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Evidence for Large Planetary Climate Altering Thermonuclear Explosions on Mars in the Past

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Abstract

Mars data presents a collection of startling and seemly contradictory isotopic data: a glaring excess of the two radiogenic isotopes $^{129}Xe/^{132}Xe$ @ 2.5 and $^{40}Ar/^{36}Ar$ @ 3000 enabled identification of MM (Mars Meteorites) because they are so different than any other major Solar System reservoir. Mars appears to have lost an original atmosphere of pressure 1 bar or greater, yet the ratio $^{14}N/^{15}N$ indicates only a loss of a few millibar by Solar Wind Erosion. The LPARE (Large Planet Altering R-process Event) hypothesis attempts to explain these major isotopic puzzles at Mars by postulating that two massive, anomalous thermonuclear explosions, rich in R-process physics, occurred over the surface of Northern Mars in the past, approximately 500 million years ago, and that these explosions created the $^{129}Xe/^{132}Xe$ excess, and the accompanying intense neutron bombardment of Mars atmosphere and regolith created the $^{40}Ar/^{36}Ar$ excess off of potassium in the surface rocks. The collateral massive and non-mass fractionating atmospheric loss, and the intense neutron bombardment of ^{14}N in the atmosphere primarily created the $^{14}N/^{15}N$ ratio we presently observe, with some mass fractionating erosion of the residual atmosphere. This LPARE hypothesis is found to explain other isotopic features of Mars atmosphere and surface. ^{80}Kr and ^{82}Kr are hyperabundant in the Mars atmosphere and in the youngest MMs indicating intense irradiation of Mars surface with neutrons. Although there is presently no plausible explanation for the nuclear events, the hypothesis can be tested through related nuclear products such as Pu-244.

Keywords

Mars, Isotopes, Xenon, Argon, Nitrogen, Potassium, Thorium, Thermonuclear Explosion

1. Introduction

Mars is a planet with an apparently complex history, manifesting itself in puzzling isotopic features in its atmosphere starkly different from Earth, such as the ratio of $^{129}Xe/^{132}Xe$, and $^{40}Ar/^{36}Ar$, both radiogenic [1] and the ratio $^{15}N/^{14}N$ suggesting a loss of only millibars of atmosphere by Solar Wind erosion over Mars geo-history while geomorphology strongly suggests atmospheric pressure 1 bar or greater in the past. Other puzzles are also present, as will be discussed. It is the aim of this article to explain these salient puzzles with a new hypothesis: that Mars was the site of massive thermonuclear explosions, of unknown cause, in the recent geologic past. These explosions created the radiogenic excesses of xenon and argon and caused the loss of atmosphere without significant fractionation of nitrogen. In the remainder of this article the salient puzzles of Mars isotopic system will be discussed as will the hypothetical events which caused them.

Mars global geomorphologies suggesting a past much different than its present state. Mars apparently had a warm dense atmosphere of approximately 1 bar or greater in pressure, that lasted for an unknown fraction of its geologic history. This is in vivid contrast to the present thin Mars atmosphere of approximately 6 mbar. This dense past atmosphere, suppressing vaporization of water and trapping heat, apparently allowed the formation of abundant water channels on terrains of both old and young age and even an apparent Paleo-Ocean on its lightly cratered Northern plains [2] [3]. Typical of this range of ages of channels are Maadim Vallis on old terrain and showing evidence of precipitation, the other Hradd Vallis on young terrain, which are believed to have been carved by water [4] [5] with magma induced melt water flows being the likely source (see **Figure 1**).

The loss of atmosphere by various mechanisms is expected to have created isotopic clues to its mechanisms that can be seen in surface atmospheric measurements and in trapped gases in MMs (Mars Meteorites). Two of those isotopic features of immediate interest are the ratio of $^{36}Ar/^{38}Ar$, which consistent

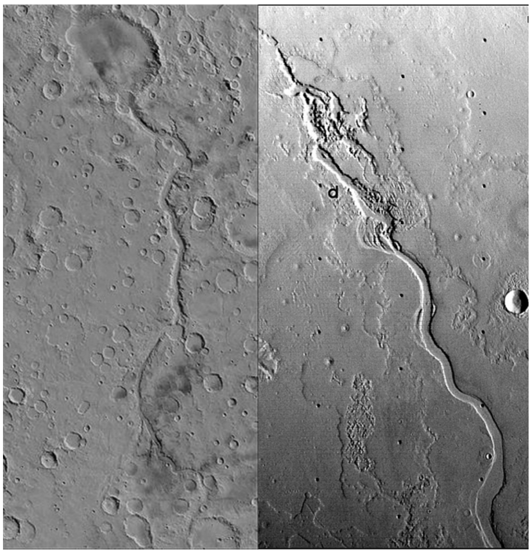

Figure 1. Maadim Vallis (L) on old terrain draining into Gusev Crater. Hradd Vallis on young terrain. Both channels are approximately 800 km long.

with a loss of 1/2 bar or greater of Mars atmosphere by diffusive sputtering and erosion by the SW (Solar Wind) [6] in the last 4 Billion years. However, in vivid contrast, the ratio $^{14}N/^{15}N$ indicates only a small loss of atmosphere, 3 mbar, by such sputtering-SW erosion over the last 4.0 Billion years [7]. This low loss rate is in agreement with measurements form orbit [8], despite being, seemly, at odds with both geomorphology and the $^{36}Ar/^{38}Ar$ data.

Given the evident large scale of Mars atmospheric change and the uncertainties in its chronology, which in turn effect models of its isotopic makeup, plus the present uncertainties in the locations and conditions of R-Process possibly observed in events in the larger Cosmos [9] and thermonuclear detonation experiments on Earth [10], the author will attempt to present a hypothesis that explains the salient points of the Mars isotopic and isotopically linked atmospheric history, and some of its major details. It must be accepted that any simple new explanation for a complex body of data, must account for many presently known mechanisms that are operating in a dynamic environment over geologic time on Mars: a changing geomagnetic field at Mars in time, atmospheric erosion, mass fractionation, outgassing, multiple isotopic reservoirs, varying Cosmic ray irradiation and spallation of isotopes in the regolith, spontaneous fission of actinides, radioactive decay of nuclides and production of daughter nuclei, to name only major mechanisms known to operate on Mars.

Analysis of the only available Mars samples, the MMs, must consider their isotopic makeup in terms of not only their geologic history on Mars but also the fact of their ejection from Mars and subsequent space irradiation by Cosmic rays, and other effects. This vast body of effects and data will cause even a successful new hypothesis aiming to explain the salient points of the data, to also create other problems in some less important details. Therefore, rather than trying explain every detail of the Mars data set, we will concentrate on explaining the main puzzles of the Mars data set and deal with higher order features in the data in later studies.

In the remainder of this article we will present the LPARE (Large Planet Altering R-process Event) hypothesis and then examine it in the light of isotopic, lander, and orbital survey data from Mars.

2. The LPARE (Large Planet Altering R-Process Events) Hypothesis

It is hypothesized that two massive R-Process events occurred in mid-air over the Northern Plains of Mars. The R-Process is inferred to occur in astrophysical events, but has been seen on Earth in thermonuclear explosions [10]. In a planetary environment a large R-process event above the planetary surface would create powerful Tunguska-like explosions. Given the nitrogen and carbon dioxide components in the Mars atmosphere such fireballs would be expected generate large amounts of nitric acid. These hypothetical R-Process events caused the $^{129}Xe/^{132}Xe$ and $^{40}Ar/^{36}Ar$ excesses and occurred during the epoch of warm-dense atmosphere on Mars, and terminated that epoch. Like all R-process events it was fission rich because fission forms the limiting process on formation of heavy actinides in an R-Process event [9]. The resulting massive loss of atmosphere due to the powerful Tunguska-like explosions created isotopic patterns in $^{36}Ar/^{38}Ar$ and $^{14}N/^{15}N$ in addition to isotopes characteristic neutron irradiation effects, and creating fireball glass deposits near the sites of the events and a global debris pattern with deposits at the approximate antipodes of the events. By the geological principle of superposition: new rocks in top layers-older rocks below, rocks older than the LPARE epoch were buried deeper than rocks of approximately LPARE Crystallization Age and so were shielded from the intense neutron radiation in the LPARE epoch. The rocks irradiated during the LPARE epoch received little neutron irradiation afterward, because the thin surviving atmosphere generated few secondary neutrons and resurfacing rates were much reduced. Thus, the rocks of Crystallization Ages approximately corresponding to the LPARE epoch received the most neutron irradiation while on Mars, or being in contact with the regolith, received such highly irradiated materials as regolith inclusions. The loss of atmosphere from Mars, under this hypothesis, was primarily hydrodynamic and catastrophic and thus not mass-fractionating [11], resembling a giant impact, with the decay of the remainder of the Mars atmosphere by sputtering and UV bombardment that was mass fractionating. The difference in mass fractionation between N and Ar is attributed to their difference in chemical activities with N being bound to the soil and outgassing later while Ar was always in the atmosphere, except for the isotope ^{40}Ar.

The total energy of these hypothetical R-Process events exceeded that estimated for the Chixulube event on Earth [12] and occurred at approximately 0.5 - 1.3 Billion years ago (see Figure 2).

