In Situ Exploration of the Giant Planets: a Horizon 2061 Perspective

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Motivation and Background

- Giant planets have played a significant role in shaping the architecture of our planetary system and the evolution of the smaller, inner worlds.

- The efficiency of remote sensing observations has some limitations, especially to study the bulk atmospheric composition.

- Example of these restrictions: 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.

- The Galileo probe provided a giant step forward regarding our understanding of Jupiter. However, it is not known whether these measurements are representative of the whole set of giant planets of the solar system.
What is needed?

- **Bulk composition**: heavy element (> $^4$He), abundances (O, C, N, S, Ne, Ar, Kr, Xe)

- **Isotopic ratios**: noble gas isotopes, D/H, $^{13}$C/$^{12}$C, $^{15}$N/$^{14}$N

- **He/H₂ ratio**: for planetary heat balance and interior processes
What is known

Planetary to solar elemental abundance ratios

Neptune
Uranus
Saturn
Jupiter

Interior processes
Hot spot

Atreya et al. (2018), Mousis et al. (2018)
What did we learn from JUNO?

Thermochemical equilibrium models predict the base of ammonia cloud in Jupiter at ~0.7 bar. However Juno MWR data show a highly complex distribution of ammonia over Jupiter: the well-mixed ammonia is reached at atmospheric pressures exceeding 100 bars!!

In the case of the icy giants, well-mixed water may be found only at several kilobars to tens of kilobars pressure levels (Atreya et al. 2018).
## Isotopic ratios measured in Jupiter, Saturn, Uranus, and Neptune

<table>
<thead>
<tr>
<th>Isotopic ratio</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
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</thead>
<tbody>
<tr>
<td>D/H (in H&lt;sub&gt;2&lt;/sub&gt;)&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>(2.60 ± 0.7) x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>1.70&lt;sup&gt;+0.75&lt;/sup&gt;-0.45 x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>(4.4 ± 0.4) x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>(4.1 ± 0.4) x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
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<tr>
<td>&lt;sup&gt;3&lt;/sup&gt;He/&lt;sup&gt;4&lt;/sup&gt;He&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>(1.66 ± 0.05) x 10&lt;sup&gt;-4&lt;/sup&gt;</td>
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<tr>
<td>&lt;sup&gt;12&lt;/sup&gt;C/&lt;sup&gt;13&lt;/sup&gt;C (in CH&lt;sub&gt;4&lt;/sub&gt;)&lt;sup&gt;(3)&lt;/sup&gt;</td>
<td>92.6&lt;sup&gt;4.5&lt;/sup&gt;-4.1</td>
<td>91.8&lt;sup&gt;8.4&lt;/sup&gt;-7.8</td>
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<tr>
<td>&lt;sup&gt;14&lt;/sup&gt;N/&lt;sup&gt;15&lt;/sup&gt;N (in NH&lt;sub&gt;3&lt;/sub&gt;)&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>434.8&lt;sup&gt;65&lt;/sup&gt;-50</td>
<td>&gt; 357</td>
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<tr>
<td>&lt;sup&gt;20&lt;/sup&gt;Ne/&lt;sup&gt;22&lt;/sup&gt;Ne&lt;sup&gt;(5)&lt;/sup&gt;</td>
<td>13 ± 2</td>
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<tr>
<td>&lt;sup&gt;36&lt;/sup&gt;Ar/&lt;sup&gt;38&lt;/sup&gt;Ar&lt;sup&gt;(6)&lt;/sup&gt;</td>
<td>5.6 ± 0.25</td>
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<tr>
<td>&lt;sup&gt;136&lt;/sup&gt;Xe/total Xe&lt;sup&gt;(7)&lt;/sup&gt;</td>
<td>0.076 ± 0.009</td>
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<tr>
<td>&lt;sup&gt;134&lt;/sup&gt;Xe/total Xe&lt;sup&gt;(8)&lt;/sup&gt;</td>
<td>0.091 ± 0.007</td>
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<tr>
<td>&lt;sup&gt;132&lt;/sup&gt;Xe/total Xe&lt;sup&gt;(9)&lt;/sup&gt;</td>
<td>0.290 ± 0.020</td>
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<tr>
<td>&lt;sup&gt;131&lt;/sup&gt;Xe/total Xe&lt;sup&gt;(10)&lt;/sup&gt;</td>
<td>0.203 ± 0.018</td>
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<td>&lt;sup&gt;130&lt;/sup&gt;Xe/total Xe&lt;sup&gt;(11)&lt;/sup&gt;</td>
<td>0.038 ± 0.005</td>
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<tr>
<td>&lt;sup&gt;129&lt;/sup&gt;Xe/total Xe&lt;sup&gt;(12)&lt;/sup&gt;</td>
<td>0.285 ± 0.021</td>
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<tr>
<td>&lt;sup&gt;128&lt;/sup&gt;Xe/total Xe&lt;sup&gt;(13)&lt;/sup&gt;</td>
<td>0.018 ± 0.002</td>
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Delivery of Volatiles to the Giant Planets – Solids

