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Author(s)	Obase, Tomoya; Nakashima, Daisuke
Citation	Icarus, 389, 115290 https://doi.org/10.1016/j.icarus.2022.115290
Issue Date	2023-01-01
Doc URL	https://hdl.handle.net/2115/93919
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Rights(URL)	https://creativecommons.org/licenses/by-nc-nd/4.0/
Type	journal article
File Information	Icarus_389_115290.pdf



Past solar wind flux recorded in solar-gas-rich meteorites

Tomoya Obase^{1,2}, Daisuke Nakashima¹

¹Division of Earth and Planetary Materials Science, Graduate School of Science, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan

² Department of Earth and Planetary Sciences, Faculty of Science, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan

Corresponding author: Tomoya Obase

Email: obase@sci.hokudai.ac.jp

Submitted to Icarus

Abstract

Astronomical observations of solar-like stars and theoretical predictions have proposed a high long-term average solar wind flux in the past, such as more than ~ 10 times higher than the present-day value at ~ 3 Ga. Solar-gas-rich meteorites are lithified asteroidal regolith materials that had been exposed to solar wind in the past and some of which may record the ancient solar wind. To test the hypothesis of dense solar wind in the past Solar System, we quantified the past solar wind ^{36}Ar particle fluxes based on the correlations between the solar and cosmogenic noble gas concentrations in individual solar-gas-rich meteorites. As a result, the past solar wind fluxes recorded in six solar-gas-rich meteorites were comparable to the present-day value except for the R chondrite PRE 95410, showing a few times higher solar wind flux. The howardite Kapoeta perhaps records the solar wind flux at some time between ~ 1 and ~ 2 Ga, suggesting that the solar wind flux in the past at least ~ 1 Ga had been similar to the present-day value. These results may indicate that the past solar wind flux had been lower than that proposed by the astronomical observations and the theoretical predictions. Otherwise, the six meteorites would have acquired recent solar wind when the solar wind flux had already been down to the present-day level.

1. Introduction

The solar wind might have contributed to the atmospheric escape of the terrestrial planets (e.g., Lammer et al., 2008; Lundin et al., 2004). Thus, the secular variation of the solar wind flux is a critical factor to understand the evolution of the planetary atmospheres. Astronomical observations of solar-like stars suggest extremely higher solar wind flux in the past. The astrospheric absorption provides a way to indirectly estimate the mass-loss rates of solar-like stars, leading to estimate how long-term average solar-like wind fluxes change with stellar age (Wood et al., 2002, 2004; Vidotto, 2021). The estimation suggests that younger stars have stronger winds. For example, the solar wind flux from the 1 Gyr old star might be ~ 50 times higher than that of the 4.6 Gyr old star (Wood et al., 2005). Although the estimation includes several assumptions and there are still only a handful of observations, theoretical studies also support this conclusion (Cranmer et al., 2011; Airapetian and Usmanov, 2016; Pognan et al., 2018). These studies suggest that the solar wind flux of the much older Sun was still high, such as ~ 10 times denser for the 2 Gyr old Sun than the present-day solar wind flux (Airapetian and Usmanov, 2016).

Airless bodies such as the Moon and asteroids have been exposed to the solar wind. The solar wind particles are directly implanted into the regolith materials on the uppermost surface of the airless bodies. Noble gases are sensitive tracers for the implanted solar wind since noble gases are scarce in solid materials due to their high volatility. Such implanted solar wind noble gases have been identified from lunar regolith and regolith breccia meteorites. The latter is known as solar-gas-rich meteorites from the asteroids and the Moon (Goswami et al., 1984; Bischoff et al., 2006).

The lunar regolith materials have been used to study a potential long-term change in the solar wind particle flux (Geiss, 1973; Wieler, 2016). The abundance of cumulated solar wind ^{84}Kr atoms in the topmost 2.4 m of the lunar regolith sampled by the Apollo 15 and Apollo 16 deep drill cores requires $\sim 1.6\text{--}2.4$ Gyr irradiation of the present-day solar wind (Wieler, 2016). Assuming that the fraction of regolith grains once exposed to the solar wind decreases with depth by a factor of $1/e$ every three meters (Fegley and Swindle, 1993), the total solar wind ^{84}Kr atoms cumulated over the lifetime of the present lunar regolith (the past up to 4 Ga) was estimated. Based on the estimation, Wieler (2016) suggested that the average solar wind flux in the past 4 Ga might have been similar to the present-day flux. Although the estimation does not exclude the earlier view by Geiss (1973) who advocated a few times higher flux in the past, the abundance of solar wind ^{84}Kr cumulated in the lunar regolith may not be consistent with the theoretical studies that predicts an extensively high solar wind flux in the past (e.g., Airapetian and Usmanov, 2016; Pognan et al., 2018; Wood et al., 2004). However, because the total amount of solar wind ^{84}Kr atoms in the lunar

regolith below the topmost 2.4 m could be much greater than the estimate, the solar wind particle flux in the past remains unclear.

Solar-gas-rich meteorites contain the past solar wind particles that had been directly implanted into the regolith materials of their parent asteroids (Eberhardt et al., 1965; Schultz et al., 1972; Wieler et al., 1989). During the solar wind irradiation, the regolith materials had also been exposed to cosmic rays that produce cosmogenic noble gas nuclides inside via spallation reactions at certain production rates (Wieler, 2002a). Hence, the exposure time to the cosmic rays (so-called cosmic ray exposure ages) can be estimated from the cosmogenic noble gas concentrations (e.g., Eugster, 2003; Obase et al., 2020; Wieler et al., 1989). Accordingly, the past solar wind particle flux would be estimated using the cosmogenic noble gases as an indicator of the duration of solar wind irradiation. In the present study, we developed a model to quantify the past solar wind ^{36}Ar particle flux using noble gas isotopic compositions of an individual solar-gas-rich meteorite. Based on the model, we estimated the past solar wind ^{36}Ar fluxes from the noble gas compositions of six solar-gas-rich meteorites reported in literature.

2. Methodology

Noble gases in solar-gas-rich meteorites are mainly a mixture of solar wind, primordial, cosmogenic, and radiogenic components. The solar wind and primordial components are often collectively referred to as trapped components. In this section, we present a model to estimate the past solar wind flux using a correlation between solar wind and cosmogenic noble gas concentrations in a solar-gas-rich meteorite. The following indices denote noble gas components: C is cosmogenic, SW is solar wind, and T is trapped.

