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Authors

McElroy, Michael B
Prather, Michael J

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Noble gases in the terrestrial planets

Michael B. McElroy & Michael J. Prather

Center for Earth and Planetary Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Abundances of primordial noble gases are lower for Mars than for Earth, but are higher for Venus. The data for Venus are attributed to implantation of solar wind in small preplanetary particles. Results for Mars are explained by escape of gas from planetesimals with radius between 5 and 100 km which form within the first 10^7 yr of the Solar System. Volatile loss is associated with melting caused by short-lived radioisotopes such as ^{26}Al.

OUR knowledge of planetary atmospheres has increased markedly over the past decade, thanks mainly to experiments on the Mariner, Pioneer and Viking missions of the United States and the Venera missions of the Soviet Union. Measurements of noble gases in the atmospheres of Mars and Venus, summarized in Table 1, are particularly puzzling: concentrations of ^{22}Ne, ^{36}Ar, ^{84}Kr and ^{132}Xe were unexpectedly low for Mars[1-3]; concentrations of ^{20}Ne, ^{22}Ne, ^{36}Ar and ^{38}Ar were very high, in contrast, for Venus[4-8].

The noble gases provide invaluable constraints on models for the formation of planets and for the evolution of their atmospheres. It is useful to distinguish from the outset between primordial gases (for example, ^{3}He, ^{4}He, ^{20}Ne, ^{36}Ar, ^{38}Ar, ^{84}Kr, ^{132}Xe) present in the original solar nebula and radiogenic gases (including ^{4}He, ^{40}Ar, ^{129}Xe) produced at least in part by decay of rock forming elements such as U, ^{40}K and ^{129}I. The half life of ^{40}K is 1.3×10^9 yr and the abundance of ^{40}Ar reflects both the initial abundance of potassium and the efficiency for degassing over the age of the planet[9,10]. Interpretation of data for ^{129}Xe is complicated in that the half life of the precursor ^{129}I, is only 1.6×10^7 yr (refs 11, 12). Thus concentrations of ^{129}Xe and ^{129}I may vary significantly over the period of planetary formation.

Primordial noble gases in meteorites fall into two classes[13,14], planetary and solar, with relative abundances as given in Fig. 1. The planetary distribution is thought to arise during condensation[15-18] though it may be modified by subsequent evolution. The solar pattern appears to reflect implantation by the solar wind and is displayed prominently in samples from the lunar surface[19]. The atmospheres of the terrestrial planets retain neon, argon, krypton and xenon[1,20-22]. Helium, in contrast, is lost rapidly to space[23,24].

An acceptable model for the terrestrial planets must account for: (1) an abundance of primordial neon and argon in Venus' atmosphere ~70 times larger than that for Earth; (2) an abundance of primordial neon and argon in Mars' atmosphere ~180 times less than that for Earth; (3) ratios of primordial neon to argon similar for all three planets; (4) occurrence of the planetary pattern for Ne, Ar, Kr and Xe in meteorites and in the atmospheres of Mars and Earth, with a departure for Kr on Venus; (5) abundance ratios ^{129}Xe/^{132}Xe and ^{40}Ar/^{36}Ar for Mars higher than for Earth; (6) a ratio ^{20}Ne/^{22}Ne for Venus similar to solar wind, though higher than for Earth; and (7) a ratio ^{36}Ar/N for Venus higher than for Earth by a factor of 20. The problem may be summarized as follows. Venus has an unexpectably high concentration of ^{36}Ar, a ratio Ne/^{36}Ar similar to Earth, Mars and the planetary component of meteorites, but a distinctly different value for the ratio ^{20}Ne/^{22}Ne. The concentration of ^{36}Ar in Mars' atmosphere is low and cannot be attributed simply to inefficient degassing.

