Krypton and xenon in nakhlite mineral separates

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ABSTRACT

Mineral separates of the martian nakhlite meteorites Nakhla and Governador Valadares were analyzed for Kr and Xe content. We found that the mesostasis and the major minerals were the predominant carrier of the elevated (atmospheric) ^{129}Xe in Nakhla. This result indicates that the elevated ^{129}Xe likely did not arise due to aqueous fractionation. Shock implantation of gas that had previously been fractionated either by adsorption or by trapping of the atmosphere into clathrates in the polar caps remain the most plausible theories to explain the elevated ^{129}Xe/^{132}Xe ratios in the nakhlites and ALH84001.

We also report whole rock analyses of Governador Valadares, Nakhla and Lafayette. The noble gases in Governador Valadares are very similar to those in the more commonly studied Nakhla and Lafayette.

1. INTRODUCTION

The SNC meteorites (shergottites, nakhlites, Chassigny, and ALH84001) are widely believed to have come from Mars. The strongest evidence to support this is from glass inclusions in the basaltic shergottite EETA79001 (lithology C). These inclusions contain noble gases with the same high $^{129}Xe/^{132}Xe$ determined in situ by the Viking mass spectrometer.

Recent noble gas studies of the SNC meteorites have focused on determining whether the observed isotopic and elemental abundances in the shergottites and nakhlites can be explained as a simple mixture of the gases found in Chassigny (presumably mantle-derived) and the EETA 79001 glass (martian atmosphere). On a plot of $^{129}Xe/^{132}Xe$ vs. $^{84}Kr/^{132}Xe$ (Fig. 1) any simple mixture of those two components would fall on a straight line between them. The shergottites fit well on this mixing line (Ott and Begemann, 1985), indicating that their gases are likely a combination of these two sources. The nakhlite data, however, plot above the mixing line, having a higher $^{129}Xe/^{132}Xe$ ratio than shergottites with the same $^{84}Kr/^{132}Xe$ ratio would. If the gases in the nakhlites contain the same two components as do the shergottites, the atmospheric component must be strongly fractionated elementally since the $^{84}Kr/^{132}Xe$ ratio is about five times lower.

This situation begs the question of the location of the fractionated component in the nakhlites. Ott et al. (1988) etched a piece of Nakhla with 6 N HCl and found that 90% of the radiogenic ^{129}Xe was removed. The etching process also removed ~15% of the mass of the meteorite, mostly olivine. Therefore they suggested that olivine might be the location of the fractionated gas.

Drake et al. (1994) instead proposed that the carrier of the fractionated component was iddingsite, a liquid-water-derived weathering product found in the nakhlites (Treiman et al., 1993; Treiman and Lindstrom, 1997). Iddingsite is composed of smectites, hematite, ferrihydrite, Ca carbonate and Ca sulfate, and its formation requires the presence of liquid water at temperatures of <50°C to 150°C (Gooding et al., 1991). To support their hypothesis, Drake et al. (1994) noted that the leaching process of Ott et al. (1988) would have removed iddingsite as well as the olivine, thereby accounting for the large drop in radiogenic ^{129}Xe after leaching. Furthermore, Drake et al. (1994) noted that all of the nakhlites have a high ^{129}Xe/^{132}Xe ratio and they all have iddingsite, whereas the shergottites and Chassigny have neither. This hypothesis would allow for the possibility that the differing solubility of Kr and Xe in liquid H_2O caused a fractionation of the martian atmosphere into the iddingsite. Bogard and Garrison (1998) suggested a similar scenario.

Because the idea that the xenon may have been fractionated by water was so interesting, Swindle et al. (2000) analyzed the iddingsite in Lafayette for noble gas content. Lafayette has the most abundant iddingsite of any of the nakhlites and individual pieces of iddingsite could be separated from the whole rock. Kr and Xe from a single sample was analyzed, and it did indeed have a high ^{129}Xe /^{132}Xe ratio (Fig. 1). Several other iddingsite samples were used for K-Ar age determinations, which verified that the iddingsite formed on Mars, and suggested ages of up to ~600 Ma for its formation.

There are many problems with the idea that the fractionation may have occurred by liquid water and is thus incorporated primarily in the iddingsite. (1) While the data of Swindle et al. (2000) are consistent with that hypothesis, the uncertainties in abundances were large enough that the iddingsite could actually be a minor carrier. (2) There does not appear to be a unique fractionated atmosphere composition, as the nakhlite data is quite scattered (Drake et al., 1994). (3) The high ^{129}Xe /^{132}Xe component is released at temperatures higher than 800°C. It is not likely that any of the minerals that compose iddingsite would be able to withstand such high temperatures, and it would be expected that the gas would be released much earlier (Drake et al., 1994). (4) ALH84001 also contains an elevated ^{129}Xe /^{132}Xe ratio but contains no iddingsite (Swindle et al., 2000; Miura et al., 1995; Murty and Mohapatra, 1997; Drake et al., 1994). (5) An additional problem is that Nakhla has a higher ^{129}Xe /^{132}Xe ratio than Lafayette despite having three times less iddingsite (Gilmour et al., 1999).

Gilmour et al. (1999) noted these problems and measured Xe in mineral separates of Nakhla with the intent of finding the site of the fractionated xenon. In their data, pyroxene and olivine separates had about the concentration found in the bulk meteorite and elevated concentrations of atmosphere-derived xenon were found in the mesostasis (intercumulus material consisting of plagioclase, pigeonite, alkali fledspar, Ti-magenetite, ilmenite, pyrite, silica-rich glass, and minor phases (Treiman et al., 1993).) Gilmour et al. suggested that the gas was incorporated into the minerals as they crystallized. Other suggestions include (1) adsorption followed by shock incorporation (Gilmour et al., 2000); (2) changing atmospheric Kr/Xe ratios as a result of preferential incorporation of Xe into polar clathrates under certain climate conditions (Musselwhite and Swindle, 2002); and (3) recent addition of a cometary component to the gas found in the nakhlites (Owen and Bar-Nun, 1995).

It is the intent of our work to add another piece of data to this picture. Mineral separates of Nakhla were analyzed for xenon and krypton content. It was originally hoped that K-Ar analysis of one or more pieces of iddingsite from Nakhla would be possible, as had been done for Lafayette (Swindle et al., 2000). This was not possible, since no individual pieces of iddingsite large enough for analysis could be seen. Instead, iddingsite-coated olivine was separated from pure olivine and was analyzed separately. We also analyzed the pyroxene and mesostasis grains from Nakhla. In the study of mineral separates of Nakhla by Gilmour et al. (1999), iddingsite was not tested, nor was krypton data obtained. Our experiment was intended to address these two issues.

Although the major topic of this paper is to report data on the Nakhla mineral separates and some mineral separates from Governador Valadares, we will also report whole rock noble gas data of Nakhla, Lafayette, and Governador Valadares that were previously reported only in abstract form (Swindle et al., 1987; Swindle et al., 1989). For Governador Valadares, these data represent the most detailed noble gas data available to date.

