

MARS, A VOLATILE-RICH PLANET

G. Dreibus and H. Wänke

Max-Planck-Institut für Chemie

Saarstrasse 23

D-6500 Mainz

F.R. Germany

The detection of a trapped Martian atmosphere-like component in the shergottite EETA 79001 provides the most conclusive evidence that SNC-meteorites are rocks from Mars. If we assume that the parent body of the SNC-meteorites is indeed Mars, these meteorites can be used to estimate the abundance of volatile elements on Mars. It is found that Mars contains a number of volatile elements in concentrations exceeding those of the Earth. The low abundance of primordial rare gases on Mars is explained by drastic depletion during the escape of the early Martian atmosphere.

INTRODUCTION

According to current models of the solar system formation (Larimer, 1967; Lewis, 1972), the concentrations of volatiles in a given planet are expected to increase with its distance from the Sun. In other words, objects closer to the Sun should be the ones most depleted in volatile species. Therefore it was a big surprise when the Viking data revealed that the primordial rare gas concentrations in the atmosphere of Mars are two orders of magnitude below the terrestrial values.

In the models of Ringwood (1979) and Wänke (1981), the degree of planetary oxidation should be parallel to the content of volatiles. This is in fact also a consequence of the equilibrium condensation model (Lewis, 1972), which predicts a sulfur-rich core for Mars and a mantle with an FeO/(FeO+MgO) ratio higher than of the Earth's mantle and an inventory of volatiles intermediate between that of the Earth and that of carbonaceous chondrites. We will show that this indeed seems to be the case.

Following Ringwood (1977, 1979), Wänke (1981) proposed that the Earth accreted from two chemically different components. However, contrary to Ringwood's model which postulated homogeneous accretion, Wänke favoured an inhomogeneous accretion of the Earth. According to this model, the highly reduced, volatile-free component A dominated in the first stage of accretion and the oxidized, volatile-containing component B was added in larger proportions only towards the end of the accretion process and after most of the metal contributed by component A has segregated to form the core. In this model (Wänke, 1981), it is assumed that component A is at least as reduced as enstatite chondrites, while component B may directly be compared with C 1 chondrites (carbonaceous chondrites type 1).

The SNC-meteorites (Shergottites, Nakhrites and Chassigny) form a distinct group of altogether eight achondrites based on their oxygen isotope signatures and various element ratios. The young crystallization ages of SNC-meteorites, their considerably fractionated REE patterns, the compositional similarity of the Martian soil and Shergotty meteorite and other observations had previously pointed quite strongly towards Mars as

the parent body of these meteorites (Nyquist *et al.*, 1979; Wasson and Wetherill, 1979; McSween and Stolper, 1980; Dreibus *et al.*, 1981; Wood and Ashwal, 1981). However the most recent and conclusive evidence of a Martian origin for the SNC-meteorites was the discovery of a trapped rare gas and nitrogen component in EETA 79001 with element and isotope ratios very different from components observed in other meteorites, but closely matching the highly characteristic element and isotope ratios (e.g. $^{40}\text{Ar}/^{36}\text{Ar}$, $^{14}\text{N}/^{15}\text{N}$, $^{14}\text{N}/^{40}\text{Ar}$ or $^{129}\text{Xe}/^{132}\text{Xe}$) of the Martian atmosphere (Bogard and Johnson, 1983; Becker and Pepin, 1984). The suggestion that some meteorites are derived from Mars is not new (Wänke, 1966 and 1968), but there is no generally accepted model for the dynamical problems involved in accelerating surface materials to escape velocity (see Wetherill, 1984). If Mars is the SPB (Shergotty parent body), the SNCs may potentially be used to estimate the bulk composition of Mars.

By assuming that the SNC-meteorites are indeed Martian rocks, Dreibus and Wänke (1984) were able to use these meteorites to estimate the bulk composition of Mars. Their results which are summarized in Table 1 (see also Fig. 1) together with new data for volatile elements agree well with geochemical and geophysical models (Wood

