COMPOSITION, CLOUDS, AND ORIGIN OF JUPITER'S ATMOSPHERE—A CASE FOR DEEP MULTIPROBES INTO GIANT PLANETS

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ABSTRACT

Current hypotheses of the formation of Jupiter and evolution of its atmosphere invoke large quantities of water, so that O/H = 1–3 × any of the other heavy elements, C, N, S, Ar, Kr, and Xe, that are 3±1 × solar, ratioed to H. However, no quantitative results on O/H in the deep well-mixed atmosphere are available. Since water was presumably the original carrier of heavy elements to Jupiter, determination of its abundance in the deep atmosphere is of fundamental importance to the models of formation of Jupiter and the origin of its atmosphere. Furthermore, since meteorological and dynamical effects could cause the mixing ratios of water and possibly other volatiles to vary over the planet, it is essential to measure the full atmospheric composition, simultaneously with the related phenomena, such as winds and cloud properties. The best way to accomplish this is by deploying deep multiprobes into different regions of Jupiter, followed by multiprobes into Saturn, Neptune and the Uranus atmospheres for comparison.

1. INTRODUCTION

A few weeks before the Galileo Probe entered Jupiter on 7 December 1995, the detection of first extrasolar planet (ESP) was announced. This ESP is a giant planet, like Jupiter, but unlike Jupiter it orbits much closer to its star—only 0.05 AU from 51 Peg compared to Jupiter at 5 AU from the Sun. One hundred and ten extrasolar giant planets (EGP) have been detected to this date, nearly all within 5 AU of their respective stars and a vast majority within only 1 AU from the stars. The close proximity of the EGPs to the stars together with the detection of EGP atmospheres present new, unprecedented challenges to planetary scientists. The quest for understanding the formation of Jupiter and the origin and evolution of its atmosphere has taken on a far greater significance and urgency than ever before, since it is only when we understand the origin and evolution of own solar system it would be possible to create credible scenarios of the formation of extrasolar planetary systems and the atmospheres within them.

In this paper I will first summarize our current understanding of the composition and related cloud structure of Jupiter's atmosphere. This will then be followed by a brief discussion of current ideas about the origin of Jupiter and its atmosphere. The case for returning to Jupiter and the other giant planets with multiprobes will emerge from this discussion.

2. COMPOSITION AND CLOUD STRUCTURE

The presently known composition of the atmosphere of Jupiter and Saturn is presented in Tables 1 and 2 of Atreya et al. [1]. The element and isotope abundances, derived from their principal reservoirs, in the *well-mixed* part of the atmosphere provide the most important constraints to the models of formation of Jupiter and the origin of its atmosphere. Therefore, these quantities are reproduced below in Table 1 (Table 2 of [1]). The principal reservoirs of C, N, O, S, and P on Jupiter and Saturn are, respectively, CH_4, NH_3, H_2O, H_2S, and PH_3. For Jupiter, the mixing ratios for all except PH_3 were measured to a depth corresponding to 20 bar pressure with the Galileo Probe Mass Spectrometer (GPMS, [2]). The same was done for the noble gases. The PH_3 abundance was obtained with infrared observations from various ground-based and earth orbiting satellites and planetary spacecraft, and it corresponds to 0.8-bar pressure level. Since PH_3 is a disequilibrium species, being thermochemically stable in the deep, hot interior of Jupiter, its mixing ratio at the 1-bar level may not be representative of its true well-mixed value. On the other hand, a better determination at Saturn was possible with the Infrared Space Observatory, indicating a supersolar P/H value on that planet. Methane has been measured in Saturn's atmosphere from ground and from Voyager at infrared wavelengths and, like P/H, the C/H ratio is found to be enriched relative to the solar value by approximately a factor of 4–6. A better determination of methane is expected by remote sensing in the infrared from the Cassini orbiter.