2. PROCEDURES

A small piece of Nakhla was acquired by one of us (A.H.T.). Because the sample was not friable, the sample was crushed with a mortar and pestle, a choice that had ramifications that will be seen later. From the crushed sample, grains of pyroxene (green), olivine (orange/brown), and mesostasis (white) were hand picked. No iddingsite was available as isolated pieces, but was found only as a coating on olivine grains. Therefore, the olivine grains were separated into two categories: pure olivine grains, if they had no brown iddingsite coating, and iddingsite-rich grains, if the grains had an abundance of the brown iddingsite coating. Because of the abundance of pyroxene, a large number of pure pyroxene grains were collected for a large pyroxene sample, and a smaller pyroxene sample was also made for comparison with the smaller amounts of olivine obtained. Mesostasis was also evident in the sample in extremely small quantities, and it was impossible to completely separate the mesostasis from the pyroxene. Therefore, our sample of mesostasis is mesostasis-rich, with a small amount of pyroxene. Again, note that the lack of separable iddingsite made it impossible to perform K-Ar studies such as had been done for Lafayette (Swindle et al., 2000).

Each sample was weighed and wrapped in tin (Sn) foil for loading into the mass spectrometer. The samples were analyzed in a VG5400 noble gas mass spectrometer at the Lunar and Planetary Laboratory, University of Arizona. The gases were extracted with a resistance-heated double-vacuum Ta furnace and purified by exposure to SAES getters in an all-metal extraction line. Mass discrimination and sensitivity were determined by measurements of aliquots of air. Our results have been corrected for blanks (1-2 x 10^{-14}cm^{3}STP/gm for ^{132}Xe and 7.5-17 x 10^{-14}cm^{3}STP/gm for ^{84}Kr, with the variation largely from one set of runs to another, rather than being temperature dependent). Krypton and xenon were analyzed for each sample. Gases were released in two temperature steps, at 500^{0}C and 1500^{0}C, except for the one larger pyroxene separate, where four temperature steps were made at 500ºC, 900ºC, 1200ºC, and 1500ºC. The low-temperature data were isotopically indistinguishable from terrestrial atmosphere. The data are tabulated in Table 1.

The nakhlite Governador Valadares was also analyzed. Three samples were handpicked from crushed material obtained from L. E. Nyquist: pyroxene, olivine, and mesostasis. Each sample was analyzed for krypton and xenon as described for Nakhla. Gases were released at two temperature steps, at 500^{0}C and 1500^{0}C. The data are tabulated in Table 2.

One unirradiated whole-rock sample each of Nakhla, Lafayette and Governador Valadares was analyzed in the noble gas laboratory at Washington University (Hohenberg, 1980), using procedures essentially identical to those of Swindle et al. (Swindle et al., 1986).

3. RESULTS

3.1 Mineral Separates

The data for the nakhlite mineral separates are reported in Tables 1 and 2. Fig. 1 is a plot of ^{129}Xe /^{132}Xe vs. ^{84}Kr/^{132}Xe and compares our data with other data from the literature. The composition of Earth's atmosphere has also been plotted for comparison. (The data and sources for all points included in Fig. 1 are reported in Table 3.) This plot is similar to the plot first shown by Ott (1988) and contains data on various SNC meteorites, particularly nakhlites. The martian atmosphere is plotted using the data from EETA 79001 (Bogard and Garrison, 1998). The actual martian atmosphere as measured by Viking is too imprecise to use for comparison purposes. The shergottites generally plot along a line between EETA 79001 and Chassigny, indicating that their gas is likely a mixture of the sources of gas for those two meteorites.

Previous whole rock studies of the nakhlites show that they do not lie along this mixing line. Instead they are all enriched in ^{129}Xe compared to shergottites with the same ^{84}Kr/^{132}Xe ratio. We expected our Nakhla data to lie along the same line as the other nakhlites. However, our data showed a significantly greater amount of ^{84}Kr than the other nakhlites, and as a result are shifted toward the location of the Earth's atmosphere in Fig. 1. Also, a line drawn from Chassigny through our mineral separates gives a wide range of values, as opposed to previous studies, where such a line would rise more steeply than the mixing line and be better constrained. Thus it appears that our sample had some terrestrial atmosphere incorporated into it. It is likely that atmospheric krypton and xenon were incorporated during the process of crushing our sample in order to pick out the various minerals (Niemeyer and Leich, 1976; Niedermann and Eugster, 1992). Previous nakhlite studies did not have this problem because their samples were more friable (Swindle et al., 2000; Gilmour et al., 1999). For the ^{129}Xe /^{132}Xe vs. ^{84}Kr/^{132}Xe analysis to be better performed in the future, any crushing of the sample must take place in an atmosphere free of noble gas, such as in a nitrogen glove box.

Because of the contamination with Earth's atmosphere, we instead plot ^{129}Xe$_{xs}$ vs. ^{132}Xe (Fig. 2.) The ^{129}Xe$_{xs}$ is the "excess" atmospheric ^{129}Xe, as defined by Gilmour et al. (1999),

$$^{129}\mathrm{Xe}_{\mathrm{XS}} = [^{132}\mathrm{Xe}] * \{(^{129}\mathrm{Xe}/^{132}\mathrm{Xe}) - 1\},$$

where ^{129}Xe$_{xs}$ and ^{132}Xe are in units of 10^{-12} cm^3 STP g^{-1}. Our data show approximately the same range of ^{132}Xe as seen in the data of Gilmour et al. (1999). In Fig. 2, our data for mesostasis and pyroxene look very similar to those of Gilmour et al. (1999). Our sample of olivine with iddingsite plotted near the olivine samples of Gilmour et al. (1999). This suggests that the hypothesis of iddingsite as the carrier of the fractionated atmosphere is incorrect. If it had been correct, the iddingsite-rich sample of olivine should have plotted much higher than the others. Ironically, the olivine sample that had no iddingsite had the highest abundance of ^{129}Xe$_{xs}$, close to the mesostasis. This olivine may have included a gas-rich inclusion.

3.2 Whole-rock Samples

Detailed data for the whole-rock samples are given in Appendices A, B, and C. In Fig. 1, our Governador Valadares measurements fall in the area of other measurements of nakhlites. In addition, the amounts (both totals and amounts of ^{129}Xe$_{xs}$) are also similar, confirming that Kr and Xe signatures in these three meteorites are very similar. The ^{129}Xe/^{132}Xe ratio in Governador

Valadares reaches as high as 1.9 in the 1000^0C temperature step, higher than in Lafayette (~1.5), though not as high as in most whole rock samples of Nakhla (>2.0). The abundance of trapped Xe is also intermediate between Lafayette and Nakhla.