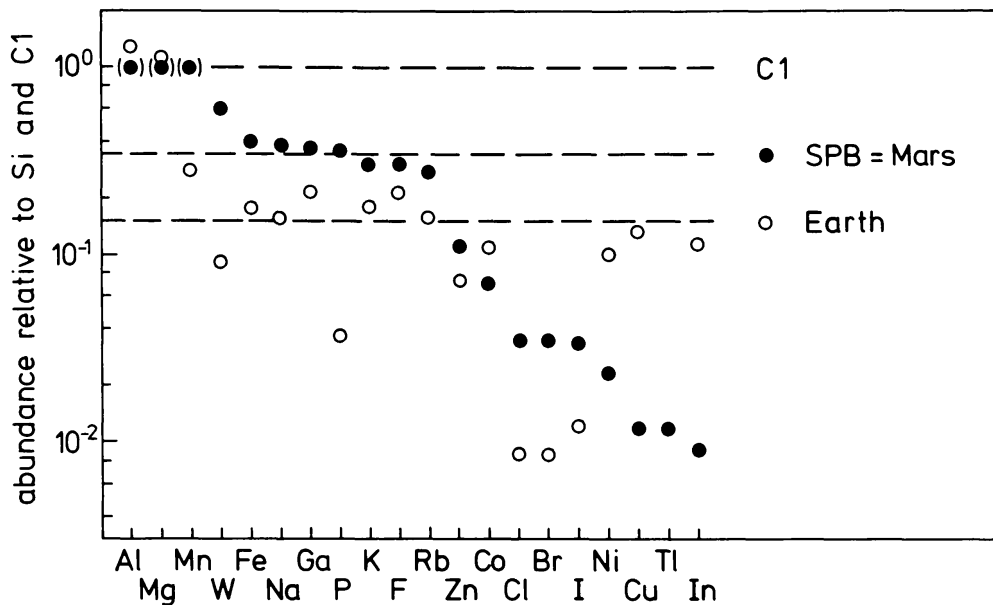


Fig. 1 Primitive mantle compositions of Earth and Mars. Note the approximately two times higher abundances of moderately siderophile and moderately volatile elements (all derived from component B) on Mars compared to the Earth. Also note the low abundance of elements with chalcophile tendencies (Co, Ni, Cu, In, Tl) on Mars. The dashed lines (Mars and Earth) indicate the mean abundances of elements derived from component B which are not altered by secondary processes (segregation of metal and/or sulfide; loss of highly volatiles during accretion). Data from Wänke (1981), Burghelle *et al.* (1983) and Dreibus *et al.* (1982).

Table 1
Estimates of the bulk composition of Mars

	Mars as SPB ^{a,b)} and this work	Anderson (1972)	Morgan a. Anders (1979)	Ring- wood (1981)	Mars as SPB rel. to Si and Cl	Earth ^{c,d)} rel. to Si and Cl
Mantle + crust						
MgO %	30.2	27.4	29.78	29.9	1.00	1.18
Al ₂ O ₃	3.02	3.1	6.39	3.1	1.00	1.35
SiO ₂	44.4	40.0	41.60	36.8	1.00	1.00
CaO	2.45	2.5	5.16	2.4	1.00	1.40
TiO ₂	0.14	0.1	0.33	0.2	1.00	1.53
FeO	17.9	24.3	15.85	26.8	0.39	0.16
Na ₂ O	0.50	0.8	0.10	0.2	0.38	0.29
P ₂ O ₅	0.16	0.34	—	—	0.36	0.032
Cr ₂ O ₃	0.76	0.6	0.65	0.4	1.00	0.56
MnO	0.46	0.2	0.15	0.1	1.00	0.28
K ppm	315	573	77	218	0.31	0.22
Rb	1.12		0.26		0.28	0.18
Zn	74		41.8		0.11	0.070
Ga	6.6		2.43		0.37	0.21
In ppb	14		0.0095		0.090	0.115
Tl	3.6		0.17		0.013	—
Cl ppm	44		0.88		0.034	0.0087
Br ppb	165		4.73		0.034	0.0090
I	37		0.59		0.034	0.012
Th	56	77	125	60	1.00	1.30
U	16	17	35	17	1.00	1.30
Core						
Fe %	77.8	72	88.12	63.7	—	—
Ni	7.6	9.3	7.99	8.2	—	—
Co	0.36	—	0.37	—	—	—
S	14.24	18.6	3.51	9.3	—	—
O	—	—	—	18.7	—	—
Core mass %	21.7	11.9	19.0	18.2	—	—

a) Burghelle *et al.* (1983); b) Dreibus and Wänke (1984); c) Wänke (1981); d) Wänke *et al.* (1984)

et al., 1981). The high FeO concentrations in the Martian regolith (McSween and Stolper, 1980 and Clark *et al.*, 1977) point to a high abundance of FeO in the Martian mantle, as FeO does not significantly fractionate during partial melting. Dreibus and Wänke (1984) argued that like the Earth Mars was formed from the same two components. However, the mixing ratio of component A/component B for Mars was found to be about 65:35, while for the Earth a mixing ratio of 85:15 was estimated (Wänke, 1981). It was also noted that contrary to the situation on the Earth all chalcophile elements are drastically depleted on Mars. This leads to the conclusion that contrary to the Earth, Mars accreted almost homogeneously. Sulphur, mainly supplied by component B, and FeNi from component A were thought to be responsible for the formation of a sulfur-rich FeNi alloy. During core formation extraction of the elements from the mantle took place, according to their sulfide-silicate partition coefficients.

