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Scientific rationale of a Saturn probe mission

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SCIENTIFIC RATIONALE OF A SATURN PROBE MISSION. O. Mousis¹, L. N. Fletcher², J.-P. Lebreton^{3,4}, P. Wurz⁵, T. Cavalie⁶, A. Coustenis⁴, D. H. Atkinson^{7,8}, S. Atreya⁹, D. Gautier⁴, T. Guillot¹⁰, J. I. Lunine¹¹, B. Marty¹², A. D. Morse¹³, K. R. Reh⁸, A. Simon-Miller¹⁴, T. Spilker¹⁵, and J. H. Waite¹⁶, ¹Université de Franche-Comté, Institut UTINAM, CNRS/INSU, UMR 6213, OSU THETA, France (olivier.mousis@obs-besancon.fr), ²Atmospheric, Oceanic & Planetary Physics, Department of Physics, University of Oxford, Clarendon Laboratory, UK, ³LPC2E, CNRS-Université d'Orléans, France, ⁴LESIA, Observatoire de Paris, CNRS, UPMC, Univ. Paris-Diderot, France, ⁵Physics Institute, University of Bern, Switzerland, ⁶Max-Planck-Institut für Sonnensystemforschung, Germany, ⁷Department of Electrical and Computer Engineering, University of Idaho, USA, ⁸Jet Propulsion Laboratory, California Institute of Technology, USA, ⁹Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, USA, ¹⁰Observatoire de la Côte d'Azur, Laboratoire Lagrange, France, ¹¹Center for Radiophysics and Space Research, Cornell University, USA, ¹²CRPG-CNRS, Nancy-Université, France, ¹³Planetary and Space Sciences, Department of Physics, The Open University, UK, ¹⁴NASA Goddard Space Flight Center, USA, ¹⁵Solar System Science & Exploration, USA, ¹⁶Southwest Research Institute (SwRI), USA.

Introduction: Remote sensing observations meet some limitations when used to study the bulk atmospheric composition of the giant planets of our solar system. A remarkable example of the unicity of *in situ* probe measurements is illustrated by the exploration of Jupiter, where key measurements such as noble gases abundances and the precise measurement of the helium mixing ratio have only been made available through *in situ* measurements by the Galileo probe. Here we describe the main scientific goals to be addressed by future *in situ* exploration of Saturn.

Planet formation: To understand the formation of giant planets and the origin of our Solar System, statistical data obtained from the observation of exoplanetary systems must be supplemented by direct measurements of the composition of the planets in our solar system. A giant planet's bulk composition depends on the timing and location of planet formation, subsequent migration and the delivery mechanisms for the heavier elements. By measuring a giant planet's chemical inventory, and contrasting these with measurements of (i) other giant planets, (ii) primitive materials found in small bodies, and (iii) the composition of our parent star and the local interstellar medium, much can be revealed about the conditions at work during the formation of our planetary system [1].

To date, the Galileo probe at Jupiter (1995) remains our only data point for interpreting the bulk composition of the giant planets. Galileo found that Jupiter exhibited an enrichment in C, N, S, Ar, Kr and Xe compared to the solar photospheric abundances, with some notable exceptions - water was found depleted, possibly due to meteorological processes at the probe entry site; and neon was also found depleted, possibly due to rain-out to deeper levels [2]. Explaining the high abundance of noble gases requires either condensing these elements directly at low-temperature in the form of amorphous ices [3], trapping them as clathrates [4-7] or photoevaporating the hydrogen and helium in

the protoplanetary disk during the planet's formation [8]. The *in situ* Galileo measurements at Jupiter also include a highly precise determination of the planet's helium abundance, crucial for studies of the structure and evolution of the planet.