Our analyses were performed on samples a factor of five to 10 smaller than the largest whole-rock sample of Nakhla analyzed by Mathew and Marti (2002). Furthermore, since Governador Valadares and Lafayette both have less Xe (per gram) than does Nakhla, we were analyzing much smaller amounts of gas than Mathew and Marti (2002). Hence we were not able to identify some of the subtle features they identified. For Fig. 3, we have summed "low-temperature" and "high-temperature" data for each of our three samples, corrected those data for spallation, and plotted them on the same axes as Fig. 1 of Mathew and Marti (2002). We have also used the same, or similar, standard points for reference. In each case, the "low-temperature" point is the sum of the 800^0 and 1000^0C extractions – since the temperature refers to the heating coil, these probably represent sample temperatures of 500^0 to 800^0 C. The "high-temperature" points are summations of two higher-temperature points representing a second release peak (1300^0 and 1400^0 C for Governador Valadares, 1400^0 and 1600^0 C for Lafayette and 1400^0 and 1550^0 C for Nakhla). Our data are basically consistent with a mixture of martian atmosphere and terrestrial atmosphere. The high-temperature points are displaced to the high-^{136}Xe side of the mixing line, indicating a fission contribution. At low temperatures, there is a hint for Nakhla and Lafayette (both at a level just less than 2σ) that an extra component may be required, as suggested by the high-precision data on larger Nakhla samples produced by Mathew and Marti (2002). Their "Chass-E" (Mathew and Marti, 2001), believed to be an interior component best represented in Chassigny, is consistent with our data.

In the light gas measurements, the most interesting are the Ne and Ar data for Governador Valadares. These are dominated by cosmogenic noble gases (except for radiogenic ^{40}Ar), and are very similar to those of Bogard and Husain (1977). Our data are compared with those of Bogard and Husain (1977) and Marty et al. (2001) in Table 4. Within the uncertainties of the data, it appears that the ages of these three nakhlites, as well as the recently found NWA 817 (Marty et al., 2001) are identical, suggesting that they all come from a single impact on Mars.

4. DISCUSSION

There are currently several different theories as to why the nakhlites and ALH84001 do not lie on the same mixing line as do the shergottites in Fig. 1. Models invoking liquid water (Drake et al., 1994; Swindle, 2002; Bogard and Garrison, 1998) appear to be ruled out, based on data presented here and that of Gilmour et al. (1999). We found that the high ^{129}Xe was concentrated largely in the mesostasis, not in the iddingsite. If the ratio had arisen due to interaction with liquid water, we would have expected to see that ratio most strongly represented in the liquid water derived weathering product, the iddingsite. This additional evidence can be combined with the problems pointed out earlier (the lack of aqueous alteration in ALH84001, the higher abundance of the atmospheric component in Nakhla than in Lafayette, and the high release temperature) to further suggest that the iddingsite is not the carrier.

Gilmour and colleagues have published several papers about the source of the fractionated component for both Nakhla and ALH84001. First, Gilmour et al. (1998) proposed that the gases in ALH84001 were trapped 4 Ga ago before the martian atmospheric ratios had evolved to their present values. They suggested that the gases were trapped in ALH84001 by a combination of low temperature adsorption followed by shock implantation. Fractionation by adsorption is well documented (Ozima and Podosek, 1983) as is shock implantation (Pepin et al., 1964). They argued that this mechanism takes into consideration the following three issues. (1) The concentration of Xe in ALH84001 is four times higher than in any other martian meteorite. (2) ALH84001 shows elemental fractionation favoring the heavy noble gases. (3) The location of the trapped gas is in the major mineral, orthopyroxene. They further pointed out that aqueous fractionation is prohibited because there is no evidence for aqueous processes occurring in ALH84001.

Gilmour et al. (1999) have also discussed the Xe isotopes in Nakhla. They found that Xe was concentrated in the Nakhla mesostasis, as our results confirm. They also found the atmospheric xenon must have been located close to the grain surfaces since it was removed on washing (Gilmour et al., 2000; Ott et al., 1988). Gilmour et al. first suggested that the Xe was incorporated from soil outgassing as the nakhlites were forming, but they later argued that gas adsorbed onto the rocks was incorporated into the rocks in a shock event.

However, if the gas is incorporated into the rocks by some mechanism that is as common as adsorption followed by shock implantation, why do we only observe the signature in the nakhlites and ALH84001? In fact, if this were the mechanism, wouldn't we expect to see an even greater signature in the shergottites? Some are vesicular basalts and therefore have more surface area on which one would expect atmospheric gas to be adsorbed. Here we present three potential solutions to this problem.

The first possibility is that perhaps this process does work on the shergottites, and it is simply that they contain sufficient gas to hide the signature. This is not the case though, as can be seen in Fig. 4. $^{129}Xe_{xs}/^{132}Xe$ vs. $^{84}Kr/^{132}Xe$ is plotted only for shergottites and nakhlites with comparable amounts of gas released (^{132}Xe concentrations from about 4 to 15 (10^{-12}cm^{3}STP/gm)). It can be clearly seen that even when the samples contain approximately the same amount of gas the nakhlites still lie distinctly above the mixing line, having more ^{129}Xe than the corresponding shergottites. There must be some other process going on that would prevent the shergottites from incorporating the excess ^{129}Xe.

One way this could happen is that the temperature could have been quite different between the two shock events. Adsorption coefficients double when the temperature is dropped from just 0°C to –20°C (Gilmour et al., 1998). On Mars, there are a number of situations that could cause huge variations in temperature. Differing latitude, season, and time of day all will affect the temperature, which can range from about 150 K in the winter to >273 K in the summer. Differing altitude will also affect the temperature somewhat; however, it must be remembered that the atmospheric pressure will also be dropping readily with altitude, leaving less gas available to be adsorbed. Therefore it is possible that just because the shock event occurred at a different time of day or year, excess ^{129}Xe could have been incorporated into the nakhlites and not the shergottites.

The third possibility is that the atmospheric composition was actually different when the shergottites were shocked. Musselwhite and Swindle (2001) suggest that variations in the Kr/Xe ratio correlate with ejection age of the meteorite. Kr and Xe could be trapped in CO_2 clathrate at the poles. During variations in martian obliquity (and hence average global temperature), the clathrates may melt somewhat, releasing Kr and Xe into the atmosphere, changing the Kr/Xe ratio. Thus, the nakhlite component would actually be a representation of the noble gas ratios at the time the rock was ejected from Mars.

There are at least two areas which could be investigated to aid in resolution of this question. One is from further multi-element studies of mineral separates. For example, Schwenzer et al. (2002) recently found that Nakhla olivine has higher amounts of trapped heavy noble gases than does the pyroxene, but it has only about half of the trapped ^{22}Ne. This indicated that the noble gases in Nakhla's olivine are more highly fractionated, suggesting that some fractionation on incorporation is involved. Another potential avenue for progress is from studies of shock implantation of adsorbed gas at low temperatures.

5. CONCLUSIONS

Our data support the observation of Gilmour et al. (1999) that the mesostasis and major minerals, rather than the iddingsite, carry the fractionated martian atmosphere in Nakhla. This will require a different fractionation method than fractionation by liquid water into the iddingsite, as had been suggested by Drake et al. (1994), Bogard and Garrison (1998), and Swindle et al. (2000). We think that shock implantation of gas that had previously been fractionated either by adsorption (Gilmour et al., 1998; Gilmour et al., 2000) or by trapping of the atmosphere into clathrates in the polar caps (Musselwhite et al., 2000; Musselwhite and Swindle, 2002) remain the most plausible theories to explain the elevated ^{129}Xe/^{132}Xe ratios in the nakhlites and ALH84001.

