A low-temperature origin for the planetesimals that formed Jupiter

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The four giant planets in the Solar System have abundances of 'metals' (elements heavier than helium), relative to hydrogen, that are much higher than observed in the Sun. In order to explain this, all models for the formation of these planets rely on an influx of solid planetesimals[17]. It is generally assumed that these planetesimals were similar, if not identical, to the comets from the Oort cloud that we see today. Comets that formed in the region of the giant planets should not have contained much neon, argon and nitrogen, because the temperatures were too high for these volatile gases to be trapped effectively in ice. This means that the abundances of those elements on the giant planets should be approximately solar. Here we show that argon, krypton and xenon in Jupiter's atmosphere are enriched to the same extent as the other heavy elements, which suggests that the planetesimals carrying these elements must have formed at temperatures lower than predicted by present models of giant-planet formation.

We are continuing the calibration of the Galileo probe mass spectrometer using a duplicate of the flight model instrument. We previously reported revised values of $^3He/^4He$ and D/H from this work[1]. Proceeding to the noble gases[2], we have now found a value of 2.1 ± 0.4 times the solar value for the argon mixing ratio, clearly indicating enrichment over the expected solar nebular value. We have also found krypton and xenon to be similarly enhanced, at 2.7 ± 0.5 and 2.6 ± 0.5 times the solar values, respectively. These new results supercede our previously published upper limits ($\leqslant 5$ times the solar value) for ^{84}Kr and ^{132}Xe, and our preliminary evaluation of the argon mixing ratio at 2.5 ± 0.5 times the solar value[3]. Aside from the neon that dissolves in the 'raindrops' of helium that are coming out of solution in the fluid metallic hydrogen in the planet's interior[4], it appears that the heavy noble gases share essentially the same enrichment as carbon and sulphur on Jupiter (Fig. 1).

This concordance invites a review of the jovian nitrogen abundance, as ground-based microwave observations have suggested that N/H is only 1.2–1.3 times the solar value[5–8]. Although we have not yet been able to obtain more than an upper limit on nitrogen from the mass spectrometer, Folkner *et al.*[9] succeeded in deriving N/H from analysis of the attenuation of the probe's radio signal by NH_3. Adjusting this determination[9] of the jovian ammonia mixing ratio to the solar abundances established by Anders and Grevesse[10] (which we use throughout), we find N/H = 3.6 ± 0.5 times the solar value at pressure levels below approximately 8–10 bar. This is consistent with our new results for noble gases as illustrated in Fig. 1. We believe the apparent discrepancy between the probe and ground-based ammonia mixing ratios can be resolved by examining the pressure levels sampled by the microwave observations and the error bars associated with these measurements. We have showed[11] that it is possible to reconcile the Folkner *et al.*[9] profile of ammonia

with the ground-based microwave spectrum of the planet, provided ammonia is depleted at pressure levels above ~4 bar.

The cause of the ammonia depletion remains unknown. It is not the result of a 10 times solar abundance of sulphur forming thick NH_4SH clouds, as de Pater[6] originally suggested, because sulphur, like carbon, is only enriched by about a factor of 3 in Jupiter's atmosphere. Some type of meteorological process seems more likely. If H_2S and H_2O both behave as NH_3 does in the globally averaged jovian atmosphere, these species will only reach their maximum mixing ratios at altitudes considerably below the equilibrium condensation levels corresponding to ~3 times solar abundances.

We conclude that the deep, well-mixed atmosphere of Jupiter exhibits essentially the same enrichment of nitrogen as it does for carbon, sulphur, the heavy noble gases, and, we assume, everything else except neon and helium. This requires that argon, krypton, xenon and nitrogen were present in solar proportions relative to carbon and sulphur in the icy planetesimals that contributed to Jupiter's formation. We know of no solid materials in the Solar System that exhibit this composition, although we have suggested it for the Kuiper belt objects[12].

