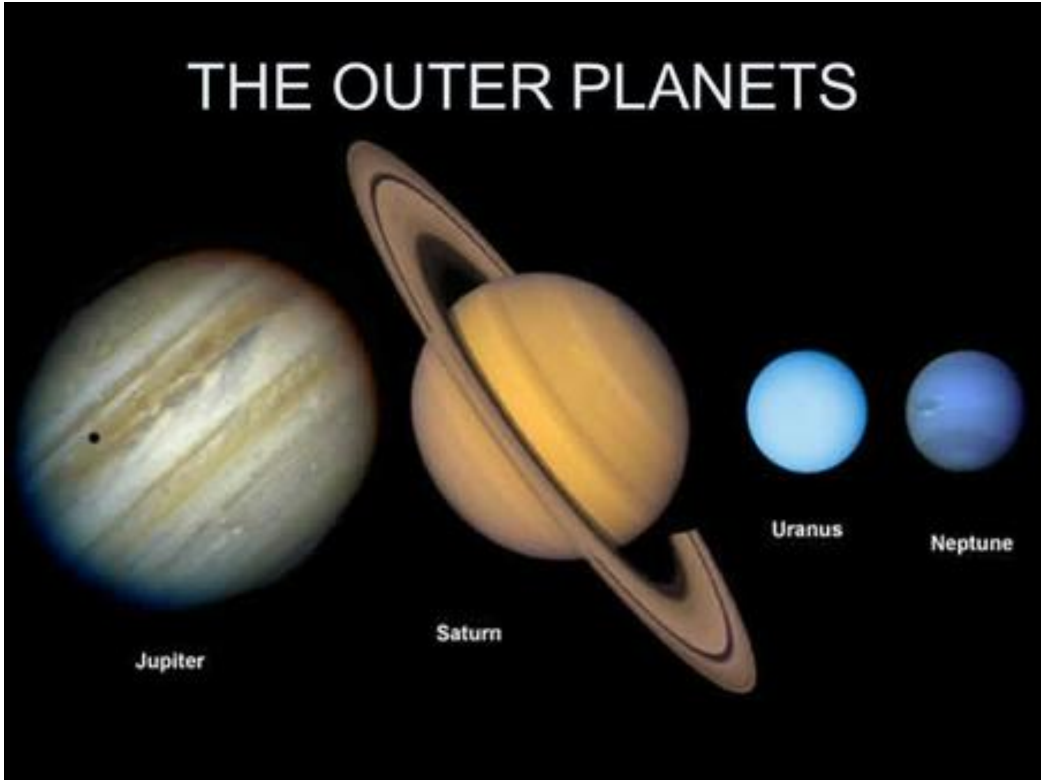
Deuterium and the formation of the Giant Planets



HIgh Resolution Mid-infrarEd Spectrometer (HIRMES) P.I. Matt Greenhouse (NASA/GSFC)

- 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.

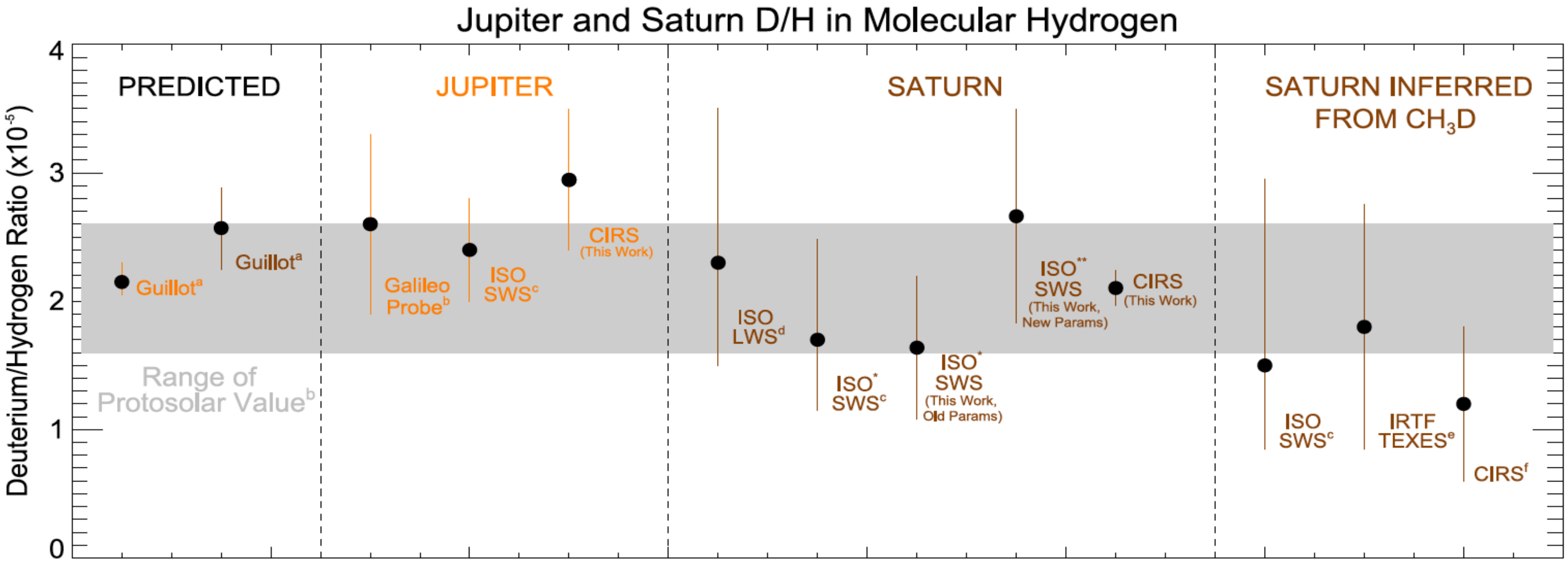
Overview: Deuterium can constrain models of Giant Planet formation