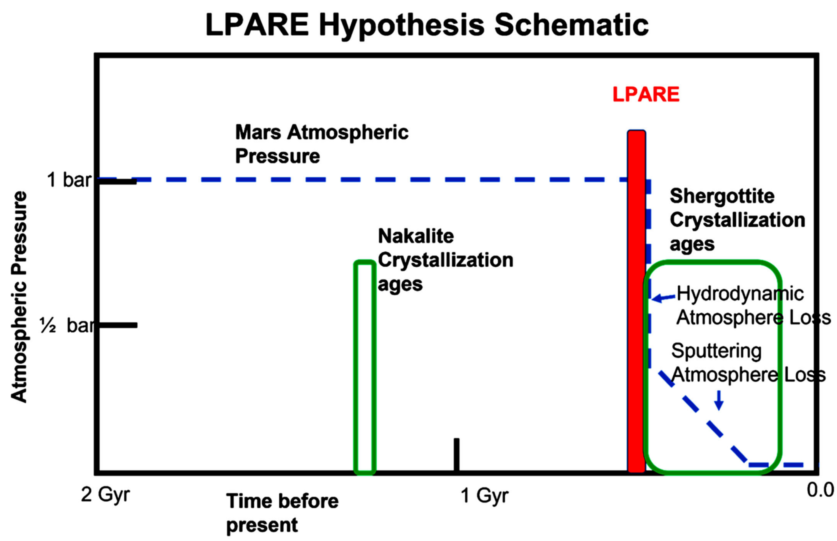

Figure 2. A schematic of the LPARE Hypotheses. Mars rocks of older Crystallization Age were shielded from Cosmic rays by a dense atmosphere and then buried before the LPARE, and the atmosphere was too thin to appreciable secondary neutron flux after the LPARE. Only rocks that crystallized near-surface in the era of the LPARE incorporate highly irradiated materials.

3. Evidence for a Geologically Recent Loss of Mars Atmosphere

Mars apparently once had a warm-dense atmosphere, of approximately 1 bar or greater pressure, as evidenced by numerous long water channels, even on recent, lightly cratered terrains [13]. This atmosphere was rapidly lost by some process, leaving only the thin present atmosphere at 6 mB. However, the $^{15}N/^{14}N$ ratio in the present Mars atmosphere indicates that the dense atmosphere was present until recent geologic time [7] and this is supported by orbiter measurements which show that present the loss rate is only ~millibar/Gyr [9]. It has been proposed that formation of large deposits of carbonate rock on Mars could explain this loss of atmosphere however, no such large amounts of carbonates have been detected [14].

This scenario of a dense atmosphere on Mars persisting until recent geologic time is supported by young average ages of the MMs, now numbering over 100, that is less than 1 Gyr, requiring average age of the Mars surface to be also young [15] [16] [17] constraining in turn the Mars cratering rate versus the Moon, the key parameter determining Mars surface ages from crater statistics. The MM crystallization ages can only be reconciled with estimates of average Mars surface ages if the rate is be much higher than presently estimated. This higher cratering rate than Lunar being consistent with Mars proximity to the asteroid belt. Thus, the northern plains of Mars and the signs of water flows and standing bodies likely have much younger ages than previously estimated.

This scenario of a dense atmosphere persisting until recent geologic times and then undergoing massive non-fractionating loss, is consistent the weak fractionation of $^{14}N/^{15}N$ and $^{36}Ar/^{38}Ar$ and with numerous instances of aqueously altered materials contained in MMs (Mars Meteorites), which are thought to represent samples of shallow subsurface rocks. The MMs include the youngest subgroup, the Shergottites, at an average age of 200 myrs.

4. Xenon Isotopes on Mars

Given the glaring excess of ^{129}Xe, which has defied credible explanation, and which apparently appeared late in Mars history based on its absence in deep interior samples of EETA79001 and ALH84001 and the primordial Olivine meteorite Chassigny [1] is extremely significant. The basic problem is that ^{129}Xe is hyperabundant in the Mars atmosphere, relative other major solar system reservoirs such as Earth (see **Figure 3**) and is attributed to decay of ^{129}I with a half life of 17 Myrs shortly after Mars accretion. However, the decay by spontaneous fission of ^{244}Pu with a half-life of 80 years, would create relatively large amounts of heavier Xenon isotopes [18] a component that has not been seen.

A more recent attempt to explain this mystery has been put forth, [19] proposing that an early Mars atmosphere dominated by water vapor, CO_2 and ^{129}Xe from short lived ^{129}I, created a regolith of phyllosilicates on top of the basement rocks. The Xe isotopes, being highly soluble in the phyllosilicates, would be

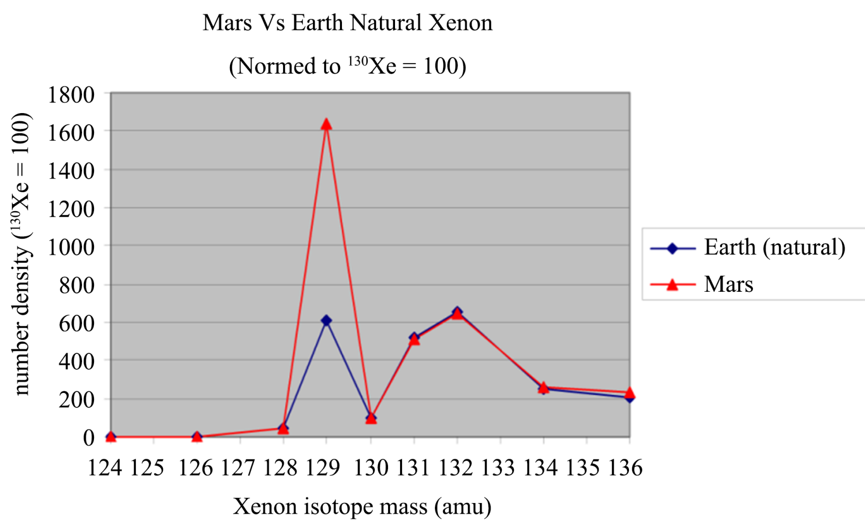

Figure 3. Mars and Earth Xenon stable isotope concentration normed to $^{130}Xe = 100$.

uniformly sequestered and preserved when the early atmosphere would be lost, to remerge later when the atmosphere was replaced by outgassing to create the present thin atmosphere, which would now be have Xe isotopes dominated by the early atmosphere's ^{129}Xe excess. However, this phyllosilicate sequestration proposal suffers from the serious flaw that the later heavier Xe isotopes from ^{244}Pu fission and other longer lived Actinides, would also be sequestered by the same phyllosilicate regolith, after upwardly diffusing from the basement rocks, and then also be outgassed later with ^{129}Xe, wiping out the ^{129}Xe excess. Another flaw is that Mars terrains of a full range of ages, and especially the most ancient terrains, show abundant water channels, indicating that any period of lost atmosphere on Early Mars was brief and quickly replaced by outgassing from both diffusion and venting of mantel sourced gases. Such gases would most likely reflect Xe isotopes found in Chassigny, where no ^{129}Xe excess appears. Because of either or both effects, there remains no likely reason that the heavy Xe isotopes from ^{244}Pu fission would be absent from the present Mars atmosphere. Therefore, the ^{129}Xe excess remains in need of an explanation.

Even more telling is the evidence, from interior samples of older Mars meteorites, such as ALH84001 and Chassigny that ^{129}Xe excess was not present on Early Mars but appeared later. It is also apparent that large amounts of fission, spontaneous or otherwise, also occurred on Mars, and that produced abundant heavier isotopes of Xe, such as $^{136}Xe/^{132}Xe$, seen in **Figure 4**, taken from [1].

The ^{129}Xe excess of the present Mars atmosphere, absent in the olivine Chassigny, and interior samples of ETTA79001 the vastly more ancient ALH84001, yet while present in surface samples of ALH84001, can be explained as correlating with the exposure of the parent rock layers to ground water carrying dissolved atmosphere. Exposure of the Olivine Chassigny to water would have destroyed it. So in its anhydrous state it could preserve the primordial mantel gas isotopic distributions, while other MM parent rocks were affected by the modern atmosphere, at least in their surface layers.

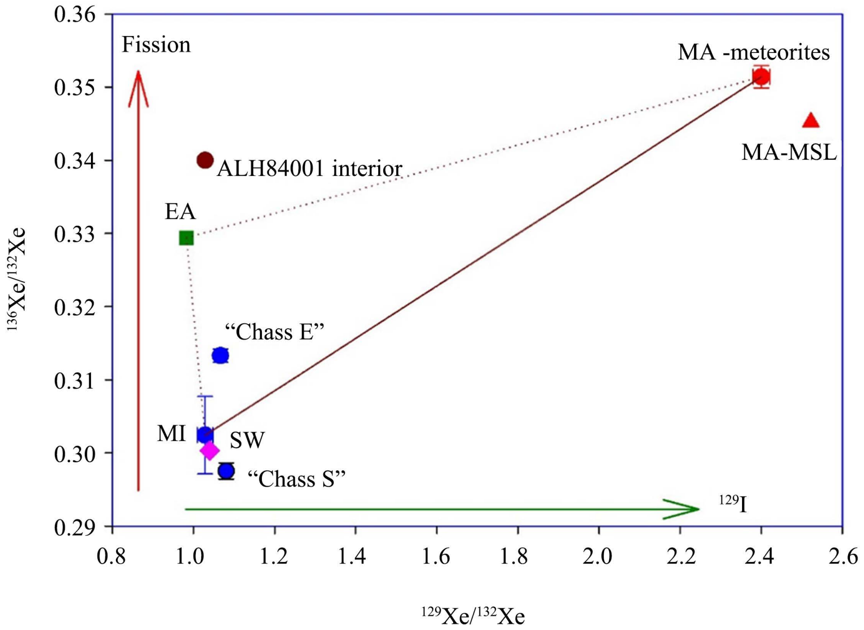

Figure 4. Mars Xe data showing that primordial Mars atmosphere trapped in older meteorites, ALH84001 and Chassigny, did not contain an ^{129}Xe excess but that it arrived later in geologic time in a Fission rich period. Figure taken from [1].

The observed ^{129}Xe hyperabundance, relative to ^{132}Xe is also seen in Xe isotopes, extracted at high temperature, from Presolar Grains in the very ancient Carbonaceous Chondrite Meteorite Allende, which is not from Mars (**Figure 5**) data from [20] [21].

The presence of a hyperabundance of ^{129}Xe in Allende pre-solar grains has been attributed to the occurrence of R-Process associated with Supernova or neutron star merger before the origin of the Solar system. The R-Process, produces characteristic isotopic distributions [22] (see **Table 1**). In particular, producing a $^{129}Xe/^{132}Xe >> 1$, this is in contrast to S-process, occurring at less intense and lower energy neutron flux (see **Table 2**) which produces $^{129}Xe/^{132}Xe << 1$.