In general, ^3He , ^{21}Ne , and ^{38}Ar are used to discuss the cosmogenic noble gas abundances in meteorites (e.g., Eugster, 2003) because they have relatively high cosmogenic/trapped ratios compared to the other isotopes. Cosmogenic noble gas nuclides are relatively tightly bound in meteoritic materials as they are released at a higher temperature than solar wind noble gases during stepwise heating experiments (e.g., Obase et al., 2020). However, $^3\text{He}_\text{C}$ is sometimes disturbed by diffusive loss (Schultz et al., 2005), and $^{38}\text{Ar}_\text{C}$ is potentially lost by terrestrial weathering because the host phases for cosmogenic Ar might be easy to be oxidized and susceptible to weathering (Okazaki et al., 2000; Patzer and Schultz, 2001).

Most of the implanted solar wind Ar atoms in solar-gas-rich meteorites have likely been retained because implanted solar wind Ar atoms are mostly preserved in the lunar regolith (Wieler, 2016), which is much more mature than the asteroidal regolith (i.e., lack of glassy agglutinates in solar-gas-rich meteorites and long cosmic-ray exposure ages for lunar regolith; McKay et al.,

1989). On the other hand, some solar wind He and Ne atoms may have been lost after the implantation because the He/Ar and Ne/Ar ratios of lunar regolith are lower than the present-day solar wind composition, sometimes by more than two orders of magnitude (Wieler, 1998). It is usually difficult to determine solar wind Kr and Xe concentrations in solar-gas-rich meteorites because they often contain non-negligible amounts of primordial Kr and Xe (e.g., Obase et al., 2021; Pedroni and Begemann, 1994; Wieler, 2016). Accordingly, we use $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$ to discuss cosmogenic and solar wind noble gas concentrations, respectively, with the assumption that both nuclides have avoided significant gas loss.

2.1. Data selection and calculation of $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$

Solar-gas-rich meteorites often exhibit dark/light structures, consisting of fine-grained dark portions and coarse-grained light ones (Suess et al., 1964). The dark portions contain solar wind and cosmogenic noble gases (e.g., Suess et al., 1964; Schultz et al., 1972; Wieler et al., 1989), indicating direct exposure to the Sun on the surface of the parent body. On the other hand, the light portions contain only cosmogenic noble gases, suggesting that they have been shielded from solar radiation.

The noble gas data of six solar-gas-rich meteorites in the literature are used in this study. The meteorites are Allan Hills (ALH) 85119 (EL3 chondrite), MacAlpine Hills (MAC) 88136 (EL3 chondrite), Fayetteville (H4 chondrite), Tsukuba (H5–6 chondrite), Mount Prestrud (PRE) 95410 (R3 chondrite), and Kapoeta (howardite) (Nakashima et al., 2002, 2006; Obase et al., 2020; Pedroni, 1989; Wieler et al., 1989). These meteorites have noble gas data of many samples ($n \geq 18$) extracted from the fine-grained dark portions, except for the two EL chondrites ALH 85119 and MAC 88136, which do not exhibit visible dark/light structures probably due to masking by limonitic staining during terrestrial weathering (Nakashima et al., 2006).

The concentrations of $^{21}\text{Ne}_\text{C}$ and/or $^{36}\text{Ar}_\text{SW}$ in some meteorites have already been reported in the literature. Otherwise, $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$ are calculated from the concentrations and isotopic ratios of Ne and Ar. The $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$ concentrations are summarized in the supplementary material (Table S1). The concentrations of $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{S}$ (solar wind ^{36}Ar) of ALH 85119 and MAC 88136 in Nakashima et al. (2006) are adopted for $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$ of ALH 85119 and MAC 88136. Two samples of A3 from ALH 85119 and M11 from MAC 88136, for which $^{36}\text{Ar}_\text{S}$ concentrations are not reported, are excluded from the calculation. M16 of MAC 88136 with extreme noble gas composition is also excluded. The concentrations of $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{S}$ (solar wind ^{36}Ar) of PRE 95410 matrix samples in Obase et al. (2020) are adopted for $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$ of PRE 95410.

The $^{21}\text{Ne}_\text{C}$ concentrations are calculated from the deconvolutions of meteorite Ne consisting of solar wind and cosmogenic components (Nakashima et al., 2002). The isotopic compositions of solar wind Ne in the meteorites are assumed to be between the unfractionated and fractionated solar wind (FSW) values of $(^{20}\text{Ne}/^{22}\text{Ne}, ^{21}\text{Ne}/^{22}\text{Ne})_\text{SW} = (13.8, 0.0328)$, $(^{20}\text{Ne}/^{22}\text{Ne}, ^{21}\text{Ne}/^{22}\text{Ne})_\text{FSW} = (11.2, 0.0295)$, respectively (Benkert et al., 1993). The $(^{20}\text{Ne}/^{22}\text{Ne})_\text{C}$ ratio is assumed to be 0.8, a typical value in meteorites (Eugster, 1988). The $(^{21}\text{Ne}/^{22}\text{Ne})_\text{C}$ ratios adopted for each meteorite are given later in the text.

$^{36}\text{Ar}_\text{T}$ (trapped ^{36}Ar) includes $^{36}\text{Ar}_\text{SW}$ and primordial ^{36}Ar . The primordial noble gases are indigenous noble gases initially trapped in accreted materials of a meteorite parent body (Ott, 2014). The $^{36}\text{Ar}_\text{T}$ concentrations are calculated from the deconvolutions of meteorite Ar using ^{36}Ar and ^{38}Ar , consisting of trapped and cosmogenic components. The $(^{38}\text{Ar}/^{36}\text{Ar})_\text{T}$ ratio is assumed to be 0.188, a typical value of trapped Ar (Ozima and Podosek, 2002). The $(^{38}\text{Ar}/^{36}\text{Ar})_\text{C}$ ratio is assumed to be 1.5, a typical value in meteorites (Wieler, 2002a).

