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ROLE OF ENTRY PROBES IN THE EXPLORATION OF THE SOLAR SYSTEM GIANTS

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Abstract

Spacecraft have explored the solar system systematically in the past six decades. The underlying strategy of such exploration has been flyby, orbit, land. In the case of the giant planets, which are gas or fluid rich and whose "land" lies tens of thousands of kilometers beneath their cloud tops, landing is not an option. Fortunately, entry probes deployed to technically feasible depths can still address the fundamental questions about their formation and the origin and evolution of their gaseous or icy envelopes. One such challenge was undertaken by the Galileo probe at Jupiter in 1995. The probe findings fundamentally altered our understanding of Jupiter in particular and the solar system formation in general. In this talk, I will review those findings, why they are so fundamental, and what needs to be done to advance our understanding of the formation and evolution of the other giant planets in our solar system, Saturn, Uranus and Neptune. In each case, I will demonstrate entry probes are absolutely crucial for achieving that goal. Finally, I will discuss how the solar system serves as best analog for extrasolar systems, and how the detailed data from exoplanets can also inform the models of the solar system formation and evolution. Reference for a comprehensive review: Atreya S. K., A. Crida, T. Guillot, J. Lunine, N. Madhusudhan, O. Mousis (2016) The Origin and Evolution of Saturn, with Exoplanet Perspective, in Saturn in the 21st Century (K. H. Baines, F. M. Flasar, N. Krupp, T. S. Stallard, editors), Cambridge University Press, Cambridge, UK.

1. INTRODUCTION

The collapse of a local interstellar cloud led to the primordial solar nebula – a cloud of gas and dust – from which the sun and the planets formed. The sun formed first, followed by the giant planets and the terrestrial planets. The leftover debris exists mainly as asteroid belt, comets and trans-Neptunian objects. The giant planets formed beyond the snow line, a hypothetical boundary in the primordial solar nebula at ~5 AU from the sun, where the temperature was ≤150 K, so that water existed in the form of ice. Ice was key to the huge growth of the giant planets. The giant planets are so massive that for all practical purposes nothing escaped from them since their formation. Thus, they still retain the primordial solar nebula material, which in turn holds the secret to the formation of the solar system itself.

The interstellar cloud from which the solar system originated does not exist any longer, but the expectation is that its *elemental* abundance ratio was reflected in the *proto*sun. The present day photosphere can give model-dependent information on protosolar composition, but the giant planets, particularly Jupiter, may reveal that information directly, at least for key elements and isotopes. The solar elemental abundances normalized to hydrogen as gleaned from current solar spectroscopy are illustrated in Figure 1. Inter-elemental ratios in the giant planets are expected to be the same, but could differ for certain elements depending on their method of delivery. We will first discuss briefly the models of the formation of the giant planets in order to illustrate the importance of measuring the elemental abundances.

2. HOW DID THE GIANT PLANETS FORM

Of the two main models of the formation of the giant planets – core accretion and the gravitational instability – the former is generally favored. The best evidence of the core accretion model comes from the observed enrichment of the *heavy* elements in Jupiter (mass greater than helium, ^{4}He, or >4AMU)), presence of first solids (millimeter size chondrules and calcium aluminum inclusions) at the very beginning of the solar system, and greater frequency of exoplanets around metal-rich stars (Atreya et al., 2016 [1], and references therein).

In the core accretion model, non-gravitational collisions between small grains comprising dust, metals, refractory material, ices and trapped volatiles lead to larger particles that grow to kilometer to hundreds of kilometer sized planetesimals and eventually form an embryo, the core. When the core is large enough, i.e. 10-15 earth masses, it is capable of gravitationally capturing the most volatile of the gases, hydrogen, helium and neon, from the surrounding protoplanetary nebula. The volatiles trapped in the core are then released during accretionary heating and form the