All noble gases were measured directly in the atmosphere of Jupiter with the GPMS, but only helium can be derived indirectly in Saturn's atmosphere. Since Cassini will not make direct, in situ measurements, helium and many other critical elements would be poorly constrained, at best, in the well-mixed atmosphere of this planet. The isotopic ratios of the noble gases in Jupiter's atmosphere are found to be essentially solar for the most part. The GPMS provided the first direct measurement of D/H in Jupiter's atmosphere, which represents also the protosolar value of D/H, as there is no deuterium in the Sun today. Similarly, the Jovian $^{15}N/^{14}N$ ratio may provide the best value for this protosolar ratio since obtaining this measurement directly and indirectly from solar wind measurements has produced contradictory results. Since this ratio is predicted to change substantially as the atmospheres of Titan and Mars, for example, evolve through loss processes, the current terrestrial $^{15}N/^{14}N$ ratio is not necessarily the best starting value for such models. In Saturn's atmosphere even from Cassini the isotopic composition will remain unknown, except for carbon, which is already known, and D/H, that is presently poorly constrained and unlikely to improve greatly.

In Jupiter's atmosphere, He and Ne are found to be subsolar (Table 1). This is believed to be the result of condensation of helium into droplets, followed by differentiation from metallic hydrogen, in the 3–5 megabar region of Jupiter's interior, and the removal of neon by the helium raindrops. The observed depletion of helium in Saturn's atmosphere is also believed to be due to the condensation and differentiation of this species in the interior of the planet.

The well-mixed part of a planet's atmosphere is generally below the level where the clouds form. For Jupiter, models predict three distinct cloud layers. For a solar composition atmosphere, these will be the clouds of ammonia ice at ~0.7 bar, ammonium hydrosulfide (NH_4SH) ice clouds at ~2 bar, and water ice clouds at ~5 bar level. The cloud bases are somewhat deeper if the species are enriched relative to solar. For example, the cloud bases would be at 0.84 bar, 2.6 bar and 7.2 bar, respectively, for NH_3 ice, NH_4SH ice, and the H_2O ice if the condensible volatiles are enriched by a factor of 3 relative to solar. Indeed the Galileo Probe measured such enrichments in NH_3 and H_2S, but well below the expected cloud bases. Fig. 1 shows, for example, the behavior of H_2S. Water, on the other hand, was found to be subsolar even at the 22-bar level, the deepest level probed, as seen in Fig. 2. At least two hypotheses—entraining downdraft, and column vertical stretching—have been proposed to explain the depletion of condensible volatiles to deep levels in the Galileo Probe entry site. None of the models can explain satisfactorily the observed behavior of all of the condensible volatiles to the full depth of the measurements. It is evident, however, that Galileo Probe entered a meteorologically anomalous region of Jupiter, commonly known as a 5 µm hotspot, which is a dry region. The resulting cloud structure would therefore also be different than the one described above.

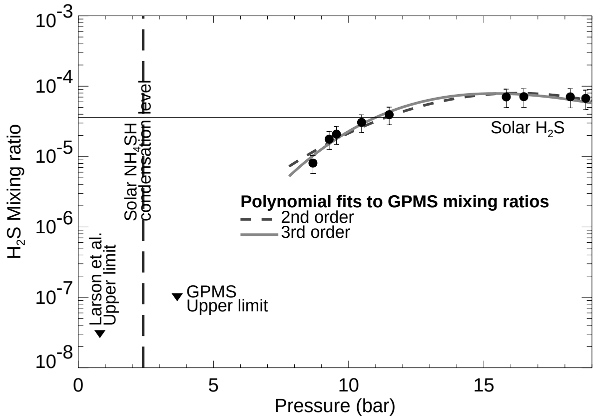

Fig. 1. The H_2S mixing ratio to H_2 vs. pressure. Black circles indicate GPMS derived mixing ratios from [34]/[13] count ratios, with error bars indicating 1-sigma uncertainties; uncertainties include contributions from a number of instrumental and calibration effects. The base of the NH_4SH cloud is predicted to be at 2.2 bar level for solar NH_3/H_2 and H_2S/H_2 as shown by the vertical broken line. After Atreya et al. [3].

