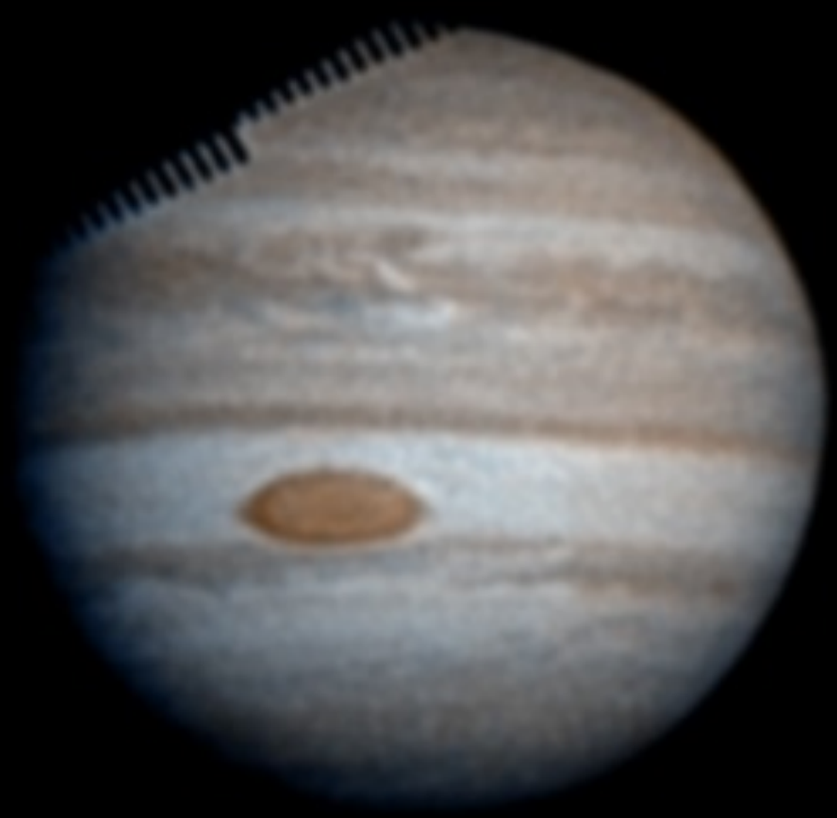
Characterizing Cold Giant Planets in Reflected Light: Lessons from 50 Years of Outer Solar System Observation and Exploration

Mark Marley & Heidi Hammel



Pioneer 10: 1973

Today

- What is important?
- Giant planet visible spectra 101
- Deriving cloud heights from narrow band images
- Deriving methane abundance from spectra
- Spectral Resolution
- Polarization
- Lessons for space based coronagraphs

Galileo probe outcomes

1	1996Sci...272..846N	153.000	05/1996	A	E	R	C
	Niemann, Hasso B.; Atreya, Sushil K.; Carignan, George R.; Donahue, Thomas M.; Haberman, John A.; Harpold, Dan N.; Hartle, Richard E.; Hunten, Donald M.; Kasprzak, Wayne T.; Mahaffy, Paul R.; and 3 coauthors	The Galileo Probe Mass Spectrometer: Composition of Jupiter's Atmosphere					
2	1996Sci...272..844S	66.000	05/1996	A	E	R	C
	Seiff, Alvin; Kirk, Donn B.; Knight, Tony C. D.; Mihalov, John D.; Blanchard, Robert C.; Young, Richard E.; Schubert, Gerald; von Zahn, Ulf; Lehmacher, Gerald; Milos, Frank S.; Wang, Jerry	Structure of the Atmosphere of Jupiter: Galileo Probe Measurements					
3	1996Sci...272..709A	64.000	05/1996	A	E	R	C
	Anderson, J. D.; Sjogren, W. L.; Schubert, G.	Galileo Gravity Results and the Internal Structure of Io					
4	1996Sci...272..839O	47.000	05/1996	A	E	R	C
	Orton, G.; Ortiz, J. L.; Baines, K.; Bjoraker, G.; Carsenty, U.; Colas, F.; Dayal, A.; Deming, D.; Drossart, P.; Frappa, E.; and 31 coauthors	Earth-Based Observations of the Galileo Probe Entry Site					
5	1996Sci...272..849V	46.000	05/1996	A	E	R	C
	von Zahn, U.; Hunten, D. M.	The Helium Mass Fraction in Jupiter's Atmosphere					
6	1996Sci...272..842A	41.000	05/1996	A	E	R	C
	Atkinson, David H.; Pollack, James B.; Seiff, Alvin	Galileo Doppler Measurements of the Deep Zonal Winds at Jupiter					
7	1996Natur.381..395G	37.000	05/1996	A	E	R	C
	Grün, E.; Baguhl, M.; Hamilton, D. P.; Riemann, R.; Zook, H. A.; Dermott, S.; Fechtig, H.; Gustafson, B. A.; Hanner, M. S.; Horányi, M.; and 12 coauthors	Constraints from Galileo observations on the origin of jovian dust streams					
8	1996Sci...272..854R	35.000	05/1996	A	E	R	C
	Ragent, Boris; Colburn, David S.; Avrin, Philip; Rages, Kathy A.	Results of the Galileo Probe Nephelometer Experiment					

composition

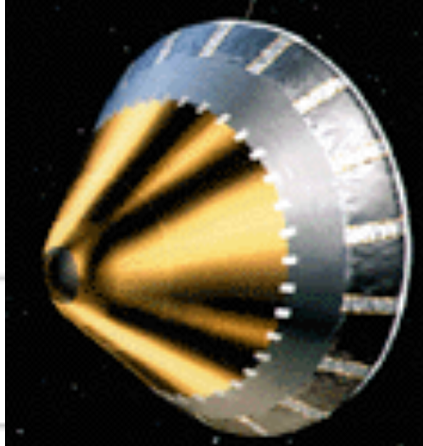
2.5x more citations than #2

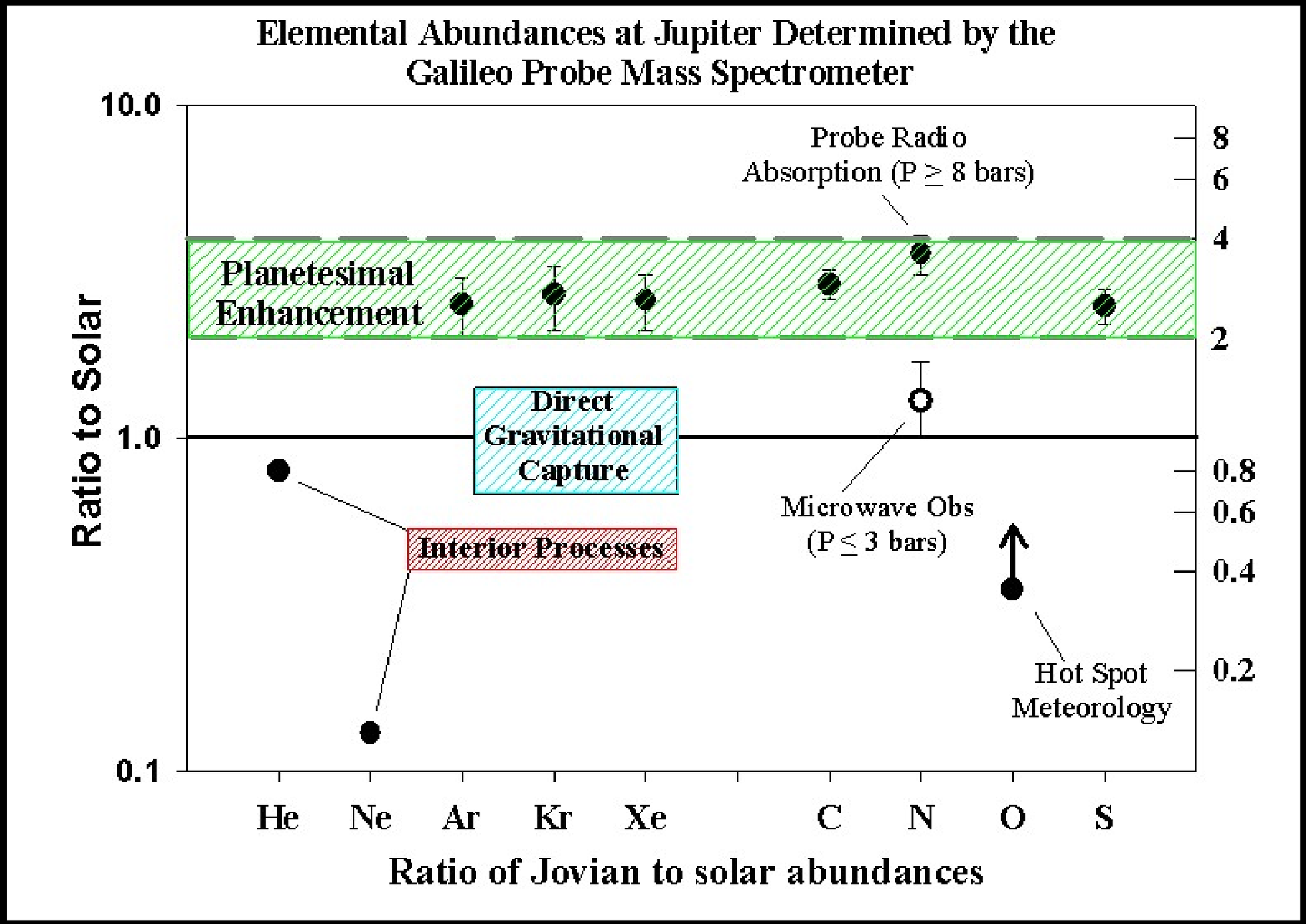
thermal structure

He abundance

winds

clouds





Owen et al. (1999)

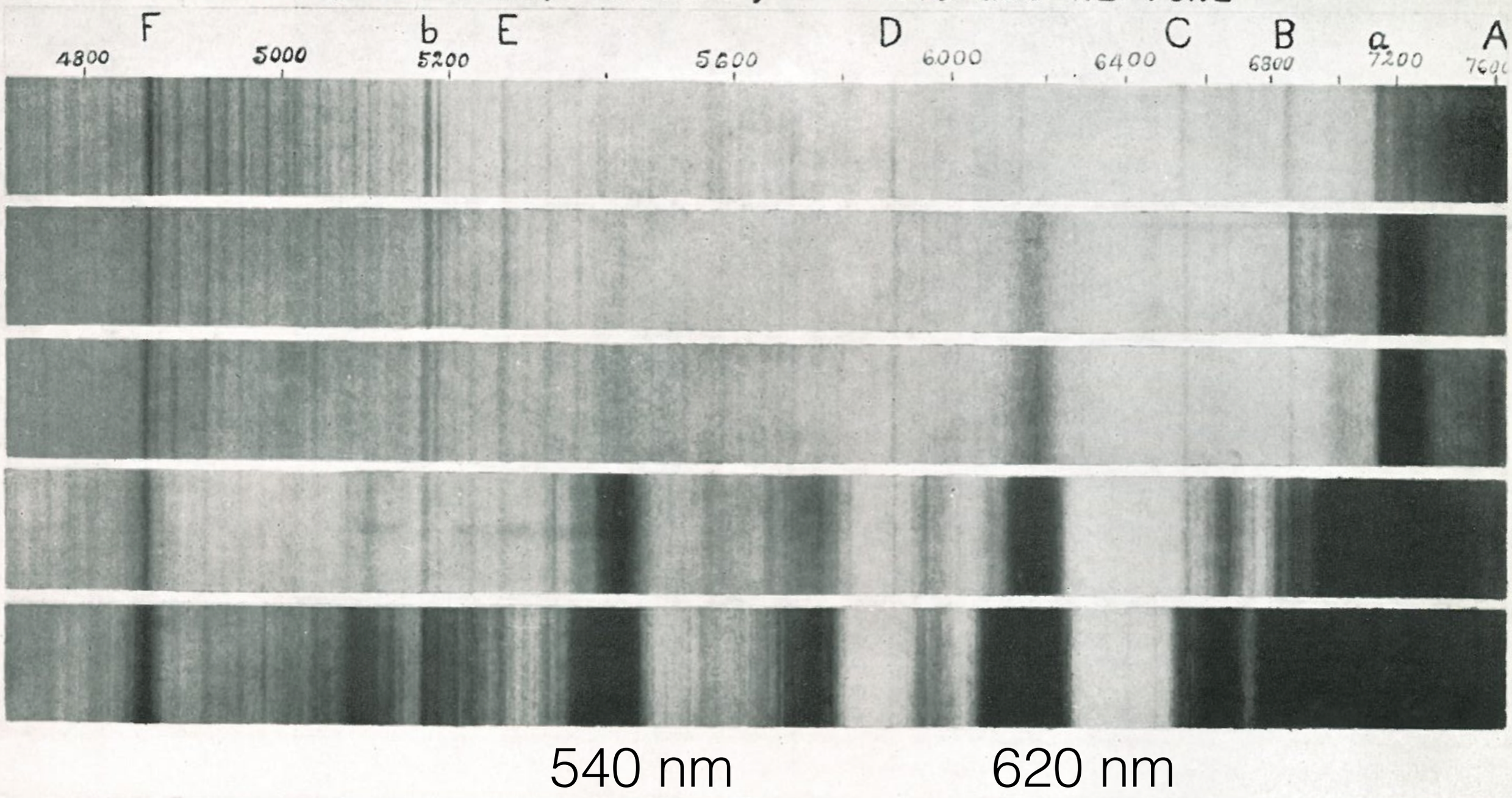
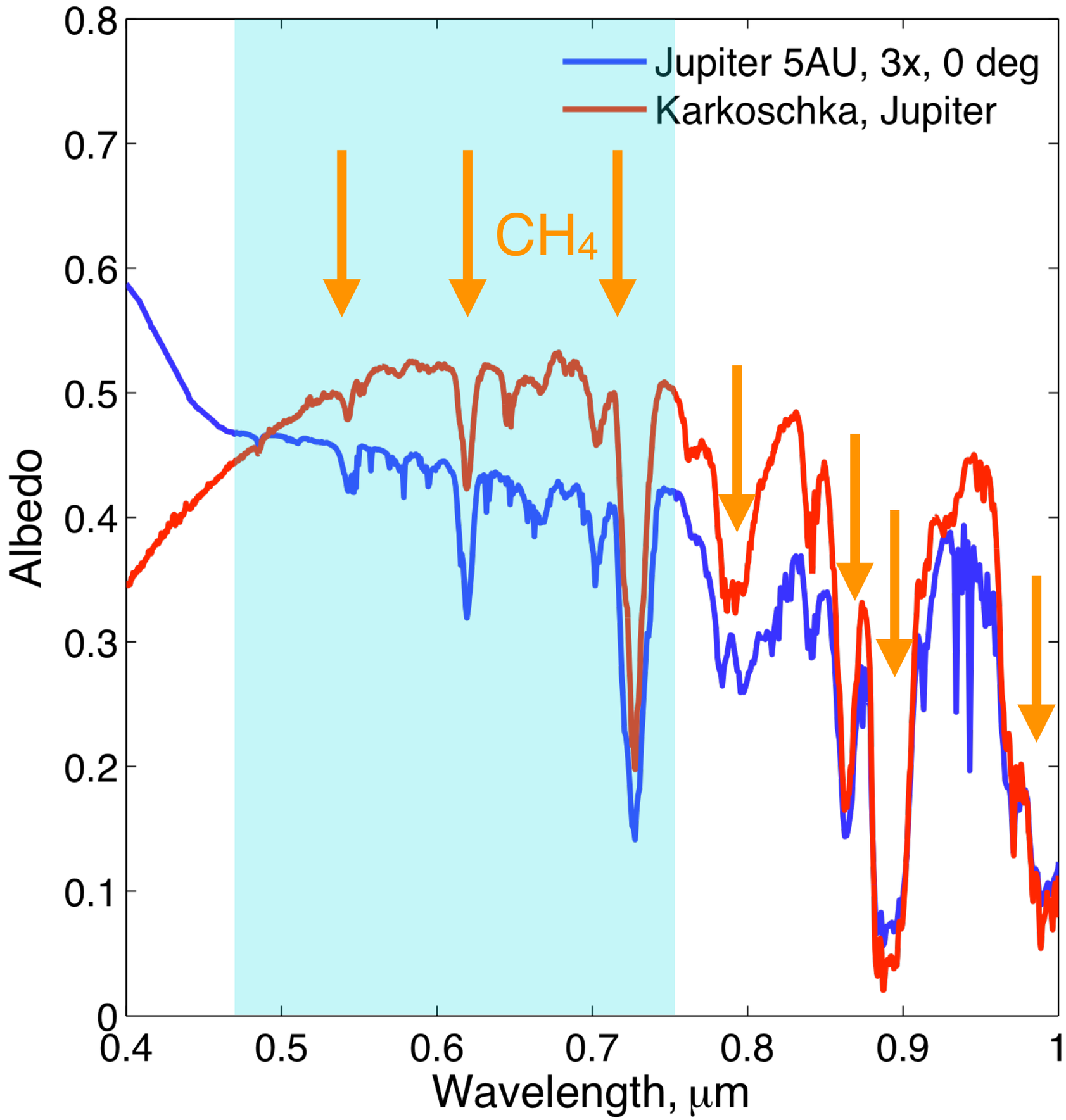


PLATE V.—V. M. Slipher: Photograph of spectra 1909 of (top line) Moon, (2) Jupiter, (3) Saturn, (4) Uranus, (5) Neptune. (From *Lowell Observatory Bulletin* 42; electro supplied by English Universities Press.)

