The exploration of Neptune: a focus on the noble gases and volatiles as keys to constrain the ice giant formation and evolution

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Abstract

Introduction: Most of the probe visiting other bodies in our Solar System only focused, due to technical challenges, on the exploration of the closer planets and bodies, including Mercury (e.g. *Mariner 10*, *Messenger*, or *BepiColombo* scheduled for 2025), Venus (e.g. the *Venera* missions), the Moon (e.g. *Apollo*, *Chang'e*, etc.), Mars (e.g. *Sojourner*, *Spirit*, *Opportunity*, *Curiosity*, and many others scheduled), and Jupiter (e.g. *Galileo*, *Juno*). However, our knowledge of the two ice-giants Uranus and Neptune is only restricted to the data which have been collected during the flyby of the *Voyager 2* mission, in January 1986 and August 1989, respectively. Ice-giants therefore represent a challenge, both in terms of scientific feasibility and knowledge. As the number of ice-giant mass detected exoplanets increased intensely in the past decades (e.g. Batalha, 2014), it becomes consequently essential, in our understanding of exoplanet candidates, to have a better knowledge of ice-giants.
Scientific backgrounds: The concentrations of noble gases in the atmosphere of Neptune, which could only be measured *in situ* by an atmospheric entry probe, have been deduced from the previous data collected by *Galileo* on Jupiter and are based on models, which input parameters are sometimes limited. An enrichment in heavy noble gases (*i.e.* Ar, Kr, and Xe) has been observed in the atmosphere of Jupiter (Mahaffy et al., 2000), and such is expected for the other gas giant and ice giant planets (Bienstock et al., 2004). Atreya and Wong (2004) or Bienstock et al., 2004 assumed an enrichment of the C/H ratio (and thus on other condensible species) of a factor of _˜20-30, relative to Solar abundance, at Uranus, and between _˜30-50 at Neptune. Measurements of such elements are necessary for our comprehension of Neptune's atmospheric dynamics and will help to constrain the formation models.

The D/H ratio in Neptune, based on ground-based measurements at Herschel-PACS (Feuchtgruber et al., 2013), is estimated to be (4.1±0.4)×10-5, which is as well really close to the one expected for Uranus, and close to the protosolar value. Measuring this ratio would better constrain the protosolar ratio, which remains uncertain. In addition, a precise measurement of D/H would allow models to study the interior of Neptune. A D/H ratio of (4.1±0.4)×10-5 at Neptune implies an ice-mass fraction of _˜14-32%, therefore in favor of Neptune's interior (and by extension Uranus's interior) being more rocky than icy (Feuchtgruber et al., 2013), in contradiction with previous thoughts (25% rock-dominated, *vs.* 60-70% ice-dominated, Guillot, 1999). In addition, the D/H ratio signature might constrain the environment on the

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Solar Nebula from where the planet have formed.

Mission profile: The proposed mission is expected to reach Neptune around 2038; the entry probe will be dropped at the equatorial zone, using the fact that at such latitude, Neptune rotates fast, which can reduce the entry speed of the probe, thus expected to be _˜22-26 km/s.

The goal is for the probe to reach a pressure is 0.1 bar, which is the interface between the stratosphere and the troposphere, the latter being considered as homogeneously mixed. It is expected that the probe will pass through the stratosphere and reach a depth of at least _˜10-20 bars, in order to obtain a complete composition and dynamics of the atmosphere (Sudhir et al., 2005).

The entry probe to Neptune might be equipped, among others, with a Gas Chromatograph Mass Spectrometer for the measurement of noble gas abundances, isotopic ratios, as well as D/H ratio (Bienstock et al., 2004), an atmospheric structure instrument, a helium abundance detector, or a near infrared-spectrometer. The latter did not exist at the time of *Voyager* and would provide the distribution of CH4, CO, and CO2 ices, in order to address *e.g.* the volatile transport on Triton and the KBOs (Hansen et al., 2009).

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