Previous models

Differences in the abundances of noble gases in the atmospheres of terrestrial planets might arise due to variations in the extent to which parent solid bodies released their original store of volatiles. The abundance of ^{40}Ar gives information on the rate and manner of degassing[9,10]. The abundance in the atmosphere of Mars is less than that in the terrestrial or Venus atmospheres by a factor of ~10. If we assume, consistent with available data[25-27], that K should be similar for all three planets, then the degassing efficiency for Mars should be about one-tenth that for Earth and Venus. These considerations suggest that the total planetary abundance of ^{36}Ar for Mars may be 10 times larger than the atmospheric abundance, 18 times less than the terrestrial value. Our estimate for the martian abundance would be reduced if K were low as suggested by Anders and Owen[20,26,28]. Table 1 includes estimates for the total abundance of ^{36}Ar in each planet. These data were derived by scaling measured concentrations of ^{36}Ar using observed values of ^{40}Ar.

The noble gas results for Mars and Venus are quite unexpected. Models for condensation in the early solar nebula suggest a pattern opposite to that observed[15,16,29-31] with concentrations highest at Mars where the nebula was relatively cold, lowest at Venus. Concentrations of ^{36}Ar in meteorites[14,32] range from undetectable to 3×10^{-9} g per g. One might attribute the abundance of ^{36}Ar in a particular planet to aggregation of materials drawn from different meteorite classes[33]. Anders and Owen[20] proposed that planetary volatiles could be associated with late accretion of volatile rich material with composition similar to meteorites of class C3V. The hypothesis was introduced to account for the Viking results and is generally consistent with the martian data summarized in Table 1. It fails, however, to account for the more recent information from Venus[28]. Pollack and Black[34], working with the Venus data, took a rather different route. They suggested that noble gases could be equilibrated with grains in the primitive nebula at a rate proportional to ambient pressure. The nebula was assumed to be isothermal between the orbits of Venus and Mars to maintain an invariant pattern in noble gases. The pressure must have declined by four orders of magnitude over this distance to account for the decrease in noble gases indicated in Table 1. This requires a scale height in the primitive nebula 20 times larger than one would calculate assuming a central mass equal to that of the contemporary Sun, a difficulty not explicitly considered by Pollack and Black.

Present model

We propose a model for the noble gas concentrations observed in all three terrestrial planets drawing on data from meteorites and lunar soils. We take the view that the origin of Venus' noble gas must be distinct from that of Earth's, as the isotopic composition of neon is different. The similarity of Venus' ^{20}Ne/^{36}Ar ratio to the terrestrial value must be considered in this case fortuitous. We suggest that Venus' noble gases are derived mainly from solar wind while the terrestrial and martian components condensed from the nebula with an origin similar to

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Table 1 Noble gases

	Atmos. ^{36}Ar (g per g)	Atmos. ^{40}Ar (g per g)	Total ^{36}Ar* (g per g)	^{20}Ne/^{36}Ar†	^{84}Kr/^{36}Ar	^{132}Xe/^{36}Ar	N/^{36}Ar	^{20}Ne/^{22}Ne	^{40}Ar/^{36}Ar	^{129}Xe/^{132}Xe
Venus‡	2.4×10^{-9}	2.7×10^{-9}	2×10^{-8}	0.3 ± 0.2	<0.007	?	2.5×10^{3}	14^{+6}_{-3}	1.0	?
Earth§	3.5×10^{-11}	1.2×10^{-8}	7×10^{-11}	0.52	0.021	7.5×10^{-4}	5×10^{4}	9.8	296	0.98
Mars‖	2.0×10^{-13}	7.0×10^{-10}	8×10^{-12}	0.38	0.032	3×10^{-3}	2×10^{6}	?	3000	2.5
Sun¶			3×10^{-5}							
Solar wind				35	0.0005	6×10^{-5}	1×10^{2}	13.3	<1	1.05
Flares				32				7.7		
Lunar fines#			8×10^{-7}							
Meteorites**										
C				0.27	0.012	1×10^{-2}	4×10^{6}	8		1–3
C3V			5×10^{-10}				3×10^{5}			
C30			2.5×10^{-9}				6×10^{4}			
H, L, LL			$0.2–5\times10^{-11}$	low	0.01	1×10^{-2}	4×10^{6}			
E			$0.1–1\times10^{-9}$							
Gas-rich			$0.02–2\times10^{-9}$	20	0.001	low		12.5		
Neon-E								<0.1		
Cosmic rays††								2.6		

