system were designed and fabricated by Aker Industries in Oakland, CA. The capillary leak arrays and secondary electron multiplier detector were manufactured by Galileo Electro Optics in Sturbridge, MA. The chemical getter material was provided by the SAES Getter of Milan, Italy. M. Wong of the University of Michigan participated in the data analysis. We also thank the Galileo Probe Project personnel at NASA Ames Research Center, and we particularly acknowledge the contributions of A. Wilhelmi, C. Sobeck, and P. Melia for their efforts during the development, spacecraft integration, and testing phases.

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The Helium Mass Fraction in Jupiter's Atmosphere

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On 7 December 1995, the NASA Galileo probe provided in situ measurements of the helium abundance in the atmosphere of Jupiter. A Jamin interferometer measured the refractive index of the jovian atmosphere in the pressure region from 2 to 14 bars. These measurements indicate that the atmospheric helium mole fraction is 0.136 ± 0.004. The corresponding helium mass fraction is slightly below the presolar value, which suggests that separation of helium from hydrogen in Jupiter's interior is only in its early stages.

In 1977, when the instruments for the Galileo probe were chosen, it was generally thought that the He abundance in the jovian atmosphere was the same as that which was created in the Big Bang and was later present in the solar nebula from which the sun and the planets were formed (*1*). An accurate measurement, therefore, would tell us something about conditions at the instant of the universe's creation. But later, Voyager results for Saturn (*2*) and Uranus (*3*), as well as more detailed knowledge of Jupiter (*2*, *4*) and the sun (*5*), all suggested that processes in Jupiter could have modified the original ratio. An accurate measurement of the He abundance in the jovian atmosphere is now viewed as providing information about the origin and evolution of the planet itself. The purpose of the He abundance detector (HAD) (*6*) aboard the Galileo probe was to determine as accurately as possible the abundance ratio of He to H in Jupiter's atmosphere.

More than 99.5 mole percent of the jovian atmosphere consists of H_2 and He. Hence, to a first approximation, this atmosphere can be considered to be a binary gas mixture, for which the mole fraction q_{He} of He can be derived from the ratio of refractive indices

$$q_{He} = \frac{n_{H_2} - n_s}{n_{H_2} - n_{He}} \qquad (1)$$

where n_{He} is the refractive index of He, n_{H_2} is the refractive index of H, and n_s is the refractive index of the sample gas (jovian gas). We use the word "sample" because the refractive index of this jovian gas is measured inside the HAD instrument and at sample gas pressures and temperatures that differ from conditions in the ambient jovian atmosphere.

For an accurate measurement of the refractive index of the jovian gas, the Galileo HAD used a two-arm Jamin interferometer (*7*). It produces a fringe pattern on an array of nine photodiodes (PDA), which does not change if both cells are filled with gas mixtures having the same refractive index. However, any difference between the refractive indices of the sample and the reference gas causes a continuous shifting of the fringe pattern with increasing pressure (that is, as the entry probe penetrates deeper into the jovian atmosphere). The signals from eight of the nine photodiodes are combined electronically inside the HAD to monitor in digital form the direction and number F of interference fringes displaced across the PDA in multiples of one-eighth of the fringe separation. The output signal of the ninth diode is used in analog form.

During launch and cruise of the Galileo spacecraft toward Jupiter, the HAD entrance orifice was closed by a thin metal diaphragm. This diaphragm was designed to burst when an outside jovian pressure of about 2 bars was reached. Subsequently, the ambient pressure operated a needle device that punched a hole in a second diaphragm that previously had closed off the reference gas in its storage volume. The reference gas passed into its interferometer reference gas cell (RGC) through a membrane valve that kept the pressure difference between cells SGC (sample gas cell) and RGC near 80 mbars. This pressure difference was also measured within a few millibars by a dedicated pressure sensor. Measurement of the subsequent fringe motion continued until the reference gas was expanded to the local ambient pressure.

