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# PENETRATION OF THE SOLAR WIND AFTER DISSIPATION OF THE SOLAR NEBULA: ORIGIN OF VENUSIAN Ar BY OFF-DISK IMPLANTATION OF THE SOLAR WIND

Sho Sasaki

*Lunar and Planetary Laboratory, University of Arizona,*
*Tucson, Arizona 85721, U.S.A.*

***Abstract:*** Implantation of the ancent solar wind is a possible noble gas source for Venus and gas-rich meteorites. During the stage of planetary accretion, dust grains re-emitted by planetesimal collisions could be targets of the solar wind implantation. The present study shows that such off-disk implantation can play an important role in noble gas capture; our results explain not only the $^{36}$Ar amount in the Venusian atmosphere but also the fact that the $^{36}$Ar abundance in Venus is 70 times as much as that in the Earth, assuming that gravitational scattering by the proto-Venus should enhance the orbital inclination of target materials. This mechanism may also have played a role in the origin of gas-rich meteorites.

## 1. Introduction

The abundant noble gas in lunar surface soils is ascribed to implantation of the present solar wind (Eberhardt *et al.*, 1970). And the implantation of the ancient solar wind is considered to be volatiles sources of gas-rich meteorites (Suess *et al.*, 1964; Heymann and Palma, 1986) and Venus (Wetherill, 1981; Bogard, 1988). The primordial solar nebula, however, prevented the solar energetic particles from penetrating into the planetary region. The solar wind became able to enter the planetary region after the solar nebula was blown off by the solar wind and UV from the T Tauri protosun (Hayashi *et al.*, 1985) or collapsed onto the sun by viscous dissipation (Lin and Papaloizou, 1985). Though the initially-existed dust was dragged away with nebular gas, new dust grains could be formed by mutual collision of planetesimals; these grains, as well as planetesimals, absorbed the solar wind whose intensity at the T Tauri stage would be more than 100 times as high as at present. If the target grains accreted onto planetesimals or planets without losing trapped gas, the implanted gas species should have affected the volatile composition of meteorites or planets.

Pioneer Venus and Venera missions revealed that $^{36}$Ar abundance ($1.5\times10^{16}$[kg]) in the Venusian atmosphere is 70 times as large as that in the Earth but Ne/Ar of Venus is consistent with the so-called planetary elemental pattern (Pollack and Black, 1982). As for Kr/Ar, data of Pioneer is similar to the solar ratio (Donahue *et al.*, 1981), whereas Venera data suggest planetary Kr/Ar with high Kr abundance (von Zahn *et al.*, 1983). If Kr/Ar on Venus is solar, the Ar enrichment is explained by the addition of solar-type gas to the noble gas inventory of Venus, though the problem of Ne deficiency is left. SHIMIZU (1979) pointed out the possibility that Venus should have grown more rapidly than the Earth and had a primordial solar-type atmosphere, which would remain and enhance $^{36}$Ar on Venus. On the other hand, WETHERILL (1981) considered that high $^{36}$Ar should be explained by accretion of planetesimals or fragments which have captured the solar-type noble gases by solar-wind implantation.

WETHERILL (1981) stated that the solar wind implantation should have occurred just at the inner edge of the disk of a planetesimal swarm, assuming that disk thickness is constant; the solar wind could not penetrate into the region distant from the sun. Venus should have gathered materials at the innermost irradiated edge and captured significant amount of $^{36}$Ar. When the mass of fragments in space decreased and the inner edge retreated to the terrestrial region, the solar wind intensity should have become so weak that the proto-Earth could not capture solar-type noble gas. WETHERILL's discussion implicitly assumed outward transport of gas-implanted materials or a smaller abundance of flux-absorbing materials inside the Venusian region. But these are not guaranteed in the formation of planets.

