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Isotopic Composition of Trapped and Cosmogenic Noble Gases in Several Martian Meteorites

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ABSTRACT

Isotopic abundances of the noble gases were measured in the following Martian meteorites: two shock glass inclusions from EET79001, shock vein glass from Shergotty and Y793605, and whole rock samples of ALH84001 and QUE94201. These glass samples, when combined with literature data on a separate single glass inclusion from EET79001 and a glass vein from Zagami, permit examination of the isotopic composition of Ne, Ar, Kr, and Xe trapped from the Martian atmosphere in greater detail. The isotopic composition of Martian Ne, if actually present in these glasses, remains poorly defined. The ^{40}Ar/^{36}Ar ratio of Martian atmospheric Ar may be much less than the ratio measured by Viking and possibly as low as ~1900. The atmospheric ^{36}Ar/^{38}Ar ratio is ≤4.0. Martian atmospheric Kr appears to be enriched in lighter isotopes by ~0.4%/amu compared to both solar wind Kr and to the Martian composition previously reported. The Martian atmospheric ^{36}Ar/^{132}Xe and ^{84}Kr/^{132}Xe elemental ratios are higher than those reported by Viking by factors of ~3.3 and ~2.5, respectively. Cosmogenic gases indicate space exposure ages of 13.9±1 Myr for ALH84001 and 2.7 ±0.6 Myr for QUE94201. Small amounts of ^{21}Ne produced by energetic solar protons may be present in QUE94201, but are not present in ALH84001 or Y793605. The space exposure age for Y793605 is 4.9 ±0.6 Myr and appears to be distinctly older than the ages for basaltic shergottites.

INTRODUCTION

Isotopic abundances of several volatile species in the Martian atmosphere were measured ***in situ*** by the Viking spacecraft, but the uncertainties on most of these data are rather large (Owen et al., 1977; Owen, 1992). The discovery that significant amounts of Martian atmospheric gases are trapped in impact glass of the EET79001 Martian meteorite (Bogard and Johnson, 1983) presented an alternative method of determining the detailed composition of some components in the Martian atmosphere. (See McSween, 1994, for a discussion of Martian meteorites.) Martian atmospheric gas apparently was incorporated into melt glass by a shock event near the Martian surface, which also injected the glass into EET79001. Experimental studies in the laboratory indicate that shock implantation of noble gases does not significantly fractionate their elemental or isotopic composition (Bogard et al., 1986). The exact time of incorporation of noble gases into EET79001 shock glass is not known. However, the observation that EET79001 and several other shergottites (a sub-class of Martian meteorites) have isotopic ages of <200 Myr (Shih et al., 1982; Nyquist et al., 1995) strongly implies that the Martian atmospheric gases were incorporated into these meteorites at a time less than 200 Myr ago. Thus, these gases represent a geologically recent sampling of the Martian atmosphere.

Until recently, all of the detailed data on the isotopic composition of atmospheric noble gases and nitrogen trapped in Martian meteorites were obtained on a single impact glass inclusion (no.27) from meteorite EET79001 (Bogard et al., 1984; Becker and Pepin, 1984; Swindle et al., 1986; Wiens et al., 1986; Wiens, 1988) and from a small impact glass vein in the Zagami shergottite (Marti et al., 1995). These data appeared to confirm several isotopic characteristics measured by Viking (Owen et al., 1977; Owen, 1992), including the elevated $^{129}Xe/^{132}Xe$ (2.5, +2-1), $^{40}Ar/^{36}Ar$ (3000 ±500) and $^{15}N/^{14}N$ (0.0059 ±.0005) ratios. However, Martian meteorite data indicated that the Martian atmospheric $^{36}Ar/^{38}Ar$ ratio lies near the lower error limit of that measured by Viking (5.5 ±1.5) and is lower than that of any other major known volatile reservoir, including the Earth, Venus, carbonaceous meteorites, and the solar wind (Pepin, 1991). Wiens et al. (1986) reported the Martian $^{36}Ar/^{38}Ar$ ratio as 4.1 ±0.2. Bogard (1997) reevaluated the Martian meteorite data base and concluded that the Martin atmospheric $^{36}Ar/^{38}Ar$ ratio is most probably <3.9 and possibly as small as ~3.5, and that the Martian $^{40}Ar/^{36}Ar$ is probably no greater than 2500. The Martian atmospheric $^{36}Ar/^{38}Ar$ ratio is an important parameter because it was produced by mass fractionation during loss of an early, but possibly secondary Martian atmosphere and thus defines the fraction of the atmosphere which was lost over a considerable period of geological time (Jakosky et al., 1994; Pepin, 1994; Hutchins and Jakosky, 1996).

The composition of trapped neon in EET79001,27 glass is very poorly constrained. With emphasis on a single temperature extraction, Wiens et al. (1986) suggested a trapped ^{20}Ne/^{22}Ne ratio of 9.6 ±0.6, assuming a trapped ^{21}Ne/^{22}Ne of 0.03. These authors also suggested that the trapped ^{20}Ne/^{36}Ar ratio in their sample was generally similar to the range reported by Viking for the Martian atmosphere. (Viking did not measure the ^{20}Ne/^{22}Ne ratio.) Bogard et al. (1984) suggested the possible presence of trapped Ne with ^{20}Ne/^{22}Ne >9.8. From a 3-isotope correlation plot, Swindle et al. (1986) suggested trapped ^{20}Ne/^{22}Ne =10.6 ±0.6. All these suggested compositions are similar to the terrestrial ratio of ^{20}Ne/^{22}Ne =9.81. However, in all these earlier analyses of EET79001,27, cosmogenic neon dominates over any trapped component, and the possibility of some terrestrial Ne contamination must also be resolved. The Martian Ne isotopic composition also would be an important parameter to further constrain atmospheric loss models, since Ne, like Ar, also is expected to be strongly mass fractionated during such losses.

Viking did not report isotopic compositions for Ne, Kr, and Xe (other than ^{129}Xe/^{132}Xe) in the Martian atmosphere (Owen et al., 1977). Detailed measurements of the isotopic composition of Kr and Xe have been reported for glass inclusion EET79001,27 (Bogard et al., 1984; Becker and Pepin, 1984; Swindle et al., 1986; and Wiens, 1988). (No Ne or Kr data were reported for the Zagami glass analyses; Marti et al, 1995.) These EET79001,27 measurements showed that Kr is isotopically mass fractionated in favor of lighter isotopes relative to both terrestrial and AVCC (carbonaceous meteorite) reservoirs and apparently contains an extra component of ^{80}Kr and ^{82}Kr produced by neutron capture by Br at the Martian surface. Isotopically, Martian Kr closely resembles solar wind Kr (Pepin, 1991). Xenon in EET79001,27 also is isotopically mass fractionated relative to terrestrial and AVCC reservoirs, but in favor of heavier isotopes, which is just opposite to the case for Martian Kr. The very different isotopic compositions of Martian atmospheric Kr and Xe, in comparison to other noble gas reservoirs, contributed to the suggestion that the early, primary atmosphere of Mars experienced massive loss of all noble gases except Xe, which was left strongly mass fractionated in the residual atmosphere (Hunten et al., 1987; Pepin, 1991). A component of Ar and Kr, which was not fractionated by this massive loss, was later added as part of a secondary Martin atmosphere, formed either by mantle outgassing or late addition of volatiles, or both. However, in this atmospheric model significant amounts of secondary Xe could not also be added, or the fractionated Xe composition resulting from the massive atmospheric loss would be altered (Pepin, 1991; Pepin, 1994). A mechanism by which Ar and Kr, the latter having near-solar composition, could be added to the secondary Martian atmosphere without also adding significant Xe has not yet been demonstrated.

It is apparent that our knowledge of the composition of the noble gases in the Martian atmosphere and their evolution over time rests on two limited data sets – 1) the Viking analyses with incomplete results and generally large uncertainties, and 2) multiple analyses of a single,~1 cm diameter, impact glass inclusion in the EET79001 meteorite, augmented by some data from a single Zagami glass vein. An obvious question to ask is how representative of the Martian atmosphere are the gases trapped in glass inclusion EET79001,27? Is it possible that atmospheric gases trapped in other impact glasses have different detailed compositions compared to gases in EET79001,27? In this paper we directly address this question by reporting noble gas analyses of two additional glass inclusions from EET79001 and impact glasses from two additional Martian meteorites for which such data have not previously been reported. Thus, the new isotopic data reported here represent a more extensive suite of impact glasses for determining Martian atmospheric noble gas compositions compared to previous investigations. In this paper we will be concerned primarily with the isotopic composition of these trapped gases. In a separate paper (Bogard and Garrison, 1998) we use a portion of these data to discuss in detail the elemental (Ar/Kr/Xe) composition of trapped gases in Martian meteorites. In this paper we also report isotopic concentrations of cosmogenic He, Ne, and Ar, produced in space by energetic particle irradiation in these glass samples and in non-glass samples of Martian meteorites QUE94201 and ALH84001. These data address another important question about Martian meteorites, which is how many impact events are required to eject Martian meteorites from Mars and when did these occur?

SAMPLES, METHODS, AND MEASURED DATA

To further characterize the isotopic composition of trapped and cosmogenic gases in Martian meteorites, we measured noble gases in three samples of ALH84001, two samples of QUE94201, two samples of Shergotty, one sample of Y793605, and two samples of EET79001. The Shergotty and Y793605 samples were impact glass taken from rare, dark veins only a few mm in width. Shergotty-B was ~90% glass and ~10% host rock, whereas Shergotty A was only ~10% glass. Sample EET79001,8 was from a small spherical glass inclusion (alpha) located in lithology-A a few cm away from the original ,27 (bravo) inclusion that yielded most of the previous data on Martian atmospheric noble gases. (Meyer (1996) gives a description of EET79001 and its glass inclusions.). Sample EET79001,104 was taken from an irregular glass inclusion located in lithology B. Most noble gases in these impact glasses were shock-implanted from the Martian atmosphere, but other gas components are also present. The analyzed samples of ALH84001 and QUE94201 were whole rock, not impact glass, and represent different subsurface depths within these meteorites. The ALH84001 samples came from depths below the fusion crust of ~0.5-2 mm (,113), ~1.5-3.0 mm (,114-1), and ~8-10 mm (,114-2). The QUE94201 samples came from depths of ~0.5-2.0 mm (,28) and from an interior sample without fusion crust but from an unknown depth (,31). Our primary purpose in analyzing these non-glass samples was to characterize those noble gas components produced during space irradiation by cosmic ray (GCR) and energetic solar (SCR) protons.

Noble gases were extracted from these samples by heating at two to four increasing temperature steps. The gases were gettered on hot Zr-Al alloy and separated into He+Ne, Ar, and Xe fractions by adsorption on charcoal at cold temperatures, and their isotopic abundances were measured with a VG-3600 mass spectrometer. The Kr apportioned between the Ar and Xe fractions, whereas 90-95% of the Ar was in the Ar fraction and ~95% of the Xe was in the Xe fraction.. The Kr isotopic composition was measured in the Xe fraction using a procedure that measures Kr and Xe isotopes simultaneously. The use of multiple charcoal fingers at liquid nitrogen temperature assured that the amount of ^{40}Ar in the He+Ne fraction was small, and consequently corrections to ^{20}Ne for doubly charged ^{40}Ar were very small. In some cases Ar and Kr concentration measurements were made on separate volume aliquots of the total gas to lessen changes in instrument sensitivity and memory resulting from high Ar pressures. Sensitivity of the spectrometer was determined after each sample analysis using calibrated gas pipettes that reproducibly deliver a known volume of an artificial mixture of noble gases. After these sample analyses, we made an extended series of calibrations of these gas pipettes using atmospheric noble gases delivered by two additional gas pipettes with accurately determined delivery volumes. In all cases, either large quantities of Ar were removed from the pipetted gases before the other noble gases were analyzed, or corrections were applied for the effects of large partial pressures of Ar on spectrometer sensitivities. We believe that measured abundances of He, Ne, Ar and Xe for individual meteorite samples are uncertain to <10% and that of Kr to <15%.

Measured isotopic concentrations of He, Ne, and Ar in these Martian meteorite samples are listed in Table 1. Tables 2 and 3 give the measured isotopic composition of Kr and Xe, respectively. Kr and Xe were not measured in the lowest temperature extraction (350 °C) of EET79001,104, and only a few isotopes of Kr and Xe were measured for the 350 °C extractions of EET79001,8 and Y793605. All Kr and Xe isotopes were measured in higher temperature extractions. Kr and Xe also were not measured for the lowest temperature extractions (450°C) of ALH84001 samples nor for any extractions of QUE94201 samples. Krypton masses 84 and 86 and all isotopes of Xe were measured for the melt extractions of ALH84001 samples.

In this paper we will utilize these data to discuss both the trapped Martian atmospheric component and the cosmogenic component in these meteorites. In discussing the trapped Martian component we will be concerned primarily with its isotopic composition. We have separately presented and discussed the relative elemental abundances of Ar, Kr, and Xe in the trapped Martian atmospheric component (Bogard and Garrison, 1998). In considerations of trapped Ar, Kr, and Xe, we will exclude that gas released at low extraction temperatures of <450°C in order to exclude small amounts of terrestrial atmospheric noble gases typically adsorbed on grain surfaces and released at low temperatures. Bogard (1997) presented an extensive discussion of the evidence for release of terrestrial Ar contamination at low extraction temperatures for previous analyses of impact glasses from Martian meteorites. Additional evidence for terrestrial contamination at low extraction temperatures for several previous and current analyses of Martian meteorites occurs as lower ^{40}Ar/^{36}Ar and ^{129}Xe/^{132}Xe ratios, which more closely resemble those of the Earth's atmosphere.

