RESULTS FROM PANEL DISCUSSION SESSION 4: OUTER PLANETS – FUTURE MISSION CONCEPTS AND TECHNOLOGY NEEDS.

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ABSTRACT

The discussion focused on the scientific priorities and technological requirements for the exploration of the outer planets with entry probes. There are two kinds of measurements that appear essential to answer at this time to understand the formation of the Solar System: the bulk abundance of water in Jupiter and other gas giants, and the abundance of noble gases in Saturn, Uranus and Neptune. Our current knowledge about the elemental composition of the Jupiter's atmosphere following the Galileo Entry Probe mission is good. Measurements of the water abundance are expected from the recently selected NASA mission, Juno. Detailed knowledge of the composition of the mixed atmosphere of Saturn as compared to that of Jupiter is fundamental as the next step in constraining models of giant planet formation and the origin of their atmospheres. **This emerged as the highest near-term priority in the exploration of the giant planets.** This will lead to a better understanding of the formation and evolution of our Solar System and consequently planetary systems around other stars. A dedicated Outer Planet Exploration Programme with an objective to visit all the outer planets was discussed. This programme would include a probe mission every 7-10 years. International partnership will be vital for such a programme.

The panel was composed by**:**

- Sushil K. Atreya (Univ. of Michigan, USA)
- Tristan Guillot (Nice Observatory, France)
- Bernard Bienstock (Boeing, USA)
- Thomas Spilker (JPL, USA)
- Ethiraj Venkatapathy (NASA/Ames, USA).

The session was moderated by Maarten Roos-Serote (Lisbon Observatory, Portugal). The goal of the discussion was to identify and prioritize the scientific questions and necessary technology and industry requirements to address these questions. The presentations in the session had already addressed some of these issues. The discussion lasted for over one hour and the audience participated most actively.

SCIENTIFIC QUESTIONS AND PRIORITIES

The knowledge of the bulk composition of the Jovian atmosphere is of vital importance to test and discriminate between models of the formation of the Solar System. The bulk composition is described in terms of elemental ratios relative to hydrogen, X/H, where X is the element. Hydrogen is by far the most abundant constituent of Jupiter (and the Universe), followed by helium. The elemental ratio X/H is then compared to the same ratio known for the solar atmosphere, as the Sun represents the original elemental ratios of the material from which the entire Solar System was formed. On giant planets, the bulk of all other elements is in the form of molecules formed by combination with hydrogen. Oxygen, in the form of water, is expected to be the most abundant of the heavy elements in the giant planets (the term *heavy element* includes all elements except hydrogen and helium). For solar abundance, water would comprise over one-half of the total heavy element mass. Water is believed to be the original carrier of heavy element material to Jupiter and the other giant planets. Water is also the molecule whose mixed-atmosphere abundance is still not known.

The Galileo Entry Probe (GEP) mission took place on December 7, 1995. In that same week, the discovery of the first extra solar planet -- a Jupiter-size planet -- was announced. The GEP mission was a great success both in terms of scientific return and technology. Unable to aim the Probe at any specific spot within Jupiter due to the constantly changing face of the planet, the GEP entered into a most atypical region, a so-called 5-

micron hotspot. It is now known that these spots, which cover about 1% of the total area of Jupiter, are mainly concentrated within 10 degrees latitude north and south of the equator and represent some of the driest places on the planet. They are caused by strong subsidence of the atmosphere, dried out of most of its condensable volatiles (water, ammonia and hydrogen-sulphide). Therefore, the GEP measurements showed unexpected behaviour in terms of the vertical profiles of condensable volatiles: uniformly mixed regions of ammonia and hydrogen-sulphide were reached at higher pressure levels than expected, and even though the water abundance kept increasing until the end of the transmission by the probe at a pressure level of 22 bar, it did not reach a constant mixing ratio level. The GEP found an enrichment by a factor of about three for all of the noble gases (except helium and neon), sulphur (in the form of hydrogen sulphide), carbon (in the form of methane) and nitrogen (in the form of ammonia). Due to the specific dynamics of the entry location, a depletion of oxygen (in the form of water) was measured down to the 22 bar level.