* Total abundance assumes that 50% of ^{36}Ar remains trapped within the Earth[86]; the efficiency of degassing for Venus and Mars is scaled by using measurements of ^{40}Ar.

† All mixing ratios are atomic.

‡ Refs 6, 8, 87.

§ Refs 88, 68, 75, for example.

‖ Refs 1, 3, and 25. Assumes ^{20}Ne/^{22}Ne = 8 and a mean pressure of 7.5 mbar (ref. 89). The ratio N/^{36}Ar in the present atmosphere is approximately 1×10^4; the ratio given here refers to the original system and includes estimates for escape of N (see text).

¶ Solar wind data are based on neon observations of Geiss *et al.*[49], photospheric abundances of neon/argon[50,90] and lunar data[53,68] (see text). Solar flare data are from refs 91 and 92.

Refs 19, 53.

** Refs 14, 20, and 32 with 93 and 94 for neon-E.

†† Refs 95 and 96.

that of the planetary component in meteorites. The low concentration of noble gases in Mars is attributed to differentiation and escape of volatiles from preplanetary martian material.

Our model is based on a postulate that condensation proceeds most rapidly in cooler outer regions of the solar nebula. The solar nebula included from the outset a heterogenous mixture of gas and particles[35–39]. The quantity of material present in the condensed phase would have increased with time as the nebula cooled. High concentrations of condensate would have appeared first in intermediate regions of the nebula where combinations of low temperature and adequate density favoured most efficient condensation[40,41]. We suggest that this region occurred near the orbits of Mars and the asteroids. The condensation sequence would have proceeded later near the orbit of Venus as cooling extended to the inner nebula. Coalescence of small particles to kilometre size could have been rapid once the amount of condensed material became comparable with that now in planets[42,43]. Goldreich and Ward[42] showed that, if the condensate was confined to a homogeneous disk <5,000 km thick, accretion of dust grains into sizeable planetesimals would take place in ~10^3 yr. As shown below, the noble gas data suggest that conditions necessary for rapid gravitational accretion were present for the pre-Mars material but did not occur in the pre-Venus environment.

The primitive nebula included significant concentrations of ^{26}Al (half life 0.7×10^6 yr)[44] in addition to trace quantities of short-lived radioisotopes such as ^{107}Pd (ref. 45) and ^{129}I (refs 11, 46). Lee *et al.*[44] noted that radioactive heat sources in certain meteoritic inclusions were sufficient to melt kilometre sized objects which formed from these materials during the first few million years. Indeed, there is evidence that iron meteorites differentiated within this time period[45]. (Smaller objects characterized by a relatively larger surface area-to-volume ratio could dispose of the excess heat by radiation and would not be expected to attain high internal temperatures.) Objects forming in cooler regions of the nebula would have included high initial concentrations of noble gases[16,17,47] which would have been modified subsequently by escape following melting and by input from the solar wind. We suggest that the rapid accretion/melting/escape sequence accounts for the deficiency of noble gas in Mars. In the inner Solar System most of the ^{26}Al would have decayed before formation of kilometre-sized objects. Loss of volatiles from preplanetary Venus material would consequently be negligible.