For Fayetteville (H4 chondrite), the noble gas data of “matrix” samples (Wieler et al., 1989) are used in this study. For Tsukuba (H5–6 chondrite), the “TD” samples extracted from dark solar-gas-rich portions of the meteorite (Nakashima et al., 2002) are used. The concentrations of $^{21}\text{Ne}_\text{C}$ in Nakashima et al. (2002) are adopted for $^{21}\text{Ne}_\text{C}$ of Tsukuba. The typical chondritic $(^{21}\text{Ne}/^{22}\text{Ne})_\text{C}$ value of 0.88 (Wieler et al., 1989) is adopted for Fayetteville to calculate the $^{21}\text{Ne}_\text{C}$ concentrations. The $^{36}\text{Ar}_\text{T}$ concentrations in the Fayetteville and Tsukuba samples were calculated to be $(144\text{--}267) \times 10^{-8} \text{ cm}^3\text{STP g}^{-1}$ and $(8.8\text{--}53) \times 10^{-8} \text{ cm}^3\text{STP g}^{-1}$, respectively. These are much higher than $^{36}\text{Ar}_\text{T}$ of $(0.2\text{--}1.6) \times 10^{-8} \text{ cm}^3\text{STP g}^{-1}$ of solar-gas-free H4 and H5 chondrites reported in Schultz et al. (1991). Since all $^{36}\text{Ar}_\text{T}$ in solar-gas-free H chondrites are primordial ^{36}Ar , the high $^{36}\text{Ar}_\text{T}$ concentrations indicate that solar wind ^{36}Ar dominates $^{36}\text{Ar}_\text{T}$ in Fayetteville (H4) and Tsukuba (H5–6). Hence, we assumed that all $^{36}\text{Ar}_\text{T}$ in Fayetteville and Tsukuba is $^{36}\text{Ar}_\text{SW}$.

For Kapoeta (howardite), the noble gas data of “dark matrix” samples (Pedroni, 1989) are used for calculation. The $(^{21}\text{Ne}/^{22}\text{Ne})_\text{C}$ value of 0.83 for Kapoeta (Pedroni, 1989) is adopted to calculate $^{21}\text{Ne}_\text{C}$. Howardites often contain foreign carbonaceous chondritic clasts having primordial noble gases (Cartwright et al., 2013). Based on the Xe isotopic composition, Xe in Kapoeta is dominated by the Q noble gas component (a primordial noble gas component enriched in heavy noble gases; Ott, 2014) (Becker et al., 1998). Assuming that all ^{132}Xe and primordial ^{36}Ar in Kapoeta are from Q, it is estimated that the primordial ^{36}Ar contribute less than 7% of the $^{36}\text{Ar}_\text{T}$ atoms in the “dark matrix” samples based on the ^{132}Xe concentration of $3.6 \times 10^{-10} \text{ cm}^3\text{STP g}^{-1}$ in Kapoeta (Becker et al., 1998) and the typical $(^{36}\text{Ar}/^{132}\text{Xe})_\text{Q}$ ratio of 76 (Busemann et al., 2000). Thus, primordial ^{36}Ar is negligible in the “dark matrix” samples of Kapoeta, and we assumed that

all $^{36}\text{Ar}_T$ in Kapoeta is $^{36}\text{Ar}_{\text{SW}}$.

2.2. Correlation of solar and cosmogenic noble gas concentrations in solar-gas-rich meteorites

Fig. 1 shows the $^{21}\text{Ne}_C$ - $^{36}\text{Ar}_{\text{SW}}$ diagrams for the fine-grained matrix samples of the six solar-gas-rich meteorites (Nakashima et al., 2002, 2006; Obase et al., 2020; Pedroni, 1989; Wieler et al., 1989). The $^{21}\text{Ne}_C$ concentrations positively correlate with the $^{36}\text{Ar}_{\text{SW}}$ concentrations in all meteorites. Hereafter, we describe an exposure model to interpret the observed $^{21}\text{Ne}_C$ - $^{36}\text{Ar}_{\text{SW}}$ correlations based on the original models in Wieler et al. (1989) and Nakashima et al. (2006). A basic assumption of our model is that the cosmogenic noble gases in a solar-gas-rich meteorite are not only acquired during the transit from the parent body to the Earth, as is the case for most other meteorites (Wieler, 2002a), but also on the surface of the meteorite parent body. The latter fraction can be directly compared with the amount of solar wind atoms in the meteorite by means of the $^{21}\text{Ne}_C$ - $^{36}\text{Ar}_{\text{SW}}$ correlation.

The surfaces of airless objects in the Solar System are continuously exposed to the solar wind, solar cosmic rays (SCRs), and galactic cosmic rays (GCRs). The typical ion energies are ~ 1 keV/nucleon, < 100 MeV/nucleon, and 100 MeV to several GeV for most nucleons, respectively (Caffee et al., 1988; Schwadron et al., 2017; Vainio et al., 2009). The solar wind ions, including noble gases, are implanted into regolith materials with penetration depths of less than $1\text{ }\mu\text{m}$ (Walker, 1980). The SCRs and GCRs penetrate a few centimeters and a few meters from the surface (Wieler, 2002a), respectively, and produce cosmogenic noble gases in the exposed materials via spallation reactions.

Regolith breccias are lithified regolith materials of the parent bodies and are mainly composed of fine grains and coarse fragments (Schultz et al., 1972; Bischoff et al., 2006). The typical grain sizes of the fine grains and the coarse fragments would be $\sim 50\text{ }\mu\text{m}$ and mm to cm, respectively (Eberhardt et al., 1965; Nakashima et al., 2006; Schultz, 1973). The fine grains contain solar and cosmogenic noble gases (e.g., Wieler et al., 1989), indicating direct exposure to the Sun on the surface of the parent body. On the other hand, the coarse fragments are mostly dominated by cosmogenic noble gases due to small surface/volume ratios.

The solar-gas-rich meteorites had experienced two exposure stages: the first exposure in the parent body regolith (parent body exposure) and the second exposure in space (space exposure). In Fig. 2a, the model of the asteroidal regolith during the parent body exposure is illustrated along with a schematic $^{21}\text{Ne}_C$ - $^{36}\text{Ar}_{\text{SW}}$ diagram in which expected $^{21}\text{Ne}_C$ - $^{36}\text{Ar}_{\text{SW}}$ compositions of the regolith materials are shown.

