SATURN PROBES: Why, Where, How?

Sushil K. Atreya

Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, MI 48109-2143, USA,
Email: atreya@umich.edu Homepage: http://www.umich.edu/~atreya

Proceedings, International Planetary Probe Workshop, IPPW-4, Pasadena, California, June 2006
(Date of Submission: 8 August 2006)

ABSTRACT

While the critical heavy element abundance data for Jupiter will exist following the measurements on deep water (O/H) from Juno in 2016/2017, together with the 1995 Galileo Probe results on other key heavy elements, no such possibility currently exists for Saturn. At the same time, it is essential to have equivalent set of measurements at both gas giant planets, in order to build robust models for the formation of the giant planets, in particular, and the solar system, in general. In an earlier paper, Atreya et al. [1] presented a scenario of *shallow* entry probes combined with microwave radiometry (MWR), as an alternative to deep atmospheric probes for composition measurements at Saturn. This paper builds on, updates, and reinforces the conclusions of that earlier paper [1], especially that a Saturn Probe mission that combines Microwave Radiometry is suitable at Saturn, and that probes deployed to only 10 bars – shallow probes – can provide the needed data [1]. Such a mission is likely to fit within the cost cap of NASA's New Frontiers program. The Saturn Probe with Microwave Radiometry should be considered as the highest priority giant planet mission for the near term. The need for and scenarios of multiprobe missions to the other giant planets, Neptune, Uranus, and Jupiter are also discussed.

1. INTRODUCTION

Comparative planetology of the giant planets is key to the origin and evolution of the solar system and, by extension, extrasolar systems. Although many measurements contribute to the constraints on planetary formation models, "bulk" composition in general, and abundance of the heavy elements (mass > ^{4}He), in particular, is most critical. Its determination is also most challenging technologically. This is because the bulk composition may be found only in the well-mixed part of the atmosphere, which lies in an extreme environment of high pressure and high temperature for the principal reservoirs of certain key elements. Measurements are generally difficult to carry out, and transmission of data poses major obstacles. Just as the Voyager 1 and Voyager 2 flyby observations of Jupiter provided the fuel for *in situ* measurements at this gas giant and led to the Galileo Probe mission, the Voyager flybys and Cassini orbiter observations of Saturn have reinforced the case for return to Saturn with entry probes. In fact, the Cassini-Huygens mission was initially conceived of as a dual probe mission, with one probe into Saturn and another into Titan. However, budgetary constraints resulted in the demise of the Saturn probe. Despite the unprecedented wealth of data collected by the Cassini orbiter about Saturn's upper atmosphere and magnetosphere (p <1 bar), the elemental abundances in the well-mixed atmosphere will continue to remain mysterious (except for C/H) even after the Cassini extended mission. However, it is precisely the heavy element abundance that is critical to acquire for an understanding of the formation of Saturn and its atmosphere. Together with similar data at Jupiter, this information will prove powerful in constraining the models of the formation of the solar system and the origin of planetary atmospheres. Although it is not known where the well-mixed region of Saturn is, pertinent data for Jupiter and their interpretation with formation models can provide a good guide. Therefore we will first review briefly the known composition information for Jupiter and Saturn and then make predictions for Saturn's well-mixed region. This will be followed by a discussion of possible scenario of a probe mission at Saturn.

2. ATMOSPHERIC COMPOSITION

Amongst the outer planets, the atmosphere of Jupiter has been studied extensively due to observations from several flyby spacecrafts, an orbiter, and an entry probe, the Galileo Probe which entered the planet's atmosphere in December 1995. The detailed composition of Jupiter has been presented previously [2, 3, 4, 5, 6]. Here we will focus on the composition as it relates to the heavy elements (mass greater than helium, or m/z > ^{4}He), since the heavy elements provide critical constraints to the planetary formation scenarios. An insight into this can be gleaned by revisiting briefly the currently accepted model for the formation of the Jupiter (and the other giant planets). According to this model, generally known as the core accretion model, the core of the planet formed first from grains of refractory material, rock, metal and ice, which also trapped gases from the protoplanetary nebula. Once the core grew to a critical mass of 10-15 M_E (earth masses), gravitational collapse of the surrounding remnant protoplanetary nebula occurred, leading to the capture of most volatile of gases, H_2, He, and Ne, on to the planet. The atmosphere was formed from these gases and those released from the core during accretionary heating phase. The heavy elements make up most of the original core, based on the elemental abundance in the Sun. The planetesimals that formed Jupiter must be cold, whether in the form of amorphous icy planetesimals [$\leq$30K; 4, 7] or clathrate-hydrates [$\leq$38K; 8]. For Jupiter, abundances of the heavy elements, except oxygen, became available from the Galileo Probe mass spectrometer in December 2005. The Probe entered a meteorologically anomalous region of Jupiter – the Sahara Desert of Jupiter – where water was found to be depleted but its well-mixed region was not reached [2,3,4,5,6]. The determination of the water abundance, hence O/H, is critical to the formation models, as water was presumably the original carrier of the heavy elements to Jupiter. Thus, it was presumably also the largest contributor (50-70%) to the heavy element (hence, core) mass. Although, the water abundance in the well-mixed atmosphere of Jupiter is not available yet, the abundances of the heavy elements that were measured provide clues to the possible range of the water abundance, based on different models of the formation of Jupiter, as discussed below.

