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The Noble Gases in the Venusian Atmosphere and the Fukutomi Chondrite

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1. Introduction

Noble gases are the most important elements in the experimental study of planetary volatiles as well as in the theoretical research on the origin of a planet, because (1) they, being chemically inert, are not affected by chemical reactions in the evolutionary process of a planet, (2) there is plentiful accumulation of data on terrestrial and extraterrestrial noble gases, and (3) techniques are available to detect trace amounts of noble gases by laboratory experiments and spacecraft measurements. A comparative study has been reviewed on the volatiles in the atmospheres of Venus, Earth and Mars (Hunten *et al.*, 1988).

In this paper, I report the close relationships between the Venus atmosphere and the Fukutomi chondrite in their noble gas compositions, and discuss a possible origin of the noble gases in the Venusian atmosphere.

2. Elemental and isotopic abundances

The comparison of noble gas abundances in terrestrial-planet atmospheres with the solar abundance, indicates that the Venus noble gas resembles the solar abundance pattern as compared to those of the Earth and Mars, except for Ne which is greatly depleted in the three planets, as shown in Fig. 1. The argon abundance in the Venus atmosphere is relatively close

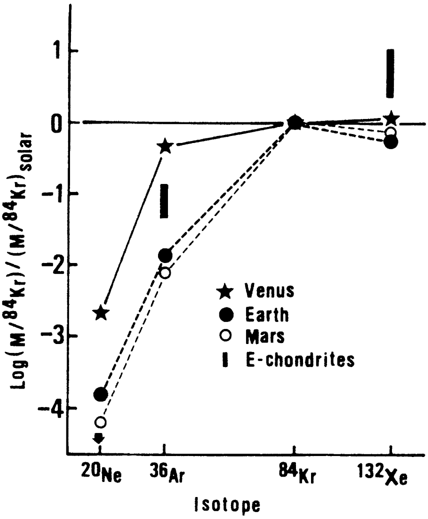

Fig. 1. Noble gas abundance ratios for terrestrial-planet atmospheres and enstatite chondrites are compared with the solar abundance ratio.

to the solar relative abundance, while in the Earth and Mars atmospheres it is significantly depleted. The relative abundances of Kr and Xe in the three planets are similar to the solar relative abundance.

One of the features of the Venus atmosphere is the high ^{36}Ar abundance (Table I). Venus is about 70 times more enriched in ^{36}Ar than the Earth. This ^{36}Ar enrichment does not result from a simple admixing of the solar-wind because the relative abundance of Ne in the Venus atmosphere is low, and is about 1/200 of the solar value. However, Venus is richer in ^{20}Ne by a factor of 30 than Earth because of the large enrichment of ^{36}Ar.

Enstatite chondrites contain a noble-gas component of a similar isotopic trend to the Venus noble-gas. It was named as the subsolar (Crabb and Anders, 1981) or Ar-rich (Wacker and Marti, 1983) component. The same component was reported in an ordinary chondrite Fukutomi (L4) (Takaoka *et al.*, 1989). Along with this, the carbonaceous chondrites Felix (CO3), Lance (CO3), Efremovka (CV3) (Mazor *et al.*, 1970), and the unique chondrites ALH-77167 (L3) (Takaoka *et al.*, 1981), Kakangari (Srinivasan and Anders, 1977) and Sharp (H4) (Zadnik, 1985) may as well contain the Ar-rich component, because their ^{36}Ar/^{132}Xe ratios are considerably high as compared to the planetary ratio (Mazor *et al.*, 1970). This suggests that the

Table I. Comparison of noble gases between Venus and Fukutomi. For comparison, data for the solar noble gases are given.

Sample	$^{36}Ar(cm^3/g)$	$^{20}Ne/^{36}Ar$	$^{84}Kr/^{36}Ar$	$^{132}Xe/^{36}Ar$	$^{20}Ne/^{22}Ne$
Venus [1)]	1.5E − 6	0.21 ± 0.12	(81 + 33)E − 4	(5.7 ± 2.7)E − 5	11.9 ± 0.7
		0.3 ± 0.2[2)]			14 ± 4
Fukutomi[3)]	2.5E − 7	0.29 ± 0.04		0.0031	12.3 ± 1.1
(Ar-rich)	(1.9E − 7)	(0.39 ± 0.06)		(= 0.0003)	
Solar[4)]	1.34E − 2	37	2.7E − 4	1.4E − 5	13.6 ± 0.3

1) Hunte *et al.* (1988) and references cited therein
2) Hoffman *et al.* (1980)
3) Takaoka *et al.* (1989)
4) Ozima and Podosek (1983) and references cited therein

Ar-rich component may not be localized in the enstatite chondrite but may be retained in other classes of meteorites and possibly in the planetesimals which accreted to form Venus.