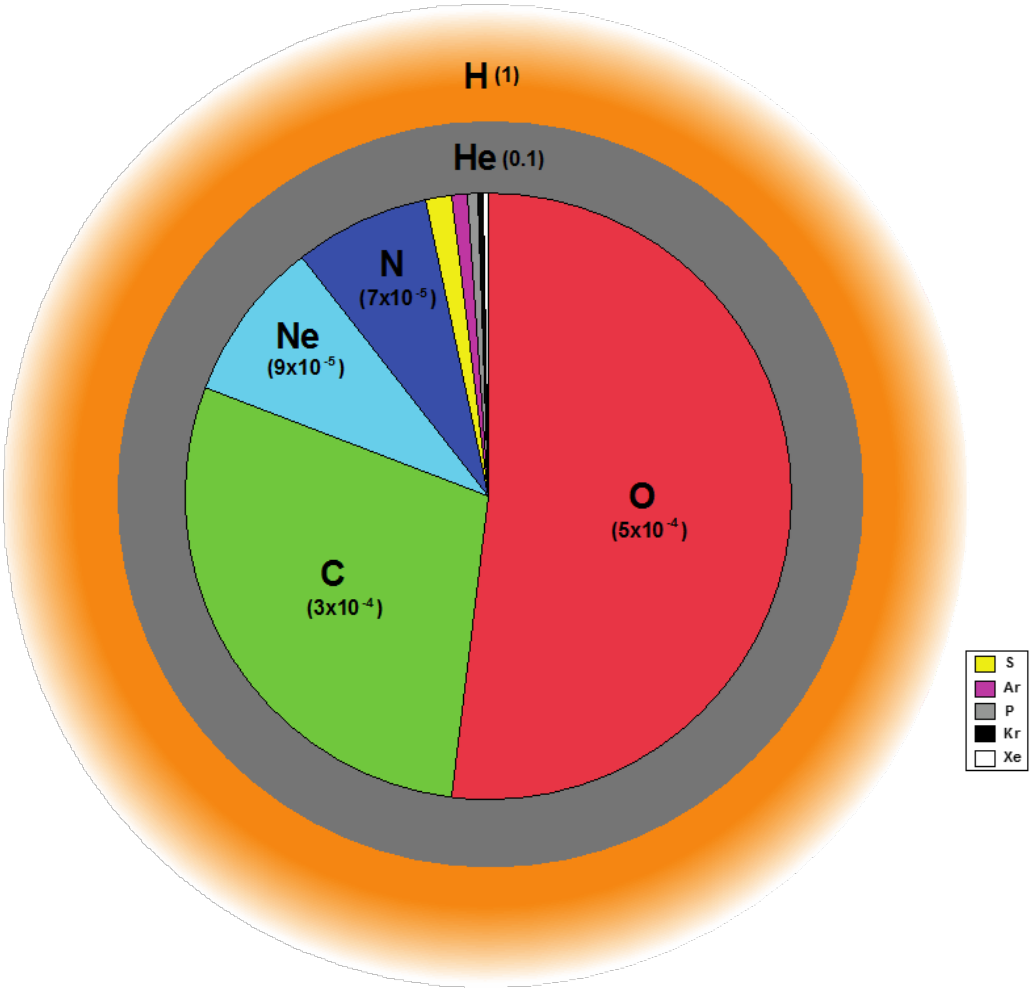

Figure 1. Distribution of the solar elements normalized to H, based on data from Asplund et al. 2009 [2].

atmosphere of the giant planet together with H_2, He and Ne. There are a number of variations to the above scenario of planet formation, in particular growth by pebbles, but the basic theme of core accretion is preserved.

The abovementioned scenario of core accretion is a slow process, taking up to several million years to form the gas giant planets, Jupiter and Saturn, whereas it could take up to tens of millions of years to form the ice giant planets, Uranus and Neptune. However, the solar nebula, from which all planets formed, dissipated in less than 5 million years, which is not long enough to form the ice giants in the conventional manner. One scenario is that they too formed for the most part where the gas giants formed and then migrated out to their present orbits, where they completed the last stage of their formation. The heavy element abundances will be important to also understand possible migration of these and the other giant planets.

Remote sensing observations can reveal the composition of only the upper atmosphere and down to ~1 bar level, i.e. in a region where chemistry, condensation and transport control the distribution of the constituents. However, bulk of the atmosphere, which alone can provide the elemental abundances in the giant planets, lies deeper in the troposphere. That part of the atmosphere is largely inaccessible to remote sensing. Hence, entry probes are the only means to measure their bulk composition. The depth to which such probes must make measurements depends on the levels where clouds form and the effect of dynamics persists, as discussed below.