- 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-μm 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) x 10^{-5} (Geiss and Gloecker 1998)

HD measured in absorption with Cassini/CIRS at a Resolving Power ~500

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

Saturn: D/H = (1.0 $\pm$ 0.06) x protosolar (Pierel et al. 2017)

- Comets and small bodies in the solar system are deuterium-rich

Comet 67P: D/H = (27 $\pm$ 4) x protosolar (Rosetta: Altwegg et al. 2014)

11 comets: D/H = (8-32) x protosolar (Paganini et al. 2017)

Phoebe (outer moon of Saturn): D/H = (62 $\pm$ 14) x protosolar (Clark et al. 2019)

- Uranus and Neptune are highly enriched in C/H

Uranus: C/H = 30 x solar (Baines et al. 1995) ;80 x solar (Sromovsky et al. 2011)

Neptune: C/H = 40 x solar (Baines et al. 1995) ;80 x 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) x protosolar Feuchtgruber et al (2013)

  Neptune: D/H = (2.0 $\pm$ 0.2) x 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 < RP< 100,000
2. Medium resolution spectroscopy: RP~ 12,000
3. Low resolution spectroscopy: RP~ 600
4. Spectral Imaging: RP~ 2000

HIRMES modes

Mode	Scanning FPI	Central Wavelength	Wavelength Range	Resolving Power	Etalon Diameter
slit	high-R LW	112 μm	86-122 μm	100,000	100 mm
slit	high-R MW	63 μm	50-86 μm	100,000	90 mm
slit	high-R SW	35 μm	25-36 μm	50,000	90 mm
slit	mid-R LW	112 μm	86-122 μm	12,000	90 mm
slit	mid-R MW	63 μm	50-86 μm	12,000	90 mm
slit	mid-R SW	35 μm	25-36 μm	12,000	90 mm
imaging	low-R SW	57 μm	50-70 μm	2000	30 mm
imaging	Low-R LW	102 μm	80-125 μm	2000	30 mm

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

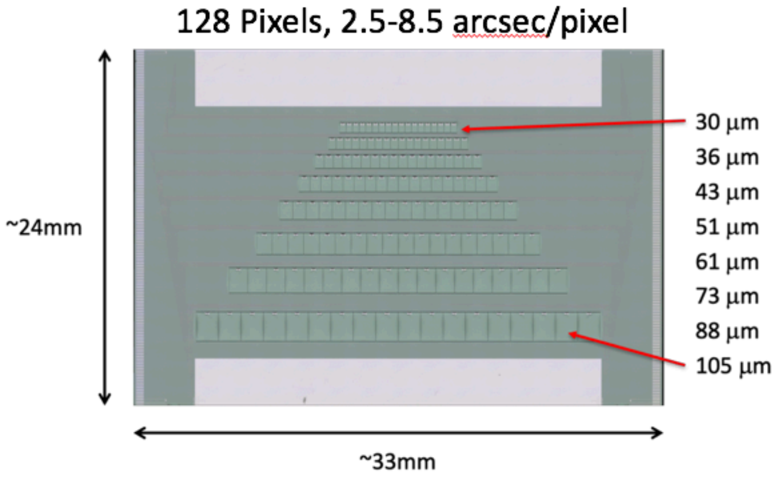
  - 8 high-res pixel sizes range from 0.4 to 1.4 mm, to match λ/D for 30 – 105 μm