As seen in Table 1a, and graphically in Figure 1, the heavy elements at Jupiter are enriched relative to their solar proportions (to H), but the enrichment factor is non uniform for different species, ranging from a factor of 2 to 6 relative to their solar values. For the sake of convenience, we assume that the elemental enrichment at Jupiter is 4±2× solar (previously, 3±1× solar, based on earlier solar values of Anders and Grevesse). Since water was presumably the original carrier of heavy elements, the cold icy planetesimal hypothesis predicts nearly equal enrichment for all heavy elements, so that water, hence O/H, is predicted to be enriched also by a factor of 4±2× solar. This hypothesis assumes the form of ice to be amorphous [4, 7]. It has been argued that the amorphous ice planetesimals may not survive the formation of the solar nebula, and would be converted to crystalline ice in the process of evaporation and recondensation [8]. Crystalline ice has poor trapping efficiency. An alternative is that the heavy elements were delivered by clathrates hydrates in the cooling, feeding zone of Jupiter [8,9]. Since large quantities of water are required to trap volatiles in the molecular cages of water ice lattice, this model predicts a huge enrichment of water, with O/H $\geq$ 15× solar [8; adjusted for the new solar elemental abundances]! The Galileo and Cassini imaging observations [10,11] and the Galileo near infrared data [12,2] provide evidence that water is at least solar at Jupiter, but presently we cannot tell what its exact enrichment relative to solar (expressed as O/H) in the well mixed atmosphere is. Water in Jupiter is like dark matter or dark energy in the universe – we know it's there, but don't know how much or where. This is about to change, at least in the case of Jupiter. The microwave radiometry experiment on the 2011 Juno mission is designed to determine the water abundance to pressures greater than one hundred bars.

Unlike Jupiter, information on the heavy elements on Saturn is sparse – limited to just carbon from CH_4 ($CH_4/H_2 = 5.1\pm1.0 \times 10^{-3}$, by CIRS on Cassini [12]) – and it will continue to remain so even after the Cassini extended mission. The currently available elemental and isotope abundances for Saturn is also presented in Tables 1a and 1b. and graphically shown in Figure 1. For the sake of completeness and comparison, we also present the known and "suspected" elemental abundances at Uranus and Neptune. However, the situation at the two ice giant planets is nearly as hopeless as at Saturn. As on Saturn, as the only heavy element whose abundance has been measured is carbon (but with large uncertainty) from ground-based observations of CH_4.

The trend of increasing enrichment factors from Jupiter to Neptune is consistent with the basic principle of the core accretion model. However, the assumption of *equal* enrichment over solar for all heavy elements at Saturn, Uranus and Neptune is biased by the icy planetesimal model. Therefore, one should exercise caution when using the tabulated values where data are presently lacking. Nevertheless, the tabulated values represent our current best guess, which is important for the purpose of mission design studies.

3. WHERE IS THE WELL-MIXED ATMOSPHERE OF SATURN?

The well-mixed region for condensible 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 condensible species would have their own bases. The deepest clouds in the upper tropospheres of all four giant planets are predicted to be made up of water (see below). Thus the base of water clouds determines not only the level below which water is well-mixed under conditions of equilibrium thermodynamics, it also represents the well-mixed atmosphere for all heavy elements. As mentioned above, the determination of the water abundance in the well-mixed atmosphere is crucial, since water was presumably the original carrier of heavy elements to the giant planets, Since variations in the abundances of condensible 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 (i.e. O/H), places the biggest constraint on the depth to which composition measurements must be made by entry probes or other means, since water clouds are the deepest. In the following paragraphs, we first present a brief summary of the cloud models, in order to ascertain the well-mixed atmosphere. Then, a discussion of the required measurement is given, followed by recommendations.

Table 1a. Elemental Abundances (1)

Elements	Sun (protosolar)	Jupiter/Sun	Saturn/Sun	Uranus/Sun	Neptune/Sun
He/H	0.09705	0.807±0.02	0.56–0.85 (2)	0.92–1.0	0.92–1.0
Ne/H	2.10×10^{-4} (3)	0.059±0.004	?	20–30 (?)	30–50 (?)
Ar/H	1.70×10^{-6}	5.34±1.07	?	20–30 (?)	30–50 (?)
Kr/H	2.14×10^{-9}	2.03±0.38	?	20–30 (?)	30–50 (?)
Xe/H	2.10×10^{-10}	2.11±0.40	?	20–30 (?)	30–50 (?)
C/H	2.75×10^{-4}	3.82±0.66	9.3±1.8 (CIRS)	20–30	30–50
N/H	6.76×10^{-5}	4.90±1.87	2.6–5	20–30 (?)	30–50 (?)
O/H	5.13×10^{-4}	0.48±0.17 (hotspot)	?	20–30 (?)	30–50 (?)
S/H	1.55×10^{-5}	2.88±0.69	?	20–30 (?)	30–50 (?)
P/H	2.57×10^{-7}	1.21	5–10	20–30 (?)	30–50 (?)