3. WHERE TO FIND THE BULK COMPOSITION IN JUPITER: THE GALILEO PROBE EXPERIENCE

Technically, the region below which the relative proportion of a given species remains unchanged is where its bulk abundance lies. This well mixed region of the atmosphere is where the elemental abundances can be determined. To understand that in the context of the giant planets, we list in Table 1 the abundances of key elements (normalized to solar and all ratioed to H), which are used to constrain the formation models. Figure 2 summarizes the information in Table 1. The noble gases, He, Ne, Ar, Kr and Xe do not condense, hence they are well mixed everywhere in the atmosphere, except above the homopause. Thus, their measurement anywhere feasible below the homopause would be representative of their bulk abundance, hence elemental ratios (to H). Considering their low abundances, that region is generally in the troposphere at pressures greater than 1 bar. However, that is not the case for the volatiles that undergo condensation. Their bulk lies below their individual cloud bases.

In the atmospheres of the gas giants, Jupiter and Saturn, the elements N, S and O are sequestered overwhelmingly in NH_3, H_2O and H_2S (ammonia, hydrogen sulfide and water), which are all condensible either thermophysically or following chemical reactions (H_2S-NH_3). In the colder ice giants, Uranus and Neptune, CH_4 (methane) condenses, in addition. Thermochemical equilibrium cloud condensation models (ECCM, Atreya et al. 1999 [7]) show that in Jupiter's atmosphere, cloud bases lie at ~ 0.5 bar (NH_3), ~ 2 bar (NH_4SH, formed from NH_3-H_2S reaction) and ~5 bar (H_2O) for no enrichment, i. e. 1× solar elemental ratio of N, S and O. For 10× solar enrichment, they would be deeper. For example, the H_2O cloud base would be at~10 bars, and a substantial aqueous-ammonia solution cloud would form from the solution of NH_3 in water droplets below the water-ice cloud above. Thus, the well-mixed regions of Jupiter's NH_3, H_2S and H_2O, should, in principle, be at atmospheric pressures greater than ~0.5, 2 and 5 bars, respectively, for 1× solar N/H, S/H and O/H.

The Galileo probe was designed to determine the bulk composition, hence the heavy element abundances in Jupiter's atmosphere. The probe succeeded in carrying out measurements to 22 bars, which is well below the expected condensation level of the deepest cloud, water, which was calculated to be between 5-10 bar level for O/H between 1-10 times solar.

The Galileo probe successfully measured the well-mixed abundances of all but one of the heavy elements, oxygen, and found them to be enriched relative to solar, by a factor of 4±2 (Atreya et al. 2016 [1]). Ne was severely depleted and He was slightly sub-solar (Table 1, Figure 2). In Jupiter, helium raindrops are expected to form at several megabar pressure levels, which would result in the removal of some helium in the interior. Ne would also be removed as it dissolves in liquid helium.

The only heavy element whose well-mixed abundance was not reached even at 22 bars was water (Wong et al. 2004 [8]). The Galileo probe entered a very dry region of Jupiter, a big 5-micron hotspot. Since water was presumably the original carrier of the heavy elements that formed Jupiter, it is crucial to measure its well-mixed abundance, hence the O/H ratio. The microwave radiometer on the Juno spacecraft is designed to map the distribution of water to several hundred bars in Jupiter's atmosphere, which should settle the question of Jupiter's oxygen elemental abundance.

The Galileo probe data are a good demonstration of the role of dynamics in the troposphere of Jupiter, which clearly show that the well-mixed abundances of the condensible gases may not be reached immediately below their cloud bases. They may require reaching down to levels much, much deeper than their respective condensation levels. From a limited set of data on ammonia this requirement seems to hold for Saturn also (Atreya et al. 2016 [1]), and could well be the case at Uranus and Neptune, as discussed later.

4. WHERE IS SATURN'S WELL-MIXED ATMOSPHERE

The only heavy element whose abundance has been determined robustly in Saturn is carbon (from CH_4), with a value of C/H=9 (Table 1). S/H derived from ground-based observations of H_2S, is highly uncertain. P/H, derived from phosphine (PH_3) upwelled to the upper troposphere from its thermochemically stable region deep in the atmosphere (~kilobar, ~1000 K level) may not be representative of the deep well-mixed atmosphere value, due possibly to fractionation during transport.