Venus and the solar wind

Effects of solar wind would have been most important for innermost regions of the nebula. Condensing preplanetary bodies would have incorporated solar wind at a rate proportional to their exposed surface area. According to the present model, the area-to-volume ratio for condensed material would have decreased as a function of distance between the orbits of Venus and Mars. The Poynting–Robertson effect and friction between particles and gas would have led to further concentration of small particles near Venus[43,48]. We expect therefore that solar wind should have a more important role for Venus than that for Earth and Mars. Our knowledge of noble gases in the solar wind and solar flares is based on a few direct measurements[49–51] and on detailed analysis of samples from the Moon[19,52–56]. Lunar soils provide an excellent example of the accumulated effects of irradiation by solar wind and flares, with bulk abundances for ^{36}Ar often as high as 8×10^{-7} g per g. The expected dependence of ^{36}Ar on particle size and exposure time is shown in Fig. 2. Dynamical considerations suggest that the final stages of planetary accretion should occupy a time between 10^7 and 10^8 yr (refs 43,57–59). We could account for ^{36}Ar in Venus' atmosphere from solar wind if Venus formed from materials with a mean radius of 10 m exposed for ~2×10^7 yr to solar wind of current strength and composition. This material could be distributed uniformly about the orbit of Venus and we would require that it extend ~10 planetary radii above the plane of the nebula, if characteristics of the early solar wind were similar to those of today. The projected surface area and exposure times would be lowered if the early wind were more intense.

One can account therefore in a straightforward fashion for the $^{20}Ne/^{22}Ne$ ratio and for the absolute abundance of ^{36}Ar in Venus' atmosphere by postulating a dominant role for the early solar wind. The ratio $^{84}Kr/^{36}Ar$ would be $\sim 5 \times 10^{-4}$, consistent with the upper limit reported by Hoffman *et al.*[6]. Indeed it would be difficult to account otherwise for the low value of ^{84}Kr in Venus. The solar wind model has greatest difficulty in accommodating the ratio observed for $^{20}Ne/^{36}Ar$. The ratio $^{20}Ne/^{36}Ar$ is typically 35 in lunar soils exposed recently to solar wind[19]. The abundance is variable for older materials[60], reflecting loss of neon by diffusion[61]. Ratios $^{20}Ne/^{36}Ar$ may be as low as 2 and are correlated often with mineral type[53,55,56]. We shall attempt here to argue that the ratio $^{20}Ne/^{36}Ar$ observed by Pioneer Venus, 0.3, may be attributed to differential diffusive loss of neon from pre-Venus material.