Table 1b. Relevant Isotopic Abundances

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

(1) Updated from Atreya and Wong [2], using new protosolar elemental abundances [13].
The protosolar elemental abundances are calculated from the present-day solar photospheric values [13], after adjusting for the effects of diffusion at the bottom of the convective zone on the chemical composition of the photosphere, together with the effects of gravitational settling and radiative accelerations, as discussed in [13]. The new solar values [13] represent an improvement over the previous conventional standard [14]. The new solar values [13] result from the use of 3D hydrodynamic model of the solar atmosphere, non-LTE effects, and improved atomic and molecular data. The Jupiter values are from the Galileo Probe Mass Spectrometer. See Figure 1 and text for explanation of elemental abundances at the other giant planets.

(2) The Saturnian helium is based on the reanalysis of the Voyager remote sensing data [16]. The Cassini (CIRS) measurements of He indicate smaller He/H of perhaps as low as 0.4× solar [M. Flasar, personal comm., 2006], shown by the vertical dashed line for Saturnian He in Fig 1. However, in the absence of in situ measurements, uncertainties will remain large.

(3) The Ne/H is based on the X-ray spectral measurements of nearby solar-type stars [15], as the abundance of neon in the Sun is poorly determined. The previous protosolar Ne/O = 0.1513 [13] was simply to maintain consistency, i.e. neon was revised downward by the same factor as oxygen in [13]. Adoption of the new Ne/O = 0.41 – which is 2.7 times the value in [13] – also results in an excellent agreement between the solar interior models and helioseismology data [15].

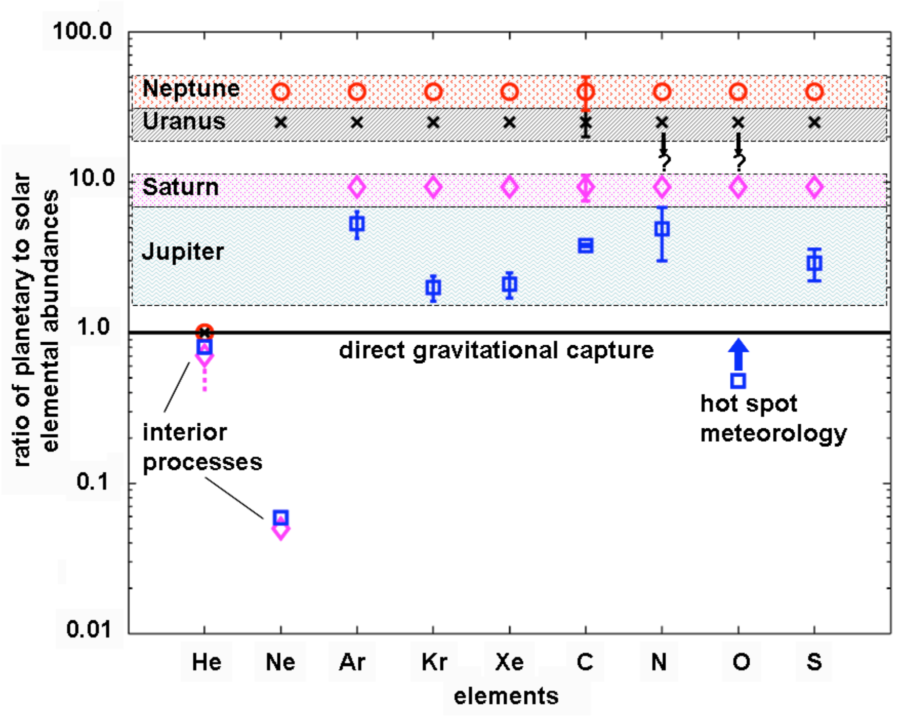


Fig. 1. Elemental abundances (relative to H) in the atmospheres of the giant planets compared to the *proto*solar values (see also Table 1 and its footnotes). The Jupiter results are those measured by the Galileo Probe Mass Spectrometer (GPMS). Solid horizontal line shows that direct gravitational capture would result in elemental abundances (ratioed to H) being the 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 4±2 (note that the factor in previous publications was 3±1, which was based on the solar elemental abundances of Anders and Grevesse [14]; the factor given here is based on the new solar values of Grevesse et al., [13]. 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 the icy planetesimal model predictions that they would be similarly enhanced as carbon (see text). Saturn's $CH_4/H_2 = 5.1\pm1.0 \times 10^{-3}$, based on the Cassini CIRS observations (Flasar, et al., 2005), results in C/H = 9.3±1.8, using the Grevesse et al. [13] *proto*solar C/H. 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. Neon is depleted to 6% solar, as neon dissolves into helium droplets. As on Jupiter, helium and neon are expected to be depleted in the upper troposphere of Saturn. He condensation could be greater in Saturn's colder interior, resulting in its greater depletion in the troposphere, as shown by the vertical dashed line for He [see footnote 2 to Table 1]. On the other hand, helium condensation is not expected in the interiors of the ice giants, Uranus and Neptune, due to their smaller masses and evolutionary history. This means that the He/H ratio would be solar or nearly solar in the upper tropospheres of these two planets, as is implied indirectly also by ground-based data on CO and HCN in the atmospheres of these ice giants [2]. 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, or it could also be enriched by similar factors as the other heavy elements, i.e. 20-50 times solar. Thus, the Ne and He measurements at the two ice giant planets are important tracers of interior processes. The presence of a putative water-ammonia ionic ocean at tens to hundreds of kilobar level would severely deplete water and ammonia above such an ocean, resulting in greatly subsolar O/H and N/H in the upper troposphere [2,17,18,19,20].