The parameter $^{129}Xe/^{132}Xe >> 1$ can thus be regarded as a signature of R-Process.

The xenon isotopic spectrum of the R-process can be seen to compare well with xenon data from Mars, but less well with Earth (**Figure 6**).

There is a change in the fission product isotopic spectrum when high energy neutrons, such as those found in R-Process, cause fission, as opposed to fission by thermal neutrons, this is seen in **Figure 7**.

The contributions of spontaneous fission to the xenon isotopic spectrum can be seen to be dominated by isotopes heavier than 129 (**Figure 8**).

Therefore, the signature $^{129}Xe/^{132}Xe > 1$ of Mars may be explained as due to a massive R-Process event on Mars rather than a loss of Mars early atmosphere.

The high concentration of ^{129}Xe in the Martian atmosphere is a unique feature of Mars atmosphere and, because of the ^{129}Xe excess, Mars Xe differs starkly

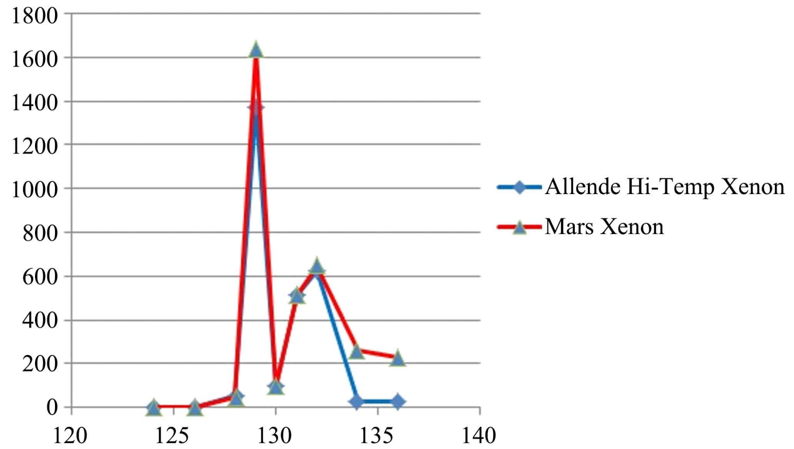

Figure 5. Mars Xe atmosphere isotopic composition compared to that found in refractory pre-Solar grains in meteorite Allende. Note the good matches at ^{130}Xe and ^{131}Xe.

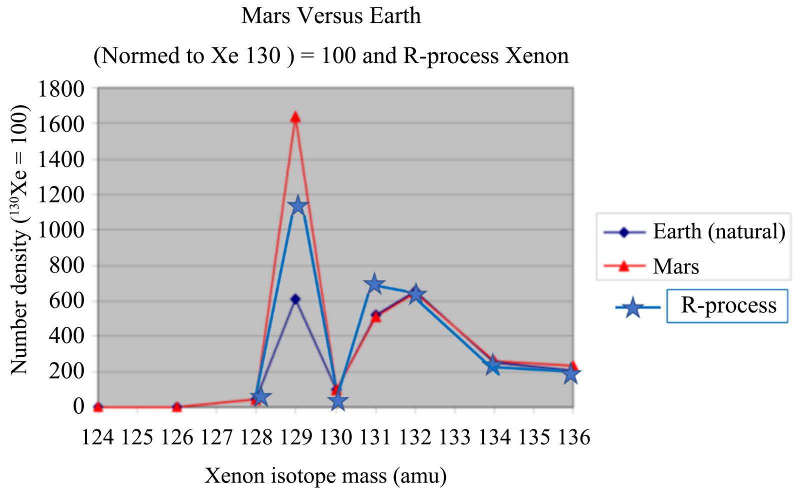

Figure 6. Mars, Earth and R-Process Xenon stable isotope concentration normed to ^{130}Xe = 100 and ^{132}Xe = 600. Data taken from [21] [22].

Table 1. End Member R-Process Isotope Compositions from models based on the assumption that ^{130}Xe is not produced. Note the large relative amount of ^{129}Xe that is produced. Table adapted from [22].

R-Process			
Composition	Min Ratio	Max Ratio	χ^2
^{124}Xe/^{132}Xe	0.00279 (04)	0.00722 (08)	234
^{126}Xe/^{132}Xe	0.00433 (03)	0.00626 (09)	336
^{128}Xe/^{132}Xe	0.00057 (30)	0.0164 (48)	232
^{129}Xe/^{132}Xe	1.538 (02)	1.529 (29)	1294
^{130}Xe/^{132}Xe	≡0	≡0	…
^{131}Xe/^{132}Xe	1.137 (02)	1.143 (01)	233
^{134}Xe/^{132}Xe	0.258 (01)	0.557 (05)	492
^{136}Xe/^{132}Xe	≡0	≡0.466	…

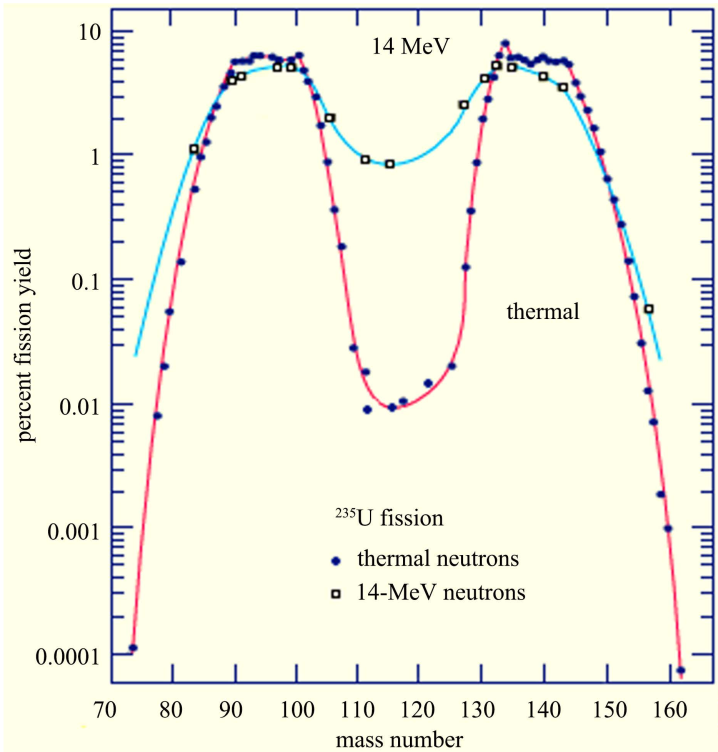

Figure 7. Mass distribution of fission fragments formed by neutron induced fission of ^{235}U when neutrons have been moderated (solid curve) and fission by 14 MeV fusion neutrons (broken curve) [23] showing increase in middle range isotopes for 14 MeV fusion neutrons. Note that very little change occurs in the atomic mass interval a = 80 - 100.

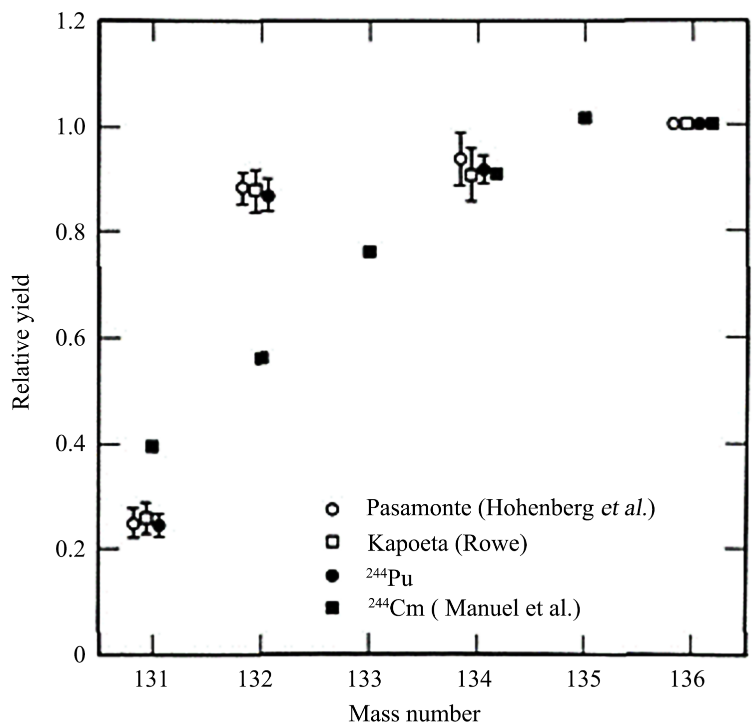

Figure 8. Xenon Isotopes produced by spontaneous fission of 244 Pu, figure taken from [24].

Table 2. Isotopic compositions determined by simulations for pure S-Process Xe isotopes under the assumption that little or no ^{136}Xe is produced. Note the very small relative amount of ^{129}Xe that is produced table taken from [22].

Ratio	S-Process	χ^2	Lewis *et al.*	Arlandini *et al.*
$^{124}Xe/^{132}Xe$	−0.00065 (08)	234	−0.0002 (01)	≡0
$^{126}Xe/^{132}Xe$	−0.00020 (02)	336	0.0003 (02)	≡0
$^{128}Xe/^{132}Xe$	0.212 (04)	232	0.216 (02)	0.202 (89)
$^{129}Xe/^{132}Xe$	0.105 (30)	1294	0.118 (11)	0.097 (03)
$^{130}Xe/^{132}Xe$	≡0.48 (01)	-	≡0.483 (04)	0.40 (17)
$^{131}Xe/^{132}Xe$	0.184 (18)	233	0.186 (12)	0.16 (05)
$^{134}Xe/^{132}Xe$	0.013 (05)	492	0.0222 (53)	0.053 (17)
$^{136}Xe/^{132}Xe$	≡0	-	0.00344 (03)	≡0

from the isotopic mass spectrum of Xe from major reservoirs existing elsewhere in the solar system. This is particularly true of Earth, the Solar Wind and the Chondritic reservoir, thought to be the source reservoir for planetary accretion, as seen in **Figure 7**. The Xenon isotopic spectrum of Comet ^{67}P resembles Mars only in its ratio of $^{129}Xe/^{132}Xe > 1$ and nowhere else. Disagreement in the heavier isotopes of Xe is particularly marked, as can be seen in **Figure 9**. Taken from [25].