TRAPPED NOBLE GAS ISOTOPIC COMPOSITIONS

Neon

Neon comprises ~2.5 (+3.5, -1.5) ppm by volume of the Martian atmosphere, but the Ne isotopic composition of the atmosphere was not measured by Viking (Owen et al., 1977). As mentioned earlier, the composition of trapped Ne in Martian meteorites previously was estimated only for a single glass inclusion, EET79001,27 (Bogard et al., 1984; Swindle et al., 1986; Wiens et al., 1986; Wiens, 1988). Cosmogenic Ne and terrestrial Ne released at low extraction temperatures appear to dominate most of the Ne inventory in this inclusion. The trapped component present, if any, seems to have an isotopic composition similar to the terrestrial value.

Figure 1 is a three-isotope neon plot for all temperature extractions of the EET79001, Shergotty, and Y793605 glass samples reported in Table 1. Any trapped Martian Ne is expected to plot on this figure toward the upper left in the vicinity of the terrestrial and AVCC components, whereas cosmogenic Ne has ^{20}Ne/^{22}Ne ratios <1.0 and would plot in the lower right. Considering our new data for impact glasses, the first (350°C) extractions of all five samples show larger ^{20}Ne/^{22}Ne ratios indicative of terrestrial or trapped Martian gas, whereas higher temperature data indicate almost pure cosmogenic Ne. The data suggest some variation in the cosmogenic ^{21}Ne/^{22}Ne ratio, consistent with shielding differences among the samples and possibly the presence of some Ne produced by energetic solar protons, as is discussed in a later section on cosmogenic gases. Most of the data could be consistent with only a two-component mixture of adsorbed terrestrial Ne and cosmogenic Ne. Also shown in Figure 1 are Ne isotopic data reported by Swindle et al. (1986), Wiens et al. (1986), and Wiens (1988) for glass inclusion EET79001,27. Additional Ne data for this inclusion (Bogard et al., 1984; Becker and Pepin, 1984) had larger analytical uncertainties and are not plotted. These older data generally show the same mixing trend as the new data reported here and are also consistent with a "trapped" Ne component which resembles that of the Earth or AVCC. Only a very few extractions suggest somewhat lower trapped ^{20}Ne/^{22}Ne ratios. (The older measurement with ^{20}Ne/^{22}Ne =5.6 and ^{21}Ne/^{22}Ne =0.15 had a large (32%) uncertainty, as did several other individual extractions from previous data.)

The extrapolated mixing line defined by three temperature extractions of sample Y793605,71 suggests a lower trapped ^{20}Ne/^{22}Ne of ~7.0 and may be distinctly different from the composition of terrestrial or AVCC Ne and the trapped composition suggested by most other glass data. Given the large mass fractionation observed in Martian ^{36}Ar/^{38}Ar (Bogard, 1997; Hutchins and Jakosky, 1996), we might expect a ^{20}Ne/^{22}Ne ratio for the Martian atmosphere which is considerably less than the values for both the earth and carbonaceous meteorites (Figure 1). However, among the new data on impact glasses presented here, only Y793605 suggests a trapped ^{20}Ne/^{22}Ne less than that of AVCC. Because only about half of the trapped Ar, Kr, and Xe in this sample was likely derived from the Martian atmosphere (Bogard and Garrison, 1998), it is hard to understand why Y793605,71 alone would show a unique Martian atmospheric Ne signature.

To help ascertain if Martian Ne is present in Martian meteorites, we can also compare the trapped ^{20}Ne/^{36}Ar ratios in impact glasses (Table 4). Although trapped ^{20}Ne/^{36}Ar reported by Viking for the Martian atmosphere is 0.5, uncertainties in the measurements permit the ratio to lie in the broad range of ~0.15-1.0 (Owen et al., 1977). For this comparison trapped ^{20}Ne is defined as the total measured quantity of ^{20}Ne (summed over all extractions) minus the cosmogenic ^{20}Ne and includes both Martian and terrestrial components. For each impact glass we calculated the concentration of cosmogenic ^{20}Ne from the concentration of cosmogenic ^{21}Ne and $[^{20}\mathrm{Ne}/^{21}\mathrm{Ne}]_{\mathrm{cos}}$ =1.06 (Table 5 and later discussion). The percentage of the total ^{20}Ne that is trapped rather than cosmogenic is 51-59% for the two EET79001 glass inclusions and ~25% for Shergotty-B and Y793605,71. Derivation of trapped ^{36}Ar concentrations (Table 4) are considerably more precise and are discussed in the following section.

Because trapped ^{20}Ne/^{36}Ar ratios are similar for Martian and terrestrial atmospheric components, this ratio in impact glasses cannot be used to distinguish between these two Ne sources. However, if the ^{20}Ne/^{36}Ar ratio in glasses were considerably less than the expected Martian ratio, that might be evidence that an adsorbed or occluded terrestrial component incorporated Ar more readily than Ne. The observation that all analyses of impact glasses in Table 4 give trapped ^{20}Ne/^{36}Ar ratios within the range of the Viking Martian value (with the exception of EET79001,8 and EET79001,104, which give values up to a factor of two less than the Martian limit) would permit, in principle, this ^{20}Ne to be Martian. However, the majority of the trapped ^{20}Ne was released at relatively low extraction temperatures of 350°C or 750°C (except for sample EET79001,8), which was not the case for trapped Ar, Kr, and Xe. Therefore, it seems equally probable that most of the trapped Ne in these glasses is terrestrial in origin. Given the uncertainties associated with the isotopic composition of trapped Ne in Martian meteorite impact glasses, and whether its origin is Martian or terrestrial, we conclude that the Ne isotopic composition of the Martian atmosphere remains undefined.

Argon

Trapped Martian Ar is clearly present in these impact glasses (Table 4), but determining its isotopic composition requires corrections for several other Ar components. The first (350°C) extractions of the five impact glass samples reported in Table 1 released relatively small amounts of argon with ^{40}Ar/^{36}Ar ratios similar to that of the Earth's atmosphere or only modestly greater. We exclude from the total Ar the contributions of these first extractions, which for all glasses were $\leq$5% of the total ^{36}Ar. The higher temperature data, which released the trapped Martian component, must be corrected for cosmogenic Ar and for radiogenic ^{40}Ar. The detailed procedure for making these corrections to literature data on impact glass in EET79001,27 and Zagami was discussed by Bogard (1997). Assuming ~180 Ma ages for these meteorites (Shih et al., 1982), corrections for radiogenic ^{40}Ar from *in situ* K decay are <1% for the EET79001 samples, ~6% for Shergotty, and ~2% for Y793605. Corrections to the ^{40}Ar/^{36}Ar ratio for cosmogenic ^{36}Ar are 1-2% for samples EET79001,8 and EET79001,104 and ~17% for Shergotty and Y793605 glasses. Corrections to the ^{36}Ar/^{38}Ar ratios are even larger due to larger cosmogenic corrections to ^{38}Ar. Our best estimate of trapped ^{36}Ar concentrations for literature data of Martian meteorite impact glasses, excluding that Ar released at the first extraction and making cosmogenic corrections based on Ar measurements of non-glass samples from the same meteorite, are discussed elsewhere (Bogard, 1997; Bogard and Garrison, 1998) and also are given in Table 4.

When appropriately corrected, glass samples EET7901,8 and EET79001,104 give trapped ^{40}Ar/^{36}Ar ratios of 1830 and 1880, with uncertainties of no more than a few percent. Shergotty-B and Y793605,71 give ^{40}Ar/^{36}Ar ratios of 1870 and 1460, with uncertainties of several percent. The corrected trapped ^{36}Ar/^{38}Ar ratios for the two EET79001 glass samples are 3.9 and 4.0, respectively, with uncertainties of no more than a few percent. Corrected ^{40}Ar/^{36}Ar and ^{36}Ar/^{38}Ar ratios previously reported by several laboratories for EET79001,27 and Zagami ranged over ~1200-2175 and ~3.5-4.3, respectively (see Bogard, 1997). The derived trapped ^{36}Ar/^{38}Ar for Shergotty-B is 4.36 (using Shergotty-A data to make cosmogenic corrections), but the corrections were much larger (58% for ^{38}Ar) and the trapped ratio is correspondingly much more uncertain. If we use the cosmogenic ^{38}Ar concentration of ~2 x10^{-9}cm^3/g reported for Y793605 (Eugster et al. ,1997b; Nagao et al., 1997), then an ~65% correction is required to our Y793605 data, and the calculated trapped ^{36}Ar/^{38}Ar is very uncertain.

Measurements obtained by the Viking spacecraft for the Martian atmosphere gave ^{40}Ar/^{36}Ar ≅3000 ±500 and ^{36}Ar/^{38}Ar ≅5.5 ±1.5 (Owen et al., 1977; Owen, 1992). From data on glass inclusion EET79001,27, Wiens et al. (1986) deduced an atmospheric ^{36}Ar/^{38}Ar ratio of 4.1 ±0.2. Bogard (1997) considered the existing meteorite data base in more detail and argued that because of the probable presence of Martian mantle Ar and/or terrestrial Ar in these impact glasses, the determined trapped ^{36}Ar/^{38}Ar ratios are only upper limits to this ratio in the Martian atmosphere. Bogard (1997) made various model assumptions as to the ^{40}Ar/^{36}Ar ratios in the Martian atmosphere and the Martian mantle and concluded that the Martian atmospheric ^{40}Ar/^{36}Ar in these glasses probably is no greater than ~2500 and that the Martian atmospheric ^{36}Ar/^{38}Ar is ≤3.9 and possibly as small as ~3.5. The Ar data presented here for two additional glass inclusions of EET79001 and probably for Shergotty glass are fully consistent with this evaluation of earlier literature data.

Apparent inconsistencies exist, however, between trapped ^{40}Ar/^{36}Ar and other trapped noble gas data from impact glasses of Martian meteorites. As discussed by Bogard and Garrison (1998), larger ^{129}Xe/^{132}Xe ratios in Martian meteorite impact glass are almost certainly indicative of greater relative amounts of trapped Martian atmospheric noble gases. From correlations among ^{129}Xe/^{132}Xe, ^{36}Ar/Xe, and Kr/Xe ratios, we concluded that the ^{129}Xe/^{132}Xe ratio of the Martian atmosphere trapped in these glasses is ~2.6. We further concluded that lower values of this ratio observed in some glass samples are due to the presence of two additional components, terrestrial contamination and a Martian mantle component, both with ^{129}Xe/^{132}Xe ≅1.0 (Ott, 1988; Swindle, 1995). With the same reasoning, one could assume that those impact glasses which show trapped ^{40}Ar/^{36}Ar ratios <2500 also contain trapped Ar from a source other than the Martian atmosphere. Thus, one might expect a mixing correlation between trapped ^{40}Ar/^{36}Ar and ^{129}Xe/^{132}Xe for impact glasses. Figure 2 shows that data for impact glasses scatter widely and that a simple mixing correlation does not exist. In addition, the four analyses by three laboratories of the single glass inclusion EET79001,27 show the greatest variation in trapped ^{40}Ar/^{36}Ar, nearly a factor of two. This variation among EET79001,27 analyses cannot be due to the small corrections (<1%) made to measured data for ^{40}Ar formed *in situ* by K decay. Neither can the variation be due to terrestrial Ar released at low extraction temperatures, as the differences in ^{40}Ar/^{36}Ar among various analyses persist throughout the extraction temperatures. It is also very unlikely that the few percent corrections made for cosmogenic ^{36}Ar were significantly in error, even if the chemical composition differed appreciably among samples.

Another inconsistency in Figure 2 data is that all whole rock samples of impact glass suggest trapped ^{40}Ar/^{36}Ar ratios significantly lower than the minimum value reported by Viking of ~2500. This observation is true even for those samples with ^{129}Xe/^{132}Xe approaching 2.6, which presumably contain nearly pure Martian atmospheric Xe. Among the individual stepwise temperature data for impact glasses, only two analyses (EET79001,27 by Becker and Pepin (1984) and Wiens et al. (1986)) gave measured ^{40}Ar/^{36}Ar ratios >1900. None of the individual temperature extractions for seven other analyses of impact glasses (including analyses of EET79001,27 in two other laboratories) gave measured ^{40}Ar/^{36}Ar >1900. However, the low ^{129}Xe /^{132}Xe of 2.07 for the analysis by Becker and Pepin (1984) suggests that their sample did not contain pure Martian atmospheric gas. (The analysis by Wiens et al. (1986) did not report Xe data.) In addition, correlations between ^{15}N/^{14}N and Ar also indicate that the EET79001,27 samples analyzed by Becker and Pepin (1984) and Wiens et al. (1986) and the Zagami samples analyzed by Marti et al. (1995) contained significant amounts of trapped Ar and N other than that derived from the Martian atmosphere.