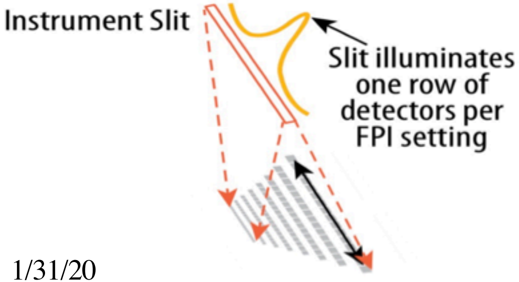
- High resolution FOV (slits)

  - 1 x16 pixels covering 2.5 x 41 arcsec (shortest λ) to 8.7 x 140 arcsec (longest λ)

- Wavelength coverage 25 – 122 μm

HIRMES array: High-Res Mode





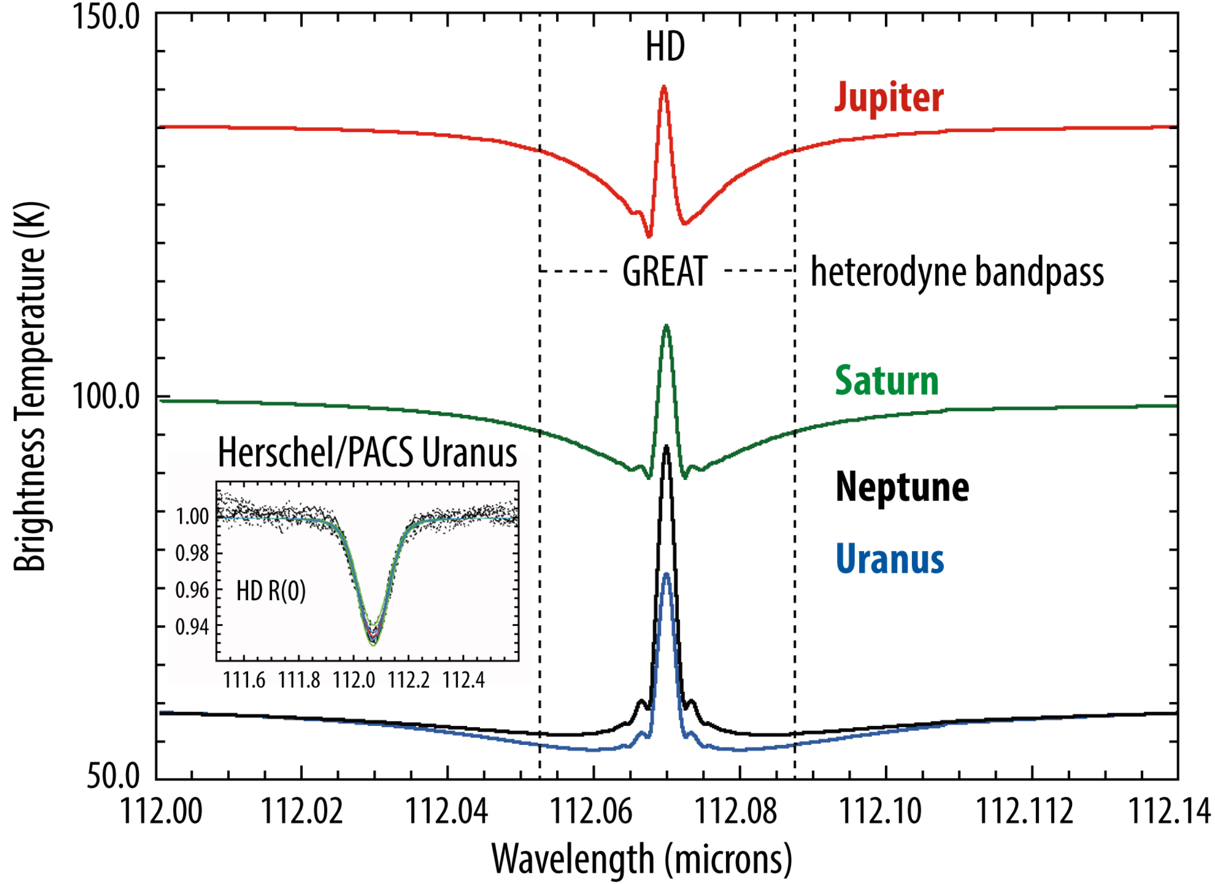
For D/H, we will observe HD at 112 μm and H_2 at 28 μm sequentially.