In order to explain the different types of accretionary scenarios for Earth and Mars, Dreibus and Wänke (1984) suggested that the volatile-free component A formed mainly at and inside the orbit of the Earth, while the oxidized, volatile-containing component B formed in the asteroidal belt. Mars, located at the transition of the region dominated by component A and the region dominated by component B, was thought to have been fed from both components simultaneously and in approximately equal proportions, while in the case of Earth and Venus the material of component B was added only during a late phase of accretion stage and in smaller proportions.

MARS' INVENTORY OF VOLATILES BASED ON EVIDENCE FROM SNC-METEORITES

a) Halogens

As shown by analysis of mid-ocean ridge basalts (Schilling *et al.*, 1980), bromine behaves like an incompatible element during partial melting processes and correlates well with La. We have determined F, Cl, Br and I in SNC-meteorites and eucrites (Table 2) and find a similar correlation in the case of the shergottites (Fig. 2), but interestingly not for the eucrites (Fig. 3). This might be explained by postulating that the eucrites lost their volatiles during eruption into the vacuum surrounding its parent body, while the shergottites solidified under closed system conditions.

Studies of the bulk composition of the Earth, the Moon and the eucrite parent body (possibly Vesta; Chapman, 1976), showed that normalized to Si the abundances of all lithophile refractory elements do not deviate from their C 1 abundances by more than a factor of 1.5 at most (Wänke, 1981). Hence, a C 1 abundance of refractory elements can probably also be assumed for the SPB.

The Br-La correlation couples Br to a refractory lithophile element. Figure 2 shows that the Br abundance on the parent body of the shergottites exceeds the terrestrial abundance by a factor of 3.8. The oceans of the Earth represent such an excellent store of halogens that in fact the Br/La ratio in MORB glasses may be somewhat lower than the bulk Earth's ratio. On Earth Cl, Br and I are observed to be present close to their C 1 abundance ratios (Wänke *et al.*, 1984). In Table 1, we have assumed for Mars C 1 abundances for chlorine and iodine relative to bromine.

The measured Cl and I concentrations in the SNCs may be influenced by contamination, as two of the four shergottites were found in Antarctica and high contaminations were observed in many Antarctic meteorites for chlorine and iodine but not for bromine (Table 2). It might be that the halogen concentrations in several Antarctic meteorites

Table 2
Halogens in eucrites and shergottites.

As is evident from comparison with non-Antarctic meteorite samples as well as from element ratios, all of the samples from Antarctica have been contaminated with Cl and I, but not with Br. Data marked (*) probably influenced by terrestrial contamination.

	F ppm	Cl ppm	Br ppm	I ppm
Eucrites				
Cachari	—	93	0.96	0.48
Stannern	25	298	0.70	0.20
Pasamonte	52	26	0.149	0.056
Sioux County	—	11.5	0.11	< 0.030
Béréba	53	16	0.102	0.134
Ibitira	6.5	28	0.055	—
Jonzac	11.8	5.7	0.093	0.010
EETA 79004	60	49	0.119	11.2*
EETA 79011	153	151*	0.081	15.2*
EETA 79005	51	105*	0.043	15.5*
Yamato 74450	—	153*	0.047	1.176*
Shergottites				
Shergotty	41	108	0.891	0.036
EETA 79001-A	39	26	0.189	< 0.10
EETA 79001-B	31	48	0.287	0.960*
EETA 79001-glass	—	35	0.378	< 0.012
ALHA 77005	22	14	0.085	1.72*

reflect contamination by material from evaporite deposits which has been incorporated into the ice. Iodate-rich nitrate deposits have been found by Johannesson and Gibson (1962) in Victoria Land Mountains.

Using data from Smith *et al.* (1984), we also find that Tl correlates satisfactorily with Br. The Tl/Br ratio points towards a high Tl abundance, which originally may have been even higher as Tl might have been depleted by sulfide segregation into the core. A rough estimate for In can be based on the In/Ga ratio in SNC-meteorites. Again the In abundance might have been lowered somewhat by sulfide segregation.

As seen from Table 1, the SNC meteorites indicate abundances of moderately volatile (Na, K, Rb, Zn) and volatile elements (Cl, Br, I, In, Tl, etc.) on Mars in excess of those on Earth, except for chalcophile elements (Zn, Tl, In).

