SF2A 2013
L. Cambrésy, F. Martins, E. Nuss and A. Palacios (eds)

SCIENCE GOALS AND CONCEPTS OF A SATURN PROBE FOR THE FUTURE L2/L3 ESA CALL

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Abstract. Comparative studies of the elemental enrichments and isotopic abundances measured on Saturn can provide unique insights into the processes at work within our planetary system and are related to the time and location of giant planet formation. In situ measurements via entry probes remain the only reliable, unambiguous method for determining the atmospheric composition from the thermosphere to the deep cloud-forming regions of their complex weather layers. Furthermore, in situ experiments can reveal the meteorological properties of planetary atmospheres to provide "ground truth" for orbital remote sensing. Following the orbital reconnaissance of the Galileo and Cassini spacecraft, and the single-point in situ measurement of the Galileo probe to Jupiter, we believe that an in situ measurement of Saturn's atmospheric composition should be an essential element of ESA's future cornerstone missions, providing the much-needed comparative planetology to reveal the origins of our outer planets. This quest for understanding the origins of our solar system and the nature of planetary atmospheres is in the heart of ESA's Cosmic Vision, and has vast implications for the origins of planetary systems around other stars.

Keywords: Saturn, formation, atmospheric processes, in situ measurements, spacecraft missions

1 Introduction

Remote-sensing observations have always been the favoured approach of astronomers for studying the giant planets of our Solar System. However, the efficiency of this technique has some limitations when used to study the bulk atmospheric composition crucial to understanding planetary origins. A remarkable example of these restrictions is illustrated by the exploration of Jupiter, where key measurements such as the determination of the noble gases and helium abundances have only been made in situ by the Galileo probe. These measurements revealed unexpected results concerning the Ar, Kr and Xe enrichments with respect to their solar abundances, which suggest 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 obtained by a dedicated instrument aboard the Galileo probe (von Zahn et al. 1998) with an accuracy of 2%. Such accuracy on the He/H_2 ratio is impossible to derive from remote sensing, irrespective of the giant planet considered, and yet precise

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knowledge of this ratio is crucial for the modelling of giant planet interiors and their thermal evolution. The Voyager mission has already shown, through remote sensing, that the He/H_2 ratios are far from being identical, which is presumably result of their evolution. An important result also obtained by the mass spectrometer aboard 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 mass spectrometer aboard Galileo unfortunately did not make measurements at levels deeper than 22 bars, precluding us from determining the H_2O abundance at levels representative of the bulk oxygen enrichment of the planet. Furthermore, the probe descended into a region depleted in certain volatiles and gases by unusual "hot spot" meteorology (Orton et al. 1998; Wong et al. 2004), so the Galileo measurements may not be representative of the planet as a whole. Nevertheless, the Galileo probe provided a giant step forward in our understanding of Jupiter, but one can wonder if these measurements are really representative or not of the whole set of giant planets of the solar system. In situ exploration of more than one giant planet is the only way to address this crucial question for planetary science.

In the following, we describe the reasons why in situ exploration is vital to understand giant planet formation and atmospheric processes from the thermosphere to deep below the clouds, and we state the case specifically for a Saturn probe as a vital comparison to the Galileo results. Despite the wealth of remote sensing data returned by the Cassini spacecraft for Saturn, several key questions still require an in situ probe to investigate.

2 Planet formation and the origin of the solar system

Formation and evolution models indicate that the total mass of heavy elements present in Jupiter may be as high as 42 $M_\oplus$whereas the mass of the core is estimated to range between 0 and 13 $M_\oplus$(Saumon and Guillot 2004). In the case of Saturn, the mass of heavy elements can increase up to 35 $M_\oplus$with the mass in the envelope varying between 0 and 10 $M_\oplus$and the core mass ranging between 0 and 20 $M_\oplus$(Helled and Guillot 2013). The masses of heavy elements are found to be in the 10.9–12.8 and 12.9–15.2 $M_\oplus$ranges for Uranus and Neptune, respectively (Helled et al. 2011). Direct access to heavy materials within giant planet cores to constrain these models is impossible, so we must use the composition of the well-mixed troposphere to infer the properties of the deep interiors. These questions must be addressed by in situ exploration. The availability of planetary building blocks (metals, oxides, silicates, ices) is expected to vary with position within the original nebula, from refractories in the warm inner nebula to a variety of different ices like water, CH_4, CO, NH_3, N_2 and other simple molecules in the cold outer nebula. Turbulent radial mixing, and the evolution of the pressure-temperature gradient in the disk could have led to distinct regions where some species dominated over others (e.g., the water-ice snow line or N_2 over NH_3). Furthermore, both inward and outward migration of the giants during their evolution could have provided access to different material reservoirs at different epochs.