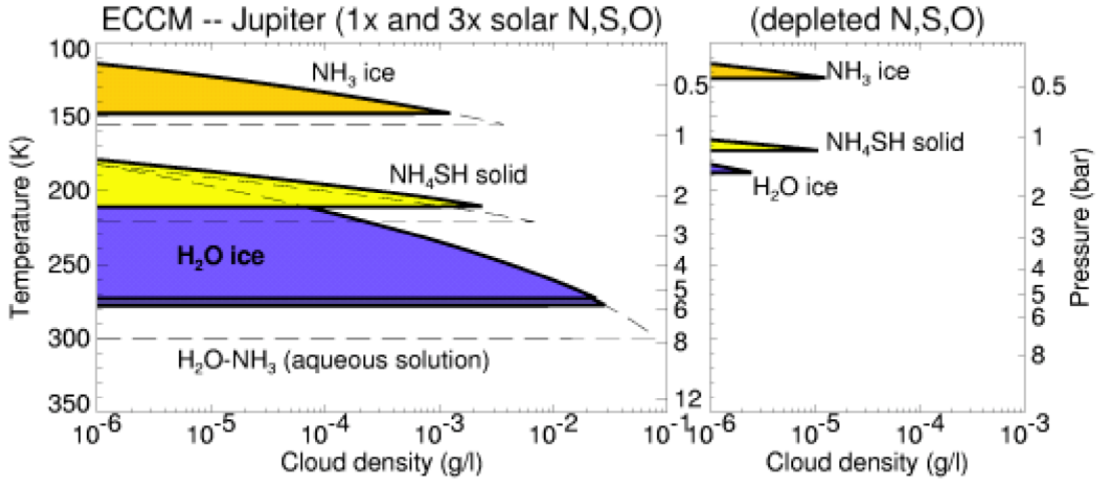
3.1 Well-mixed atmospheres: Equilibrium cloud condensation model (ECCM)

ECCM's date back to the pre-Voyager epoch. The model was first developed by Weidenschilling and Lewis [21], and has undergone further development, as described in Atreya and Romani [22] and Atreya [23]. 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 condensible 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 condensible volatiles.

Thermochemical equilibrium considerations suggest that NH_3, H_2S and H_2O are the only species that are likely to condense in the upper tropospheres (to pressures less than a few hundred bars) 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 shown in Table 1, N/H (from NH_3) and S/H (from H_2S) are enriched relative to solar, but O/H (from H_2O) is subsolar even at the deepest level in the region of entry of the Galileo Probe at Jupiter. If the original heavy element carrying water arrived at Jupiter as cold amorphous ice, O/H would be expected to be enriched by a similar factor as the other heavy elements, i.e. 4±2× solar [revised from the earlier values of 3±1× solar, as discussed in the caption to Fig.1]. If the heavy elements were delivered by clathrate hydrates, then the water abundance would be more than 15× solar in Jupiter's well-mixed atmosphere [see Table 1 for current solar elemental abundances]. In either case, condensation of water both as ice and droplets is inevitable in Jupiter's troposphere. The same condensation scenario is expected at Saturn, but at deeper levels due to greater enrichment of the heavy elements compared to Jupiter (based on C/H measured from the Cassini orbiter, Table 1) and twice the scale height compared to Jupiter's. The O/H at Saturn may be smaller if the solar nebula at Saturn's orbit was "ice-starved". However, for the purpose of determining the possible deepest level for well-mixed water at Saturn, we assume that the enrichment factor for O/H is the same as that of C/H. We will present the cases with different enrichment factors at Saturn, comparing them to Jupiter which is our guide.

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 the aqueous-ammonia solution ("droplet") clouds of Jupiter and Saturn. The ECCM calculations for Jupiter shown in Fig. 2 are with the condensible volatiles taken as 1× solar and 3× solar. The base of the water cloud is found to be at approximately 5 bar, 6.5 bar and, 9 bar level (not shown), respectively, for 1× solar, 3× solar and 10× solar enrichment of the condensible volatiles. The ECCM calculations for Saturn are shown with the condensible volatiles taken as 1× solar, 5× solar and 10× solar. The 10× solar or greater enhancement of the heavy elements is the more likely scenario for Saturn, based on the Cassini CIRS determination of $CH_4/H_2 = 5.1\pm1.0\times10^{-3}$ [12], which yields C/H = 9.3±1.8× solar (Table 1). The 10× solar case should be regarded as the nominal case for the purpose of mission design. For this case the ECCM calculations yield the base of the water cloud to be at approximately 20 bars. In thermodynamic "equilibrium" the region below 20 bars would then be the well-mixed region for water at Saturn. Since the atmosphere of Saturn is colder than Jupiter's, condensation of the species with equal enrichment factors occurs at much greater pressure levels. For example, with solar O/H, the base of the water cloud on Saturn (~12 bars) is at more than twice the pressure it is at Jupiter.