Alternatively, to the LPARE Hypothesis, it would seem reasonable to suggest that Mars Xe was simply pre-Solar, however, samples of deep interior and older Mars meteorites contain Mars original ancient atmosphere and the $^{129}Xe/^{132}Xe > 1$ excess is absent in them [1] as seen in **Figure 3** previously. Instead, the ^{129}Xe excess appears in Mars meteorites of much later crystallization ages, as seen also in **Figure 10** further below. Therefore the $^{129}Xe/^{132}Xe$ excess can be explained by the LPARE Hypothesis.

5. Evidence from Krypton of Large R-Process Events on Mars

The physics of the Classical R-Process is that of intense, high energy, neutron bombardment of heavy elements [9]. In the case of the LPARE hypothesis we would expect any R Process Event on Mars to leave evidence in the krypton family of isotopes of an intense neutron bombardment of the surface rocks of Mars. One measure of such a bombardment would be the level of ^{84}Kr generated in surface layers MM parent rocks by neutron absorption on ^{83}Kr from Mars atmosphere retained in the rock by water infiltration or shock implantation, while the rock was on Mars. Such a bombardment can successively create ^{84}Kr from ^{83}Kr and ^{82}Kr due to the latter two isotopes having large neutron absorption cross sections. This would be in addition to Kr created in the LPARE directly. This appears consistent with the data presented in **Figure 10** where it is seen that ALH84001, and the Nakalites, older and therefore probably more deeply buried than the younger Shergottites, was spared such bombardment.

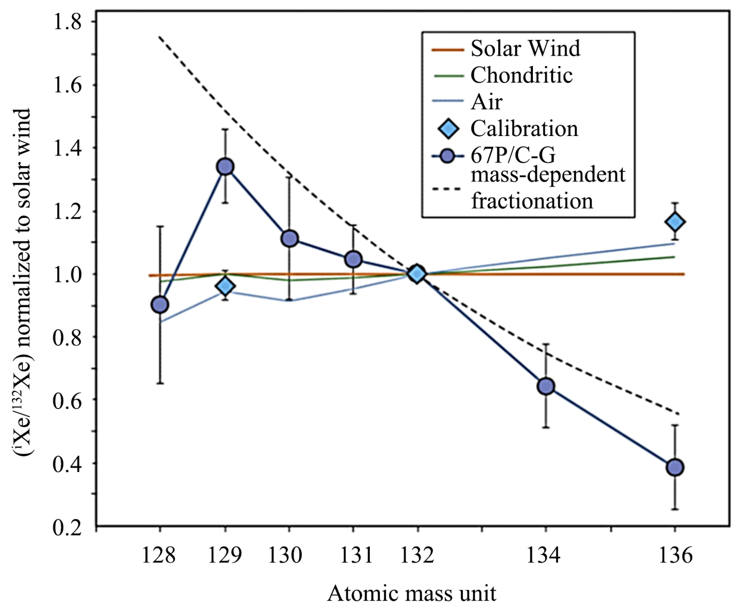

Figure 9. Xenon isotopic compositions of the Solar Wind, Earth's Atmosphere, average Chondrite and primordial Comet ^{67}P. Figure taken from [25].

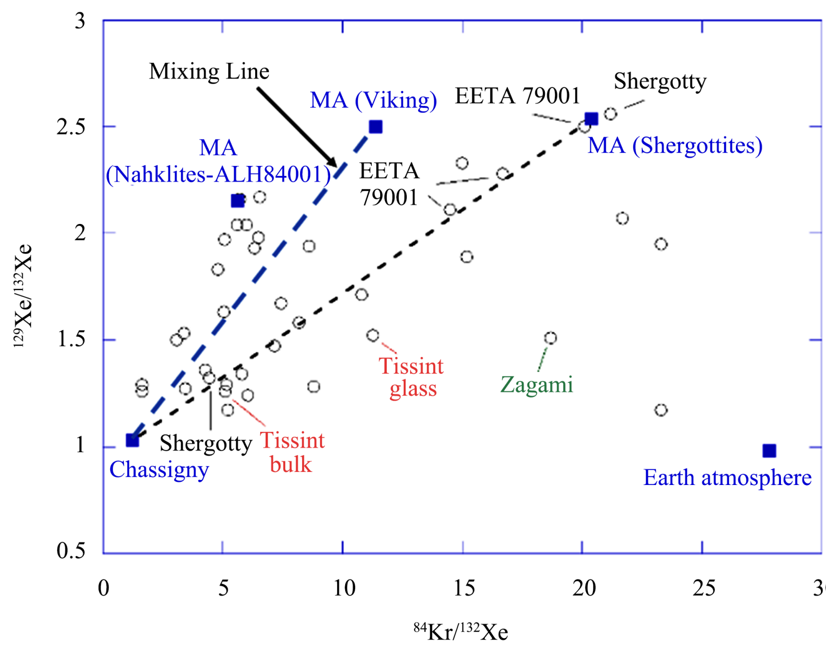

Figure 10. ^{129}Xe in Mars meteorites versus fission product Kr 84, both normed to ^{132}Xe showing an evolution of Mars environment from "primordial" Chassigny at 1.5 Gyr old to younger rock samples at 0.2 Gyr old and finally the modern Mars atmosphere. This shows an addition of a fission component to the Mars environment after its formation. Graph adapted from [1].

The only distribution of krypton isotopes that resembles that of Mars atmosphere are those of the Sun itself, a nuclear furnace, as seen in **Figure 11**, where neutrons produced by fusion irradiate an array of elements, including Kr that was originally chondritic, as is seen in the primordial MM Chassigny. [26] and

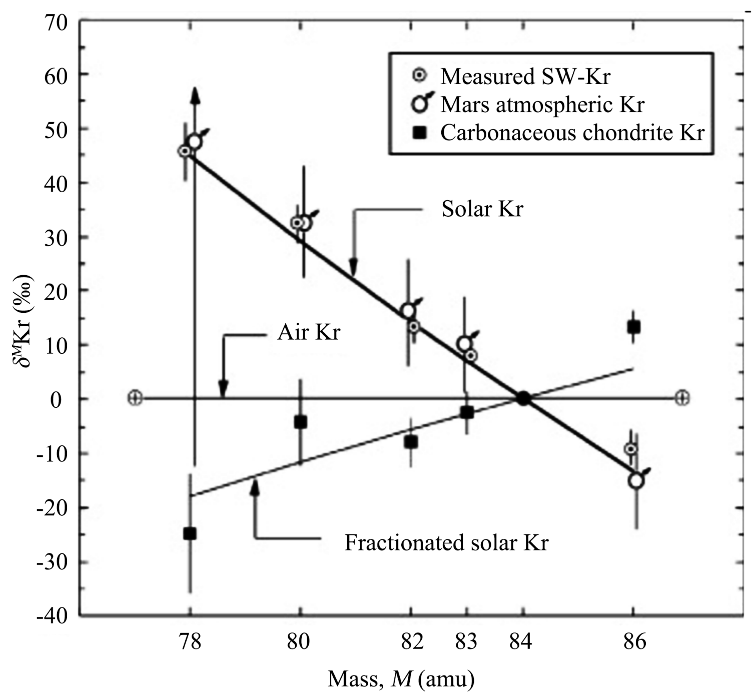

Figure 11. Mars krypton isotope abundance compared to Earth's atmosphere and the Solar Wind [21].

which formed the likely basis for Mars original atmosphere. Fission produces both Xe and Kr, with Xe being produced more strongly with a ratio of approximately Xe/Kr @6 [27] The ratio Xe/K = 0.27 on Mars, or nearly equal, in vivid contrast to Earth where Xe/Kr = 0.076 [28] is consistent, like the ratio of ^{136}Xe/^{123}Xe in the Mars atmosphere, with a large fission component in the Mars atmosphere. Thus Xe/Kr is large on Mars relative to Earth.

Krypton isotopes are a product of fission reaction that can occur as part of the R-process. As can be seen in **Figure 8**, [1] the rise in concentration of ^{84}Kr and ^{129}Xe in Mars rock forms an approximate "mixing line " between the primordial Xe and Kr in ancient Mars rocks such as Chassigny and rocks and that found in the younger Mars meteorites and Mars present atmosphere. This would indicate that the R-process Xenon appeared at the same time as the ^{84}Kr.

This correlation between the appearance of hyperabundances of ^{129}Xe and ^{84}Kr in the Mars environment is consistent with the occurrence on Mars of the fission-rich R-process events on Mars late in geologic time.

A large R-Process fission-rich event on Mars would also produce other effects, such as a large irradiation of the surface with neutrons, and would also produce large amounts of other krypton fission product isotopes. We can thus look for these other signs of a large R-Process fission-rich event in Krypton isotopes.

The ^{80}Kr and ^{82}Kr abundances in Mars Shergottites and in Mars atmosphere [1] are consistent with exposure to a neutron flux of 10^{14}/cm^2 - 10^{15}/cm^2, with capture on ^{80}Br and on ^{81}Br in the Mars regolith with subsequent outgassing, depending on the neutron energy spectrum [29] (see **Figure 12** taken from [1]).