If the C/H is representative of the ratios of other heavy elements also, they would all be around 10× solar. Unlike Jupiter, those ratios are presently unknown in Saturn's atmosphere. In the colder gas giant, Saturn, the NH_3-H_2O solution cloud would form even deeper than Jupiter, i.e. at ~20 bars, for 10× solar enrichment of H_2O (Atreya et al. 2016 [1]). Though nearly at twice the atmospheric pressure than Jupiter for the same enrichment, the corresponding temperatures would be

Table 1. Planetary to protosolar ratios of key elements in the giant planets

Elements	Sun-Protosolar[(a,b)]	Jupiter/ Protosolar[(c)]	Saturn/ Protosolar[(c)]	Uranus/ Protosolar[(d)]	Neptune/ Protosolar[(e)]
He/H	9.55×10^{-2}	0.82±0.02	0.71±0.13 (?)	~ 1	~ 1
Ne/H	9.33×10^{-5}	0.13±0.001			
Ar/H	2.75×10^{-6}	3.31±0.66			
Kr/H	1.95×10^{-9}	2.38±0.44			
Xe/H	1.91×10^{-10}	2.34±0.45			
C/H	2.95×10^{-4}	4.02±0.98	8.98±0.34	80±20	80±20
N/H	7.41×10^{-5}	4.48±1.7 5.40±0.68	1.08-3.84; 3.06±0.77 with $f_{NH3}=4\pm1\times10^{-4}$		
O/H	5.37×10^{-4}	0.46±0.15 (hotspot)			
S/H	1.45×10^{-5}	3.08±0.73	13.01		
P/H	2.82×10^{-7}	3.83±0.21	12.91±0.85		

(a)Protosolar values based on the solar photospheric values of Asplund et al. (2009 [2], table 1).
(b)According to Asplund et al. (2009) [2], the protosolar metal abundances relative to hydrogen can be obtained from the present day photospheric values (table 1 of Asplund et al., 2009 [2]) increased by +0.04 dex, i.e. ~11%, with an uncertainty of ±0.01 dex; the effect of diffusion on He is very slightly larger: +0.05 dex (±0.01). Note that Grevesse et al. (2005 [3], 2007 [4]) used the same correction of +0.05 dex for all elements. dex stands for "decimal exponent", so that 1 dex=10.
(c)Atreya et al. (2016 [1]) Table 1, cites the references for Jupiter and Saturn.
(d)Sromovsky et al. (2011 [5]); E. Karkoschka and K. Baines personal communication. (2015).
(e)Karkoschka and Tomasko (2011 [6]).

similar, since thermodynamics depends largely on temperature at such pressures. But, herein lies a technical challenge. Any probe measurements to determine well mixed H_2O in Saturn would need to ensure survival of the probe to pressures of 50-100 bars and transmission of data from such great depths.

5. WHAT ABOUT URANUS AND NEPTUNE: AN IONIC OCEAN?

The only heavy element determined in the atmospheres of the ice giant planets, Uranus and Neptune, is carbon from CH_4, and that too has large uncertainty. The C/H ratio is found to be 80±20× solar, or greater, in both Uranus and Neptune (Karkoschka and Tomasko 2011 [6]; Sromovsky et al. 2011 [5]; Atreya et al. 2016 [1]). The increasing C/H ratio from Jupiter to Saturn to Uranus and Neptune, from 4× solar at Jupiter to 9× solar at Saturn to ≥80× solar at Uranus and Neptune, is what one would expect on the basis of the core accretion model. However, this is a premature conclusion about this or any other formation scenario of these planets in the absence of data on the remaining suite of the heavy elements.

The ECCM calculations for Uranus and Neptune predict the cloud bases of CH_4, NH_3, NH_4SH and H_2O (ice) and H_2O-NH_3 solution to be at, respectively, 0.75, 10, 30, 53 and 88 bars for uniform 1× solar ratios for all elements, and at approximately 1, 13, 44, 39 and 495 bars for 80× solar ratios (Atreya and Wong 2004 [9], and 2005 [10], but revised using the current solar elemental abundances given in Table 1 and applying the inter-molecular force corrections at high pressures from Atreya and Wong 2004 [9]). The current models for Neptune are shown in Figure 3. Considering the effects of dynamics, as seen in the Galileo probe entry at Jupiter, the well-mixed levels of the condensible volatiles could lie much, much deeper, perhaps many