Amorphous ice
Owen et al. (1999),
Bar-Nun et al. (2007)

Clathrates + pure condensates
Gautier et al. (2001),
Mousis et al. (2009, 2012)
Gas opening and consequence for the accretion of pebbles/planetesimals

Gap formation halts the accretion of pebbles -> Giant planets supersolar metallicities cannot be acquired during the growth of the envelope!!

(Lambrechts & Johansen 2014)
Delivery of Volatiles to the Giant Planets – Vapors

Production of amorphous ice via photoevaporation (Monga & Desch 2015)

Release of volatiles at the ACTZ (Mousis, Ronnet, & Lunine 2019)
Release of volatiles from the ACTZ: the water abundance in Jupiter?

Influence of Jupiter’s formation location on the oxygen content in its envelope, assuming that H2O is the main O–bearing volatile in the PSN. Here, Jupiter’s feeding zone contains water in both solid and vapor forms while the other volatiles remain exclusively in vapor phase once released from the amorphous particles crossing the ACTZ. Two extreme cases can be envisaged for the oxygen abundance in Jupiter’s envelope:

1. Jupiter’s formation around the ice line where the O abundance is supersolar,
2. Formation around the ACTZ where Jupiter’s O abundance is smaller, and eventually subsolar

Mousis, Ronnet & Lunine (2019)
Different scenarios of volatile enrichments in giant planets

Mousis, Atkinson et al. (2018)
Where does the bulk composition lie?
The cases of Uranus and Neptune

- **Noble gases and their isotopes:**
  Anywhere below 1-bar level

- **CH$_4$, NH$_3$, H$_2$S, H$_2$O:**
  below the cloud. being much colder than Jupiter, the clouds of Uranus and Neptune lie much deeper

Atreya et al. (2018)
Heritage and Previous Studies

Galileo probe

The Galileo Probe

Deceleration Module Alt Cover

Main Chute

Descent Module

Main Chute

Descent Module Aeroshell

Prior to and During Entry

During Descent

Deceleration Module

Main Chute Riser (Not to Scale)

Swivel

Main Chute Bridge

ESATRONICAL MEMORANDUM

NASA 1973

Mission Planning for
Pioneer Saturn/Neptune
Atmospheric Probe Missions

By: Byron L. Swenson, Edward L. Tinsley,
and Larry A. Manning

NASA Research Center

Kronos, ESA KRONOS proposal

Huygens probe

PEP study

PEP - Planetary Entry Probes

NASA 1973

ESA Huygens probe

Introduction

IFP

ESTEC, 30th June 2010

Prepared by the PEP CDF Team

PEP - Assessment Study

ESA KRONOS proposal

ESA PEP study

Prepared by the PEP CDF Team