The new feature of the present study is to take into account the vertical distribution of flux-absorbing materials. Actually the assumption of constant disk thickness is not assured. The vertical distribution of dust grains is controlled by orbital inclinations, in other word, random velocity of planetesimals. In the presence of the solar nebula, the random velocity of large planetesimals could be suppressed since a gravitationally-attracted atmosphere should increase the gas drag coefficient (OHTSUKI *et al.*, 1988); if this distribution was retained, different from WETHERILL's assumption, the thickness of the dust cloud might increase with the distance from the sun. In order to pursue the effect of the vertical structure of the dust cloud on solar wind implantation, we at first calculate the decrease in solar wind flux when the inclination of dust orbit is constant and we show that off-disk implantation is important for gas capture. Then, assuming a possible radial change in the inclination, we explain the difference in $^{36}$Ar amount between Venus and the Earth. The outward transport of materials or the absence of dust-absorbing materials inside Venusian region is not necessary. In discussion, we also touch on the possible origin of gas-rich meteorites.

## 2. Assumptions and Basic Equations

In this study, we use the following assumptions.

(1) The dust disk is axisymmetric and the spatial density distribution of dust is expressed in a form:

$$\rho_{\mathrm{dust}}(a, z)=5.85\times10^{-9} f\left(\frac{a}{1\mathrm{AU}}\right)^{-q} \exp\left\{-\left(\frac{z}{h}\right)^{2}\right\} \ [\mathrm{kg/m^3}] \qquad (a>a_0) \qquad (1)$$

where $a$ and $z$ are distances from the sun and the disk midplane, respectively. $f$ is mass abundance of dusts relative to the total solid materials; the numerical coefficient is taken from HAYASHI *et al.* (1985) so that eq. (1) is consistent with the solid material distribution prior to the planetesimal formation when $f$ is unity and $q$ is 2.75. The vertical scale height $h$ can be expressed as

$$h = ai \tag{2}$$

where the mean orbital inclination of grains $i$ should correspond to that of planetesimals producing grains.

(2) The relative dust abundance $f$ and dust size $d$ are constant throughout the disk.

(3) During the irradiation of the solar wind (duration being denoted by parameter $\tau$), the dust size $f$, the dust abundance $d$, the distribution exponent $q$, the position of the inner boundary $a_0$, and the relative intensity of the solar wind $\alpha$ are constant. Distribution of $i$ is not changed.

(4) The implanted species (here $^{36}$Ar) is retained without loss and captured by a planet. We find that the diffusion coefficient of Ar in $SiO_2$ is $1\times10^{-26}$ [m$^2$/s] at 330 [K] (temperature at the Venusian region), extrapolating experimental data (Fig. 4.6 in OZIMA and PODOSEK, 1983). The resulting diffusion time through $1\times10^{-5}$ [m] thickness is $3\times10^{9}$ [yr] and much larger than a timescale of the planetary accretion $10^7$–$10^8$ [yr]. Hence the diffusive loss of Ar is negligible.

The absorption of energetic particles by a dust swarm is expressed in an analogy of light extinction. Since the decrease in the particle flux $dI$ is proportional to the absolute value of the flux $I$, the geometrical cross section, number density of dusts $n_{\mathrm{dust}}$, and distance $dx$, we have

$$dI = -I\pi d^2 n_{\mathrm{dust}} dx = -I\pi d^2 \frac{\rho_{\mathrm{dust}}}{m} dx \tag{3}$$

where $m$ and $d$ is the mass and the radius of a dust particle, respectively. This equation can be rewritten by

$$\frac{d \ln I}{dx} = -\frac{1}{l} \tag{4}$$

In the above, $l$ is the absorption length (*i.e.* the distance through which particle flux becomes $1/e$) and expressed as

$$l = \frac{4d\bar{\rho}}{3\rho_{\mathrm{dust}}} \tag{5}$$

where $\bar{\rho}$ is the solid density of dust grains and set to be 2000 [kg/m$^3$] in the present study. Since $\rho_{\mathrm{dust}}$ is given by eq. (1), the absorption length $l$ is also expressed by a function of $a$ and $z$, and we find that both $f$ and $d$ should appear only in a form $f/d$.

