MULTIPROBE EXPLORATION OF THE GIANT PLANETS – SHALLOW PROBES

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ABSTRACT

Comparative planetology of the giant planets is key to the origin and evolution of the solar system and, by extension, extrasolar systems. In particular, elemental composition of well-mixed atmospheres is the most critical measurement, but it is also most challenging. This is because the well-mixed region for certain species lies well below the clouds, a deep region where measurements are difficult to make and the data are hard to transmit from. Here we discuss a new approach, which combines microwave radiometry with *shallow* entry probes, that could alleviate much of these problems. At Saturn and Jupiter, the probes need to be deployed to only about 10 bars. At the ice-giants, Uranus and Neptune, neither probes – even deep probes – nor radiometry would be of much help in determining the elemental abundance of oxygen, and possibly nitrogen. However, the lack of determination of O/H and N/H at Uranus and Neptune is not detrimental, provided that all other critical elements have been measured and compared with those on the gas giants. Therefore probes to 10 bars, with a maximum to 50 bars would be sufficient at the ice giants. At these depths, all critical elements, except O and N can be accessed. We recommend multiple probes at each of the giant planets, together with microwave radiometry from flyby or orbiter spacecraft. The value of microwave radiometry at Uranus and Neptune requires further study. It is quite conceivable that the first such mission – a Saturn flyby with probes and microwave radiometry – could be ready in the near short term within the cost cap of NASA's New Frontiers class. Multinational partnerships are desirable for the highest science return as well as possible cost savings.

1. INTRODUCTION

It was well-known even before the start of the Voyager Project in 1974 that a thorough understanding of the giant planets would require more than just the flyby spacecrafts. This thinking led to a near simultaneous development of the Galileo mission to Jupiter, complete with an entry probe and an orbiter. The mission was approved and the scientific payload selections were announced in August 1977, nearly coinciding with the launch of the first of the two Voyager spacecrafts. The highly successful Voyager missions discovered new worlds each time they flew by a new giant planet, culminating with the flyby of the Neptune system by Voyager 2 in 1989, and then on to the interstellar medium. The Voyager observations further reinforced the need to return to all four giant planets with probes and orbiters. The Cassini-Huygens mission at Saturn is a partial response to such a need. Initially the mission was designed as a dual probe mission, with one probe into Saturn and another into Titan. Budgetary constraints led to the eventual demise of the Saturn probe. Despite the unprecedented wealth of data about Saturn collected by the Cassini orbiter, the elemental composition in well-mixed atmosphere of the planet will continue to remain unknown for the most part even after the extended mission. Such measurements are critical to the models of the formation of Saturn and its atmosphere. Up until recently, conventional thinking was that deep probes deployed to 50-100 bars will be needed to access the well-mixed atmospheres, especially for water (e.g., [1, 2, 3]). However, the selection of Juno-Jupiter Polar Orbiter New Frontiers mission in July 2005 has provided credibility to a new approach based on microwave radiometry from spacecraft, that will be used to determine the abundance of water to pressure levels of 100 bars or greater. We discuss in this paper how a Saturn flyby with microwave radiometry and probes deployed to only 10 bars can yield the missing pieces of the puzzle of the formation of Saturn and the origin and evolution of its atmosphere. We also argue that shallow probes, deployed to only 10-50 bars at Uranus and Neptune, are capable of collecting the critical composition data at these planets. We first review the available composition data for all four giant planets. This is followed by a discussion of thermodynamic models of clouds, in order

to gain an insight into the well-mixed regions of the four giant planets.