The concentration of ^{36}Ar trapped in Fukutomi is 3.5 times higher than the highest value so far reported for the type-4 ordinary chondrites (Schultz and Kruse, 1989), except for the solar-gas-rich chondrites. The elemental ratio $^{36}Ar/^{132}Xe$ of 320 is significantly high compared to the ratio of 90 for the planetary-type gas (Mazor *et al.*, 1970). The $^{20}Ne/^{36}Ar$ ratio of 0.29 for Fukutomi is compatible with the ratio of 0.2 or 0.3 for Venus (Table I). The ^{132}Xe concentration is in the range of typical values for the type-4 ordinary chondrites. The Fukutomi noble gas is a mixture of the Ar-rich and the planetary components in view that most ordinary chondrites retain considerable amounts of planetary gas, in particular Ar, Kr and Xe. The planetary Ne is depleted in Fukutomi because the Ne isotopic ratio is solar, as seen in Table I. The trapped Ne in Fukutomi could not be separated from the Ar-rich component by step-heating, and hence, we suppose that this Ne is associated with the Ar-rich component. In this respect, the Fukutomi Ar-rich component is different from that identified originally in the enstatite chondrite by Crabb and Anders (1981), and the isotopic ratio of enstatite chondrite Ne is not solar but planetary. With the assumption of $^{36}Ar/^{132}Xe = 3300$ for the Ar-rich component and $^{36}Ar/^{132}Xe = 90$ for the planetary component, ^{36}Ar from the Ar-rich component was estimated to be 1.9×10^{-7} cm^3/g, or 75% of the measured trapped ^{36}Ar. The $^{36}Ar/^{132}Xe$ ratio of 3300 is an average of 2700 for South Oman (E4-5) and an upper limit of 3800 estimated by Crabb and Anders (1981). Therefore, seven percent of the measured ^{132}Xe, or 6×10^{-11} cm^3/g, is the Ar-rich component. A $^{36}Ar/^{132}Xe$ ratio between 7800 and 96000 was reported for the Venus atmosphere (*e.g.*, Hunten *et al.*, 1988). The $^{36}Ar/^{132}Xe$ ratio adopted above for the Ar-rich component is small compared to this value.

The isotopic ratios are diagnostic instruments for the identification of noble gas components. The estimated ratio of $^{20}Ne/^{22}Ne = 12.3 \pm 1.1$ for Fukutomi trapped Ne (Takaoka *et al.*, 1989) is compatible with the ratio $^{20}Ne/^{22}Ne = 11.9 \pm 0.7$ (Istomin *et al.*, 1982) or 14 ± 4 (Hoffmann *et al.*, 1980) for Venus. The $^{40}Ar/^{36}Ar$ ratio of 6.4 for Fukutomi, corrected for the cosmogenic gas, is higher than that of 1.0 for Venus, but this is due to radiogenic ^{40}Ar mixed with trapped Ar. No reliable data are available for the Kr and Xe isotopic ratios of Venus, although $^{129}Xe/^{132}Xe = 1$ has been reported (Donahue *et al.*, 1981). Fukutomi Xe has an isotopic composition similar to that for the enstatite chondrite (Takaoka *et al.*, 1989).

3. Discussion

The noble gas abundances of the Venus and Mars atmospheres oppose to those expected from the condensation models in the early solar nebula, in which the abundance should be higher in Mars, originated from the relatively cold nebula than that in Venus. A variety of models (*e.g.*, see Hunten *et al.*, 1988) have been proposed to explain for the noble gas result for the planetary atmospheres. However, problems remain to be solved: First, primordial Ne and Ar are highly overabundant on Venus compared to Earth, Mars, and chondritic meteorites. Secondly, the abundance pattern of Ar, Kr, and Xe on Venus is different from that of planetary gas, but rather similar to the solar pattern. In addition, the $^{20}Ne/^{36}Ar$ ratio is planetary, but the $^{20}Ne/^{22}Ne$ ratio resembles the solar value.