This suggestion was based on laboratory studies of the trapping of highly volatile gases in amorphous ice forming at temperatures below 75 K (refs 12, 13). These experiments show that trapping argon and N_2 in solar abundances relative to carbon in icy planetesimals requires condensation of the ice at temperatures $\leqslant 30$ K (capturing neon in this proportion requires a temperature $T < 17$ K). Such temperatures would be appropriate to the region of the original solar nebula beyond the orbit of Pluto, where we now find the Kuiper belt. In contrast, the Oort cloud comets are thought to have formed in the Uranus–Neptune region, where solar nebula temperatures were of the order of 55 K (ref. 14). Ice forming there could only have trapped 1% of the ambient argon and N_2. It is generally accepted that $\geqslant 70\%$ of interstellar (and hence outer solar
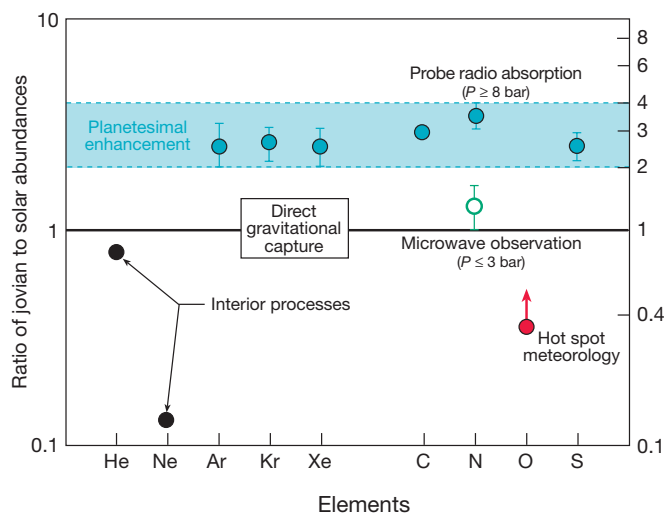

Figure 1 Elemental abundances (relative to hydrogen) in Jupiter's atmosphere compared with solar values. All the elements except nitrogen were measured by the Galileo probe mass spectrometer. The nitrogen abundance was determined by Folkner *et al.*[9] from the attenuation of the probe radio signal by ammonia in Jupiter's atmosphere. These data were derived from calibrations carried out with a duplicate model of the mass spectrometer used on the Galileo probe, known as the Engineering Unit. These calibrations may be more accurate, in many cases, than those carried out before launch on the Flight Unit, as they exercise the full range of the instrument's capabilities—including the enrichment cells—under conditions that duplicate those encountered during the descent. For example, gas mixtures are used in the Engineering Unit calibrations that are more representative of the actual jovian atmosphere than mixtures used to calibrate the Flight Unit before launch and the temperatures realized by enrichment cells during the descent can be duplicated in these experiments. Recent refurbishment has restored the Engineering Unit to a condition that even more closely resembles that of the Flight Unit.

nebula) nitrogen is in the form of N_2 (refs 15–17); this explains the observed deficiency of nitrogen (argon has not yet been detected) in Oort cloud comets[18–20].

It seems to us that the only explanation for the uniform enrichment of heavy elements that we observe on Jupiter is that these elements came to the planet in very cold ($T < 30$ K) icy planetesimals. This differs from conventional models, which relate the formation of giant planets to the threshold distance from their stars where it first becomes cold enough for water ice to condense in the circumstellar disks. In these 'snowline' models, the ice condenses at $T \approx 160$ K (~5 AU in our Solar System)[14,17]. Argon and N_2 would be depleted by over 4 orders of magnitude in icy planetesimals formed at such temperatures[12].

We need to devise ways in which such low temperature material could have been produced and transported to the giant planets. Could planetesimals have formed in the interstellar medium during the early phases of cloud fragmentation and collapse? Or was the solar nebula much colder than current models predict? Or did Jupiter migrate to its present position from beyond 30 AU? The difficulties inherent in each of these suggestions emphasize the significance of this new constraint.