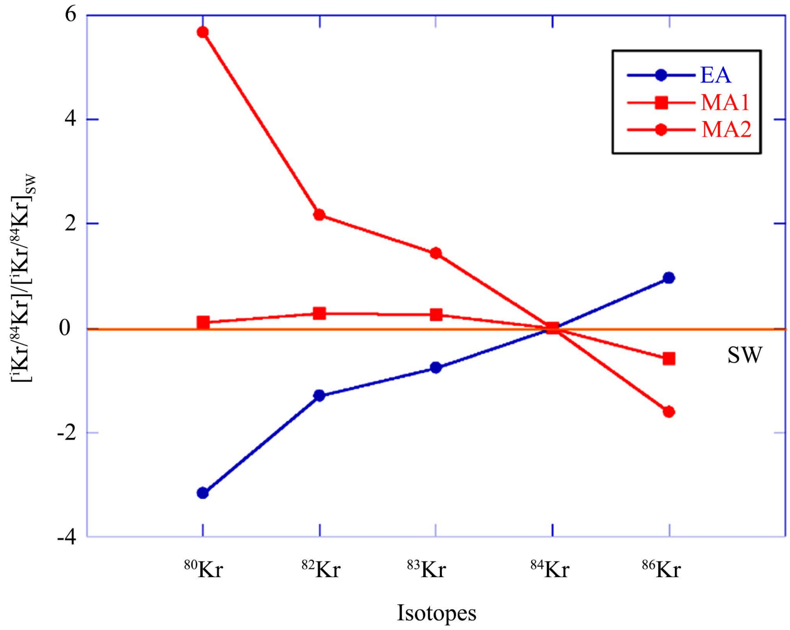

Figure 12. Krypton isotopes measured in different samples from glass inclusions in EETA 79001 showing MA2 (Mars atmosphere 1 (modern) with evidence of ^{80}Kr and ^{82}Kr excesses over the EA (Earth atmosphere) relative abundances.

In the Shergottite EETA 79001, of approximate crystallization age of 180 Myrs, there is seen a composite of three distinct lithologies [30] of approximately the same age. Signs of intense neutron radiation are seen in glass inclusions [29] [31] but the enclosing matrix rock shows barely detectable levels. This pattern appears to be repeated in the Shergotites SaU 005 and Dho 019, of crystallization ages of approximately 500 Myrs [29] [31]. Evidence of intense neutron exposure in the glass inclusions is seen not just in Kr isotopes but in isotopes of Sm and Gd and apparently occurred on Mars, because the exposure does not correlate with the MMs space exposure to cosmic rays after ejection into space [31] (see **Figure 13**).

The concentration of intense neutron exposure in glass inclusions in the Shergottites is consistent with the exposure of Mars regolith to the intense irradiation with its later being engulfed and melted by molten lava issuing from deep-shielded reservoirs. The intense neutron irradiation associated with the LPARE can thus be said to predate the oldest Shergottites but to have occurred after the formation of the Nakalites at approximately 1.3 Gyrs, which, being more deeply buried under the Principle of Geologic Superposition, were shielded from the neutron irradiation of the LPARE. This places the epoch of intense neutron irradiation somewhere between 1.3 and 0.5 Gyrs ago on Mars.

Changes in relative isotopic abundances can have many causes. Various processes can erode a planet's atmosphere over time, especially if it has no strong magnetic field like the situation of Mars. These processes tend to erode the top of the planet's atmosphere, and thus erode lighter isotopes more that heavier ones. The result is that such processes of atmospheric erosion tend to

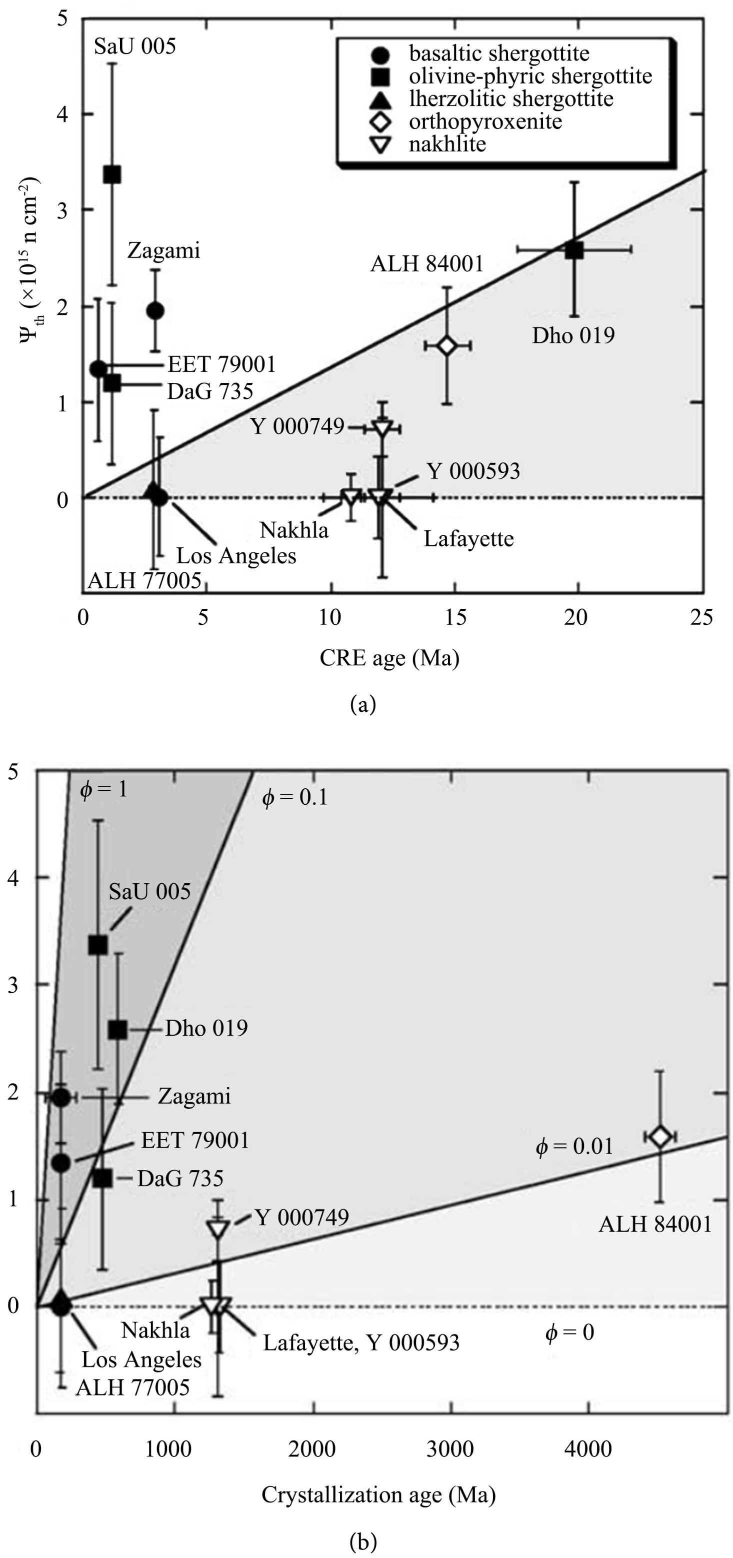

Figure 13. (a) and (b) The level of neutron irradiation measured in various MMs showing in (a) the concentration of intense irradiation in the Shergottites, which have the youngest crystallization ages of the MMs. The subfigure (b) shows the level of neutron exposure for most Shergottites does not correlate with their space exposure to cosmic rays. Figure taken from [31].

fractionate, or disturb, the distribution of isotopes in a way that makes heavier isotopes relatively more abundant than lighter ones [21]. Massive atmospheric loss from giant impacts can also produce some mass fractionation, but much less than slow erosion [11] However, on Mars, whatever process disturbed the krypton isotopes made lighter isotopes relatively more abundant that heavier ones. Thus, Kr is "reverse fractionated" (**Figure 8**). This requires a predominately nuclear process rather than diffusive mass fractionation. This can also be compared to Kr isotopes found in comet ^{67}P [32] (**Figure 14**). Comets have been proposed as the source of parts of planetary atmospheres.

Therefore, there exists evidence consistent with the LPARE hypothesis in the two rarest gases contained in Mars atmosphere and rocks. We will now discuss isotopic evidence in some of the most abundant gases in the Mars atmosphere.

6. Lower Atomic Weight Isotopic Systems on Mars

Signs of intense neutron radiation of Mars are also present in argon and nitrogen isotopes on Mars. The light nuclei in the Mars atmosphere, aside from hydrogen which is easily mass fractionated on Mars, and where large reservoirs and outgassing sources of H_2O and CO_2 are believed to participate in atmospheric evolution, show only mild fractionations relative to the Earth, as seen in **Table 3**. Earth is believed to have mostly preserved its primordial atmosphere, so its isotopes are a reasonable standard for such primordial ratios. Therefore, mild Mass fractionations relative to Earth would be expected for oxygen and carbon for atmospheric loss via sputtering and UV bombardment with outgassing and large reservoirs being available for replenishment. Added to this sputtering loss under the LPARE Hypothesis would be a preceding event would be a large and catastrophic loss of atmosphere by mostly non-fractionating hydrodynamic escape. So Earthlike isotope ratios would not be surprising. However, this picture of mild fractionation relative to Earth is spoiled by the stark exceptions of isotopes^{129}Xe, and the low atomic weight pairs ^{15}N/^{14}N and ^{40}Ar/^{36}Ar. Therefore, one must look for another process besides mass fractionation to explain these isotopic ratios.

Table 3. Various Isotopic Systems on Mars and Earth, data from [35].