2. ATMOSPHERIC COMPOSITION

Amongst the outer planets, the atmosphere of Jupiter has been studied most due to several flyby spacecrafts, an orbiter, and an entry probe, the Galileo Probe, that entered the planet's atmosphere in December 1995. The composition of Jupiter has been presented in detail previously [4, 5, 6, 7, 8]. The abundance of "heavy" elements in the well-mixed regions of the outer planets is the most critical composition data for constraining models of the formation and the origin and evolution of atmospheres of these planets. Heavy elements are those that are heavier than helium, i.e. with $m/z \geq 4$. For Jupiter, the heavy element information is now available, except for oxygen, as the Galileo Probe entered a meteorologically anomalous region of Jupiter that was like the Sahara Desert [3, 5, 9, 10]. Moreover, the Probe sampled only a single site on Jupiter. For Saturn, the information on the heavy elements is sparse and will continue to remain so even after the Cassini orbiter data are fully in hand. And, the situation is hopeless at the two outermost giant planets, Uranus and Neptune. The only element whose abundance has been measured at all four giant planets is carbon. The trend of its increasing abundance relative to hydrogen from Jupiter to Neptune is consistent with the basic principle of the core accretion model. However, in the absence of the abundance data for the other heavy elements and isotopes, no model is satisfactory to answer the fundamental questions of the origin and evolution of the solar system. The currently available elemental abundance data for all four giant planets is given in Table 1a, whereas the important isotope data are listed in Table 1b. The elemental abundances are shown in Fig.1. Please see caption to Fig. 1 for additional details.

3. WHERE IS THE WELL-MIXED ATMOSPHERE?: THERMOCHEMICAL CLOUD MODEL

The well-mixed region for condensable gases in the atmospheres of the outer planets lies below the bases of their respective cloud layers. Under conditions of thermodynamic equilibrium, this region should exist "just" below such cloud bases. Unlike Earth where a single volatile, water, undergoes condensation, the giant planets are expected to have multiple cloud layers, composed of different species. Thus, there is no single base of the clouds. Clouds of each condensable species would have their own base. The deepest clouds in the upper tropospheres of all four giant planets are predicted to be made up of water (see below). The base of water clouds then determines the well-mixed region for water under equilibrium thermodynamics. Since water was presumably the original carrier of heavy elements to the giant planets, the determination of its abundance in the well-mixed atmosphere is crucial. As variations in the abundances of condensable volatiles can exist to depths below their equilibrium cloud bases, it is important to make their measurements to depths "well" below the cloud bases in order to arrive at the elemental abundance. Thus, water, hence the oxygen elemental ratio (to H), places the biggest demand on the depth to which composition measurements must be made by entry probes. In the following paragraphs, we first present a brief summary of the cloud models. Then, a discussion of the required measurement is given, followed by recommendations.

Table 1a. Elemental Abundances[1]

Elements	Sun	Jupiter/Sun	Saturn/Sun	Uranus/Sun	Neptune/Sun
He/H	0.0975	0.807±0.02	0.56–0.85	0.92–1.0	0.92–1.0
Ne/H	1.23×10^{-4}	0.10±0.01	?	20–30 (?)	30–50 (?)
Ar/H	3.62×10^{-6}	2.5±0.5	?	20–30 (?)	30–50 (?)
Kr/H	1.61×10^{-9}	2.7±0.5	?	20–30 (?)	30–50 (?)
Xe/H	1.68×10^{-10}	2.6±0.5	?	20–30 (?)	30–50 (?)
C/H	3.62×10^{-4}	2.9±0.5	6±1 (CIRS)	20–30	30–50
N/H	1.12×10^{-4}	3.0±1.1	2–4	20–30 (?)	30–50 (?)
O/H	8.51×10^{-4}	0.29±0.1 (hotspot)	?	20–30 (?)	30–50 (?)
S/H	1.62×10^{-5}	2.75±0.66	?	20–30 (?)	30–50 (?)
P/H	3.73×10^{-7}	0.82	5–10	20–30 (?)	30–50 (?)