Equilibrium

Hot Spot

Fig. 2. Results of ECCM calculations for Jupiter, with 1x solar and 3x solar condensible volatile abundances in the left panel, and greatly depleted condensible volatiles in the right panel in order to simulate the LCL of the clouds detected in the Galileo Probe Entry Site (a 5-micron hot spot). Since the Galileo Probe entered a dry region, the condensible 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].

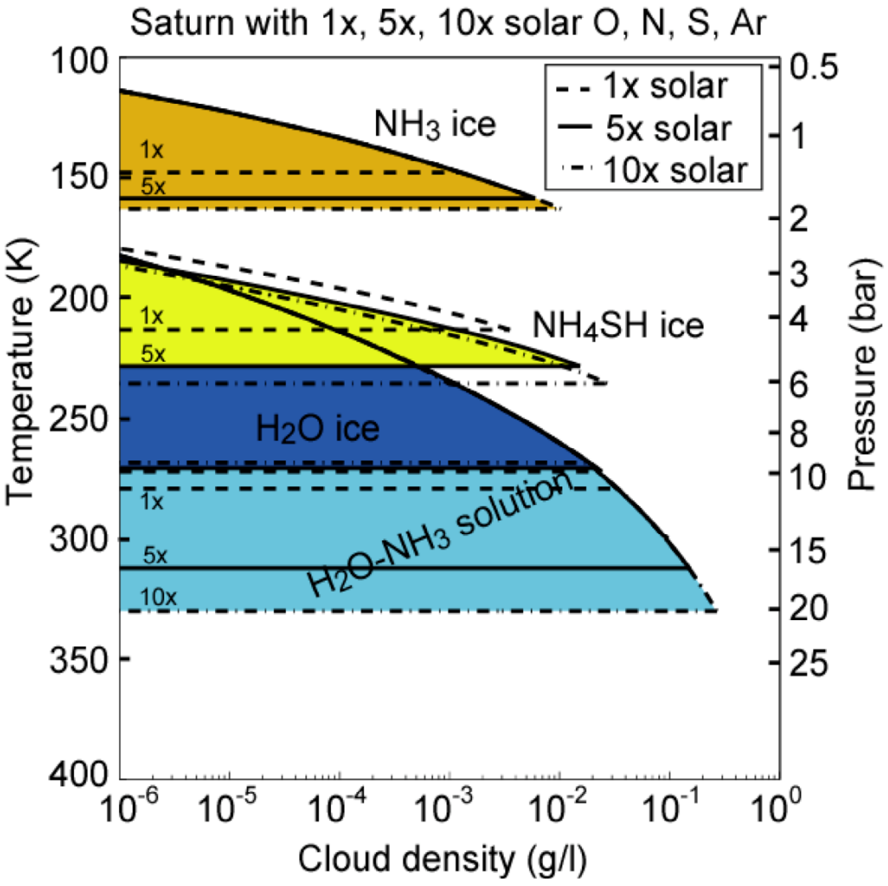


Fig. 3. Results of ECCM calculations for Saturn, with 1x solar, 5x solar, and 10x solar condensible volatile abundances. The 10x solar case should considered "nominal", based on model predictions of equal enrichment of all heavy elements. Only C/H = 9.3x solar has actually been determined. The cloud 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.

4. SATURN PROBES: DEEP OR SHALLOW?

The "Equilibrium" thermodynamics model discussed above predicts the well-mixed region for water at Saturn below 20 bars for the nominal case of 10x solar condensible volatile abundances. However, it could be well below this level. In fact, it is expected to be well below this level, since Saturn, like Jupiter, is a highly convective and stormy planet. This nature of Saturn is evident in the Cassini Imaging observations in the visible and the Cassini VIMS observations of 5-micron emission which originates from 6-8 bar level [K. H. Baines, personal comm., 2006]. Considerations of non-equilibrium thermodynamics and convection in the deep atmosphere are thus expected to push the well-mixed regions for water to much deeper levels, perhaps to 50-100 bars. The technological challenges of measurements at high pressures of 50-100 bars with correspondingly high temperatures of 400-500 K at Saturn are daunting. 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.

On the other hand, if water could be measured by another means than on entry probes, the technological challenges would not be insurmountable. Except for water, all other relevant heavy elements and isotopes can be accessed by probes deployed to approximately ten bars! The microwave radiometry (MWR) technique to be used on the Juno-Jupiter Polar Orbiter for measuring water appears to be the solution at Saturn also. MWR is a promising technique, designed to measure the water abundance to atmospheric pressures of several hundred bars at Jupiter [24]. Employing several antennas ranging in the wavelength coverage from 0.5 to 50 cm, both NH_3 and H_2O will be measured to high pressures by passive microwave remote sensing from an orbiting spacecraft, Juno. Although the peak of the weighting function for the longest wavelength (50 cm) is around 50 bars, the function is broad, making it possible to retrieve the information from as deep as several hundred bars.