The overall enrichment can be interpreted in terms of the way the planet should have formed: first a core accreted from smaller building blocks, planetesimals, made out of ice and silicates. The ice (mostly water) can trap volatiles and bring them into the core. The efficiency of this trapping depends on the surrounding temperature and the ice structure. Once a core has formed with a mass somewhere around 10 Earth masses, solar composition gas (largely H_2 and He) starts to be accreted onto it forming an atmosphere. The release of the trapped volatiles from the core enriches the atmosphere. This scenario has been proposed for several decades, but the enrichment in noble gases found by Galileo came as a surprise. Noble gases are difficult to trap. In general, the scenario still presents some severe difficulties in terms of the formation time scales and the temperatures at which the planetesimals should have formed (Atreya *et al.* 1999, 2005, Gautier *et al.* 2001, Alibert *et al.* 2005, Owen and Encrenaz, 2003). A new idea was presented by T. Guillot, in which the material from which the planet formed was already enriched before the planets formation (see paper by T. Guillot for more details).

In summary, **there are two kinds of measurements that are important to understand the formation of the Solar System: the bulk abundance of water in Jupiter and other gas giants, and the abundance of noble gases in Saturn, Uranus and Neptune**. Water is crucial because of its large abundance and its role in the formation of the early building blocks of planets. The comparison of the noble gas abundances in Jupiter and other giant planets will inform us directly on processes that occurred in the primordial protosolar disk from which the planets were born. The question of the water abundance can be addressed by entry probes penetrating to 50-100 bar level. However this poses a major technological challenge, especially in terms of communication, as radio signals are strongly absorbed by water and ammonia in the Jovian atmosphere.

Fortunately, help is on the way with the recent approval by NASA of the Juno, Jupiter Polar Orbiter. One of the main goals of the mission is to use microwave measurements with wavelengths up to 50 cm, to probe the deep atmosphere of Jupiter (down to pressures in excess of 100 bar) from within the radiation belts. Non thermal synchrotron noise from these belts precludes such deep atmospheric measurements to be made from Earth. A highly elliptical polar orbit, with a pericenter just 4000 km above the cloud tops, will allow for global coverage of Jupiter. This mission is expected to contribute immensely to solving the big puzzle about the bulk oxygen abundance in the Jovian atmosphere, hence the formation of the planet. Launch is scheduled in 2009/2010 with an arrival at Jupiter in 2015/2016.

Although the Juno mission will make a major step forward in our understanding of Jupiter, comprehensive and simultaneous composition and contextual dynamics measurements in the deep atmosphere will still be needed. However, any future probe mission/s to Jupiter must take into account the results that will be obtained by Juno. In fact, Juno will also be able to help guide future probe missions. For example, it is expected to provide information on the pressure level where water reaches its well-mixed abundance. This will also represent the level of the well-mixed bulk atmosphere, as other species reach their well-mixed levels well above water, as seen by GEP. The well-mixed level of water will be the minimum pressure level that a future probe will have to reach.

The bulk composition of the atmospheres of the other giant planets is poorly constrained. Higher enrichment factors with increasing distance from the Sun are expected on the basis of methane (C/H) measurements at all four giant planets, but data on other elements are non existent. Good data on carbon at Saturn, with C/H of 6 ± 1 relative to the

Sun have now been obtained. Ground based measurements also exist for phosphine (PH_3) at Saturn, giving an enrichment of 5 – 10 P/H. Being a thermochemical disequilibrium species, the phosphine measurements cannot be used with confidence to predict the bulk P/H, but PH3 and other disequilibrium molecules are important nontheless as they are tracers of interior processes.

	Jupiter	Saturn
Helium	**GEP**	H-He phase diagram; J/S evolution **(SP)**
Major species except water	**GEP**	Some addressed by Cassini and ground based (see text) **(SP)**
Water	Solar System water inventory. Planet formation; Meteorology **(SP, Juno for Jupiter)**	
Noble gases	**GEP**	Test formation scenarios; Envelope enrichment by planetesimal delivery or gas accretion from chemically evolved disk **(SP)**
Disequilibrium species (CO, PH_3, …)	**GEP**	Some addressed by Cassini and ground based
Isotopic ratios (D/H, $^{14}N/^{15}N$, ….)	Timing of planet formation; Location of planet material in the protosolar disk **(SP-DP)**	
Extinct radionuclides with gas loving daughter species (^{41}Ca – ^{41}K, …)	Ice/Rock ratio; Timing of planet formation **(SP-DP)**	