Additional tests will require more probes to the outer planets. We predict that the global oxygen abundance on Jupiter should show the same enrichment as the other elements. The apparent depletion in Fig. 1 must result from the same local, meteorological effect acting on H_2O, that has depleted H_2S and NH_3 in the upper part of the probe's trajectory[21–23]. Perhaps all the outer planets show the same enhancement of Ar and N as we find on Jupiter. The presence of HCN in the upper atmosphere of Neptune may indicate that this is the case, as this gas appears to require planetary N_2 for its existence[24]. □

1. Mahaffy, P. R., Donahue, T. M., Atreya, S. K., Owen, T. & Niemann, H. B. in *Primordial Nuclei and their Galactic Evolution* (eds Prantzos, N., Tosi, M. & von Steiger, R.) 239–250 (Kluwer, Dordrecht, 1998).
2. Mahaffy, P. R., Niemann, H. B., Alpert, A., Atreya, S. K., Donahue, T. M. & Owen, T. Heavy noble gases in the atmosphere of Jupiter. *Bull. Am. Astron. Soc.* 30, 1066 (1998).
3. Niemann, H. *et al.* The composition of the Jovian atmosphere as determined by the Galileo probe mass spectrometer. *J. Geophys. Res.* 103, 22831–22845 (1998).
4. Roulston, M. S. & Stevenson, D. J. Production of neon depletion in Jupiter's atmosphere (abstract). *Eos* 76, F343 (1995).
5. de Pater, I. & Massie, S. T. Models of the millimeter-centimeter spectra of the giant planets. *Icarus* 62, 143–171 (1985).
6. de Pater, I. Jupiter's zone-belt structure at radio wavelengths. *Icarus* 68, 344–365 (1986).
7. Joiner, J. & Steffes, P. B. Modelling of Jupiter's millimeter wave emission utilizing laboratory measurements of ammonia (NH_3) opacity. *J. Geophys. Res.* 96, 17463–17470 (1991).
8. Romani, P. N., de Pater, I. & Zahnle, K. Galileo, SL9 and Jupiter's deep atmosphere. *Bull. Am. Astron. Soc.* 27, 81 (1995).
9. Folkner, W. M., Woo, R. & Nandi, S. Ammonia abundance in Jupiter's atmosphere derived from attenuation of the Galileo probe's radio signal. *J. Geophys. Res.* 103, 22847–22856 (1998).
10. Anders, E. & Grevesse, N. Abundances of the elements: Meteoritic and solar. *Geochim. Cosmochim. Acta.* 53, 197–214 (1989).
11. Atreya, S. K., Wong, M. H., Owen, T., Mahaffy, P. R., Niemann, H., de Pater, I., Drossart, P. & Encrenaz, Th. A comparison of the atmosphere of Jupiter and Saturn: Deep atmospheric composition, cloud structure, vertical mixing and origin. *Planet. Space Sci.* (in the press).
12. Owen, T. & Bar-Nun, A. Comets, impacts and atmospheres. *Icarus* 116, 215–226 (1995).
13. Bar-Nun, A., Kleinfeld, I. & Kochavi, E. Trapping of gas mixtures by amorphous water ice. *Phys. Rev. B* 38, 7749–7754 (1988).
14. Cassen, P. Utilitarian models of the solar nebula. *Icarus* 112, 405–429 (1994).
15. Linke, R. A., Guelin, M. & Langer, W. O. Detection of $H^{15}NN^+$ and $HN^{15}N^+$ in interstellar clouds. *Astrophys. J.* 271, L85–L88 (1983).
16. Womack, M., Wyckhoff, S. & Ziurys, L. M. Observational constraints on Solar Nebula nitrogen chemistry: N_2/NH_3. *Astrophys. J.* 401, 728–735 (1992).
17. Van Dishoeck, E. F., Blake, G. A., Draine, B. T. & Lunine, J. I. in *Protostars and Planets III* (eds Levy, E. H. & Lunine, J. I.) 163–244 (Univ. Arizona Press, Tucson, 1993).
18. Geiss, J. Composition of Halley's Comet: Clues to origin and history of cometary matter. *Rev. Modern Astron.* 1, 1–27 (1988).
19. Krankowsky, D. in *Comets in the Post-Halley Era* (eds Newburn, R. L. Jr, Neugebauer, M. & Rahe, J.) 855–878 (Kluwer, Dordrecht, 1991).
20. Wyckoff, S., Tegler, S. C. & Engel, L. Nitrogen abundance in Comet Halley. *Astrophys. J.* 367, 641–648 (1991).
21. Owen, T., Atreya, S. K., Mahaffy, P., Niemann, H. B. & Wong, M. H. in *Three Galileos: The Man, The Spacecraft, The Telescope* (eds Barbieri, C., Rahe, J., Johnson, T. V. & Sohus, A.) 289–297 (Kluwer, Dordrecht, 1997).
22. Atreya, S. K., Owen, T. C., Wong, M. H., Niemann, H. B. & Mahaffy, P. R. in *Three Galileos: The Man, The Spacecraft, The Telescope* (eds Barbieri, C., Rahe, J., Johnson, T. V. & Sohus, A.) 289–297 (Kluwer, Dordrecht, 1997).
23. Showman, A. P. & Ingersoll, A. P. Interpretation of Galileo Probe data and implications for Jupiter's dry downdrafts. *Icarus* 132, 205–220 (1998).
24. Marten, A. *et al.* First observations of CO and HCN on Neptune and Uranus at millimeter wavelengths and their implications for atmospheric chemistry. *Astrophys. J.* 406, 285–297 (1993).