Microwave radiometry from a flyby or orbiter spacecraft is expected to work well for measuring water at Saturn also. However, the MWR design, including the choice of wavelengths, remote sensing from spacecraft vs. from probes, achievable vs. desirable spatial resolutions, latitudinal/longitudinal coverage, etc. would require considerable modelling effort, beyond the initial, but very promising, work on possible architecture of such a mission [25]. The technological challenges associated with microwave radiometry are different at Saturn than at Jupiter. The radiation environment is less severe at Saturn, and Saturn's rings absorb much of the radiation. Thus, our preliminary analysis shows that plunging the spacecraft to low heights, such as 5000 km or so above the 1-bar level planned for Juno in order to fly inside the radiation belts of Jupiter, is not required at Saturn. On the other hand, flying close to the planet provides the best spatial resolution, but flying close may not be an option. Unlike Jupiter, the Saturn rings could pose a hazard, especially the D-ring debris. In that case the spacecraft may have to fly at approximately $2R_S$ or farther. Distant flying may also be required due to considerations of the delivery of and communication from the probes [25]. In that scenario, the spatial resolution achievable by the MWR could become undesirable. An alternative is to mount the antennas on the probe itself, and carry out the MWR experiment from the probes, rather than from the carrier spacecraft [25]. This might alleviate the above problem of low spatial resolution and the ring hazard, for example, but the coverage over the planet will be limited, unlike MWR from either a flyby or an orbiter spacecraft. The MWR experiment from the probe will need to be done during entry, then jettisoning the MWR payload before commencing the measurements of composition, etc. with the other payload instruments on the probe.

Communication from the probes is another challenging area. Conventional method is to transmit data from the probe to the flyby or orbiter spacecraft, which in turn relays it to the earth, as was done on the Galileo and the Huygens missions. The relay technique adds complexity, constrains the mission architecture, and requires extra resources. An alternative is direct-to-earth (DTE) communication from the probes, as proposed by Bolton and Owen [26]. However, consideration of mission architecture of the above Saturn flyby mission rule out direct-to-earth data transmission, even with potential availability of Square Kilometer Array (SKA), according to a recent study [25]. In another independent study of DTE [27], it is argued that even if a way could be found, e.g. by using UHF, improved DSN, etc., DTE without a reliable backup is not a desirable option, considering the chances of single-point-failure. Initial analysis also indicates that there is little advantage of any DTE over conventional relay technique [25]. In my opinion, minimum safe and desirable distance of spacecraft from Saturn, acceptable spatial resolution, and data transmission are critical science and mission architecture issues that still require additional investigation and trade-off studies.

As mentioned above, preliminary studies show that microwave radiometry (MWR) is feasible on a probe mission to Saturn [25], not withstanding the architecture of such a mission. And, since MWR is expected to permit measurement of water in the mixed atmosphere of Saturn, the need for the probes to carry out measurements to deep levels is no longer there. Therefore, probes need not be deployed to more than 10 bars. *Shallow* probes will do the job just fine [1]. 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, CO, PH_3, AsH_3, GeH_4, SiH_4, can be measured at pressures less than or equal to 10 bars. Combined with O/H from microwave radiometer measurements of water, the data from the probes will provide the critical set of elemental composition information required for constraining the 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 for understanding the formation of the solar system and, by extension, the extrasolar systems.

5. SUMMARY AND RECOMMENDATIONS

I recommend a Saturn Probe with Microwave (SP-MWR) mission as the highest priority giant planet mission for the near term. Such a mission could conceivably fit within the cost cap of NASA's New Frontiers class of planetary missions. At least two probes, one to an equatorial latitude and another to a midlatitude location, are most desirable in order to be able to sample a diversity of possible convective scenarios, and for mitigating risk. Although microwave radiometry from the spacecraft, rather than from the probes, is preferable, mission architecture scenarios might permit MWR only from the probes, which would probably not compromise critical science significantly, but needs to be studied further. I recommend a flyby mission, rather than an orbiter with probes. Besides being capable of delivering the required data sets, the Saturn Probe with Microwave Radiometry mission will be relatively less expensive, with fewer technological hurdles, and is possible to do in the near term. Moreover, another orbiter mission at Saturn cannot be justified now, scientifically or otherwise, in view of the highly successful Cassini orbiter mission. However, it is important to stress that the composition measurements recommended here for the next big scientific breakthrough at Saturn are independent of the nature of the mission, whether it is a flyby or an orbiter, with probes. Finally, multinational partnerships should be explored vigorously for maximizing and enhancing science return while realizing cost savings to NASA and to all nations interested in exploring Saturn.