A complete calculation of the He mole fraction q_{He} needs to take into account quantitatively (i) the pressures of the sample gas P_s and the reference gases P_r (or instead of the latter, the pressure difference between sample and reference gases) at the start (i) and end (e) of the measurement in the jovian atmosphere; (ii) the absolute temperatures of the sample gas T_s and the reference gas T_r at the start (i) and the end (e) of the measurement; (iii) the Lorentz-Lorenz function that connects the refractive index n of a nonpolar gas with its mass density ρ; (iv) the non-ideal gas characteristics of H_2, He, Ar, and Ne as described by their compressibilities Z and virial coefficients $B(T)$; and (v) the effects of an absorber in front of the SGC, which eliminates the traces of jovian methane from the measured gas sample. The aggregate equation for calculating q_{He} contains four terms, shown below as f_1, through f_4; the mole fraction is (*8*):

$$q_{He} = f_1(n_r) + f_2(F^e - F^i) + f_3(P^{e,i}_{s,r}, T^{e,i}_{s,r}) + f_4(q_{He}, T_{absorber}) \qquad (2)$$

where f_1 is dominated by the refractive index n_r of the reference gas, f_2 represents the contribution from the observed fringe displacement $DF = F^e - F^i$, f_3 is dominated by the pressure difference $P_s - P_r$, and f_4 represents an empirical correction required by the presence of absorbers for the trace gases H_2O, NH_3, and CH_4, which absorb small amounts of H_2 too. These terms are of the order 0.11, 0.03, 0.0005, and −0.004, respectively.

The HAD instrument was designed to perform best in the pressure range from 2 to 12 bars (*6*). During the descent of the probe, the reference gas storage volume

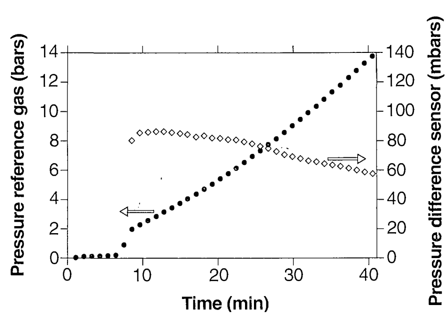

Fig. 1. Pressure inside the reference gas in the RGC (left ordinate) and the pressure difference between the SGC and the RGC (right ordinate) versus time [for definitions, see (*7*) and text] during the descent into Jupiter's atmosphere. The opening of the reference gas reservoir is notable close to 7 min.

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opened close to 2 bars (Fig. 1; left ordinate scale). The reference gas pressure closely followed the sample gas pressure up to 17 bars, as indicated by the sensor for the pressure difference (Fig. 1; right ordinate scale).

The analog signal of photodiode number 9 clearly registered the passage of about seven interference fringes while the probe descended from the 2.3-bar to the 14-bar level (Fig. 2). The contrast of the fringe pattern began to decrease about 20 min into the descent. This effect may be caused by some mild condensation on exposed parts of the interferometer optics. The digital fringe counter reversed its direction of counting after the reference gas had been fully expanded near 17 bars. This fact proves that the jovian gas has a smaller refractivity (which corresponds to a higher equivalent He content) than our reference gas. Figure 3 shows the readings of the digital fringe counter versus the ratio of pressure P_r to temperature T_r (proportional to density for an ideal gas) of the reference gas in the RGC. The slope of this line determines the second term in Eq. 2; the slight curvature reflects the deviation from the ideal of the actual gases.

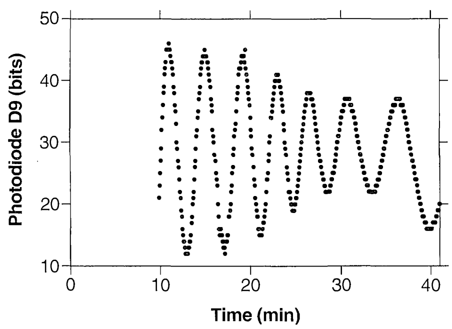

Fig. 2. Analog count of interference fringes moving across photodiode number 9 versus time. The signal train is shown over the pressure range used for the evaluation of the He abundance.

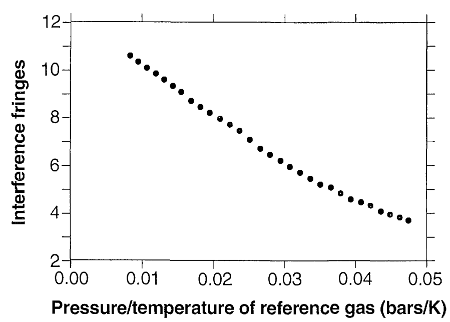

Fig. 3. Digital count of interference fringes moving across the photodiode array versus the ratio of presssure to temperature of the reference gas in the RGC.