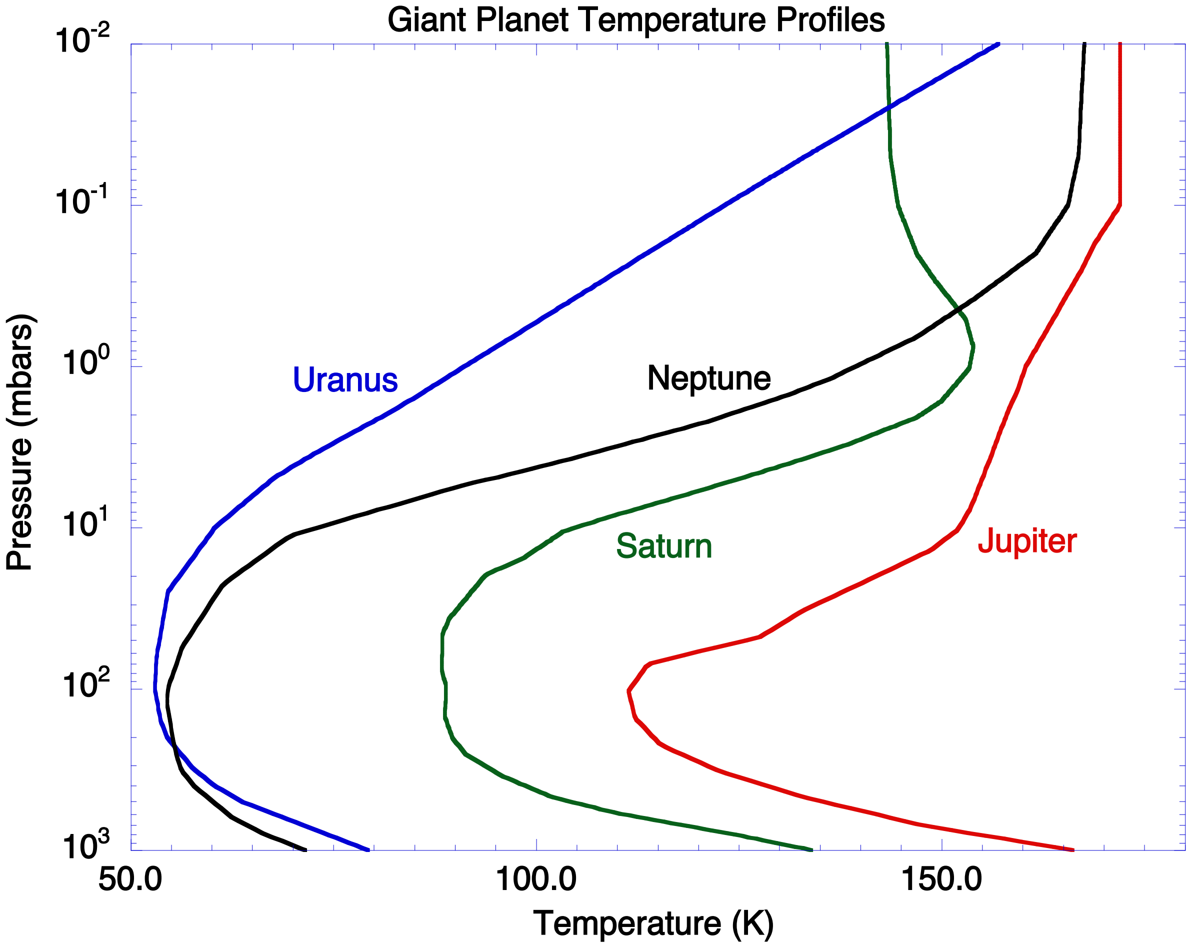
The bottom row will be used to image the HD line with 1x16 spatial pixels in High-Res mode. At 112 μm, the slit width is 11.4 arcsec and each pixel is 8.7 arcsec.

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.