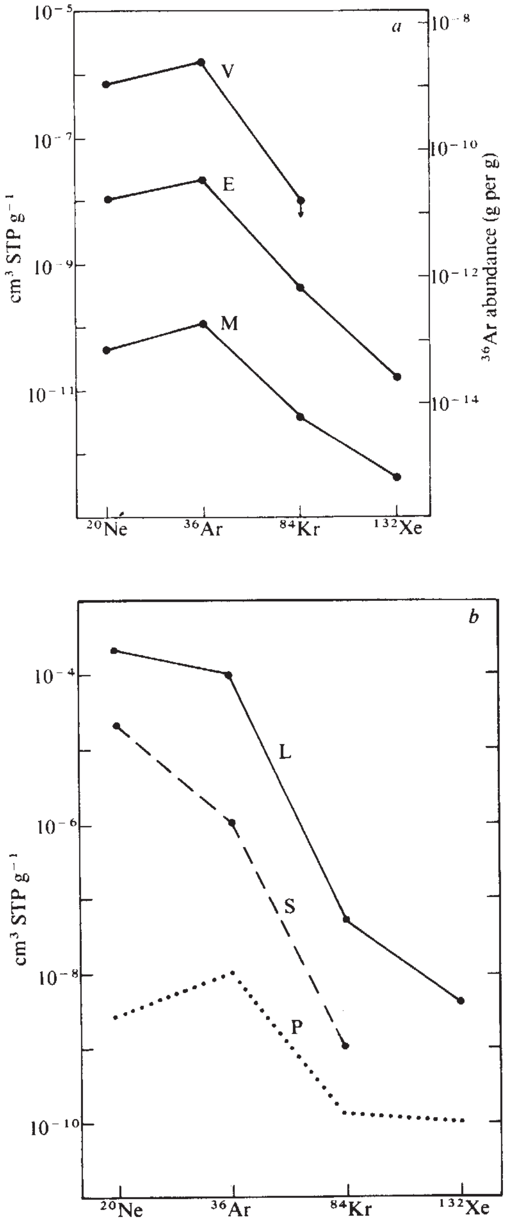

Fig. 1 *a*, Abundances of primordial noble gases observed in the atmospheres of Venus (V), Earth (E) and Mars (M). Abundances are quoted as ratios referenced to mass of the parent planet. The abundance of ^{20}Ne for Mars is based on an assumed ratio $^{20}Ne/^{22}Ne$ of 8. The abundance indicated for ^{84}Kr on Venus is an upper limit. *b*, Relative abundances of primordial noble gas for lunar fines (L), the solar component (S) found in 'gas-rich' meteorites and the planetary component of meteorites (P). Abundances of ^{36}Ar for L, S and D are set arbitrarily equal to 10^{-4}, 10^{-6} and 10^{-8}, respectively. For absolute abundances of ^{36}Ar see Table 1.

The time scale, *t*, for removal of neon may be represented by

$$t = a^2/D \qquad (1)$$

where D is a diffusion coefficient and a is the penetration depth for solar wind, typically $\sim 3 \times 10^{-5}$ cm (ref. 19). Diffusion of noble gas through minerals at temperature T may be characterized by

$$D = D_0 \exp(-E/RT) \qquad (2)$$

where R is the gas constant, and E is the activation energy. Values of D_0 for noble gases range from 10^{-3} cm^2 s^{-1} in vitreous silica[62,63] to 10^{-7} cm^2 s^{-1} in alumina–glass mixtures[64]. Activation energies[62,65] vary from 5 to >65 kcal mol^{-1}, and gas may be trapped at individual sites characterized by a spectrum of values for E (refs 66, 67). We expect $^{20}Ne/^{36}Ar$ to have an initial value of ~35. The ratio should decrease with time on various time scales t_i reflecting applicable values of E_i and the thermal history of the sample.

Assume that Venus formed in $\sim 5 \times 10^7$ yr; neon released from the condensed phase after this epoch would be retained by the planet. Neon evolved earlier would be lost. Assume that the preplanetary material was characterized by a temperature of 333 K (an appropriate temperature for a black body exposed to present sunlight at the orbit of Venus; the actual temperature of preplanetary material could differ depending on conditions in the nebula and the luminosity of the early Sun.) It follows from equations (1) and (2) that neon trapped at sites with $E_i <$ 26 kcal mol^{-1} would be lost; neon at sites with $E_i >$ 26 kcal mol^{-1} would be retained. Studies based on step heating of lunar samples[68–70] suggest that >95% of neon implanted in preplanetary Venusian material would be lost in 2×10^7 yr at 333 K (equivalent to 1 h at 1,050 K). Loss of ^{36}Ar and ^{84}Kr would be negligible, see Fig. 3. The resulting value for $^{20}Ne/^{36}Ar$ should lie between 0.5 and 2.0, consistent with the observed value[6], 0.3 ± 0.2.