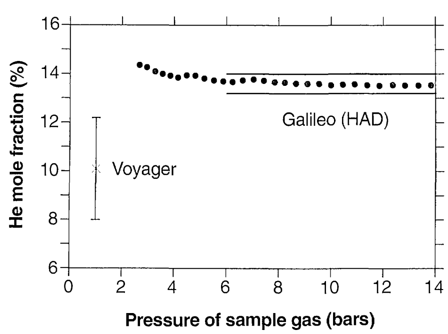

Fig. 4. Successive solutions for the He mole fraction as calculated from various HAD data sets, all having as initial set the data taken at a sample gas pressure of 2.4 bars. The horizontal lines indicate the estimated total error bar of ±0.4%. The result of the Voyager experiments is from (*2*).

With the equation in (*8*), any set of parameter readings at two different sample pressures can be used to calculate a He mole fraction q_{He}. The error bar on the result decreases considerably, however, when larger pressure differences are chosen. We use as initial pressure the third reading (P_r = 2.3 bars) after the opening of the HAD inlet (which provides more than 2 min for stabilization of all parameters). As shown in Fig. 4, the value for q_{He} converges at successively higher pressures toward the value of 13.6%. The uncertainty of the calculated solution is less than 0.1%. In this well-mixed part of the atmosphere, q_{He} is independent of depth. As outlined in (*6*), additional uncertainties contribute to the total error bar of our result, which we currently estimate to be no larger than ±0.4%. The mixing ratio of He to H_2 is found to be 0.157.

The He mass fraction $Y/(X + Y)$ is 0.238 ± 0.007, where X, Y, and Z are the mass fractions of H + H_2, He, and all heavier elements, respectively (*9*). For the comparisons in Table 1, we adopt the standard solar-system value Z = 0.019 (*10*) and obtain Y = 0.234 from our HAD data (because Jupiter's own Z may be somewhat larger, this Y does not actually pertain to Jupiter itself). Estimates of Y for the current solar atmosphere are obtained from analysis of seismic waves and fall in the range 0.23 to 0.25 (*11*). Evolutionary models of the sun, many of which were generated to account for the deficit in neutrino flux, find that some He has diffusively separated to deeper levels in the radiative zone, so that the value of Y in the atmosphere is less than the protosolar one (Table 1) (*12, 13*). We chose the protosolar value Y = 0.28 (Table 1) for comparison with Jupiter's atmosphere, although other values have been obtained for the different regions of the sun (*13*). The primordial Y is obtained by observations of ancient objects in which little He can have been generated by nucleoysnthesis and is 0.232 ± 0.005 (*14*).

It can be seen that there is a fair agreement between our He abundance and the astrophysical estimates. The most appropriate one for comparison is the protosolar estimate, which is greater by 18%; the combined error estimates do not overlap. The results support a small He depletion into Jupiter's interior. The Voyager result is seen to be low, but the difference is not much greater than the estimated errors. A strong and unambiguous depletion is seen for Saturn, but there is no evidence of such depletion at Uranus. He depletion is believed (*15, 4*) to stem from the formation of He-rich drops deep inside the planet; the pressure level at which this behavior begins is uncertain but may be between 1.5 and 2 Mbars. These drops then fall to a somewhat deeper level before they redissolve. Some models also suggest that there is a first-order phase boundary between molecular and metallic H; if true, there would be a small partitioning effect that would act in the same direction (*4, 16*). The absence of a detectable depletion in the atmosphere of Uranus is explained by the lower pressures that occur in its interior. Jupiter is a borderline case; it certainly generates high pressures but at temperatures substantially higher than those of Saturn. The phase separation is not experimentally accessible; all these conclusions depend on theoretical computations, supplemented by the planetary observations we are discussing.

Since the appearance (*2*) of the revised results from Voyager (see Fig. 4), it has been thought that there is a substantial depletion of He in Jupiter's atmosphere and therefore that the phase separation does occur in that planet. The HAD result supports this inference insofar as there is some depletion in-

Table 1. He mass fractions. The entries for Jupiter, Saturn, and Uranus are from combined analysis of Voyager infrared and radio-occultation data (*2, 3*).

Source	$Y/(X + Y)$	Y	References
Galileo HAD	0.238 ± 0.007	0.234*	This paper
Voyager			
Jupiter		0.18* ± 0.04	(*2*)
Saturn		0.06* ± 0.05	(*2*)
Uranus		0.262* ± 0.048	(*3*)
Helioseismology	0.245*	0.24 ± 0.01	(*11*)
Protosolar	0.280*	0.275 ± 0.01	(*12, 13*)
Primordial	0.232 ± 0.005	0.232 ± 0.005	(*14*)

*Adjusted to Z = 0.0192.

dicated, although the degree of depletion is much less than that inferred from the Voyager result. Another argument in favor of an actual depletion of He is the large depletion of Ne observed by the mass spectrometer on the Galileo probe (*17*). A plausible explanation that deserves further exploration (*18*) is that Ne is soluble in the He-rich drops and is carried down by them.