Slipher 1909 spectra


Jupiter 5AU, 3x, 0 deg
Karkoschka, Jupiter
CH4
Albedo
Wavelength, μm
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0.7
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0.5
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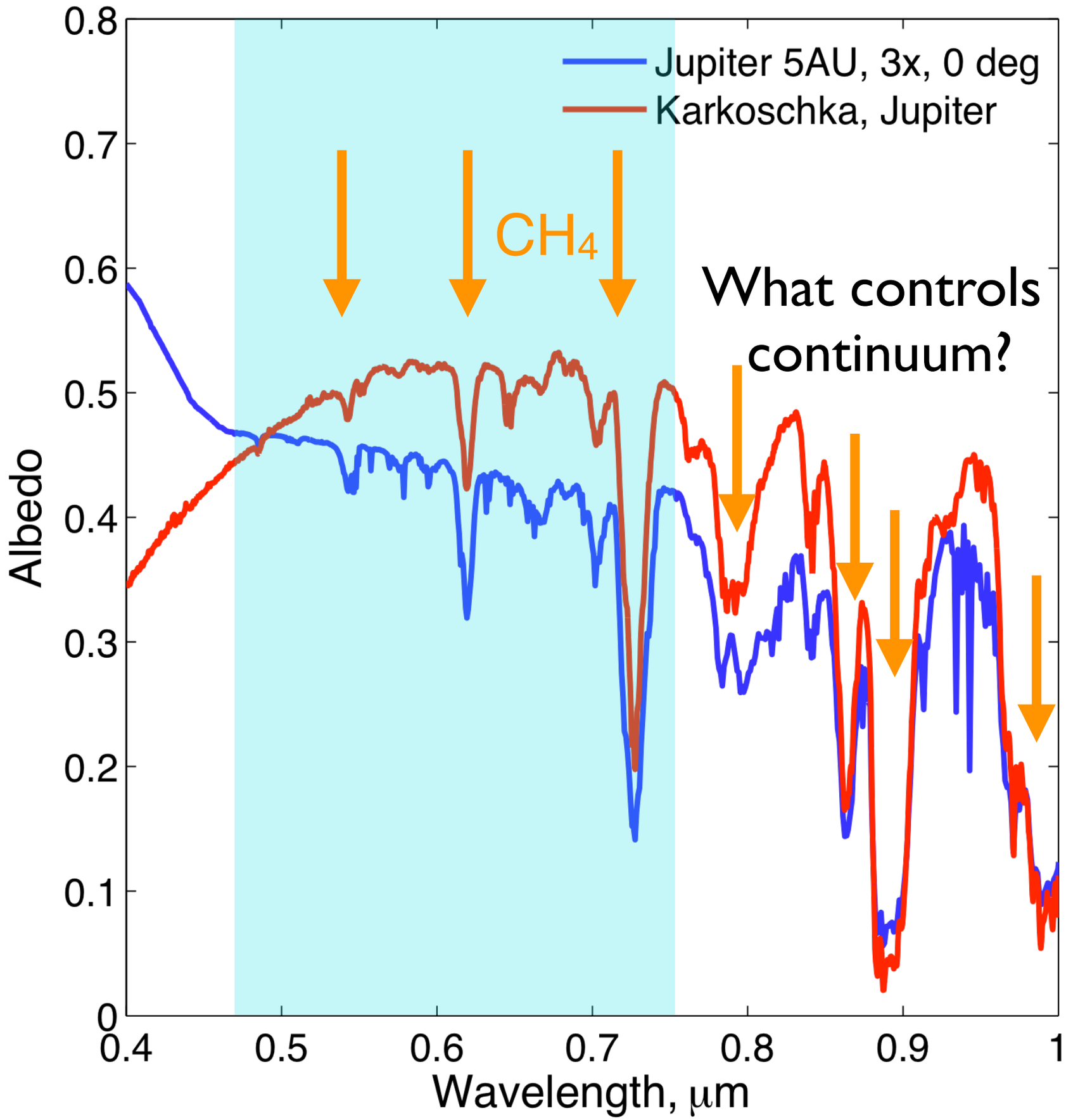
Jupiter 5AU, 3x, 0 deg
Karkoschka, Jupiter
CH_4
What controls continuum?
Albedo
Wavelength, μm
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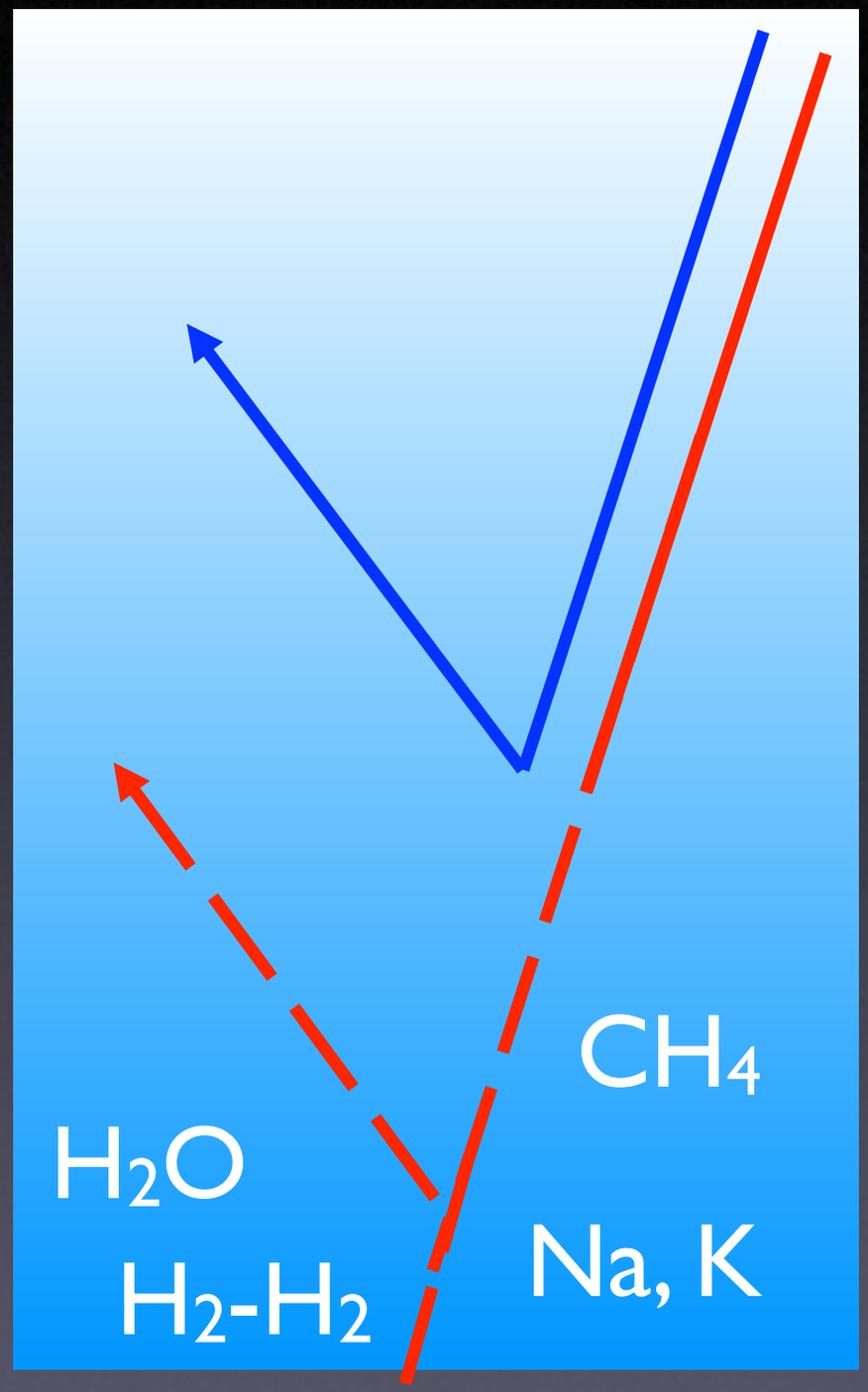
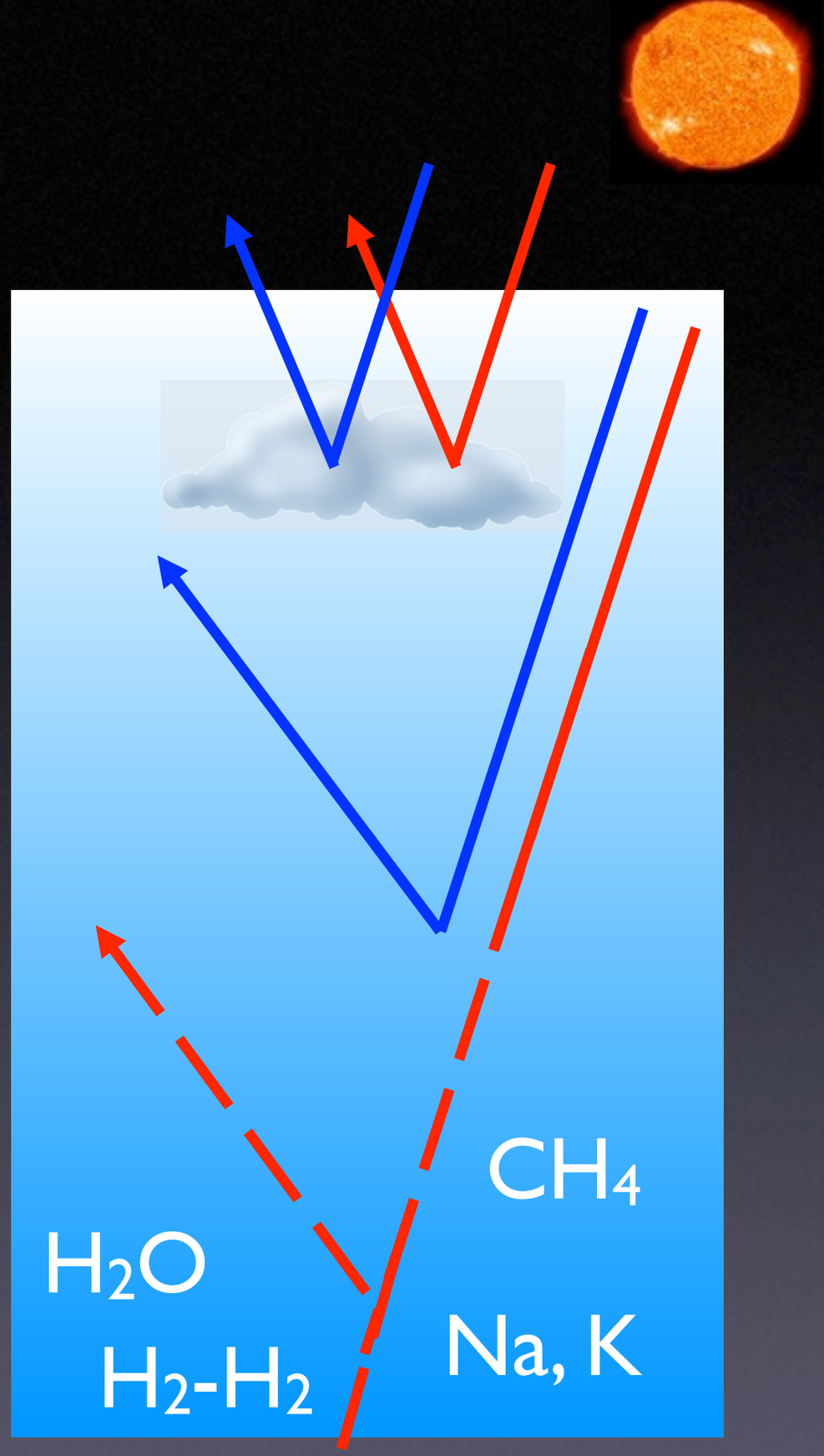
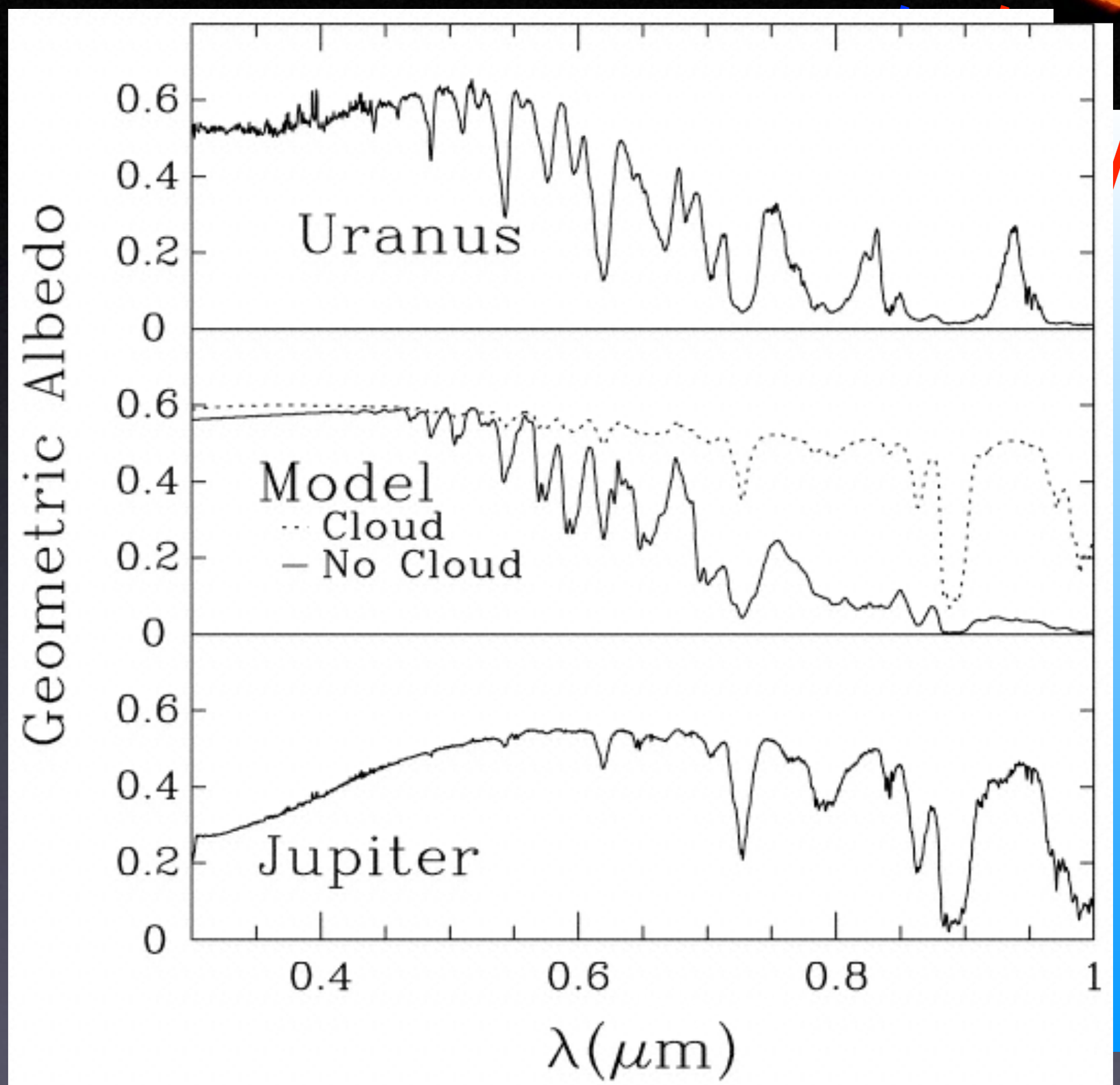

CH_4
H_2O
Na, K
H_2-H_2

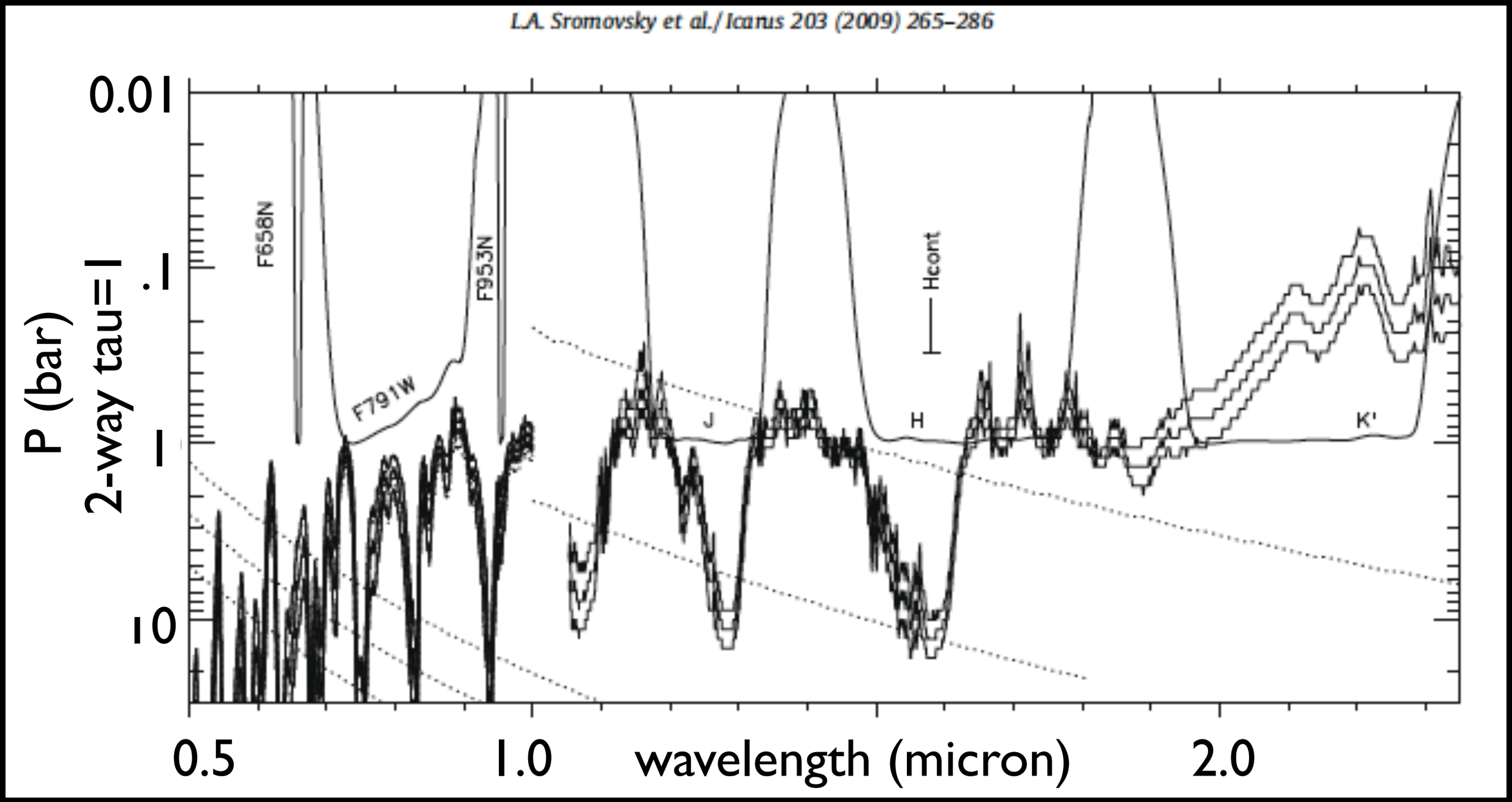

CH_4
H_2O
Na, K
H_2-H_2



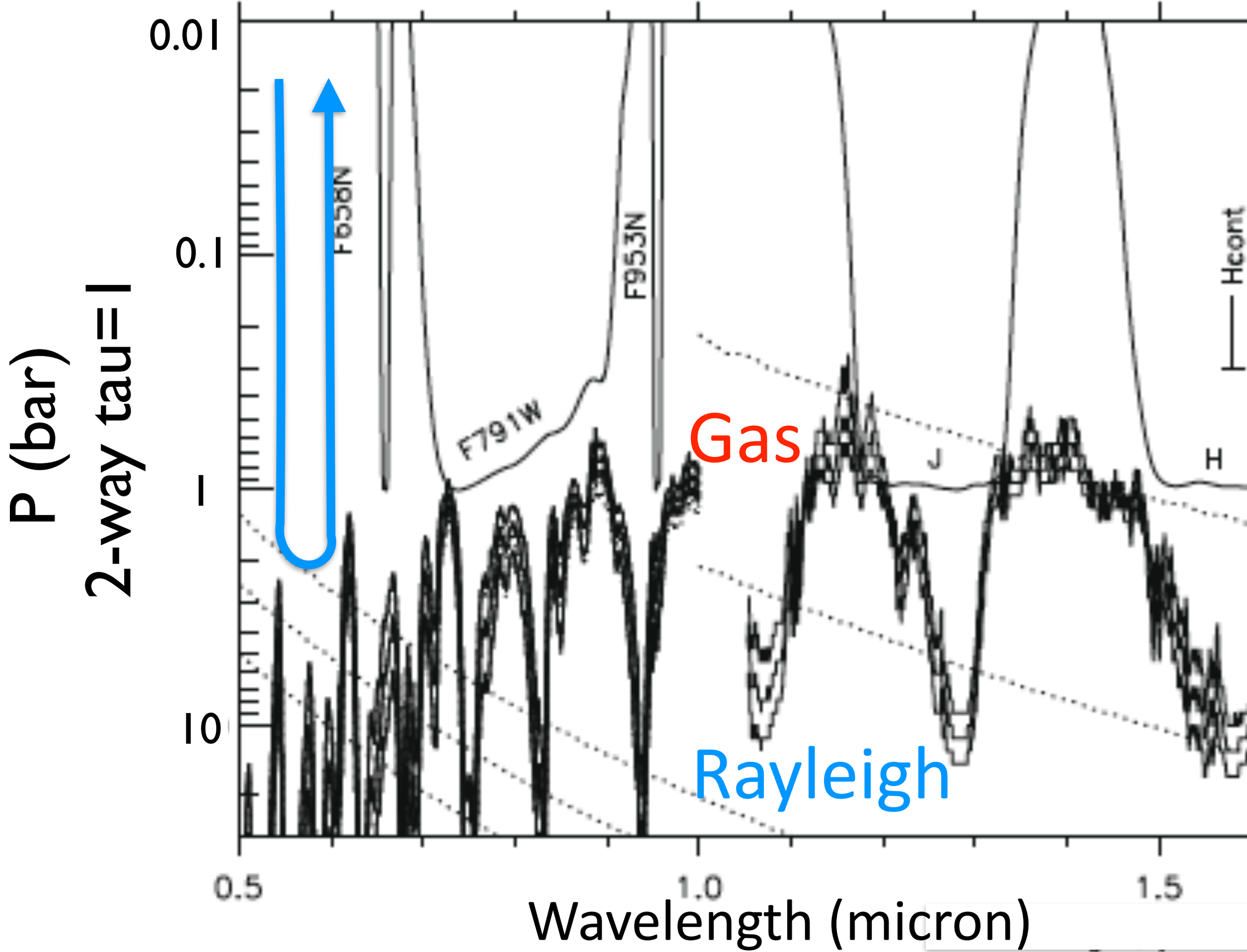
Huge influence on Bond Albedo and T_{eq}

Marley et al. (1999)

“Baines Diagram”



