COMETS, METEORITES AND ATMOSPHERES

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Abstract. The relatively low value of Xe/Kr in the atmospheres of Earth and Mars seems to rule out meteorites as the major carriers of noble gases to the inner planets. Laboratory experiments on the trapping of gases in ice forming at low temperatures suggest that comets may be a better choice. It is then possible to develop a model for the origin of inner planet atmospheres based on volatiles delivered by comets added to volatiles originally trapped in planetary rocks. The model will be tested by results from the Galileo Entry Probe.

1. Introduction

This is a summary of the talk given at Mariehamn, which was based in part on a paper currently in press (Owen and Bar-Nun 1995). The central hypothesis of this paper is that impacts by icy planetesimals (comets) have been largely responsible for the inventories of volatile elements that we find on the inner planets today. An obvious corollary of this model is that impacts can also remove volatiles, especially if a planet is small, like Mars. It is the balance between delivery and removal that ultimately determines how much of an atmosphere a given body will possess.

2. The Difficulty with Meteorites

The traditional approach to the problem of atmospheric origin has been to propose one or more classes of chondritic meteorites as the volatile carriers that augmented whatever gases were trapped in the rocks composing the bulk of these planets (Turekian and Clark 1975, Anders and Owen 1977, Dreibus and Wänke 1987, 1989). These meteorites are thought to have supplied a late-accreting veneer of volatile-rich material that degassed upon impact and through subsequent processing on the planets, ultimately producing the atmospheres we observe today. On Earth alone, this simple picture has been strongly modified by the existence of liquid water, plate tectonics, and life, but a reconstruction of the Earth's volatile inventory reveals nearly the same abundances of carbon and nitrogen (per gram of rock) that we find today in the atmosphere of Venus (Donahue and Pollack 1983) and

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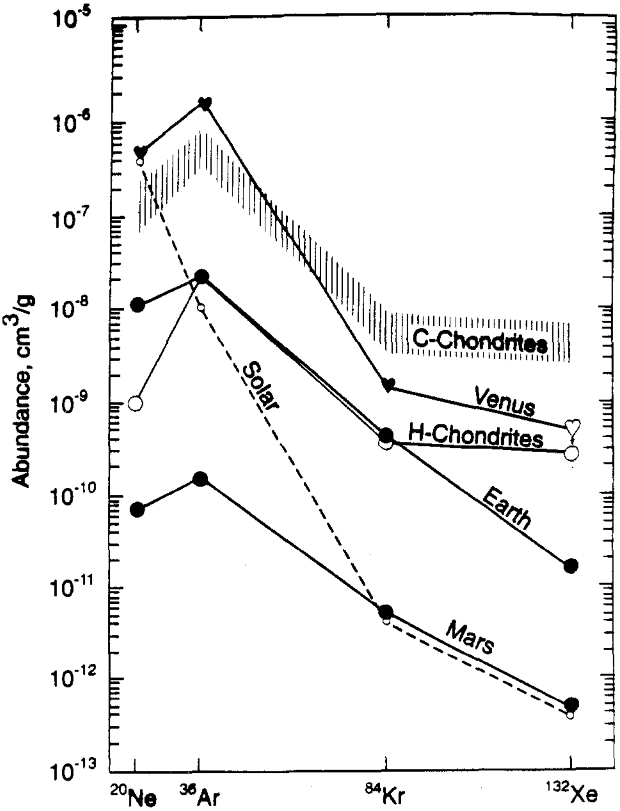

Fig. 1. Abundances of the noble gases per gram of rock for the atmospheres of Venus, Earth, Mars and the ordinary and carbonaceous chondrites. Solar relative abundances are shown for reference.

about the same proportion of C/N that we see in the current atmospheres of both Venus and Mars (Owen et al. 1977).