Table 1b. Relevant Isotopic Abundances[1]

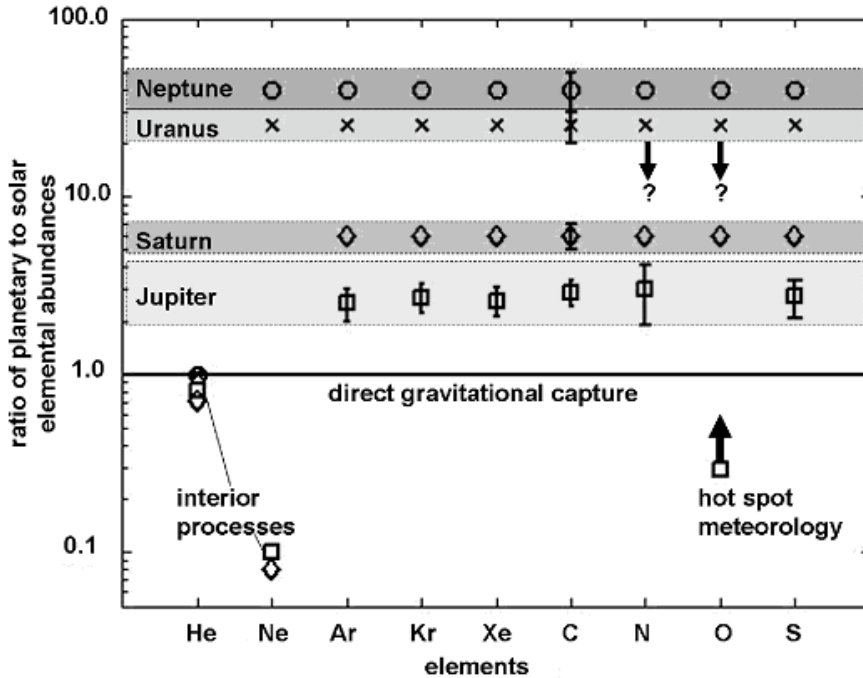| Isotopes	Sun	Jupiter	Saturn	Uranus	Neptune
D/H	$2.1\pm0.5\times10^{-5}$	$2.6\pm0.7\times10^{-5}$	$2.25\pm0.35\times10^{-5}$	$5.5\ (+3.5, -1.5)\times10^{-5}$	$6.5\ (+2.5, -1.5)\times10^{-5}$
$^3He/^4He$	$1.5\pm0.3\times10^{-4}$	$1.66\pm0.05\times10^{-4}$			
$^{15}N/^{14}N$	$\leq2.8\times10^{-3}$	$2.3\pm0.3\times10^{-3}$			

[1]Atreya and Wong [3]

Fig. 1. Elemental abundances (relative to H) in the atmospheres of the giant planets compared to the solar values. The Jupiter results are those measured by the Galileo Probe Mass Spectrometer (GPMS). Solid horizontal line shows that direct gravitational capture would result in elemental abundances (ratioed to H), same as in the Sun. However, at Jupiter the heavy elements, Ar, Kr, Xe, C, N, and S are all found to be enriched by a factor of 3±1. The only heavy element measured at Saturn, Uranus and Neptune is carbon, which is shown with error bars. The other elements shown by the diamonds (Saturn), crosses (Uranus) and circles (Neptune) do not represent data, but are based on model predictions that they would be similarly enhanced as carbon (see text). Condensation of helium into droplets in the 3-5 megabar region of Jupiter's interior reduces the He/H ratio to approximately 80% solar in the upper troposphere [5]. Neon is depleted to 10% solar, as neon dissolves into helium droplets [5]. Helium depletion in Saturn's troposphere may be even greater than at Jupiter, as is already indicated by the re-analysis of the Voyager data. This would lead to a larger depletion factor for Ne/H at Saturn compared to Jupiter. On the other hand, helium condensation is not expected in the ice giants, Uranus and Neptune, due to their smaller masses and evolutionary history. This means the He/H would be solar or nearly solar in the tropospheres of these two planets, as is implied indirectly also by ground-based data on CO and HCN in the atmospheres of the ice giants [3,5]. The lack of helium droplets also implies that neon will not be removed either in the interiors of Uranus and Neptune, resulting in at least solar Ne/H, but most likely Ne/H will be enriched by similar factors as the other heavy elements, 30-50 times solar. Thus, the Ne and He measurements at these two planets are important tracers also of interior processes.