We simply assume that there are two materials in the regolith: fine grains and coarse

fragments (Fig. 2a). The asteroidal regolith is exposed to the solar wind and GCRs, and continuously mixed by bombardments of cosmic dust and meteoroids within a certain depth (regolith mixing depth). The regolith is also exposed to the SCRs, but the contribution of the SCR irradiation to the total $^{21}\text{Ne}_\text{C}$ production in regolith materials is negligible (Wieler et al., 1989). Therefore, the regolith materials in total obtain $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$ in the ratio of ΣP_{21} (atoms $\text{cm}^{-2} \text{s}^{-1}$) (total production rate of $^{21}\text{Ne}_\text{C}$ per unit area of regolith) to F'_{36} (atoms $\text{cm}^{-2} \text{s}^{-1}$) (incoming solar wind ^{36}Ar per unit time and per unit area of regolith). We also assume that the regolith mixing depth is greater than the depth to which GCR cosmogenic nuclide production is active (0–520 g cm^{-2} , Leya et al., 2001). This depth corresponds to >2.6 m if the regolith density is $\sim 2 \text{ g cm}^{-3}$. If so, each regolith material within the regolith mixing depth averagely obtains $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$ in the ratio of $\Sigma P_{21}/F'_{36}$. In this case, the larger regolith mixing depth results in the slower $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$ accumulation rate for individual regolith materials, but the materials also obtain both noble gases in the ratio of $\Sigma P_{21}/F'_{36}$. Some fractions of regolith materials may escape into space due to the weak gravitational fields of asteroids (Housen et al., 1979). However, the $^{21}\text{Ne}_\text{C}/^{36}\text{Ar}_\text{SW}$ ratio in the remaining regolith does not change because it is well-mixed.

The assumption of deep regolith mixing may be valid because of the following reasons. The close-up images of asteroids taken by spacecrafts revealed that many asteroids retain significant regolith layers (Belton et al., 1992, 1996; Jaumann et al., 2012; Veverka et al., 2001), which are much thicker than the GCR active depth range. For instance, the regolith thickness of asteroid 433 Eros ($\sim 17 \text{ km}$ in diameter) is tens of meters on average (Robinson et al., 2002) and that of asteroid 4 Vesta ($\sim 530 \text{ km}$ in diameter) often exceeds 1 km (Denevi et al., 2016). The high-resolution imaging and spectroscopic analyses showed that the asteroidal regolith materials are locally well-mixed by impacts that continually stir the regolith (Denevi et al., 2016; Pieters et al., 2012; Robinson et al., 2002). Both observations and numerical simulations suggested that impact-induced vibration also causes large-scale movement of regolith materials, resulting in efficient erasure of craters less than $\sim 100 \text{ m}$ in diameter on 433 Eros (Richardson et al., 2005, 2020; Robinson et al., 2002). Furthermore, impacts on asteroids that generate craters larger than a few tens of meters in diameter excavate regolith more than a few meters in depth (Marchi et al., 2015). Such impact events are not rare because craters larger than a few tens of meters are commonly present on the surface of asteroids visited by spacecrafts (e.g., Chapman, 2002; Marchi et al., 2015; Robinson et al., 2002). Thus, the asteroidal regolith materials may be mixed to the depth greater than the GCR active depth range.

On small asteroids such as 25143 Itokawa ($\sim 0.3 \text{ km}$ in diameter), the regolith mixing process would be different from that assumed in this model because fine regolith particles tend to

escape from the asteroid rather than accumulate due to the weak gravitational field (Nagao et al., 2011). The volume of the regolith on 25143 Itokawa is relatively small, corresponding to a thickness of ~0.4 m if spread evenly across the entire asteroid (Barnouin-Jha et al., 2008). Even if the regolith materials on such small asteroids could be consolidated by impact-induced compression or heating, such regolith may be volumetrically negligible compared with the regolith on larger asteroids. Therefore, it is likely that the parent bodies for most solar-gas-rich meteorites are much larger asteroids, and our model does not take into account the case for the regolith on small asteroids like Itokawa.

Since solar wind noble gases do not exist inside of the coarse fragments, $^{36}\text{Ar}_{\text{SW}}$ may concentrate in the fine grains. However, for simplicity, we assume that the fine grains obtain $^{21}\text{Ne}_{\text{C}}$ and $^{36}\text{Ar}_{\text{SW}}$ in the ratio of $\Sigma P_{21}/F'_{36}$, which is identical to the ratio that the regolith materials in total obtain. If so, the fine grains exposed longer contain larger amounts of both noble gas nuclides in the ratio of $\Sigma P_{21}/F'_{36}$ (Fig. 2a). Consequently, the fine grains plot along a straight line in the $^{21}\text{Ne}_{\text{C}}\text{-}^{36}\text{Ar}_{\text{SW}}$ diagram, and the slope value a of the line reflects the $\Sigma P_{21}/F'_{36}$ ratio. On the other hand, the $^{36}\text{Ar}_{\text{SW}}$ concentrations in coarse fragments are quite low and the $^{21}\text{Ne}_{\text{C}}$ concentrations are comparable to those of the fine grains because of their small surface/volume ratios.

After ejection from the parent asteroid as a cm-sized to meter-sized meteoroid (typical pre-atmospheric radius of stony meteorites; Wieler, 2002a), all the materials in the meteoroid obtain extra cosmogenic noble gases by GCR exposure during transit to the Earth (space exposure). Hence, all data points shift upwards in the $^{21}\text{Ne}_{\text{C}}\text{-}^{36}\text{Ar}_{\text{SW}}$ diagram (Fig. 2b). The correlation line for the fine grains also shifts upwards, but the slope does not change. As the meteorite data points in this study were obtained from the fine-grained matrices, the slope values of the regression lines in Fig. 1 correspond to the slope a in Fig. 2.

2.3. Calculation of past solar wind flux on meteorite parent body

As discussed above, the slope a of the correlation line for the fine grains (Fig. 2b) may be identical to the ratio of ΣP_{21} to F'_{36} . Hence, F'_{36} is obtained by:

$$F'_{36} = \Sigma P_{21}/a \quad (1)$$

where, a is a slope of a regression line of fine-grained matrix samples in the $^{21}\text{Ne}_{\text{C}}\text{-}^{36}\text{Ar}_{\text{SW}}$ diagram. The regression lines for the six meteorites in this study are obtained by the algorithm of error-weighted least squares with over dispersion (model-3) provided in the software IsoplotR

(Vermeesch, 2018).