KEY concept is that CH_4 does not condense for our objects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0.1
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Wavelength (micron)
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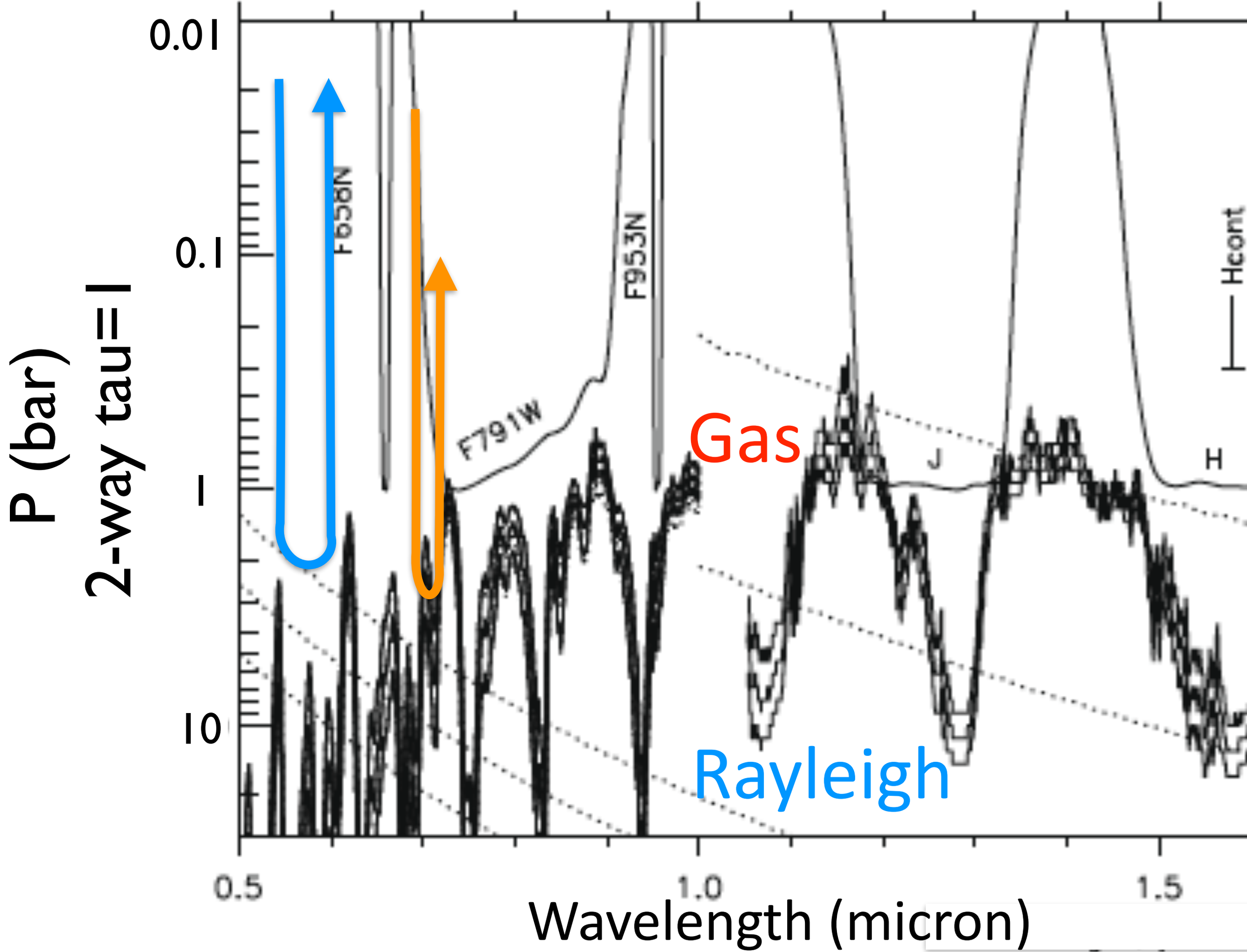
F953N
F791W
J
H
Hcont
Gas
Rayleigh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Wavelength (micron)
F658N
F953N
F791W
J
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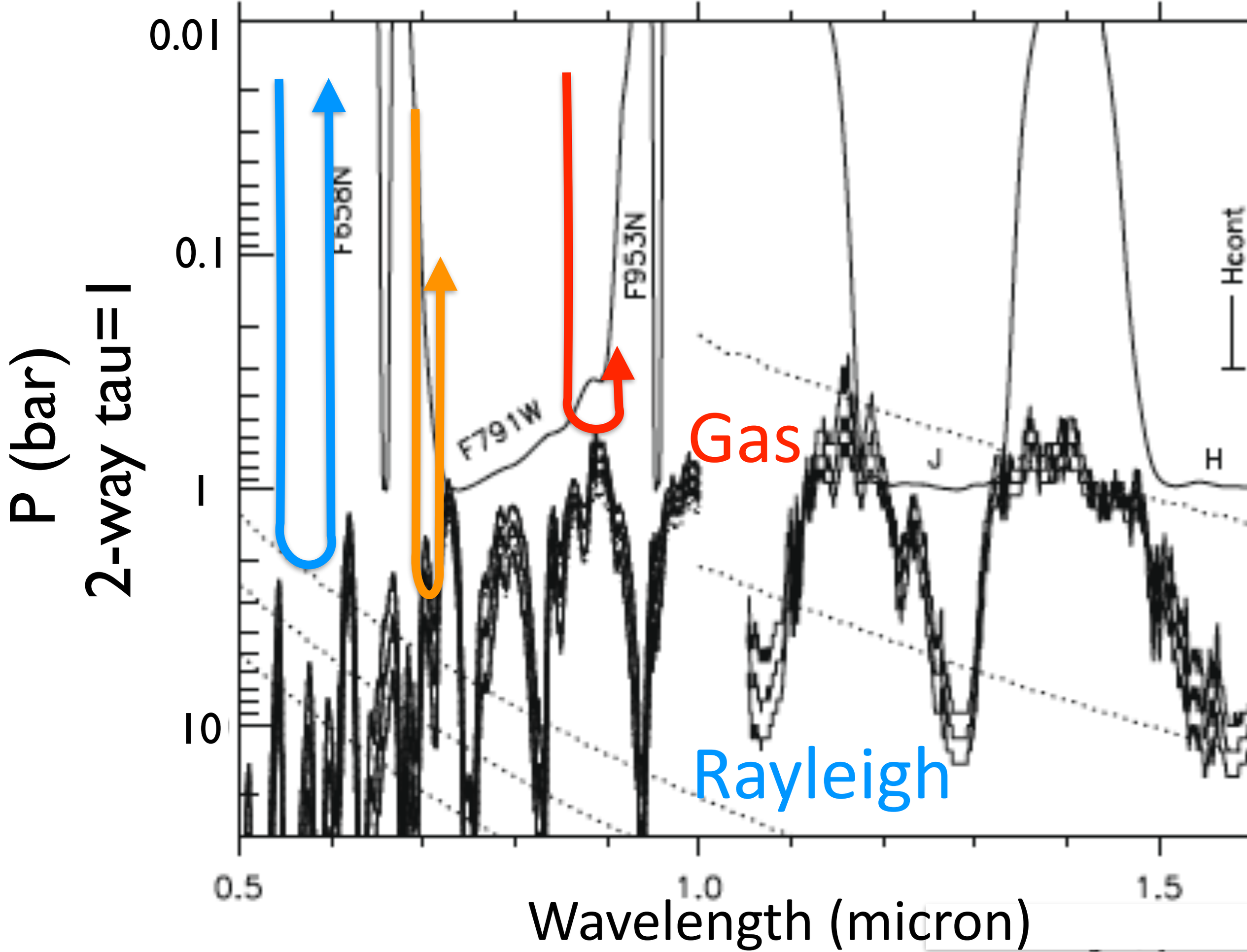
Hcont
Gas
Rayleigh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Wavelength (micron)
F658N
F953N
F791W
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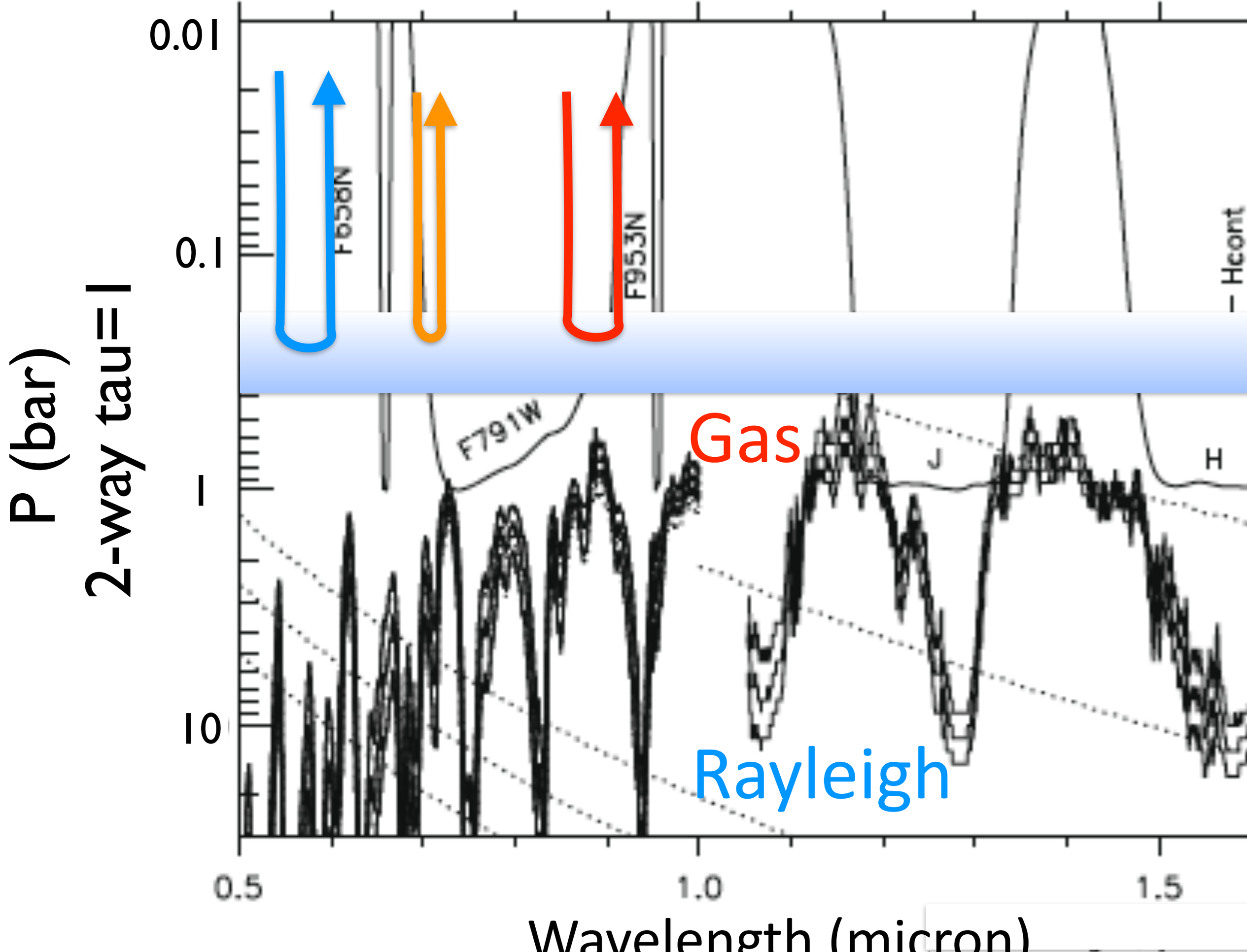
Hcont
Gas
Rayleigh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Wavelength (micron)
F658N
F953N
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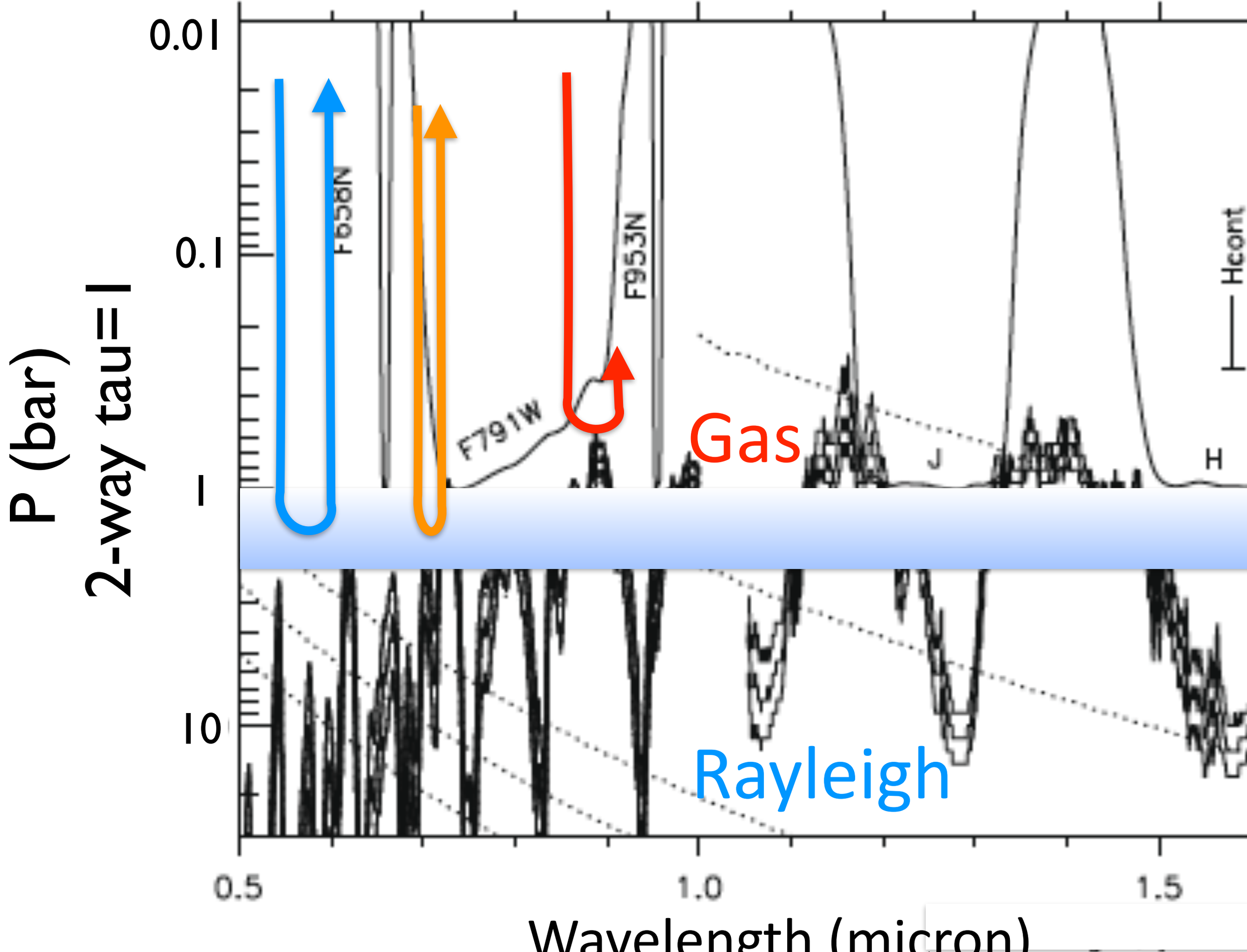
Gas
Rayleigh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P (bar)
2-way tau=1
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F791W
Gas
Rayleigh
Hcont
J
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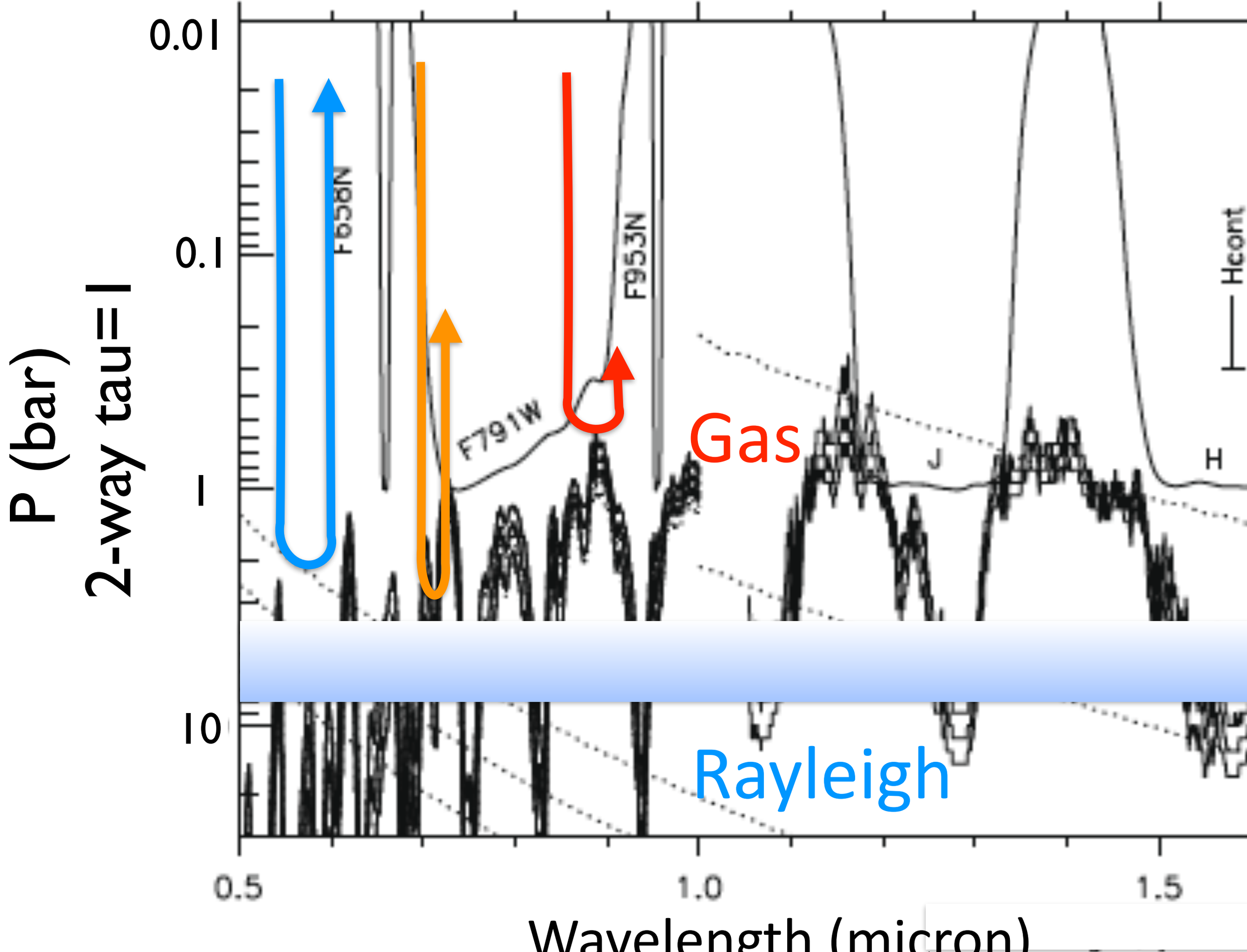
Wavelength (micron)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1
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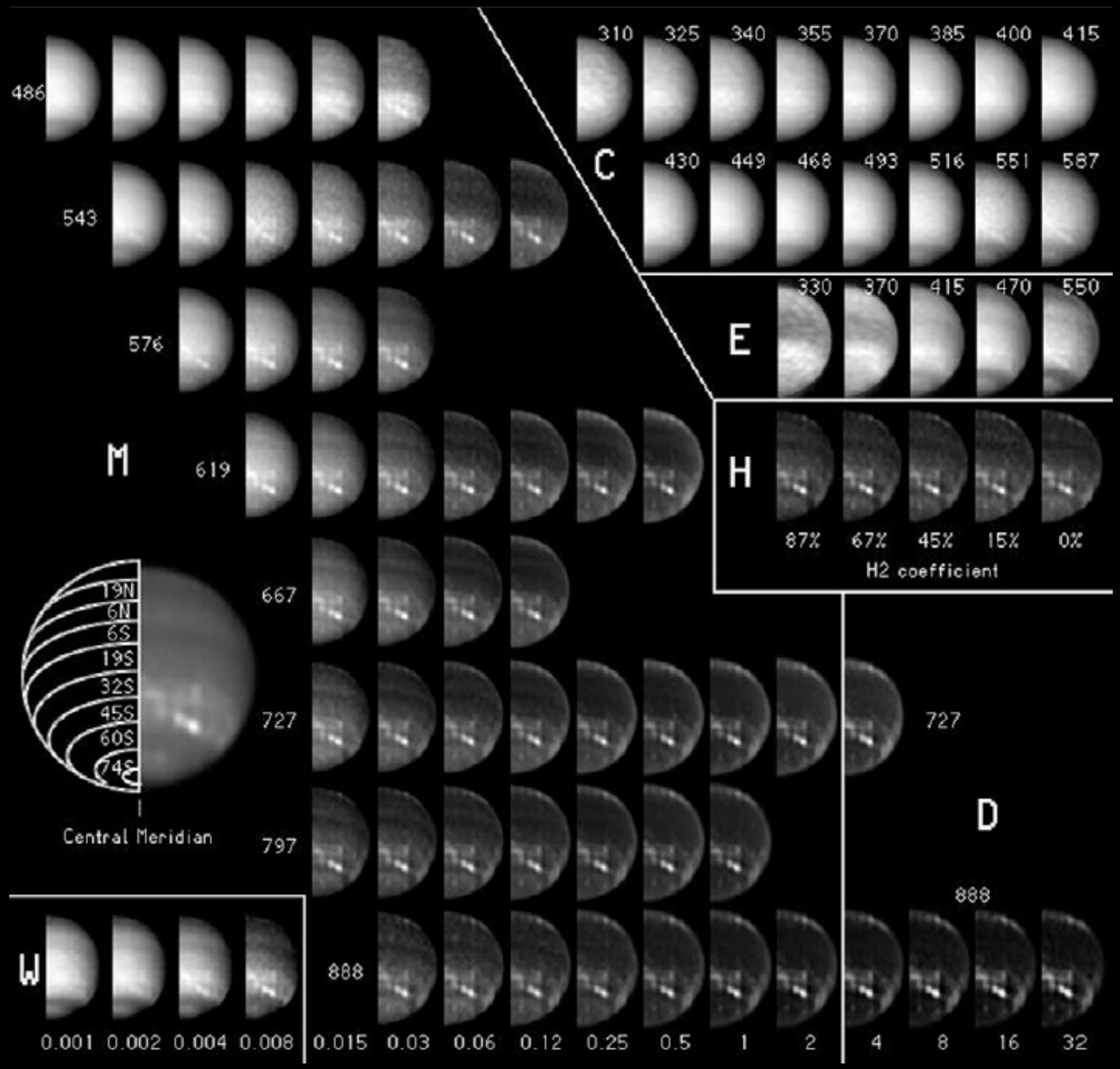
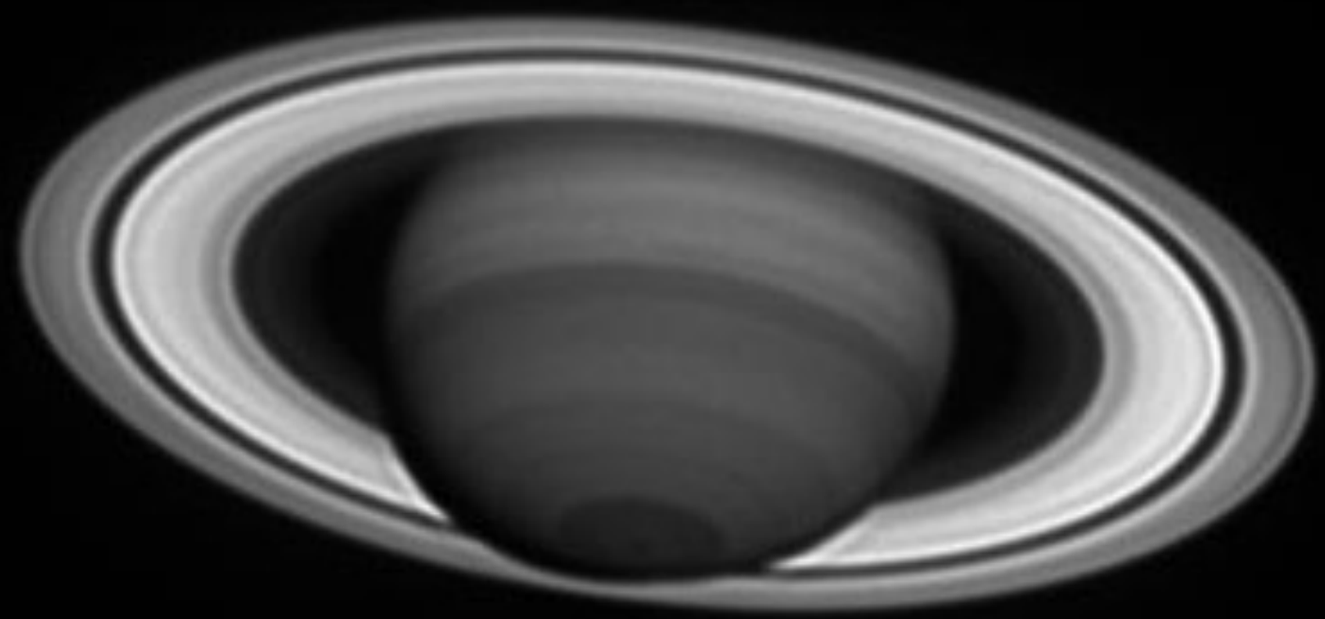
Wavelength (micron)
F658N
F953N
F791W
J
H
Hcont
Gas
Rayleigh

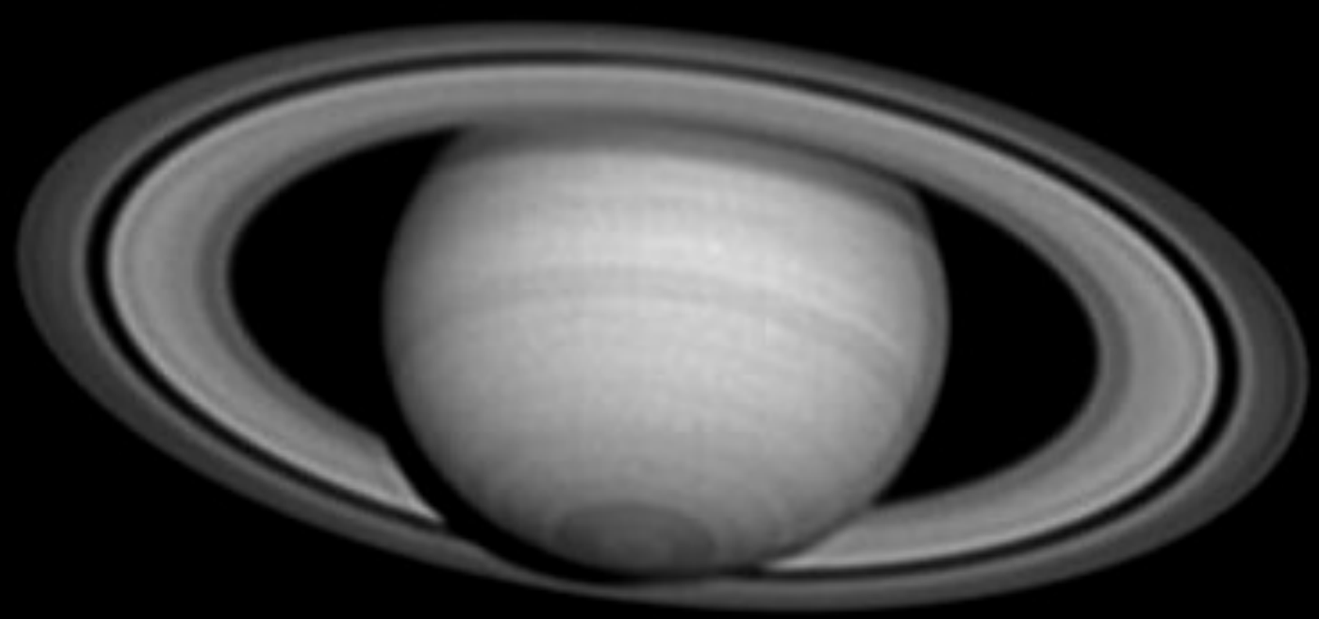
Imaging



Hammel+



Weak methane (727 nm)



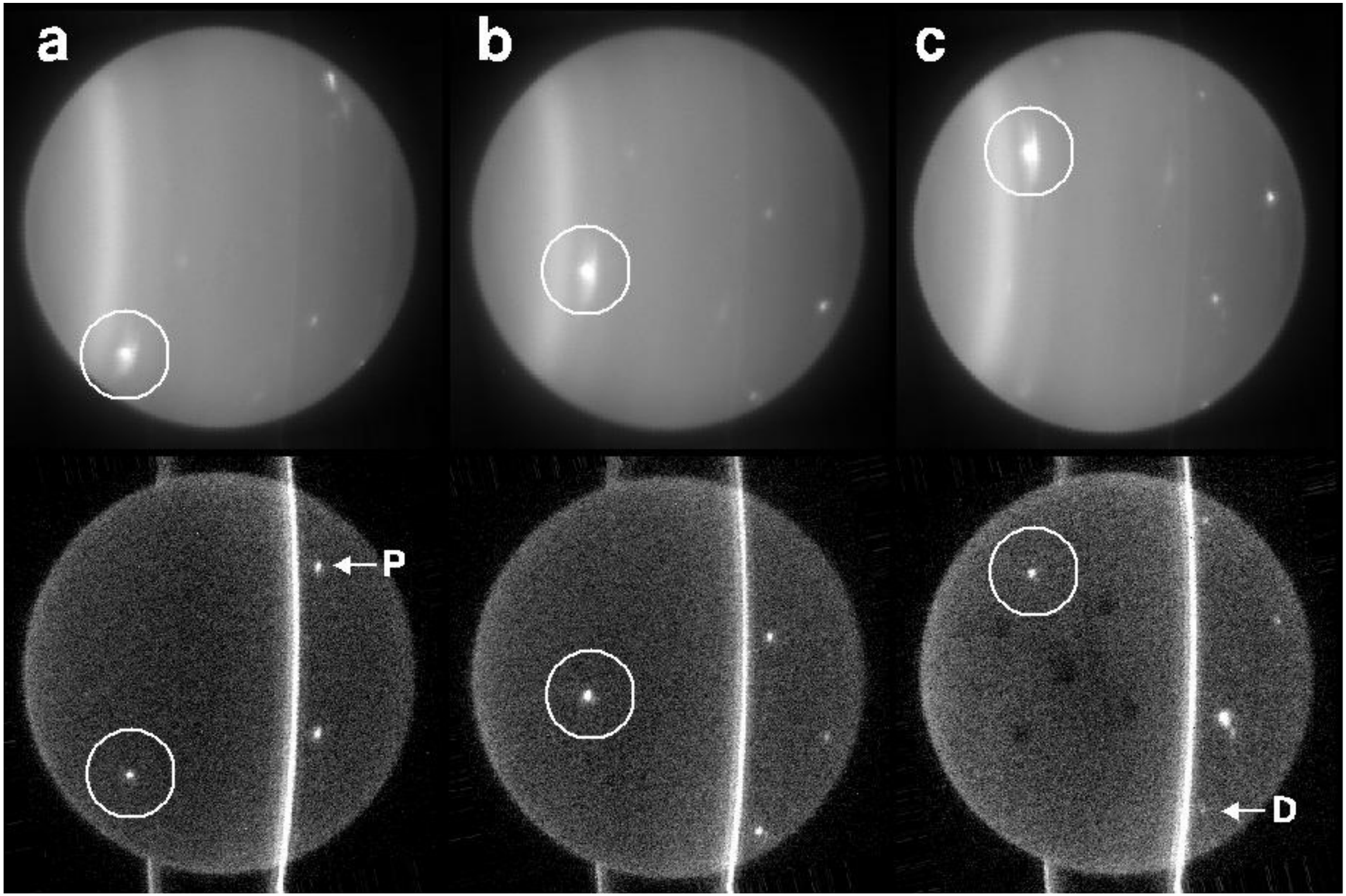
Continuum (751 nm)