3.1 Equilibrium cloud condensation model (ECCM)

ECCM's date back to the pre-Voyager epoch. The model was first developed by Weidenschilling and Lewis [11], and has undergone further development, as described in Atreya and Romani [12] and Atreya [13]. The lifting condensation level (LCL), i.e. the base of the cloud, is calculated by comparing the partial pressure (e) and the saturation vapor pressure (e_c) of the condensable volatile. The LCL is reached at the altitude where relative humidity (e/e_c) of 100% is attained. The amount of condensate in the ECCM is determined by the temperature structure at the LCL and vicinity. The release of latent heat of condensation modifies the lapse rate, hence the temperature structure, of the atmosphere. Thus, the composition and structure of the clouds depend on the composition of the atmosphere, and in particular the distribution of condensable volatiles.

Thermochemical equilibrium considerations suggest that NH_3, H_2S and H_2O are the only species that are likely to condense in the atmospheres of Jupiter and Saturn. In the gas phase, H_2S can combine with NH_3 to form NH_4SH, i.e., $NH_3(g) + H_2S(g) \rightarrow NH_4SH$, or ammonium sulfide, $(NH_4)_2S$, which is less likely. NH_4SH would condense as a solid in the environmental conditions of all giant planets. NH_3 could also dissolve in H_2O, resulting in an aqueous solution (droplet) cloud. The extent of such a cloud depends on the mole fractions of NH_3 and H_2O. Additional cloud layers are possible at Uranus and Neptune, as discussed below.

As shown in Table 1, N (from NH_3) and S (from H_2S) are enriched relative to solar, but O (from H_2O) is subsolar even at the deepest level in the region of entry of the Galileo Probe at Jupiter. If the original ice did not reach Jupiter as clathrate hydrate, as proposed by Gautier et al. [14, 15], O/H would be expected to be enriched by a similar factor as the other heavy elements, i.e. 3±1 [5, 7], since current ideas of the formation of Jupiter favor a core accretion model in which cold planetesimals are the original carriers of heavy elements (m/z ≥ 4). If the heavy elements were delivered by clathrate hydrates, then the water abundance would be more than 9 times solar in Jupiter's well-mixed atmosphere [14, 15]. In either case, condensation of water both as ice and droplets is inevitable in Jupiter's troposphere. The same is expected at Saturn, but at deeper levels due to greater enrichment factor of the heavy elements compared to Jupiter as indicated by C/H

measured from the Cassini orbiter (Table 1). The Saturn story might be different if the solar nebula at Saturn's orbit was "ice-starved" [16].

We present in Figs. 2 and 3 model results on the bases and concentrations of possible condensates of ammonia ice, ammonium hydrosulfide-solid, water ice, and aqueous-ammonia solution ("droplet") clouds of Jupiter and Saturn. The ECCM calculations for Jupiter are shown in Fig. 2 with the condensable volatiles taken as 1× solar and 3× solar. The base of the water cloud is found to be at 5.7 bar, 7.2 bar and, 9 bar level (not shown), respectively, for 1× solar, 3× solar and 10× solar enrichment of the condensable volatiles. The ECCM calculations for Saturn are shown with the condensable volatiles taken as 1× solar and 5× solar. The 5× solar or greater enhancement of the heavy elements is the more likely scenario for Saturn, based on the Cassini determination that C/H is indeed 6±1× solar, as indicated by previous measurements in the thermal infrared (M. Flasar, G. Orton, personal comm., 2005). Since the atmosphere of Saturn is colder compared to Jupiter, condensation of the same species occurs at much greater pressure levels on Saturn than Jupiter. For example, with solar O/H, the base of the water cloud on Saturn (12.6 bars) is at nearly twice the pressure it is at Jupiter (5.7 bar); for 5× solar, the Saturn water cloud base is at 21 bars!