The ΣP_{21} values are given by following equation:

$$\Sigma P_{21} = 1.79[\text{Na}] + 2.01[\text{Mg}] + 0.69[\text{Al}] + 0.58[\text{Si}] + 0.07[\text{Ca}] + 0.01[\text{Fe}] + 0.01[\text{Ni}] \quad (2)$$

where, the coefficients (atoms $\text{cm}^{-2} \text{s}^{-1}$) are the integrated values of $^{21}\text{Ne}_C$ production rates for 2π exposure at the shielding depths from 0 to 520 g cm^{-2} given for each target element in Leya et al. (2001). The [elements] are weight fractions of each element.

The following data are used to calculate ΣP_{21} : the average chemical composition of EL chondrites (Wasson and Kallemeyn, 1988) for ALH 85119 and MAC 88136; the average chemical composition of H chondrites (falls; Jarosewich, 2006) for Fayetteville and Tsukuba; the average chemical composition of R chondrites (Bischoff et al., 2011) for PRE 95410; and the whole-rock chemical composition of Kapoeta (Mittlefehldt et al., 1998) for Kapoeta. ΣP_{21} might change if GCR flux had been different in the past. However, the previous studies on cosmogenic nuclides in iron meteorites suggest that the GCR intensity of the long-term average in the past 500–1000 Ma has been the same as the average in the past few million years within a factor of about 1.5 (Wieler et al., 2013).

In this model, we assume a spherical parent body rotating perpendicular to the ecliptic plane and the solar wind exposure near the equator of the parent body. The number of incoming solar wind atoms on the surface of a rotating object is depleted by a factor of π relative to the solar wind flux at the specific heliocentric distance. Therefore, the solar wind ^{36}Ar flux at the heliocentric distance of the meteorite parent body (F_{36} (atoms $\text{cm}^{-2} \text{s}^{-1}$)) is given by:

$$F_{36} = \pi F'_{36} \quad (3)$$

The solar wind flux is lower at the higher latitudes on the parent asteroid due to the shallower angles of the incident. Thus, the calculated F_{36} values might be underestimated. For example, the solar wind fluxes at the latitudes of 43° and 72° are $\sim 27\%$ and $\sim 69\%$ lower than that at the equator, respectively. However, because the area is smaller at the higher latitude, there is a lower possibility for parent body exposure taking place at the higher latitude. The latitude ranges of $0\text{--}43^\circ$ and $0\text{--}72^\circ$ occupy 68% and 95% of a total surface area of a spherical parent body, respectively. If the probability of a location where the exposure took place follows the Gaussian

distribution, the meteorite had been exposed to the solar wind at somewhere in the latitude between 0° and 43° with 68% (1σ) probability. Therefore, the potential underestimation for the F_{36} values due to the exposure at high latitudes is not more than ~27% in most cases, and that does not affect the main conclusion of this study.

3. Results

We estimated the past solar wind ^{36}Ar fluxes at the heliocentric distances of the parent bodies (F_{36}) from the six solar-gas-rich meteorites: ALH 85119, MAC 88136, Fayetteville, Tsukuba, PRE 95410, and Kapoeta (Nakashima et al., 2002, 2006; Obase et al., 2020; Pedroni, 1989; Wieler et al., 1989). The parameters a and ΣP_{21} used for the calculations are summarized in Table 1. The F_{36} values are 166 ± 65 atoms $\text{cm}^{-2} \text{s}^{-1}$ for ALH 85119, 116 ± 38 atoms $\text{cm}^{-2} \text{s}^{-1}$ for MAC 88136, 90 ± 30 atoms $\text{cm}^{-2} \text{s}^{-1}$ for Fayetteville, 46 ± 17 atoms $\text{cm}^{-2} \text{s}^{-1}$ for Tsukuba, 238 ± 62 atoms $\text{cm}^{-2} \text{s}^{-1}$ for PRE 95410, and 53 ± 9 atoms $\text{cm}^{-2} \text{s}^{-1}$ for Kapoeta (Fig. 3 and Table 2).

In Fig. 3 and Table 2, the present-day solar wind ^{36}Ar fluxes at the heliocentric distances of asteroids that are spectrally analogous to each meteorite (DeMeo and Carry, 2014) are also shown. The analogous asteroids are assumed to be E-type asteroids for EL chondrites, S-type asteroids for H and R chondrites (DeMeo et al., 2015), and the asteroid 4 Vesta for the howardite Kapoeta (Mittlefehldt, 2015). The present-day fluxes are estimated from the solar wind ^{36}Ar flux at 1 au obtained by the Genesis mission (Heber et al., 2009), assuming that the solar wind flux is inversely related to the square of the heliocentric distance (Adhikari et al., 2014). Although the Genesis collection period is 2.3 years, the Genesis sample is representative of the long-term average present-day ecliptic solar wind because the dynamic pressure, which is the parameter that has shown the clearest solar cycle variation (Richardson et al. 2001), is the same to better than 1 % between the Genesis period and the forty-year average (Reisenfeld et al., 2013).

Contaminations of coarse fragments may decrease the slope of the $^{21}\text{Ne}_{\text{C}}\text{-}^{36}\text{Ar}_{\text{sw}}$ regression line (Nakashima et al., 2006) because fragments once experienced the parent body exposure plot close to the y-axis with $^{21}\text{Ne}_{\text{C}}$ concentrations larger than the intercept value of the correlation line for fine grains (Fig. 2) (see Sec. 2.2). In this case, the slope of the regression line should be a lower limit of a , and the calculated F'_{36} and F_{36} values should be upper limits. For the calculations, we used the noble gas data of the samples derived from the fine-grained matrices of the meteorites or those reported as they are free from coarse fragments or clasts, except for the two EL chondrites ALH 85119 and MAC 88136. Since both EL chondrites do not exhibit typical dark/light structures, probably due to masking by limonitic staining during terrestrial weathering, the samples might contain some coarse fragments (Nakashima et al., 2006). Thus, the calculated

F_{36} values for ALH 85119 and MAC 88136 are upper limits.