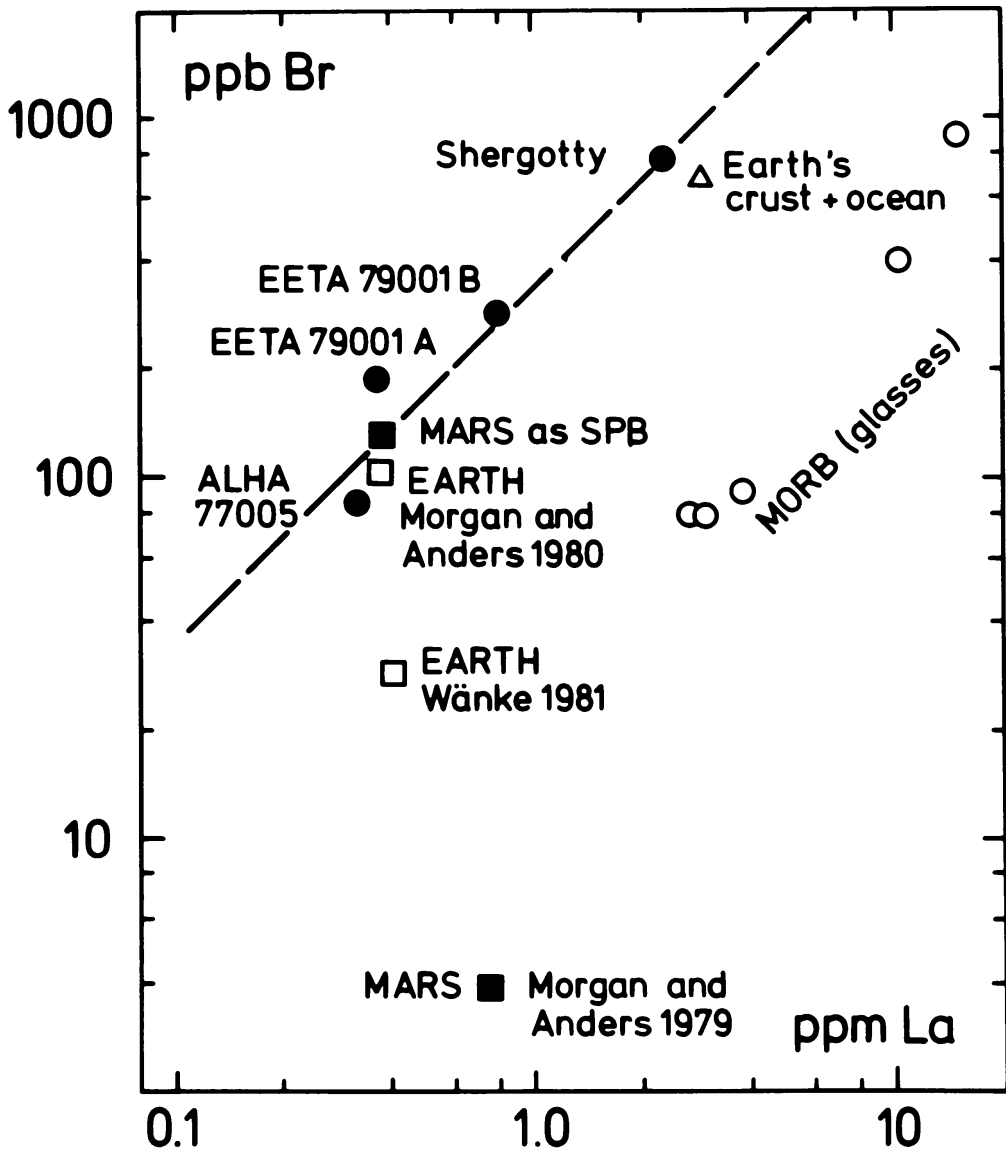


Fig. 2 Br vs. La in shergottites and MORB samples (Schilling *et al.*, 1980). The data point for Mars as SPB is obtained from the Br/La correlation line, assuming a Si normalized C 1 abundance of La.