These pleasing similarities come to an end when we consider the noble gases. Taking Earth as our standard, we find that Venus has far more neon and argon than Earth possesses, more even than exists in type I carbonaceous chondrites, per gram of rock. Furthermore, the relative abundances of krypton and argon on Venus are dramatically different from those on Earth, Mars, or in the meteorites. The ratio of Ar/Kr on Venus is closer to the solar value than the ratio we find in these other sources (Figure 1).

In contrast, Mars shows nearly the same relative abundance pattern as the Earth, but the absolute abundances of noble gases per gram of rock are over two orders of magnitude *lower* than those in Earth's atmosphere or the ordinary chondrites (Figure 1). Finally, on both Mars and Earth, Kr/Xe ~ 10, whereas in the meteorites, this ratio is near unity.

On Earth, this last deficiency is often referred to as the "missing xenon problem". For many years, people assumed that this missing xenon must be trapped in shales, ice, or clathrate hydrates. It now seems clear that it simply isn't there (e.g. Wacker and Anders 1984).

3. A Cometary Solution

This was the background for our attempt to see if comets might be a suitable substitute for the meteorites. While this idea has certainly come up before (e.g. Sill and Wilkening 1978), it has suffered from the absence of data. We now have much better information about abundances of elements and compounds in the interstellar medium, in comets, and in planetary atmospheres. There are still no observations of noble gases in comets, which is not surprising in view of the fact that the ground-state transitions of these elements produce emission lines only in the far ultraviolet region of the spectrum. The mass spectrometers on the Giotto spacecraft also failed to detect any noble gases (Geiss 1988).

We have therefore relied on laboratory investigations to simulate the formation of cometary ices in the outer solar nebula (Bar-Nun et al. 1985, 1988; Owen et al. 1991). These experiments have shown that amorphous ice forming at temperatures in the range 16–190 K will trap gases in amounts that are a strong function of the temperature at which the trapping occurs. Hydrogen and helium are only trapped at very low temperatures; above 25 K even neon is not retained by the ice. A solar mixture of argon, krypton and xenon is trapped in its original proportions at 30 K, but is severely fractionated at 50 K.

This result led us to suspect that comets might indeed serve as the volatile carriers we were seeking. We tried the simple hypothesis of assuming that both Mars and Earth obtain their heavy noble gases (argon, krypton and xenon) from two reservoirs – one internal: the rocks that make up the bulk of the planet, and one external: impacting icy planetesimals (comets). We constructed a three-element plot on which the proportions of these three noble gases in the atmospheres of Mars and Earth would correspond to two points (Figure 2). The ratios of Ar/Xe and Kr/Xe found in various chondritic meteorites and the sun are also illustrated as is the domain of possible values for the atmosphere of Venus, where only an upper limit for xenon exists at the present time.

In our simple model, a straight line connecting Mars and Earth in such a plot will extend into the domain of the external reservoir at one end and into the internal reservoir at the other. In the logarithmic plot illustrated in Figure 2, this "mixing line" appears curved, since it is a simple linear function. Here we see that the point from the laboratory experiments that