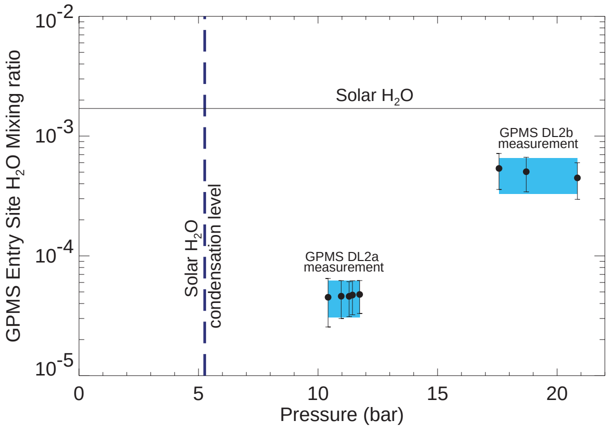

Fig. 2. GPMS measured mixing ratio of water vapor as a function of atmospheric pressure. The mixing ratio increased dramatically, by nearly a factor of 10, between 10 and 22 bar levels, but remained subsolar even at the deepest level probed. The condensation level for solar water is shown by broken vertical line, i.e. the base of water ice cloud would be at approximately 5 bar. After Wong et al. [4].

Indeed in the Galileo Probe entry site, only very tenuous clouds were detected. Fig. 3 shows a comparison between the above predictions (left panel) and the model simulation of the clouds actually detected (right panel). It is remarkable that the volatile mixing ratios used in the simulation are consistent with those actually measured (or extrapolated) in the Galileo Probe entry site. Very thin, wispy clouds are seen at 1.3 bar and 0.5 bar, presumably made up of NH_4SH ice and NH_3 ice, respectively, whereas a possibly thinner cloud at

1.6 bar is due to H_2O ice. Although the observed behavior of clouds appears consistent with the observed depletion in the condensible volatile abundances, many mysteries remain. What is the deep well-mixed abundance of water? How do the condensible volatiles as well as other species behave in other parts of Jupiter? How deep would the probe have to go before it finds stable, well-mixed abundances of all the detectable species?

Table 1. Elemental and Isotopic Abundances (a)

Elements

Elements	Sun	Jupiter/Sun	Saturn/Sun
He/H	0.0975	0.807±0.02	0.56-0.85
Ne/H	1.23×10^{-4}	0.10±0.01	
Ar/H	3.62×10^{-6}	2.5±0.5	
Kr/H	1.61×10^{-9}	2.7±0.5	
Xe/H	1.68×10^{-10}	2.6±0.5	
C/H	3.62×10^{-4}	2.9±0.5	~6
N/H	1.12×10^{-4}	3.0±1.1 (hotspot, 9-12 bar)	2–4 (uncertain)
O/H	8.51×10^{-4}	0.033±0.015 (hotspot, 12 bar) 0.30±0.1 (hotspot, 19 bar)	
S/H	1.62×10^{-5}	2.75±0.66 (hotspot, 16 bar)	
P/H	3.73×10^{-7}	0.82	5–10

Isotopes

Isotopes	Sun	Jupiter	Saturn
$^{13}C/^{12}C$	0.011	0.0108±0.0005	0.011
$^{15}N/^{14}N$	$\leq 2.8\times10^{-3}$	$(2.3\pm0.3)\times10^{-3}$ (0.8–2.8 bar)	
$^{36}Ar/^{38}Ar$	5.77±0.08	5.6±0.25	
$^{136}Xe/Xe$	0.0795	0.076±0.009	
$^{134}Xe/Xe$	0.0977	0.091±0.007	
$^{132}Xe/Xe$	0.265	0.290±0.020	
$^{131}Xe/Xe$	0.217	0.203±0.018	
$^{130}Xe/Xe$	0.0435	0.038±0.005	
$^{129}Xe/Xe$	0.274	0.285±0.021	
$^{128}Xe/Xe$	0.022	0.018±0.002	
$^{20}Ne/^{22}Ne$	13.81±0.08	13±2	
$^{3}He/^{4}He$	$1.5\pm0.3\times10^{-4}$ (meteoritic)	$1.66\pm0.05\times10^{-4}$	
D/H	$2.1\pm0.5\times10^{-5}$ $3.0\pm0.17\times10^{-5}$ *protosolar values*-models	$2.6\pm0.7\times10^{-5}$ (GPMS)	$1.7(+0.75, -0.45)\times10^{-5}$ (ISO)

(a) After Atreya et al. [1]. See [1, 3] for references. Current results for O, S and N reported in this table are from [4]. The solar values are taken from Anders and Grevesse [12] in order to maintain a standard reference. However, note that certain solar values (O/H, e.g.) may be revised somewhat due to recent reanalysis (see footnote to Table 2 in [1]).

