ice coagulated to form planetesimals. In the Jupiter-forming zone, enough of this material (perhaps several Earth masses) somehow concentrated in one body. Gravitational influence then led to a steady inflow of gas, building up the planet that we now see. The gas envelope consisted mainly of hydrogen and helium, with an overall composition that was enriched in heavier elements. This story is compatible with models of Jupiter as it is now⁴, although one might expect the atmosphere to be depleted in water (because the water is in the core) or any other condensate. However, it may have been that planetesimals still entering Jupiter during and after the gas inflow broke up, their constituents mixing with the gas^{3,5}. Convective mixing from the interior might also bring heavier elements up from the core. Support for enrichment comes from observations of carbon (as methane) in the atmosphere⁵.

Noble gases present a different set of issues. Helium and neon do not condense or stick to solid particles at the temperatures concerned, so it is reasonable to suppose that they were initially in cosmic proportions in the atmosphere. However, helium is believed to be insoluble in hydrogen at very high pressures, even at very high temperatures, because the hydrogen metallizes, and the interaction between light noble gases and conduction electrons is highly repulsive⁶. As Jupiter cooled over time, runs the argument, helium would 'rain out' in the deep interior, and because of that and convective mixing the atmosphere would become depleted in the element. Neon is far less abundant and thus unlikely to form its own raindrops, but would partition into the helium raindrops and perhaps undergo even larger depletion than helium⁷. Heavy noble gases, on the other hand, stick to solid particles or form inclusion compounds with water ice, and are moreover likely to be far more soluble in a metallic medium.

So to the Galileo results, which reveal that the oxygen to hydrogen ratio at the deepest regions sampled (below the expected depth of water cloud formation) is about the same as in the Sun. Sulphur is somewhat lower than the solar mixing ratio. Neon is markedly less than solar (by perhaps two orders of magnitude), and helium is 13.7% by mass (about half the primordial solar value). But krypton and especially xenon may substantially exceed solar abundance. The dryness of the atmosphere is compatible with the low cloudiness measured by the probe, the higher temperatures than predicted (actually suggesting even lower water abundances than a solar mixing ratio), and the net flux radiometric measurements.

So what can we deduce from these data? Lower than expected water might mean that the planetesimals hitting

Jupiter early in its history had a carbon to oxygen ratio in excess of solar. Or perhaps the water depletion is just a meteorological effect peculiar to the place that the probe went in. Or there might even be some continuing process within the planet that depletes oxygen.

The unexpectedly low levels of helium must be reconciled with the energy output of the planet, because helium rainout releases huge amounts of energy^{8,9}. Perhaps the depletion begins either higher up (for example at one megabar pressure or less) or deeper down (many megabar) than was supposed. In the first case, a smaller mass-fraction of the planet undergoes depletion (maybe only 10%); in the second, the helium falls less distance. Perhaps the deepest part of the planet is stably stratified and not releasing heat by convection. In any event, neon and perhaps some argon will go along for the ride in helium raindrops. The lower abundance of helium might also lend support to the existence of a deep radiative zone¹⁰, because the outer envelope is otherwise not dense enough to be compatible with the gravity field. The high xenon is perhaps the hardest to explain, but it could result from delivery by planetesimals and some internal partitioning within the planet. Sharpening the speculations will require more precise data than released thus far, as well as the incorporation of the latest ideas of how hydrogen may metallize¹¹.

The probe also recorded high east-west winds, even at the greatest depths sampled, less lightning than many expected, and an inner radiation belt inside Jupiter's dust ring. In all, the observations will keep scientists occupied until well after the excitement picks up anew when Galileo starts to encounter the planet's satellites, beginning with Ganymede next June. □

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1. Wildt, R. in *The Solar System*, Vol. 3, *Planets and Satellites* (eds Kuiper, G. P. & Middlehurst, B. M.) 159–212 (Univ. Chicago Press, 1961).
2. Low, F. J. *Lowell Observ. Bull.* **129**, 184–187 (1965).
3. Pollack, J. B. & Bodenheimer, P. in *Origin and Evolution of Planetary and Satellite Atmospheres* (eds Atreya, S. K., Pollack, J. B. & Matthews, M. S.) 564–604 (Univ. Arizona Press, Tucson, 1989).
4. Zharkov, V. N. & Gudkova, T. V. *Ann. Geophysicae* **9**, 357–366 (1991).
5. Gautier, D. & Owen, T. in *Origin and Evolution of Planetary and Satellite Atmospheres* (eds Atreya, S. K., Pollack, J. B. & Matthews, M. S.) 487–512 (Univ. Arizona Press, Tucson, 1989).
6. Stevenson, D. J. *J. Phys. F. (Metal Physics)* **9**, 791–801 (1979).
7. Roulston, M. S. & Stevenson, D. J. *EOS (Abstr. Fall Meeting)* 343 (1995).
8. Smoluchowski, R. *Nature* **215**, 691–695 (1967).
9. Salpeter, E. E. *Astrophys. J. Lett.* **181**, L183–L186 (1973).
10. Guillot, T., Gautier, D., Chabrier, G. & Mosser, B. *Icarus* **112**, 337–353 (1994).
11. Weir, S. T., Mitchell, A. C. & Nellis, W. J. *Phys. Rev. Lett.* (in the press).

Small and slippery

IN large chunks, graphite has a planar layered structure. For small chunks, this laminar form is no longer optimal. A spherical 'onion' form is stabler; the absence of dangling edge-bonds more than compensates for the strain energy needed to bend the carbon sheets. Soot can contain spherical sub-micrometre 'buckyonions' of nested fullerene shells, and spherical graphite inclusions as large as 0.1 mm across occur in cast iron.

Daedalus now wants to create an alloy with sub-micrometre spherical inclusions which rotate freely in their metal matrix. Where they protrude from the surface they will act as ball-bearings, almost abolishing skin friction. Buckyonions seem ideal for this job; the field is advancing so fast that they should soon be available in quantity. Daedalus plans to include them, not in iron, but in a metal lattice carefully designed to be slightly mismatched to their peripheral atomic spacing. Each buckyunion will then have no preferred orientation in its metal matrix. In any orientation some regions on its surface will match the matrix atom-to-atom, while in other regions its atoms will coincide with matrix interatomic spaces. This is the Merkle principle for a nanotechnological bearing. By mismatching the atomic spacing of shaft and bearing, lattice 'cogging' is overcome, and the shaft spins freely.

The resulting alloy will be far more slippery than ice. Its obvious use will be in machine tools, drills, and cutters generally. Almost all the power needed for cutting and machining, and all the forces to be withstood, arise from the rubbing of the sheared metal against the cutting tool. But Daedalus's 'Buckalloy' tools will offer no friction to the sliding, deforming metal. It will ride smoothly on innumerable free-spinning buckyonions, each protruding a little from the surface of the tool. Strong and smooth as carbon fibre, they will carry the heaviest load uncomplainingly.

This cunning surface will resist wear, too. Even if it slowly abrades away, new buckyonions will be exposed as fast as old ones are undercut and fall out. By the same token, Buckalloy will be hard to shape or grind. It will have to be cast and chemically etched into shape.

Once it has won its spurs as a pricey tool steel, Buckalloy will slide down-market into wider low-friction duties. Wonderfully smooth heavy-duty bearings, slides, gears and pivots will be possible, each with a Buckalloy surface rolling against a hard smooth steel one, and none of them needing any oil. Freed from the stigma of oily hands, engineers may even attain the social status of stockbrokers.

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