The actual solar wind expands spherically and the wind flux $F$ is proportional to $r^{-2}$ in the absence of absorption. Equation (4) is rewritten by

$$\frac{d \ln F}{da} = -\frac{1}{l} - \frac{2}{a} \tag{6}$$

The flux decrease by the first term in the right-hand side corresponds to the amount of implanted species on dust grains.

The inner boundary of the dust cloud can be determined by evaporation of grains. At the evaporation boundary, the dust particles would become so small as to be pushed away by radiation pressure and the neutral gas from evaporated materials could be dissipated owing to drag by the solar wind. The assumption $a_0$=0.1[AU] is then assured, since the equilibrium temperature at 0.1[AU] is 1570[K] when the thermal state is controlled by solar radiation whose intensity is 10 times higher than the present one. At the disk inner edge, a large amount of the solar gas was captured at the inner edge of dust cloud. However, the transport of most solid materials from 0.1[AU] to the Venusian region was hardly possible, and anyway, the temperature was so high that trapped gas should easily escape from the dust surface. The trapped gas at the inner evaporation boundary could not contribute to noble gas inventory of Venus.

## 3. Results

The decrease in the solar wind flux is illustrated in Fig. 1 in the case $f/d$=1[m$^{-1}$], $q$=2.75, $a_0$=0.1[AU] and $i$=0.05. The solar wind is strongly absorbed in the neighborhood of the inner boundary. Figure 2 (a), (b) shows the dependence of flux decrease on $f/d$, $q$ and $a_0$. In the case of large dust abundance $f$ or small dust size $d$, the wind particle can hardly penetrate through the equatorial plane of the disk. The flux is reduced when the inner boundary of the disk $a_0$ is closer to the sun or the exponent of power-law distribution $q$ is large, since the dust density distribution is proportional to $a^{-q}$ and absorption near the inner edge becomes dominant. This seems to support the discussion by WETHERILL (1981).

However, the solar wind should be trapped not only in the neighborhood of the midplane. Figure 3 shows absorbed amount of wind particles per unit length at various heights, *i.e.*, distances from the equatorial plane. The amount is integrated for azimuthal and radial directions, where the radial integration range is set to be 0.65~0.75[AU] (Venusian region). So long as $f/d<10^{-1}$, the flux absorption is confined to the equatorial region of the disk. When $f/d>1$, to the contrary, the solar wind is trapped in a region distant from the equatorial plane. It is because the wind

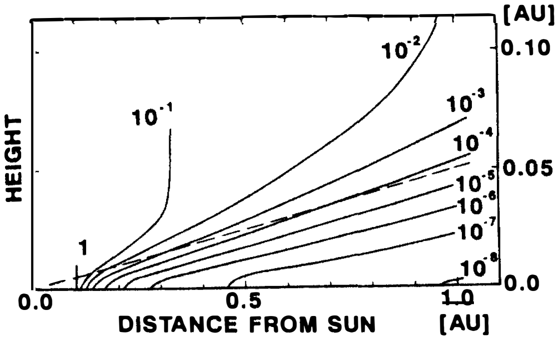

*Fig. 1. Change in the solar wind flux going through a dust disk. We use $a_0$=0.1 [AU], $f/d$=1 [m$^{-1}$], $q$=2.75 and $i$=0.05. The curves express the flux intensity normalized to the value at the inner boundary. The dashed line denotes $h=ia=0.05a$ where the dust density is 1/e times smaller than at the midplane.*