In addition to the clouds of NH_3, NH_4SH and H_2O as on Jupiter and Saturn, additional cloud layers may be possible at Uranus and Neptune, because of their colder temperatures and possibly greater elemental enrichment. The ECCM model (Fig. 4) predicts the topmost cloud layer to be composed of methane ice at Neptune and Uranus. The Voyager radio science observations confirm the existence of a cloud at the pressure level predicted for the CH_4-ice cloud by the ECCM. Another cloud composed of H_2S may exist between 3 and 8 bars if a deep ionic ocean exists ([17], see below). Due to their similar p-T structures, the model results for Neptune and Uranus are similar. Assuming 30–50× solar enhancement for the condensable species, as expected from formation models, we find that the base of the droplet cloud is at the 370 bars for 30× solar, and at 500 bars for 50× solar cases [3, 18].
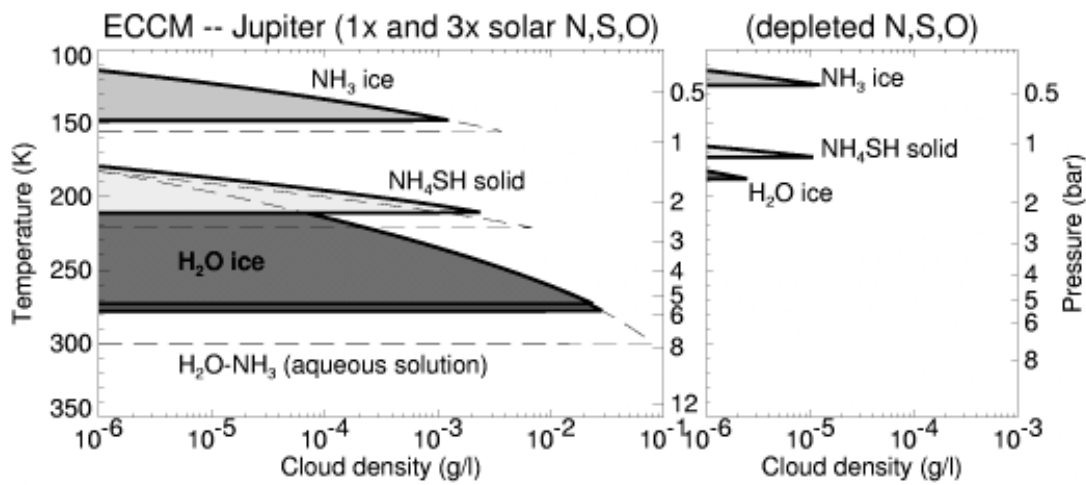
Fig. 2. Results of ECCM calculations for Jupiter, with 1x solar and 3x solar condensable volatile abundances in the left panel, and greatly depleted condensable volatiles in the right panel in order to simulate the LCL of the clouds detected in the Galileo Probe Entry Site (PES). Since the Galileo Probe entered a dry region, the condensable volatiles were found to be greatly depleted to levels well below their expected condensation levels. The cloud densities represent upper limits, as cloud microphysical processes (precipitation) would almost certainly reduce the density by factors of 100–1000 or more. However, the LCL's, i.e. cloud bases are expected to remain unaffected [5].
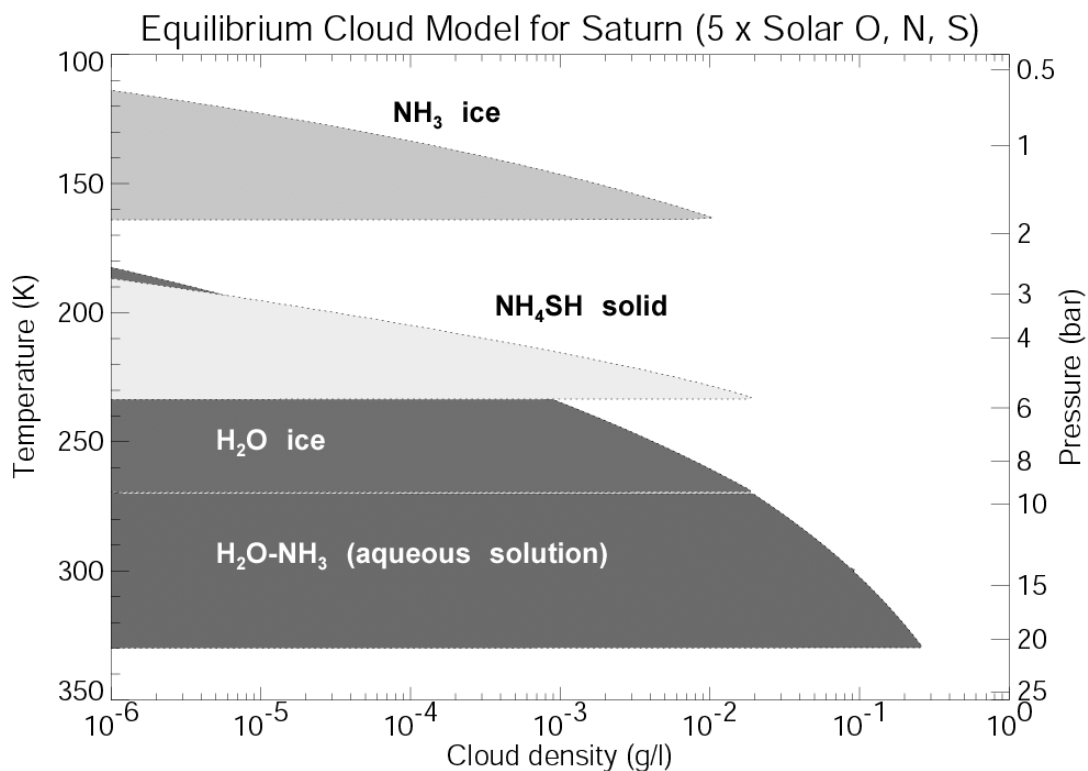