	Uranus	Neptune
Helium	Helium fractionation in the protosolar disk (thermal evaporation?) **(SP).**	
Major species except water	Atmospheric enrichment **(SP)**; Meteorology; Planetesimal delivery –**(DP).**	
Water	Dynamics of the deep atmosphere **(EDP).**	
Noble gases	Test formation scenarios; Envelope enrichment by planetesimal delivery or gas accretion from chemically evolved disk **(SP).**	
Disequilibrium species (CO, PH_3, …)	Constraints on mixing in the deep atmosphere and compositions **(SP).**	
Isotopic ratios (D/H, $^{14}N/^{15}N$, ….)	Timing of planet formation; Location of planet material in the protosolar disk **(SP-DP)**	
Extinct radionuclides with gas loving daughter species (^{41}Ca – ^{41}K, …)	Ice/Rock ratio; Timing of planet formation **(SP-DP)**	

Note, Multiple Probes are desirable in all cases
SP = Shallow (≤ 20 bar) Probe,
DP = Deep (50-100 bar) Probe
EDP = Extremely Deep (>10^4 bar) Probe
GEP = Galileo Entry Probe

Whereas Jupiter's mixed atmosphere will have been explored with Juno - complemented with the Galileo Probe results, the Cassini orbiter will *not* provide much of the heavy element (mass > He) and isotope data that is key to formation and origin models. **Detailed knowledge of the composition of the mixed atmosphere of Saturn as compared to that of Jupiter is fundamental as the next step in constraining models of giant planet formation and the origin of their atmospheres. This emerged as the highest near-term priority in the exploration of the giant planets.**

For the longer-term, a Neptune Orbiter mission with multiple probes (and possibly a Triton lander) was recommended. Neptune, together with Uranus, are the so-called Ice Giants. They incorporated much more icy material than Jupiter and Saturn and consequently show much higher enrichments of the heavy elements. Their composition holds very important clues about the timing of planet formation as a function of distance from the Sun and by the way the heavy material was brought into the planets. Probes will be essential to accurately address the question of composition, in particular in terms of the noble gases and isotopic ratios. With the exception of water (O/H) and ammonia (N/H), which require that probes descend deep into the atmosphere, this question can be addressed with probes descending to about the 20 bar pressure level. A comparative planetology approach where we have complete composition data for Jupiter and Saturn, but non-accurate O/H and N/H values for the Ice Giants would still be sufficient to constrain planetary formation models. The table (adapted from the presentation by T. Guillot) gives the requirements in terms of depth that a probe should reach to address certain questions.

MISSION IDEAS, PRIORITIES AND TIMEFRAMES

From the discussion of the scientific priorities, the idea of a program of deploying probes into all giant planets was born. A sustained program with strong international partnership and with probe missions every 5-7 years is highly desirable. It is understood that in addition to composition measuring instruments, such missions will and should carry other complementary payloads, including those that will help determine the existence of a core, etc.

A strong consensus emerged in support of a **Saturn flyby with multiple probes and microwave radiometers** mission. The Saturn mission was **considered the highest priority for the near-term**. The microwave radiometers on such a mission will measure oxygen and nitrogen enrichments to great depths (50-100 bar levels), *i.e.* well into the mixed atmosphere. Other critical heavy elements (C/H, S/H, Ne/H, Ar/H, Kr/H, Xe/H), isotopes ($^{14}N/^{15}N$, $^{3}He/^{4}He$, noble gas isotopes, and D/H in methane), He/H, can be measured by probes (see Table). The value required for the final pressure level such a probe should reach must be more accurately established by future detailed studies, but is now believed to be on the order of 20-30 bar. Disequilibrium species (PH_3, AsH_3, GeH_4, CO) can be measured and are tracers of interior processes. It is very important to note that with remote sensing techniques either from space (Cassini) or from the ground it has been possible to measure only the C/H and P/H ratio accurately. The N/H ratio can perhaps be measured accurately in the near future. Yet, the interpretation of the data on other species is model dependent. Probes are therefore essential. Thus, the combination of microwave radiometers and probes can be a powerful technique for exploring Saturn's deep atmosphere. The Saturn results, when contrasted with those for Jupiter from Juno and Galileo, will provide the data necessary for constraining the models of formation of gas giants and the origin of their atmospheres. Such a mission could be ready in the next 7-10 years, and could possibly fit into NASA's New Frontiers line (NF, 700-800 Million USD) or an enhanced NF line of about 1 billion USD.