A giant planet's bulk composition therefore 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 it with measurements of (i) other giant planets, (ii) primitive materials found in comets and asteroids, and (iii) the abundance of our parent star and the local interstellar medium, can reveal much about the conditions at work during the formation of our planetary system. Furthermore, comparison to the compositions of the larger ensemble of extrasolar giant planets would place our own planetary origins in a broader context.

Galileo at Jupiter: 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 carbon, nitrogen, sulfur, argon, krypton and xenon compared to the solar photospheric abundances, with some notable exceptions – water was found depleted, may be due to meteorological processes at the probe entry site; and neon was depleted, possibly due to rain-out to deeper levels (Niemann et al. 1998, Wong et al. 2004). In any case the oxygen abundance in Jupiter remains an enigma. The Juno mission, which will arrive at Jupiter in 2016, may provide an estimate of the tropospheric O/H ratio. Interestingly, the nitrogen isotope composition of Jupiter is similar within uncertainties to the protosolar nebula value (Marty et al. 2011) whereas the N isotope composition of comets is very different (enriched in ^{15}N by a factor of two). Explaining the high abundance of noble gases requires either condensing these elements directly at low temperature in the form of amorphous ices (Owen et al. 1999), trapping them as clathrates in ices (Gautier et al. 2001; Hersant et al. 2008; Mousis et al. 2009, 2012) or photoevaporating the hydrogen and helium in the protoplanetary disk during the planet's formation (Guillot and Hueso 2006). The Galileo measurements at Jupiter also include a precise determination of the planet's helium abundance, crucial for calculations of the structure and evolution of the planet. Figure 1 represents fits of the volatile enrichments measured at Jupiter in the context of two different formation models, both being based on the hypothesis that Jupiter's building blocks formed from a mixture of rocks and crystalline ices but postulating a different oxygen abundance in the formation zone of Jupiter in the primordial nebula. While the quality of matching the volatile abundances is fairly similar, these two scenarios provide different predictions of the oxygen abundance in Jupiter. These calculations illustrate the strong connection between the formation conditions of the planet and its bulk composition, and similar measurements for Saturn or an ice giant would enable comparison of their formation mechanisms with Jupiter.

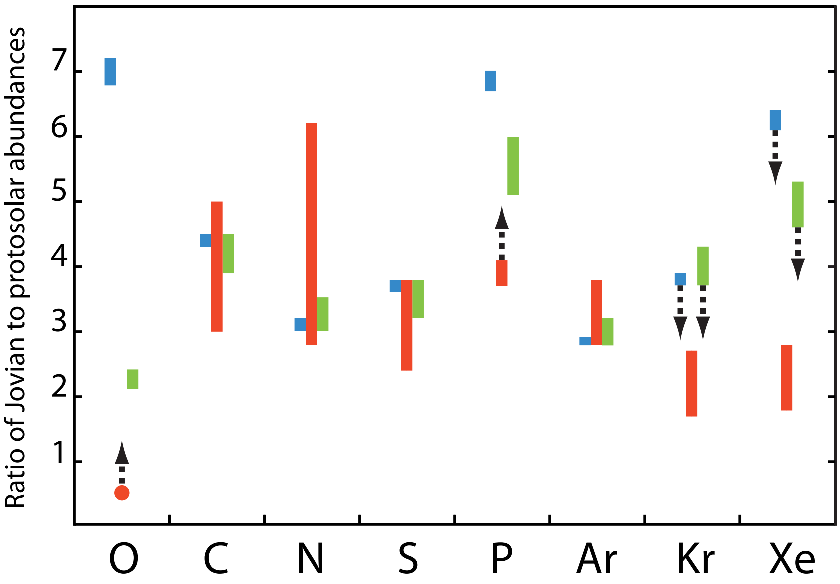

Fig. 1. Ratio of Jovian to protosolar abundances (adapted from Mousis et al. 2012). Red bars and the red dot correspond to observations made by the Galileo probe. Green and blue bars correspond to calculations based on an oxygen abundance that is 0.5 and 1 times the protosolar value in the feeding zone of Jupiter, respectively. The corresponding oxygen abundances are predicted to be about 2 and 7 times protosolar in the Jovian atmosphere. Arrows pointing up correspond to the possibility that the measured oxygen and phosphorus abundances are lower than their bulk abundances, and arrows pointing down to the possibility that planetesimals could be depleted in krypton and xenon (Mousis et al. 2009).