The neon problem

The ratio $^{20}Ne/^{22}Ne$ is variable in the Solar System, with values typically between 7 and 14 (see Table 1). The range of values observed for $^{20}Ne/^{22}Ne$ is thought to reflect fractionation of neon in the primitive nebula[12] and, in addition, heterogeneity associated most probably with material synthesized in different nuclear environments[71–74]. (Note that the ratio $^{36}Ar/^{38}Ar$ is remarkably uniform for all materials sampled to date[6,14,37]; it is unlikely therefore that the variety in $^{20}Ne/^{22}Ne$ can be attributed solely to diffusive separation[12].) There is uncertainty concerning the value for the $^{20}Ne/^{22}Ne$ ratio of the Sun and presumably for the original nebula. Solar flares show a ratio of ~8, while the ratio in solar wind is 13.6. It is unclear which, if either, of these values is representative of the Sun. A ratio $^{20}Ne/^{22}Ne$ of ~8 is typical for the planetary component in meteorites and seems to be favoured for condensation in the early nebula. Materials modified by solar wind exhibit ratios in the range 11–14. We could account for the terrestrial ratio of 9.8 if 40% of Earth's neon were derived from solar wind, with the remainder drawn from the planetary component. We might expect preplanetary Earth to retain solar wind neon with higher efficiency than Venus, as temperatures and effective diffusion coefficients would have been lower at the orbit of Earth. Sources of ^{36}Ar, ^{84}Kr and ^{132}Xe from the solar wind would be negligible compared with quantities of these gases trapped during condensation. We could account for terrestrial neon if preplanetary material of mean radius 50 km were exposed to solar wind for 2×10^7 yr.

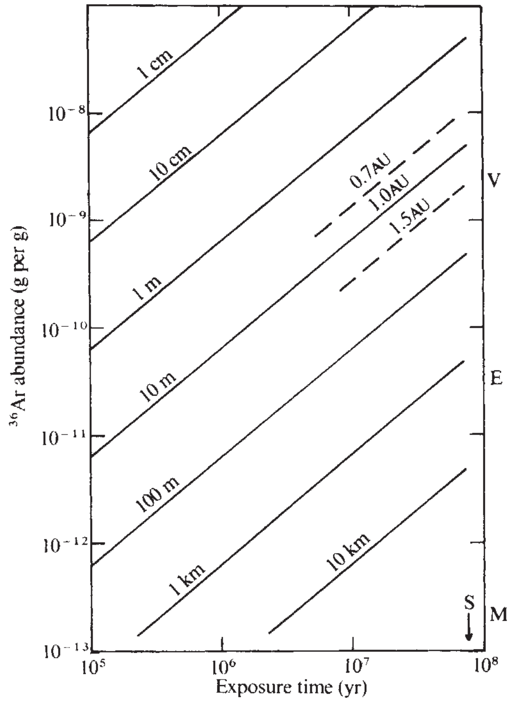

Fig. 2 Mean abundance of ^{36}Ar (g per g) accumulated by planetesimals from the solar wind as a function of exposure time. Planetesimals are assumed to follow an exponential distribution in radius ($N(r)dr = \exp(-r/a)\,dr$) and to have a mean density of $3\ \mathrm{g\ cm^{-3}}$. Each solid line refers to a particular distribution with mean radius a as given. Abundances are quoted for exposure to present solar wind at the orbit of Earth (1.0 AU). The effect of location is shown for a mean radius of 10 m, with data for Venus (0.7 AU) and Mars (1.5 AU) indicated by dashed lines. The saturation limit[85], $10^{-2}\ \mathrm{cm^3}$ STP of gas $\mathrm{cm^{-2}}$, is denoted by S. Abundances of ^{36}Ar for the atmospheres of Venus (V), Earth (E) and Mars (M) are indicated.

Mars

We expect neon implanted by the solar wind to be retained with relative ease by preplanetary Mars. The solar wind component would be characterized by a ratio ^{22}Ne/^{36}Ar of about 1 (refs 19, 54, 68, 75) in contrast to the value 0.047 observed for Mars[3]. We might hope to use these data to place limits on the time for effective exposure of preplanetary material to solar wind at the orbit of Mars. The data in Fig. 2 and Table 1 suggest that 100-km objects could be exposed to solar wind for no more than 5×10^5 yr, a somewhat paradoxical result at first sight. We require preplanetary Mars material to melt and differentiate early, and its average size to be small enough to permit efficient escape of gases as heavy as xenon. On the other hand, dynamical considerations require that final stages of planetary accretion should occupy a time interval of at least 10^7 yr (refs 43, 57, 59). It is likely that planetesimals at Mars' orbit may have been shielded to some extent from solar wind by material in the inner Solar System. The paradox may also be resolved if ionization of gases evolved from preplanetary bodies were to provide a shield insulating surfaces from solar wind[76,77]. Indeed this shield must be operative at present as the flux of ^{22}Ne in the current solar wind would account for the abundance of neon in Mars' atmosphere in as little as 10^7 yr.