Chanover+: Air Force Advanced Electro-Optical System (AEOS) 3.6-m telescope on Maui

High Clouds on Uranus

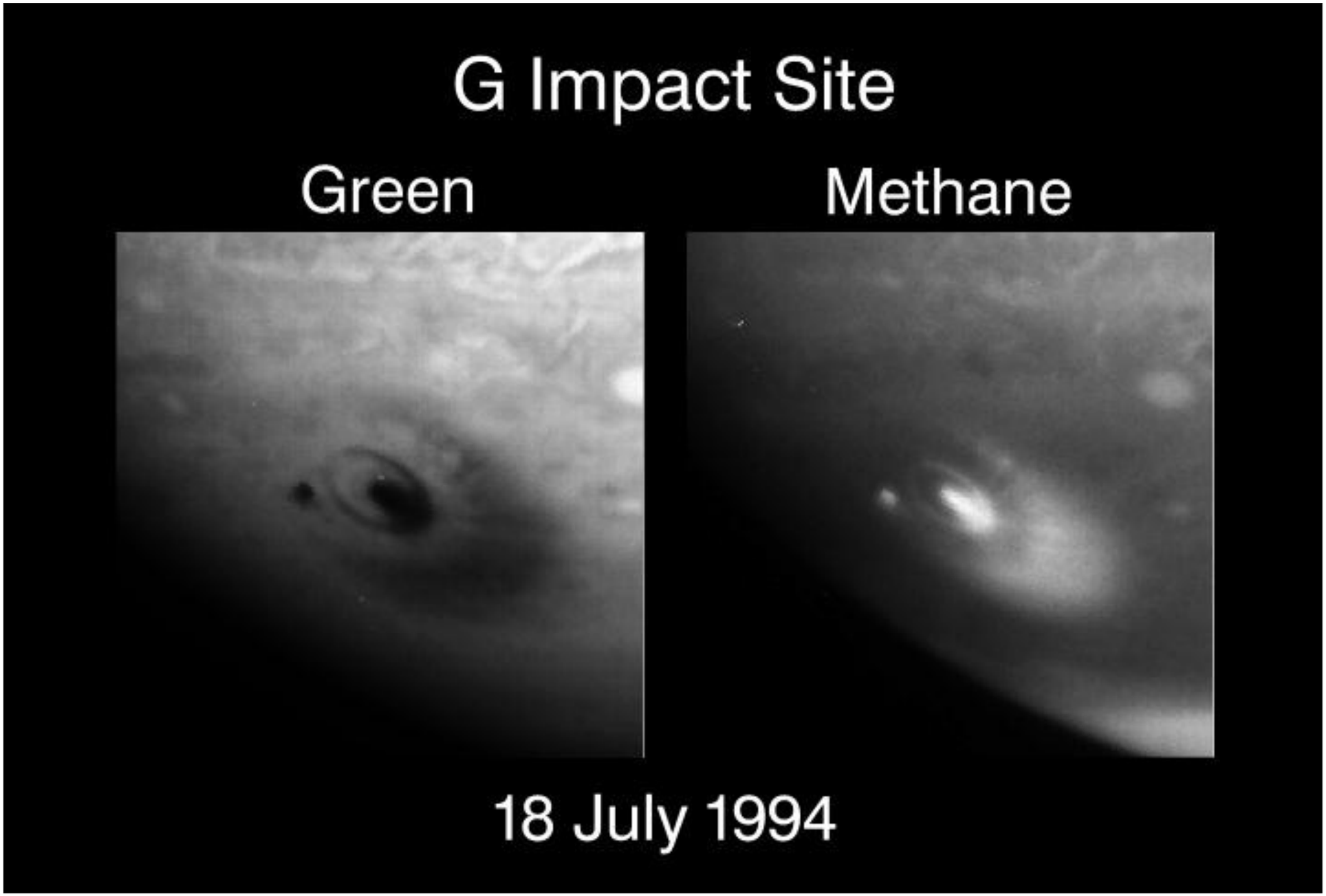
H

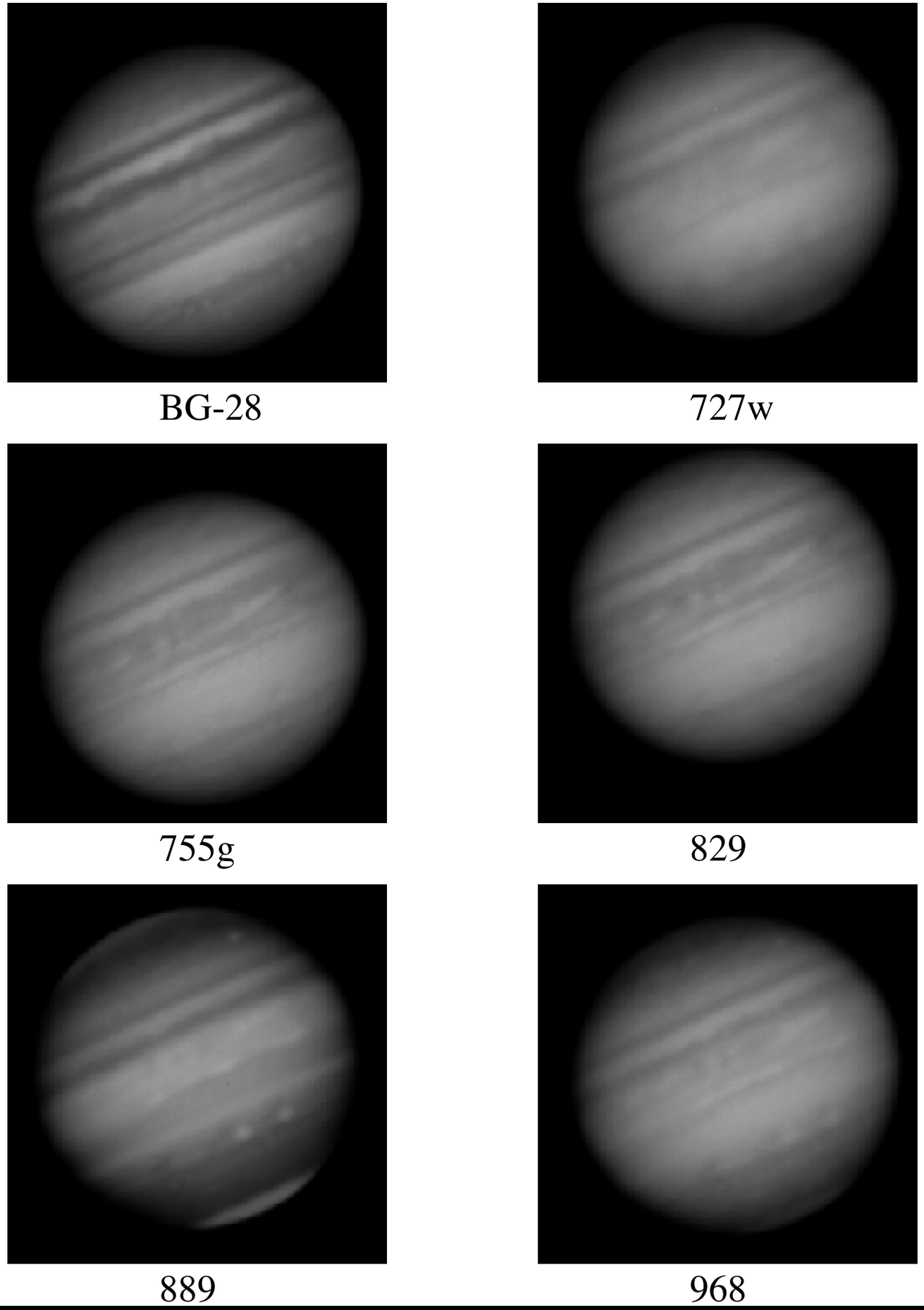
K’



Hammel et al.

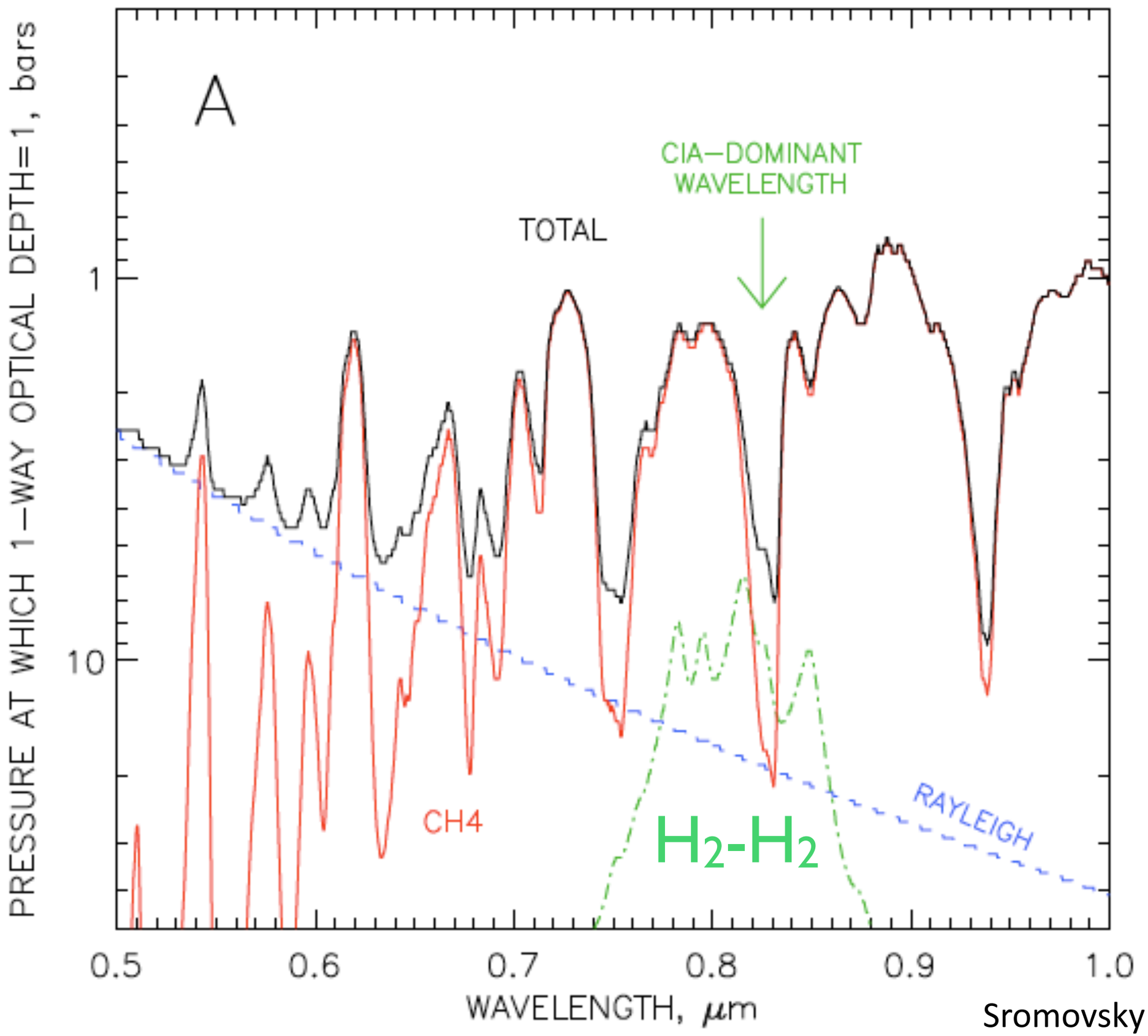
Shoemaker-Levy 9 Impact on Jupiter seen with Hubble





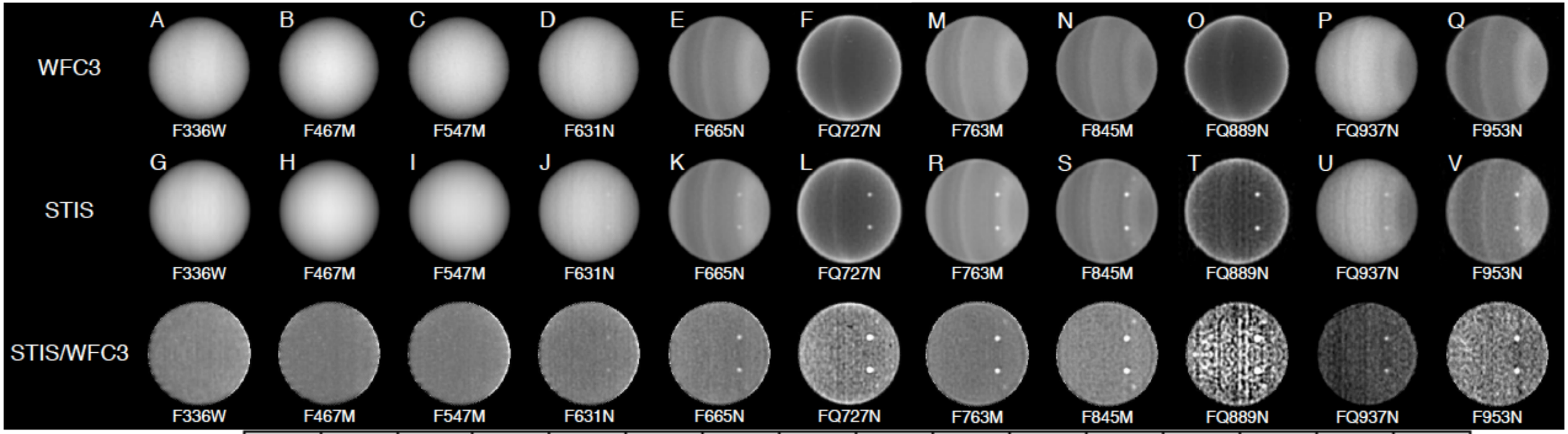
- Ground based Jupiter monitoring from A-Mountain in Las Cruces
- Decades of coverage
- Broad band imaging + weak and strong CH_4

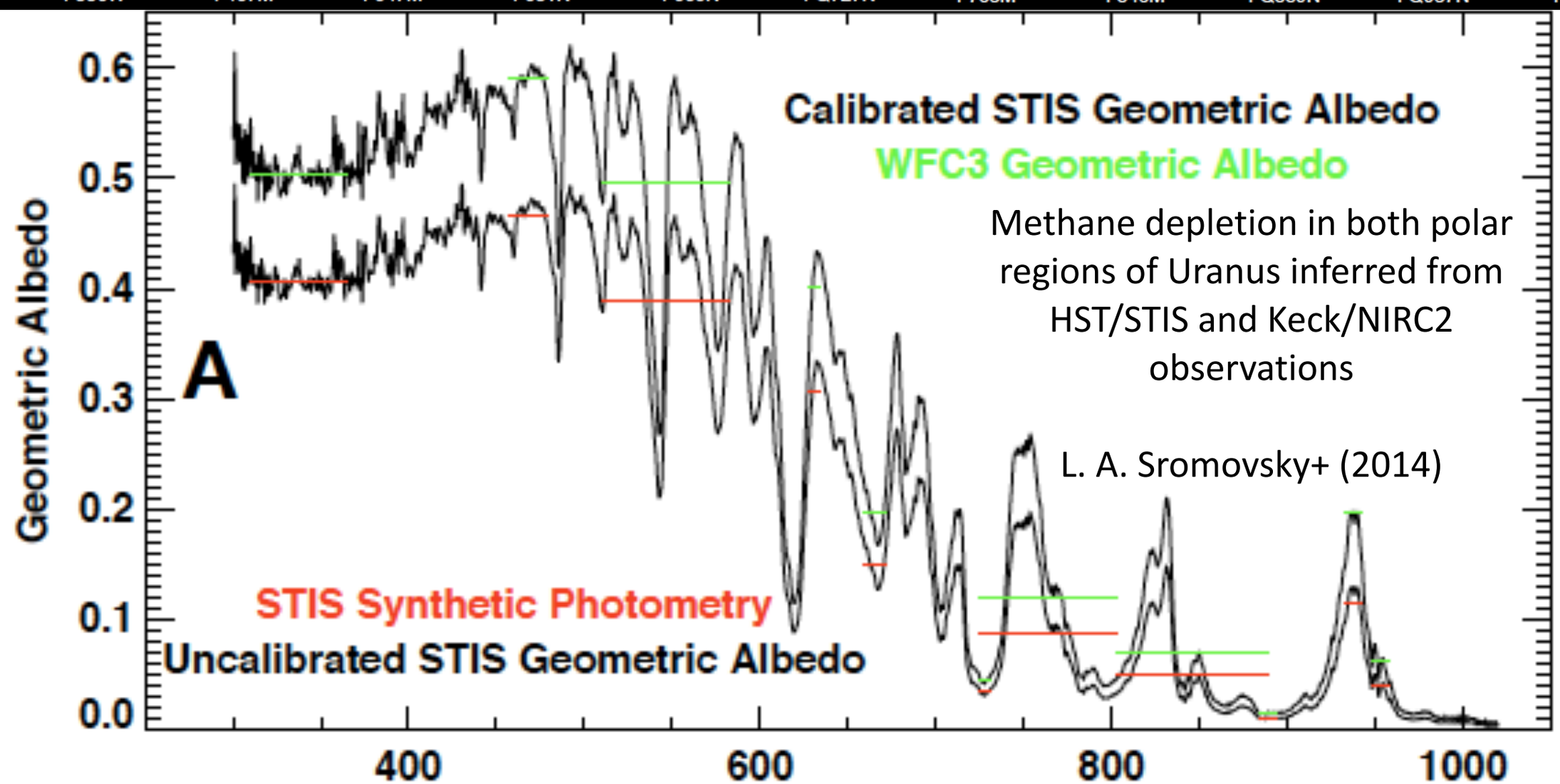
H_2 Important in Ice Giants



Sromovsky et al. (2014)

Uranus with Hubble/STIS



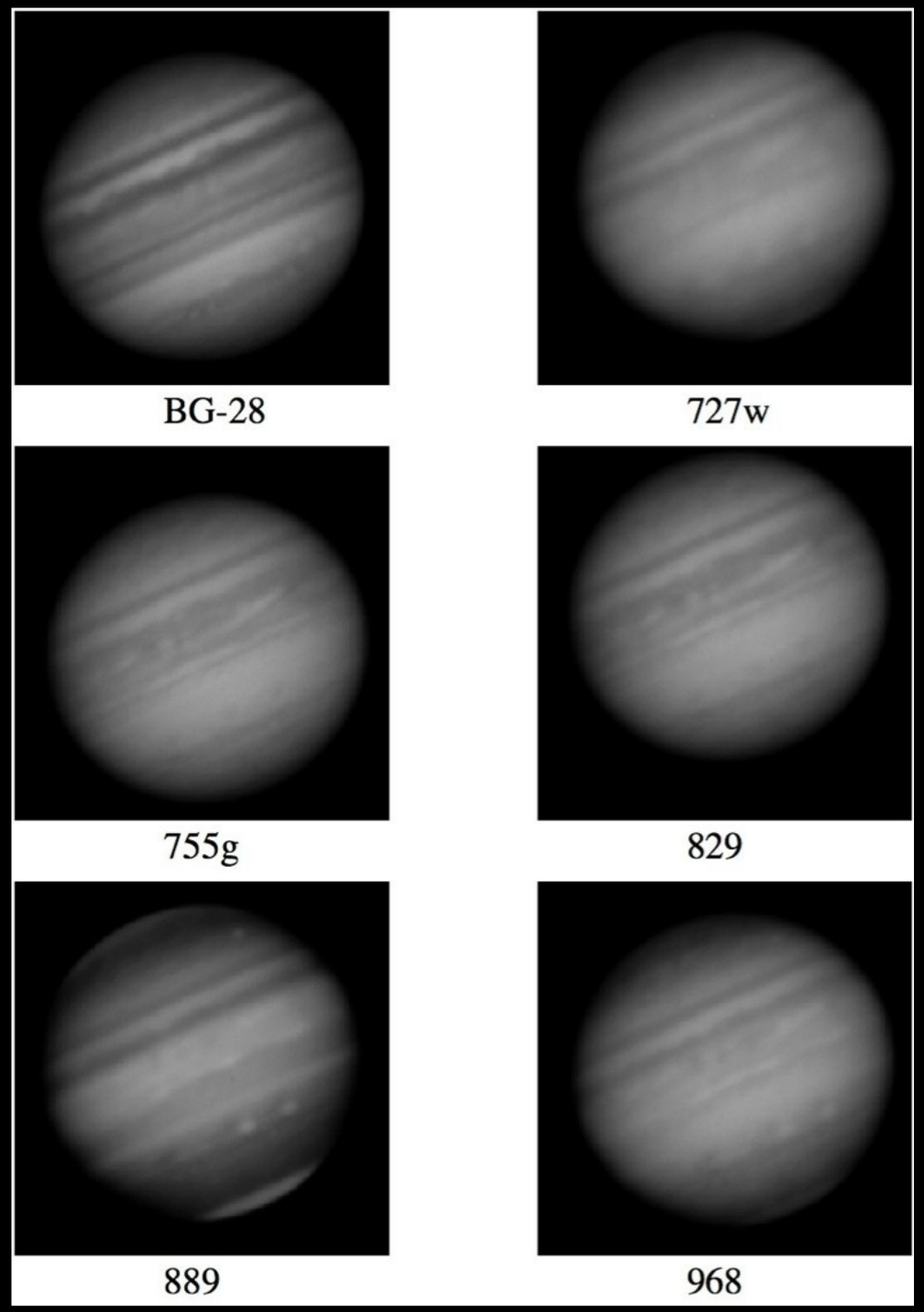


Methane depletion in both polar regions of Uranus inferred from HST/STIS and Keck/NIRC2 observations

L. A. Sromovsky+ (2014)

Uses of Broad Band Images

- Cloud heights
- Atmospheric features
- Wind profiles, dynamics
- Center-to-limb brightness variations
- Cloud height primarily relevant to exoplanets



