Deuterium and the formation of the Giant Planets

THE OUTER PLANETS

Jupiter  Saturn  Uranus  Neptune
HIgh Resolution Mid-infrarEd Spectrometer (HIRMES)
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- HIRMES primary science is to investigate protoplanetary disk physics and addresses the questions:
  - How does the disk mass evolve during planetary formation (using HD)?
  - What is the distribution of oxygen, water ice, and water vapor in different phases of planet formation?
  - What are the kinematics of water vapor and oxygen in protoplanetary disks?
  - *Over riding theme is discover how protoplanetary systems evolve*
HIRMES LEGACY SCIENCE PROGRAM (LSP)

- A Legacy Science Program (LSP) will be observed in the first 2-3 years of HIRMES science operations.
- The HIRMES LSP is designed to reach ambitious science goals as soon as possible after commissioning as part of a large, coherent survey in the context of the original HIRMES science themes.
- A portion of the flight time will be devoted to Solar System science, including D/H in comets and in the Giant Planets.
Overview: Deuterium can constrain models of Giant Planet formation

• Jupiter and Saturn should have protosolar D/H. Cassini observations indicate that Saturn may have depleted D/H compared with Jupiter. What could deplete D/H?

• Uranus and Neptune are expected to have enhanced D/H close to that in comets, which are a proxy for the planetesimals that formed the Ice Giants.

• *Herschel*-PACS data show much less D/H in Uranus & Neptune than in all 11 comets where deuterium has been measured, including the Rosetta comet 67P. Surprising!

• HIRMES will observe the 112-\(\mu\)m line of HD at 100 times higher spectral resolution. Combined with existing measurements of heavy element enhancements such as carbon, this will lead to improved formation models for all 4 Giant Planets.
Protosolar: $D/H = (2.1 \pm 0.50) \times 10^{-5}$ (Geiss and Gloecker 1998)

HD measured in absorption with Cassini/CIRS at a Resolving Power $\sim 500$

Jupiter: $D/H = (1.4 \pm 0.26) \times$ protosolar (Pierel et al. 2017)

Saturn: $D/H = (1.0 \pm 0.06) \times$ protosolar (Pierel et al. 2017)
• Comets and small bodies in the solar system are deuterium-rich
  Comet 67P: \( \frac{D}{H} = (27 \pm 4) \times \text{protosolar} \) (Rosetta: Altwegg et al. 2014)
  11 comets: \( \frac{D}{H} = (8-32) \times \text{protosolar} \) (Paganini et al. 2017)
  Phoebe (outer moon of Saturn): \( \frac{D}{H} = (62 + 14) \times \text{protosolar} \) (Clark et al. 2019)

• Uranus and Neptune are highly enriched in C/H
  Uranus: \( \frac{C}{H} = 30 \times \text{solar} \) (Baines et al. 1995) ;80 \( \times \) solar (Sromovsky et al. 2011)
  Neptune: \( \frac{C}{H} = 40 \times \text{solar} \) (Baines et al. 1995) ;80 \( \times \) solar (Karkoschka et al. 2011)

• We expect Uranus and Neptune to be enriched in deuterium!
• Herschel-PACS measured HD in Uranus and Neptune

Resolving power of 1000

Uranus: \( D/H = (2.2 \pm 0.2) \times \text{protosolar} \) Feuchtgruber et al (2013)
Neptune: \( D/H = (2.0 \pm 0.2) \times \text{protosolar} \) Feuchtgruber et al (2013)

• How do you form Uranus and Neptune from planetesimals abundant in deuterium, carbon, and other heavy elements and end up with D/H as low as 2 x protosolar?

• The “Ice Giant” planets are really “Rock Giant” planets??

• NASA is planning Flagship missions to Uranus & Neptune:
  Earth-based observations need to be done now!
HIRMES Technical Capabilities

- HIRMES is a spectrometer using very sensitive detectors covering the 25 to 122 µm spectrum in 4 operating modes:

1. High resolution spectroscopy: $50,000 < \text{RP} < 100,000$
2. Medium resolution spectroscopy: $\text{RP} \approx 12,000$
3. Low resolution spectroscopy: $\text{RP} \approx 600$
4. Spectral Imaging: $\text{RP} \approx 2000$
## HIRMES modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Scanning FPI</th>
<th>Central Wavelength</th>
<th>Wavelength Range</th>
<th>Resolving Power</th>
<th>Etalon Diameter</th>
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<tbody>
<tr>
<td>slit</td>
<td>high-R LW</td>
<td>112 µm</td>
<td>86-122 µm</td>
<td>100,000</td>
<td>100 mm</td>
</tr>
<tr>
<td>slit</td>
<td>high-R MW</td>
<td>63 µm</td>
<td>50-86 µm</td>
<td>100,000</td>
<td>90 mm</td>
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<td>25-36 µm</td>
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<td>imaging</td>
<td>Low-R LW</td>
<td>102 µm</td>
<td>80-125 µm</td>
<td>2000</td>
<td>30 mm</td>
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</table>
HIRMES utilizes a three-stage optical system

• Plate scale, F/#
  - HIRMES re-images to f/13.3 to set a 6.2 arcsec per mm plate scale
  - 8 high-res pixel sizes range from 0.4 to 1.4 mm, to match $\lambda/D$ for 30 – 105 $\mu$m

• High resolution FOV (slits)
  - 1 x 16 pixels covering 2.5 x 41 arcsec (shortest $\lambda$) to 8.7 x 140 arcsec (longest $\lambda$)

• Wavelength coverage 25 – 122 $\mu$m
For D/H, we will observe HD at 112 µm and H$_2$ at 28 µm sequentially. The bottom row will be used to image the HD line with 1x16 spatial pixels in High-Res mode. At 112 µm, the slit width is 11.4 arcsec and each pixel is 8.7 arcsec. The top row will be used to image the H$_2$ line. At 28 µm, the slit width is 2.8 arcsec and each pixel is 2.5 arcsec. The Fabry-Perot is scanned spectrally to build up an image cube.
Planets have seasons:
A thermometer is required to measure the temperature of the stratosphere to interpret the core of the HD emission line.
Conclusions

- HIRMES has the sensitivity, resolving power ($10^5$) and broad bandpass to derive D/H from the HD line at 112 $\mu$m for all 4 Giant Planets. HIRMES will spectrally resolve the line profile of HD revealing a stratospheric emission core and a tropospheric absorption wing.

- Best thermometer of the stratosphere for Jupiter and Saturn: CH$_4$ at 119.6 $\mu$m. CH$_4$/H$_2$ is well known for these planets and does not vary with latitude. HIRMES pixel size (8.7") is the same for HD and CH$_4$ and it is smaller than Jupiter & Saturn.

- Best thermometer of the stratosphere for Uranus and Neptune: H$_2$ at 28.2 $\mu$m. H$_2$, unlike CH$_4$, does not vary with latitude. HIRMES pixel size (2.5") is larger than Neptune.

- Using line shape and temperature information, HIRMES will improve the accuracy of D/H for all 4 Giant Planets. This, in turn, will provide strong constraints to formation models for all of the outer planets. Since Neptune-sized planets are common in the galaxy, these results will be of interest to exoplanet researchers.