Saturn Probe: because of the absence of in situ measurements, the noble gas abundances are unknown in Saturn. However there is some indication for a non-uniform enrichment in C, N and S. Hersant et al. (2008) suggest that ground-based and space-based (Cassini) observations are well fitted if the atmospheric carbon and nitrogen of the planet were initially mainly in reduced forms at 10 AU in the solar nebula. Alternatively, Mousis et al. (2009) find that it is possible to account for the volatile enrichments in Saturn in a way that is consistent with those measured at Jupiter if the building blocks of the two planets shared a common origin. A determination of the oxygen abundance on Saturn via in situ exploration would distinguish between these scenarios. Furthermore, a determination of noble gases is essential in understanding the formation conditions of Saturn. On one hand, Hersant et al. (2008) predict that Ar and Kr should be solar in Saturn while Xe could be supersolar, whereas Mousis et al. (2009) find that all these species should be significantly supersolar. In addition, a determination of the volatile enrichments in Saturn could also provide a constraint on its rotation period, which will help to better infer its internal structure (Helled and Guillot 2013; Nettelmann et al. 2013). Moreover, as Saturn's atmosphere is believed to be depleted in helium as a result of H_2/He phase separation and subsequent helium rain, a precisely measured He/H_2 value of Saturn's atmosphere is crucial for probing the theoretical H/He demixing phase diagram, which is impossible with current laboratory technology for high-pressure physics. Helium-rain has long been predicted to occur in Saturn as an explanation for its high luminosity. Therefore, an entry probe measurement of the helium abundance is required to resolve this riddle.

3 Planetary atmospheric processes

Planetary atmospheres constitute our only accessible gateway to the processes at work within the deep interiors of the giant planets, and yet we must extrapolate from this thin, dynamic region over many orders of magnitude in pressure, temperature and density to infer the planetary properties far below the clouds. Remote sensing at a wide range of wavelengths 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 the environmental conditions below the clouds. The scientific objectives, which have relevance for Saturn, are summarized in Fig. 2.

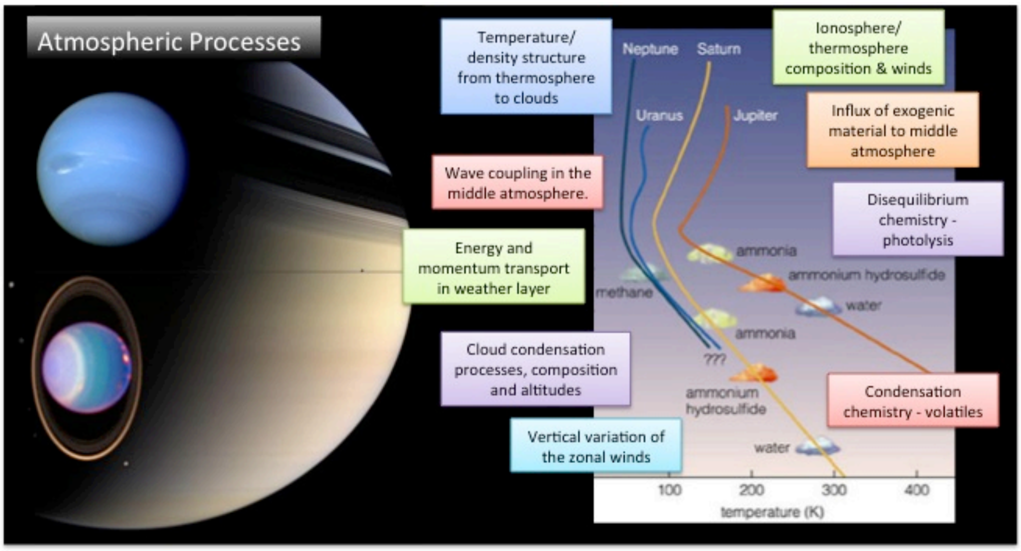

Fig. 2. Examples of the vertical temperature structures of the giant planets, highlighting the scientific themes to be addressed via in situ and remote sensing. Vertical profiles of temperature, density, radiant flux, chemical and aerosol composition will all be acquired during the descent of an entry probe from the upper atmosphere to depths within and below the cloudforming regions.

4 Conclusions

The in situ exploration of Saturn addresses two major science themes: the formation history of our Solar System and the processes at work in the atmospheres of giants. The concept of a Saturn probe can be considered as the next natural step beyond Galileo's in situ exploration of Jupiter, and the Cassini spacecraft's orbital reconnaissance of Saturn. Considered mission designs include the KRONOS concept previously proposed to ESA (Marty et al. 2009) and other studies for future missions are currently in place.

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