The most likely interpretation for the observed scatter in the trapped ^{40}Ar/^{36}Ar and ^{129}Xe/^{132}Xe isotopic ratios for Martian meteorite impact glasses is that most of these samples contained trapped components other than that acquired from the Martian atmosphere. The relative abundances of these additional trapped components were not the same for all sample analyses and perhaps not the same for Ar and Xe. It has been suggested that trapped noble gases in Chassigny, with ^{129}Xe/^{132}Xe =1.03, may represent a Martian mantle component present in varying amounts in many Martian meteorites (Ott, 1988; Swindle, 1995; Bogard, 1997). Figure 2 shows the loci of two component gas mixing between a possible Martian atmospheric component with ^{129}Xe/^{132}Xe =2.6 and ^{40}Ar/^{36}Ar =1900 and trapped noble gases in Chassigny. Because Chassigny has a much lower trapped ^{36}Ar/^{132}Xe =19 (Ott, 1988) compared to the Martian atmospheric value of 900±100 (Bogard and Garrison, 1998), the mixing trend between these two components is strongly curved downward. Trapped ^{40}Ar/^{36}Ar in Chassigny is not known, and we have assumed a ratio of 300, which is intermediate between values of 0 and 500 considered by Bogard (1997). However, the mixing trend between these two components is not sensitive to the choice of trapped ^{40}Ar/^{36}Ar in Chassigny, and values in the broad range of 0-1000 do not appreciably change the vertical portion of the Mars/Chassigny mixing trend..

It is also possible that some of these glass analyses released terrestrial Ar not excluded with the low temperature extractions, a conclusion reached by Bogard and Garrison (1998). The terrestrial Ar/Xe ratio (1350) is larger than that for the Martian atmosphere, and consequently the mixing trend between a Martian atmospheric component and the terrestrial component bends slightly upward (Figure 2). A third alternative explanation for the data scatter in Figure 2 is that the highest $^{40}Ar/^{36}Ar$ ratios seen in some individual temperature extractions of EET79001,27 may represent excess radiogenic ^{40}Ar. This is a component which we recently suggested exists in non-glass samples of Zagami, QUE94201, and ALH84001 (Garrison and Bogard, 1997).

The likely presence of up to four trapped components (Martian atmosphere, Martian mantle, terrestrial contamination, and excess radiogenic ^{40}Ar) in different relative proportions among samples could explain all of the scatter in the plotted glass data in Figure 2 (with the possible exception of the low $^{40}Ar/^{36}Ar$ measured in EET79001,27 by Swindle et al., 1986). The fact that one of these components (excess radiogenic ^{40}Ar) can increase trapped $^{40}Ar/^{36}Ar$ without affecting $^{129}Xe/^{132}Xe$ means that the meteorite data are not constrained to lie within the boundaries defined by the two mixing curves of Figure 2. Further, the $^{40}Ar/^{36}Ar$ ratio of the Martian atmosphere is not required from meteorite data to be as large as the lower limit of ~2500 set by the uncertainty given to the Viking measurement. In fact, better agreement of meteorite data with these various possible Ar components is obtained assuming a lower value for Martian atmosphere $^{40}Ar/^{36}Ar$. Comparing these glass data to various mixing trends suggests Martian atmospheric $^{40}Ar/^{36}Ar \cong 1900$, which is the value used in Figure 2. If Martian atmospheric $^{40}Ar/^{36}Ar$ is as low as ~1900, those samples with the highest $^{129}Xe/^{132}Xe$ ratios would then contain nearly pure Martian atmospheric noble gas, a conclusion also reached by Bogard and Garrison (1998) from consideration of $^{129}Xe/^{132}Xe$ and the $^{36}Ar/Kr/Xe$ elemental ratios. Thus, one reasonable interpretation of the Ar data is that the $^{40}Ar/^{36}Ar$ ratio of Martian atmospheric gases trapped in these meteorites is considerably less than the lower limit set by Viking and possibly as low as ~1900.

The possibility of a considerably lower $^{40}Ar/^{36}Ar$ ratio for the Martian atmosphere would affect the conclusion reached by Bogard (1997) that the atmospheric $^{36}Ar/^{38}Ar$ ratio must be <3.9 and possibly much less. We used the same model calculation parameters as previously, but assumed Martian atmospheric $^{40}Ar/^{36}Ar = 1900$, and calculated Martian atmospheric $^{36}Ar/^{38}Ar$ for the new analyses of EET79001 glass presented here and for the literature data reported for EET79001,27 and Zagami. The calculated atmospheric $^{36}Ar/^{38}Ar$ ratios increase somewhat, and most data define a range of ~3.4-4.0. In the case that atmospheric $^{40}Ar/^{36}Ar = 1900$, the model calculations of atmospheric $^{36}Ar/^{38}Ar$ are not particularly sensitive to assumptions about the $^{40}Ar/^{36}Ar$ ratio of additional trapped components, be they terrestrial or Martian mantle. Thus, a consequence of a possibly lower $^{40}Ar/^{36}Ar$ ratio for the Martian atmosphere is that the atmospheric $^{36}Ar/^{38}Ar$ ratio may be slightly higher, but still ≤4.0.

Krypton

Terrestrial noble gases can be adsorbed on grain surfaces of meteorites or can be incorporated into small amounts of terrestrial weathering products, and this terrestrial gas can be relatively difficult to remove during stepwise heating in the laboratory, especially in the case of Kr and Xe. We have observed significant amounts of terrestrial Ar released at low temperatures from several Antarctic meteorites, including Martian meteorites. In addition, most analyses of impact glasses from Martian meteorites show much lower ^{129}Xe/^{132}Xe ratios at low extraction temperatures, which in some cases approach the terrestrial value (e.g., Table 3; Swindle et al., 1986; Becker and Pepin, 1984; Wiens, 1988). For these reasons we believe that Kr and Xe released at lower extraction temperatures from Martian impact glass should not be used in determining the composition of Martian atmospheric gases. For EET79001,104 we did not measure Kr and Xe in the 350°C extraction. For the other samples we do not consider that gas released at the 350°C and 750°C extractions (Tables 3 and 4). Fortunately, most of the Kr and Xe in impact glasses is released at higher extraction temperatures.

It has been pointed out that the isotopic composition of Martian Kr derived from the EET79001,27 glass inclusion shows an apparent mass fractionation trend compared to terrestrial Kr and resembles Kr measured for the solar wind (Swindle et al., 1986; Pepin, 1991). Further, Ott (1988) reported that the isotopic composition of Xe in the Chassigny Martian meteorite closely resembles that of the solar wind and suggested that this Xe represents a Martian mantle component. For these reasons we compare the isotopic composition of Kr determined in meteorite impact glasses against the composition of solar wind Kr as measured in lunar soils and a few meteorites. Unfortunately, the isotopic composition of solar Kr is not exactly known, and several different compositions have been suggested in the past. Solar wind noble gases usually experience variable degrees of mass fractionation upon implantation into exposed grain surfaces. Consequently, even among favorable samples for such studies, the derived solar Kr compositions show isotopic variations of ~2% at each isotopic mass. Pepin et al. (1995) summarized the preferred data for determining the solar wind Kr composition and suggested an average solar composition called Kr-1.

Figure 3 plots the ^{i}Kr/^{84}Kr ratios measured in the 1000°C and 1550°C extractions of EET79001,8 and EET79001,104 and the 1550°C extractions of Shergotty-B and Y793605,71. All ratios have been normalized to the solar wind Kr-1 composition. Thus, deviations of specific EET79001 isotopic ratios from the horizontal line of value 1.0 measure differences in these compositions compared to solar Kr-1. Compared to EET79001 glass analyses, Kr measured in Shergotty-B and Y793605 glass samples tend to scatter more and have larger analytical uncertainties. Our ^{78}Kr measurements suggest some hydrocarbon contamination at this mass, although none was observed in blank analyses, and consequently mass 78 data are not further considered. Also plotted in Figure 3 for comparison are the 1600°C extraction of EET79001,27 reported by Swindle et al. (1986), which released 53% of the total Kr present in their sample, and the 1500°C extraction of EET79001,27 reported by Becker and Pepin (1984), which released 77% of the total Kr present in their sample. These two extractions showed the smallest analytical uncertainties of all extractions from these respective samples. Some other extractions of these samples show Kr compositions that more closely resemble that for the Earth and, in our opinion, likely contain some terrestrial Kr contamination. The data in Figure 3 represent three impact glass inclusions in EET79001 as measured in three laboratories, as well as less precise data from impact glasses in two additional meteorites. Our new data for EET79001 have generally comparable or smaller analytical uncertainties compared to previous measurements, but all data show generally similar trends. One difference is that ^{80}Kr/^{84}Kr ratios in some of our analyses are slightly higher than those previously reported. This may be due to small effects of charge exchange on ^{40}Ar ions so as to be detected as mass 80 within the mass spectrometer. Although most of the Ar was separated from the Kr fraction analyzed, the ^{40}Ar/^{80}Kr ratio typically was still $\sim 10^5$ (versus $>6\times10^6$ in EET79001 total). Previous reports of ^{80}Kr/^{84}Kr in EET79001 glass do not state if corrections for ^{40}Ar were applied.

Figure 4 compares Kr isotopic data for EET79001 glass inclusions with several other compositions, all normalized to the same solar wind Kr-1 composition. Plotted are the average (and one standard deviation) of the six analyses of three inclusions of EET79001 shown in Figure 3 and the 1550°C extraction of EET79001,8, which possesses the overall smallest uncertainty. Also plotted are the Kr isotopic data for Chassigny (Ott, 1988), the composition for the Earth, the average composition observed in carbonaceous chondrites (AVCC), and the composition of the Martian atmosphere derived by Pepin (1991) from Martian meteorite data. From Figure 3 it can be seen that the EET79001 data are isotopically lighter compared to solar Kr-1, but that the ^{80}Kr abundance is in excess in comparison to the mass trend suggested by the other isotopes. This excess in ^{80}Kr has been attributed to neutron capture on bromine at the Martian surface (Bogard et al., 1984; Becker and Pepin, 1984; Swindle et al., 1986). If excess ^{80}Kr was produced by neutron capture, then a small component of neutron-capture ^{82}Kr must also be present. The excess, neutron-capture ratio of ^{80}Kr/^{82}Kr is expected to vary from ~3.5 for thermal neutrons to ~2 for neutrons having kev energies (Marti et al., 1966). The EET79001 ^{82}Kr data shown in Figure 4 have been corrected for this neutron component, assuming production by thermal neutrons and a neutron excess of 7.5% in ^{80}Kr/^{84}Kr, which is the average of analyses reported by Becker and Pepin

(1984) and Swindle et al. (1986). This correction amounted to only 0.5% in the ^{82}Kr/^{84}Kr ratio. A very similar correction was applied by Pepin (1991) to EET79001,27 data.

The line labeled "Mars atmosphere" (Figure 4) represents our suggested composition for Martian atmospheric Kr incorporated into meteorite impact glass. To enable comparison with other Kr reservoirs, a likely neutron capture component of ^{80}Kr and ^{82}Kr has been removed from this atmospheric composition, although this neutron component was probably shock-implanted along with the derived atmospheric component. (Because mass 80 was used as the basis for this correction, the Martian atmospheric composition in Figure 4 does not include ^{80}Kr.) The Martian atmospheric trend line is defined by the more precise data from the 1550°C extraction of EET79001,8, but is completely consistent with the average of six EET79001 temperature measurements made in three laboratories. This Martian composition suggests a fractionation trend that is ~0.4%/amu lighter compared to the solar Kr-1 composition and ~1.2%/amu lighter compared to terrestrial Kr. Within respective uncertainties, the Kr composition of the Martian atmosphere derived by Pepin (1991) marginally overlaps that of the EET79001 data (Figure 4). However, the EET79001 data indicate slightly higher ^{82}Kr/^{84}Kr and ^{83}Kr/^{84}Kr ratios and lower ^{86}Kr/^{84}Kr ratios compared to Pepin's derived composition. We suggest that use of all temperature extractions for EET79001 by Pepin (1991) incorporated some terrestrial Kr adsorbed on sample EET79001,27 and caused slight rotation of his derived Martian Kr composition toward the terrestrial trend in Figure 4. Some specific temperature extractions in these original data suggest such a terrestrial contamination.

We can speculate on the possible relationship between the Kr isotopic composition for the Martian atmosphere derived here and that of solar Kr derived from implanted solar wind. First we note that Martian atmospheric ^{82}Kr and ^{83}Kr appear to be ~0.5-1% in excess compared to a linear mass fractionation trend defined by ^{84}Kr and ^{86}Kr. In other words, Martian atmospheric Kr appears not to define a precise linear fractionation trend compared to either terrestrial or solar Kr compositions. As mentioned above, implanted solar wind commonly shows mass fractionation and isotopic differences among samples. Thus, the apparent ~0.4%/amu average mass difference between Martian Kr and solar Kr-1 may reflect small amounts of mass fractionation present in the solar component. The Martian mantle may have acquired a solar component by direct incorporation into pre-planetary grains rather than by ion implantation from the solar wind, and the mass fractionation effects for the two mechanisms may not be the same. On the other hand, the composition of Kr measured in Chassigny (Ott, 1988) appears to be different from either Martian or solar Kr, and shows large excesses at masses 80 and 83 and a small excess at mass 82. These excesses do not closely resemble the Kr spectrum expected from cosmic ray interactions. Because Xe in Chassigny closely resembles solar wind Xe (Ott, 1988), we might expect that Chassigny Kr would also. Assuming that this single analysis of Kr in Chassigny is accurate, Martian atmospheric Kr might be explained as a mixture of mostly solar Kr-1 and a smaller proportion of Chassigny Kr. Such a mixture could produce the non-linear fractionation pattern for Martian atmospheric gases compared to terrestrial and solar wind Kr. Variable proportions of a Chassigny-like component might also explain small observed differences in Kr compositions among EET79001 analyses.(Figure 3). This explanation assumes that the Chassigny component is indigenous to EET79001 and not shock-implanted (Ott, 1988; Bogard, 1997). If Chassigny Kr is mantle-derived, the high relative abundances of ^{80}Kr and ^{82}Kr are unlikely to have been caused by neutron capture effects, and an origin for the excess ^{83}Kr in Chassigny is even more difficult to explain.