Fig. 3. Results of ECCM calculations for Saturn, with 1x solar and 5x solar condensable volatile abundances. The cloud densities represent upper limits, as cloud microphysical processes (precipitation) would almost certainly reduce the density by factors of 100–1000 or more. However, the LCL's, i.e. cloud bases are expected to remain unaffected [5].

Some models (e.g. [19, 20]) predict the presence of an ionic ocean of water and ammonia in the 0.1 megabar region, much deeper than even the aqueous ammonia solution cloud discussed above. Such an ocean is most likely also responsible for the depletion of ammonia in the upper troposphere as seen in the VLA observations. The NH_3 depletion is significantly more severe than can be explained by the loss of this species in the formation of an NH_4SH cloud. The consequence of purported ionic ocean is that both NH_3 and H_2O will have been depleted well below their cloud bases shown in Fig. 4. The greatly depleted amount of NH_3 will manifest itself in yet another way – near absence of an NH_4SH cloud. This would allow H_2S to be present above the level where the NH_4SH cloud would have removed it. In turn, this will then result in the formation of a cloud of H_2S

itself. Such a cloud could form in the 3-8 bar region, depending upon the degree of loss of NH_3 in the water-ammonia ionic ocean [17]. In fact, ground-based observations of Uranus and Neptune require a cloud in this region [21, 22]. The conventional ECCM model (Fig. 4), i.e. one without the depletion of NH_3 (and H_2O) in an ionic ocean, does not allow a cloud to form in this region. Thus the presence of greatly subsaturated NH_3 in the upper troposphere as inferred from the VLA data and the requirement of a cloud in the 3-8 bar region are a strong indicator of the existence of an ionic ocean of ammonia and water at tens of kilobar level. This means that water and ammonia will be severely depleted relative to their mixed atmosphere values at lower pressures, and that their mixed atmosphere values cannot be reached even at tens of kilobar level!
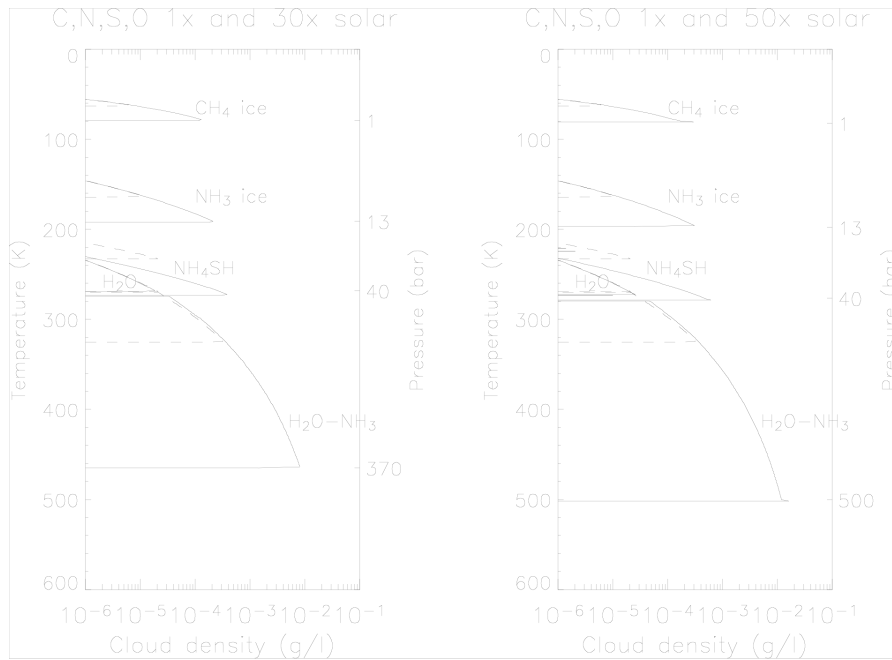