4. Discussion

Solar-gas-rich meteorites had been exposed to the GCRs for 10^6 – 10^7 years on the parent bodies (Nakashima et al., 2002, 2006; Obase et al., 2020; Wieler, 2002a; Wieler et al., 1989), indicating that the estimated solar wind ^{36}Ar fluxes are the averages of 10^6 – 10^7 years at sometimes in the past. To understand the long-term variation of the solar wind flux, it is necessary to know when the parent body exposure occurred. The regolith production had probably been more active in the younger Solar System due to the higher impact flux (Bottke et al., 2012). Therefore, it is often believed that most solar-gas-rich meteorites collected ancient solar wind (Wieler, 2002b), such as ~ 4 Ga or older. However, little is known about the actual time when the meteorites obtained solar wind particles because any direct estimation technique has never been well-established.

It should be noted that the solar wind implantation for some meteorites might have occurred recently. Long-term changes in the solar wind composition may provide direct constraints on the time when the implantation took place. For example, a secular change of $(^{84}\text{Kr}/^{132}\text{Xe})_{\text{sw}}$ ratio has been suggested; 4.1–6.1 for the “old” lunar soils with the antiquity of 1–4 Ga and 7.4–9.9 for the “young” lunar soils with the antiquity of ~ 100 Ma and the present-day solar wind (Wieler, 2016). The $(^{84}\text{Kr}/^{132}\text{Xe})_{\text{sw}}$ ratio of 9.0 in Fayetteville (H4) is similar to the “young” lunar soils, suggesting the implantation took place not more than ~ 100 Ma ago (Wieler, 2016). However, this method is only applicable to meteorites that contain exceptionally abundant solar wind noble gases or meteorites that are poor in the primordial noble gases, which are enriched in Kr and Xe. Therefore, the timings of when meteorites collected solar wind noble gases are uncertain in most cases.

The mass-loss history of the Sun empirically derived from the astronomical observations of solar-type stars of various ages suggests that the solar wind fluxes of the 0.7 Gyr and 2 Gyr old Sun were ~ 50 and ~ 10 times denser than the present-day flux (Wood et al., 2005), and the theoretical prediction (Airapetian and Usmanov, 2016) supports this estimation. Thus, some solar-gas-rich meteorites may record significantly high solar wind flux. However, the past solar wind ^{36}Ar fluxes estimated from the meteorites in this study are similar to the present-day values, except for the R chondrite PRE 95410 (238 ± 62 atoms $\text{cm}^{-2} \text{s}^{-1}$) which is a few times higher than the present-day value at the heliocentric distances of S-type asteroids (35 – 92 atoms $\text{cm}^{-2} \text{s}^{-1}$) (Fig. 3 and Table 2).

The consistency between the past and present fluxes can be explained by three potential

scenarios: (1) the solar-gas-rich meteorites are samples of recent asteroidal regolith; (2) the solar wind flux in the past had been comparable to the present-day flux; or (3) the heliocentric distances of parent bodies had been greater than those of the analogous asteroids. However, the scenario (3) is less likely because even if the parent body exposure occurred at 2.7 Ga when the solar wind flux might have been ~ 10 times denser (Airapetian and Usmanov, 2016), the heliocentric distances of parent bodies should have been more than three times greater than the analogous asteroids (1.8–3.4 au), which is beyond the Jupiter’s orbit (~ 5.2 au). The asteroids beyond 3.9 au from the Sun are dominantly C-type, D-type, and P-type asteroids which are spectrally different from the six meteorites in this study (DeMeo et al., 2015; DeMeo and Carry, 2014).

The high solar wind flux recorded in PRE 95410 may indicate that the solar wind flux had been a few times higher than the present-day flux at the time of parent body exposure, or a short heliocentric distance of the parent body. The reflectance spectra of the Mars trojan asteroid 5261 Eureka in a stable orbit with a semi-major axis of 1.52 au qualitatively matches an R chondrite (Rivkin et al., 2007). The present-day solar wind ^{36}Ar flux at 1.52 au is 176 ± 3 atoms $\text{cm}^{-2} \text{s}^{-1}$. This is consistent with the past solar wind ^{36}Ar flux of 238 ± 61 atoms $\text{cm}^{-2} \text{s}^{-1}$ for PRE 95410 within errors (Fig. 3). Hence, it is likely that Eureka is the parent body of PRE 95410, and the high solar wind flux is due to a short heliocentric distance of the PRE 95410 parent body (Obase et al., 2020). However, we do not exclude the possibility that PRE 95410 records a few times higher solar wind flux during its parent body exposure.

In the case of the howardite Kapoeta, a xenolithic clast shows a K-Ar age of ~ 2 Ga (Pedroni, 1989), indicating that the compaction of Kapoeta occurred after ~ 2 Ga. A thick slab specimen ($\sim 20 \times 10 \times 3$ mm) of Kapoeta has a cross-cutting glass vein that is 12 mm in length and ~ 1 mm in width (Lindsay et al., 2015a, 2015b). Based on the $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the glass and several feldspar grains close to the glass vein, Lindsay et al. (2015a) suggested that the glass vein was formed by a recent impact event at ~ 1 Ga. Because the vein structure may not survive a gardening process on the surface regolith, the compaction of Kapoeta was perhaps before ~ 1 Ga. These chronologies constrain the compaction age of Kapoeta between ~ 1 Ga and ~ 2 Ga. Thus, the solar wind irradiation might have occurred sometime between ~ 1 Ga and ~ 2 Ga.

The astronomical observations and the theoretical prediction suggest that the solar wind flux at 1 Ga was a few times higher than the present-day value (Airapetian and Usmanov, 2016; Wood et al., 2005). The similar solar wind ^{36}Ar fluxes in the past (53 ± 9 atoms $\text{cm}^{-2} \text{s}^{-1}$ for Kapoeta) and the present (73 ± 1 atoms $\text{cm}^{-2} \text{s}^{-1}$ for 4 Vesta) may indicate that the past solar wind flux proposed by the astronomical observations and the theoretical prediction is overestimated. It should be noted that the Kapoeta samples used for the noble gas measurements (Pedroni, 1989)

were extracted from a different specimen than that with the glass vein studied by Lindsay et al. (2015a). Therefore, we cannot rule out the possibility that the solar wind noble gases in the samples of Pedroni (1989) are much younger. Future noble gas measurements for matrix and a $^{40}\text{Ar}/^{39}\text{Ar}$ dating for a glass vein within the same specimen are desirable.