Xenon

As in the case with Kr, most of the Xe in impact glasses was released at extraction temperatures >750°C (Table 3), and only this gas was considered in evaluating the trapped Xe isotopic composition. Unfortunately, the quantity of Xe measured in these Martian glasses was lower than that for Kr and the uncertainties of the Xe isotopic measurements were larger. Figure 5 plots the ^{i}Xe/^{132}Xe ratios measured in the 1550°C extraction of EET79001,8 and the average of four EET79001 analyses, both normalized to the composition of the Martian atmosphere reported by Swindle et al. (1986). Also plotted in Figure 5 are the data for the 1600°C extraction of EET79001,27 (Swindle et al., 1986) and for Chassigny (Ott, 1988). The isotopic composition of trapped Xe in impact glass EET79001,8 generally agrees within one sigma uncertainties with both the 1600°C extraction of EET79001,27 and with the Martian atmospheric component deduced by Swindle et al. (1986). The one exception is ^{129}Xe, which shows somewhat greater enrichment in EET79001,8. Thus our new isotopic data on Xe in Martian meteorite glasses support the Martian atmospheric Xe composition reported by Swindle et al. (1986) from analysis of EET79001,27. The isotopic composition of Xe in Chassigny resembles that of the solar wind and is quite different from the that in Martian atmosphere. Possible reasons for this difference include mass fractionation of Xe during early, massive loss of the Martian atmosphere, as discussed by Pepin (1991).

Relative Elemental Composition

These new data on impact glasses, when combined with literature data, permit a more accurate determination of the relative elemental abundances of Ar, Kr, and Xe for Martian atmospheric gases trapped in Martian meteorites. Determination of the trapped ^{36}Ar/^{84}Kr/^{132}Xe ratios from these data are discussed in detail in Bogard and Garrison (1998). In that paper we use the ^{129}Xe/^{132}Xe ratio as a measure of the relative amounts of Martian atmospheric gases present in impact glass and conclude that a value of ~2.6 the is most probable value for the Martian atmosphere. By comparing ^{129}Xe/^{132}Xe against ^{36}Ar/^{132}Xe and ^{84}Kr/^{132}Xe ratios, we conclude that trapped noble gases in impact glasses represent three components. One component is the Martian atmosphere, which is most prominent in impact glasses; a second component probably derives from the Martian mantle and resembles noble gases trapped in the Martian meteorite Chassigny (Ott, 1988); the third component is contamination by terrestrial noble gases, possibly in weathering products. Still a fourth component with smaller Xe/Kr and Xe/Ar ratios compared to the Martian atmosphere is present in nakhlites and ALH84001. This component probably represents mass fractionation of the Martian atmosphere, either during its adsorption by Martian weathering products as suggested by Drake et al. (1994) or by its dissolution in Martian water, which was then incorporated into secondary minerals, as suggested by Bogard and Garrison (1998).

Figure 6 plots ^{36}Ar/^{132}Xe versus ^{84}Kr/^{132}Xe ratios for the same sample analyses of Martian meteorites considered by Bogard and Garrison (1998), including the impact glass data of Table 4. Argon and Xe data, but not Kr data, were also reported for an impact glass vein from Zagami (Marti et al., 1995). Figure 6 is less useful in identifying the various noble gas components compared to plots involving ^{129}Xe/^{132}Xe used in our previous paper, but it does summarize the trapped Martian components in these samples. The preferred ^{36}Ar/^{132}Xe and ^{84}Kr/^{132}Xe elemental ratios for Martian atmospheric gas trapped in impact glass are 900 ±100 and 20.5 ±3, respectively (Bogard and Garrison, 1998). These two ratios differ from the values reported by the Viking spacecraft (Owen et al., 1977; Owen, 1992) by factors of ~3.6 and ~2.5 respectively (Figure 6). Compared to the Martian atmospheric composition previously deduced by Hunten (1987) and Pepin (1991) from a more limited suite of Martian meteorite analyses, the Kr/Xe ratio derived here is essentially the same, but the ^{36}Ar/Xe ratio differs substantially. Impact glass data, as well as data for several non-glass samples of Martian meteorites, define a mixing array between the Martian mantle (Chassigny) component and the Martian atmospheric component derived by Bogard and Garrison (1998). Contributions from terrestrial noble gas contamination mimic the Martian atmospheric component on this mixing array (but not on plots involving ^{129}Xe/^{132}Xe), and thus the terrestrial and Martian atmospheric contributions cannot be resolved in Figure 6. (One exception is glass inclusion EET79001,54 plotting closest to the Earth point, for which atmospheric-like ^{40}Ar/^{36}Ar and ^{129}Xe/^{132}Xe ratios indicate that terrestrial contamination makes the dominant contribution.) Ar/Kr/Xe present in ALH84001 and the nakhlites is represented by those plotted points with lower Ar/Xe ratios which fall below the Martian mantle/atmosphere mixing array. These samples have noble gases mass fractionated in favor of heavier elements (Drake et al., 1994; Bogard and Garrison, 1998).

COSMOGENIC NOBLE GASES

Concentrations of cosmogenic ^{3}He, ^{21}Ne, and ^{38}Ar are given in Table 5 for most Martian meteorite analyses listed in Table 1. Measured ^{3}He was taken to be entirely cosmogenic in origin. Ne and Ar were assumed to be two component mixtures between a cosmogenic component and a trapped component. However, all measured ^{21}Ne concentrations are >99% cosmogenic. Cosmogenic ^{21}Ne/^{22}Ne ratios listed are either measured ratios for single extractions releasing most of the Ne (e.g., ALH84001 samples) or were obtained from extrapolations of temperature data on 3-isotope Ne plots (see below). To calculate ^{38}Ar$_{cos}$ for most samples, we assumed that trapped ^{36}Ar/^{38}Ar has the terrestrial value of 5.32 and that cosmogenic ^{36}Ar/^{38}Ar =0.66. Because trapped ^{36}Ar/^{38}Ar is dominated by Martian atmospheric Ar in both samples of EET79001 and Shergotty-B, we cannot calculate ^{38}Ar$_{cos}$ for these samples. Figure 2 suggests that Ar in our glass sample of Y793605 consists of approximately equal parts of Martian atmospheric Ar and either terrestrial or trapped Martian mantle Ar. Thus, we assumed a trapped ^{36}Ar/^{38}Ar ratio of 4.6 (an average of values 3.9 and 5.3) to calculate ^{38}Ar$_{cos}$ =1.76 x10^{-9}cm^{3}/g. If we assume trapped ^{36}Ar/^{38}Ar values of 3.9 and 5.3, ^{38}Ar$_{cos}$ becomes 1.5 and 2.0 x10^{-9}cm^{3}/g, respectively. Also listed in Table 3 are cosmogenic He, Ne, and Ar data for four Martian meteorites as recently reported by other laboratories.

GCR and SCR Irradiation

In most meteorites the majority of the cosmogenic Ne and Ar is produced by irradiation of galactic cosmic ray particles and is referred to as a GCR component. However, surfaces of objects exposed in space also acquire cosmogenic noble gases produced to depths of a few cm by energetic (>10 MeV) solar protons. The relative production rates of the solar-produced, or SCR component, are comparable to the GCR production rates under conditions of no shielding, but the SCR/GCR production ratio rapidly decreases with sample depth. (See Rao et al., 1994 for a discussion of SCR and GCR noble gases.) Resolution of SCR noble gases from GCR noble gases can be difficult, but in principle can be made on the basis of concentration profiles as a function of sample depth and from the ^{21}Ne/^{22}Ne ratio. In many meteorites, the SCR ^{21}Ne/^{22}Ne ratio is expected to be ~0.57-0.63 and the GCR ^{21}Ne/^{22}Ne ratio, ~0.78-0.094 (Garrison et al., 1995). Both sets of ratios vary with the degree of shielding of the sample from the energetic particles, with smaller GCR ^{21}Ne/^{22}Ne ratios occurring for conditions of lower shielding. SCR-Ne obviously cannot occur without GCR-Ne, so that cosmogenic ^{21}Ne/^{22}Ne ratios approaching the pure SCR composition are not observed in natural samples. Garrison et al. (1995) suggested that for meteorites having the chemical composition of ordinary chondrites or the lherzolite shergottites (e.g., ALH77005, Y793605, and LEW88516), the approximate smallest GCR ^{21}Ne/^{22}Ne ratio that can be produced without also producing SCR-Ne is ~0.78. This ratio can be slightly smaller for samples having smaller Mg/(Si+Al) ratios, as would be the case for the basaltic-like shergottites (e.g., Shergotty, QUE94201) and the nakhlites.

Garrison et al. (1995) measured cosmogenic ^{21}Ne/^{22}Ne ratios of 0.71-0.78 in eight samples of Martian meteorite ALH77005 and concluded that these indicated the presence of variable amounts of SCR-Ne. Low ^{21}Ne/^{22}Ne ratios for a few analyses in the literature of EET79001, Zagami, and Shergotty also suggested the presence of SCR Ne. The significance presence of SCR-Ne in shergottites, whereas it is rare in chondrites, could imply different orbital parameters for these Martian meteorites, which caused less ablation loss during atmospheric entry to earth (Garrison et al., 1995). Eugster et al. (1997a) reported additional analyses of Zagami and LEW88516 that gave cosmogenic ^{21}Ne/^{22}Ne ratios of ~0.81, which would be consistent with GCR production under low shielding and need not indicate the presence of SCR-Ne. These authors also measured ^{21}Ne/^{22}Ne of 0.76 in two samples of QUE94201, which when corrected to assumed cosmogenic ^{20}Ne/^{22}Ne ratios of ~0.85, give cosmogenic ^{21}Ne/^{22}Ne of 0.78. Swindle et al. (1996) report for a sample of QUE94201 ^{21}Ne/^{22}Ne =0.76 and ^{20}Ne/^{22}Ne =0.68. Ratios of 0.76-0.78 could indicate some SCR-Ne in QUE94201.

Figure 7 is a 3-isotope plot of Ne for those temperature extractions of Martian meteorites listed in Table 1 which show primarily a cosmogenic composition and give ^{20}Ne/^{22}Ne ratios <2.0. Those extractions releasing very small fractions of the total Ne in each sample also have larger uncertainties in isotopic ratios. Several extractions give ^{20}Ne/^{22}Ne ≅0.84, the ratio expected for pure cosmogenic Ne (Garrison et al., 1995). Three extractions of sample QUE94201,28 have small uncertainties and define a relatively linear array which gives ^{21}Ne/^{22}Ne ≅0.79 at ^{20}Ne/^{22}Ne ≅0.84. Neon ratios for two extractions of QUE94201,31 give larger uncertainties and do not define a reasonable mixing trend. The ^{20}Ne/^{22}Ne ratios for two extractions of Shergotty-A indicate pure cosmogenic Ne, but give different ^{21}Ne ^{22}Ne ratios of ~0.77 and ~0.81, whereas one extraction of Shergotty-B indicates an intermediate ratio of ~0.79. Neon ratios for all extractions of two samples of EET79001 have larger uncertainties because of small cosmogenic concentrations and could be consistent with cosmogenic ^{21}Ne/^{22}Ne ratios in the range of~0.76-0.80. The 1550°C extractions of two samples of ALH84001,114 taken from different depths just below the fusion crust indicate pure cosmogenic Ne and give identical ^{21}Ne/^{22}Ne of 0.845. Our sample ALH84001,113, a different chip from near the fusion crust, gives a ^{21}Ne/^{22}Ne of 0.83. Similar ^{21}Ne/^{22}Ne ratios of ~0.83-0.85 were reported for LH84001 by Miura et al. (1995), Eugster et al.(1997a), and Swindle et al. (1995).(Table 5). The 1550°C extraction of our Y793605,71 sample gives ^{21}Ne/^{22}Ne =0.83, which is similar to ratios of ~0.81-0.83 reported for Y793605 by Eugster et al. (1997b) and Nagao et al. (1997).

None of the Ne isotopic data for ALH84001 or Y793605 indicate the presence of a SCR-Ne component such as we found for ALH77005 (Garrison et al., 1995). ALH84001 and Y793605 were probably GCR irradiated in space under several cm of shielding (Graf et al., 1990). On the other hand, all analyzed samples of QUE94201 possibly contain small amounts of SCR-Ne, which is consistent with this meteorite having been irradiated in space as a very small object. Our samples of Shergotty, and EET79001 may have contained small amounts of SCR-Ne. However, the amounts of SCR-Ne in these two meteorites were undoubtedly small in comparison to the GCR-Ne concentrations and are unlikely to have a significant effect on calculation of GCR exposure ages. Eugster et al. (1997a) came to a similar conclusion for their samples of Zagami and LEW88516.

Space Exposure Ages

Eugster et al. (1997a) recently calculated the space exposure ages of several Martian meteorites using production rates obtained by Eugster and Michel (1995) from analyses of achondritic meteorites. One of their interesting conclusion is that the exposure age of the lherzolite-shergottites (~3.8 Myr) is distinctly longer than that of the basaltic-shergottites (~2.8 Myr), which if true, might require ejection from Mars in different cratering events. On the other hand, ejection of several related Martian meteorites possessing young and similar isotopic formation ages in more than one cratering event raises important issues about the age distribution of rocks on the Martian surface (Nyquist et al., 1998). Because the chemical composition of lherzolitic and basaltic shergottites are quite different, the noble gas production rates used to calculate exposure ages are not the same, but can differ by almost a factor of two. Further, determination of cosmogenic noble gases and major elemental abundances are rarely made in aliquot samples, and the prospect of sample heterogeneity raises additional uncertainties about relative cosmogenic noble gas production rates. In addition, noble gas production rates must be corrected for differences in shielding based on the ^{21}Ne/^{22}Ne ratio. This correction is not well determined in the case of very low shielding as is exhibited by several Martian meteorites. Below we will address some of the effects of these uncertainties on space exposure ages for the four Martian meteorites listed in Table 5.