Isotopic ratio	Atmosphere		
	Mars	Earth	Mars/Earth
D/H (in H_2O)	9.3‰ ± 1.7‰	1.56‰	~6
^{12}C/^{13}C	85.1 ± 0.3	89.9	0.95
^{14}N/^{15}N	173 ± 9	272	0.64
^{16}O/^{18}O	476 ± 4.0	499	0.95
^{36}Ar/^{38}Ar	4.2‰ ± 0.1‰	5.305	0.79
^{40}Ar/^{36}Ar	1900 ± 300	298.56 ± 0.31	~6
C/^{84}Kr	(4.4 - 6) × 10^6	4 × 10^7	~0.1
^{129}Xe/^{132}Xe	2.5221 ± 0.0063	0.97	~2.5

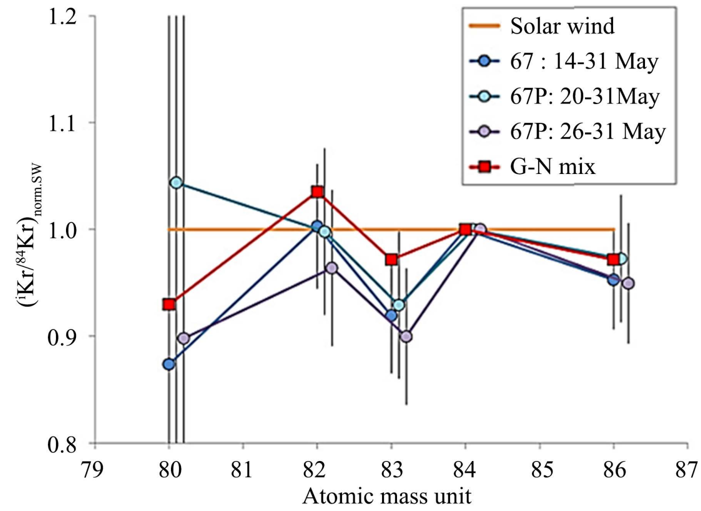

Figure 14. The fractional abundances of krypton isotopes in comet ^{67}P relative to a Solar Wind [22].

It is of great interest that the ^{15}N and ^{40}Ar pair are easily produced by the impact of thermal neutrons on ^{14}N and ^{39}K [33]. Also, the predominate isotope of potassium, ^{39}K, upon thermal neutron irradiation converts to ^{40}K, which for intense neutron irradiation can become ^{40}Ar. For its part ^{14}N can absorb a neutron and become ^{15}N with the emission of a gamma ray. This reaction has been easily observed in open air tests of nuclear weapons [34]. This is in contrast to isotopes of oxygen and carbon, who have low reactivity with thermal neutrons and hence make good components for moderators in nuclear reactors. Thus, the intense irradiation of the Mars atmosphere and surface with thermal neutrons over several seconds could be expected to produce glaring differences with Earth isotopic abundance ratios, for ^{40}Ar and $^{14}N/^{15}N$ but leave the oxygen and carbon and relatively undisturbed, to undergo conventional fractionation as the remaining atmosphere was lost to space. This is, in fact, consistent with what is found.

Under the LPARE hypothesis the production of large amounts of ^{40}Ar would occur promptly in the Mars due to neutron irradiation, become part of the regolith and would then outgas to become part of the Mars atmosphere. ^{40}Ar can also result from the slow decay of ^{40}K, half-life 1.2 Billion years, but also from the prompt process of an n, p reaction on ^{40}K. It is this latter prompt process for ^{40}Ar production, that, under the LPARE hypothesis produced the dominant amount of ^{40}Ar now found in the Mars atmosphere. This would be more prominent in the North of Mars under the LPARE hypothesis, because of the events hypothetically occurring there and could account for the puzzling discrepancy between the Curiosity measurements of $^{40}Ar/^{36}Ar$ @1900, in the Southern Hemisphere of Mars [35] and those at the Viking sites in the North @ 3000.

A large amount of ^{36}Ar would also be produced under the LPARE hypothesis, from the neutron absorption on ^{35}Cl forming unstable ^{36}Cl, with a half-life of 0.3 Myrs to form stable ^{36}Ar. This would form in the soil and outgas unless trapped in melt glass inclusions. As with Kr isotopes formed by intense neutron bombardment of the regolith under the LPARE hypothesis, argon isotopes would form in larger amounts in the younger regolith rocks of the Northern Hemisphere of Mars, because the LPARE events appear to have occurred there and because chlorine was found abundantly in the regolith at both Viking lander sites. The Northern Hemisphere of Mars with its younger estimated surface ages is also believed to be the source region for the Shergottites. Also, conversely, Solar Wind erosion of heated remaining atmosphere after the explosions would mass fractionate the remaining ^{36}Ar ^{38}Ar system perhaps exceeding the ^{36}Ar gain because of neutron irradiation of ^{35}Cl in the regolith.

Interestingly, ^{15}N formed in the atmosphere, being chemically active, would be expected to become part of the regolith also. The formation of Tunguska-like fireballs would create large amounts of nitric acid [36] which would react with siderite and other carbonates in the regolith to form nitrates. Such nitrates, thought due to meteor trails and lightning, have been measured in the Martian soil, though at low levels [37] Nitrates in the Martian soil, would be expected in time to react by oxidizing iron in the form of Siderite ($FeCO_3$) the soil and Olivine ($FeSiO_3$). Creating Hematite (Fe_2O_3), SiO_2 and outgassing molecular nitrogen and CO_2. Alternatively, the Mars impact flux could also free nitrogen bound as nitrates in the soil, as was discussed in [38] Thus, both ^{15}N, ^{36}Ar, and ^{40}Ar would diffuse into the Mars atmosphere from the regolith after formation under the LPARE hypothesis.

Such a joint outgassing of ^{15}N and ^{40}Ar would be expected to occur at approximately similar rates. Evidence of this is seen in MMs and Mars atmosphere measurements that appear to form a linear array of values. (**Figure 15**) Alternatively, the observed linear array may simply be a mixing line between primordial

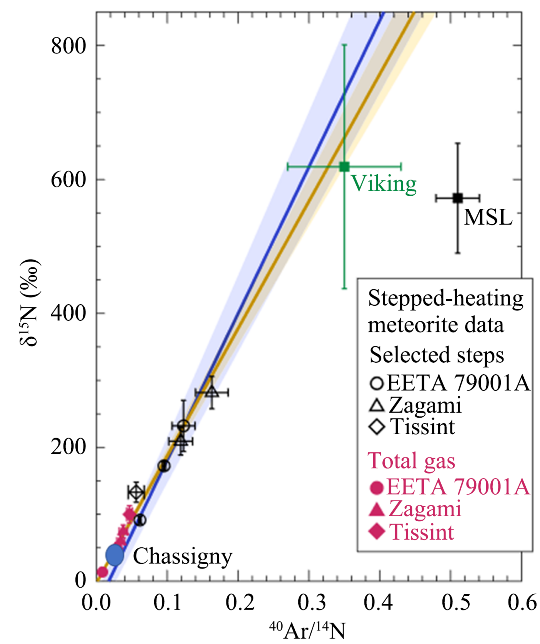

Figure 15. Apparently correlated ^{40}Ar and ^{15}N data found in MMs and in the Mars atmosphere. Figure taken from [38].

values in MMs and exposure to Mars atmosphere which received both ^{40}Ar and ^{15}N together, shortly following the LPARE. Production of ^{36}Ar by neutron irradiation of ^{37}Cl would also occur, lessening the effect of the LPARE neutron irradiation on $^{40}Ar/^{36}Ar$ and the atmospheric erosion mass fractionation on $^{38}Ar/^{36}Ar$.

7. Alternative Hypotheses

The ^{129}Xe anomaly together with the matching abundance and reverse fractionation pattern of the krypton isotope abundances in the Martian atmosphere plus the ^{40}Ar and ^{15}N features, can be explained by a large R-process fission event in Mars history. The alternative hypothesis can be proposed that Mars was the site of a natural nuclear reactor. This hypothesis was initially favored by the author [39]. Such a large amount of fission requires either a chain reaction or a large fusion event to supply the required neutrons. Only a fission chain reaction can occur in nature under Martian conditions. Uranium 235 is the only naturally occurring isotope that can sustain a chain reaction, however, it always occurs mixed in nature with much more abundant ^{238}U. Even a billion years ago, the relative abundance of ^{235}U at 3% allowed chain reactions in to only occur in nature in the presence of moderating groundwater which slowed the neutrons and allowed the large cross section for fission at low energies to dominate and allow a small reaction mean free path. Given the presence of impurities that absorb neutrons in nature and thus compete with fission in absorbing neutrons, a short reaction mean free path is necessary for a chain reaction to occur.

A chain reaction with fast fission neutrons can also occur because fast neutrons quickly slow down by collisions but it is more difficult to achieve. Thus, a fast neutron spectrum chain reaction, must occur quickly and in a compact region for it to be feasible in nature. However, the high neutron energy, such as a raw fission neutron spectrum, also requires a high density of fissionable material because of the shrinking of the fission cross section at high energies means that chain reaction is not possible without moderation for any natural abundance of U235. The natural nuclear reactor must then produce approximate S-process Xe compositions without a ^{129}Xe excess. Without moderation, and thus without an S-process, no chain reaction is possible in natural uranium. Consistent with this conclusion, the only fission reactors known to operate without moderation, must do so using highly enriched uranium, nearly weapons grade, to make up for the loss of reaction cross section that occurs at high neutron energies. Therefore, the ^{129}Xe super-abundance, which means that the fission event was dominated by high energy neutrons, means that it cannot have been a natural uranium-based natural nuclear reactor. The R-process event is thus required.

Another alternative hypothesis to the R-process event on Mars is that Mars could have had Earth-like Xe isotopes and then suffered large impact late in its geologic history, by a comet or comets of the same primordial isotopic composition as ^{67}P. Such a massive impact could have largely replaced the Mars atmosphere with one of pre-Solar composition. However, two problems exist with such a comet-impact hypothesis.

The comet would have to be very large to replace a major fraction of the Mars atmosphere to create the observed present composition. Mars atmosphere has a mass of 2.5 × 10^{16} kg, approximately the mass of comet Hale-Bopp [40], among the largest of comets studied.