Spectroscopy

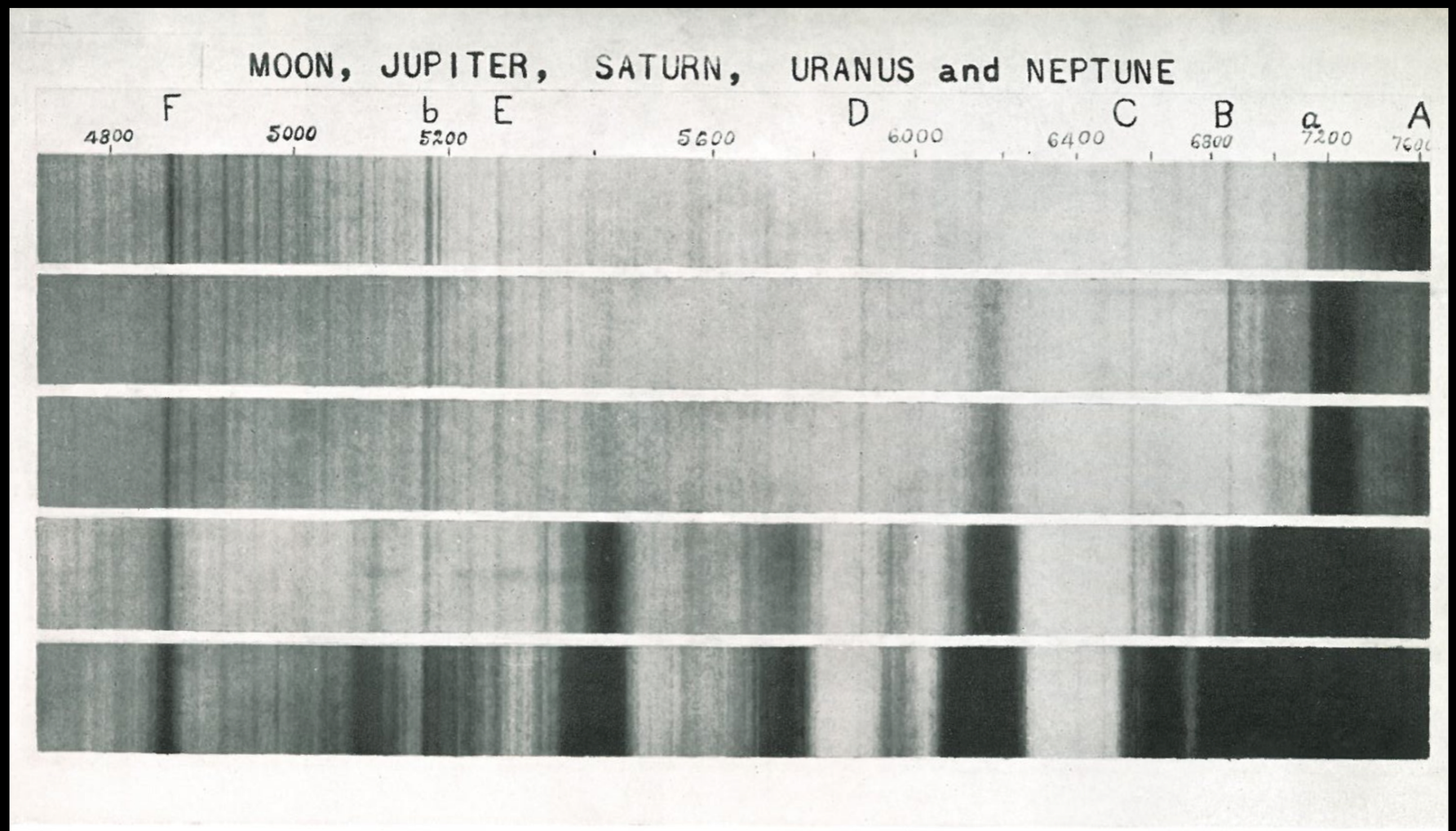
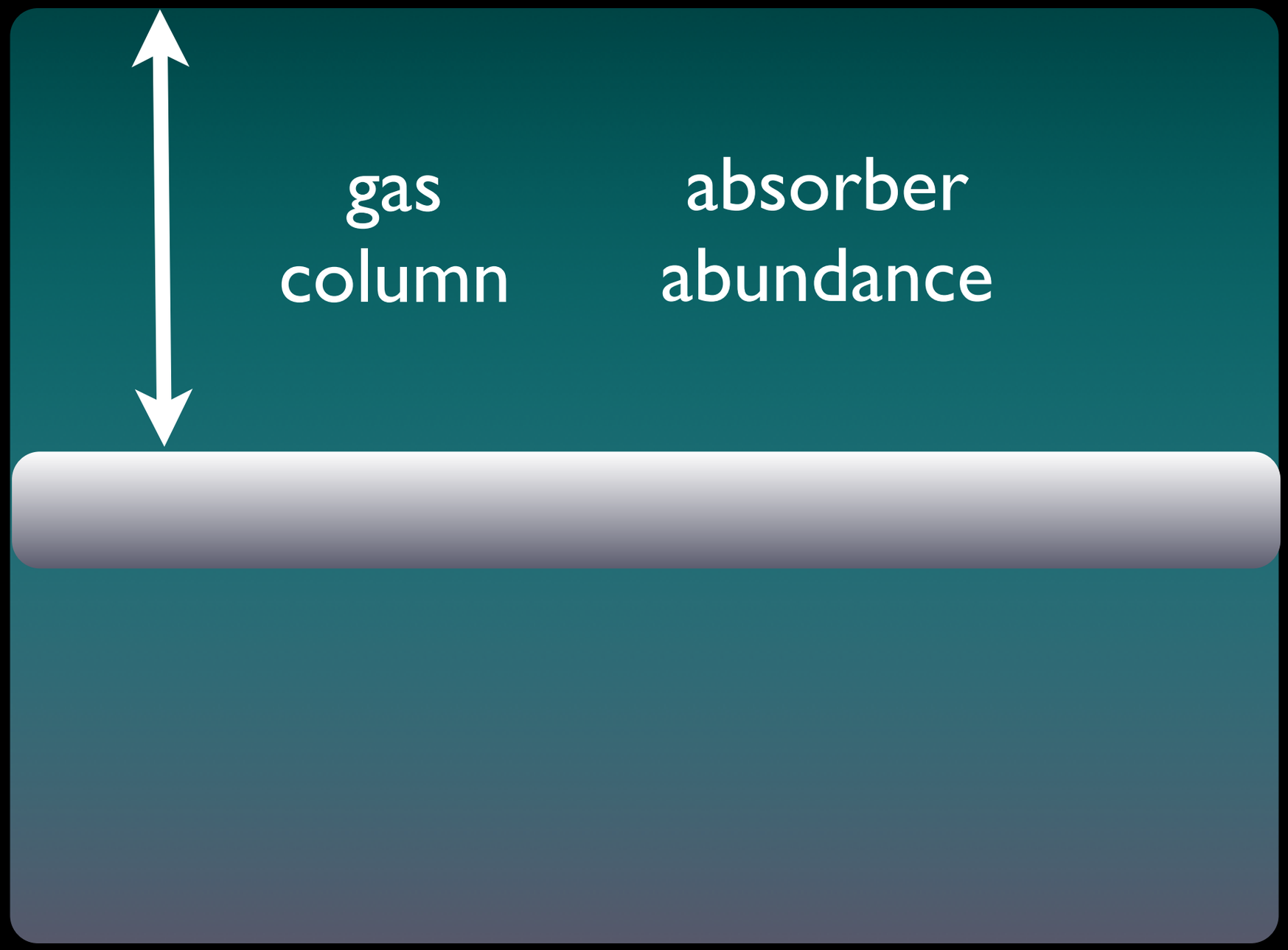
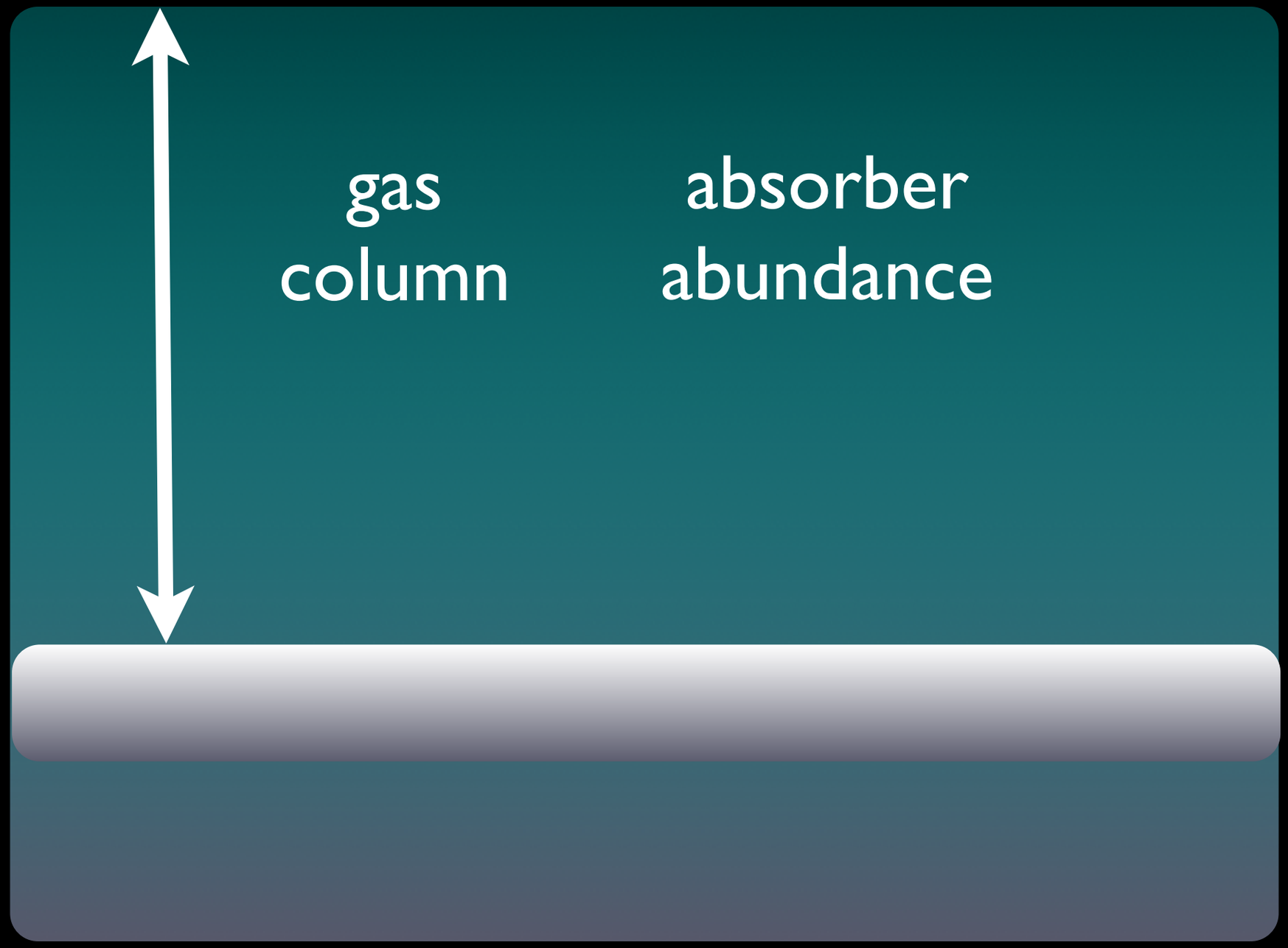


PLATE V.—V. M. Slipher: Photograph of spectra 1909 of (top line) Moon, (2) Jupiter, (3) Saturn, (4) Uranus, (5) Neptune. (From *Lowell Observatory Bulletin* 42; electro supplied by English Universities Press.)


gas
column
absorber
abundance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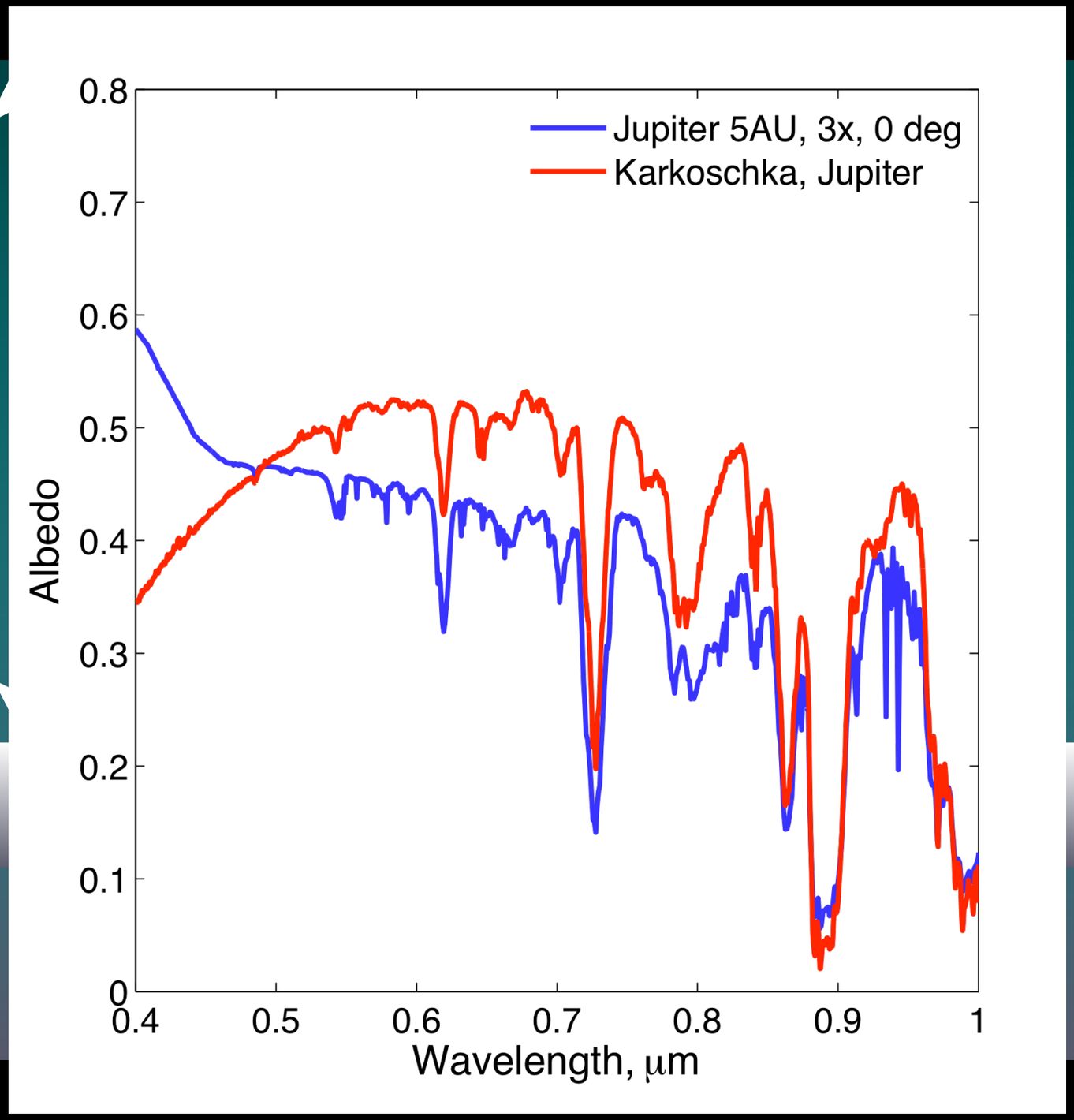
Jupiter 5AU, 3x, 0 deg
Karkoschka, Jupiter
Albedo
Wavelength, μm
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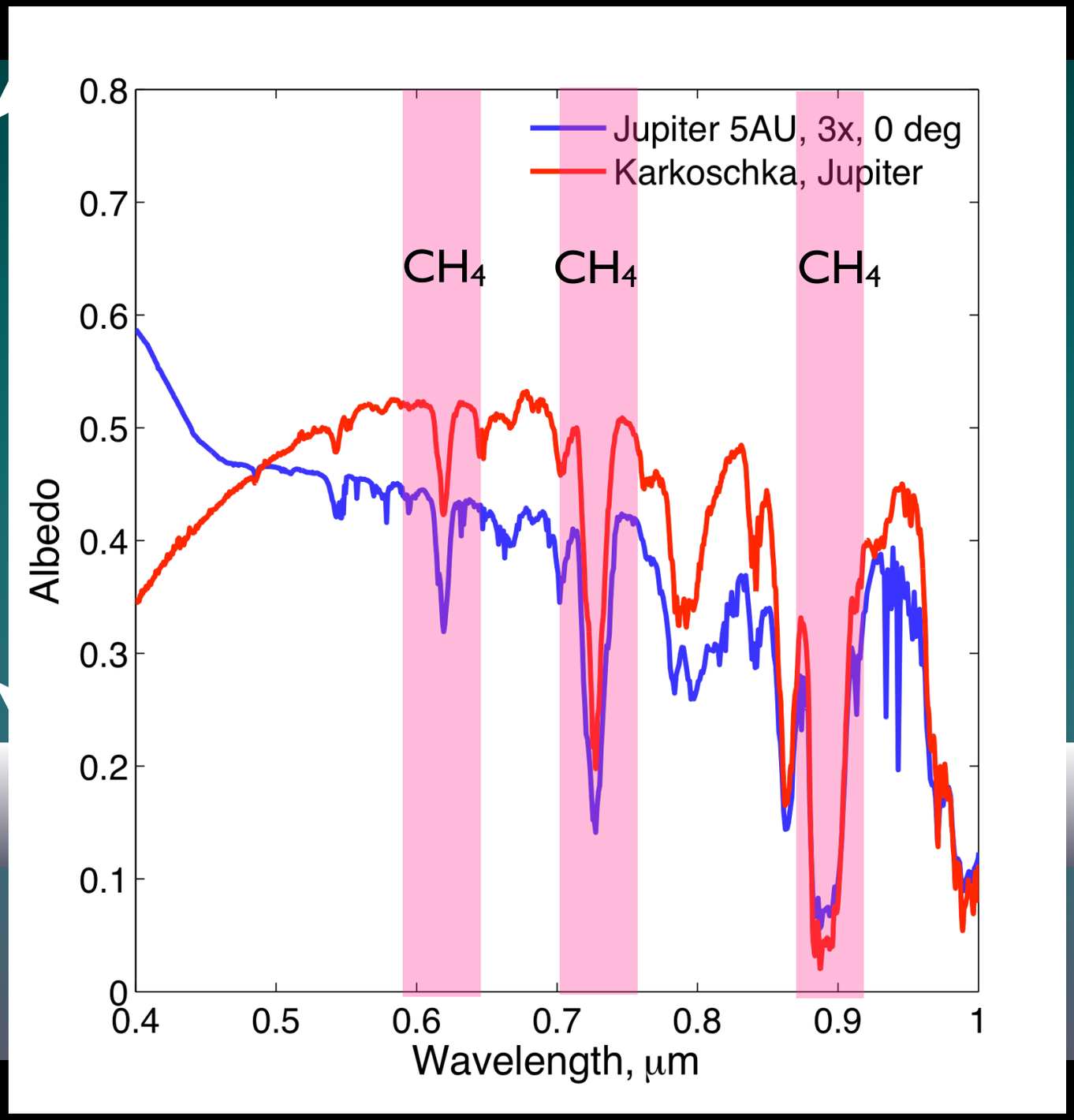
Jupiter 5AU, 3x, 0 deg
Karkoschka, Jupiter
CH4
CH4
CH4
Albedo
Wavelength, μm
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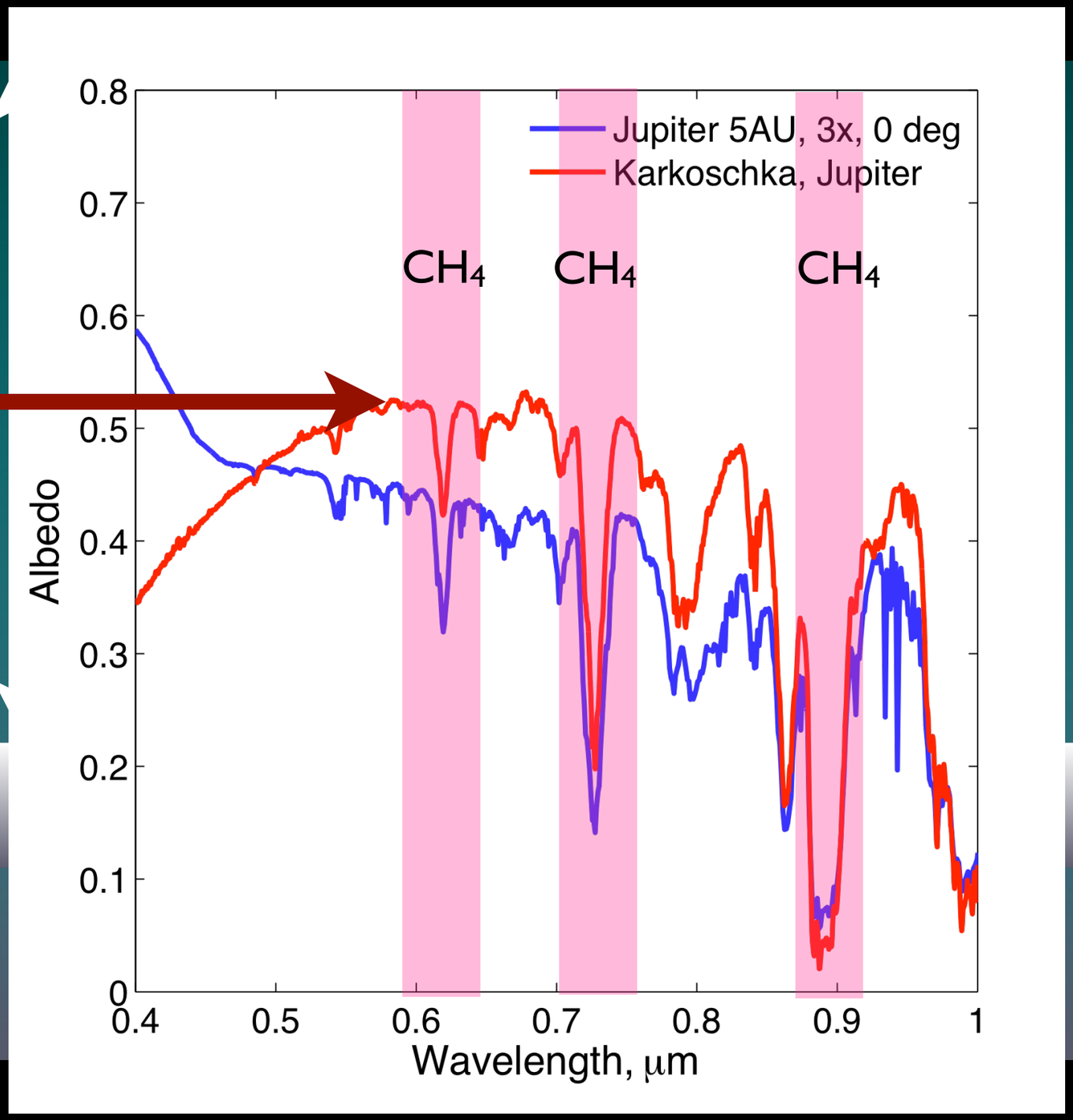
continuum