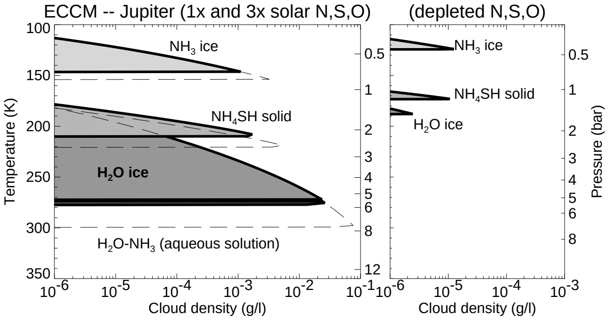

Fig. 3. Left panel: Jovian deep abundances of condensible volatiles were taken at 1 × solar (solid area) and 3 × solar (dashed lines) values (see Table 1), and used to calculate the equilibrium cloud concentrations. The cloud concentrations (in gram/litre) represent upper limits, as microphysical processes followed by precipitation would certainly reduce the values substantially. The cloud bases would, however, remain unaffected. Right panel: as left panel, but with the following depleted condensible volatile abundances (relative to H) compared to solar: H_2O: 0.01%; NH_3: 1%; H_2S: 0.5%. After Atreya et al. [3]

3. ORIGIN

The heavy elements, C, N, S, Ar, Kr, and Xe, in Jupiter's atmosphere are all found to be enriched by a factor of 3±1 relative to their solar ratios to hydrogen (Fig. 4 and Table 1). Three scenarios—all leading up to cold planetesimals—are proposed as possible explanations for the enriched abundances of the heavy elements [3, 5]. They are: formation of Jupiter at 30 AU or farther and subsequent migration to its present orbit, much cooler solar nebula at 5 AU, or pre-solar formation of Jupiter. The last scenario appears to be most promising. It requires that the planetesimals that formed Jupiter must have an extremely low temperature of ≤30 K. This is due to the fact that in laboratory experiments, trapping of nitrogen and argon in ice requires such low temperatures. Therefore, the "Jovian" icy planetesimals would have to originate from the low temperature environment of the Interstellar Medium (ISM) before the solar nebula formed. The ISM temperature is ≤10 K, and the ice is in the amorphous phase, just the right conditions for trapping the most difficult of the volatiles, nitrogen and argon. Since water was presumably the original carrier of heavy elements according to the cold icy planetesimal hypothesis, it is also expected to be enriched relative to solar by about the same factor as the other heavy elements, i.e. between a factor of 2–4.

Gautier et al. [6, 7] have argued that the nature of ice that gets formed upon condensation of water vapor in the solar nebula is crystalline, not amorphous, when the temperature of the feeding zone of Jupiter at 5 AU drops to 150 K. With further cooling, most of the water condenses as crystalline ice, leaving behind insignificant amounts of amorphous ice. Therefore, they suggest an alternate hypothesis that relies on trapping of the volatiles containing above heavy elements in *cold* clathrate hydrates in the cooling feeding zone of Jupiter. If this scenario is correct, Gautier et al. [6] estimate that the water abundance, hence the O/H ratio in Jupiter's atmosphere, would be at least 9.4 times solar, i.e. more than twice that predicted by the cold icy planetesimals hypothesis, and more than two times greater than the abundance of the other heavy elements. This interesting alternative to the cold planetesimal hypothesis is not yet supported by laboratory experiments demonstrating the formation of clathrates under the temperature and pressure conditions postulated for the Jupiter feeding zone. It also overestimates the abundance of sulfur on Jupiter, and the authors' explanation for this calculated overabundance—that a substantial amount of sulfur is consumed in the inner solar nebula through the reaction of H_2S with Fe alloy grains to form troilite (FeS)—has not yet been demonstrated quantitatively [8]. Finally, to form the clathrate of argon, solar nebula temperatures of ≤38 K are required [6], again placing a remarkably low temperature constraint on the proto-Jovian environment.