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Appendix A
Governador Valadares whole rock noble gas data
Mass = 0.0782 g

Temp (^{o}C)	[^{20}Ne]	^{21}Ne/^{20}Ne	^{22}Ne/^{20}Ne	[^{36}Ar]	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar
600	18	0.0245 (14)	0.46 (33)	10	0.211 (94)	384 (92)
800	189	0.48 (25)	0.585 (29)	187	0.745 (17)	5950 (110)
1000	897	0.842 (17)	0.991 (14)	302	1.328 (53)	18290 (620)
1100	1224	1.02 (14)	1.226 (15)	154	0.919 (23)	8950 (200)
1200	3175	1.0392 (85)	1.2168 (94)	250	1.014 (14)	3592 (46)
1275	447	1.078 (27)	1.194 (23)	82	1.535 (56)	436 (13)
1300	1789	1.047 (15)	1.242 (11)	380	1.319 (15)	1035 (10)
1400	5626	1.0479 (46)	1.2253 (55)	6434	1.5156 (66)	13.571 (93)
1500	2043	1.061 (12)	1.2686 (97)	3539	1.5248 (78)	1.44 (16)
1600	455	0.979 (24)	1.105 (33)	476	1.492 (16)	-0.4 (1.1)
1800	107	0.372 (21)	0.581 (38)	188	1.486 (29)	21.3 (2.7)
Total	16023	1.0183 (37)	1.1987 (37)	11929	1.4747 (46)	791 (16)

Temp (^{o}C)	[^{84}Kr]	^{78}Kr/^{84}Kr	^{80}Kr/^{84}Kr	^{82}Kr/^{84}Kr	^{83}Kr/^{84}Kr	^{86}Kr/^{84}Kr
600	2.284	0.030 (20)	0.041 (28)	0.158 (37)	0.241 (62)	0.292 (74)
800	5.957	0.031 (13)	0.113 (22)	0.264 (22)	0.257 (21)	0.345 (43)
1000	4.306	0.039 (14)	0.166 (37)	0.251 (33)	0.354 (60)	0.254 (57)
1100	2.019	0.074 (26)	0.189 (53)	0.57 (11)	0.426 (88)	0.301 (73)
1200	1.915	0.086 (38)	0.283 (47)	0.532 (96)	0.71 (10)	0.14 (12)
1300	2.169	0.126 (32)	0.325 (83)	0.508 (67)	0.504 (88)	0.249 (45)
1400	2.170	0.118 (35)	0.364 (85)	0.64 (10)	0.70 (18)	0.214 (45)
1500	0.331	0.26 (16)	0.41 (23)	0.54 (32)	1.38 (69)	0.17 (23)
1800	0.406	0.151 (89)	0.02 (14)	-0.04 (26)	0.43 (30)	0.10 (43)
Total	21.478	0.068 (14)	0.197 (38)	0.371 (49)	0.429 (59)	0.265 (40)

Temp (^{o}C)	[^{132}Xe]	^{124}Xe/^{132}Xe	^{126}Xe/^{132}Xe	^{128}Xe/^{132}Xe	^{129}Xe/^{132}Xe	^{130}Xe/^{132}Xe
600	0.731	0.00414 (85)	0.00329 (80)	0.0715 (53)	0.991 (19)	0.1483 (75)
800	1.574	0.00404 (90)	0.00729 (90)	0.0841 (41)	1.248 (15)	0.1532 (33)
1000	2.012	0.0122 (11)	0.0217 (13)	0.1047 (31)	1.884 (16)	0.1707 (40)
1100	0.385	0.0671 (65)	0.1296 (69)	0.252 (12)	1.662 (37)	0.2811 (13)
1200	0.430	0.206 (11)	0.350 (15)	0.606 (20)	1.583 (42)	0.511 (18)
1275	0.051	0.260 (51)	0.58 (11)	0.98 (15)	1.51 (15)	0.72 (11)
1300	0.455	0.319 (12)	0.555 (19)	0.838 (25)	1.575 (30)	0.635 (19)
1400	0.513	0.1642 (79)	0.253 (11)	0.437 (19)	1.627 (33)	0.351 (12)
1500	0.074	0.094 (18)	0.124 (24)	0.228 (29)	1.68 (12)	0.190 (24)
Total	6.238	0.0639 (16)	0.1091 (25)	0.2290 (41)	1.535 (11)	0.2474 (31)

Temp (^{o}C)	^{131}Xe/^{132}Xe	^{134}Xe/^{132}Xe	^{136}Xe/^{132}Xe
600	0.797 (17)	0.3667 (91)	0.350 (10)
800	0.785 (11)	0.3773 (82)	0.3410 (78)
1000	0.820 (11)	0.3821 (68)	0.3382 (63)
1100	1.009 (28)	0.384 (12)	0.299 (11)
1200	1.499 (38)	0.298 (13)	0.233 (12)
1275	2.00 (24)	0.192 (55)	0.142 (46)
1300	1.874 (40)	0.242 (15)	0.1993 (92)
1400	1.262 (25)	0.351 (12)	0.2836 (13)
1500	0.939 (70)	0.464 (35)	0.331 (33)
Total	0.9918 (74)	0.3605 (39)	0.3147 (37)

<u>Notes</u>

*Numbers in parentheses indicate error in the last digits.

** Gas concentrations are in 10^{-12}cm^{3}STP/gm.

Appendix B
Nakhla whole rock noble gas data
Mass = 0.0879 g

Temp (^{o}C)	$[^{36}$Ar]	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar	$[^{132}$Xe]	^{124}Xe/^{132}Xe	^{126}Xe/^{132}Xe
800	478.8	0.320 (10)	628 (14)	5.902	0.00420 (29)	0.00427 (23)
1000	2660.4	0.6747 (90)	4241 (35)	2.218	0.00531 (50)	0.00625 (52)
1100	156.7	1.041 (45)	9730 (310)	0.501	0.0152 (18)	0.0253 (30)
1250	122.8	1.023 (43)	8270 (270)	0.988	0.0283 (16)	0.0507 (23)
1400	149.3	0.904 (31)	1663 (46)	1.582	0.0476 (20)	0.0940 (35)
1550	1248.4	1.411 (12)	99.20 (67)	1.332	0.1537 (33)	0.2518 (49)
1700	5998.5	1.4912 (86)	3.595 (32)	0.678	0.0449 (28)	0.0736 (40)
1850	9.7	0.08 (15)	65 (23)	0.097	0.0074 (47)	0.077 (44)
2000	11.7	0.37 (15)	116 (37)	0.075	0.0012 (38)	0.0032 (34)
Total	----	----	----	13.374	0.02868 (47)	0.04763 (72)