The key measurement from the SP-MWR mission is composition of the well-mixed atmosphere. Deep winds and meteorology measurements are also most desirable for context, complementarity, and dynamics,. Determination of the core is another important science objective on such a mission. Accommodation of other secondary objectives will depend on the cost of the payload and resource requirements. For power, battery-assisted solar cell source is preferred in view of limited availability of the RPS/RTG material and other considerations. However, the effectiveness and feasibility of solar cells at Saturn still needs to be demonstrated. Although technological challenges of the Saturn probe mission do not seem daunting [25], they will require immediate, intensive studies and certain level of investment in enabling technology in order to be able to carry out a Saturn Probe with Microwave Radiometry mission in the near term.

What about the other giant planets?

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. Unlike at Jupiter and Saturn, microwave radiometry on Uranus and Neptune orbiters is not expected to be particularly useful, because of the requirement of accessing tens of kilobar region to find well-mixed water (and ammonia) if a water-ammonia ionic ocean actually exists, and to several kilobars to reach well-mixed water if it doesn't [1,2,20].

On the other hand, the rest of the critical elements and isotopes, including He, Ne, Ar, Kr, Xe, C, $^{15}N/^{14}N$, D/H and $^{3}He/^{4}He$, together with the disequilibrium species – PH_3, GeH_4, and AsH_3, CO – as tracers of internal processes, could be accessed and measured by entry probes at shallower depths with pressures of less than 10 bars [1]. Measurement of S/H may require going to approximately 50 bars. However, further studies are warranted on the criticality of the sulfur measurement, as well as on the possibility of dissolving H_2S in the purported water-ammonia ionic ocean in the deep atmosphere which may make the measurement of H_2S in the upper tropospheric non-representative of the true S/H value. Although O/H and N/H will most likely remain unknown even 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 possibly Saturn). Unlike Jupiter and Saturn, the probe missions at Neptune and Uranus should be complemented with orbiters, not flybys, because of the dearth of complementary orbital science data. The Neptune polar orbiter probe mission will be even more attractive if a lander on Triton is also included. Clearly the probe mission at Neptune requires much additional work beyond that done under NASA's Visions Program. Such studies will benefit the architecture of a similar mission to Uranus as well.

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.

Multiple probes to all four the giant planets are needed for understanding the formation of our solar system, and by extension, extrasolar systems. However, such missions are technologically most demanding. An investment in enabling technology, especially in (a) TPS (thermal protection system, or heat shield) and the Giant Planet Facility for characterizing the TPS, (b) communication from microwave absorber-rich atmospheres of the giant planets, including DTE, (c) power, using battery-assisted solar cells, or conventional RTG/RPS (radioisotope) at Saturn, (d) operation in extreme environment of relatively high temperature and pressures, and (e) integrated payload systems, is essential now to realize the ambitious probe missions to the giant planets in the near and long term. Further studies on the feasibility of retrieval of deep water with microwave radiometers mounted on the Saturn probes or on flyby spacecraft are also required, and they will need to carried out hand in hand with modeling studies to encompass various composition and condensation scenarios based on formation and thermochemical models.

ACKNOWLEDGEMENTS

This study was supported by NASA’s Planetary Atmospheres Program. Patricia A. Egeler helped with the preparation of Figs. 1 and 3.

6. REFERENCES

1. Atreya, S.K. et al., Multiprobe Exploration of the Giant Planets – Shallow Probes, Proceedings of Third International Planetary Probe Workshop, IPPW3, Anavyssos, Greece, July 2005, *ESA SP-WPP263*, 2006. See also Atreya's presentation to NASA's OPAG (Outer Planets Assessment Group) on 7 October 2005, "How Atmospheric Probes Fit into the Giant Planets Exploration": <http://www.lpi.usra.edu/opag/oct_05_meeting/agenda.html>

2. Atreya, S.K. and Wong, A.S., Coupled Chemistry and Clouds of the Giant Planets – A Case for Multiprobes, in *Outer Planets* (eds. Encrenaz, T., Kallenbach, R., Owen, C., Sotin), pp121-136, Springer-Verlag, 2005. Also in, *Space Sci. Rev.,* 116 (nos. 1-2), 121-136, 2005.

3. Niemann, H.B., Atreya, S.K., Carignan, G.R., Donahue, T.M., Haberman, J.A., Harpold, D.N., Hartle, R.E., Hunten, D.M., Kasprzak, W.T., Mahaffy, P.R., Owen, T.C. and Way, S.H., The Composition of the Jovian Atmosphere as Determined by the Galileo Probe Mass Spectrometer, *J. Geophys. Res.,* 103, 22,831–22,846, 1998.

4. Atreya, S.K., Wong, M.H., Owen, T.C., Mahaffy, P.R., Niemann, H.B., de Pater, I., Drossart, P. and Encrenaz, Th., A Comparison of the Atmospheres of Jupiter and Saturn: Deep Atmospheric Composition, Cloud Structure, Vertical Mixing, and Origin, *Planet. Space Sci.*, 47, 1243, 1999.

5. Atreya, S.K., Mahaffy, P.R., Niemann, H.B., Wong, M.H. and Owen, T.C., Composition and Origin of the Atmosphere—An Update, and Implications for the Extrasolar Giant Planets, *Planet. Space Sci.*, 51, 105–112, 2003.