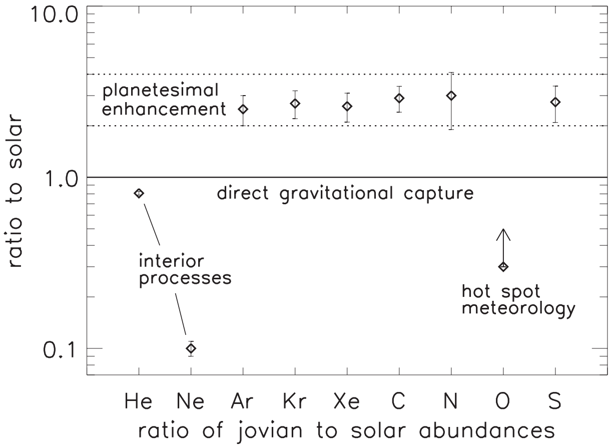

Fig. 4. Elemental abundances (relative to H) in Jupiter's atmosphere compared to the solar values. The Jupiter results are those measured by the GPMS. Solid horizontal line shows that direct gravitational capture would result in elemental abundances (ratioed to H) same as in the Sun. However, heavy elements, Ar, Kr, Xe, C, N, and S are all found be enriched by a factor of 3±1. Figure updated from Owen et al. [5].

In summary, it is evident that although both the cold icy planetesimal and the clathrate hydrate hypotheses are attractive, both have inherent difficulties that would require new planetary measurements and further modeling and laboratory work to determine how Jupiter formed. In principle, it is easy to distinguish between these two hypotheses by measuring the mixing ratio of water in the well-mixed portion of Jupiter's atmosphere. The factor of more than two difference between the two models would be obvious. Unfortunately, the Galileo Probe measurements stopped at 22 bar—not deep enough for water to have reached its well-mixed abundance in the hot-spot entry site of the Probe.

4. DISCUSSION AND RECOMMENDATIONS

The composition of a planetary atmosphere provides useful information on the current physico-chemical processes and dynamics on the planet. More importantly, elemental abundances in the atmosphere of Jupiter are crucial as they provide the essential constraints to the models of formation of Jupiter and the origin and evolution of its atmosphere. The elemental abundances are derived from measurement of volatiles in the deep well-mixed atmosphere. As discussed previously, many heavy elements have been quantified for the first time, but the abundance of water, which was presumably the original carrier of the heavy elements, continues to remain a mystery in the deep well-mixed part of Jupiter's atmosphere. All measurements correspond to a single Galileo Probe entry site.

Although much progress has been made on the models of the origin of Jupiter and its atmosphere, the situation is less than satisfactory. The models are based on a limited set of presently available data, largely from the Galileo Probe. Besides being from a single location, the data correspond to a meteorologically anomalous location on the planet. And, no information on water, hence O, the most crucial of the heavy elements, in the deep well mixed atmosphere is available. Since dynamical processes can and do affect the distribution of volatiles over the planet, *global map* of the abundance of *all* accessible heavy elements in the *deep well-mixed atmosphere* of Jupiter will be essential for understanding unambiguously the formation of Jupiter and the origin of its atmosphere.

The tropospheric composition is closely coupled also to meteorology and possibly certain other physical and chemical processes. Therefore the next Jupiter probe mission should be designed to deploy several (3–5) probes into different locations of Jupiter. Only a carefully instrumented multiprobe mission that combines the composition measurements with other critical observations in situ, such as winds, cloud structure, etc. can help achieve the ambitious goal of understanding the formation of the planet and the origin of its atmosphere. Still, a *comparative planetology* approach will have the best chance of producing the most credible scenarios of the formation of Jupiter and its atmosphere. This approach would of course help us understand the formation of the other giant planets as well, and by analogy, the extrasolar planets. Multiprobe missions to Saturn and beyond pose bigger technological challenges, as can be gleaned from examining the cloud structures of Saturn and Neptune (or Uranus).