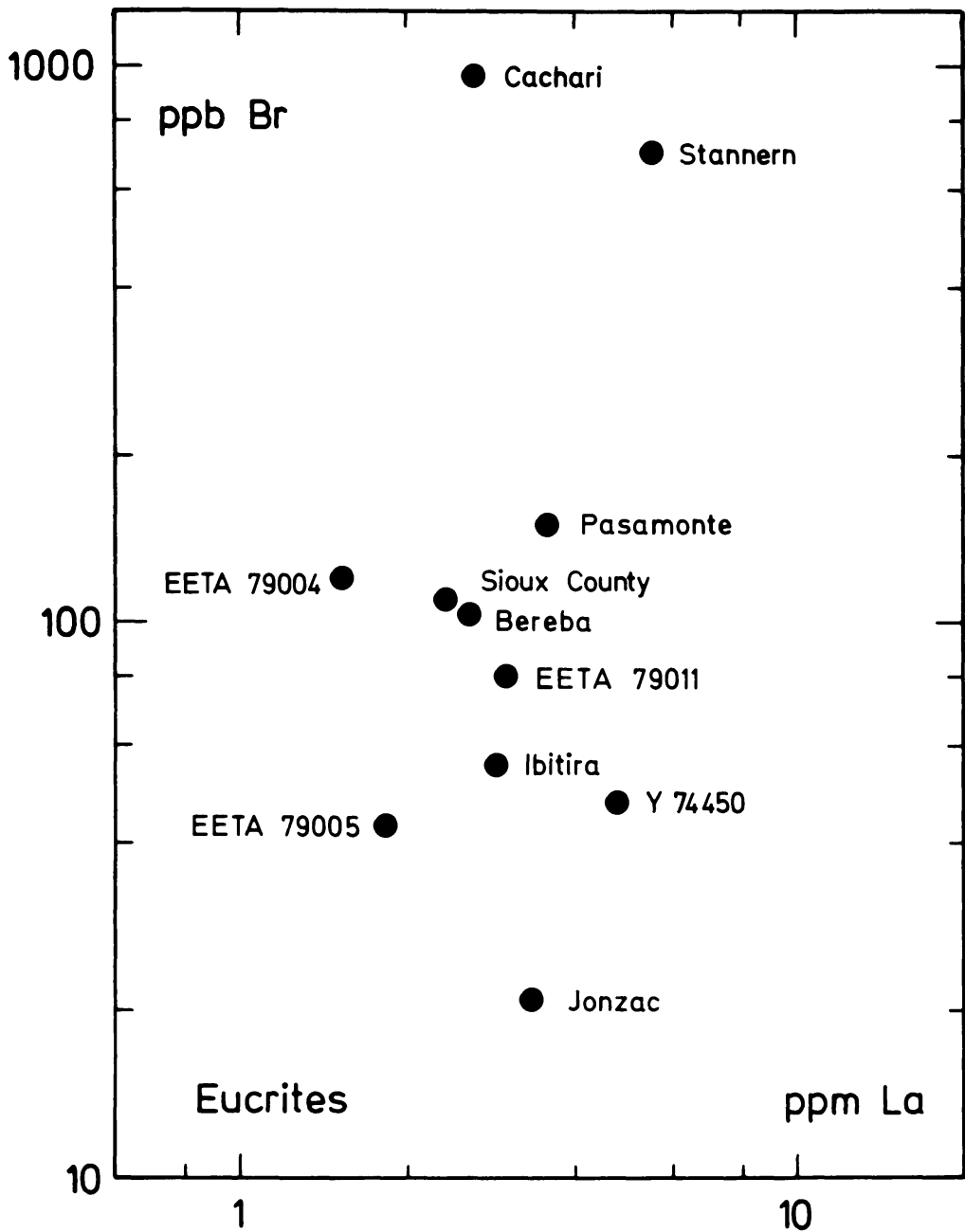


Fig. 3 Br vs. La in eucrites. The Br concentrations and Br/La ratios in eucrites are generally lower than in shergottites. The absence of a Br/La correlation may indicate loss of halogens into free space at the time of solidification.

Anders and Owen (1977) and Morgan and Anders (1979) took the low abundance of ^{36}Ar in the Martian atmosphere as evidence for a low abundance of all elements that condensed below 600 K under solar nebula conditions. However, the use of the rare gas isotope ^{36}Ar to estimate the abundances of elements like Cl, Br, In, Tl, etc. may be highly misleading. The permanent gases can be easily depleted before accretion, and can also be removed from the early atmosphere of the planet without affecting chlorine for example, an element which can be locked up in certain minerals like apatite. The solubility of HCl in molten silicates also exceeds that of rare gases by orders of magnitude (Anderson, 1975). However, the one order of magnitude lower abundance of Cl, Br, and I as compared to moderately volatile elements like K as observed in this work could mean that considerable portions of these elements went into the early atmosphere and were later removed together with other gaseous species (Wänke and Dreibus, 1985).

Studies within the Shergotty Consortium (Laul *et al.*, 1985) have yielded new data for elements for which the concentrations were not known previously. Iodine is one of these elements and we now find that the assumption of C 1 abundance ratios for Cl, Br and I was correct within about a factor of 3; Shergotty Cl/Br = 121; Br/I = 25; the respective C 1 ratios are 268 and 4.5 (Palme *et al.*, 1981). According to the halogen data of the Shergotty meteorite, iodine seems to be depleted relative to Cl and Br by about a factor 3 to 5. However, most terrestrial basalts also show a considerable depletion of iodine which is thought to be due to a sea water effect (Dreibus *et al.*, 1983). It would be exciting if a similar effect occurred on Mars.

b) Water

Similarly as in the case of the Earth's mantle and as illustrated in Figure 1, almost all moderately volatile and moderately siderophile elements are present in about equal abundances (normalized to Si and C 1) in spite of their highly different geochemical behaviour. In the two component model both the moderately volatile and the moderately siderophile (in oxidized form) elements are supplied by component B. The mean abundance of these elements (Fe, Na, Ga, P, K, F, and Rb) in the Martian mantle (see also Fig. 1) is 0.35. Dreibus and Wänke (1984) used this value of 0.35 as the abundance of component B and thus obtained a mixing ratio of component A to component B of 65:35.