The NASA Roadmap recommends a Flagship mission to the **Neptune** system and with a start in the 2026 time frame, with a price tag comparable to such Flagship Missions as Cassini-Huygens and Galileo (2-3 billion USD). The Neptune mission is not in competition with above proposed Saturn mission, being in a different time frame and cost category.

INSTRUMENTATION AND TECHNOLOGY CHALLENGES

In terms of instrumentation the Gas Chromatograph Mass Spectrometer (GCMS) is clearly identified as a priority instrument onboard any entry probe. The smart use of instruments and dual (or more) functionality and highly integrated systems was stressed. B. Bienstock indicated that extreme environment (temperature, pressure) electronics and battery technologies comprise a most interesting challenge for industrial development, with application in several other areas (for example aircraft engines, high temperature ovens). The issue was raised about the need for many measurements versus a single measurement during a descent. A single measurement clearly requires different technologies than multi-measurements. It became clear that at least some information about the vertical profile (multiple measurements) is needed to contextualize the deepest measurements, as exemplified by the GEP measurements for water vapour.

During the discussion it came to light that solar panels may be adequate even at Saturn. Solar panels are being used on the Juno mission to Jupiter and have been studies by ESA in the context of a Jupiter mission. Currently, the ESA Rosetta spacecraft is using solar power at a 5 AU distance scale. If solar panels are possible this will reduce the need for radioisotope power sources, and consequently also considerably reduce the mission cost and other complications. Solar panels as a source of power for a mission to Saturn need to be studied and evaluated carefully.

Even though the more benign radiation environment at Saturn will make the Saturn flyby mission less difficult than at Jupiter, the larger abundance of microwave absorbers in the atmosphere will make probe communication more challenging. The absorption by ammonia for example descreases strongly with descreasing frequency. Yet, lower frequencies require larger and thus heavier antennas to provide a similar gain. S. Bolton argued that direct probe to Earth communication could be promising, but it imposed many limits on the mission profile. Other participants were not so convinced about the applicability of this technique for Saturn. Communication is clearly an area of technology readiness that needs to be studied and evaluated.

Thermal Protection Systems become easier to construct as the mass of the target planet decreases. As an example, the TPS for the GEP contained about 60 % of the total GEP mass, whereas for a Saturn probe TPS may be more on the order of 25%. E. Venkatapathy commented that the type of facility needed for the qualification, characterisation and calibration of the TPS material for the GEP will also be required for any giant planet probe mission. He recommended that a destination specific mission architecture study be done for Saturn. It was agreed that the NASA/Ames group led by E. Venkatapathy will evaluate the TPS situation again, in view of the possibility of a near-term Saturn probe mission. One option would be to design a series of tailorable aeroshells that can be used on multiple mission. The advantage of this would be that the cost of design can be spread out over various missions. It was also stressed that TPS technologies for giant planets are applicable for the terrestrial planets as well. However, there are important disadvantages as well, as B. Bienstock pointed out: any common aeroshell design would result in sub-optimal designs for all applications that would result in increased aeroshell mass and perhaps decreased performance.

Propulsion systems were shortly discussed in terms of low versus high thrust technologies.

FINAL CONSIDERATIONS

As a conclusion of the panel discussion it was felt that a Saturn flyby and probe mission should be considered as the next highest priority mission to the outer planets in the near-term. It is important to recall that interest in Saturn probe is not new. In the early stages of the Cassini mission development dual probes, one to Saturn and another to Titan, were considered. Budget limitations resulted in the demise of Saturn probe. The proposed Saturn mission could potentially be ready for launch in the next 7-10 years. Ideally it should be part of a dedicated programme to study all the outer planets and it should be a programme with highly visible international partnership.

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