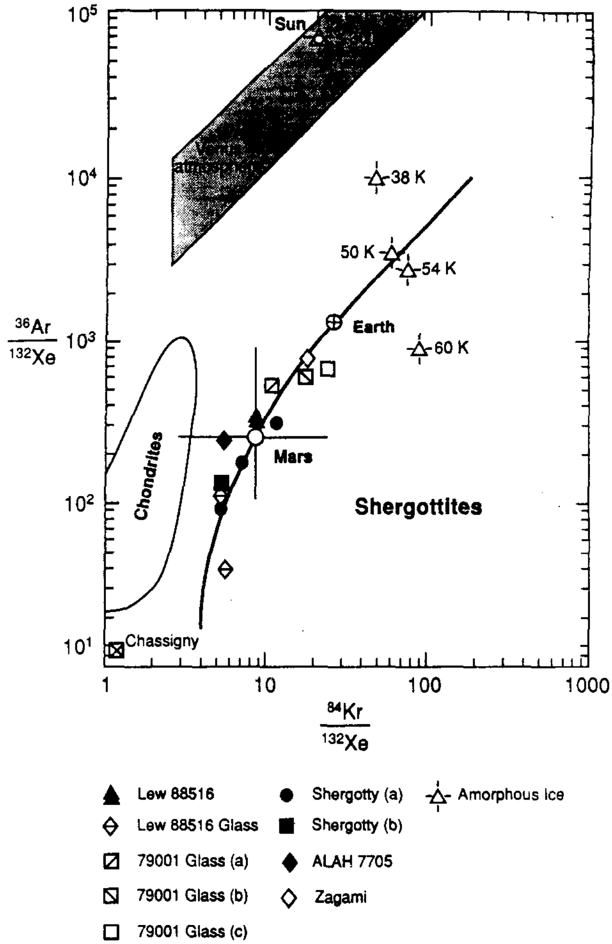

Fig. 2. Ratios of the heavy noble gases in planetary atmospheres, chondritic meteorites and the SNC meteorites. The mixing line described in the text is the heavy line through the points for the atmospheres of Earth and Mars. Only an upper limit exists for Xe on Venus, hence the trapezoidal uncertainty.

corresponds to the mixture of noble gases trapped by ice at 50 K falls right on an extrapolation of this mixing line. Icy planetesimals that formed at about 50 K thus constitute a plausible external reservoir for the heavy noble gases on these two planets. This is a significant result, because 50 K is the canonical temperature for the Uranus-Neptune region of the solar nebula where most of the Oort cloud comets are thought to have formed (Boss et al. 1989, Oort 1990).

The rocky reservoir is then located at the other end of the mixing line, somewhere below the point for Mars. Why are Mars and Earth so far apart on this diagram? Evidently Mars is missing much of its cometary complement of gases. This conclusion is consistent with the present thinness of the

Martian atmosphere and the low abundances of the noble gases on Mars that we see in Figure 1. Melosh and Vickery (1989) have shown that Mars must have lost an amount of atmosphere equivalent to at least 100 times the atmosphere we see today as a result of impact erosion during the early heavy bombardment. Impact erosion also appears to be the only process that can account for the high values of $^{129}Xe/^{130}Xe$ and $^{40}Ar/^{36}Ar$ that we find on Mars, respectively 2.5 and 100 times the terrestrial ratios (Owen et al. 1977, Owen 1992). Evidently many of the cometary impacts that on Earth would have delivered volatiles, failed to do so on Mars. Both impacting comets and asteroids would contribute to an erosion of the Martian atmosphere that would have been more severe than that which occurred on the more massive Earth.

Figure 2 also contains points for noble gases measured in a number of Shergottite meteorites (see Owen et al. 1992 and Owen and Bar-Nun 1993 for references). These meteorites are now generally acknowledged to have originated on Mars, as demonstrated in part by the gases they contain (Bogard and Johnson 1983, Becker and Pepin 1984). What we see in Figure 2 is that samples of the noble gases extracted from these meteorites (sometimes different samples of the same stone or even different temperature releases from the same sample) exhibit proportions of argon, krypton and xenon that lie along the mixing line. Some samples fall above the Mars atmosphere point (based on the Viking Lander measurements of Owen et al. 1977) and some fall below. Our interpretation of these data is that the meteorites represented by the lowest points contain a mixture of Martian atmosphere with samples of the internal reservoir. The recent measurements of Becker and Pepin (1993) in the samples of glass from LEW 88516 tend to strengthen the mixing line formulation. As we move up the mixing line toward the Earth, it appears that the meteorites are adding cometary gas to the mixture they contain. This suggests that the impactor that blew them off the surface of Mars was a comet. On the other hand, the large error bars on the Viking Mars atmosphere measurement allow the possibility that the highest points on this curve, for Zagami and EETA 79001, may represent the Martian atmosphere, and the lower points simply correspond to increasingly greater proportions of gas from the internal, rocky reservoir. Additional analysis of the gases from the other SNC meteorites, especially the Nakhlites, will be required to settle this question.