REFERENCES AND NOTES

1. J. S. Lewis, *Sci. Am.* **230**, 51 (March 1974); M. Podolak and A. G. W. Cameron, *Icarus* **25**, 627 (1975).
2. B. J. Conrath, D. Gautier, R. A. Hanel, J. S. Hornstein, *Astrophys. J.* **282**, 807 (1984). Even though that paper deals predominantly with Saturn, it also contains the revised and most recent value for the He mass fraction in Jupiter's atmosphere as obtained from the Voyager experiments.
3. B. Conrath, D. Gautier, R. Hanel, G. Lindal, A. Marten, *J. Geophys. Res.* **92**, 15003 (1987).
4. W. B. Hubbard, in *Origin and Evolution of Planetary and Satellite Atmospheres*, S. K. Atreya, J. B. Pollack, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1989), pp. 539–563.
5. M. Stix, *The Sun* (Springer Verlag, Berlin, Germany, 1989).
6. U. von Zahn and D. M. Hunten, *Space Sci. Rev.* **60**, 263 (1992).
7. F. A. Jenkins and H. E. White, *Fundamentals of Optics* (McGraw-Hill, New York, ed. 4, 1976). The light source is a light-emitting diode operating at a wavelength (λ) of 900 nm. An interference filter aids in producing near-monochromatic light. Two plane-parallel glass plates (Jamin plates) produce and recombine two parallel and coherent light beams. The SGC and RGC house the sample gas and a reference gas, respectively. Each has an effective length of 200 mm. Additional optical elements produce a well-defined pattern of consecutive equidistant bright and dark interference fringes at a linear array of nine photodetectors (PDA). The reference gas consists of a mixture of Ar and Ne having the same refractive index as a mixture of 10.95% He and 89.05% H_2. The reference gas was carried along to Jupiter within the instrument.
8. To write down the aggregate equation for calculating q_{He} we introduce the refractivities $R = 10^6\,(n - 1)$. Also, all parameters with the superscript 0 are taken at standard temperature and pressure. Other symbols are defined in the text before Eq. 2. One then obtains

$$q_{He} = +\frac{R^0_{H_2} Z^0_{H_2} - R^0_r Z^0_r}{R^0_{H_2} Z^0_{H_2} - R^0_{He} Z^0_{He}} + \frac{1}{R^0_{H_2} Z^0_{H_2} - R^0_{He} Z^0_{He}} \left(\frac{10^6\,\lambda P^0}{LT^0}\right)\left(\frac{F^e - F^i}{P^e_s/T^e_s Z^e_s - P^i_s/T^i_s Z^i_s}\right) + \frac{R^0_r Z^0_r}{R^0_{H_2} Z^0_{H_2} - R^0_{He} Z^0_{He}}\left[1 - \frac{P^e_r/T^e_r Z^e_r - P^i_r/T^i_r Z^i_r}{P^e_s/T^e_s Z^e_s - P^i_s/T^i_s Z^i_s}\right] \quad (3)$$

$$- (0.03301) q_{He,uncorr.} - 0.02189 + (7.933 \times 10^{-5}) T_{absorber}$$

9. For a binary gas mixture of H_2 and He, the mass fraction Y is obtained from the He mole fraction q_{He} by

$$Y = \frac{q_{He}}{m_H \frac{2}{m_{He}} + \left(1 - m_H \frac{2}{m_{He}}\right) q_{He}} \quad (4)$$