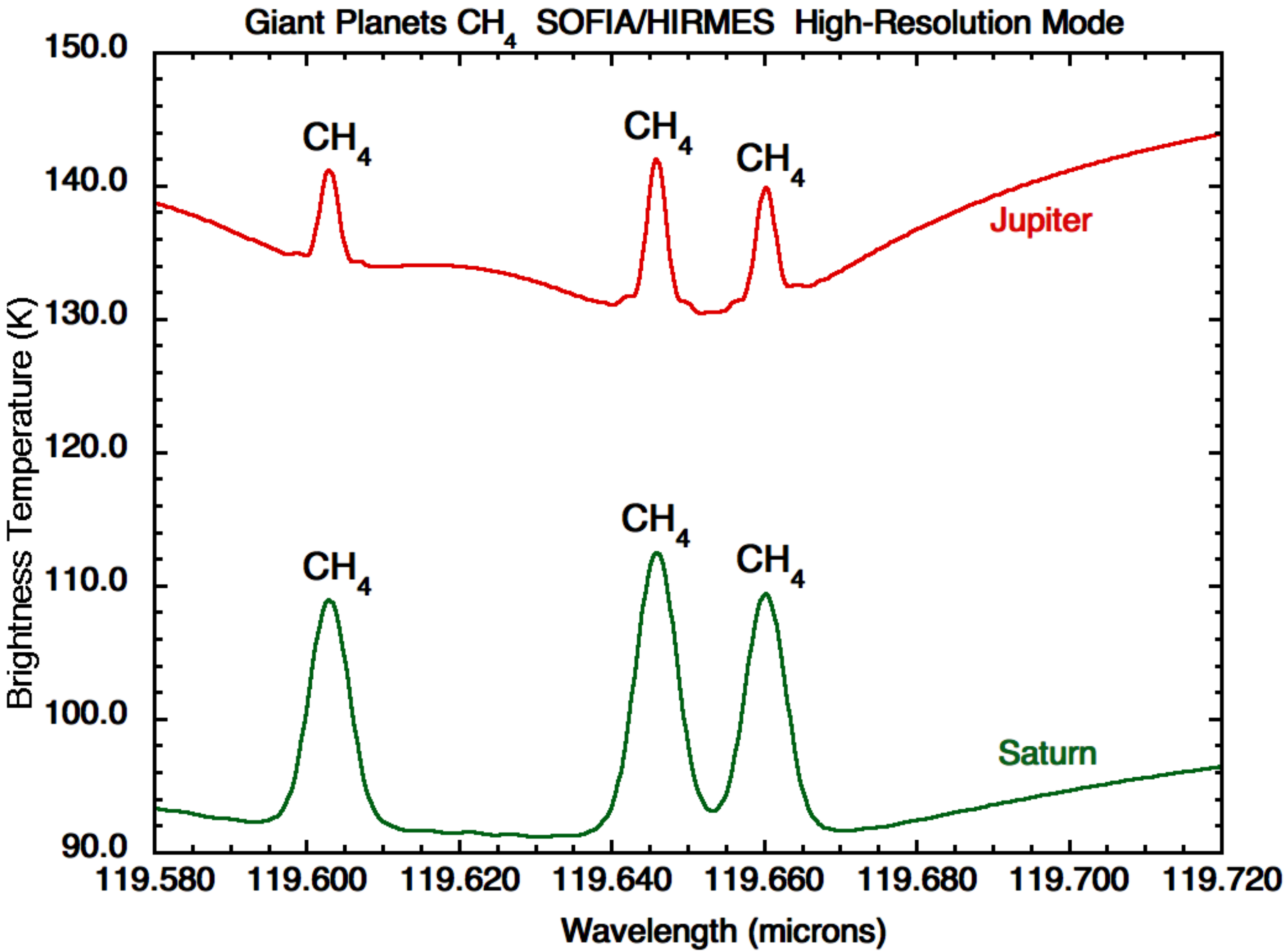
Giant Planets HD R0 SOFIA/HIRMES High-Resolution Mode

