

Viewpoint

Peering into Jupiter

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Ab initio simulations account for the peculiar abundance characteristics of noble gases in Jupiter

Subject Areas: **Astrophysics**

A Viewpoint on:

Sequestration of Noble Gases in Giant Planet Interiors

Hugh F. Wilson and Burkhard Militzer

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Attaining *in situ* data from planets in our solar system is an extremely difficult undertaking. Decades of planning go into designing missions, and careful consideration is made for what measurements should be made to yield the greatest scientific gain, and to make the cost and risks worthwhile. NASA's Galileo mission, whose detailed planning began in 1970s, studied the Jovian system from 1995 to 2003. The Galileo entry probe was released from the main spacecraft, and plummeted into Jupiter's atmosphere at 48 km/s on December 7, 1995. The data that was returned on the abundances of atoms and molecules in the planet's atmosphere are unique constraints on our quantitative understanding of the interior structure, thermal evolution, and formation of the planet. Since Jupiter is our prototype giant planet, in a class that now numbers nearly 300 "gas giants" in other planetary systems, this data is even more valuable than it was 15 years ago. In a recent work in *Physical Review Letters*[1], Hugh Wilson and Burkhard Militzer from the University of California at Berkeley, US, have used an *ab initio* calculation of the mixing properties of noble gases under extreme conditions to explain one of the more curious measurements from the Galileo probe—the low abundances of the two lightest noble gases.

Jupiter is composed mostly of H and He, like the Sun. However, we can look at the enhancements or decrements in the abundances of the atoms more massive than He ("metals" in astronomical parlance), compared to the measured abundances in the Sun and meteorites, to give us clues about the formation and interior physics of the planet itself. The probe stopped returning data at a pressure of only 22 bars, while most of the planet is at significantly higher pressure, in the range 1–40 Mbar (100–4000 GPa). However, efficient convection is expected to dominate in the interior, homogenizing the composition of the vast H-He envelope. Data from the Galileo probe showed that of the nine elements mea-

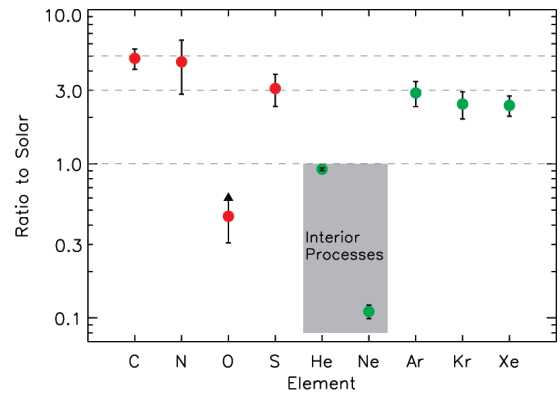


FIG. 1: Abundances of elements in the atmosphere of Jupiter as a ratio to that of the protosolar nebula. Jupiter data are from Mahaffy *et al.* (2000) [3] and Wong *et al.* (2004) [4]. Protosolar nebula data are from Lodders *et al.* (2009) [14]. Noble gases are shown in green. The mixing ratios of these elements in the protosolar nebula are derived primarily from observations of the solar photosphere and from meteorites. Determinations of the abundances of C, N, and O in the Sun have fallen in recent years, so the Jovian ratios have increased. (Illustration: NASA Johnson Space Center (NASA-JSC))

sured, six were enhanced by factors of 2 to 4 times that of the Sun [2–4] (see Fig. 1). These included the noble gases Ar, Kr, Xe, and the abundant elements C, N, and S. Oxygen was depleted by a factor of 2, but a detailed visual and computational study of the probe entry point showed that it entered through one of the anomalously dry regions that make up a few percent of Jupiter's visible surface [5]. The *in situ* measurements allow precise models to be devised of the composition of the solid "planetesimals" that were incorporated into Jupiter during its formation.

The abundances of He and Ne were depleted, which

is particularly odd, since the three other noble gases (which also do not participate in solar system chemistry) are enhanced by a uniform factor of 2. The depletion of He was expected by some, since in the 1970s it was calculated that He should have a limited solubility in the liquid metallic hydrogen that makes up the bulk of Jupiter's mass [6, 7]. Recently, *ab initio* models yielded good agreement with this earlier work [8, 9]. The pressure-temperature region where phase separation is expected to occur (1–10 Mbar, 10^4 K) is barely accessible to experiment. The pure H phase diagram has been sparsely explored with dynamic experiments, but has never been explored for He, let alone for H-He mixtures. If He phase separates from the mixture, and coalesces to form droplets that rain down to deeper layers, this could deplete He from layers above the rain region as well, due to homogenization of composition by convection [10]. The modest He depletion in Jupiter's atmosphere is strong evidence that phase separation has started in Jupiter and will continue for the lifetime of the planet.

The very strong depletion in Ne has always been a bit curious. Just before Galileo arrived at Jupiter, Roulston and Stevenson [11] published a one paragraph abstract suggesting that Ne would dissolve into the separated He droplets, and would also be lost to deeper layers. Indeed, this was exactly what was seen, but there has always been lingering dissatisfaction, since no details of this suggestion were ever published. How strong should the Ne depletion be in this picture? Can it match observations? Would the heavy noble gases dissolve as well? If so, this would "contaminate" the measured noble gas abundance levels that theorists have been incorporating into detailed formation models.

Wilson and Militzer have now provided the foundation for understanding the Galileo probe measurements for Ne and Ar. Ne has been shown to strongly prefer the He-rich droplet phase, leading to the measured strong depletion in the normal H-rich phase that makes up the visible atmosphere. A further detailed study of Ar shows that it does not share this behavior, and that the atmospheric abundance of this atom is the planet's "true" value. It would be worthwhile in the future to consider if other elements that were measured by the entry probe strongly prefer one phase over another. Perhaps an alternative to the "weather" explanation for the

low abundance of oxygen could be found?

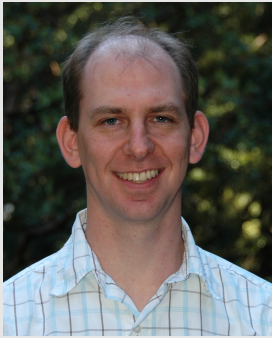
This work has applications far beyond Jupiter. Saturn, which is only 30% of Jupiter's mass and has a lower pressure and colder interior, should be much further into the pressure-temperature space of He phase separation. Saturn has not had an entry probe, but difficult spectroscopic measurements indicate a larger atmospheric depletion of He than found in Jupiter, but the error bars are large [12]. The He-rain in Saturn is calculated to be so prevalent in the planet's deep interior that this planet-wide differentiation process explains the long-noted excess luminosity of the planet [13]. If a Saturn entry probe is finally sent, a much stronger depletion in Ne, but a similar ratio of depletion between He and Ne compared to Jupiter, is expected. He phase separation and corresponding Ne depletion surely happens in several-gigayears-old Jovian planets found around other stars as well. We are gradually beginning to understand these planets as a class of astrophysical objects. It is the wide-ranging study of these extrasolar planets, along with the complementary detailed study of the planets close to home, which will move us forward on this path.

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Jonathan Fortney is an assistant professor in the Department of Astronomy and Astrophysics at the University of California, Santa Cruz. He received his B.S. in physics from Iowa State University and Ph.D. in planetary sciences from the University of Arizona. His research focuses on modeling the interiors and atmospheres of planets outside the solar system, as well as the giant planets close to home. In February 2010 he received a Sloan Research Fellowship.