However, an abundance of 35% of component B as estimated from the mean abundances of Fe, Na, Ga, P, K, F, and Rb is probably somewhat too high. As we shall see later on, part of the FeO comes from the oxidation of metallic iron. The decrease in the abundance of the alkali elements (Na = 0.38; K = 0.31, Rb = 0.28 and Cs = 0.20) may indicate either a small contribution of component A for the least volatile elements (Na, K) or a slight depletion of the most volatile elements (i.e., Rb and Cs) in component B. In the following we will use the abundance of K (i.e., $0.31 \times \text{C 1}$) for the abundance of component B. The measured H_2O content in the C 1-chondrite Orgueil is close to 20%, however the preterrestrial content of H_2O in this meteorite is only 4.5% (Kaplan, 1971), the rest comes from the combustion of hydrocarbons as well as from terrestrial contamination. Hence in order to find the composition of component B which we assume to be identical to C 1 chondrites, we divide the C 1 values by 0.85. The value of 315 ppm K (see Table 1) for the Martian mantle corresponds to 247 ppm K in the whole planet. In this way we find for Mars a weight portion of component B of 40%.

Assuming a C 1 abundance' of water in component B, we find that 2.1% H₂O was added during the accretion of Mars, which on reaction (homogeneous accretion) with metallic Fe from component A, produced 8.4% FeO, while the bulk FeO concentration on Mars is 14.0%. Approximately the same amount of oxygen is supplied in the form of sulfate. However the probable presence of metallic Si in component A (as in E 4 chondrites) must also be taken into account, as for example 1% Si will reduce 0.7% H₂O. The actual scenario is more complicated, because in addition to metallic Si, other species like Ni, Cr, Mn (in component A) and especially carbon (component A and B) are also present in reduced form. For the Earth, Ringwood (1979) proposed a scenario in which the reduction of H₂O to H₂ would mainly occur in the primitive atmosphere during infall of material of component A. In an open system (loss of H₂), homogeneous accretion of components A and B in about equal proportions will lead to a highly oxidized and volatile-rich planet. There is no doubt that Mars is highly oxidized and was initially destined to become volatile-rich. In regard to halogens and other highly volatile elements it still is. Of the water originally added, however, all except trace amounts was converted to H₂ which furthered the escape of rare gases and some other volatile species as discussed below.

In order to estimate the amount of water left on Mars after accretion we assume that all H₂O liberated during accretion was reduced by Fe and H₂ and was lost. Thus, at the end of accretion the surface H₂O concentration is assumed to be zero. For the whole planet we found a Cl concentration of 34 ppm. Compared with 320 ppm Cl to be expected from component B we find a Cl depletion factor of 0.11. The solubility of HCl in basaltic melts exceeds that of H₂O by about a factor 200 (Anderson, 1975), yielding an expected depletion factor for H₂O of 5.5×10^{-4} . With this factor and an amount of 2.1% H₂O added during accretion we find a total of 11.5 ppm H₂O retained in the interior of the planet corresponding to 14.7 ppm H₂O in the mantle. Making the unrealistic assumption of a 100% release, 11.5 ppm H₂O would yield a water layer of 51 m covering the whole planet.

ABUNDANCE OF VOLATILES ON MARS BASED ON VIKING DATA OF THE MARTIAN ATMOSPHERE

Now we will try to reconcile our findings with the Viking data on the Martian atmosphere (Owen *et al.*, 1977). There can be no doubt that accretion is the most effective degassing stage in the evolution of planets (Arrhenius and Alfvén, 1974; Lange and Ahrens, 1983). In the following we assume that loss of rare gases occurs only from the early atmosphere during the accretion stage of the planets and, hence, radiogenic rare gases ⁴⁰Ar and ¹²⁹Xe_{rad} subsequently produced by the decay of ⁴⁰K and ¹²⁹I in the planetary interior are not affected. However as the half-life of ¹²⁹I is in the range of the accretion time of the inner planets, ¹²⁹Xe_{rad} produced during accretion will probably be lost to an appreciable extent also. The high ¹²⁹Xe_{rad}/¹³²Xe ratio in the Martian atmosphere is a clear indication of an extensive depletion of ¹³²Xe together with the other primordial rare gas nuclides on Mars (see Table 3).