In summary, any positive evidence for the high past solar wind flux is not recorded in the six solar-gas-rich meteorites. This perhaps reflects the fact that the solar wind flux has been nearly constant for most of the solar history. Otherwise, all six solar-gas-rich meteorites are samples of recent asteroidal regolith (i.e., less than one billion years ago).

Mars lost most of its atmosphere in the early Solar System that may have been sufficiently thick to produce greenhouse warming to have allowed liquid water to be stable at the surface (Jakosky et al., 2017; Pollack et al., 1987). Solar wind ions may play an important role in the escape process of the Martian atmosphere (Lundin et al., 2004; Ramstad et al., 2018). Thus, the solar wind flux in the past is one of the critical parameters to study the evolutionary history of the Martian atmosphere. The absence of any high solar wind flux record, which is more than several times higher than the present-day value, in both meteorites and lunar regolith (Wieler, 2016) may be inconsistent with the extremely dense past solar winds proposed by astronomical observations of solar-like stars and some theoretical predictions that have been used to interpret the evolutionary process of the Martian atmosphere. However, to conclude this, a better understanding of the antiquities of solar wind particles in solar-gas-rich meteorites is required.

5. Conclusions

We quantified the past solar wind ^{36}Ar flux recorded in six solar-gas-rich meteorites based on the correlations between the solar and cosmogenic noble gas concentrations. The estimated fluxes are similar to the present-day value except for the R chondrite PRE 95410, showing a few times higher solar wind flux. Based on chronological constraints in the previous studies, the howardite Kapoeta perhaps records the solar wind flux at some time between ~ 1 Ga and ~ 2 Ga. Thus, the solar wind flux in the past at least ~ 1 Ga might have been comparable to the present-day value. These results may indicate that the past solar wind flux had been lower than that proposed by the astronomical observations of solar-like stars and some theoretical predictions. Otherwise, the six meteorites would have acquired recent solar wind when the solar wind flux had already been down to the present-day level.

Acknowledgements

The authors are grateful to the anonymous reviewers for their constructive and insightful suggestions, improving our paper in its present form.

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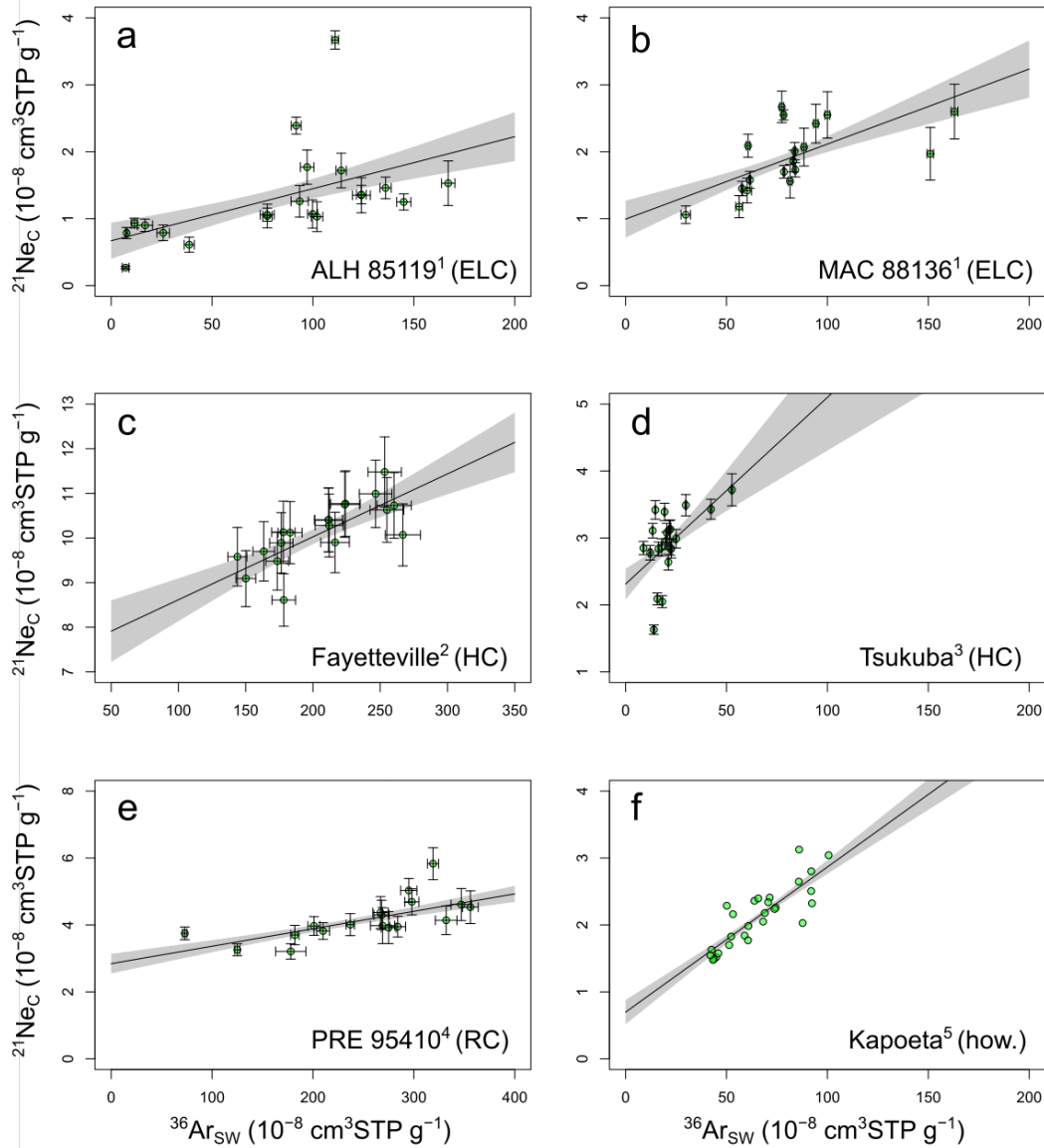
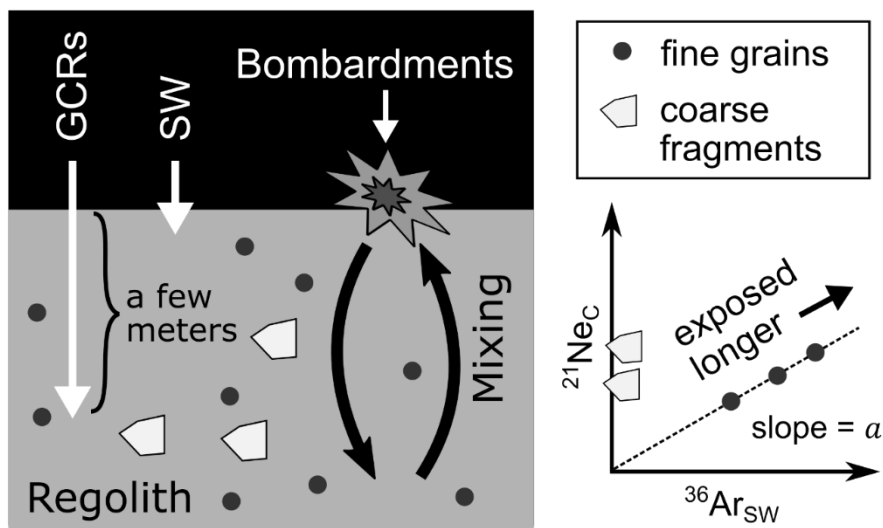