Temp (^{o}C)	^{128}Xe/^{132}Xe	^{129}Xe/^{132}Xe	^{130}Xe/^{132}Xe	^{131}Xe/^{132}Xe	^{134}Xe/^{132}Xe	^{136}Xe/^{132}Xe
800	0.1323 (17)	1.0836 (53)	0.1572 (14)	0.8050 (45)	0.3852 (25)	0.3273 (23)
1000	0.1567 (45)	1.227 (26)	0.1626 (45)	0.794 (14)	0.394 (11)	0.3233 (88)
1100	0.1231 (59)	2.158 (39)	0.1606 (79)	0.839 (12)	0.391 (12)	0.349 (11)
1250	0.1476 (35)	2.112 (22)	0.1984 (56)	0.876 (13)	0.3803 (69)	0.3232 (80)
1400	0.2053 (47)	2.045 (22)	0.2295 (45)	0.958 (13)	0.3667 (73)	0.3211 (53)
1550	0.4321 (66)	1.966 (15)	0.3687 (67)	1.273 (16)	0.3401 (70)	0.2860 (63)
1700	0.1657 (61)	1.986 (22)	0.1837 (67)	0.916 (16)	0.393 (11)	0.3349 (78)
1850	0.105 (11)	0.975 (39)	0.135 (16)	0.785 (37)	0.362 (25)	0.322 (29)
2000	0.104 (13)	0.969 (43)	0.168 (15)	0.821 (35)	0.389 (31)	0.292 (21)
Total	0.1770 (14)	1.4696 (63)	0.1921 (14)	0.8804 (41)	0.3802 (26)	0.3225 (22)

* Numbers in parentheses indicate error in the last digits.

** Gas concentrations are in 10^{-12}cm^{3}STP/gm.

Appendix C
Lafayette whole rock noble gas data
Mass = 0.0446 g

Temp (^{o}C)	$[^{36}$Ar]	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar	$[^{132}$Xe]	^{124}Xe/^{132}Xe	^{126}Xe/^{132}Xe
800	159.4	0.248 (22)	263 (11)	7.473	0.00315 (37)	0.00375 (29)
1000	103.1	0.511 (45)	2110 (150)	0.945	0.0049 (13)	0.0071 (17)
1200	264.4	0.687 (27)	6840 (200)	1.110	0.0104 (15)	0.0159 (17)
1400	293.5	0.684 (30)	5300 (150)	4.026	0.477 (71)	0.0218 (14)
1600	398.7	1.414 (29)	1032 (18)	6.387	0.03153 (98)	0.0468 (12)
1800	5048.3	1.4800 (89)	17.408 (95)	2.153	0.0434 (15)	0.0639 (25)
2000	70.6	0.331 (34)	173.6 (9.7)	0.501	0.0047 (12)	0.0061 (19)
Total	----	----	----	22.596	0.01755 (37)	0.02569 (51)

Temp (^{o}C)	^{128}Xe/^{132}Xe	^{129}Xe/^{132}Xe	^{130}Xe/^{132}Xe	^{131}Xe/^{132}Xe	^{134}Xe/^{132}Xe	^{136}Xe/^{132}Xe
800	0.0726 (18)	1.0023 (76)	0.1522 (16)	0.7909 (69)	0.3890 (51)	0.3237 (43)
1000	0.0794 (51)	1.222 (19)	0.1526 (67)	0.786 (17)	0.381 (10)	0.3190 (82)
1200	0.0943 (42)	1.598 (28)	0.1710 (67)	0.832 (17)	0.3867 (90)	0.3345 (89)
1400	0.0982 (27)	1.373 (12)	0.1659 (35)	0.8234 (92)	0.3983 (63)	0.3381 (46)
1600	0.1364 (19)	1.529 (14)	0.1905 (35)	0.8648 (80)	0.3797 (43)	0.3341 (38)
1800	0.1509 (47)	1.500 (17)	0.1915 (49)	0.911 (11)	0.3717 (86)	0.3271 (76)
2000	0.0756 (60)	1.052 (24)	0.1502 (76)	0.823 (19)	0.416 (16)	0.355 (12)
Total	0.1040 (11)	1.3043 (57)	0.1701 (14)	0.8316 (39)	0.3866 (26)	33.06 (22)

* Numbers in parentheses indicate error in the last digits.

** Gas concentrations are in 10^{-12}cm^{3}STP/gm.

Table 1: Nakhla mineral separates

	Mass (mg)	Temp (^{o}C)	^{132}Xe	^{129}Xe/^{132}Xe	±σ	^{129}Xe$_{xs}$	^{84}Kr	^{84}Kr/^{132}Xe
large pyroxene	28.781							
		500	606.88	0.97	0.02	---	643.52	1.06
		900	8.22	0.99	0.04	---	15.82	1.92
		1200	4.70	1.19	0.06	0.88	15.72	3.34
		1500	0.70	1.14	0.14	0.10	3.20	4.57
		Total	620.51	0.97	0.02	---	678.26	1.09
small pyroxene	6.062							
		500	255.79	0.99	0.01	---	1960.50	7.66
		1500	9.14	1.07	0.06	0.65	78.63	8.60
		Total	264.94	0.99	0.01	---	2039.13	7.70
mesostasis	2.678							
		500	468.90	0.98	0.02	---	2262.79	4.83
		1500	28.55	1.38	0.07	10.82	128.03	4.48
		Total	497.45	1.00	0.02	1.84	2390.82	4.81
olivine	4.353							
		500	420.91	0.95	0.01	---	3296.38	7.83
		1500	31.99	1.32	0.10	10.08	251.71	7.87
		Total	452.90	0.98	0.01	---	3548.09	7.83
olivine with iddings	5.739							
		500	530.19	1.02	0.02	8.16	3719.61	7.02
		1500	25.50	1.17	0.05	4.22	50.25	1.97
		Total	555.69	1.02	0.02	12.39	3769.85	6.78

Gas concentrations in 10^{-12}cm^{3}STP/gm.

^{129}Xe$_{xs}$ is calculated over ^{129}Xe/^{132}Xe = 1 (terrestrial atmosphere, Chassigny).

Table 2: Governador Valadares mineral separates

	Mass (mg)	Temp (^{o}C)	^{132}Xe	^{129}Xe/^{132}Xe	±σ	^{129}Xe$_{xs}$	^{84}Kr	^{84}Kr/^{132}Xe
pyroxene	1.091							
		500	1679.74	0.96	0.01	---	20176.13	12.01
		1500	169.05	0.85	0.04	---	375.94	2.22
		Total	1848.79	0.95	0.01	---	20552.08	11.12
mesostasis	0.186							
		500	7611.31	0.97	0.03	---	57996.16	7.62
		1500	174.81	1.09	0.10	15.07	898.89	5.14
		Total	7786.12	0.97	0.03	---	58895.05	7.56
olivine	0.058							
		500	31955.97	0.98	0.02	---	224339.63	7.02
		1500	1241.47	0.76	0.10	---	11767.39	9.48
		Total	33197.44	0.97	0.02	---	236107.03	7.11

Gas concentrations in 10^{-12}cm^{3}STP/gm.