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Lithium nucleosynthesis in the Sun inferred from the solar-wind ^{7}Li/^{6}Li ratio

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The abundance of lithium measured in meteorites has generally been assumed to be the 'Solar System value', which presumably reflects the abundance in the gas cloud out of which the Sun formed[1]. Lithium is a factor of 140 less abundant in the solar photosphere than in meteorites[2]; this difference has been attributed to the destruction of lithium (through nuclear reactions) at the base of the Sun's convection zone[3–5]. If this is correct, then the ratio of ^{7}Li/^{6}Li in the Sun's photosphere should be ~10^6 (ref. 6), as ^{6}Li is destroyed much more easily (at a lower temperature) than ^{7}Li: the meteoritic abundance ratio is ^{7}Li/^{6}Li = 12.14 (ref. 7). Here we report that ^{7}Li/^{6}Li = 31 ± 4 for lithium in the solar wind that has been implanted in lunar soil. This low ratio suggests that lithium is produced when energetic protons from solar flares induce spallation reactions with ^{16}O and ^{12}C present in the photosphere.

Solar-wind particles, because of their low energy (~8 keV), are implanted within the first ~0.03 μm of the grains constituting the lunar soils[8]. With the exception of volatile elements[9,10], the isotopic composition of the solar wind has never been measured because of the difficulty of extracting selectively the solar fraction of nonvolatile elements from lunar rocks. We describe here an approach to this technical problem, using ion-probe shallow-depth profiling for the determination of the ^{7}Li/^{6}Li ratio of the trapped solar wind. Four samples of lunar soils (79261, 79035, 79221, 10060) have been analysed for Li (19 depth profiles corresponding to ~4,000 determinations of the ^{7}Li/^{6}Li ratios and Li concentrations). Examples of depth profiles are shown in Fig. 1. The total depth of each profile, and the maximum and minimum measured ^{7}Li/^{6}Li ratios, are reported in Table 1.

In the soil samples marked departures of the ^{7}Li/^{6}Li ratio from the Solar System range[7] are observed as a function of the sputtering time. With one exception (sample 10060,4), Li sputtered from the first 0.01 μm is enriched in ^{7}Li (^{7}Li/^{6}Li ratios up to 22.8) compared to that from further in. Since the solar wind Li (SW Li) should be enriched in ^{7}Li due to the rapid astration (Li destruction in stars) of ^{6}Li compared to ^{7}Li (refs 6, 11), this surface ^{7}Li-rich component can be ascribed to solar-wind implantation. The low ^{7}Li/^{6}Li ratios (down to 6.8) are generally observed deeper than SW Li. This ^{6}Li-rich component can be ascribed to spallation reactions (spall-L Li) taking place through the interaction between lunar soils and the solar (or galactic) energetic cosmic rays which yields[12] a ^{7}Li/^{6}Li ratio close to 2. At greater depth the measured ^{7}Li/^{6}Li ratios approach 12,