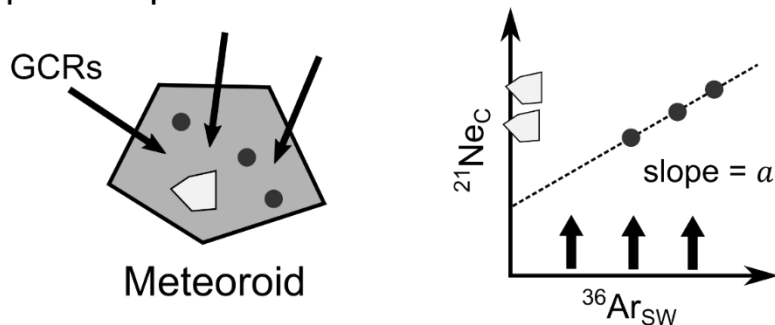
Fig. 1 $^{21}\text{Ne}_\text{C}$ - $^{36}\text{Ar}_\text{SW}$ diagrams for the fine-grained matrix samples of the six solar-gas-rich meteorites. The regression lines (solid lines) are shown along with 1σ confidence intervals (gray areas). The concentrations of $^{21}\text{Ne}_\text{C}$ and $^{36}\text{Ar}_\text{SW}$ show positive correlations. ELC, HC, RC, and how. denote EL chondrite, H chondrite, R chondrite, and howardite, respectively. Data sources are as follows: ¹Nakashima et al. (2006), ²Wieler et al. (1989), ³Nakashima et al. (2002), ⁴Obase et al. (2020), and ⁵Pedroni (1989). Uncertainties for the Kapoeta samples are not given in the reference.

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(a) Parent body exposure



(b) Space exposure



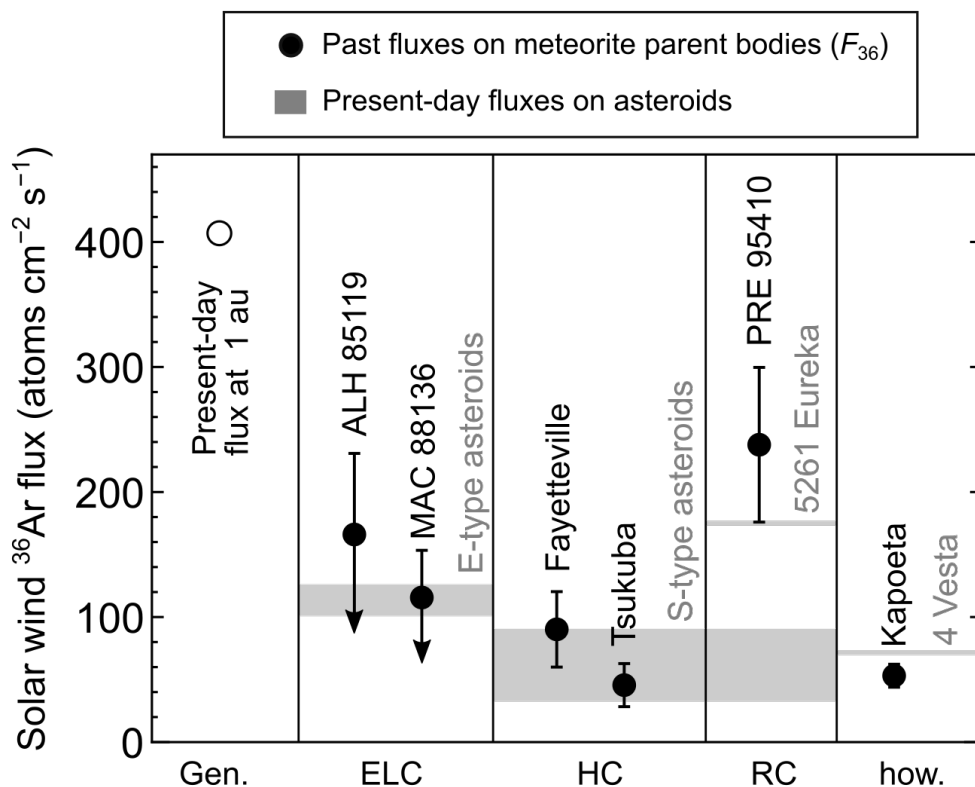
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709 Fig. 2 Schematic illustrations and $^{21}\text{Ne}_C$ - $^{36}\text{Ar}_{SW}$ diagrams for materials during (a) parent body
 710 exposure and (b) space exposure. The $^{21}\text{Ne}_C$ - $^{36}\text{Ar}_{SW}$ diagrams show typical compositions of $^{21}\text{Ne}_C$
 711 and $^{36}\text{Ar}_{SW}$ in fine grains and coarse fragments.

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717 Fig. 3 The past solar wind ^{36}Ar fluxes at the locations of parent bodies of the six solar-gas-rich
 718 meteorites (filled circles). The present-day solar wind ^{36}Ar flux at 1 au obtained by the Genesis
 719 mission (open circle; Heber et al., 2009) and the present-day fluxes at the locations of the
 720 spectrally analogous asteroids (gray areas) are also shown. ELC, HC, RC, how., and Gen. denote
 721 EL chondrite, H chondrite, R chondrite, howardite, and Genesis data, respectively.

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