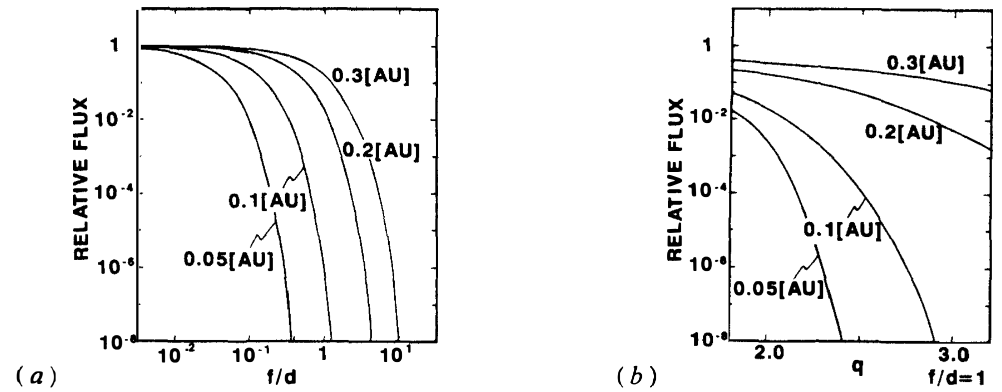

*Fig. 2. Change in the relative wind flux for various parameters at the midplane* ($z=0$) *and* $a=1$ [*AU*]. *The relative flux is normalized to the flux of the non-dust transparent case. Figure* (*a*) *shows the effect of f/d and* $a_0$ *and figure* (*b*) *shows the effect of q and* $a_0$.

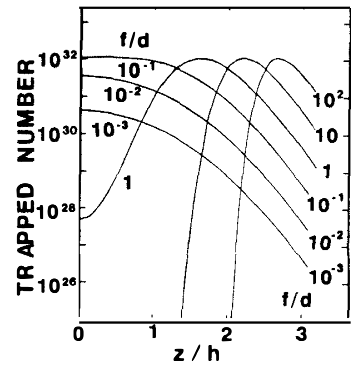

*Fig. 3. The absorption rate of wind particles which is integrated between 0.65 and 0.75* [*AU*] (*Venusian region*). *Parameters are* $q=2.75$, $a_0=0.1$ [*AU*] *and* $i=0.05$. *The vertical axis is distance from the equatorial plane normalized to* $h=0.05a$. *The number beside each curve is f/d.*

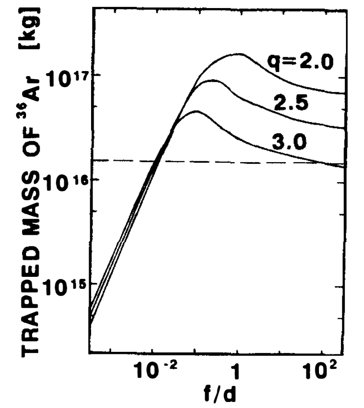

*Fig. 4. The total mass of trapped* $^{36}$*Ar between 0.65 and 0.75* [*AU*] (*Venusian region*) *for various f/d and q. Other parameters are* $a_0=0.1$ [*AU*], $i=0.01$ *and* $\alpha\tau=1\times10^9$ [*yr*] (*e.g. the solar wind flux is 100 times larger than the present one and the flux duration is* $1\times10^7$ [*yr*]). *The horizontal dashed line expresses the present* $^{36}$*Ar amount in the Venusian atmosphere.*

flux can penetrate into the off-disk region even when the flux can hardly go through along the equatorial plane (see Fig. 1).

Figure 4 shows the vertically integrated amount of the absorbed flux in terms of trapped $^{36}$Ar. The present solar wind flux at the Earth's region is $9.0\times10^{11}$ [$m^{-2}$ $s^{-1}$] and the relative solar abundance of $^{36}$Ar to hydrogen atom is $3.22\times10^{-6}$. We assume that the product of the solar wind enhancement factor $\alpha$ and the duration of the intense solar wind $\tau$ is $1\times10^9$ [yr] (*e.g.*, $\alpha$ is 100 and $\tau$ is $10^7$ [yr]). So long as *f/d* is larger than $1\times10^{-2}$, the present $^{36}$Ar amount in the Venusian atmosphere is explained.