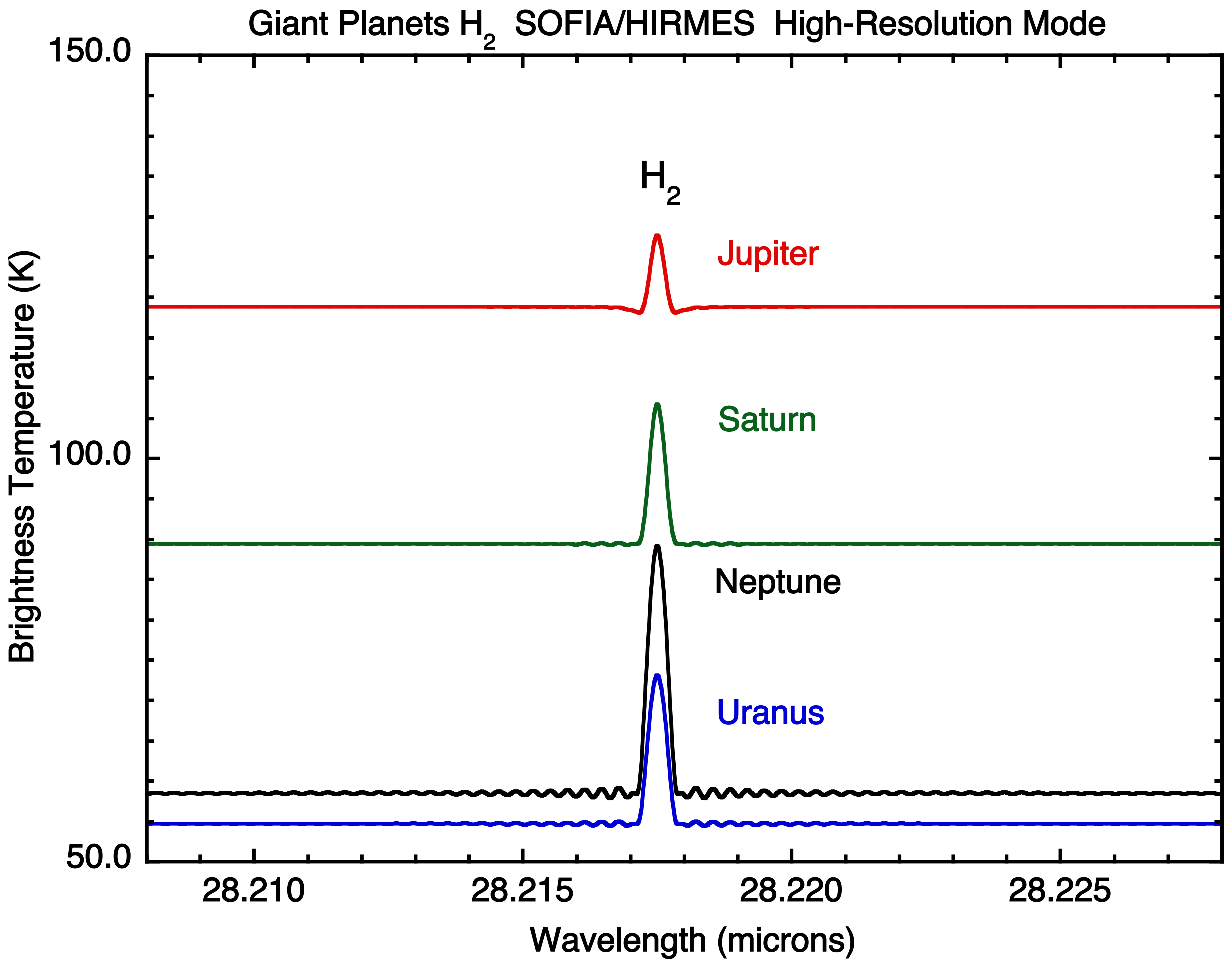




Planets have seasons:

A thermometer is required to measure the temperature of the stratosphere to interpret the core of the HD emission line.


Giant Planets CH4 SOFIA/HIRMES High-Resolution Mode
CH4
CH4
CH4
Jupiter
CH4
CH4
CH4
Saturn
Brightness Temperature (K)
150.0
140.0
130.0
120.0
110.0
100.0
90.0
119.580
119.600
119.620
119.640
119.660
119.680
119.700
119.720
Wavelength (microns)



Giant Planets H_2 SOFIA/HIRMES High-Resolution Mode
H_2
Jupiter
Saturn
Neptune
Uranus
Brightness Temperature (K)
150.0
100.0
50.0
28.210
28.215
28.220
28.225
Wavelength (microns)

Conclusions

- HIRMES has the sensitivity, resolving power (10^5) and broad bandpass to derive D/H from the HD line at 112 μm 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 μm. 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 μm. 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.