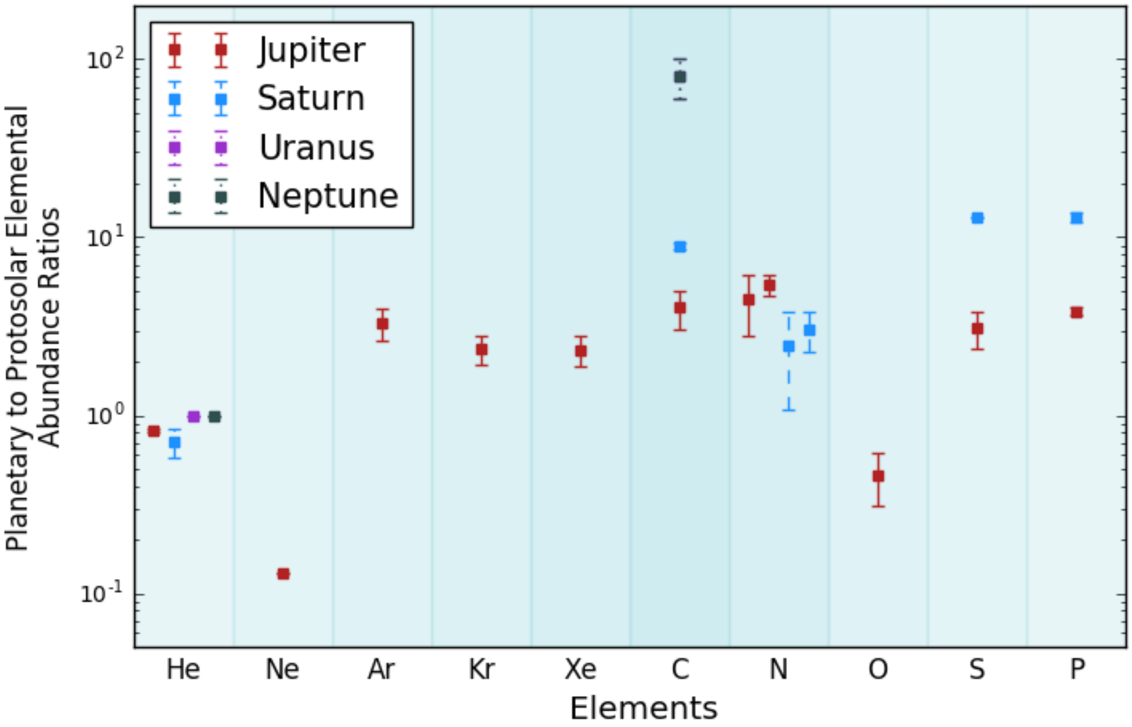

Figure 2. Elemental abundances in Jupiter, Saturn, Uranus and Neptune normalized to protosolar values. For Jupiter's N/H, results are shown from both Galileo probe mass spectrometer and the attenuation of radio signal from probe to orbiter. See text for caveats about Saturn's values, except for carbon.

times the cloud bases levels of the ECCM. For the 80× solar O/H, well-mixed water may be at several kilobar level in that case. In Fact, it may be even deeper than that because of possible presence of an ionic ocean at hundreds of kilobar level (Atreya and Wong 2005 [10]).

Molecular dynamics calculations predict a superionic phase of water at temperatures above 2000 K and pressures above 30 GPa, (Goldman et al., 2005 [11]). Such a phase change would not only result in the depletion of water at ≥300 kilobar, it may even deplete ammonia due to the solubility of NH_3 in H_2O. A likely composition of such an ionic ocean is $H_3O^+{\cdot}NH_4^+{\cdot}OH^-$, together with free electrons in the plasma. The dynamo that drives the internal magnetic field of Uranus and Neptune may be the result of such an ionic ocean at Uranus and Neptune (Ness et al. 1986 [12]), since, metallic hydrogen, which drives the dynamo of Jupiter and Saturn, may not form in the interiors of Uranus and Neptune. The large depletion of NH_3 observed in the tropospheres of Uranus and Neptune by the VLA (Mark Hofstadter, personal comm., 2016; de Pater et al., 2003 [13]) could also be a consequence of the removal of ammonia in the deep ionic ocean.