Because of the lack of *in situ* measurements, Saturn noble gas abundances are unknown and their determination is missing to properly understand its formation conditions. There is however some indication for a non-uniform enrichment in C, N and S. [5] suggests that observations are well fitted if the atmospheric C and N of the planet were initially mainly in reduced forms at 10 AU in the protosolar nebula. Alternatively, [6] finds that it is possible to account for these enrichments in a way consistent with those measured at Jupiter if the building blocks of the two planets shared a common origin. As in Jupiter, the missing piece of the puzzle remains the measurement of the oxygen abundance. Precisely measuring *in situ* the He/H₂ ratio in Saturn is also needed for properly modeling its interior and thermal evolution. To address the origin of Saturn, the key measurements that should be targeted from an *in situ* probe are the following:

- The atmospheric fraction of He/H₂ with a 2% accuracy on the measurement;
- The elemental enrichments in cosmogenically abundant species C, N, S and O. C/H, N/H, S/H, and O/H should be sampled with an accuracy better than +/- 10%.
- The elemental enrichments in minor species delivered by vertical mixing (e.g., P, As, Ge) from the deeper troposphere. P/H, As/H and Ge/H should be sampled with an accuracy better than +/- 10%.
- The isotopic ratios in hydrogen (D/H), oxygen (¹⁸O/¹⁶O, ¹⁷O/¹⁶O), carbon (¹³C/¹²C) and nitrogen (¹⁵N/¹⁴N), to determine the key reservoirs for these species (e.g., delivery as N₂ or NH₃ vastly alters

the $^{15}\text{N}/^{14}\text{N}$ ratio in the giant planet's envelope). The isotope ratios $^{13}\text{C}/^{12}\text{C}$, $^{18}\text{O}/^{16}\text{O}$ and $^{17}\text{O}/^{16}\text{O}$ should be sampled with an accuracy better than $\pm 1\%$. D/H, $^{15}\text{N}/^{14}\text{N}$ should be analyzed in the main host molecules with an accuracy of the order of $\pm 5\%$.

- The abundances and isotopic ratios for the chemically inert noble gases He, Ne, Xe, Kr and Ar, provide excellent tracers for the materials in the subreservoirs existing in the protosolar nebula. The isotopic ratios for He, Ne, Xe, Kr and Ar should be measured with an accuracy better than $\pm 1\%$.

Planetary Atmospheric Processes: Saturn's complex and cloud-dominated weather-layer is our principle gateway to the processes at work within the deep interior of this giant planet. We must extrapolate from this thin, dynamic region over many orders of magnitude in pressure, temperature and density to infer the planetary properties deep below the clouds [1]. Remote sensing provides insights into the complexity of the transitional zone between the external environment and the fluid interior, but there is much that we still do not understand. *In situ* measurements are the only method providing ground-truth to connect the remote sensing inferences with physical reality, and yet this has only been achieved twice in the history of outer solar system exploration, via the Galileo probe for Jupiter and the Huygens probe for Titan.

In situ studies provide access to atmospheric regions that are beyond the reach of remote sensing, enabling us to study the dynamical, chemical and aerosol-forming processes at work from the thermosphere to the troposphere below the cloud decks. Two crucial questions in this theme remain i) the nature of the processes at work in planetary atmospheres, shaping the dynamics and circulation from the thermosphere to the deep troposphere (e.g., [9]), and ii) the chemical properties and conditions for cloud formation as a function of depth and temperature in planetary atmospheres (e.g., [10]). To address these important points, key measurements include:

- Atmospheric temperature and pressure throughout the descent to study (i) stability regimes as a function of depth through transition zones (e.g., the adiabatic-convective boundary); (ii) atmospheric drag and accelerations; and (iii) the influence of wave perturbations and cloud formation on the vertical temperature profile (e.g., [11]);
- Determination of the vertical variation of horizontal winds using Doppler measurements of the

probe's carrier frequency (driven by an ultra-stable oscillator) during the descent [12]. This includes a study of the depth of the zonal wind fields, as well as the first measurements of middle atmospheric winds;

- Vertical profiling of a host of atmospheric species via mass spectrometry [13], including atmospheric volatiles (H_2O , H_2S and NH_3 in their saturated and sub-cloud regions); disequilibrium species (e.g., PH_3 , AsH_3 , GeH_4 , CO) convected upwards from the deeper atmosphere; photochemical species (e.g., hydrocarbons and HCN in the troposphere and stratosphere; hydrazine and diphosphine in the upper troposphere) and exogenic inputs (e.g., oxygenated species in the upper atmosphere) (e.g., [14]);
- Measurements of the vertical structure and properties of Saturn's cloud and haze layers [10]; including determinations of the particle optical properties, size distributions, number and mass densities, opacity, shapes and, potentially, their composition.

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