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The Origin of Inner Planet Atmospheres [and Discussion]

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The origin of inner planet atmospheres

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In a series of laboratory experiments, A. Bar-Nun and colleagues (Bar-Nun *et al.* 1985, 1988; Owen *et al.* 1991) have succeeded in analysing the amounts of gases trapped in amorphous ice forming at low temperatures (16–190 K). They found that a temperature-dependent fractionation of noble gases occurs. The relative abundances of argon, krypton and xenon trapped by ice formed at 50 K fit an extrapolated mixing line that passes through points for the abundances of these same gases in the atmospheres of Mars and Earth on a three-isotope plot. The noble gases in the Shergottites, one of the three types of meteorites originating on Mars, also fall on this line (figure 1). A study of the xenon isotopes in the Shergottites and Nakhlites (a second type of Martian meteorite) suggest that these meteorites contain gases from the Martian interior and atmosphere, and the Shergottites may also include a component from the impactor that expelled them from the planet (Owen & Bar-Nun 1993). Taken together, these data provide a good indication that icy planetesimals (comets) that formed in the Uranus–Neptune region ($T \sim 50$ K) played a major role in delivering the noble gases to Mars and the Earth. Venus could have obtained its noble gases from the impact(s) of one or more comets formed at the lower temperatures ($T \sim 30$ K) prevailing in the Kuiper Belt (Owen *et al.* 1992; Owen & Bar-Nun 1993).

Given that ice is the carrier, one naturally expects that comets could have brought in *all* the volatiles. This idea is buttressed by a study of nitrogen. The same laboratory experiments referenced above demonstrate that CO is trapped twenty times more efficiently than N_2 in ice forming at 50 K. Since N_2 is expected to be the dominant carrier of nitrogen in the solar nebula, whereas CO is likely to contain no more that 15–30% of the total carbon, this would lead to a severe depletion of nitrogen in icy planetesimals. In evaluating C/N in Halley's comet, the atmospheres of Venus and Mars, and the volatile inventory of the Earth, one sees exactly this effect. In all four inventories $C/N = 20 \pm 10$, whereas the solar value is 3.2. Thus we again discover support for the cometary delivery hypothesis (Owen & Bar-Nun 1994).

Impacts can also result in the *loss* of volatiles, as has been stressed by Melosh & Vickery (1989). These authors found that impact erosion of the Martian atmosphere could have removed at least 100 times the present mass of gas, without fractionating the constituents. This is an elegant explanation for the otherwise baffling thinness of the present Martian atmosphere. It also explains the surprisingly high values of $^{129}Xe/^{132}Xe$ and $^{40}Ar/^{36}Ar$ found on Mars (Owen *et al.* 1977; Owen 1992).

Adopting the comet-impact model, it is possible to evaluate the total existing Martian volatile inventory. Starting from the present atmosphere and using ^{36}Ar as the indexing volatile, one expects an atmosphere with a surface pressure of

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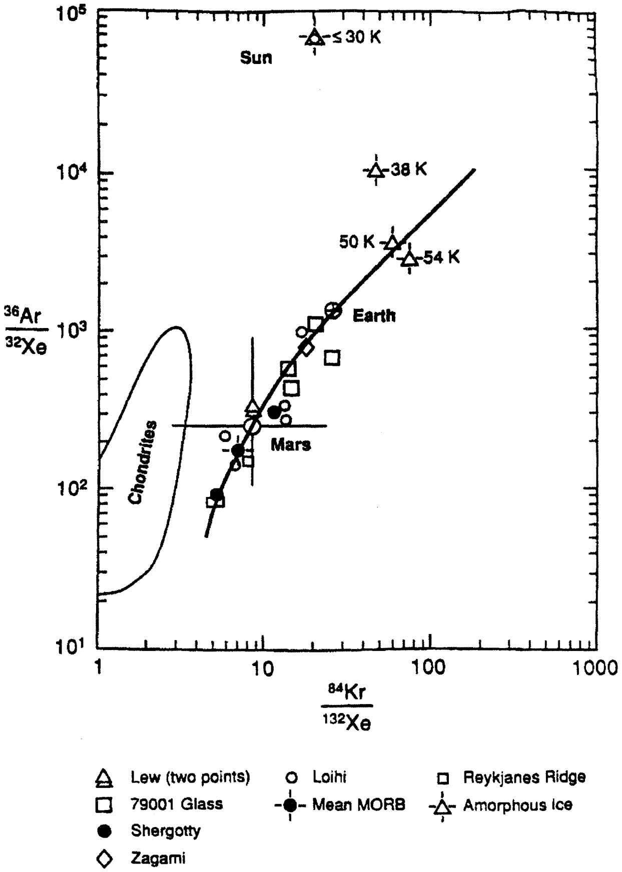

Figure 1. The heavy noble gases measured in the atmospheres of the Earth (CRC Handbook) and Mars (Owen *et al.* 1977) define a mixing line that passes through abundances measured in the Shergottite meteorites and samples of amorphous ice formed at $T \sim 50$ K in a solar mixture of gases (Owen & Bar-Nun 1993). Points for various submarine basalts (Loihi, Mean MORB, Reykjanes Ridge) are shown for comparison.

about 40 mb, instead of the observed 6 mb. This is similar to the total surface pressure obtained from examining the nitrogen heavy-isotope enrichment (Fox 1989) and assuming the standard ratio of $C/N = 20 \pm 10$. The missing CO_2 may well be trapped in the regolith, while the absent nitrogen has escaped from the planet, leading to the observed high value of $^{15}N/^{14}N$. But this atmosphere has too little water associated with it to account for the planet's famous fluvial features. For this it is necessary to involve impact erosion, which is *required*, as noted above, to explain the excess nucleogenic isotopes. Comparison with the Earth's inventory then suggest that Mars could originally have held about 5 bars of CO_2, with an associated amount of H_2O equivalent to a 0.5 km layer on the planet. Much of this water may still be there, since it would not have been ejected by the impact erosion process.