6. ENTRY PROBES: TECHNICAL CHALLENGES

The above discussion illustrates that the well-mixed atmospheres of the giant planets are relatively deep, and not accessible to remote sensing. Passive microwave remote sensing technique employed on Juno spacecraft can provide information on only those gases that absorb at radio wavelengths. That essentially limits the measurement to just ammonia and water vapor. However, O and N elemental abundances by themselves are insufficient to constrain the models of the formation of these planets. It is essential to have the data on the other heavy elements and certain isotopes. In the case of Jupiter the Galileo entry probe collected those data in 1995. Juno is designed to complete that suite by the determination of the oxygen elemental abundance by measuring the water vapor abundance to levels well below the expected condensation level of water, i. e. to several hundred bars. For Saturn, Uranus and Neptune, none of the heavy elements, with the exception of carbon, have yet been determined. To access them requires deployment of atmospheric entry probes.

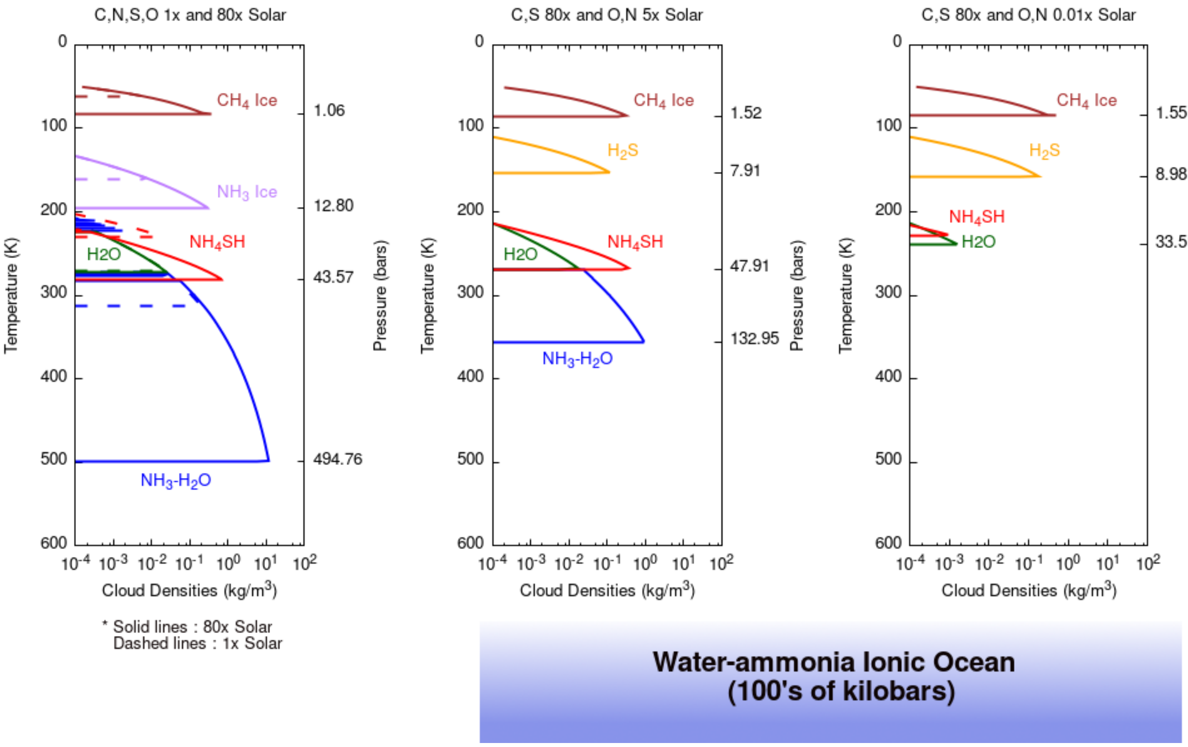

Figure 3. Cloud structure of Neptune assuming (i) 1× solar and 80× solar abundances for *all* condensible elements (left panel), (ii) 80× solar for C and S (CH_4 and H_2S), but O and N reduced to 5× solar to illustrate the effect of possible removal of water and ammonia in a purported deep ionic ocean; notice the complete absence of the ammonia cloud, but appearance of an H_2S cloud instead, and (iii) same as (ii) except that O and N are reduced even further, to 0.01× solar (NH_3 was measured at this level by the VLA in the upper troposphere); as expected, the water cloud is nearly non existent now. The cloud bases are robust, but the concentrations are *upper limits*, because precipitation and dynamical effects are likely to reduce them by up to several orders of magnitude as in the Earth's troposphere. A more realistic cloud density treatment is given in Wong et al. 2015 [14]. The Neptune calculations shown above are illustrative also of the Uranus cloud structure and locations, especially when plotted against the temperature scale (left ordinate). Only minor adjustments to account for the relatively small differences in their gravity and tropospheric temperature structure, hence lapse rates, are required.

