Planetary and Space Science 104 (2014) 29–47

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Scientific rationale for Saturn's *in situ* exploration

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ARTICLE INFO

Article history:
Received 31 December 2013
Received in revised form
22 September 2014
Accepted 25 September 2014
Available online 8 October 2014

ABSTRACT

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 superiority of *in situ* probe measurements is illustrated by the exploration of Jupiter, where key measurements such as the determination of the 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. This paper describes the main scientific goals to be addressed by the future *in situ* exploration of Saturn placing the

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http://dx.doi.org/10.1016/j.pss.2014.09.014
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Keywords:
Entry probe
Saturn atmosphere
Giant planet formation
Solar system formation
In situ measurements
Elemental and isotopic composition

Galileo probe exploration of Jupiter in a broader context and before the future probe exploration of the more remote ice giants. *In situ* exploration of Saturn's atmosphere addresses two broad themes that are discussed throughout this paper: first, the formation history of our solar system and second, the processes at play in planetary atmospheres. In this context, we detail the reasons why measurements of Saturn's bulk elemental and isotopic composition would place important constraints on the volatile reservoirs in the protosolar nebula. We also show that the *in situ* measurement of CO (or any other disequilibrium species that is depleted by reaction with water) in Saturn's upper troposphere may help constraining its bulk O/H ratio. We compare predictions of Jupiter and Saturn's bulk compositions from different formation scenarios, and highlight the key measurements required to distinguish competing theories to shed light on giant planet formation as a common process in planetary systems with potential applications to most extrasolar systems. *In situ* measurements of Saturn's stratospheric and tropospheric dynamics, chemistry and cloud-forming processes will provide access to phenomena unreachable to remote sensing studies. Different mission architectures are envisaged, which would benefit from strong international collaborations, all based on an entry probe that would descend through Saturn's stratosphere and troposphere under parachute down to a minimum of 10 bar of atmospheric pressure. We finally discuss the science payload required on a Saturn probe to match the measurement requirements.

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1. Introduction

Giant planets contain most of the mass and the angular momentum of our planetary system and must have played a significant role in shaping its large scale architecture and evolution, including that of the smaller, inner worlds (Gomes et al., 2005). Furthermore, the formation of the giant planets affected the timing and efficiency of volatile delivery to the Earth and other terrestrial planets (Chambers and Wetherill, 2001). Therefore, understanding giant planet formation is essential for understanding the origin and evolution of the Earth and other potentially habitable environments throughout our solar system. The origin of the giant planets, their influence on planetary system architectures, and the plethora of physical and chemical processes at work within their atmospheres make them crucial destinations for future exploration. Because Jupiter and Saturn have massive envelopes essentially composed of hydrogen and helium and (possibly) a relatively small core, they are called gas giants. Meanwhile, Uranus and Neptune also contain hydrogen and helium atmospheres but, unlike Jupiter and Saturn, their H_2 and He mass fractions are smaller (5–20%). They are called ice giants because their density is consistent with the presence of a significant fraction of ices/rocks in their interiors. Despite this apparent grouping into two classes of giant planets, the four giant planets likely exist on a continuum, each a product of the particular characteristics of their formation environment. Comparative planetology of the four giants in the solar system is therefore essential to reveal the potential formational, migrational, and evolutionary processes at work during the early evolution of the early solar nebula.

Much of our understanding of the origin and evolution of the outer planets comes from remote sensing by necessity. However, the efficiency of this technique has limitations when used to study the bulk atmospheric composition that is crucial to the understanding of planetary origin, namely due to degeneracies between the effects of temperatures, clouds and abundances on the emergent spectra, but also due to the limited vertical resolution. In addition, many of the most common elements are locked away in a condensed phase in the upper troposphere, hiding the main volatile reservoir from the reaches of remote sensing. It is only by penetrating below the “visible” weather layer that we can sample the deeper troposphere where those most common elements are well mixed. A remarkable example of the superiority of *in situ* probe measurements is illustrated by the exploration of Jupiter, where key measurements such as the determination of the noble gases' abundances and the precise measurement of the helium mixing ratio have only been possible through *in situ* measurements by the Galileo probe (Owen et al., 1999).

The Galileo probe measurements provided new insights into the formation of the solar system. For instance, they revealed the unexpected enrichments of Ar, Kr and Xe with respect to their solar abundances, which suggested that the planet accreted icy planetesimals formed at temperatures possibly as low as 20–30 K to allow the trapping of these noble gases. Another remarkable result was the determination of the Jovian helium abundance using a dedicated instrument aboard the Galileo probe (von Zahn et al., 1998) with an accuracy of 2%. Such an accuracy on the He/H_2 ratio is impossible to derive from remote sensing, irrespective of the giant planet being considered, and yet precise knowledge of this ratio is crucial for the modelling of giant planet interiors and thermal evolution. The Voyager mission has already shown that these ratios are far from being identical, which presumably results from slight differences in their histories at different heliocentric distances. An important result also obtained by the mass spectrometer onboard the Galileo probe was the determination of the $^{14}N/^{15}N$ ratio, which suggested that nitrogen present in Jupiter today originated from the solar nebula essentially in the form of N_2 (Owen et al., 2001). The Galileo science payload unfortunately could not probe to pressure levels deeper than 22 bar, precluding the determination of the H_2O abundance at levels representative of the bulk oxygen enrichment of the planet. Furthermore, the probe descended into a region depleted in volatiles and gases by unusual “hot spot” meteorology (Orton et al., 1998; Wong et al., 2004), and therefore its measurements are unlikely to represent the bulk planetary composition. Nevertheless, the Galileo probe measurements were a giant step forward in our understanding of Jupiter. However, with only a single example of a giant planet measurement, one must wonder whether from the measured pattern of elemental and isotopic enrichments, the chemical inventory and formation processes at work in our solar system are truly understood. *In situ* exploration of giant planets is the only way to firmly characterize the planet compositions in the solar system. In this context, a Saturn probe is the next natural step beyond Galileo's *in situ* exploration of Jupiter, the remote investigation of its interior and gravity field by the JUNO mission, and the Cassini spacecraft's orbital reconnaissance of Saturn.

In situ exploration of Saturn's atmosphere addresses two broad themes. First, the formation history of our solar system and second, the processes at play in planetary atmospheres. Both of these themes are discussed throughout this paper. Both themes have relevance far beyond the leap in understanding gained about an individual giant planet: the stochastic and positional variances produced within the solar nebula, the depth of the zonal winds, the propagation of atmospheric waves, the formation of clouds and hazes and disequilibrium processes of photochemistry and vertical mixing are common to all planetary atmospheres, from terrestrial planets to gas and ice giants and from brown dwarfs to hot exoplanets.

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