With this model, we can explain the unusual noble gas pattern found in the atmosphere of Venus by invoking an impact by one or more comets from the Kuiper Disk (Kuiper 1951, Duncan et al. 1988, Jewitt and Luu 1993). These objects will have formed at temperatures near 30 K, thereby trapping the noble gases in nearly solar proportions. Obviously comets from both the Kuiper Disk and from the Uranus-Neptune region must have struck all these inner planets. What we are therefore suggesting is that Venus received a dominating share of its heavy noble gases from the colder source.

Because neon is only trapped in ice at temperatures below 25 K, we suggest that the neon in these atmospheres is a relic of gas trapped almost exclusively in the rocks that make up most of the mass of these planets. The severe fractionation $^{20}Ne/^{22}Ne$ that we observe today may then reflect early escape processes whose effects on nitrogen and the other noble gases have been masked by subsequent cometary delivery of these volatiles.

4. Conclusions, Implications, and Tests

The laboratory experiments on the trapping of argon, krypton and xenon in ice at temperatures characteristic of the Uranus-Neptune region of the solar nebula demonstrate a fractionation pattern of noble gas abundances found in the atmospheres of Mars and Earth. This suggests that these gases were delivered to the inner planets by icy planetesimals, a.k.a. comets. If that is true, other volatiles would be brought in as well, most notably water, carbon and nitrogen. The hydrogen that is bound up in carbon and nitrogen compounds in the comet nuclei would become available on the planets to make compounds, offering the potential for early reducing atmospheres. On Mars, because of its small size, impacts apparently carried off more atmosphere than they produced, leaving the thin envelope we find today.

This model can be tested in a number of ways, as described in our complete paper (Owen and Bar-Nun 1995). The first test is simply to see if argon rather than neon is present in dynamically new comets. This will require either a dedicated rocket launch for observations of the UV spectrum of a bright comet, or a comet mission that includes the option of examining volatiles trapped in the interior of a comet nucleus.

Future missions to Mars and Venus can determine more details about atmospheric noble gases. For example, we would predict that the krypton/xenon ratio on Venus is very close to the solar value. Accurate values for the krypton and xenon isotopes on Mars would allow more meaningful interpretation of the SNC data, including the possible role of a comet in expelling the Shergottites from Mars.

Perhaps the first test of the general model of icy planetesimal delivery of volatiles will come from the Galileo spacecraft encounter with Jupiter in December 1995. The Galileo Probe will carry a mass spectrometer capable of measuring abundances and isotopic ratios to a depth of about 10 bars. We already know that $C/H \approx 3\times$ solar in Jupiter's atmosphere, but the value of N/H is somewhat uncertain. The enrichment of carbon is commonly attributed to the release of gases from the condensed matter (icy planetesimals) that formed the original core of the planet. The model therefore predicts that N/H will be approximately solar, rather than enhanced to the same degree as C/H. The reason is that ice formed in Jupiter's region of the solar nebula would not have been able to trap N_2, only nitrogen compounds. While most of the carbon in the original solar nebula was presumably in the form of compounds with relatively low-volatilities, most of the nitrogen was present as N_2. Hence N/C in the icy material should have been sub-solar, as it was found to be in Halley's Comet (Geiss 1988).

On the other hand, the envelope of nebula gas that has provided most of Jupiter's atmosphere would contain that N_2. Therefore, we expect $N/H \approx$ solar and $N/C <$ solar in the atmosphere. Because this nitrogen came from N_2, rather than from N-compounds that the model suggests were the source of our atmospheric nitrogen, the isotope ratio $^{14}N/^{15}N$ may be different on Jupiter as well.

The mass spectrometer on the probe will have an opportunity to measure both N/C/H and $^{14}N/^{15}N$, although the former measurement will be particularly difficult owing to the tendency for NH_3 to absorb on the metallic walls of the instrument and its inlet system.

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