The low ⁴⁰Ar abundance in the Martian atmosphere indicates a small release factor for radiogenic rare gases compared to the terrestrial value. The release factor is defined as the ratio of abundance in the atmosphere to the abundance of the whole planet (atmosphere and interior). In all probability, the terrestrial release factor for ⁴⁰Ar lies somewhere

Table 3
Rare gas isotopes in planetary atmospheres and chondrites

	^{36}Ar $10^{-10}\text{cm}^3/\text{g}$	^{40}Ar $10^{-8}\text{cm}^3/\text{g}$	$^{40}\text{Ar}/^{36}\text{Ar}$	$^{129}\text{Xe}_{\text{rad}}$ $10^{-12}\text{cm}^3/\text{g}$	^{132}Xe $10^{-12}\text{cm}^3/\text{g}$	$^{129}\text{Xe}_{\text{rad}}/^{132}\text{Xe}$
Mars ^{a)}	1.6	48	3000	1.12	0.75	1.49
Earth ^{a)}	210	612	291	1.04	15.6	0.067
Venus ^{b,c)}	21000	225	1.07	—	—	—
Chondrites						
C1 ^{d)}	7700	476	6.2	380	7600	0.050
C3V ^{d)}	3440	1500	44	780	3000	0.26
E4 ^{e)}	3310	8606	260	3890	961	4.05

between 0.5 and 0.9, as the ^{40}Ar content of the Earth's atmosphere corresponds to a bulk K concentration of 78 ppm (release factor 1.0), while most estimates for bulk K are below 160 ppm (Morgan and Anders, 1980; Wänke, 1981).

Anders and Owen (1977) calculated for Mars a bulk K content of 100 ppm, using a fixed U content and a K/U ratio of 3000 as based on the first publication of the results of the γ -ray experiment on the Soviet orbiter Mars 5 (Surkov and Fedoseyev, 1977). In later publications this ratio was raised to a value of 6700 (Surkov, 1981), corresponding to a K concentration of 220 ppm. Considering the large uncertainty of the K/U ratio, this value agrees very well with the value of 247 ppm for the whole planet deduced from SNC-meteorites (Table 1). Hence, we may safely assume the abundance of K on Mars to be equal to, or more likely higher than, that of the Earth. An estimated K content of Mars 1.5 times higher than that of the Earth leads to an expected ^{40}Ar abundance in the Martian atmosphere of $920 \times 10^{-8} \text{ cm}^3/\text{g}$, assuming an identical release factor for Mars and Earth. The observed Martian atmospheric ^{40}Ar abundance of $48 \times 10^{-8} \text{ cm}^3/\text{g}$, indicates that, compared to the Earth, the Martian release factor of ^{40}Ar must be about 20 times lower.

Normalized to the planet's mass the concentration A of a radiogenic isotope in the atmosphere is proportional to its release factor R(A) and the concentration of its parent nuclide, e.g. $[^{40}\text{Ar}] \sim [\text{K}] \times R(^{40}\text{Ar})$. With $[^{40}\text{Ar}]_E/[^{40}\text{Ar}]_M = 12.8$ (Table 3, E and M denoting Earth and Mars), and taking the estimates of the SPB at face value, for Mars we find $[\text{K}]_E/[\text{K}]_M = 0.6$ (Table 1), and $R(^{40}\text{Ar},E)/R(^{40}\text{Ar},M) = 12.8/0.6 = 21$. Assuming that the release factor for ^{40}Ar is identical to that for $^{129}\text{Xe}_{\text{rad}}$, i.e. $R(^{40}\text{Ar},E)/R(^{40}\text{Ar},M) = R(^{129}\text{Xe}_{\text{rad}},E)/R(^{129}\text{Xe}_{\text{rad}},M)$ and that both planets had an identical $^{129}\text{I}/^{127}\text{I}$ ratio at the end of accretion we find:

$$\frac{[^{129}\text{Xe}_{\text{rad}}]_E}{[^{129}\text{Xe}_{\text{rad}}]_M} = \frac{R(^{129}\text{Xe}_{\text{rad}},E)}{R(^{129}\text{Xe}_{\text{rad}},M)} \cdot \frac{[I]_E}{[I]_M} = 21 \frac{[I]_E}{[I]_M} \quad (1)$$

Because terrestrial xenon may be partially trapped in shales (Canales *et al.*, 1968) and because of the large uncertainty of the absolute xenon concentration in the Martian

atmosphere, we use the ^{36}Ar depletion factor in order to estimate the Martian ^{132}Xe concentration, i.e. $[^{132}\text{Xe}]_E/[^{132}\text{Xe}]_M = [^{36}\text{Ar}]_E/[^{36}\text{Ar}]_M = 130$.

