁸Ar ratio of 6.69 ± 0.17
922 agrees within uncertainties with the coma ³⁶Ar/³⁸Ar 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}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 ^4He
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}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 ^3He . One of the MMs (of FgC/Xtal variety)
978 shows a ^3He 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}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}Xe and ^{136}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 ~ 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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