^{129}Xe$_{xs}$ is calculated over ^{129}Xe/^{132}Xe = 1 (terrestrial atmosphere, Chassigny).

Table 3: References and data for figures 1 & 4

meteorite	sample	^{84}Kr/^{132}Xe	^{129}Xe/^{132}Xe	Reference*
Nakhla mineral separates	large pyroxene	4.57	1.14	this work
	small pyroxene	8.6	1.07	this work
	mesostasis	4.48	1.38	this work
	olivine	7.87	1.32	this work
	olivine with iddingsite	1.97	1.17	this work
Nakhla whole rock	P1	5.05	1.378	1
	P2/3/4	5.38	1.557	1
	H1	3.22	1.793	1
	R12 etched	1.9	1.18	2
Lafayette	L11	1.63	1.26	2
	L3	1.65	1.29	2
	iddingsite	6	2.04	3
Governador Valadares mineral separates	pyroxene	2.22	0.85	this work
	mesostasis	5.14	1.09	this work
	olivine	9.48	0.76	this work
Governador Valadares	GV1	3.4	1.504	this work
ALHA 77005		3.82	1.116	4
EETA 79001	,122 glass	14	2.422	4
	,27 glass #2	20.5	2.07	5
	,245 glass	31.5	1.212	6
	,34A	2.3	0.977	5
	,245 glass	25.3	1.95	6
LEW 88516		8.8	1.284	7
	,4 glass	2.6	1	8
	,4 glass	5.3	1.14	8
Shergotty	KP3 (>800)	5.37	1.186	1
	SIII/IV (800-1200)	7.1	1.338	1
	SIII/IV (>1200)	11.7	1.499	1
Zagami	Z1	18.75	1.51	2
ALH 84001	,28	4.8	1.83	9
	,29	5.1	2.028	9
Chassigny	PB4	1.14	1.029	1
Mars' Atmosphere		20.5	2.6	11
Earth's Atmosphere		27.8	0.98	10

*References: 1. Ott (1988); 2. Ott et al. (1988); 3. Drake et al. (1994)
4. Swindle et al. (1986); 5. Becker and Pepin (1984); 6. Wiens (1988)
7. Ott and Lohr (1992); 8. Becker and Pepin (1993); 9. Swindle et al. (1995)
10. Ozima and Podosek (1983); 11. Bogard and Garrison (1998)

Table 4
Comparison of light noble gases

Sample	*Cosmogenic*			*Radiogenic*
	^{21}Ne	*^{22}Ne/^{21}Ne*	*^{38}Ar*	*^{40}Ar*
Governador Valadares				
Bogard and Husain (1997) #1	2.10	1.15 ± .04	1.36	628
Bogard and Husain (1997) #2	---	---	1.21	847
this work	1.63	1.18	1.76	944
Nakhla				
Bogard and Husain (1997) #1	3.10	---	2.64	790
Bogard and Husain (1997) #2	2.32	1.12	2.17	950
Lafayette				
Bogard and Husain (1997) #1	2.70	---	2.17	610
NWA 817				
Marty et al. (2001)	---	1.19	---	---
NWA 480				
Marty et al. (2001)	---	1.22	---	---

Gas concentrations in 10^{-8}cm^{3}STP/gm.

FIGURE CAPTIONS

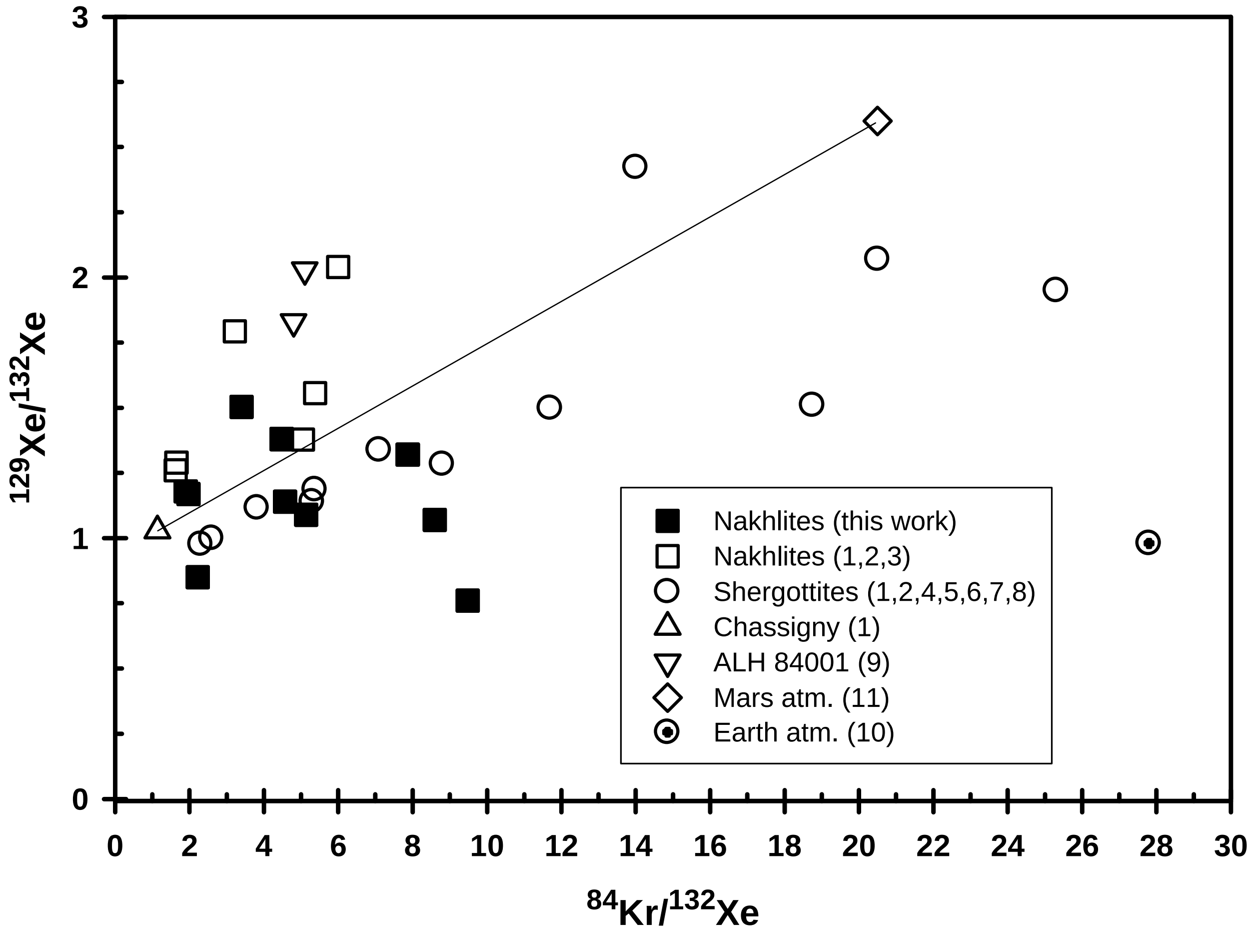
Fig.1: Plot of $^{129}Xe/^{132}Xe$ vs. $^{84}Kr/^{132}Xe$. Solid line is the mixing line between Chassigny (representing the martian mantle) and EETA 79001 (representing the martian atmosphere). Error bars on our data are variable; see Tables 1 and 2. Literature data plotted here is recorded in Table 3. Shergottites tend to plot along the mixing line (or on the terrestrial contamination side of it), whereas nakhlites tend to plot above it.