The ratio ^{129}Xe/^{132}Xe is 2.5 for Mars, 0.98 for Earth, 1.05 for solar wind, and ranges between 0.6 and 3.0 for bulk meteorites with much higher values for specific inclusions[3,11,12,68,75,78–80]. High values of ^{129}Xe/^{132}Xe require a mechanism to deplete xenon relative to iodine in materials forming Mars and certain meteorites. Depletion must occur within 3×10^7 yr following incorporation of ^{129}I in planetesimals. The relatively high value for ^{40}Ar/^{36}Ar in Mars' atmosphere seems to require a corresponding mechanism to deplete argon relative to potassium and is explained by the melting/degassing scenario envisaged here.

Mars' atmosphere is composed mainly of CO_2 with trace quantities of N_2, H_2O and photochemical products such as CO, O_2 and O_3, in addition to the noble gases discussed above[2,3,81,82]. Nitrogen is especially interesting. Its isotopic composition differs significantly from that of Earth and other Solar System materials. The difference is attributed to preferential escape of ^{14}N relative to ^{15}N, and implies an initial abundance for atmospheric N_2 of no less than 8×10^{22} molecules $\mathrm{cm^{-2}}$, more probably $\sim1.3\times10^{24}$ molecules $\mathrm{cm^{-2}}$ (refs 1, 83). One might assume that nitrogen is released from the solid body with an efficiency only slightly less than that for argon. In this case nitrogen in the early Mars would be $\sim2.6\times10^{-6}$ g per g, certainly no less than 1.6×10^{-7} g per g, with 5% of the total in the primitive atmosphere. The ratio N/^{36}Ar would be at least as large as 1×10^5, more probably $\sim2\times10^6$. By way of comparison the ratio is 5×10^4 for Earth and 2.5×10^3 for Venus (see Table 1). The low value for Venus is attributed to addition of argon from the solar wind in the preplanetary phase, a process which would not significantly affect nitrogen. The high value for Mars could