The proposed models were categorized into two types: A single-source type and a dual-source type. The single-source-type model assumes that the noble gases were brought by the nebula materials into which the solar wind was implanted. Hence, the noble gas compositions were originally solar. In this respect, the terrestrial-like $^{20}Ne/^{36}Ar$ ratio is regarded as a fortuitous result. The escape of Ne occurred in such way as to give a $^{20}Ne/^{36}Ar$ ratio so close to the terrestrial ratio (Wetherill, 1981). McElroy and Prather (1981) assumed that Ne was lost by the solar heating from trapping sites of activation energy of less than 26 kcal/mol, but the escape of ^{36}Ar was negligible. To account for $^{20}Ne/^{36}Ar$ on Venus, the Ne abundance should be reduced by a factor of 200. If the Ne escape is subjected to a simple Rayleigh process, the $^{20}Ne/^{22}Ne$ ratio on Venus would decrease from 13.6 to 10.4 by a factor of 1.3. A candidate process for the Ne escape accompanied by no isotopic fractionation is shock degassing, as an inverse process to shock implantation. Since the shock degassing of implanted solar wind would accompany an Ar escape as well, this is also problematic.

The dual-source model assumes that Ne was brought by nebula materials into which the solar wind was implanted to a proper abundance to give the Venusian $^{20}Ne/^{36}Ar$ ratio, and mixed with heavy gases which were brought by an impact of a 150 km-sized icy planetesimal. Hence, the icy source should be unusually enriched in primordial Ar, but not in Ne. The $^{20}Ne/^{36}Ar$ ratio for Venus was therefore a fortuitous result as well (Hunten *et al.*, 1988). The remaining questions are: Why did only Venus suffer a large icy impact? Did the icy planetesimal carry heavy noble gases of the solar abundance pattern, and no Ne? Will the Ne of the proper isotopic ratio and abundance, to account for Venus, be observed in comet nuclei? A discussion on these problems was given in Hunten *et al.*, (1988).

It is interesting to note that various kinds of lithic fragments are embedded in the Fukutomi chondrite. One of them is composed of tridymite which is a product in reduced circumstances. It is supposed that the tridymite mixed by impact (Shima *et al.*, 1979). Since the enstatite chondrite is constituted by highly reduced minerals and bears the Ar-rich component, the above observation suggests that the projectile(s) which collided with the parent-body of Fukutomi and impressed the noble-gas signatures on Fukutomi, was composed of materials produced in reduced circumstances such as those of the inner planetary space. Such projectiles are supposed to have carried noble gases of a similar composition to the Fukutomi Ar-rich component, associated with Ne of the solar isotopic ratio. As found in Table I, the ^{36}Ar abundance for the Fukutomi Ar-rich component was an order of magnitude lower than that for Venus. This does not extend to the low ^{36}Ar abundance in the projectiles, because the Ar-rich component should be localized in a relatively small portion of the meteorite. Hence, if we assume such projectiles as carrying the Fukutomi Ar-rich gas as the planetesimal analogues which formed Venus, we can reproduce the elemental and isotopic compositions of noble gases in the Venusian atmosphere.

The remaining problem is how did the projectile acquire the noble gases of the relevant isotopic ratio and abundance. Sasaki (1989) proposed a model in which only the nebula materials or planetesimals moving close to the Venus orbit acquired the solar wind with high efficiency through off-disk implantation, assuming that gravitational scattering by proto-Venus should enhance the orbital inclination of target materials. With this model, the trapped noble gas has the solar composition. Therefore, more than 90% of the implanted Ne should be lost to account for the Venusian Ne/Ar ratio. The escape of Ne without the isotopic fractionation is still the remaining problem. Although there is no good idea on a mechanism solving the above problem, the result on the Fukutomi Ar-rich component presents observational evidence of the existence of a noble gas component similar to Venus in the relative abundance and isotopic ratios.

4. Conclusion

The Ar-rich component found in the Fukutomi (L4) chondrite is associated with Ne with $^{20}Ne/^{36}Ar$ of 0.4 and $^{20}Ne/^{22}Ne$ of 12.3. If planetesimals consisting of materials bearing the Fukutomi Ar-rich component are assumed as the planetesimal analogues which formed Venus, and if the Venusian atmosphere originated from the degassing of these, we can reproduce the relative abundance and the isotopic ratio for the Venus noble gas. Nevertheless, there remains the problem that the $^{20}Ne/^{36}Ar$ ratio is as low as the planetary one but the $^{20}Ne/^{22}Ne$ ratio is as high as the solar. To clear this dilemma, we need to collect more reliable isotopic data on the Venus noble gases and extend on the space exploration to the measurement of comet noble gases.

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