Fig. 2: Plot of $^{129}Xe_{xs}$ vs. ^{132}Xe (units: 10^{-12} cm^3 STP g^{-1}). Mesostasis and olivine samples are shown to be enriched in $^{129}Xe_{xs}$ relative to pyroxene and iddingsite coated olivine.

Fig. 3: Plot of $^{129}Xe/^{132}Xe$ vs. $^{136}Xe/^{132}Xe$ for sum of high-temperature and low-temperature extractions Governador Valadares (GV), Nakhla (Nak) and Lafayette (Laf) from this study. Standard points (triangles) from compilation of Swindle (2002), except for “Chass-E” from Mathew and Marti (2001). See text for discussion and details about data points.

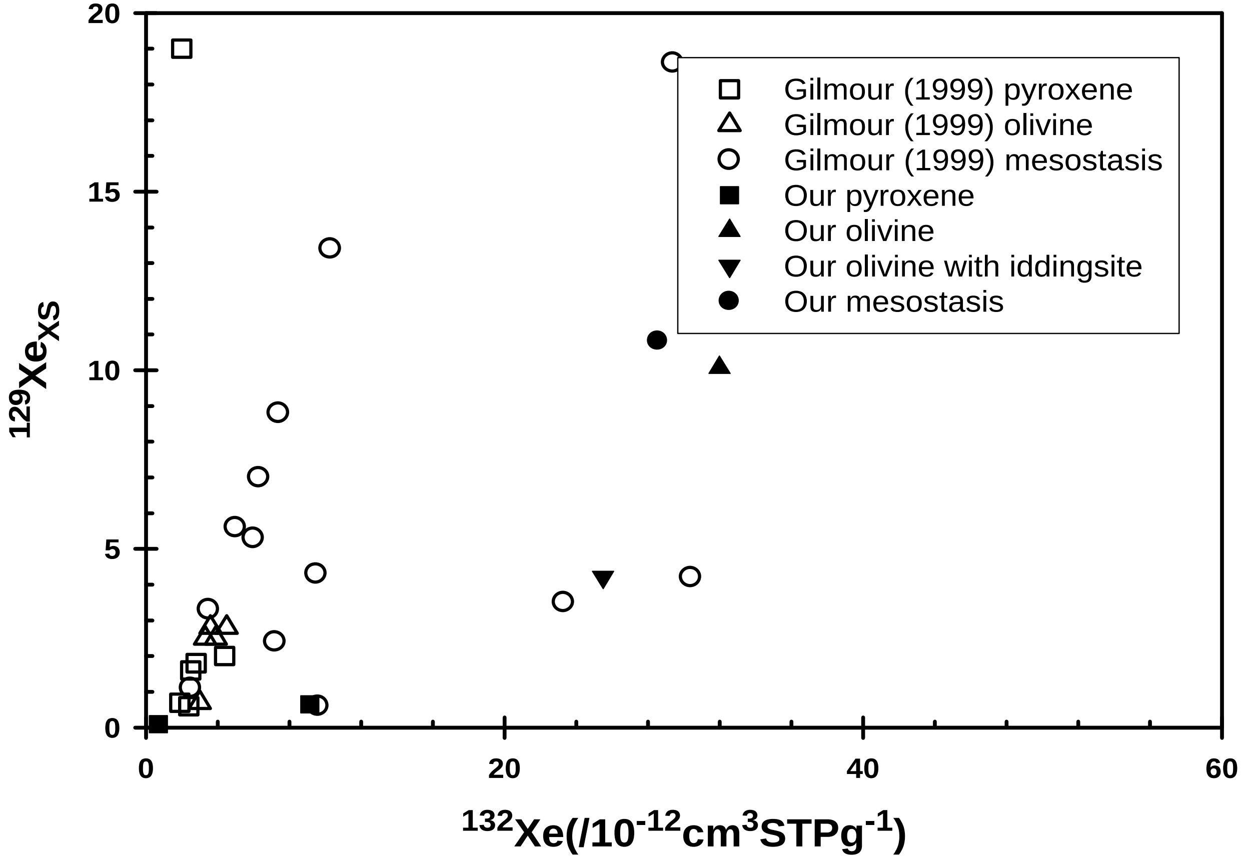
Fig. 4: Plot of $^{129}Xe/^{132}Xe$ vs. $^{84}Kr/^{132}Xe$ plotting only shergottites and nakhlites with comparable amounts of gas released (<20 x $10^{-12}cm^3$STP/gm ^{132}Xe.) Mixing line is the same as in Fig. 1. Data are recorded in Table 3.

Figure 1



3
2
1
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
^{129}Xe/^{132}Xe
^{84}Kr/^{132}Xe
■ Nakhlites (this work)
□ Nakhlites (1,2,3)
○ Shergottites (1,2,4,5,6,7,8)
△ Chassigny (1)
▽ ALH 84001 (9)
◇ Mars atm. (11)
⊙ Earth atm. (10)

Figure 2



20
15
10
5
0
0
20
40
60
$^{129}Xe_{XS}$
$^{132}Xe(/10^{-12}cm^3STPg^{-1})$
□ Gilmour (1999) pyroxene
△ Gilmour (1999) olivine
○ Gilmour (1999) mesostasis
■ Our pyroxene
▲ Our olivine
▼ Our olivine with iddingsite
● Our mesostasis