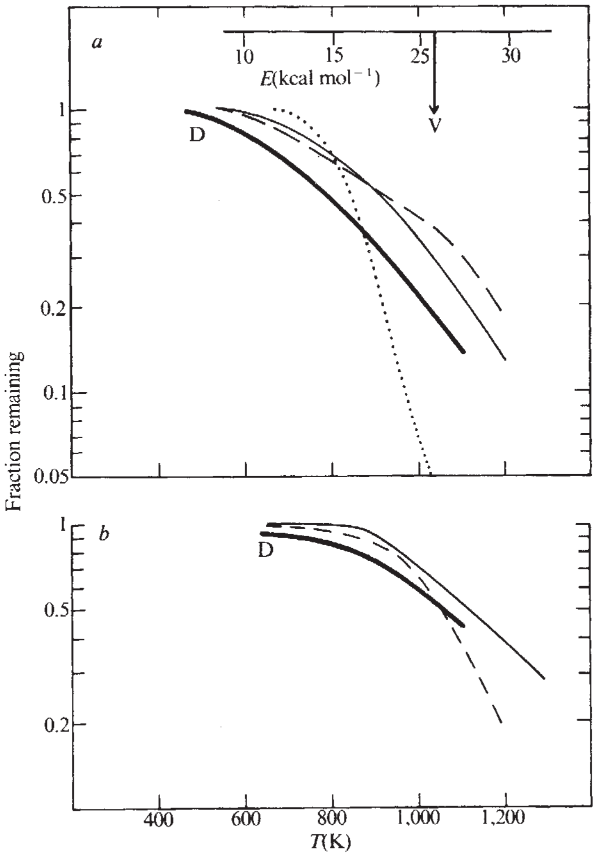

Fig. 3 Fraction of noble gas remaining in lunar samples after heating at a given temperature for 1 h. The initial ^{20}Ne/^{36}Ar ratio in these materials is typically 6. The mean rate of degassing of neon and krypton was measured for three lunar samples by Drozd *et al.*[70] and is indicated by the thick line D (^{20}N in *a*, ^{84}Kr in *b*). Other data are from Pepin *et al.* (ref. 69). Solid lines are for lunar fines 10084 (^{22}Ne in *a*, ^{84}Kr in *b*); dashed lines, lunar rock 10069 (^{22}Ne in *a*, ^{36}Ar in *b*); dotted line, lunar breccia 10061 (^{22}Ne in *a*). The energy scale refers to the activation energy of an implanted gas which would be released in the following conditions: heated at the given temperature for 1 h following implantation at a mean depth of 3×10^{-5} cm, with $D_0 = 10^{-7}\ \mathrm{cm^2\ s^{-1}}$ (see text). The arrow labelled V denotes the maximum activation energy consistent with relatively complete escape of gas in 5×10^7 yr from an object at the orbit of Venus (333 K), see text.

reflect preferential retention of chemically bound N (ref. 84) relative to Ar during melting.

Conclusions

We may summarize now our response to the questions raised earlier: (1) the abundance of neon and argon in Venus' atmosphere is dominated by implantation of solar wind in preplanetary material; (2) the deficiency of primordial noble gases in Mars' atmosphere is attributed to differentiation of preplanetary material; (3) the origin of Venus' neon is different from that of Earth and Mars and the similarity of Ne/Ar for Venus to values for the other inner planets is fortuitous; (4) the discrepancy between Venus' noble gases and the planetary pattern is due to large additions of gas from preplanetary solar wind; (5) the ratio $^{40}Ar/^{36}Ar$ for Mars is higher than for Earth due to escape of ^{36}Ar in the preplanetary phase, and the higher value for $^{129}Xe/^{132}Xe$ arises because Mars formed early with high concentrations of ^{129}I; (6) Venus' neon is derived from solar wind and reflects its isotopic composition; (7) the solar wind would not add significant quantities of nitrogen and the high value of $^{36}Ar/N$ on Venus is attributed to excess ^{36}Ar. Our model suggests that the pattern of noble gases for Mars should resemble the planetary pattern of meteorites, that the ratio $^{20}Ne/^{22}Ne$ should be ~ 8. Krypton and xenon on Venus would be derived in part from solar wind, in part by condensation from the primitive nebula. We expect a ratio $^{132}Xe/^{84}Kr$ in Venus' atmosphere of ~ 0.1, intermediate between the values observed for Earth and solar wind, with $^{129}Xe/^{132}Xe \sim 1$.

More precise observations are required to test and develop these ideas. It is clear that they could be refined and would be more quantitative if formulated in the context of a comprehensive physical model of planetary formation. There are reasons to expect, in turn, that observations of noble gases in meteorites, comets, asteroids and planets should provide invaluable clues to processes in the early nebula, aiding significantly in the development of such a model.

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Note added in proof: After completion of this work we learned of an independent conclusion by G. Wetherhill[97] that Venus' ^{36}Ar is derived from solar wind. Further analyses of the Pioneer data by Donahue *et al.*[98] give ratios for $^{84}K/^{36}Ar$, $^{132}Xe/^{84}Kr$ and $^{129}Xe/^{132}Xe$, of 10^{-3}, 0.25, and about 1, respectively, in excellent agreement with the model discussed here.

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