At Saturn, probes capable of making measurements to at least 50-100 bars will be required to reach a level that is well below the expected water condensation level, which is at ~20 bars if O is as enriched as C, i.e. ~10× solar. Entry probes to such depths are technically highly challenging from point of view of their survival, performance of instruments and the transmission of data through a thick atmosphere that absorbs at radio wavelengths. A Galileo-Juno like scenario, where relatively shallow entry probes to ~10 bars are employed to measure the noble gases and their isotope ratios, CH_4, NH_3, H_2S, $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{34}S/^{32}S$ and D/H (possible, even if H_2O is only solar), and microwave remote sensing to measure water would be ideal. If microwave for H_2O is not feasible because of cost constraints, the rest of the suite measured by entry probes would still provide robust constraints to the models of the models of formation of Saturn, especially since comparison of those elements and isotopes with the ones in the atmosphere of the other gas giant, Jupiter, would establish a trend that could be used to predict Saturn's O/H from water to a reasonable degree of confidence. Alternative approaches for determining Saturn's O/H, such as from CO, may also be possible, provided that the primordial CO component is distinguished from any upper atmospheric source and transport from the deep atmosphere is well constrained.

For Uranus and Neptune, entry probes are most useful for determining the noble gases and their isotopes, and CH_4 and $^{13}C/^{12}C$ from it. The He/H_2 is of particular interest for it is essential to understand the interior processes and the planetary heat balance. These measurements can be done with probes to ~10 bars. In order to make robust measurements of N, S, and O elemental abundances, probes to several kilobar levels are required. Current technology does not permit such measurements. Even if future technological advances could allow that, the data may be still be ambiguous, considering the possibility of an ionic ocean at several hundred kilobars, as discussed above. The ionic ocean would not only lead to the removal of water, it would deplete NH_3 and H_2S, both of which dissolve in water. The lack of O, S and N elemental abundances would not be a disaster, however, for constraining the models of the ice giant planets, since robust data on the noble gases and their isotopes, and CH_4 and $^{13}C/^{12}C$ will have been collected by probes deployed to 10 bars. These data will be sufficient, especially if the data for the gas giants are available for comparison.

Besides the survival of the probe and its payload and communication of data from the probe, thermal protection of the probe during entry is a major technical challenge as the entry speeds are punishing. The heat shield material for the 1995 Galileo entry probe developed in the 1980's is no longer manufactured. New technology and new materials are needed for the next generation of atmospheric entry probes to the other giant planets.

7. SUMMARY AND FUTURE

It is important to stress that although this paper is focused on the fundamental questions of the origin and evolution of the giant planets, which only the entry probes can address, remote sensing observations for understanding the dynamics, chemistry, energetics, interior, rings and moons are essential, in addition, to understand the planetary *system* as a whole. The Jovian system is most advanced in this sense, with already completed or in-progress dedicated missions, including the Voyager flybys, Galileo probe and orbiter, Juno and JUICE. Cassini orbiter will need to be complemented with an entry probe in the future to fully comprehend the origin and evolution of Saturn and workings of the Saturn system. Uranus and Neptune are poorly understood, with only the 1980's flybys of Voyager, whose payload was not optimized for these cold and distant objects. Future missions to the ice giant planets will need to be a combination of flybys, probes and orbiters, as in the case of the gas giants. NASA's New Frontiers 4 list of candidates includes a Saturn probe, and ESA's Cosmic Vision program may offer another opportunity. The US NRC's 2013 Visions and Voyages (Planetary Decadal Survey) recommends exploration of the ice giant planets by a flagship mission, and NASA has commissioned a Science Definition Team to identify science drivers and the options for such missions. In summary, the diversity and richness of the giant planets and their importance to understanding the beginnings and history of the solar system is all the more relevant now in light of rapid advances in the field of extrasolar planets. Conversely, valuable insights into our own solar system can be gained from composition and structure of extrasolar giant planets, especially the ones that are close analogs of the giant planets.

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