Cosmogenic noble gas data for ALH84001 have been reported by four laboratories and show relatively small variations among samples (Table 5). This suggests that significant measurement biases among these laboratories do not exist. Our samples ALH84001,113 and ,114-1 were taken from near the meteorite fusion crust, and diffusive loss probably explains their relatively lower ^{3}He concentrations; sample ,114-2 apparently did not lose ^{3}He. The small differences in cosmogenic ^{21}Ne and ^{38}Ar among all analyses of ALH84001 may represent compositional variations. Somewhat larger variations in cosmogenic gas concentrations exist among all analyses of QUE94201 and Y793605, although these variations tend to be less among different samples reported by the same laboratory. In the case of basaltic meteorites (e.g., QUE94201 and Shergotty), greater variations in cosmogenic noble gases may reflect the significant abundance of both feldspar and pyroxene, with very different ^{21}Ne and ^{38}Ar production rates, whereas ~95% of ALH84001 consists of the single mineral orthopyroxene.

Eugster et al. (1997a) assumed that small differences in ^{21}Ne/^{22}Ne among individual analyses of ALH84001 and QUE94201 were caused by real differences in shielding and from this derived ^{21}Ne production rates that differ by factors of ~15% and ~50%, respectively. If shielding is the explanation for observed variations in ^{21}Ne/^{22}Ne, then a positive correlation should exist between ^{21}Ne/^{22}Ne and ^{21}Ne$_{cos}$ concentrations. However, the extensive data set for ALH84001 (Table 5) does not show such a positive correlation, but may even show a slight negative correlation. Neither do the data for QUE94201 show an obvious positive correlation. This implies that differences in shielding are not the explanation for small observed variations in ^{21}Ne/^{22}Ne among analyses of ALH84001 and QUE94201 (Table 5). Rather, analytical uncertainties and compositional differences among samples probably cause the observed ~2% spread in ^{21}Ne/^{22}Ne in these two meteorites. Further, theoretical models do not support large variations in ^{21}Ne production rates for relatively small changes in ^{21}Ne/^{22}Ne. A change in ^{21}Ne/^{22}Ne comparable to the total spread observed for ALH84001 or QUE94201 would produce ≤10% change in the ^{21}Ne production rate of ordinary chondrites (Michel et al., 1991) with compositions similar to lherzolitic meteorites and ~6% change in the ^{21}Ne production rate of Mg-poor eucrites (Eugster and Michel, 1995) with compositions similar to basaltic Martian meteorites.

The above considerations suggests that analytical uncertainties and compositional variations among samples account for much of the variation in cosmogenic noble gas data for Martian meteorites. A reasonable method to partially compensate for these differences is to utilize average noble gas data from multiple sample analyses, but excluding those analyses with unusually large deviations from these averages. We then use the equations of Eugster and Michel (1995) to calculate production rates for these average data. Chemical compositions used for ALH84001, QUE94201, and Shergotty were those reported by Eugster et al. (1997a). Chemical compositions used for Y793605 were those reported by Mittlefehldt et al. (1997). The derived production rates and the calculated ^{3}He, ^{21}Ne, and ^{38}Ar space exposure ages obtained in this manner are given in Table 5. The uncertainty associated with each age represents only the one-sigma uncertainty for the average of each cosmogenic gas concentration, and does not include the uncertainty in the production rate used. Thus, these age uncertainties may be lower limits to the actual uncertainty in calculated exposure ages.

The ^{3}He, ^{21}Ne, and ^{38}Ar exposure ages obtained for ALH84001 are the same within their relative uncertainties, although the ^{38}Ar age is lower. The most probable ALH84001 age of 13.9±1 Myr is similar to several calculated ^{3}He and ^{21}Ne ages of ~12-14 Myr reported for Chassigny and the nakhlites (Eugster et al., 1997a). Although these authors conclude that ALH84001 has a distinctly older age compared to these other Martian meteorites, we believe that some uncertainty still exists with this conclusion. On the other hand, the significant differences in petrology and isotopic formation ages between ALH84001 and these other meteorites suggest that it is unlikely a single impact crater ejected all these meteorites from Mars (Nyquist et al., 1998). The nakhlites do yield younger ^{38}Ar ages of ~9-10 Myr (in comparison to their ^{3}He and ^{21}Ne ages), but in the compilation of Eugster et al. (1997a), younger ^{38}Ar ages also occur for Chassigny and some of the basaltic shergottites, as well as ALH84001. In our opinion, some biases between calculated ^{21}Ne and ^{38}Ar production rates for diverse chemical compositions may yet exist.

The ^{3}He and ^{38}Ar ages for the two basaltic shergottites QUE94201 and Shergotty are identical within uncertainties at 2.0-2.5 Myr. The ^{21}Ne exposure ages of these two meteorites, 3.3-3.4 Myr, appear somewhat higher, however (Table 5). One possible explanation for this is that these meteorites contain some amounts of SCR-Ne produced by energetic solar protons, as discussed above. Alternatively, the ^{21}Ne production rate used may be slightly low as a consequence of adopting a given chemical composition for samples used for noble gas analyses. Eugster et al. (1997a) report similar ^{3}He and ^{38}Ar ages of ~2.2-2.9 Myr and ^{21}Ne ages of 3.0-3.3 Myr for a third basaltic shergottite, Zagami. Concentrations of ^{10}Be is similar in these three shergottites and indicate a space exposure age for QUE94201 of 2.6 ±0.5 Myr (Nishiizumi and Caffee, 1996). Although QUE94201 has a terrestrial age of ~0.3 Myr (Nishiizumi and Caffee, 1996), its space exposure age cannot be resolved from the other two shergottites. We conclude that the most likely space exposure age for basaltic shergottites is ~2.7 Myr, but that the uncertainty in this age may be as large as ±0.6 Myr. Although all the basaltic shergottites likely were ejected from Mars in a common cratering event, that conclusion is not absolutely required by the noble gas data.

The space exposure ages calculated for the Martian lherzolite Y793605 appear distinctly older than those of basaltic shergottites (Table 5). The ^{3}He and ^{21}Ne ages of Y793605 are the same within relative uncertainties at ~5.0 Myr. Variations in reported Ca concentrations make the ^{38}Ar ages less certain. Our glass-rich sample was an aliquot of a sample which gave Ca=1.57% (Mittlefehldt et al., 1997). For this sample the ^{38}Ar production rate would be 0.52 x10^{-9}cm^3/Myr and the ^{38}Ar age 3.4 Ma. For Y793605 whole rock, Mittlefehldt et al. (1998) report Ca =1.93%, whereas Warren et al. (1997) report Ca =2.9%. Using the former Ca value and the average ^{38}Ar$_{cos}$ for the bulk sample analyses reported by Nagao et al. (1997) and Eugster et al. (1997b) gives a ^{38}Ar production rate of 0.54 x10^{-9}cm^3/Myr and an ^{38}Ar age of 4.0 Myr. Both of these ^{38}Ar ages are significantly less than the ^{3}He and ^{21}Ne ages.

The equations of Eugster and Michel (1995) derived from achondrites do not make corrections to the ^{38}Ar production rate for differences in shielding. Yet, it is observed from studies of chondrites, whose chemical composition is similar to Y793605 and other Martian lherzolites, that ^{38}Ar$_{cos}$ does depend upon shielding (Graf et al., 1990 and references therein). In his study of noble gas production rates of chondrites, Eugster (1988) gives a method for correcting the ^{38}Ar production rate for shielding. Thus, we used the shielding relationship of Eugster (1988) and the composition relationship of Eugster et al. (1997a) to calculate shielding corrected ^{38}Ar production rates for Y793605. These rates are 0.43 x10^{-9}cm^3/Myr for our glass-rich sample and 0.45 x10^{-9}cm^3/Myr for the bulk samples analyzed by Nagao et al. (1997) and Eugster et al. (1997b). These production rates give ^{38}Ar exposure ages for Y793605 of 4.1 Myr and 4.8 Myr, for the glass and bulk samples respectively, in much better agreement with the ^{3}He and ^{21}Ne exposure ages. We conclude that the space exposure age for Y793605 is 4.9 ±0.6 Myr.

Eugster et al. (1997a) report ^{3}He and ^{21}Ne space exposure ages for Martian lherzolites ALH77005 and LEW88516 of 3.2-4.5 Myr and ^{38}Ar ages of 2.9-3.9 Myr. Because these two meteorites were also irradiated as small objects, shielding corrections to the ^{38}Ar production rates also may be required, which would raise these ^{38}Ar ages by ~20%. The average (shielding-corrected) age for Y793605 of 4.9 ±0.6 Myr appears slightly older than the largest calculated age of ~4.5 Myr for these other lherzolites (Eugster et al., 1997a). This apparent difference is more likely due to uncertainties in noble gas production rates than to different cratering events. Thus, we see no good argument for concluding that the exposure age of Y793605 is older than that of other Martian lherzolites. However, the exposure age of Y793605 is almost a factor of two greater than that of the basaltic shergottites. Either Martian lherzolites have an older exposure age than basaltic shergottites and thus were ejected by a different cratering event, as concluded by Eugster et al. (1997a), or compositional corrections to production rates are much more uncertain than currently understood.

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Table 1. Measured He, Ne, and Ar data in temperature extractions of Martian meteorites. Gas concentrations are to be multiplied by the exponents indicated and are in units of cm^{3}STP/g. Uncertainties for isotopic ratios are one-sigma and are derived from measurements uncertainties and corrections for blanks and doubly charged ^{40}Ar.

Sample / Temp.°C	^{3}He e-9	4He e-8	^{22}Ne e-9	^{36}Ar e-9	^{40}Ar e-8	^{20}Ne/^{22}Ne	±	^{21}Ne/^{22}Ne	±	^{38}Ar/^{36}Ar	±
ALH84001,113, 0.5-2 mm											
250	16.83	43.25	0.13	0.21	9.8	2.072	0.364	0.523	0.036	0.201	0.030
450	190.13	214.10	2.73	0.33	102.1	0.894	0.025	0.852	0.006	0.397	0.023
1550	0.92	76.19	44.17	3.90	402.6	0.828	0.006	0.829	0.005	1.165	0.023
Total	207.88	333.64	47.03	4.43	514.5	0.836	0.002	0.829	0.001	1.063	0.002
ALH84001,114-1, 1.5-3.0 mm											
450	197.47	257.35	2.07	0.47	107.4	0.875	0.051	0.833	0.009	0.336	0.026
1550	15.81	119.54	44.69	3.91	523.1	0.838	0.003	0.845	0.001	1.161	0.013
Total	213.28	376.89	46.72	4.38	630.5	0.840	0.004	0.845	0.001	1.072	0.012
ALH84001,114-2, 8-10 mm											
450	213.18	252.86	1.76	0.61	97.7	0.959	0.042	0.836	0.006	0.311	0.015
1550	19.38	113.83	41.11	4.27	998.0	0.835	0.002	0.844	0.001	1.079	0.008
Total	232.56	366.69	42.94	4.89	1095.7	0.840	0.003	0.844	0.001	0.983	0.007
QUE94201,28, 0.5-2.0 mm											
400	4.19	18.43	0.85	0.36	12.8	1.694	0.009	0.678	0.003	0.210	0.005
800	19.58	28.02	1.84	0.38	35.9	1.050	0.006	0.755	0.002	0.642	0.011
1200	4.01	20.84	2.98	2.43	166.1	0.938	0.004	0.778	0.003	1.027	0.003
1600	0.00	16.64	0.04	0.33	20.6	6.080	0.183	0.480	0.043	0.941	0.042
Total	27.78	83.93	5.70	3.49	235.4	1.119	0.002	0.754	0.001	0.893	0.001
QUE94201,31, interior											
400	5.21	27.43	2.53	0.71	22.2	3.025	0.060	0.603	0.004	0.213	0.005
1000	20.64	38.54	2.99	8.41	249.6	1.513	0.034	0.747	0.005	0.417	0.001
1600	0.00	22.64	0.42	0.77	39.0	0.824	0.135	0.757	0.009	0.928	0.032
Total	25.85	88.62	5.94	9.89	310.8	2.109	0.024	0.687	0.003	0.442	0.001
Shergotty-A, 10% glass											
350	20.51	89.19	0.39	0.10	9.3	3.395	0.219	0.550	0.014	0.105	0.034
750	21.07	147.59	2.87	0.64	124.8	0.838	0.017	0.772	0.003	0.601	0.015
1550	0.01	7.99	3.49	2.15	102.6	0.849	0.013	0.806	0.001	1.333	0.018
Total	41.60	244.80	6.76	2.80	236.7	0.993	0.015	0.777	0.002	1.164	0.004
Shergotty-B, glass											
350	13.43	49.33	0.25	0.18	9.1	4.618	0.720	0.503	0.051	0.025	0.008
1550	23.35	119.54	5.72	12.44	2091.2	0.941	0.036	0.780	0.005	0.441	0.005
Total	36.79	168.91	5.97	12.62	2100.3	1.097	0.046	0.768	0.005	0.438	0.005
Y793605,71, glass											
350	4.72	70.57	0.29	0.41	13.9	4.525	0.397	0.373	0.034	0.141	0.024
750	37.34	64.67	2.79	1.21	100.2	1.585	0.045	0.733	0.006	0.299	0.011
1550	22.54	3.47	9.55	6.33	845.6	0.893	0.013	0.830	0.002	0.444	0.004
Total	64.60	138.72	12.63	7.53	959.7	1.130	0.013	0.798	0.002	0.421	0.004
EET79001,8, glass											
350	2.34	46.90	0.08	0.08	4.0	4.333	0.377	0.476	0.025	0.135	0.025
750	5.29	10.99	0.87	1.81	293.2	1.860	0.062	0.643	0.006	0.252	0.002
1000	0.35	1.93	0.36	4.76	856.9	1.364	0.404	0.717	0.009	0.269	0.001
1550	0.07	7.76	0.58	22.67	4189.9	1.401	0.056	0.702	0.006	0.270	0.001
Total	8.06	25.37	1.90	29.24	5344.0	1.737	0.086	0.668	0.004	0.269	0.001
EET79001,104, glass											
350	0.01	5.87	0.05	0.55	18.2	7.413	0.840	0.296	0.023	0.177	0.007
750	5.92	30.75	1.00	1.73	307.8	1.471	0.067	0.682	0.005	0.273	0.002
1000	0.05	3.26	0.37	6.31	1180.8	0.859	0.302	0.761	0.010	0.293	0.001
1550	0.00	3.73	0.11	3.72	712.5	0.667	0.169	0.733	0.025	0.319	0.002
Total	5.99	43.61	1.53	11.76	2219.3	1.467	0.089	0.691	0.004	0.298	0.001

Table 2. Concentrations of ^{84}Kr (10^{-11}cm^3 STP/g) and Kr isotopic abundances relative to ^{84}Kr =1.00. Analytical uncertainties are shown beneath each ratio. Kr isotopic data were not taken for the 350°C extractions of EET79001,8 and Y793605,71, and only ^{84}Kr abundances were measured for the three ALH84001 samples.