Fig.5 shows an equilibrium cloud condensation model of Saturn. This model assumes that all condensible species (NH_3, H_2S, H_2O) are enhanced relative to solar by a factor of 5, which is consistent with the enrichment in C and P derived from CH_4 and PH_3, respectively. The base of the water cloud in this case would be at approximately 20 bars compared to 7 bars for Jupiter with 3 × solar abundance of the condensible volatiles. Moreover, an extensive solution, i.e. droplet, cloud is expected at Saturn unlike Jupiter's puny one. Should the enrichment at Saturn be greater, 10 × solar, for example, then the base of the solution cloud would be much deeper at approximately 27 bars. Even if water were only solar at Saturn, the base of the solution cloud would still be at almost twice the pressure compared to Jupiter.

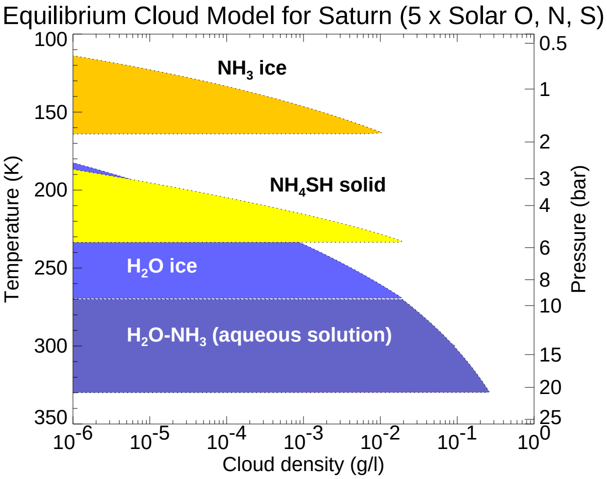

Fig. 5. Equilibrium cloud condensation model of Saturn, assuming a five-fold enrichment of the condensible volatiles, so that N/H, S/H, and O/H are each 5 × solar. The cloud concentrations (in gram/litre) represent upper limits, as microphysical processes followed by precipitation would certainly reduce the values substantially. The cloud bases would, however, remain unaffected.

The situation at Uranus and Neptune is much more dramatic, as seen in Fig. 6. The base of the water ice cloud for solar proportion of water is expected to be at approximately 90 bar level, whereas for solution clouds it is at approximately twice this pressure. However, solar abundance of the elements is most likely not going to be the situation at Uranus and Neptune. In fact, the C/H ratio at Uranus is approximately 20 × solar and perhaps between 30 × and 50 × solar at Neptune, as derived from the measurement of methane. C is the only heavy element that has been measured so far in the atmospheres of Uranus and Neptune, and the only one on all four giant planets. And, the trend of progressively greater heavy element ratios (to H) from Jupiter to Neptune, as seen in C/H, is consistent with current ideas of the formation of the giant planets. Therefore, it is expected that like carbon, O/H, hence water, would also be enhanced by factors of 20–30 or more relative to solar in the atmospheres of Uranus and Neptune. For purposes of illustration, a case with 10 × solar enrichment of the condensible volatiles (CH_4, NH_3, H_2S, H_2O) is also shown in Fig. 6. In this case the water solution cloud base would be at 1500 bars! Indeed if the enrichment were similar to the observed value in C/H, i.e. 30 × solar or more, then the base of the water solution cloud would be at several thousand bars! Although it is not deep enough still to encounter the possible ammonia ocean on Neptune or Uranus, predicted by some models to be at around 0.1 Mbar (see e.g. [10]), probing the icy giants to even few thousand bars could give clues to the existence of such an ocean if ammonia were found to be greatly depleted in the upper troposphere, more so than can be explained by the loss of this species in the aqueous solution and the ammonium hydrosulfide clouds.