Fig. 4. ECCM results for Neptune, assuming 1× (dashed lines), and 30× (left panel) or 50× solar enrichment (right panel), of condensable volatiles (CH_4, NH_3, H_2S, H_2O ratioed to H) relative to solar. Cloud bases for 30× and 50× solar cases are marked on the right ordinates. The cloud densities represent upper limits, as cloud microphysical processes (precipitation) would almost certainly reduce the density by factors of 100–1000 or more. However, the LCL's, i.e. cloud bases are expected to remain unaffected. The structure and locations of the clouds at Uranus are very similar to the 1× and 30× solar (left panel) cases for Neptune due to similar thermal structure (p-T) and 20–30× solar enrichment of condensable volatiles, noble gases and the other heavy elements. Van der Waals corrections have been accounted for [3, 18].

4. SHALLOW ENTRY PROBES, TOGETHER WITH MICROWAVE RADIOMETRY

From the above discussion, it is apparent that the well-mixed region for water at Jupiter lies below approximately ten bars, taking into consideration the extreme of water abundance predictions. For Saturn, it is below at least 20 bars. The well-mixed region for water and ammonia may be at tens of kilobar level at Uranus and Neptune. Considerations of non-equilibrium thermodynamics and convection in the deep atmosphere could result in the well-mixed regions for water at Jupiter and Saturn to be around 50-100 bars. The technological challenges of measurements at high pressures of 50-100 bars with correspondingly high temperatures of 400-500 K at Jupiter and Saturn are enormous. Survival of the probe structure and scientific payload in this environment and the difficulty of data transmission from such great depths are only two of a multitude of obstacles. It is therefore a great relief that Juno-Jupiter Polar Orbiter is going to show the way. Microwave radiometry from the orbiter is designed to probe to hundreds of bars at Jupiter [23]. This novel approach, employing wavelengths ranging from 0.5 to 50 cm, works beautifully for water, which is the real driver for probing deep. This approach will work well for measuring water at Saturn as well. In fact, microwave radiometry may be considerably simpler at Saturn in view of its benign radiation environment compared to Jupiter. Probes will be required to measure the other critical heavy elements at Saturn. However, *shallow* probes will suffice, as water could be measured with microwave radiometry from flyby spacecraft, as mentioned above. All noble gases, He, Ne, Ar, Kr and Xe, together with their isotopes, C, N, S, and D/H and $^{15}N/^{14}N$, and the disequilibrium species can be measured at pressures less than 10 bars. Combined with O/H from microwave radiometer measurements of water, this will provide the set of elemental composition data that are critical for constraining models of the formation of Saturn and the origin and evolution of its atmosphere. Comparative planetology with the other gas giant, Jupiter, will be even more valuable, and possible after the Juno measurements. The need for multiple entry probes into Jupiter will still exist, as "simultaneous" measurements of all heavy elements and isotopes at multiple locations are essential. The Juno measurements will be a tremendous asset and guide for the design of a Jupiter multiprobe mission.