Sample	[^{84}Kr]	^{86}Kr	^{83}Kr	^{82}Kr	^{80}Kr	^{78}Kr
EET79001,8						
350 °C	0.26	0.3184	n.m.	n.m.	n.m.	n.m.
		0.0225				
750 °C	1.67	0.2905	0.1951	0.2072	0.0341	0.0998
		0.0094	0.0031	0.0066	0.0040	0.0076
1000 °C	12.86	0.2932	0.2047	0.2080	0.0466	0.0219
		0.0018	0.0013	0.0013	0.0003	0.0027
1550 °C	52.46	0.2975	0.2058	0.2099	0.0432	0.0935
		0.0007	0.0008	0.0006	0.0002	0.0017
EET7901,104						
750 °C	1.97	0.2886	0.2079	0.2100	0.0552	0.0326
		0.0079	0.0031	0.0042	0.0028	0.0048
1000 °C	15.73	0.2984	0.2076	0.2127	0.0469	0.0151
		0.0018	0.0013	0.0011	0.0006	0.0011
1550 °C	9.55	0.2999	0.2085	0.2081	0.0479	0.0129
		0.0032	0.0025	0.0023	0.0012	0.0017
Shergotty-A						
350 °C	0.22	0.3527	0.2355	0.2210	0.0564	0.4461
		0.0681	0.0504	0.0428	0.0259	0.7292
750 °C	1.06	0.2858	0.2237	0.2019	0.0219	0.2307
		0.0172	0.0139	0.0120	0.0166	1.4456
1550 °C	1.31	0.2546	0.2892	0.3256	0.0750	0.2684
		0.0401	0.0313	0.0298	0.0151	0.4043
Shergotty-B						
350 °C	1.10	0.2794	0.2725	0.2360	0.0678	0.4546
		0.0542	0.0463	0.0498	0.0243	0.0553
1550 °C	23.17	0.2915	0.2020	0.2042	0.0469	0.0380
		0.0110	0.0076	0.0067	0.0067	0.0047
Y793605,71						
350 °C	2.90	0.3208	n.m.	n.m.	n.m.	n.m.
		0.0124				
750 °C	2.14	0.3176	0.1663	0.1863	0.0255	0.4173
		0.0438	0.0364	0.0404	0.0231	0.0294
1550 °C	12.06	0.3036	0.1997	0.2136	0.0306	0.0845
		0.0053	0.0041	0.0045	0.0040	0.0053
ALH84001,113						
1550 °C	17.02					
ALH84001,114-1						
1550 °C	11.38					
ALH84001,114-2						
1550 °C	18.41					

Table 3. Concentrations of ^{132}Xe (10^{-12} cm^3 STP/g) and Xe isotopic abundances relative to ^{132}Xe =1.00. Analytical uncertainties are shown beside each ratio. Some specific isotopic ratios were not measured (n.m.), nor were any ratios for 450°C extractions of ALH84001.

Sample	[^{132}Xe]	^{136}Xe	±	^{134}Xe	±	^{131}Xe	±	^{130}Xe	±	^{129}Xe	±	^{128}Xe	±	^{126}Xe	±	^{124}Xe	±
EET79001,8																	
350°C	0.23	1.017	0.285	0.423	.0163	1.030	0.382	n.m.		1.315	0.461	n.m.		n.m.		n.m.	
750°C	0.94	0.437	0.050	0.409	0.048	0.981	0.117	0.285	0.038	1.353	0.193	0.113	0.042	0.057	0.030	0.086	0.031
1000°C	4.59	0.3454	0.0109	0.3840	0.0110	0.8166	0.0212	0.1483	0.0051	2.1564	0.0590	0.0764	0.0131	0.0129	0.0069	0.0249	0.0071
1550°C	27.89	0.3533	0.0047	0.4043	0.0059	0.8100	0.0117	0.1561	0.0022	2.5904	0.0308	0.0751	0.0033	0.0013	0.0012	0.0052	0.0017
EET79001,104																	
750°C	1.40	0.351	0.050	0.420	0.054	0.799	0.109	0.162	0.031	1.219	0.162	0.0091	0.0075	n.m.		n.m.	
1000°C	9.09	0.3611	0.0103	0.3953	0.0113	0.7941	0.0224	0.1707	0.0046	2.3510	0.0562	0.0695	0.0060	0.0117	0.0038	0.0052	0.0050
1550°C	5.85	0.3497	0.0226	0.4247	0.0246	0.8322	0.0514	0.1873	0.0101	2.4095	0.1232	0.0786	0.0190	0.0006	0.0005	0.0014	0.0013
Shergotty-A																	
350°C	<0.3	0.138	0.093	0.503	0.073	0.737	0.095	n.m.		1.232	0.173	0.137	0.103	n.m.		n.m.	
750°C	1.94	0.2694	0.1033	0.4533	0.0723	1.0970	0.1389	0.4292	0.0769	1.1991	0.1623	0.2448	0.0518	0.0476	0.0364	0.1417	0.0550
1550°C	3.37	0.4559	0.0939	0.276	0.072	0.0827	0.0446	0.0668	0.0294	0.2265	0.0489	1.3969	0.2258	0.2449	0.0594	0.8746	0.1835
Shergotty-B																	
350°C	1.54	0.774	0.248	1.275	0.374	2.387	0.695	0.648	0.203	0.662	0.279	0.723	0.260	0.234	0.081	0.558	0.196
1550°C	10.95	0.2011	0.0615	0.3155	0.0729	0.9774	0.2040	0.1525	0.0367	2.5621	0.4165	0.0210	0.0149	0.0105	0.0075	0.0238	0.0173
Y793605,71																	
350°C	2.98	0.606	0.160	0.961	0.170	1.224	0.280	n.m.		1.037	0.276	n.m.		n.m.		n.m.	
750°C	3.23	0.5164	0.0938	0.4424	0.0948	1.2999	0.2516	0.2206	0.0833	1.3539	0.2676	0.1230	0.0627	0.1059	0.0578	0.0000	0.0000
1550°C	9.91	0.3769	0.0392	0.4441	0.0442	0.8310	0.0641	0.1509	0.0358	1.8281	0.1336	0.0662	0.0121	0.0558	0.0327	0.0389	0.0133
ALH84001,113																	
1550°C	19.78	0.3664	0.0156	0.3854	0.0218	0.8196	0.0426	0.1489	0.0259	1.9396	0.0633	0.0708	0.0114	0.0206	0.0118	0.0201	0.0138
ALH84001,114-1																	
1550°C	15.85	0.2875	0.0245	0.3421	0.0290	0.7238	0.0606	0.1342	0.0114	1.4719	0.0797	0.0955	0.0072	n.m.		n.m.	
ALH84001,114-2																	
1550°C	24.69	0.3898	0.0224	0.3967	0.0184	0.8163	0.0402	0.1511	0.0212	1.668	0.0665	0.0488	0.0294	n.m.		n.m.	

Table 4. Concentrations of trapped ^{20}Ne and ^{36}Ar (units 10^{-9} cm^3 STP/g) and ^{20}Ne/^{36}Ar and ^{40}Ar/^{36}Ar ratios in Martian meteorite impact glasses. ^{40}Ar/^{36}Ar literature data are from Bogard (1997). Viking data are from Owen et al. (1977).

Sample	^{20}Ne	^{36}Ar	^{20}Ne/^{36}Ar	^{40}Ar/^{36}Ar
New Data:				
EET79001,8	1.96	28.9	0.068	1830
EET79001,104	1.14	11.6	0.098	1880
Shergotty-B	1.70	10.5	0.16	1870
Y793605,71	3.61	6.2	0.58	1460
EET79001,27 Literature Data:				
Bogard et al., 1984	7.1	28.3	0.25	1540
Swindle et al., 1986	6.1	24.1	0.25	1185
Becker & Pepin, 1984	2.34	19.3	0.12	2177
Wiens et al., 1986	15.3	14.1	1.08	2075
Wiens, 1988	5.2	14.0	0.37	1660
Zagami				
A, Marti et al., 1995	---	38.7	---	1515
B, Marti et al., 1995	---	34.1	---	1500
Mars, Viking			0.15-1.0	~3000
Earth			0.52	296

Table 5. Martian meteorite cosmogenic gas concentrations (10^{-9} cm^3 STP/g) and exposure ages. Production rates were calculated from Eugster et al. (1997). Age uncertainties reflect only the 1-sigma variations in average gas concentrations and not the uncertainty in production rates.

Meteorite	/ Source	Wt. mg.	^{3}He	^{21}Ne	^{38}Ar	^{21}Ne/^{22}Ne
			x10^{-9} cm^3 STP/g			
ALH84001						
,113	(1)	43.4	208	39.0	4.44	0.829
,114-1	(1)	25.5	213	39.5	4.43	0.845
,114-2	(1)	36.2	233	36.2	4.45	0.844
#1	(2)	19.5	254	39.5	4.45	0.830
#2	(2)	43.2	256	39.1	5.13	0.834
#1	(7)	513	249	40.2	4.28	0.839
#2	(7)	447	248	35.1	4.81	0.853
,28	(11)	18.1	234	40.4	5.68	0.826
Average			237	38.6	4.71	0.837
(1σ)			±18	±1.9	±0.48	
Prod. Rate			16.3	2.69	0.371	
Exposure Age, Myr			14.5	14.4	12.7	
(1σ)			±1.2	±0.7	±1.3	
QUE94201						
,28	(1)	70.5	27.8	4.29	2.82	0.778
,31	(1)	37.2	25.9	4.05	2.88	0.757
,23#1	(2)	21.6	34.3	4.25	4.53	0.762
,23#2	(2)	30.1	33.8	4.29	3.72	0.756
bulk	(4)	23.7	30.	9.2*	4.4	0.76
,18	(5)	96	35.7	5.4	4.1	n.r.
Average		--	31.3	4.45	3.74	0.763
(1σ)			±3.9	±0.54	±0.75	
Prod. Rate			16.0	1.30	1.49	
Exposure Age, Myr			2.0	3.4	2.5	
(1σ)			±0.2	±0.4	±0.5	
Shergotty						
#A	(1)	66.4	41.6	5.24	3.12	0.79
#B	(1)	17.6	36.1	5.14	n.r.	0.78
bulk	(3)	100.9	40.8	5.94	3.88	0.79
KP3	(8)	153	45.8	5.71	3.06	0.78
S3/4	(8)	658	37.8	5.20	2.90	0.78
,8	(9)	43.8	38.0	4.53	2.63	0.78
,21	(9)	81.0	36.8	4.96	2.53	0.75
#817	(10)	??	52*	5.8	4.0	0.67*
Average			39.6	5.30	3.16	0.779
(1σ)			±3.4	±0.47	±0.57	
Prod. Rate			16.0	1.61	1.36	
Exposure Age, Myr			2.5	3.3	2.3	
(1σ)			±0.2	±0.3	±0.4	
Y-793605						
,71	(1)	25.3	64.6	10.1	1.76	0.830
#1	(3)	20.8	78.0	11.3	2.26	0.826
#2	(3)	20.5	73.9	10.5	2.59	0.806
#1	(6)	17.9	89.1	12.6	2.09	0.814
#2	(6)	51.0	83.5	11.2	1.76	0.818
Average			77.8	11.1	2.09	0.819
(1σ)			±9.3	±1.0	±0.35	
Prod. Rate			16.0	2.13	0.43	
Exposure Age, Myr			4.9	5.2	4.8**	
(1σ)			±0.6	±0.5	±0.8	

* These analyses were not included in averages; n.r.= not reported ** ^{38}Ar age for Y793605 has been corrected for shielding (see text)..