Jupiter 5AU, 3x, 0 deg
Karkoschka, Jupiter
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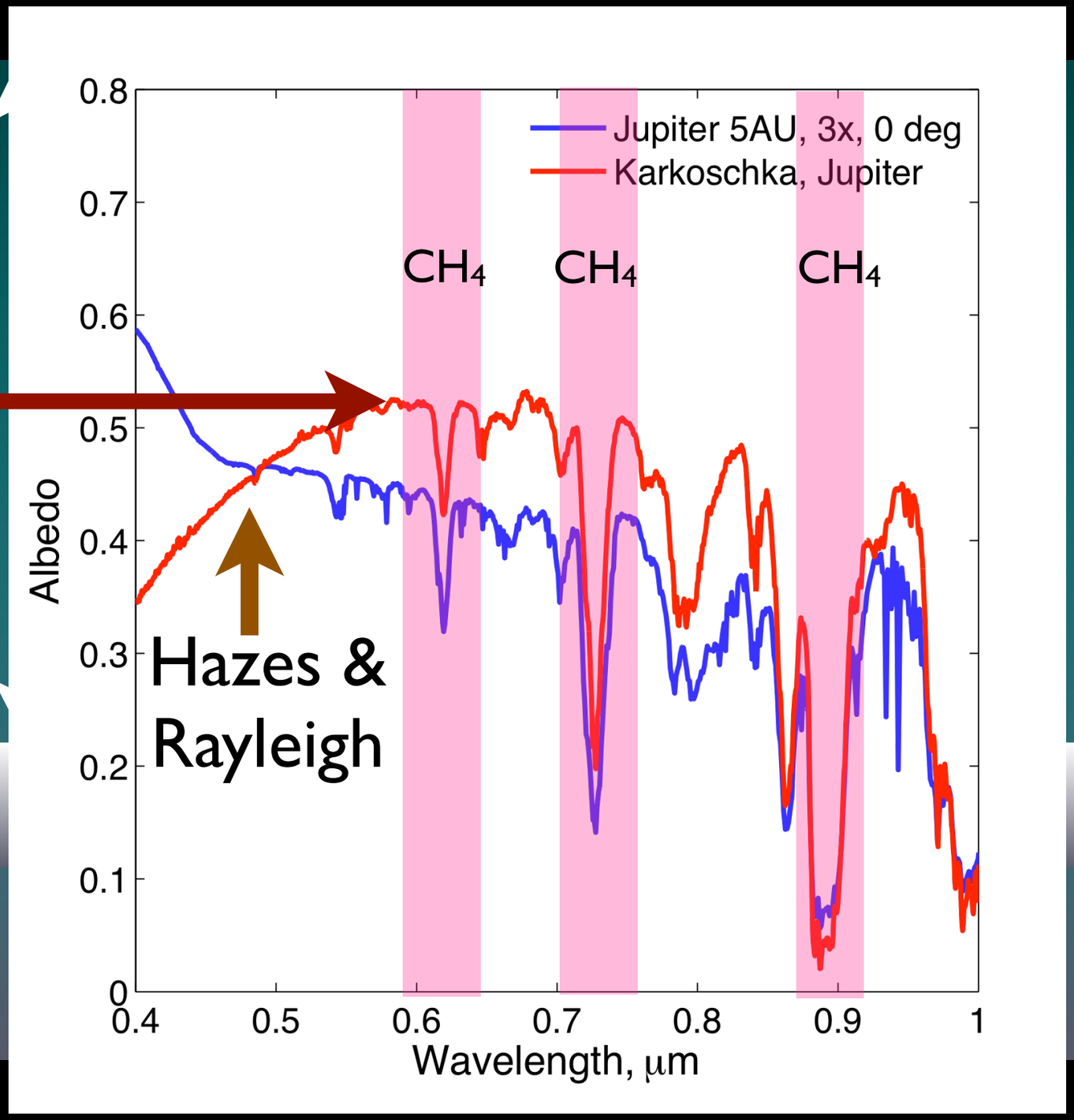
continuum


Jupiter 5AU, 3x, 0 deg
Karkoschka, Jupiter
CH4
CH4
CH4
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Rayleigh
Albedo
Wavelength, μm
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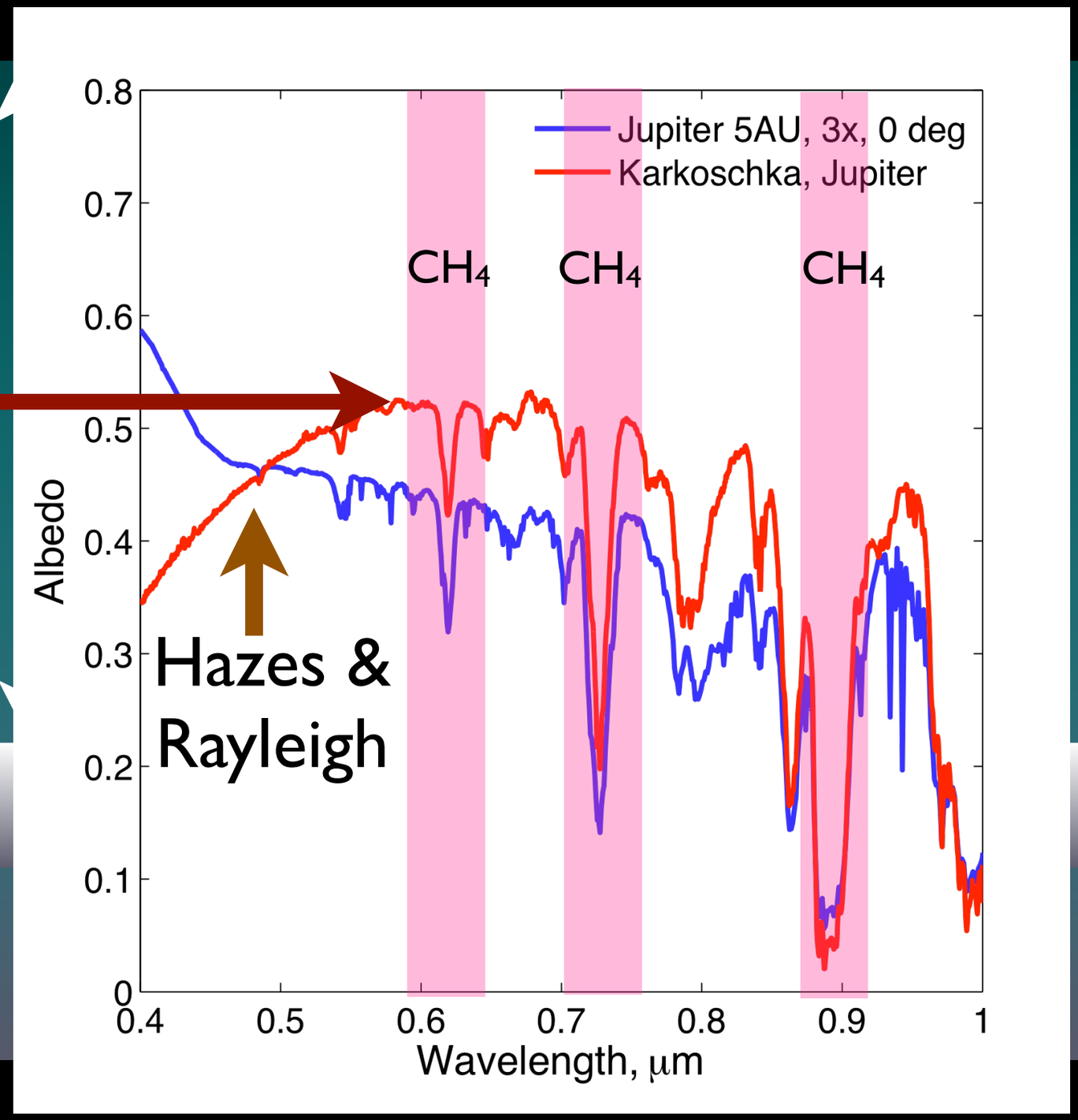
continuum



Iteratively derive cloud height & abundances

Example

Jupiter's Atmospheric Composition and Cloud Structure Deduced from Absorption Bands in Reflected Sunlight

MAKIKO SATO AND JAMES E. HANSEN

NASA Goddard Institute for Space Studies, Goddard Space Flight Center, New York, NY 10025

(Manuscript received 2 March 1979)

Classic 1979 paper on deriving giant planet abundances

lent width. Since there are available observations of both weak and strong methane bands, we expect to be able to obtain at least one parameter describing the vertical cloud structure in addition to obtaining the methane abundance.

Data: Visible spectra 400 -1000 nm

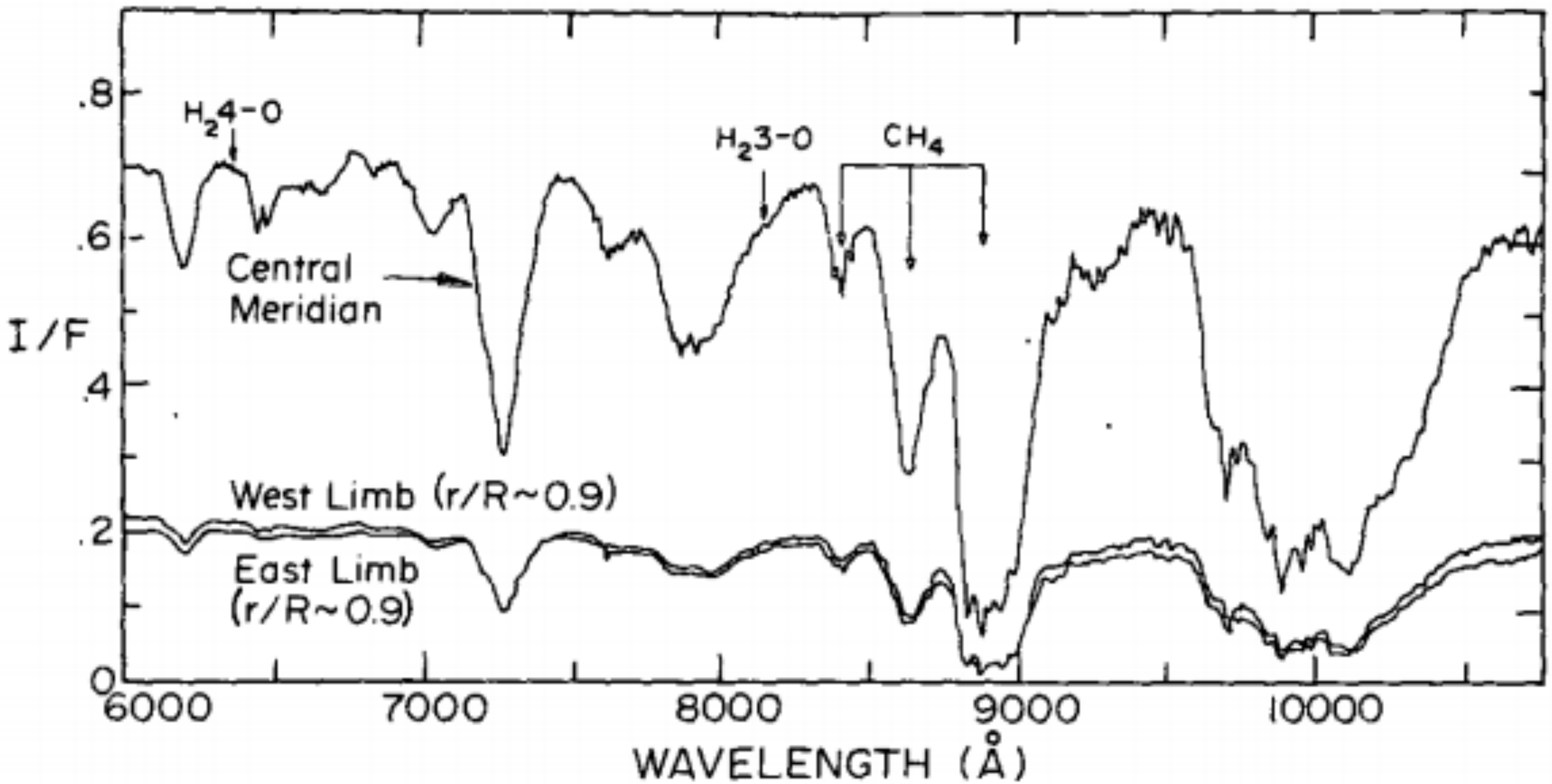


FIG. 4. Reflectivity of the ER observed by Woodman *et al.* (1979).

Step 1: Cloud Model

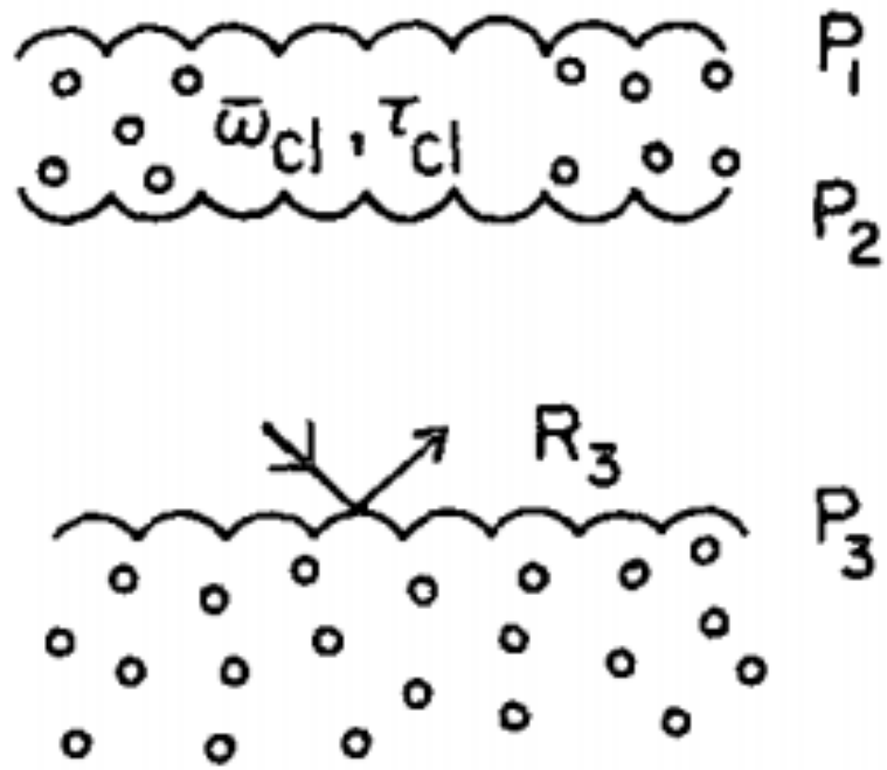
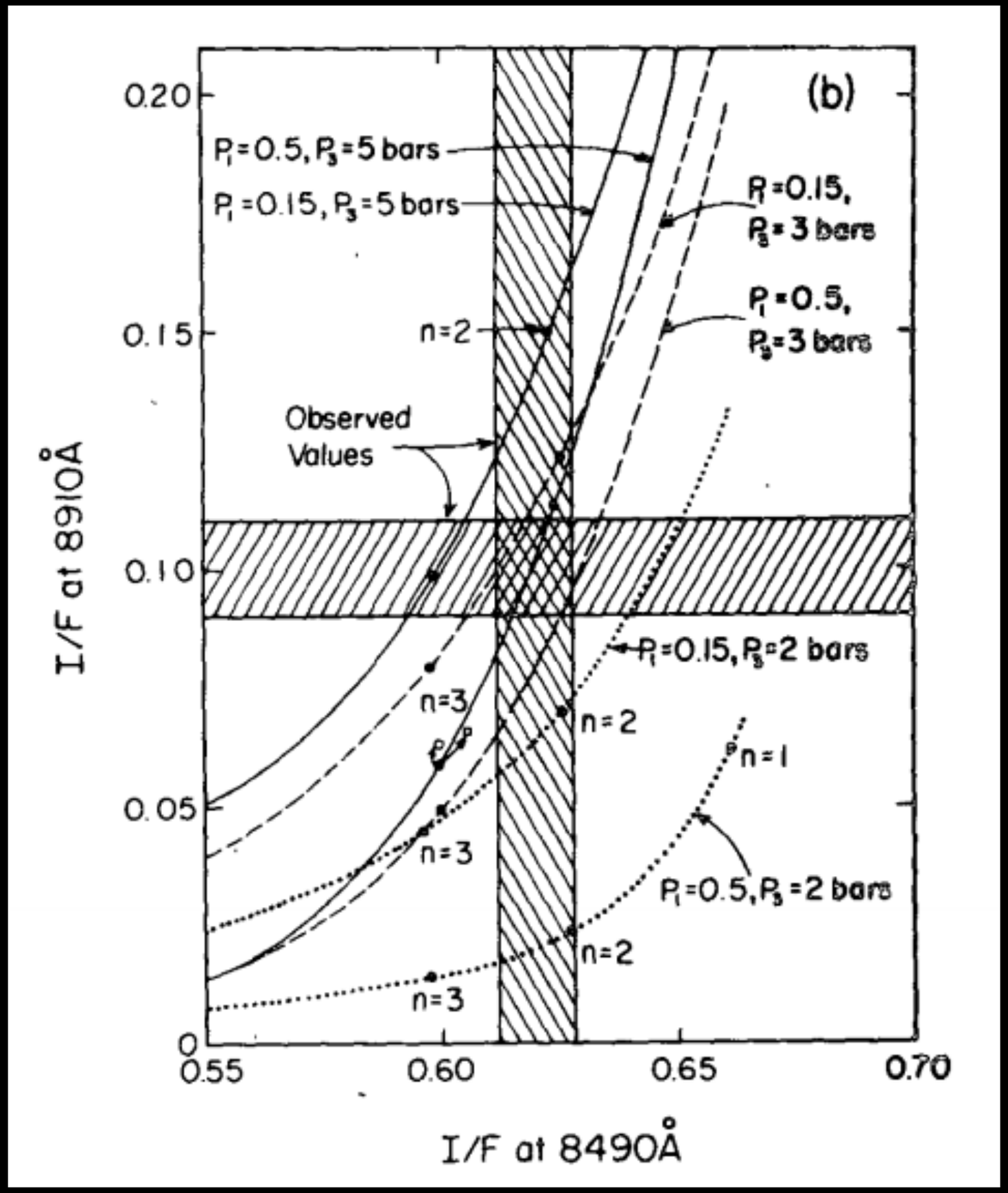


FIG. 6. Schematic illustration of the 6 parameters in our version of the two-cloud model.

First use H_2 quadrupole lines (Carleton & Traub(!)1974) to constrain 1 cloud parameter. Not an option for us.

For each model we include the constraint that it yield the observed equivalent width for the 4-0 $S(1)$ hydrogen quadrupole line (Section 4). We

Strong CH_4

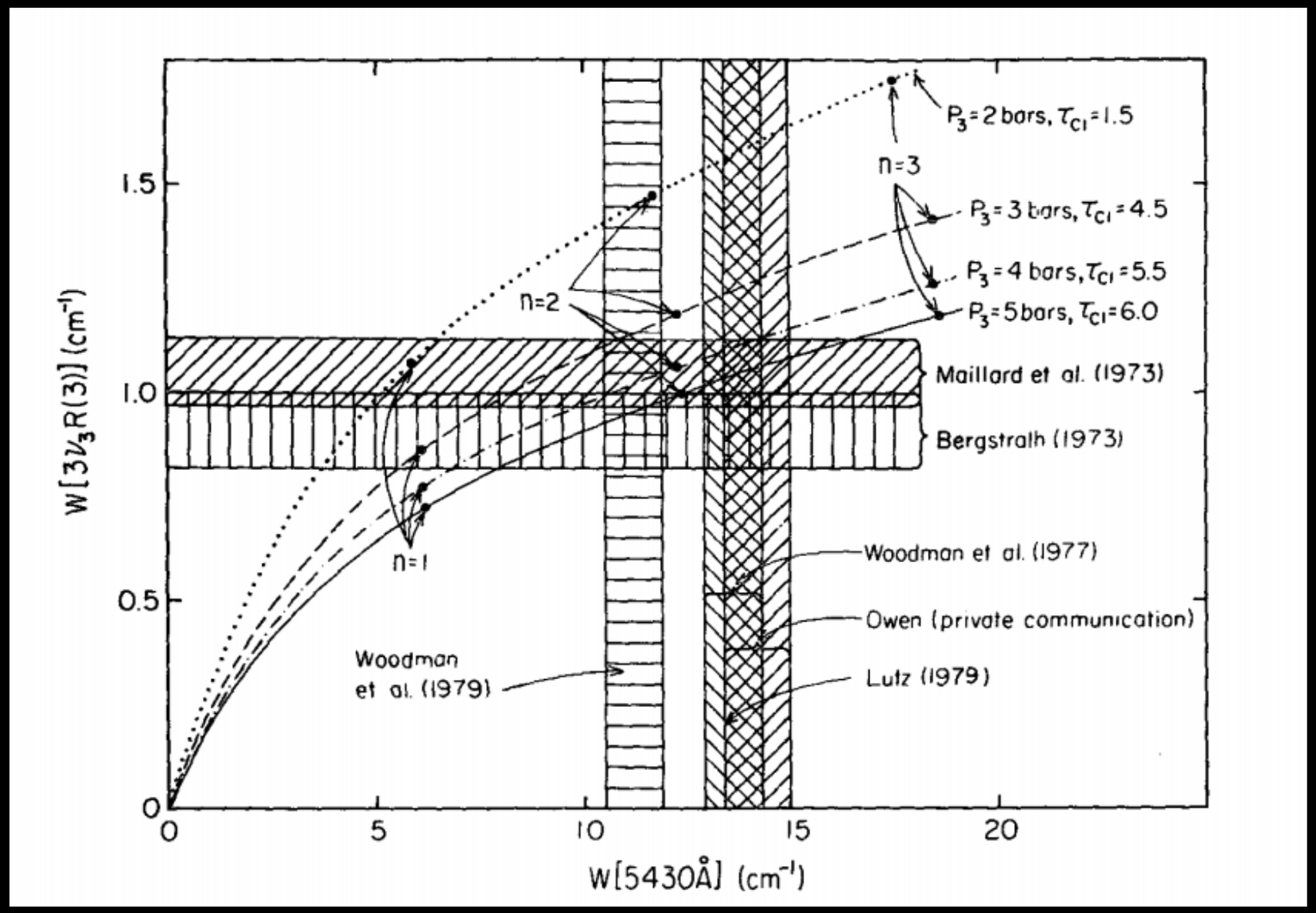


Albedo in 2 methane bands + continuum constrains clouds

Medium CH_4

Step 2: CH_4 Abundance

Cloud model plus equivalent widths of *two other methane bands* gives CH_4 abundance



Step 3: Consistency Checks

- Utilize entire spectrum to check derived abundance
- Further constrain high altitude hazes and NH_3 abundances
- Mainly by bootstrapping using multiple CH_4 bands plus continuum
- Caveat: also cross-checked with CTL profiles

Accuracy?

Our results indicate that CH_4 is enriched in the envelope of Jupiter, with an abundance $n(CH_4) \sim 2$ times larger than its solar abundance. Since NH_3 and H_2O are less volatile than CH_4, one would expect their abundances relative to the solar values to be at least as great. Our conclusion that $n(NH_3) \sim 1.5 \pm 0.5$ for $P \sim 1$–4 bars is consistent with $n(NH_3) \sim 2$ through the bulk of the envelope.