6. Wong, M.H., Mahaffy, P.R., Atreya, S.K., Niemann, H.B. and Owen, T.C., Updated Galileo Probe Mass Spectrometer Measurements of Carbon, Oxygen, Nitrogen, and Sulfur on Jupiter, *Icarus*, 171, 153, 2004.

7. Owen, T., Mahaffy, P.R., Niemann, H.B., Atreya, S.K., Donahue, T., Bar-Nun, A. and de Pater, I., A Low-Temperature Origin for the Planetesimals That Formed Jupiter, *Nature*, 402, 269–270, 1999.

8. Gautier, D., Hersant, F., Mousis, O., Lunine, J.I., Enrichment in Volatiles in Jupiter: A New Interpretation of the Galileo Measurements, *Astrophys. J.*, 550, L227–L230, 2001. Correction in *Astrophys. J.*, 559, L183, 2001.

9. Hersant, F, Gautier, D., and Lunine, J., Enrichment in Volatiles in the Giant Planets of the Solar System, *Planet. Space Sci,*. 52, 2004.

10. Gierasch, P.J., Ingersoll, A.P., Banfield, D., Ewald, S.P., Helfenstein, P., Simon-Miller, A., Vasavada, A., Breneman, H.H., Senske, D.A., and the Galileo Imaging Team, 2000. Observation of moist convection in Jupiter’s atmosphere’, *Nature* 403, 628–630.

11. Dyudina, U.A., Del Genio, A.D., Ingersoll, A.P., Porco, C.,West, R.A., Vasavada, A.R., Barbara, J.M., 2004, ‘Lightning on Jupiter Observed in the H-alpha line by the Cassini Imaging Science Subsystem’, *Icarus* 10.1016/j.icarus.2004.07.014.

12. Flasar, M., and the CIRS Team, Temperature, Winds, and Composition in the Saturnian System, *Science*, 307, 1247, 2005.
13. Grevesse, N, Asplund, M., Sauval, J, The New Solar Composition, in Element Stratification in Stars, 40 Years of Atomic Diffusion (G. Alecian, O. Richard, S. Vauclair, eds.), *EAS Publications Series*, 2005.
14. Anders, E, Grevesse, N. Abundances of the elements: meteoritic and solar. *Geochimica et Cosmochimica Acta,* 53, 197-214, 1989.
15. Drake J. J., Testa, P., The "solar model problem solved by the abundance of neon in nearby stars, *Nature*, vol. 436/28 July 005/doi:10.1038/nature03803.
16. Conrath, B., Gautier, D., Saturn Helium Abundance: A Reanalysis of the Voyager Measurements, *Icarus*, 144, 124, 2000.
17. Atreya, S.K., Baines, K.H., Egeler, An Ocean of Water-Ammonia Ionic Ocean on Neptune and Uranus – Clues from Tropospheric Hydrogen Clouds Structure, *Bull. Am. Astronom. Soc.* Abstract, DPS/AAS Meeting, Pasadena CA, October 2006.
18. Atreya, S.K., Egeler, P.A., Wong, A.S., Water-Ammonia Ionic Ocean on Uranus and Neptune – Clues from Tropospheric Hydrogen Sulfide Clouds, *American Geophysical Union Meeting* Abstract P11A-0088, San Francisco, CA, 2005.
19. Water-Ammonia Ionic Ocean on Neptune and Uranus? S. K. Atreya, P. E. Egeler, K. H. Baines, Abstract, *European Geosciences Union Meeting*, Vienna, Austria, April 2006.
20. Atreya, S.K. and Wong, A.S., Clouds of Neptune and Uranus, in *Proceedings of Second International Planetary Probes Workshop NASA/CP-2004-213456* (ed. E. Venkatapathy, et al,), pp 107-110 2005.
21. Weidenschilling, S.J. and Lewis, J.S., Atmospheric and Cloud Structure of the Jovian Planets, *Icarus*, 20, 465–476, 1973.
22. Atreya, S.K. and Romani, P.N., Photochemistry and Clouds of Jupiter, Saturn and Uranus, in *Planetary Meteorology*, (ed. G. E. Hunt), pp. 17–68, Cambridge University Press, 1985.
23. Atreya S.K., *Atmospheres and Ionospheres of the Outer Planets and their Satellites*, Chapter 3, Springer-Verlag, New York-Berlin, 1986.
24. Bolton, S.J., Owen, T., Atreya, S.K., Guillot, T., *IPPW-3* Abstract, Anavyssos, Greece, 2005.
25. Balint, T. and SSEP Team, On the feasibility of a New Frontiers Class Saturn Probe Mission, *IPPW-4* Abstract, 2006.
26. Bolton, S.J., Owen, T., *IPPW-3 Proceedings*, 2006.
27. Atkinson, D.H., Spilker, T., Baines, K., Asmar, S., Oudrhiri, K., Bienstock, B., Sichi, S., Direct-To-Earth Communication for Outer Planetary Probe Entry Probe Missions, *IPPW-4* Abstract, 2006.