(1) this work; (2) Eugster et al., 1997a; (3) Eugster et al., 1997b; (4) Swindle et al., 1996; (5) Dreibus et al., 1996; (6) Nagao et al., 1997; (7) Miura et al., 1995; (8) Ott, 1988; (9) Becker and Pepin, GCA 1986; (10)Heymann et al; 1968; (11) Swindle et al., 1995.

Figure Captions

Figure 1. Neon 3-isotope plot for stepwise temperature extractions of impact glass from Martian meteorites. Data are those in Table 1 and those reported by Swindle et al. (1986), Wiens et al. (1986), and Wiens (1988). Extrapolation of the Y793605,71 data to ^{21}Ne/^{22}Ne =0.029 (solid line) suggest trapped ^{20}Ne/^{22}Ne of ~7.0. Most other data suggest considerably higher ^{20}Ne/^{22}Ne.

Figure 2. Relation between trapped ^{40}Ar/^{36}Ar and ^{129}Xe/^{132}Xe in Martian meteorite impact glasses. The composition for the earth and two possible compositions for the Martian atmosphere are also indicated. The dashed and solid lines represent two component mixtures between a Martian composition having ^{40}Ar/^{36}Ar $\cong$1900 and ^{129}Xe/^{132}Xe =2.6 and the earth or the Chassigny Martian meteorite, respectively.

Figure 3. Isotopic composition of Kr in Martian meteorite glasses normalized to mass 84 and to the composition of solar wind Kr (Pepin et al., 1995). Two extractions each (1000°C and 1550°C) are shown for samples EET79001,8 and EET79001,104. One extraction releasing the largest amount of Kr is shown for each of the Shergotty-B and Y793605,71 samples and for analyses of EET79001,27 reported by Swindle et al. (1986) and Becker and Pepin (1984). Analytical uncertainties are indicated for each isotopic ratio.

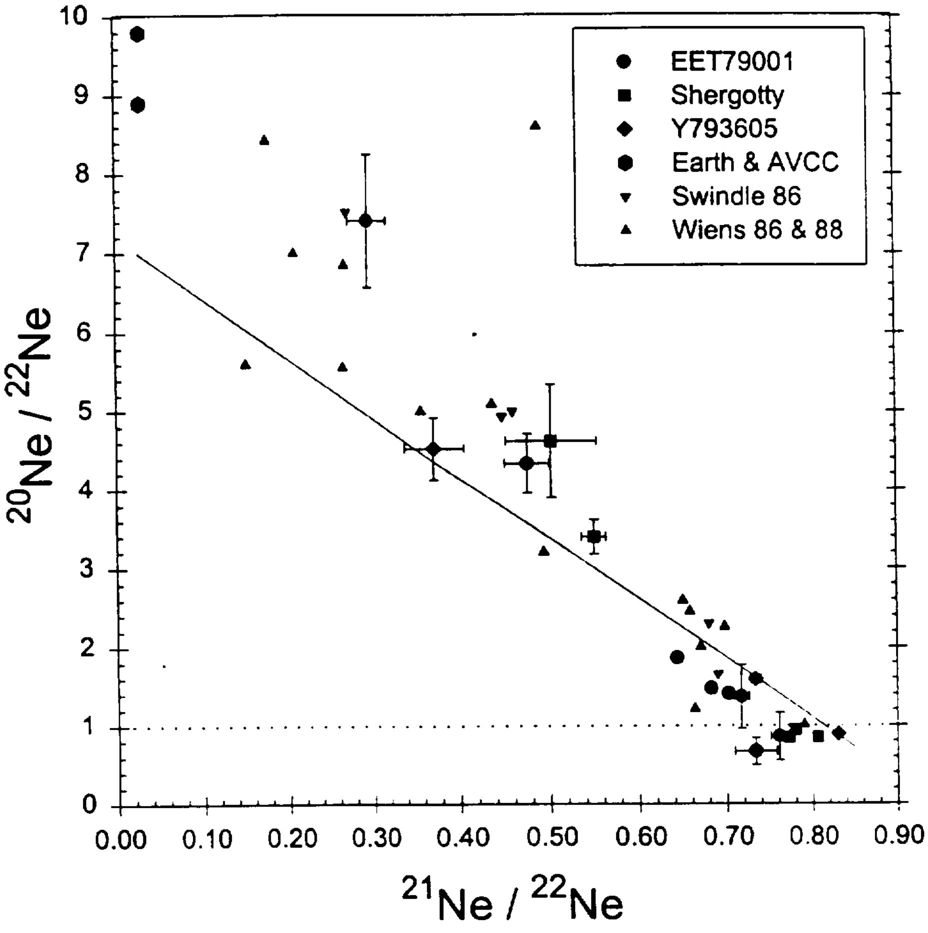
Figure 4. Isotopic composition of Kr in Martian meteorite glasses, the earth's atmosphere, average carbonaceous chondrites (AVCC) and Chassigny, all normalized to mass 84 and to the composition of solar wind Kr. The isotopic composition of Kr in the Martian atmosphere is defined by both the average of six preferred analyses from Figure 3 and by the 1550°C extraction of sample EET79001,8. The Martian composition previously estimated by Pepin (1991) is also shown.

Figure 5. Isotopic composition of Xe in EET79001 impact glasses normalized to mass 132 and to the composition of Martian atmospheric Xe derived from glass inclusion EET79001,27 by Swindle et al. (1986). Compositions shown are an average of four temperature extractions of EET79001,8 and ,104, the 1550°C extraction of EET79001,8, and the 1600°C extraction measured by Swindle et al. (1986). The composition of Xe in Chassigny (Ott, 1988) is also shown. Analytical uncertainties are indicated for each isotopic ratio.

Figure 6. Relationship of trapped ^{36}Ar, ^{84}Kr, and ^{132}Xe in Martian meteorite impact glasses and in several bulk (non-glass) analyses of other Martian meteorites. Compositions are indicated for Chassigny (Ott, 1988), the earth, analyses of the Martian atmosphere made by Viking (Owen et al., 1977), a previous derivation of atmospheric composition made from EET79001,27 data by Pepin (1991), and the composition of the Martian atmosphere derived from an extensive data set on impact glasses by Bogard and Garrison (1998).

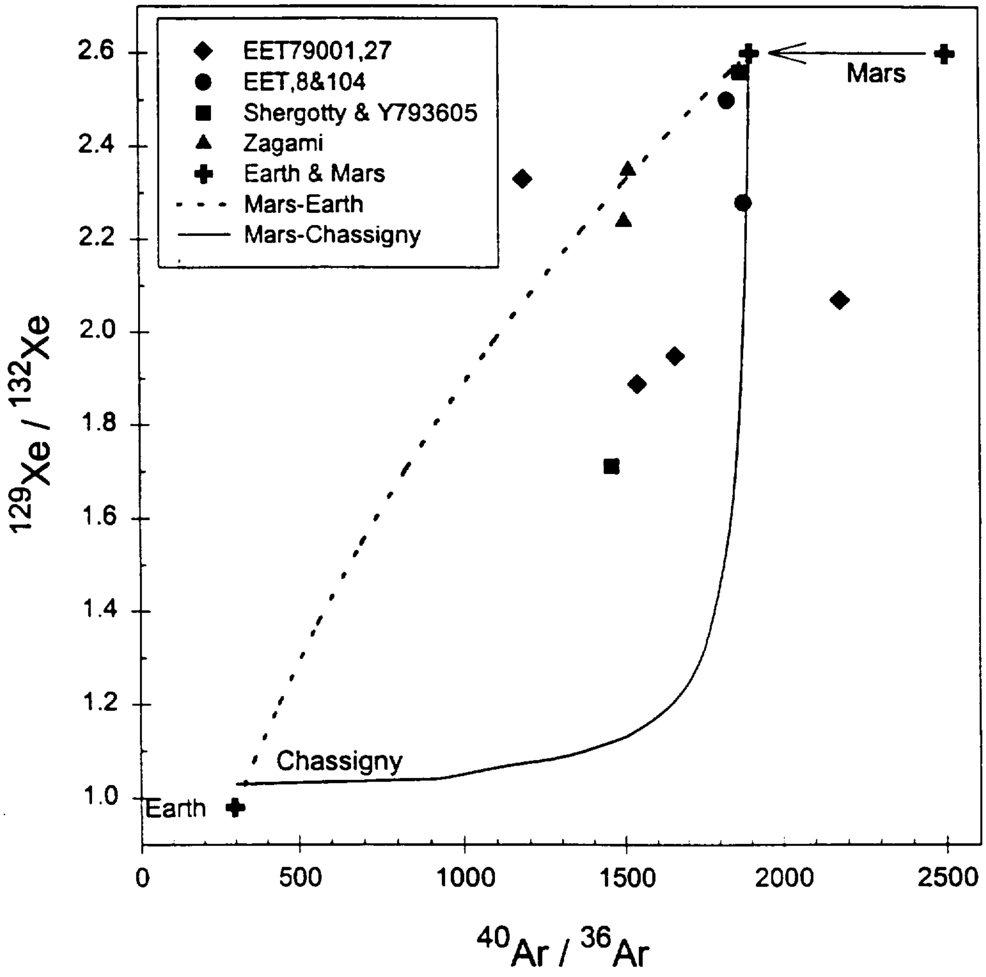
Figure 7. Neon 3-isotope correlation plot for those temperature extractions in Table 1 which give ^{20}Ne/^{22}Ne <2.0 and are dominated by cosmogenic Ne. The dashed line indicates a mixing trend between cosmogenic Ne with ^{21}Ne/^{22}Ne =0.76 and a trapped component with a Ne composition that of the earth's atmosphere. Analytical uncertainties are either indicated or are smaller than the symbol.

Fig. 1



10
9
8
7
6
5
4
3
2
1
0
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
$^{20}Ne / ^{22}Ne$
$^{21}Ne / ^{22}Ne$
● EET79001
■ Shergotty
◆ Y793605
⬢ Earth & AVCC
▼ Swindle 86
▲ Wiens 86 & 88

Fig. 2



EET79001,27
EET,8&104
Shergotty & Y793605
Zagami
Earth & Mars
Mars-Earth
Mars-Chassigny
Mars
Chassigny
Earth
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
500
1000
1500
2000
2500
$^{129}Xe / ^{132}Xe$
$^{40}Ar / ^{36}Ar$