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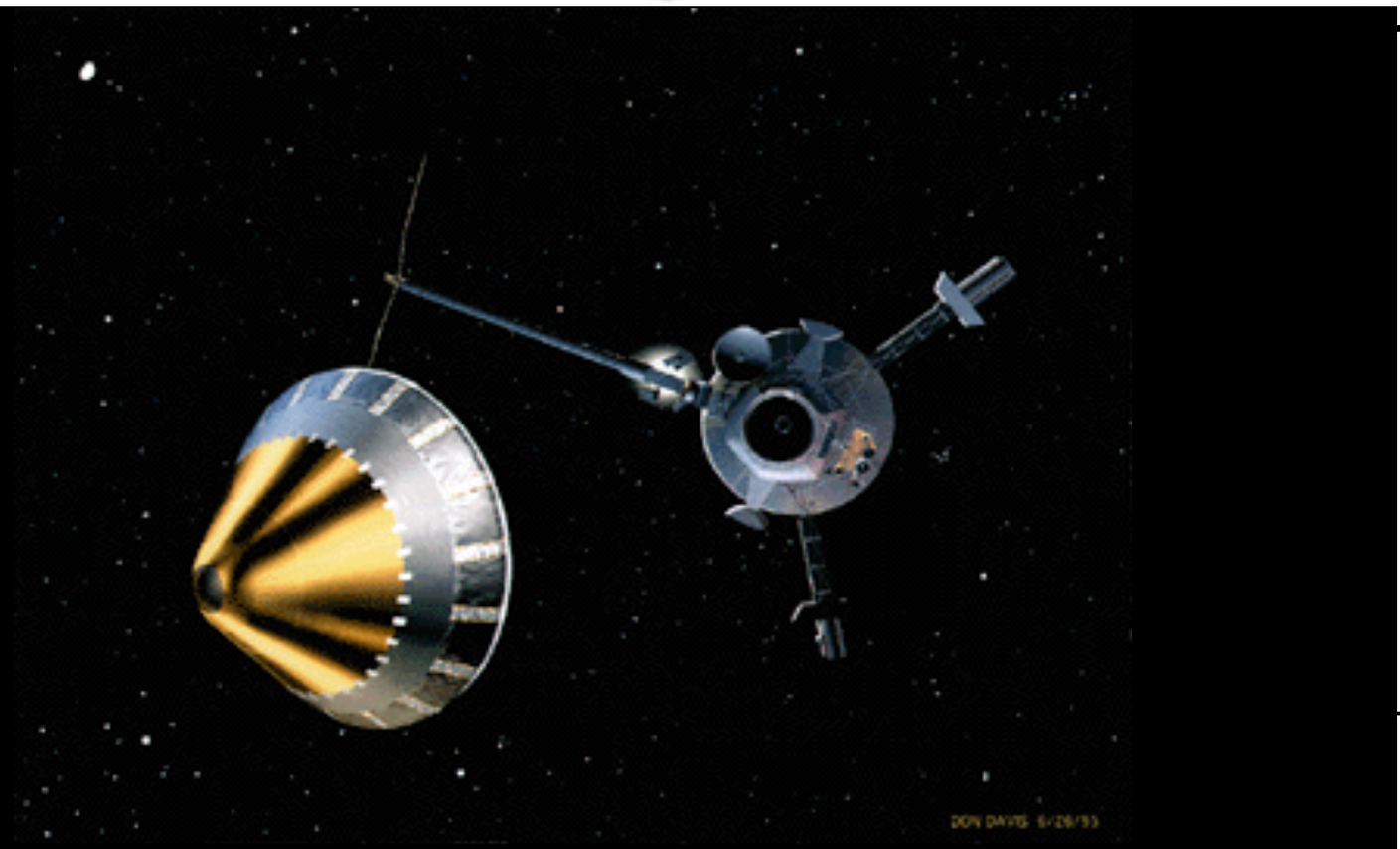
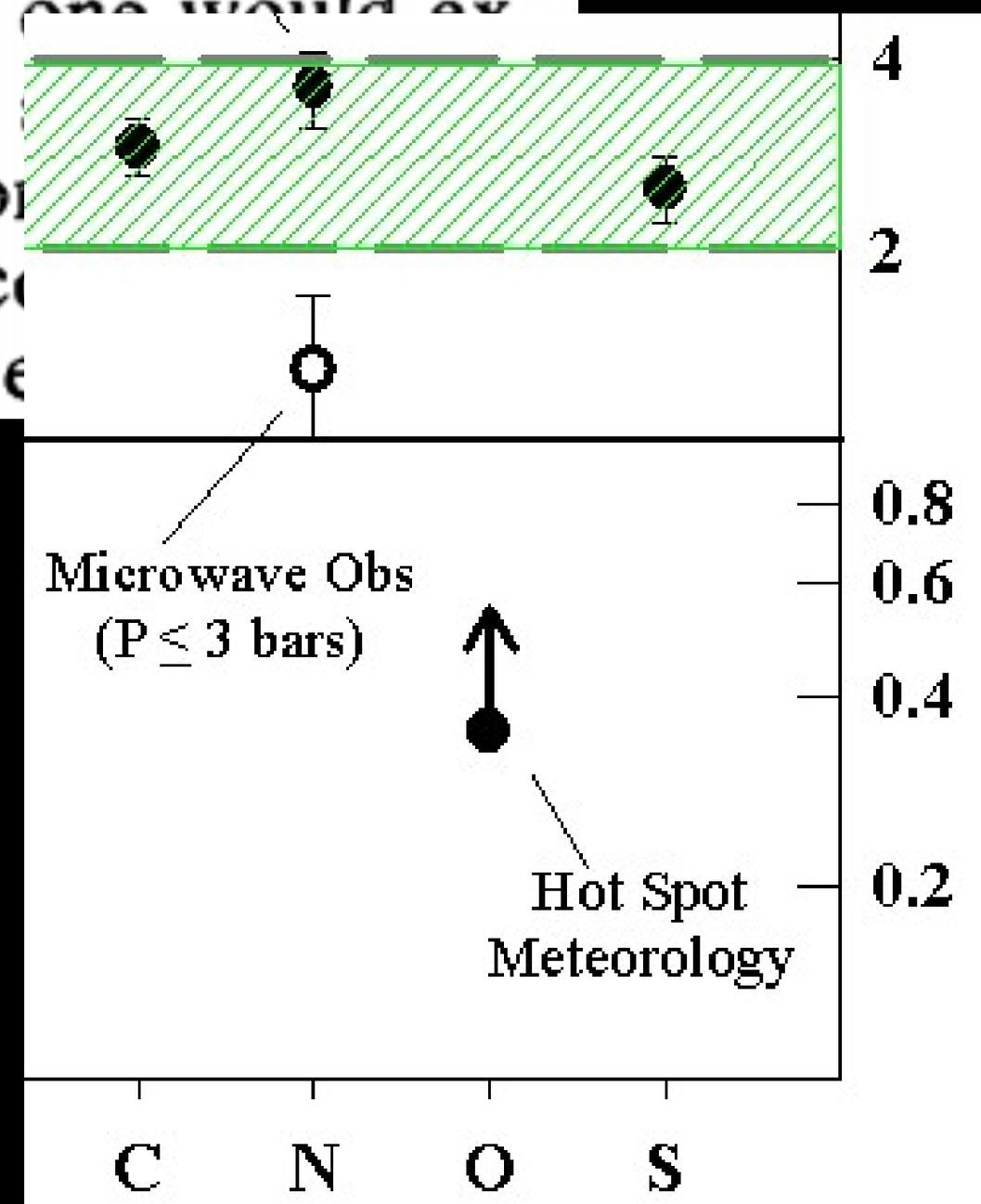
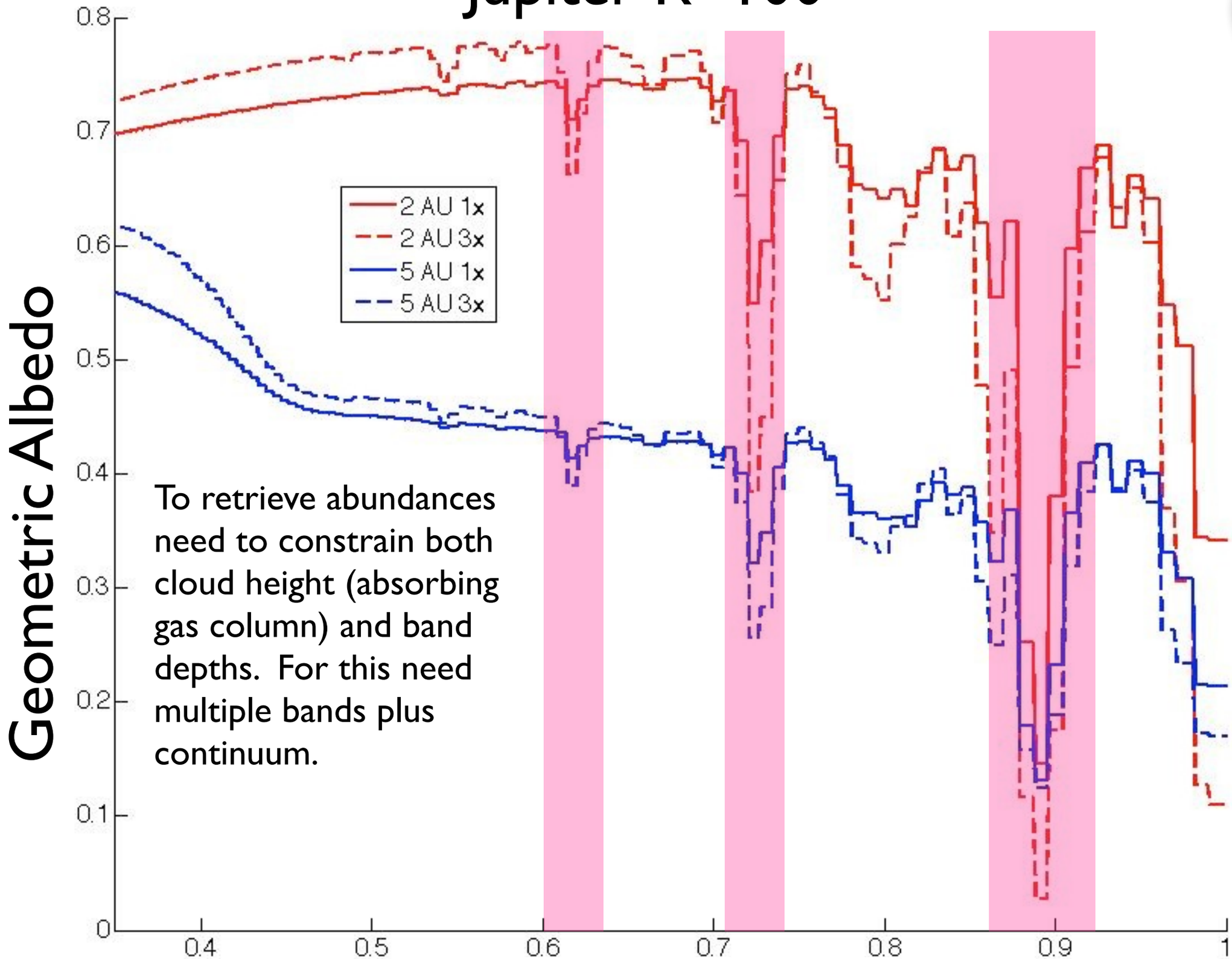
$\sim 1.5 \pm 0.5$ for $P \sim 1$–4 bars is c
$n(NH_3) \sim 2$ through the bulk of the e





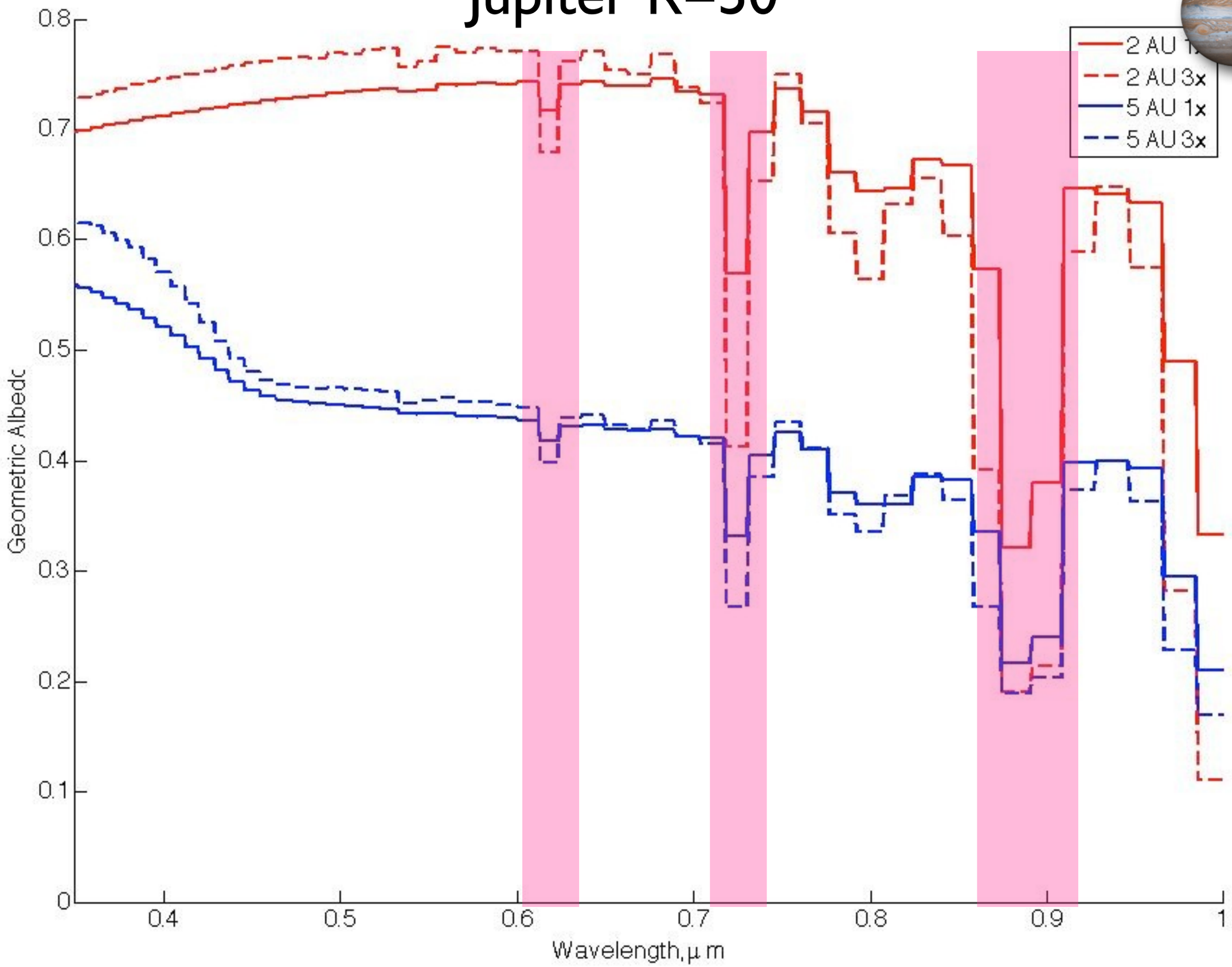
Required Spectral Resolution

Jupiter R=100

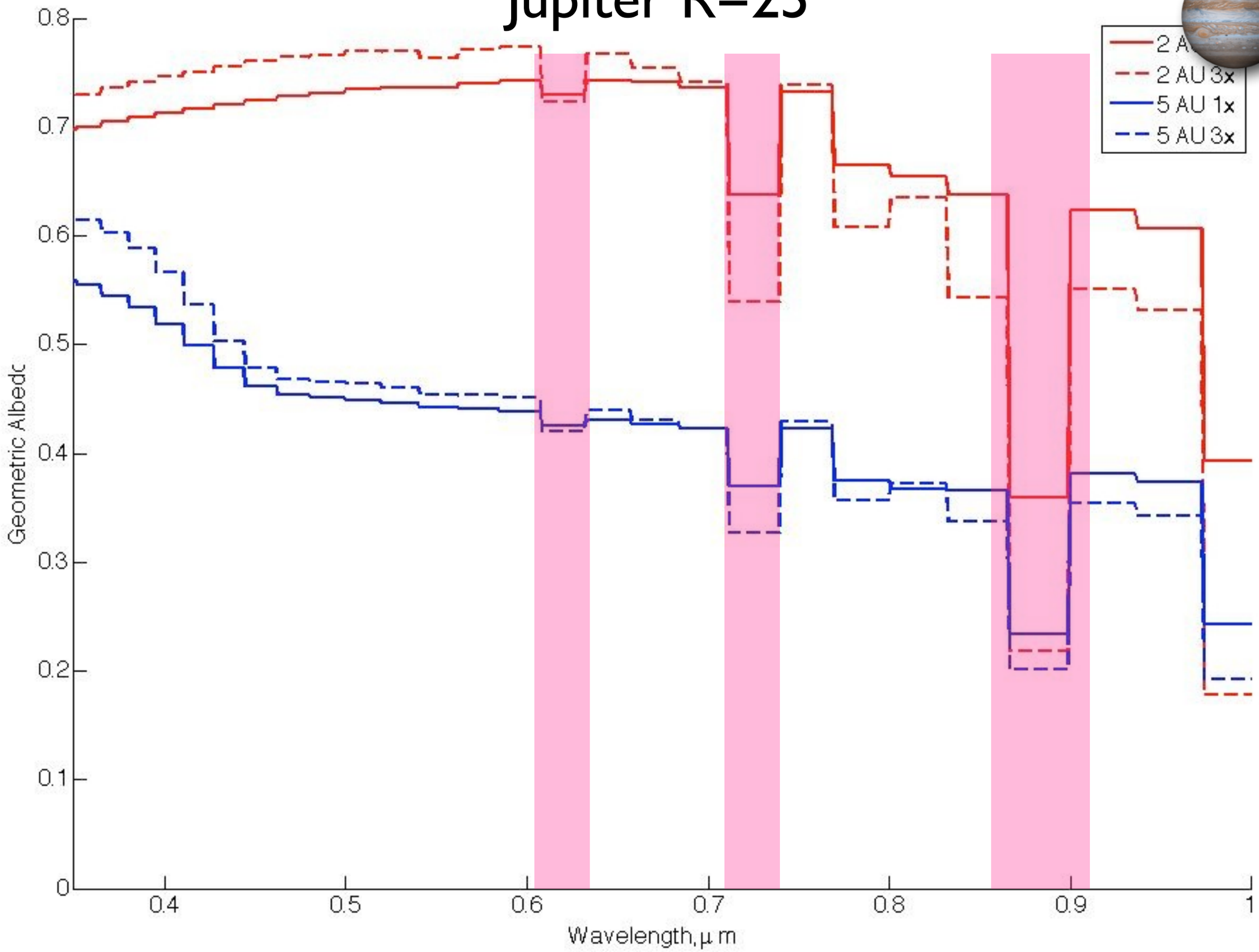


To retrieve abundances need to constrain both cloud height (absorbing gas column) and band depths. For this need multiple bands plus continuum.

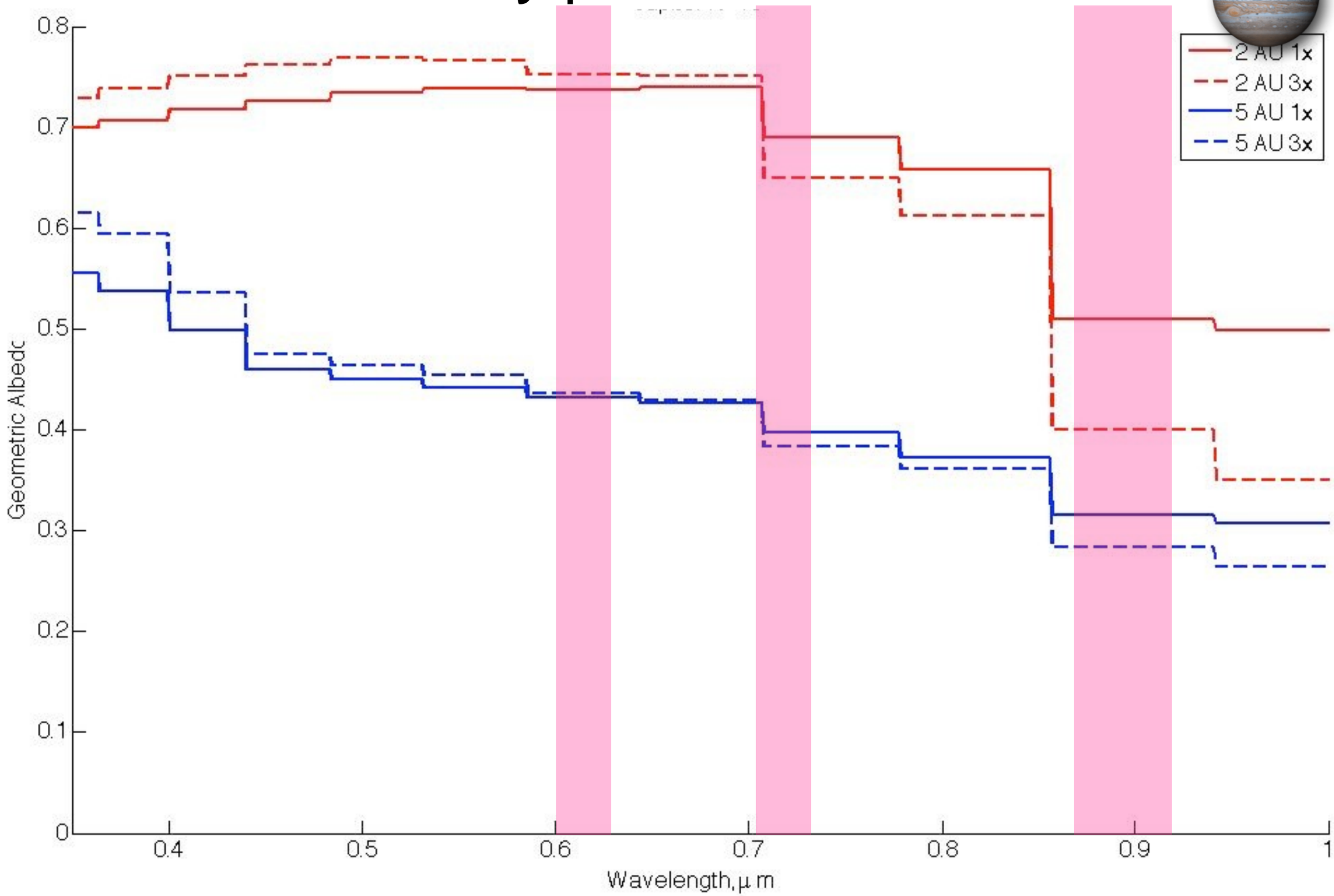
Jupiter R=50


2 AU 1x
2 AU 3x
5 AU 1x
5 AU 3x
Geometric Albedo
Wavelength, μ m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.4
0.5
0.6
0.7
0.8
0.9
1

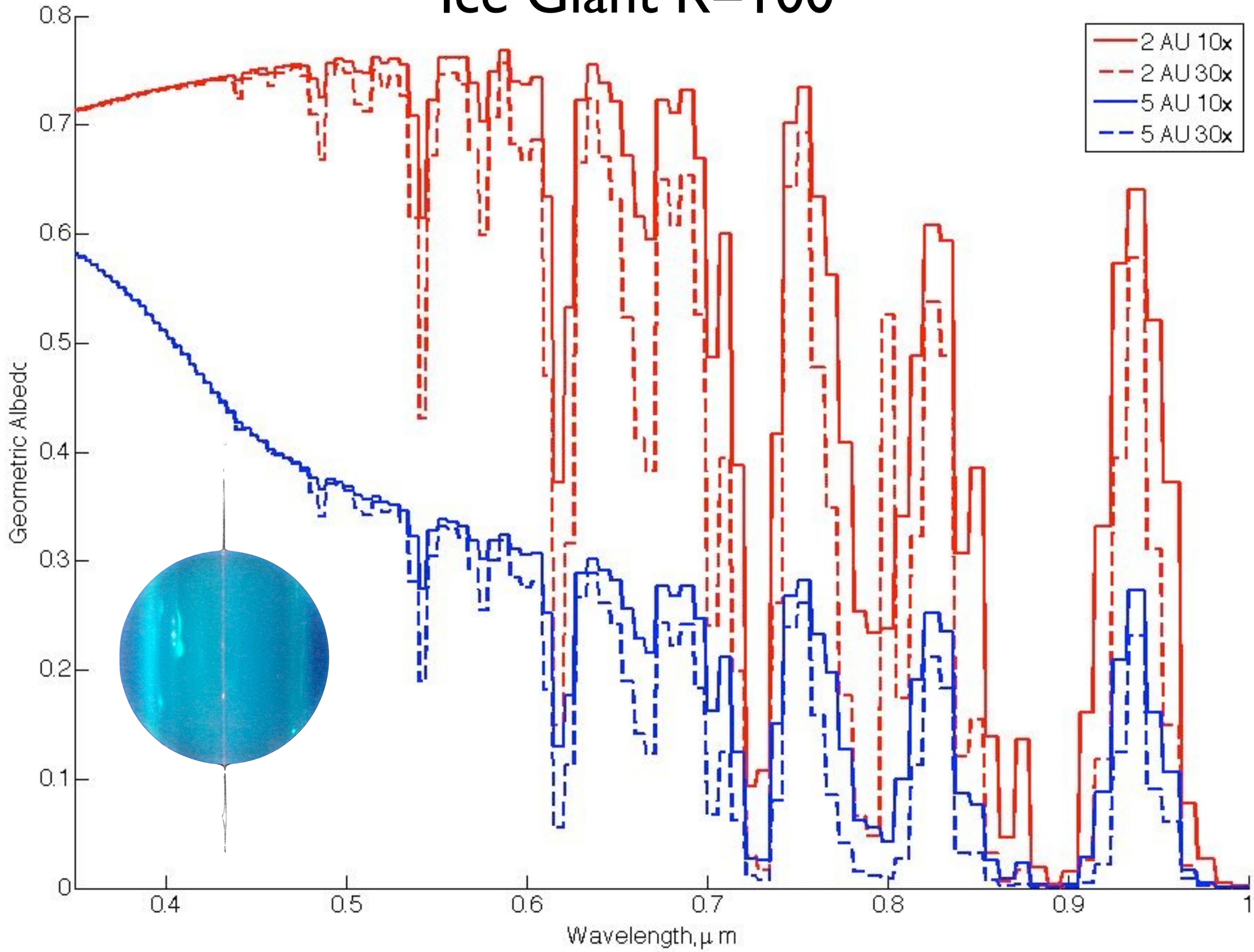
Jupiter R=25


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Geometric Albedo
0.4
0.5
0.6
0.7
0.8
0.9
1
Wavelength, μ m
2 AU
2 AU 3x
5 AU 1x
5 AU 3x