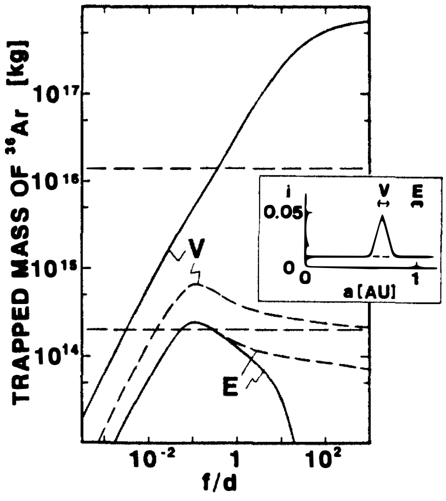

*Fig. 5.* *The total mass of trapped $^{36}Ar$ in the case that i is large in the Venusian region. The horizontal axis denotes f/d. Parameters are $q=2.75$, $a_0=0.1$ [AU] and $\alpha\tau=1\times10^7$ [yr]. The dashed curves express the case where $i=h/a$ is constant and 0.01; solid curves express the case where i is large in the Venusian region (see the small figure illustrating distribution of i). The curves named "V" express total absorbed $^{36}Ar$ between 0.65 and 0.75 [AU] and the curves "E" express that between 0.95 and 1.05[AU]. The upper and the lower horizontal lines express the present $^{36}Ar$ amounts in the Venusian and terrestrial atmospheres, respectively.*

When $f/d$ is small, the flux can penetrate into the deep planetary region, but wind particles cannot be trapped efficiently since effective target area for implantation is reduced; the total trapped amount of $^{36}$Ar diminishes with decreasing $f/d$. But in the case of high $f/d$, increase in opacity is canceled by a change of gas-trapping region toward the off-disk direction and the total trapped amount is not greatly decreased. Therefore off-disk trapping of the solar wind should play an efficient role in the origin of Venusian Ar.

Off-disk implantation also explains the present difference of $^{36}$Ar abundance between Venus and Earth. Figure 5 compares the trapped $^{36}$Ar in the Venusian region with that in the terrestrial region for two cases of the dust orbital inclination: one is constant $i$ ($i=0.01$) and the other is that $i$ is appreciably enhanced in the Venusian region. The formation theory of planets predicts earlier growth of Venus than the Earth, and the larger proto-Venus may scatter ambient planetesimals gravitationally and enhance their mean orbital inclination. As a result, $i$ of the dust cloud may become larger in the Venusian region. When $i$ is constant, trapped $^{36}$Ar in Venus is only 2.7 times larger than that in the Earth. However, when $i$ in the Venusian region is enhanced, trapped $^{36}$Ar in Venus becomes far larger than that in the Earth, and when $f/d>1$ the present difference in Ar abundance between Venus and the Earth is explained.

In the last stage of the Earth's accretion, inclination of the dust cloud should be enhanced also at the terrestrial region. But the efficient trap of solar $^{36}$Ar by the Earth-forming materials could be avoided and difference between Venus and the Earth was maintained, because remaining dust within the Earth's orbit could largely absorb the wind flux and/or the solar wind flux should have become weak after the T Tauri stage of the protosun.

## 4. Discussion

i) Position of inner boundary

The position of the evaporation inner boundary is changed to be 0.05~0.2[AU] by assuming a different intensity of the solar radiation. But the change of the inner boundary would not have a large effect on the off-disk absorption. When $a_0=0.2$ [AU] and absorption at the inner edge is less, the wind flux at the equatorial plane would be $10^5$ times larger than that in the case $a_0=0.1$ [AU] (where $f/d=1$ and $q=2.75$, see Fig. 2(a)). However, the trapped $^{36}$Ar amount in the Venusian region in the case $a_0=0.2$ [AU] is only 1.6 times larger than that in the case $a_0=0.1$ [AU]. Even when $a_0=0.05$ [AU] and the dust abundance is very high at the inner edge, the trapped $^{36}$Ar is only 3 times less than that in the case $a_0=0.1$ [AU].