Figure 3

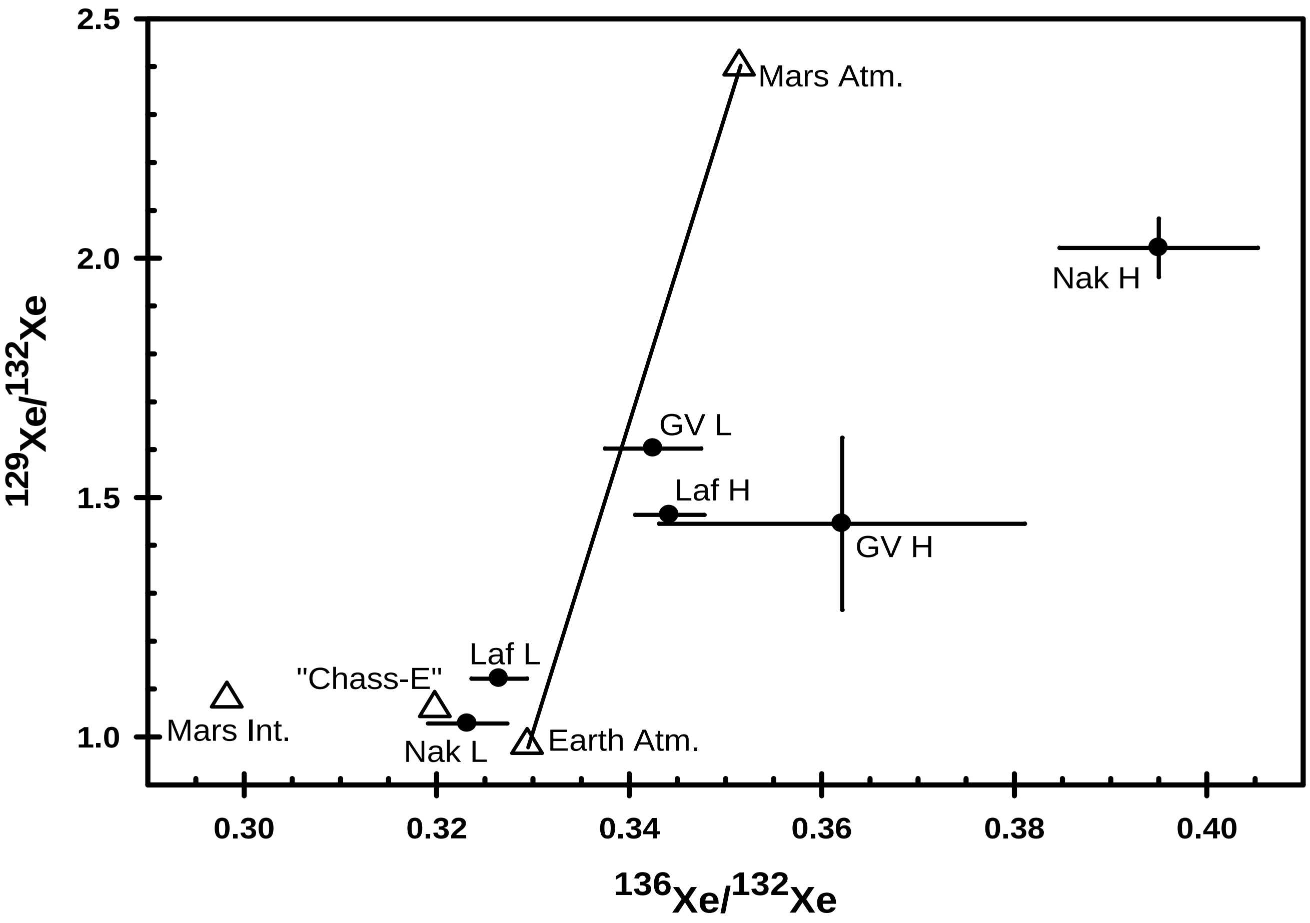
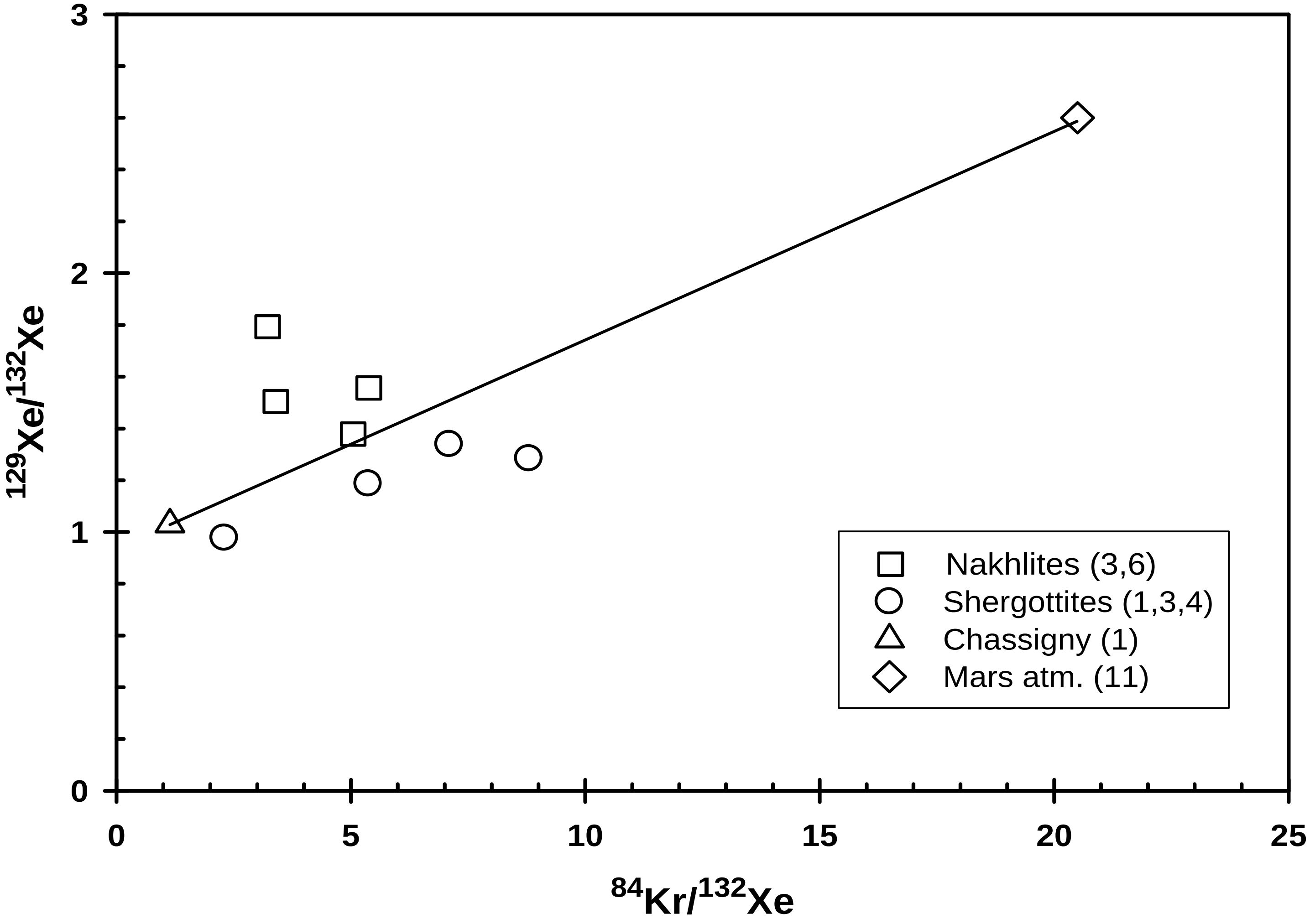

2.5
2.0
1.5
1.0
^{129}Xe/^{132}Xe
0.30
0.32
0.34
0.36
0.38
0.40
^{136}Xe/^{132}Xe
Mars Atm.
Nak H
GV L
Laf H
GV H
Laf L
"Chass-E"
Mars Int.
Nak L
Earth Atm.

Figure 4


3
2
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25
$^{129}Xe/^{132}Xe$
$^{84}Kr/^{132}Xe$
□ Nakhlites (3,6)
○ Shergottites (1,3,4)
△ Chassigny (1)
◇ Mars atm. (11)