with m_{H2} and m_{He} being the masses of a H_2 molecule and a He atom, respectively (m_{H2}/m_{He} = 0.5036).
10. E. Anders and N. Grevesse, *Geochim. Cosmochim. Acta* **53**, 197 (1989).
11. A. G. Kosovichev *et al.*, *Mon. Not. R. Astron. Sci.* **259**, 536 (1992); F. Perez-Hernandez and J. Christensen-Dalsgaard, *ibid.* **269**, 475 (1994); S. Basu and H. M. Antia, in *Helioseismology*, J. T. Hoeksma, V. Domingo, B. Fleck, B. Battrick, Eds. [European Space Agency (ESA) special publication 376, ESA Publications Division, Noordwijk, Netherlands, 1995), p. 35.
12. J. N. Bahcall and M. H. Pinsonneault, *Rev. Mod. Phys.* **64**, 885 (1992).
13. C. R. Proffitt, *Astrophys. J.* **425**, 849 (1994). One of these models has a protosolar y = 0.280 and an atmospheric y = 0.251, and at the center y = 0.649 from hydrogen burning.
14. K. A. Olive and G. Steigman, *Astrophys. J. Suppl.* **97**, 49 (1995).
15. R. Smoluchowski, *Nature* **215**, 691 (1967); E. E. Salpeter, *Astrophys. J. Lett.* **181**, L183 (1973); D. J. Stevenson and E. E. Salpeter, *Astrophys. J. Supp.* **35**, 221 (1977); *ibid.*, p. 239.
16. G. Chabrier, D. Saumon, W. B. Hubbard, J. I. Lunine, *Astrophys. J.* **391**, 817 (1992); T. Guillot, G. Chabrier, P. Morel, D. Gautier, *Icarus* **112**, 354 (1994).
17. H. B. Niemann *et al.*, *Science* **272**, 846 (1996).
18. M. S. Roulston and D. J. Stevenson, *Eos* (fall suppl.) **76**, 343 (1995).
19. We thank our many colleagues and students for their diligent and untiring efforts on behalf of the HAD experiment. Over the years, H. J. Hoffmann contributed heavily to the instrument development effort; W. Mett was responsible for radiation hardening of instrument subsystems and W. Schulte for laboratory simulations of the instrument descent into the jovian atmosphere; H. Schütze performed the calibration and environmental tests of the three units of HAD instruments; H. Schütze and G. Lehmacher supported integration of the instrument into the spacecraft and systems tests; K. Pelka and G. Lehmacher assisted us through software development; and W. B. Hubbard was most helpful with advice on the high-pressure behavior of H-He mixtures. The interferometer part of the HAD instrument was developed by C. Zeiss, Oberkochen, Germany, and the other portion of the HAD was developed by Messerschmitt-Bölkow-Blohm, Ottobrunn, Germany. Supported by grants 50QJ90060 and 50QJ9501 of DARA GmbH; the German Space Agency, Bonn; and contract 958696 from the Jet Propulsion Laboratory.

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Solar and Thermal Radiation in Jupiter's Atmosphere: Initial Results of the Galileo Probe Net Flux Radiometer

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The Galileo probe net flux radiometer measured radiation within Jupiter's atmosphere over the 125-kilometer altitude range between pressures of 0.44 bar and 14 bars. Evidence for the expected ammonia cloud was seen in solar and thermal channels down to 0.5 to 0.6 bar. Between 0.6 and 10 bars large thermal fluxes imply very low gaseous opacities and provide no evidence for a deep water cloud. Near 8 bars the water vapor abundance appears to be about 10 percent of what would be expected for a solar abundance of oxygen. Below 8 bars, measurements suggest an increasing water abundance with depth or a deep cloud layer. Ammonia appears to follow a significantly subsaturated profile above 3 bars. Unexpectedly high absorption of sunlight was found at wavelengths greater than 600 nanometers.

As the Galileo probe descended into Jupiter's atmosphere, the net flux radiometer (NFR) measured net solar and thermal radiation fluxes to determine where and how the atmosphere was being heated and cooled by radiation. The net flux, which is the difference between upward and downward fluxes, is useful because its divergence is equal to the radiative power per unit volume absorbed by the atmosphere. Thus, the vertical derivative of the NFR measurements defines the vertical distribution of radiative heating and cooling, which leads to buoyancy differences that power atmospheric circulations. NFR data also contain information about the opacity structure of Jupiter's atmosphere, which helps determine the distribution of particles and gases through which radiative transfer occurs. The relation between opacity sources and the radiative energy exchanges is important to understand in applying these very local measurements at the probe entry site, where exceptional atmospheric clarity is implied by ground-based observations (*1*), to other regions of Jupiter having different cloud structures and absorbing gas profiles.

The NFR (*2*) used an optical head that extended through the probe wall to obtain views of the jovian atmosphere. It sampled upward and downward fluxes with 40° (full angle) conical fields of view centered at directions ±45° from horizontal, avoiding most of the direct solar beam, but admitting a small fraction near the limits of its angular response. The NFR made measurements in five parallel spectral channels (Fig. 1). Two

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