ii) Abundance and size of dust grains: parameter $f/d$

The dust grains are produced from the mutual collision of planetesimals after the dissipation of the solar nebula. We can write

$$\frac{e_1e_2}{\tau_{\text{prod}}}=\frac{f}{\tau_{\text{loss}}} \tag{7}$$

where $\tau_{\text{prod}}$ and $\tau_{\text{loss}}$ are typical time for dust production and dust loss, respectively, $e_1$ is mass fraction of planetesimals to the total solid mass, a large fraction of which is already in a protoplanet, and $e_2$ is mass fraction of collisionally-ejected dust grains to planetesimal mass. The dust grains are finally captured by planetesimals; typical timescales for dust production $\tau_{\text{prod}}$ and dust loss $\tau_{\text{loss}}$ are essentially the same and denoted by $(n_{\text{pl}}\sigma v)^{-1}$ where $n_{\text{pl}}$ is number density of planetesimals, $\sigma$ is collisional cross section and $v$ is relative velocity. Here the dust abundance $f$ is expressed simply by $e_1e_2$. Though precise values of $e_1$ and $e_2$ are not obtained, let us assume $e_1, e_2\sim 10^{-2}$. Size of dust particles may become smaller and smaller due to dust-dust collisions which should occur more frequently than dust-planetesimal collisions; we may consider that micron-sized grains compatible with interstellar dust should be dominant (submicron size being cut off by Poynting-Robertson effect). Assuming $d\sim 10^{-6}$[m], we have $f/d\sim 10^2$. The above is, of course, a rough estimate but we may tentatively say that the condition $f/d\geqq 1$ corresponding to the off-disk implantation could be realized in the course of evolution of the solar system.

iii) Origin of gas-rich meteorites

Some meteorites called "gas-rich" have noble gases with solar-type elemental and isotopic ratios, where $^{36}$Ar abundance is as high as that of Venus (*e.g.* Pesyanoe (MARTI, 1969), Fayetteville (PEPIN and SIGNER, 1965)). The solar-type noble gas in gas-rich meteorites are considered to be provided by the ancient solar wind (SUESS *et al.*, 1964). Since anisotropy of the solar-flare track is observed, the implantation could occur at the surface regolith of small heavenly bodies rather than into floating dust grains in space (GOSWANI *et al.*, 1984).

The off-disk implantation may contribute to the origin of the abundant solar-type gas in gas-rich meteorites, irrespective of the size of implanted bodies. In the course of planetary accretion, the gravitational scattering of Jupiter which grew rather quickly should enhance the random velocity of planetesimals in the asteroid region. The orbital inclination $i$ of planetesimals and/or collisionally-produced dust grains was enhanced and they would capture the solar wind gas rather efficiently; as in the case of Venus, the trapped solar gas should increase in the asteroid region.

iv) Low abundance of Ne in the atmosphere of Venus

The relative deficiency of Venusian Ne is an important remaining problem. Different from heavier noble gases, the planetary $^{20}$Ne/$^{36}$Ar in the Venusian atmosphere is 100 times smaller than the solar ratio. Some mechanism should have diminished Ne of the implanted solar gas. One explanation is that Ne should have diffused out of implanted dust grains (WETHERILL, 1981). The observed Ne deficiencies in the solar-type noble gas of lunar regolith (EBERHARDT *et al.*, 1970) and South Oman E-chondrite (CRABB and ANDERS, 1981) are considered to be due to the diffusive loss of Ne. The diffusion coefficient of Ne in $SiO_2$ is estimated to be $3\times10^{-15}$ [m$^2$/s] at 330[K] from experimental data (OZIMA and PODOSEK, 1983); a typical Ne diffusion time through $1\times10^{-5}$[m] thickness is as short as $1\times10^{-3}$[yr] which is much smaller than mutual collision time of grains (larger than 0.1[yr]). Hence, different from Ar with a larger atomic radius, Ne could diffuse out of implanted grains. Another explanation is that after the accumulation of solar gas onto Venus a large amount of lighter Ne should have escaped from the Venusian atmosphere due to drag by outgoing hydrogen. At present, we do not have any strong evidence to support either of the above. The future precise determination of $^{20}$Ne/$^{22}$Ne of the Venusian atmosphere will provide an important constraint: $^{20}$Ne/$^{22}$Ne must be much smaller than the solar ratio ($\sim$13.6) if Ne was lost by atmospheric escape, whereas $^{20}$Ne/$^{22}$Ne should be similar to the solar ratio if the diffusive loss from dust grains caused Ne deficiency.

v) Noble gas deficiency in Mars

The noble gas abundance in the Martian atmosphere is very small: the relative abundance of $^{36}$Ar (to Si) is 160 times smaller than the Earth (POLLACK and BLACK, 1982), and moreover, the elemental pattern of noble gas species is of the fractionated "planetary" type. If the difference of the solar wind implantation should have caused the difference of noble gas abundance between Mars and Earth, the Martian noble gas would have had the solar pattern. The deficiency of noble gas in the Martian atmosphere should reflect another mechanism: *e.g.* inefficient degassing or hydrodynamic escape of the atmosphere (HUNTEN *et al.*, 1987).