After substitution in (1)

$$\frac{(^{129}\text{Xe}_{rad}/^{132}\text{Xe})_E}{(^{129}\text{Xe}_{rad}/^{132}\text{Xe})_M} = \frac{21 [I]_E}{130 [I]_M} \quad (2)$$

and with the observed values (Table 2) we find

$$\frac{21 [I]_E}{130 [I]_M} = \frac{0.067}{1.49} \text{ or } [I]_M = 3.6 [I]_E$$

Hence, from the Viking data, and with the above assumptions, we find that the iodine abundance on Mars is 3.6 times higher than on Earth. This factor is close to the value of 2.8 obtained from the Br/La ratio in shergottites assuming a C1 Br/I ratio (Table 1). Although the closeness of the match is probably fortuitous, this is an independent indication of a high content of volatiles on Mars.

PRIMORDIAL RARE GASES ON VENUS, EARTH, AND MARS; DIFFERENT SUPPLY OR DIFFERENT LOSS?

The amount of ^{36}Ar in the Martian atmosphere per gram of the planet's mass (see Table 3) is a factor 100 lower than in any class of unfractionated meteorites. As there can be no doubt that accretion is the most effective degassing stage in the evolution of planets, a huge gas loss from the primitive atmosphere of Mars seems the almost inevitable conclusion. On the other hand, the ^{36}Ar content of the Venusian atmosphere exceeds that of the Earth by a factor of about 100, and even exceeds that in any known meteorite. However, it is conceivable that the original gas content of these meteorites was considerably higher but has declined due to gas loss by diffusion during their 4.5 b.y. of history.

In the two component model for Earth (Wänke, 1981) and Mars (Dreibus and Wänke, 1984) briefly outlined above, the volatiles are derived from component B. If component B contains primordial rare gases at the C 1 level, the amount of ^{36}Ar originally supplied was 2300 times higher than the concentration presently observed in the Martian atmosphere. As the Martian ^{36}Ar abundance is a factor of 130 below the terrestrial value, an absolute depletion factor of 2300 for Mars would yield a terrestrial depletion factor of 17. If only 15% of component B was added to the Earth (Wänke, 1981) a terrestrial depletion factor of 6 is obtained.

So far all attempts to explain the huge differences in the primordial rare gas content of Venus, Earth and Mars have been based on different initial inventories. We instead propose to explain the observed differences mainly by large differences in gas loss during accretion. As discussed by various authors two quite different processes are thought to be of importance for the removal of the primitive atmospheres: 1) Hydrodynamic escape due to presence of large amounts of H_2 which leads to low values for the mean molecular weight and 2) removal by large impacts. Because of lower gravity, both processes will be more efficient for Mars when compared to Earth and Venus.

Inhomogeneous accretion as it is proposed for the Earth (Wänke, 1981) and probably also valid for Venus, will not only generate large amounts of H_2 but will also

make impact induced gas loss more efficient, as impacts of bodies from both populations (component A and B) will be effective. In the case of inhomogeneous accretion the oxidized, volatile-containing component B is added only towards the end of accretion and gas loss by impact is restricted to that period. Therefore considerable portions of gases released during planetary accretion will be continuously lost into space. On Earth and Venus, accretional energy leads to formation of huge magma oceans (Kaula, 1979), in which substantial portions of rare gases redissolved and subsequently were even carried into the solid regions of the highly convecting mantles. On Mars melting occurred only on a much smaller scale as the energy of accretion and core formation per unit mass are about 4 times lower. In this respect we should note, that the amounts of gases redissolved depend on the thickness of the layers which equilibrate with the atmosphere and only to a lesser degree on the gas/solid partition coefficients.

Impact induced fission of the Proto-Earth seems the most likely model for the origin of the Moon (Hartmann and Davis, 1975; Cameron and Ward, 1976; Ringwood, 1979). The mass of the projectile probably considerably exceeded that of the Moon; its impact towards the end of terrestrial accretion may have completely removed any atmosphere present at that moment. Clearly, gas loss has also to be expected in the case of Venus. However, unlike the Earth, Venus was probably not hit late in its accretion history by an object of sufficient mass to form a moon. The observed amounts of primordial rare gases on Venus can be taken as a lower limit of the amounts added. Relative to Venus the Earth has lost 10s, and Mars 10 ρ , times more of their primordial rare gases. Aside from a low release factor, atmospheric removal by impacts occurring over geologic history (Watkins and Lewis, 1984) could at least in part be responsible for the low ρ mAr content of Mars' atmosphere.

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