Fig. 3

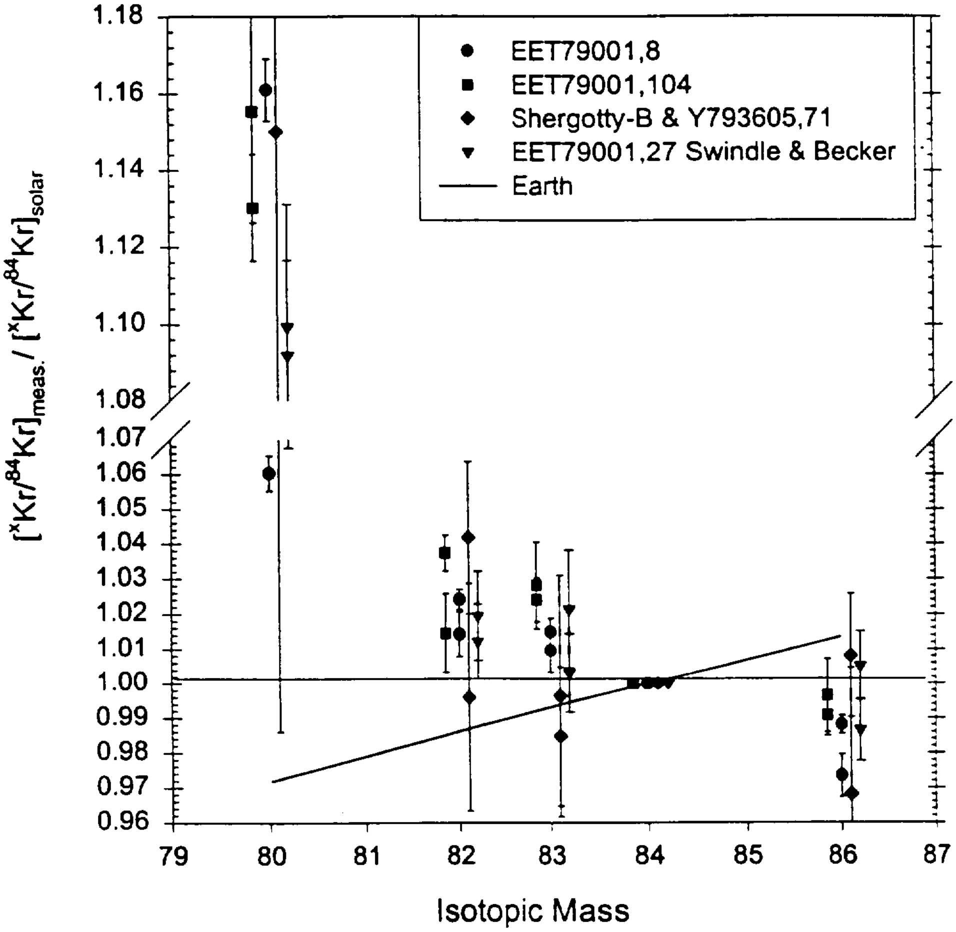
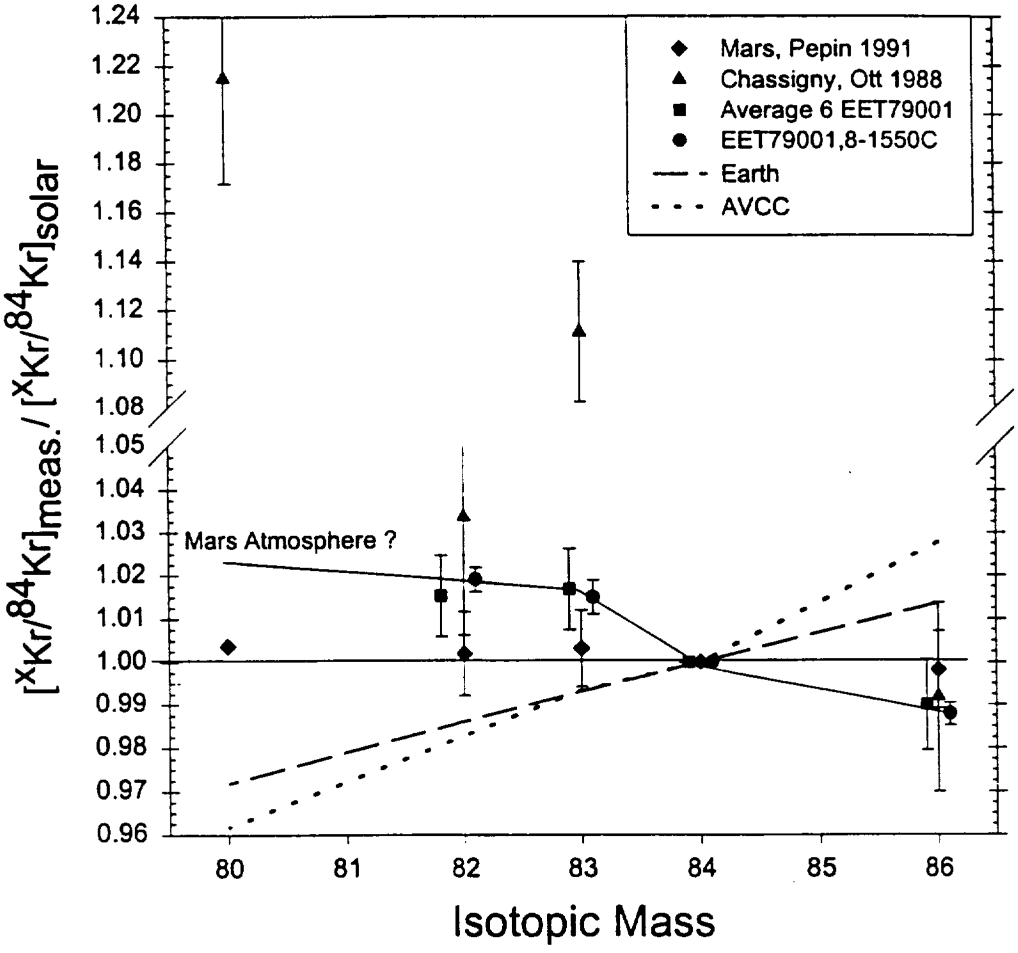
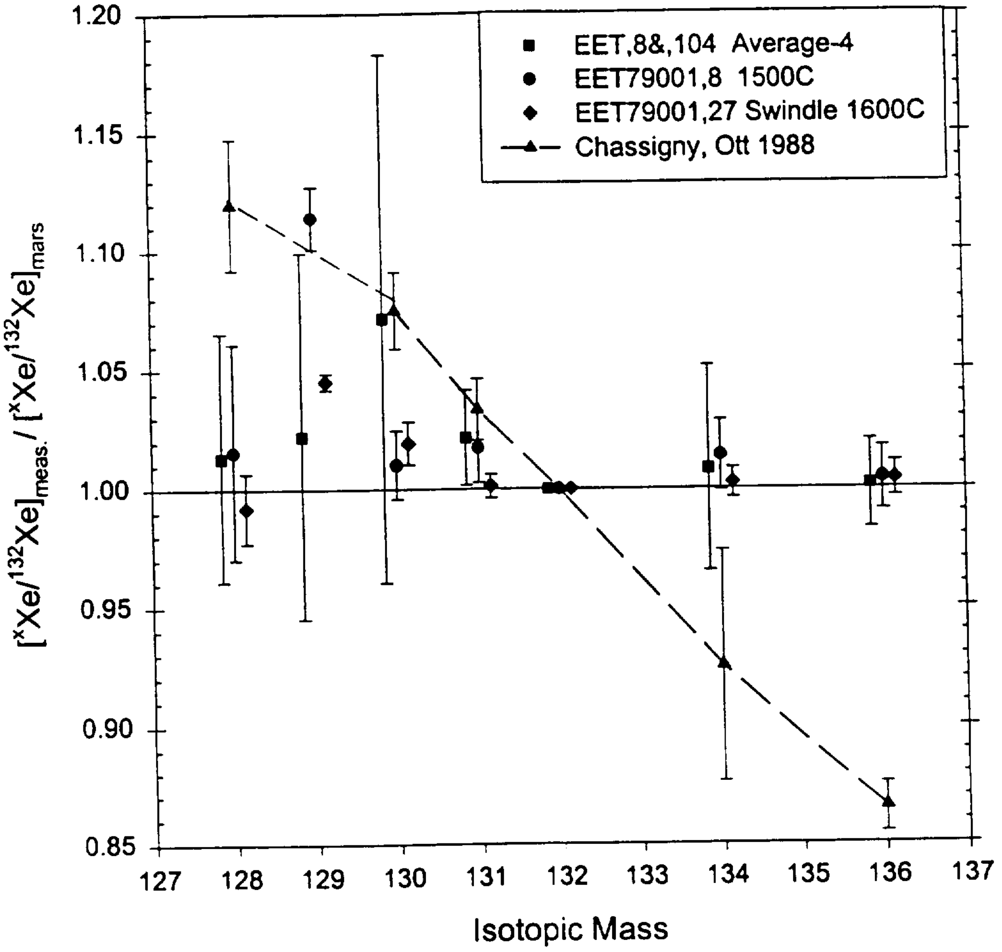

1.18
1.16
1.14
1.12
1.10
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.96
79
80
81
82
83
84
85
86
87
Isotopic Mass
$[^xKr/^{84}Kr]_{meas.}/[^xKr/^{84}Kr]_{solar}$
● EET79001,8
■ EET79001,104
◆ Shergotty-B & Y793605,71
▼ EET79001,27 Swindle & Becker
— Earth

Fig. 4



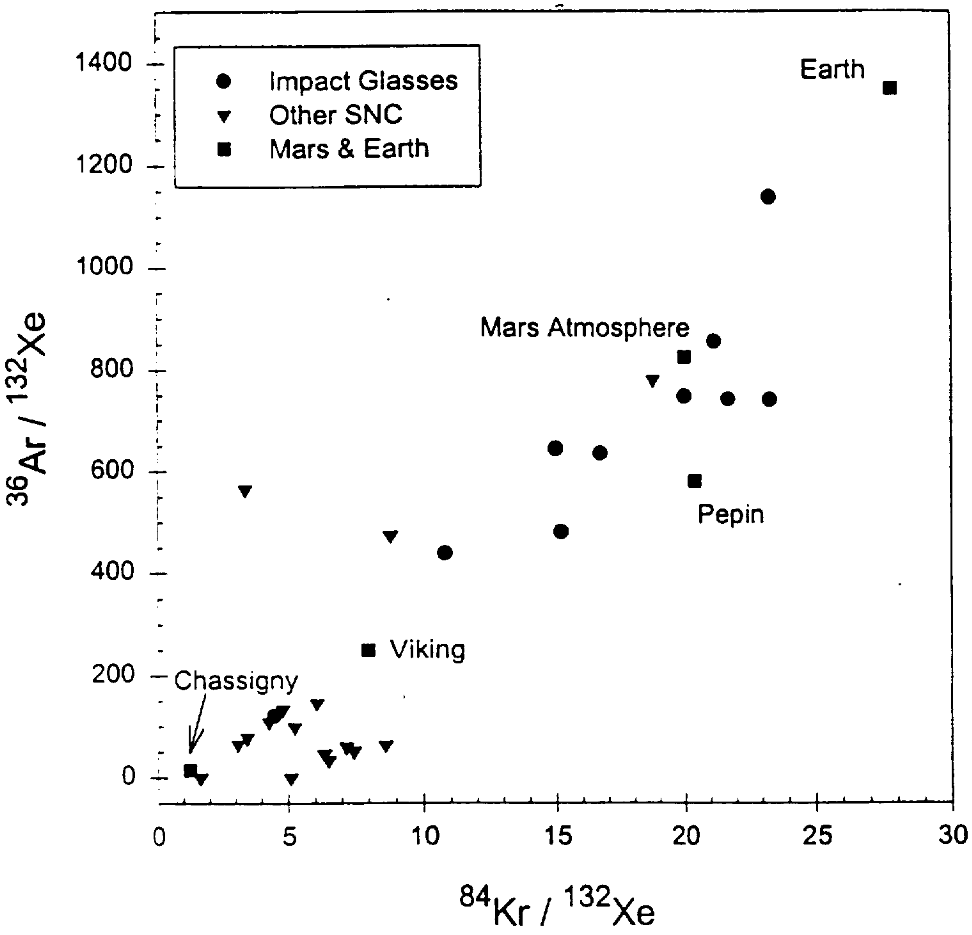
Mars, Pepin 1991
Chassigny, Ott 1988
Average 6 EET79001
EET79001,8-1550C
Earth
AVCC
Mars Atmosphere ?
1.24
1.22
1.20
1.18
1.16
1.14
1.12
1.10
1.08
1.05
1.04
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.96
80
81
82
83
84
85
86
Isotopic Mass
[^xKr/^84Kr]meas. / [^xKr/^84Kr]solar

Fig. 5



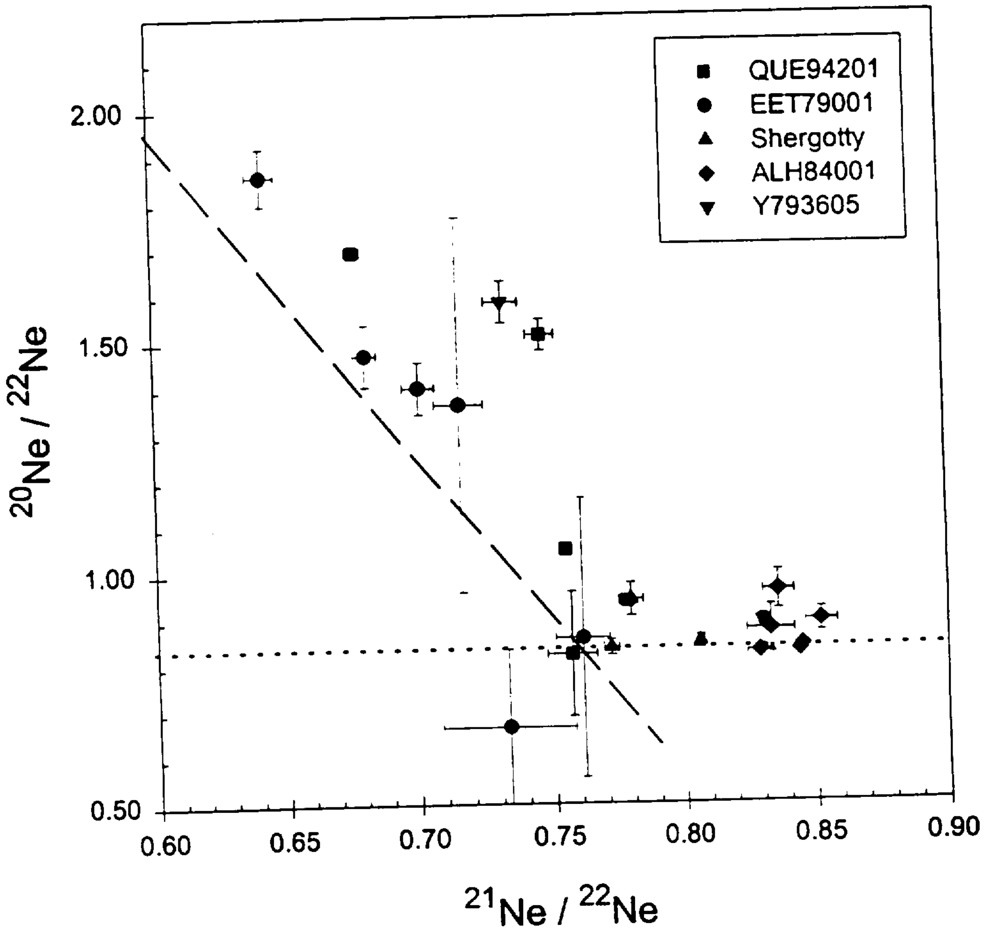
■ EET,8&,104 Average-4
● EET79001,8 1500C
◆ EET79001,27 Swindle 1600C
—▲— Chassigny, Ott 1988
$[^{x}Xe/^{132}Xe]_{meas.} / [^{x}Xe/^{132}Xe]_{mars}$
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
127
128
129
130
131
132
133
134
135
136
137
Isotopic Mass

Fig. 6



● Impact Glasses
▼ Other SNC
■ Mars & Earth
Earth
Mars Atmosphere
Pepin
Viking
Chassigny
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
$^{36}Ar / ^{132}Xe$
$^{84}Kr / ^{132}Xe$

Fig. 7



QUE94201
EET79001
Shergotty
ALH84001
Y793605
2.00
1.50
1.00
0.50
0.60
0.65
0.70
0.75
0.80
0.85
0.90
^{20}Ne / ^{22}Ne
^{21}Ne / ^{22}Ne