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## References

BOGARD, D. D. (1988): On the origin of Venus' atmosphere; Possible contribution from simple component mixtures and fractionated solar wind. Icarus, **74**, 3–20.

CRABB, J. and ANDERS, E. (1981): Noble gases in E-chondrites. Geochim. Cosmochim. Acta, **45**, 2443–2464.

DONAHUE, T. M., HOFFMAN, J. H. and HODGES, R. R., Jr. (1981): Krypton and xenon in the atmosphere of Venus. Geophys. Res. Lett., **8**, 513–516.

EBERHARDT, P., GEISS, J., GRAF, H. GRÖGLER, N., KRÄHENBÜHL, U., SCHWALLER, H., SCHWARZMÜLLER,

J. and STETTLER, A. (1970): Trapped solar wind noble gases, exposure age and K/Ar-age in Apollo 11 lunar fine material. Proc. Apollo 11 Lunar Sci. Conf., 1037–1070.

GOSWANI, J. N., LAL, D. and WILKENING, L. L. (1984): Gas-rich meteorites; Probe for particle environment and dynamical processes in the inner solar system. Space Sci. Rev., **37**, 111–159.

HAYASHI, C., NAKAZAWA, K. and NAKAGAWA, Y. (1985): Formation of the solar system. Protostar and Planets II, ed. by D.C. BLACK and M.S. MATTHEWS. Tucson, Univ. Arizona Press, 1100–1153.

HEYMANN, D. and PALMA, R. L. (1986): Discovery of solar wind neon in the Allende meteorite. Proc. Lunar Planet. Sci. Conf., 16th (J. Geophys. Res., **91**, D460–466).

HUNTEN, D. M., PEPIN, R. O. and WALKER, J. C. G. (1987): Mass fractionation in hydrodynamic escape. Icarus, **69**, 532–549.

LIN, D. N. C. and PAPALOIZOU, J. (1985): On the dynamical origin of the solar system. Protostar and Planets II, ed. by D.C. BLACK and M.S. MATTHEWS. Tucson, Univ. Arizona Press, 981–1072.

MARTI, K. (1969): Solar-type xenon; A new isotopic composition of xenon in the Pesyanoe meteorite. Science, **166**, 1263–1265.

OHTSUKI, K., NAKAGAWA, Y. and NAKAZAWA, K. (1988): Growth of the Earth in nebular gas. Icarus, **75**, 552–565.

OZIMA, M. and PODOSEK, F. A. (1983): Noble Gas Geochemistry. Cambridge, Cambridge Univ. Press, 50.

PEPIN, R. O. and SIGNER, P. (1965): Primordial rare gases in meteorites. Science, **149**, 253–265.

POLLACK, J. B. and BLACK, D. C. (1982): Noble gases in planetary atmospheres; Implications for the origin and evolution of atmospheres. Icarus, **51**, 169–198.

SHIMIZU, M. (1979): Implications of argon-36 excess on Venus. Moon Planets, **20**, 317–319.

SUESS, H. E., WÄNKE, H. and WLOTZKA, F. (1964): On the origin of gas-rich meteorites. Geochim. Cosmochim. Acta, **28**, 595–607.

VON ZAHN, U., KUMAR, S., NIEMANN, H. and PRINN, R. (1983): Composition of the Venus atmosphere. Venus, ed. by D. M. HUNTEN *et al.* Tucson, Univ. Arizona Press, 299–430.

WETHERILL, G. W. (1981): Solar wind origin of $^{36}$Ar on Venus. Icarus, **46**, 70–80.

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