The technological challenge associated with entry probes at Uranus and Neptune are insurmountable, if one were to probe to the well-mixed region of water, which could be close to the megabar level! On the other hand, the rest of the critical elements and isotopes, including He, Ne, Ar, Kr, Xe, C, $^{15}N/^{14}N$, and D/H and $^{3}He/^{4}He$ can be accessed and measured at shallower depths with pressures of less than 10 bars. Measurement of S/H may require going to approximately 50 bars, as seen from the base of the NH_4SH cloud in Fig. 4. On the other hand, the determination of the S/H ratio may yet be possible from H_2S measurements down to 10 bars, if an H_2S cloud is indeed present in the 3-8 bars region. As mentioned previously, such a cloud would result if NH_3 has been removed in an ionic ocean, thus reducing the likelihood of the removal of H_2S by an NH_4SH cloud at 40 bars. Further studies are warranted on the criticality of the sulfur measurement, as well as on the models of ionic ocean and its manifestation in the upper troposphere. Complementary information on the disequilibrium species, PH_3, GeH_4, and AsH_3, CO at these planets, as well as at Jupiter and Saturn, and the cloud, wind, and lightning characteristics would greatly enhance the value of the above elemental compositional data. Although O/H and N/H will most likely remain unknown after the probe missions at the ice giants, their absence will not be a major impediment, as the trend will have been established by comparing all other heavy elements to the results at Jupiter and Saturn.

5. SUMMARY AND RECOMMENDATIONS

In summary, multiple probes to the giant planets are critical for collecting the data required for understanding the formation of our solar system, and by extension, extrasolar systems. Shallow probes deployed to only approximately 10 bars, combined with microwave radiometry from the spacecraft is ideally suited to collect the critical composition data, including water, at Saturn and Jupiter.

A Saturn flyby mission with probes and microwave radiometry should be the highest priority for a near-term mission to the outer planets, since (i) comparative planetology of the two gas giants, Jupiter and Saturn, is crucial, and (ii) the technological challenges of such a mission could conceivably be surmounted and the mission realized within the cost cap of NASA's New Frontiers class. We recommend a flyby, instead of an orbiter at Saturn, because Cassini orbiter in its prime and extended missions will have made most, if not all, other high priority science measurements. Hence, a simpler and less costly flyby mission with the probe and microwave capability will do the job, and can be easily justified scientifically (and politically). However, it is important to stress that the measurements recommended here for the next big scientific breakthrough about

Saturn and the giant planets are independent of the nature of the mission, whether it is a flyby or an orbiter.

Shallow probes at Uranus and Neptune can also collect most of the critical composition information. When combined with the data at Saturn and Jupiter, their scientific value will be enhanced greatly. The probe missions at Neptune and Uranus should be complemented with orbiters, not flybys, because of the dearth of complementary orbital science data. Unlike at Jupiter and Saturn, microwave radiometry on Uranus and Neptune orbiters is not expected to be particularly useful, because of the requirement of reaching tens of kilobar region to find well-mixed water (and ammonia) on the ice giants.

A Jupiter multiprobe mission should be considered after data from Juno, especially on water, have been received and analyzed, as the Juno results will be valuable to the design of a multiprobe mission to Jupiter.

An investment in enabling technology, especially (a) the thermal protection system (TPS, or heat shield), (b) communication from microwave absorber-rich atmospheres of the giant planets, (c) radioisotope power sources, (d) possible use of solar power at Saturn, (e) operation in extreme environment of relatively high temperature and pressures, and (f) integrated payload systems, is required now to realize the ambitious probe missions to the giant planets in the near and long term. Technology readiness and feasibility studies are also required, and they should be carried out hand in hand with further modeling studies to encompass various composition and condensation scenarios based on formation and thermochemical models. Finally, multinational partnerships should be explored vigorously to maximize science return and to realize cost savings.

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