The first objection to the late comet-impact hypothesis is that the isotopic compositions of species other than Xe measured at comet ^{67}P, differ significantly from Mars. Even for Xe isotopes, despite displaying ^{129}Xe/^{132}Xe >> 1, the remainder of the Xe isotopic abundance, relative to ^{132}Xe, is quite different from Mars. Krypton isotope composition at ^{67}P is seen in **Figure 11** and bears no resemblance to that seen on Mars, seen in **Figure 8**, which resembles a Solar pattern. Mars values for Kr isotopic composition adhere to the Solar pattern to within a percent, whereas the ^{67}P Kr is scattered and varies by 10% from Solar values. The Comet ^{67}P ratio of ^{36}Ar/^{38}Ar = 4.5 is a good match to Mars at ^{36}Ar/^{38}Ar = 4.3. However, the absence of neon from the comet [32], despite it being easily detectable in the Mars atmosphere [1] and much more abundant than krypton or xenon in that atmosphere, also makes this comet impact scenario seem unlikely.

The second objection to the comet-impact hypothesis is that while such an impact would create a massive explosion, it would create no nuclear reactions, whereas the R-process on Mars hypothesis would be expected to create many. As has been seen, the hypothesized R-process event on Mars appears to have been associated with a massive neutron irradiation event on Mars, producing large excesses of ^{40}Ar and ^{80}Kr, as would be expected. Thus, a large comet impact on Mars to explain the Xe isotope data would also require a separate catastrophic event to create the evidences of a massive episode of neutron irradiation, such as ^{80}Kr, ^{15}N, and ^{40}Ar abundances. The principle of Economy of Hypothesis thus makes this cometary impact hypothesis seem less likely. Further anomalies on Mars exist.

8. The Potassium-Actinide Anomaly on Mars

Meteoritic samples of Mars rock, thought to be originally subsurface, are depleted in uranium and thorium relative to Earth by a factor of 10 to 3 whereas the surface rocks appear Earthlike in abundance, as seen in **Figure 12**. This paradox was found in the Phobos and Mars probe data [41], which showed enhanced levels of Uranium and Thorium, in approximately chondritic ratio to each other, in the top layer of the Mars surface, that can be measured from orbit. This has been confirmed for Thorium by the Odyssey GRS (Gamma Ray Spectrometer) [42]. However, this is in vivid contrast to the much lower abundances of potassium and thorium found in meteorites from Mars (see **Figure 16**). Hot spots of thorium and potassium in Mars Acidalium centered at approximately 35W, 55N and Utopia Planitia at approximately 95E and 55N can be seen in **Figures 17 (a)-(d)**, with another concentration at the approximate antipode of the center of the hypothetical explosions, approximately 160E 40S. These antipode deposits,

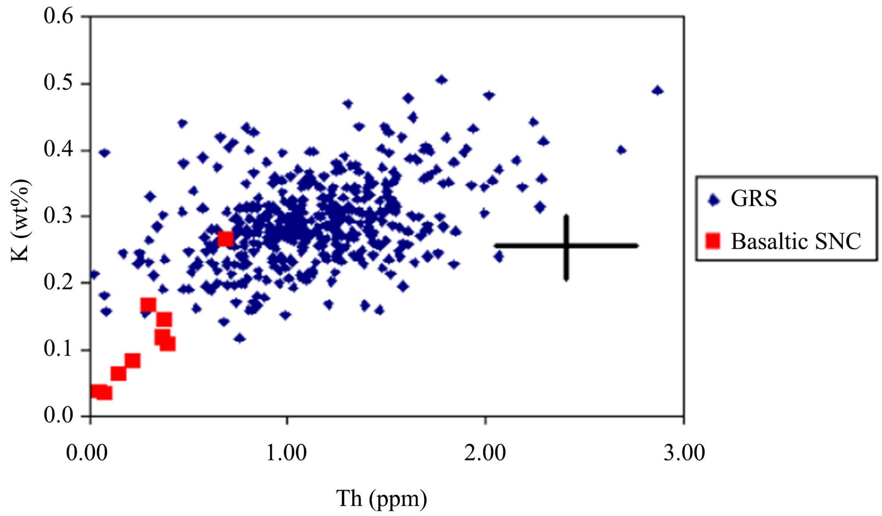

Figure 16. K, Th variations on Mars compared to Mars Meteorites (SNC). Typical Uncertainty is shown on the right. Figure taken from [42]. For comparison K is 2% wt. and Th 6 ppm of Earth's crust.

first pointed out by Dr. Edward McCullough [Private Communication], are consistent with large Tunguska-like explosions sending shock waves around the planet, and are thus consistent with the interpretation of this being due to a massive R-Process Event. Such an event which would have irradiated large areas of planet's surface with neutrons and then scattered this irradiated debris all around the planet, the maps of radioactive ^{40}K shows the same features, including the antipodal feature (see **Figure 13**). It therefore seems possible that a large concentrated uranium and thorium body existed on Mars and exploded in a R-Process event, giving rise to a global surface layer of debris enriched in uranium and thorium and irradiated large areas of the planet with intense neutron radiation.

9. Fission Yield Calculations

Based on the observed abundances of Mars Xe and Kr isotopes and the observed enriched layer of U and Thorium on its surface, it is possible to estimate the number of fissions that occurred under this R-Process hypothesis and thus the Fission energy release. Based on the abundance of ^{129}Xe in the Mars atmosphere and assuming it was all produced in the explosion at approximately a fractional mass yield F^{129} into the atomic mass 129 channel of F^{129} = 3% for a fast neutron spectrum we can write for the total energy released based on ^{129}Xe [12]:

$$W_{Xe} = W_{fission} n_{Xe129} HA / F^{129} = 1.5 \times 10^{26}\ \text{J} \quad (1)$$

where $W_{fission}$ is the energy released per fission of 200 Mev or 3.2×10^{-11} J, $n_{Xe129} = 9 \times 10^{10}\ \text{cm}^{-3}$ is the number density of ^{129}Xe in the Mars atmosphere, $H = 1.1 \times 10^{6}$ cm, is the Martian atmosphere scale height-giving a columnar density of $10^{17}\ \text{cm}^{-2}$ or 3×10^{18} fissions per cm^2 of planetary surface and A is the surface area of Mars of $1.4 \times 10^{18}\ \text{cm}^2$. This is a large energy, equivalent to the impact of a 70 km diameter asteroid into Mars and sufficient to produce a global ejecta layer of

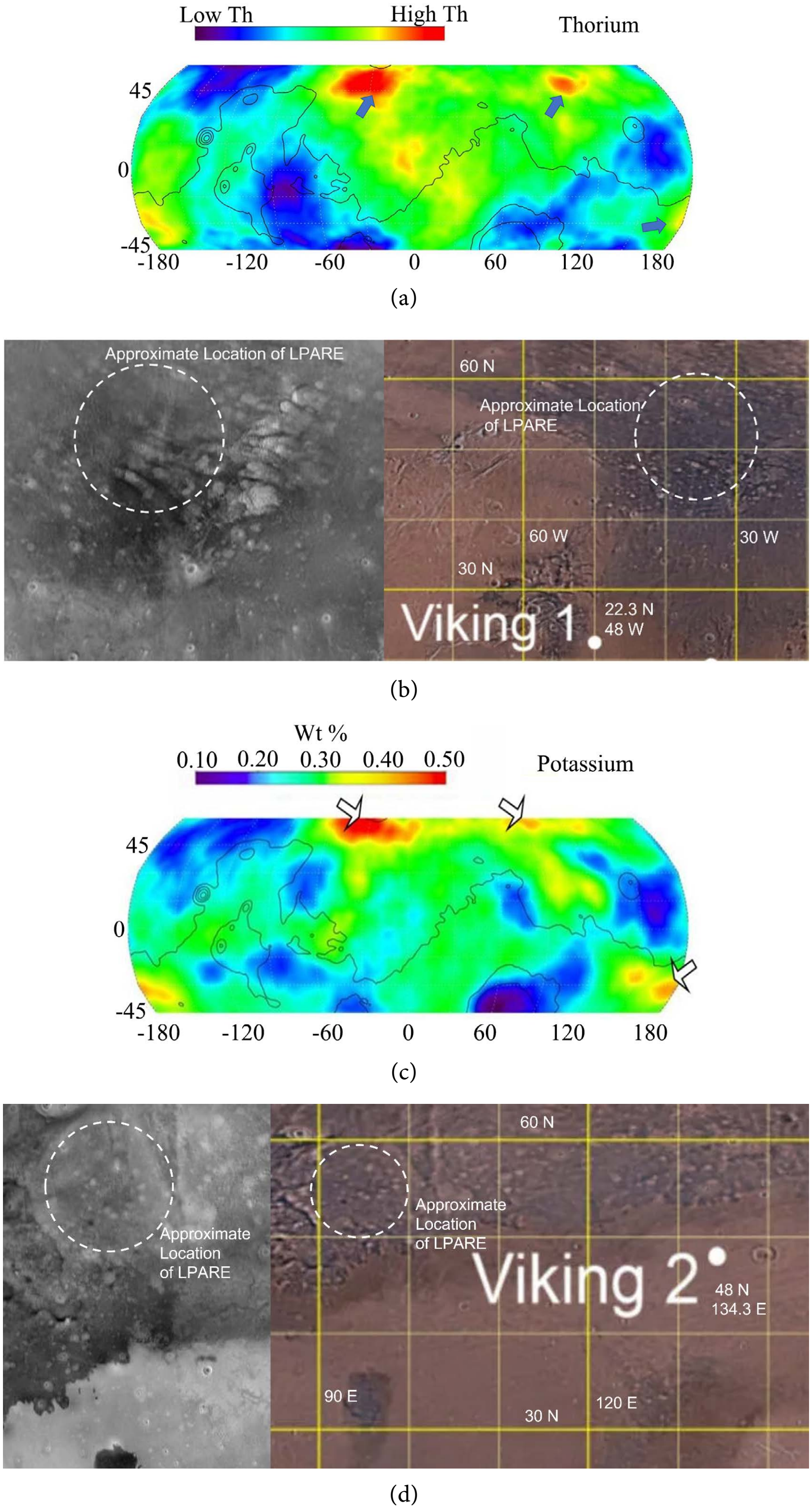

Figure 17. (a) Map of Mars global concentrations of ^{232}Th adapted from [42]. (b) Map and image of Acidalia Planetia LPARE site. (Google Mars) Note the absence of major craters or volcanic features. (c) Map of Mars global concentrations of radioactive ^{40}K. Arrows mark hot spots including the approximate antipode of the largest hot spot. Map adapted from [42]. (d) Map and image of Utopia Plantitia LPARE site. (Google Mars). Note the absence of major craters or volcanic features.