An interesting aspect of this model is that it allows episodic intervals of high surface pressure and hence clement climatic conditions during the early intense bombardment (4.5–3.8 AE). The mass of the atmosphere would fluctuate in response to low-velocity comet impacts – bringing volatiles in – and higher-velocity impacts of comets and asteroids that would drive the volatiles off. The availability of liquid water during these clement periods leaves open the fascinating possibility of the origin of life. This possibility becomes even more interesting when one realizes that the atmosphere created by these cometary impacts would have been hydrogen-rich, given the composition of cometary nuclei (e.g., Encrenaz *et al.* 1991).

The model we have developed is subject to several tests, as we have repeatedly stressed. The first one is simply to find noble gases in comets. We expect argon to be detectable, but not neon, since the latter is not trapped in ice even at 25 K (Bar-Nun *et al.* 1985). The Ar/N_2 ratio in comets formed at 50 K should be about 0.3, based on laboratory experiments. A more imminent test will come from the Galileo probe into Jupiter's atmosphere, which will occur in December 1995. We expect N/H on Jupiter to have the solar value, even though C/H is nearly three times the solar value. More nitrogen should have been captured as N_2 directly from the solar nebula than in compounds that were in the icy planetesimals that formed Jupiter's core during early accretion and the later ones that dissolved in the gaseous envelope when they impacted the growing planet. Organic compounds in these planetesimals were presumably the source of the enriched carbon. With $C/N \sim 20$ they could not have supplied the majority of Jupiter's nitrogen. In contrast, the model dictates that the nitrogen in our own atmosphere came primarily from these nitrogen compounds. The $^{15}N/^{14}N$ ratio on Jupiter may therefore be distinctly different from the value on Earth. If nitrogen follows hydrogen in this respect, we anticipate that $^{15}N/^{14}N$ will be lower on Jupiter than on Earth.

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Discussion

W.M. Kaula (*UCLA, U.S.A.*). An attractive hypothesis to explain the great difference in inert gas abundance between Venus and the Earth – particularly primordial argon – is that the biggest impact into Earth was more massive than the biggest into Venus. But does preservation of the difference limit addition of volatiles by icy planetesimals from the outer Solar System?

T. Owen. In fact, the amount of primordial argon per gram of planet is larger on Venus than on Earth. It is not just the amount that is different, however, it is the ratio of argon to krypton, which on Venus resembles the solar value rather than the terrestrial one. It is for this reason that we feel a low-temperature icy planetesimal is required to deliver the gases to Venus. Ice formed at ~ 30 K can trap about 25 times as much as gas as ice formed at 50 K, and at 30 K no fractionation of the trapped gases occurs. Hence the potential to produce both the effects observed in the noble gases on Venus could be realized by impacts from low-temperature icy planetesimals. Earth and Mars should also have suffered such bombardment. The difference would be that Venus simply had a larger proportion of them relative to the 50 K planetesimals.

I. P. Wright (*Department of Earth Sciences, Open University, U.K.*). There are some meteorites (such as Bencubbin), which are anomalous for a number of reasons, but of interest here is that they show evidence of shock melting and enrichments in ^{15}N. It would appear that the meteorites are the result of impact into a pre-existing regolith of some sort. There are no *a priori* reasons to expect that the ^{15}N comes from the meteorites themselves – rather it would appear that the isotopically enriched nitrogen comes from the body that caused the shock melting (i.e. the impactor). Having embraced the notion that some of the noble gases in SNC meteories could originate from an impactor (e.g. an icy planetesimal), to what extent are the ^{15}N/^{14}N data from these samples likely to be affected by gases from an external source? Could the high ^{15}N/^{14}N values observed in the Martian atmosphere (normally attributed to atmospheric loss processes) be in any way the result of gases added by impacting bodies?

T. Owen. It is impossible to rule out categorically the delivery of isotopically anomalous nitrogen to Mars by some family of impactors, but it seems highly unlikely. The reason is the absence of an appropriate reservoir of such objects. It is certainly true that there are some meteorites with anomalously heavy nitrogen, there are others – such as Allende and Murchison – that contain material with very light nitrogen. Most of the nitrogen presumably has the telluric value. What about the comets? We don't yet have a direct measurement of nitrogen isotopes in cometary gas. Bar-Nun and I are suggesting that it will again prove to be telluric, except in N_2, but this is certainly a measurement that needs to be done. It would also be good to know the value of this ratio in the Sun and in interstellar clouds. As we have pointed out, if N/H proves to be solar on Jupiter, the Galileo probe has a good chance of determining the solar value of ^{15}N/^{14}N. On Mars, it seems to be easy to explain the observed enrichment of ^{15}N by means of non-thermal escape from the atmosphere. Indeed the problem at present is that existing models produce too much enrichment! This is an active area of research and should lead to an improvement in our ideas about the evolution of the Martian atmosphere.