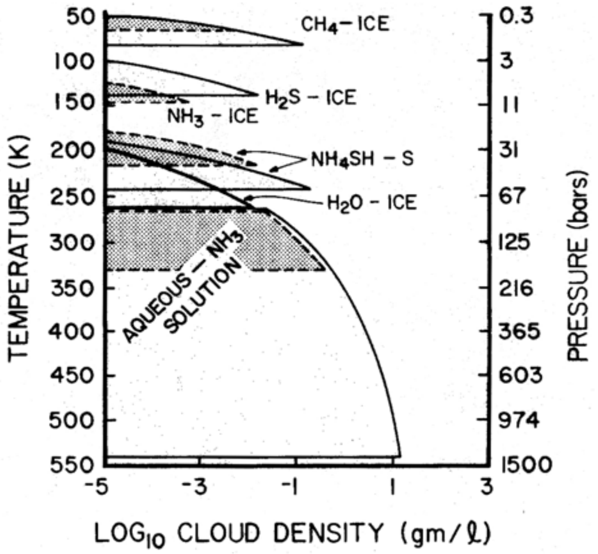

Fig. 6. Equilibrium cloud condensation model for Neptune. Results are shown for 1 × and 10 × enrichment of the condensible volatiles relative to solar (ratioed to H). The 1 × solar case is shown by broken line curves. The cloud concentrations (in gram/litre) represent upper limits, as microphysical processes followed by precipitation would certainly reduce the values substantially. The cloud bases would, however, remain unaffected. The structure and locations of the clouds at Uranus would be very similar due to similar thermal structure and atmospheric density in the tropospheres of the two planets. Because of uncertainty in the p-T structure, the aqueous solution cloud levels are uncertain by a few hundred bars, but still very deep. After Atreya [9].

In summary, development of a carefully thought out *program of multiprobe missions* to the giant planets is recommended. The Jupiter multiprobe mission should be followed by a multiprobe mission to the other gas giant, Saturn, and to at least one icy giant, preferably Neptune. A probe into the Uranus atmosphere is desirable, but if only one mission to the icy giants is possible, a probe mission to Neptune would be more valuable as it will give additional insights into the formation of the icy giants in particular, and giant planets in general, that a Uranus probe alone may not. In all cases the probe measurements should be carried out to depths well below the expected base of the water cloud. Drawing lessons from the Galileo Probe experience, I would recommend probing the atmospheres of Jupiter and Saturn to at least 50 bars, and preferably to 100 bars. The Neptune/Uranus probes must collect data to several thousand bars for them to be valuable in providing critical elemental abundances in the well-mixed part of this planet's atmosphere. The well-mixed atmosphere abundances of many of the heavy elements, including noble gases and isotopes can be measured by probes at shallower depths, reaching 100-200 bar levels on Uranus and Neptune. However, mixed atmosphere abundance of several critical species, particularly NH_3, PH_3, and of course H_2O, would require probing through the aqueous ammonia-water solution cloud, i.e. to pressures of thousands of bars. This is because of the possibility of loss of large quantities of ammonia and phosphine in the (liquid) water cloud. Moreover, an unambiguous result on the S/H elemental abundance is also related to the ammonia measurements deeper in the atmosphere, as only one mole of H_2S can be taken out by one mole of NH_3 in the process of formation of an NH_4SH cloud. In other words, the elemental abundances of N, S, P, and O on Uranus and Neptune are intertwined through the aqueous solution cloud, unlike Jupiter where the aqueous solution cloud is not expected to be as extensive (Figs. 3 and 6).

Successful operation of the probes (including data transmission) and the scientific payload under the severe environmental conditions encountered in the deep atmospheres of the giant planets is highly challenging, and it will require development of new technologies. This will take time, dedicated and sustained resources, and extraordinary scientific and engineering talent. An international collaboration that includes at least NASA, ESA, and JAXA (Japan Aerospace Exploration Agency) is highly desirable to guarantee success, minimize costs, and expedite the exploration of multiple worlds by multiprobes. Finally, the design and execution of the Jupiter multiprobe mission would benefit from less expensive, near term missions that could give at least some estimates on the water abundance and clues to its variability over the planet. One possibility is microwave radiometry from a spacecraft at Jupiter [11].

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