4 meters, and enough to devastate the planet [43]. 1 Megaton of energy is approximately 4 × 10^{15} J so an energy release for the R-Process Event of 10^{26} J is approximately 25 billion megatons.

Based on the neutron fluence $F_{neutron}$ = 10^{15}/cm^2 neutron fluence required to explain the irradiation of glass lithogies of EETA79001 and account for the ^{80}Kr anomaly, and assuming this was a planet-wide occurrence from delayed neutrons of an approximate fraction $F_{delayed}$ = 0.1% that were radiated immediately after the event by fission fragments in the planet-wide ejecta layer, we can calculate and approximate number of fissions in the event as approximately 10^{18} fissions per cm^2 of planetary surface and thus have an independent estimate of the yield. We can then estimate the yield from the ^{80}Kr anomaly:

$$W_{Kr} = W_{fission} F_{neutron} A / F_{delayed} = 4.6 \times 10^{25} \text{ J} \tag{2}$$

where the values of other quantities $W_{fission}$ and A are the same as in Equation (1). Thus the Fission energy release, calculated from two pieces of evidence arrives at an approximate energy release in the R-Process Events as approximately 10^{25} J this is a yield of approximately 10 billion megatons (1 MT = 4 × 10^{15} J) This is exceeds estimates of the energy released in the Chixulube Impact on Earth, estimated to be 10^{23} J [43], and indicates these R-Process Events would have created a global catastrophe on Mars and could have permanently changed Mars climate.

10. Tests of the LPARE Hypothesis

Two preliminary tests of the LPARE hypothesis can be made. One is geochemical: Tunguska-like fireballs in the atmosphere of could be expected to sweep up regolith fines and turn them into glasses similar to Trinitite, these glass particles would also be expected to etched by nitric acid created by the fireballs in the CO_2 and N_2 atmosphere of Mars, as was created at Tunguska [44] and believed to occur on Mars in atmospheric meteor trails [37]. Evidence exists from NIR (Near Infrared) spectral features concentrated near the hypothesized LPARE sites in Acidalia Planitia and Utopia Planitia [45] (see **Figure 18** and **Figure 19**) The presence of oxidizing acid etching was inferred by similar NIR features seen in experiments using mixed strong sulfuric acid and hydrogen peroxide solutions to etch basaltic rocks [46]. Similar etching on glass has been demonstrated using hot nitric acid [47]

As can be seen in **Figure 18** and **Figure 19**, iron rich glass showing up as yellow in red on **Figure 18** and **Figure 19** and acid etching of this glass, shown in blue, is concentrated around the hypothetical LPARE sites at 30W 55N, in Acidalia Planitia, and at 95W and 55N in Utopia Planitia.

The second test of the LPARE Hypothesis is isotopic, and is the search for ^{244}Pu, or other long lived isotopes with R process origins, in Mars samples. If the LPARE occurred within the last Billion years then detectable trace levels, above those with R process origins from galactic background infall [48], should be found.

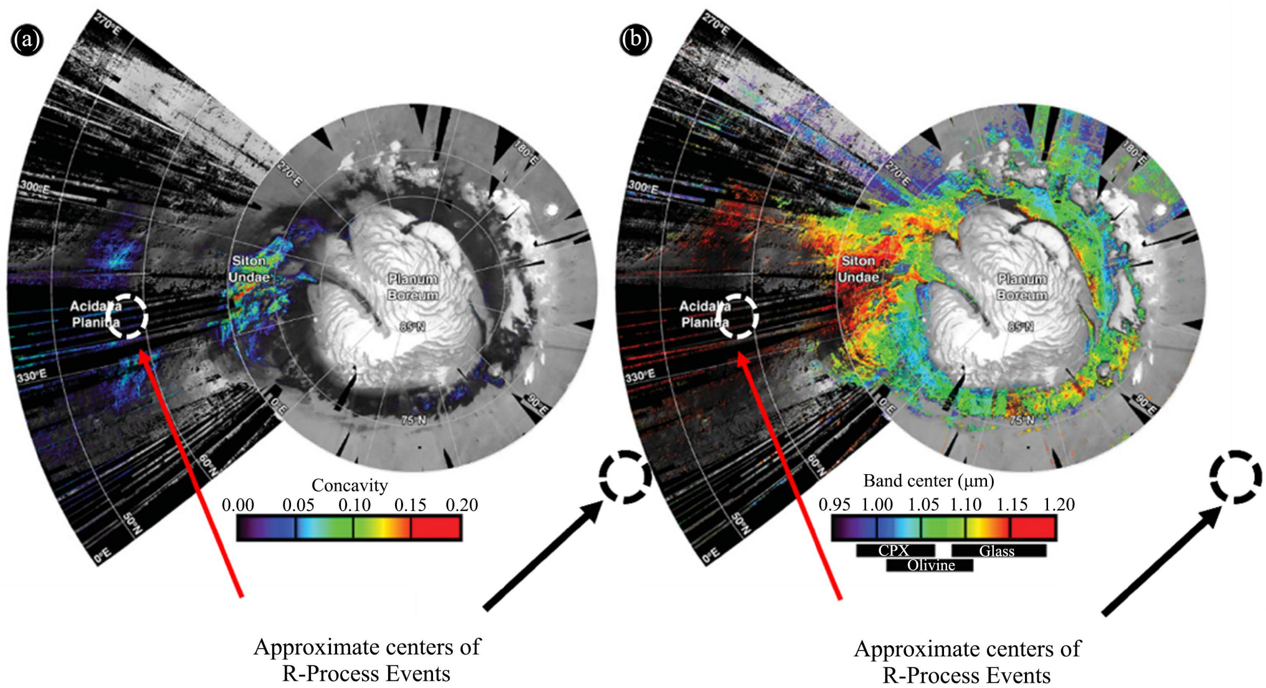

Figure 18. Maps taken from orbit by Mars Express, showing A. NIR features associated with (in blue) basaltic rock etched by oxidizing acid, and B. NIR features (in red) associated with iron rich glass. Figure adapted from (Horgan [45]).

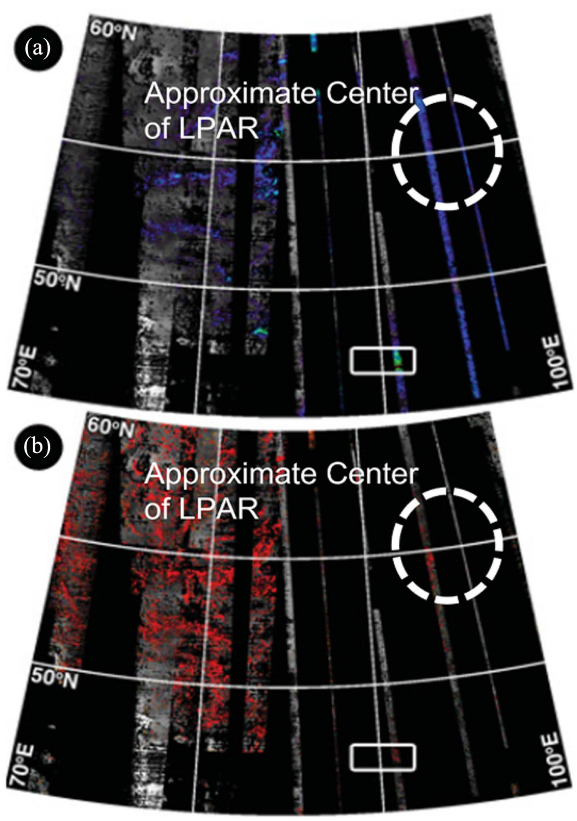

Figure 19. Maps taken from orbit by Mars Express, showing (a). NIR features associated with (in blue) basaltic rock etched by oxidizing acid, and (b). NIR features (in red) associated with iron rich glass. Figure adapted from [45].

11. Summary

Therefore, several glaring Mars isotopic anomalies can be understood in terms of R-process events occurring between 0.5 - 1.3 Gyr years ago. Evidence for R-process events on Mars is found in atmospheric xenon, krypton, argon, and nitrogen; and in surface concentrations of potassium and thorium. The puzzle of the excess ratio of $^{129}Xe/^{132}Xe$, and $^{40}Ar/^{36}Ar$, relative to Earth, is explained as due to massive R-process driven explosions, of unknown cause, that occurred over Northern Mars surface, which created both large amounts of ^{129}Xe directly and large amounts of ^{40}Ar by intense neutron bombardment of K in the regolith. The mild mass fractionation ratio $^{15}N/^{14}N$, despite evidence of large Mars atmospheric loss, is due, under this hypothesis to massive hydrodynamic atmospheric loss without appreciable mass fractionation due to the R-process explosions plus neutron capture on ^{14}N. Neutron capture on bromine led to a measured excess of light Kr isotopes. The $^{36}Ar/^{38}Ar$ ratio, so at seeming variance with that in nitrogen, is due, under this hypothesis, primarily to Solar Wind erosion of the heated remaining atmosphere after the explosions, moderated by ^{26}Ar outgassing from the regolith after neutron irradiation of ^{35}Cl. The surface evidence puts the R-process events at Acidalia Planitia and Utopia Planita, in the northern hemisphere. These events left no craters, implying they occurred at some height above the surface. The global fission yield of the R-process events is estimated at 10^{25} J, or 10^{10} megatons. This yield is an order of magnitude larger than estimates of the energy of the Chixulub impact and consistent with massive hydrodynamic atmospheric loss. The R-process energy estimates are consistent with what appears to be a global debris pattern with concentrations at the approximate antipodes. Oxidizing acid etched glass, resembling trinitite, is found at the approximate location of the explosions. The R-process hypothesis can be verified by measurements of anomalous amounts of ^{244}Pu in Mars samples.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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