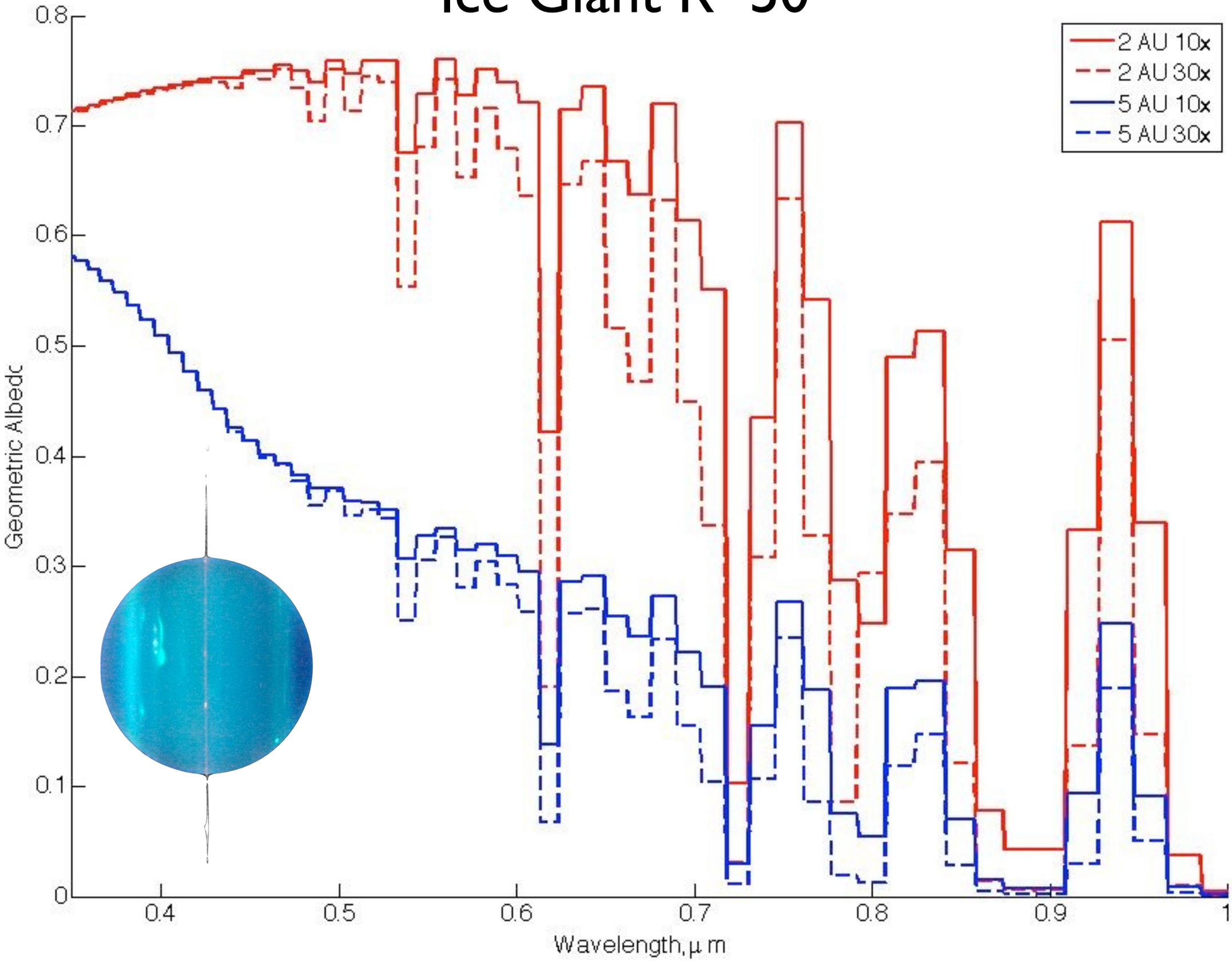
Jupiter R=10


2 AU 1x
2 AU 3x
5 AU 1x
5 AU 3x
Geometric Albedo
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.4
0.5
0.6
0.7
0.8
0.9
1
Wavelength, μ m

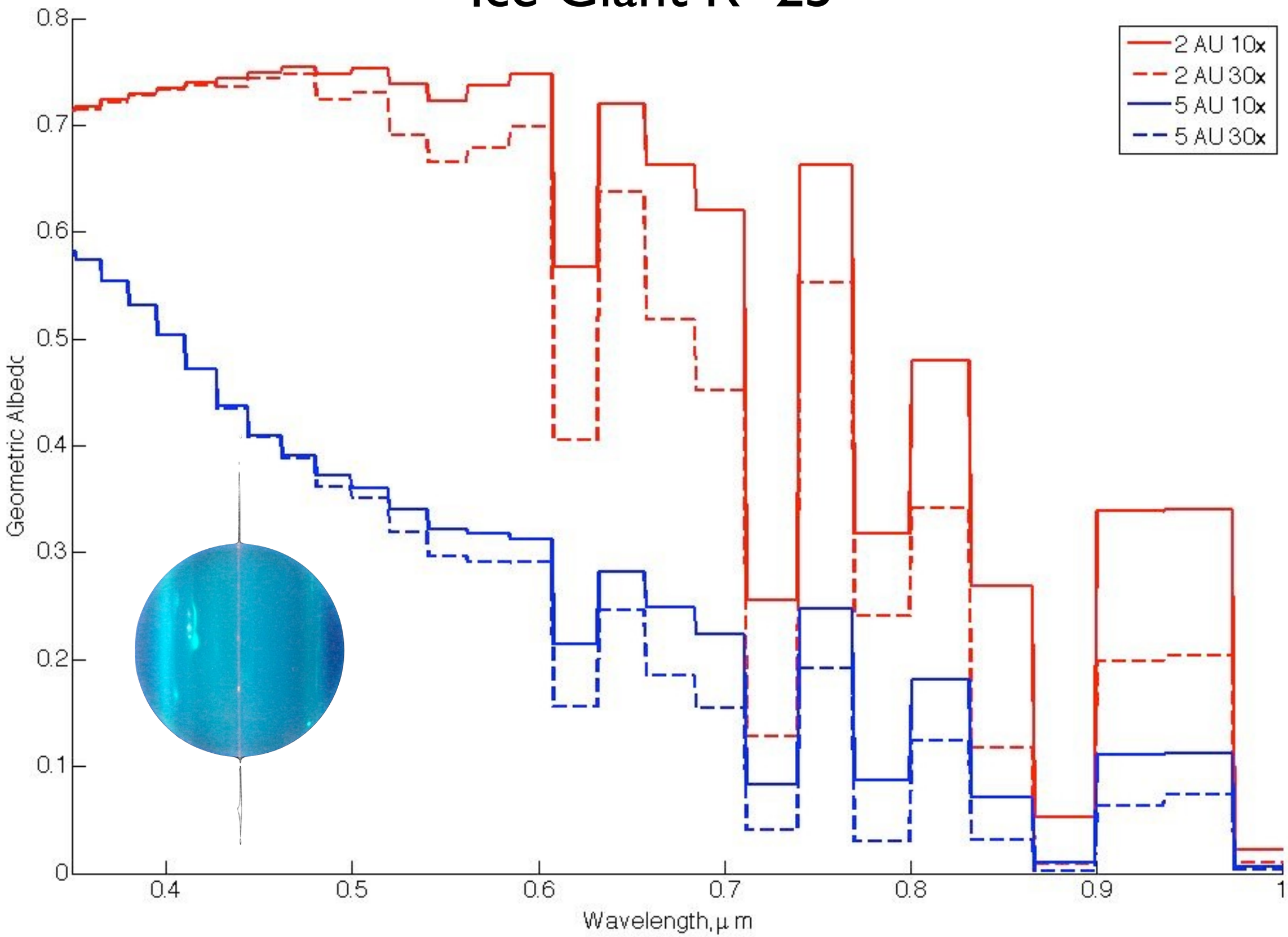
Ice Giant R=100



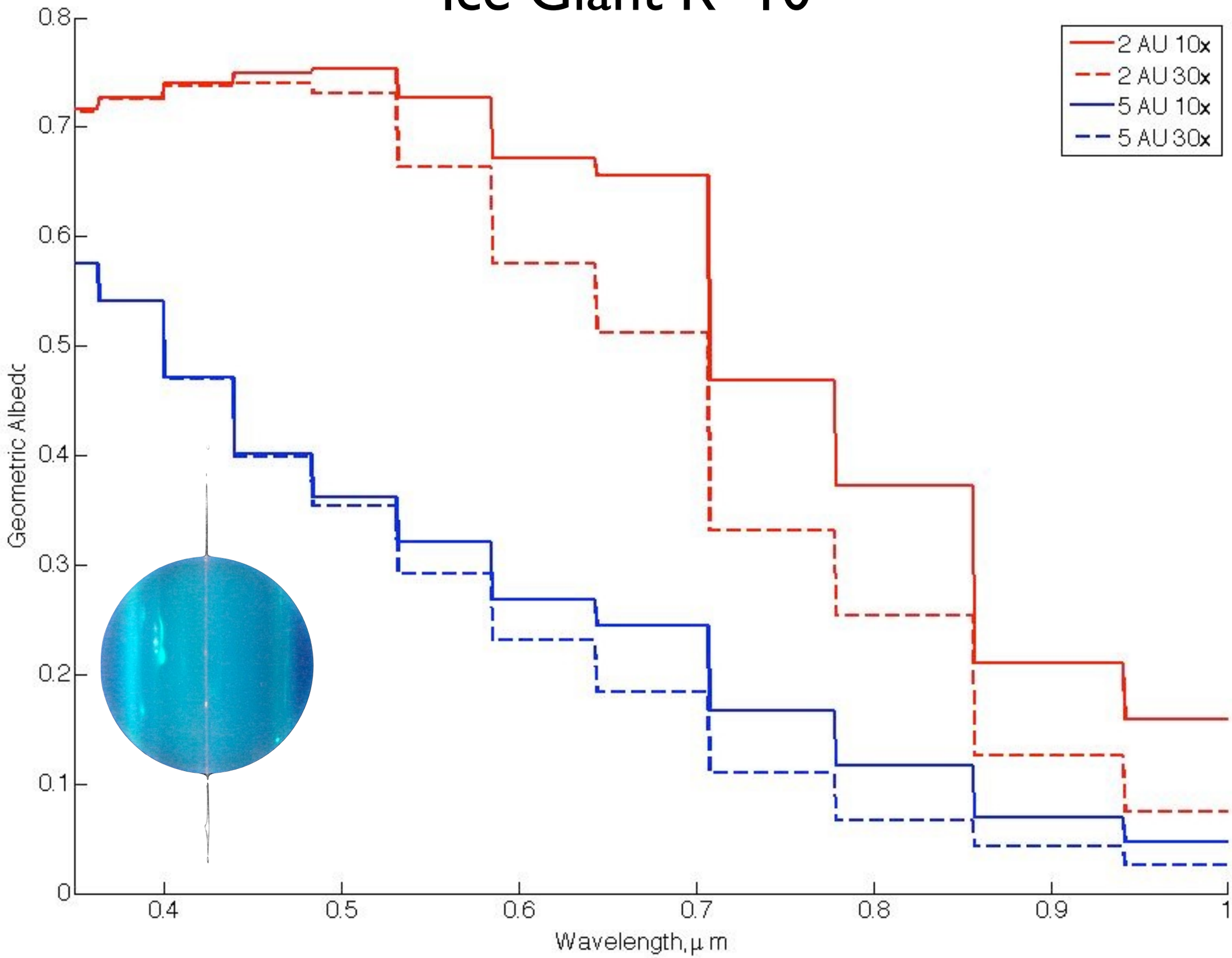
Ice Giant R=50



Ice Giant R=25



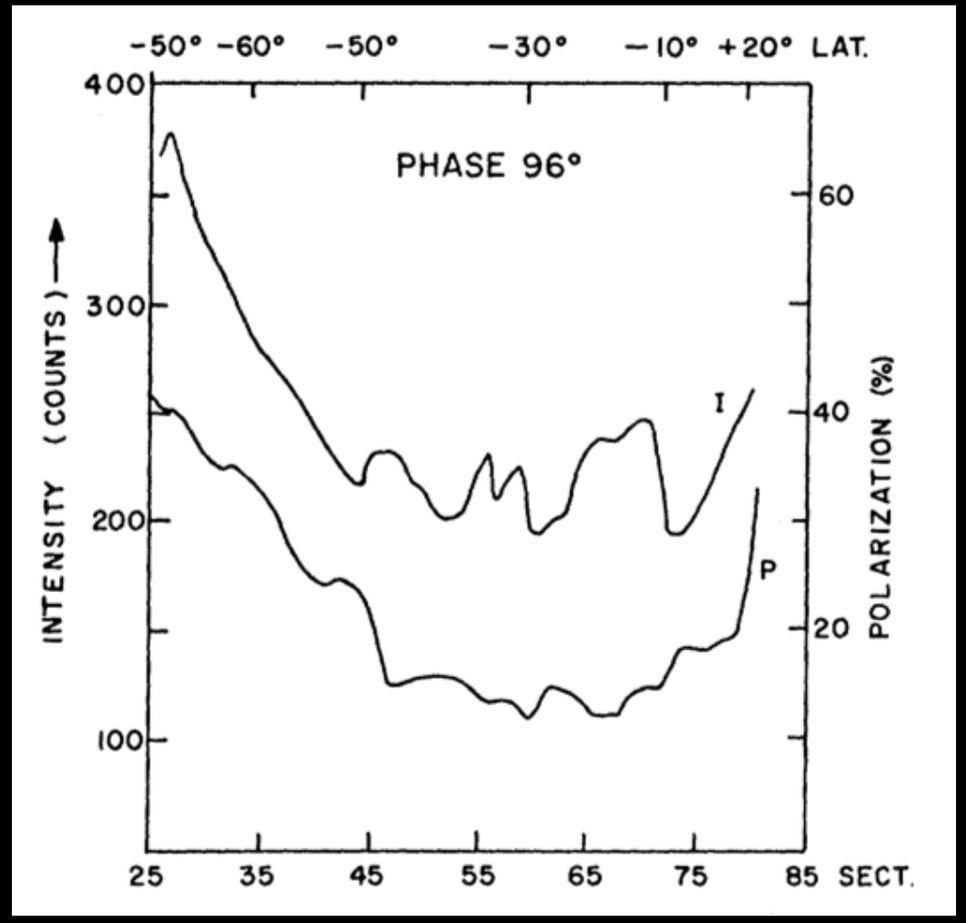
Ice Giant R=10



Polarization?

The Imaging Photopolarimeter Experiment on Pioneer 11

Abstract. *For 2 weeks continuous imaging, photometry, and polarimetry observations were made of Jupiter and the Galilean satellites in red and blue light from Pioneer 11. Measurements of Jupiter's north and south polar regions were possible because the spacecraft trajectory was highly inclined to the planet's equatorial plane. One of the highest resolution images obtained is presented here along with a comparison of a sample of our photometric and polarimetric data with a simple model. The data seem consistent with increased molecular scattering at high latitudes.*



Baker et al. (1975)

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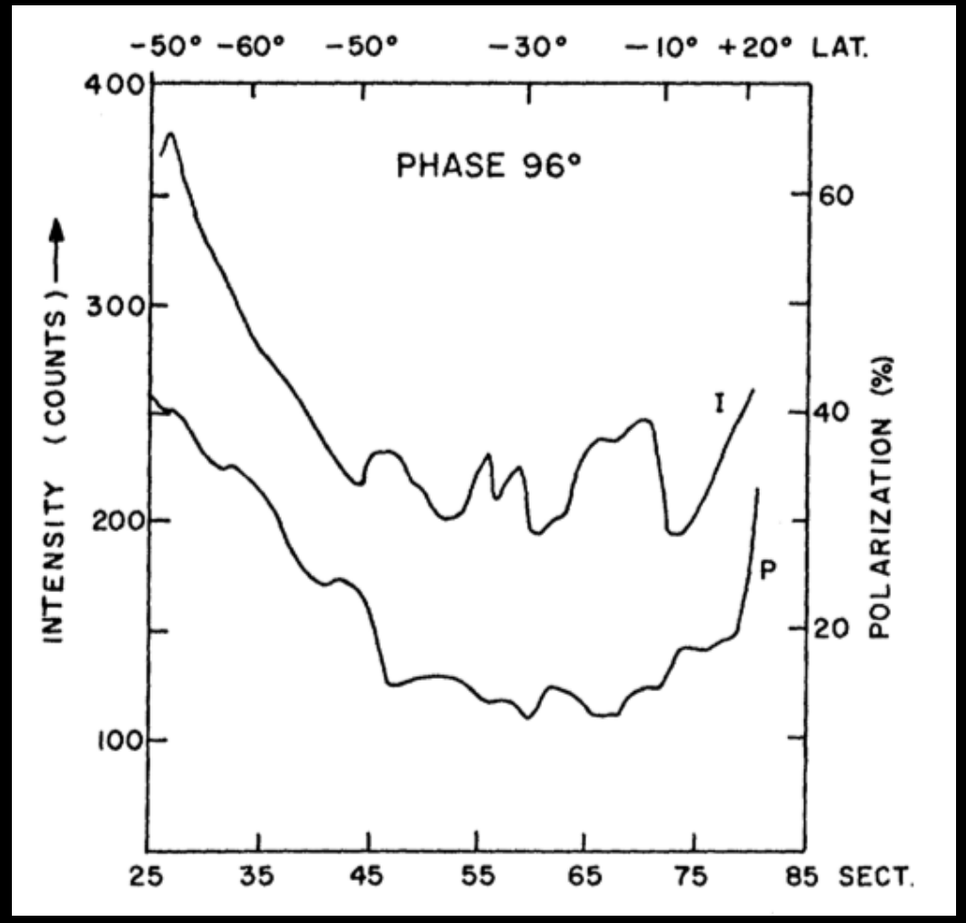

Baker et al. (1975)

1 citation

Conclusions

- Decades of experience extracting atmospheric composition for solar system giants
- Both methane AND continuum samples are CRUCIAL for determining altitudes and compositions
- Observing more than one methane band REQUIRED to constrain altitudes and abundances
- Spectral resolution R~75 higher priority than polarization
- Final thought: Just detecting CH_4 is not very interesting

Backup: Polarization of Venus Dollfus & Coffeen (1970)

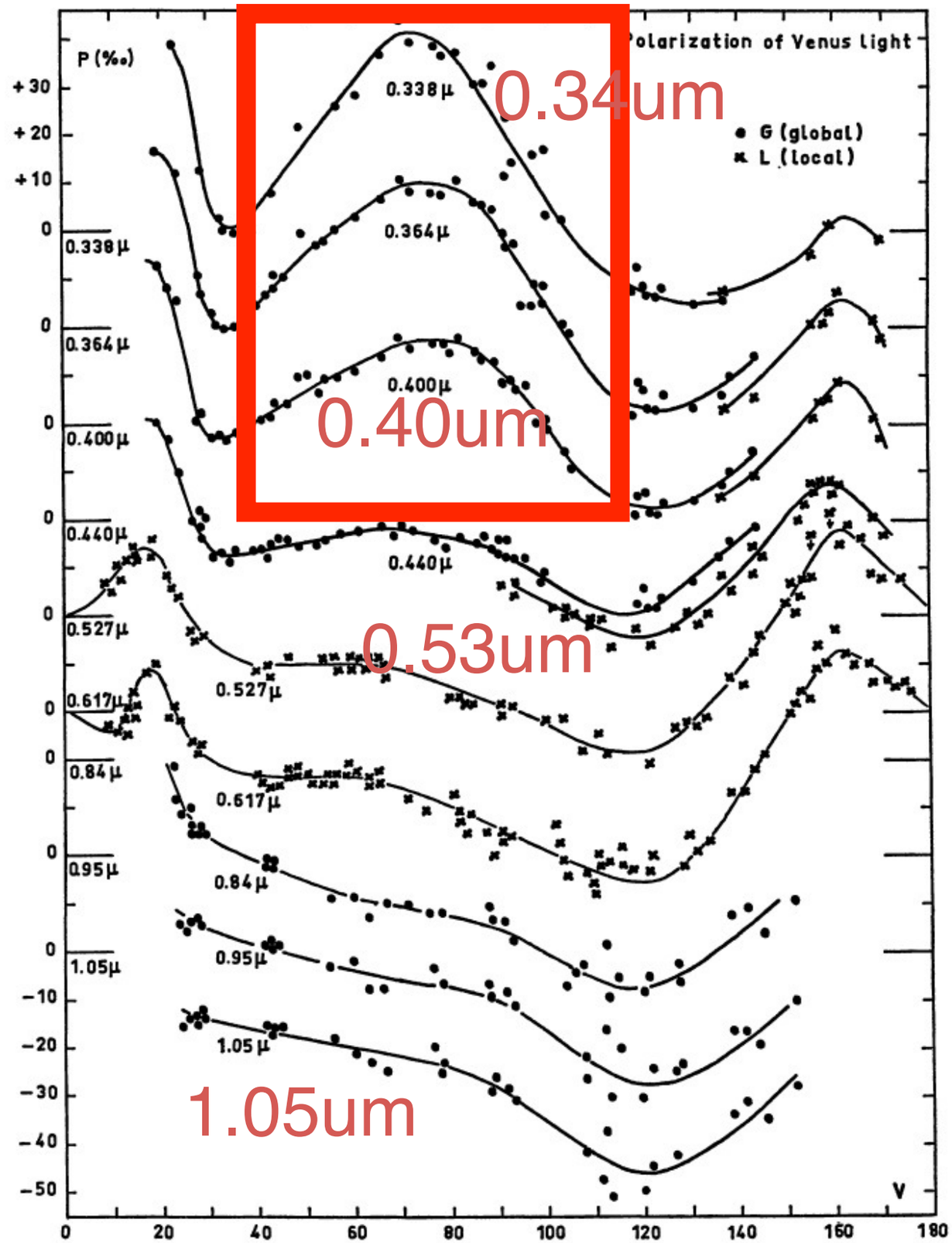

Fig. 1. Polarization of Venus. French Observations. 1950—1970

Backup: Polarization of Venus Dollfus & Coffeen (1970)

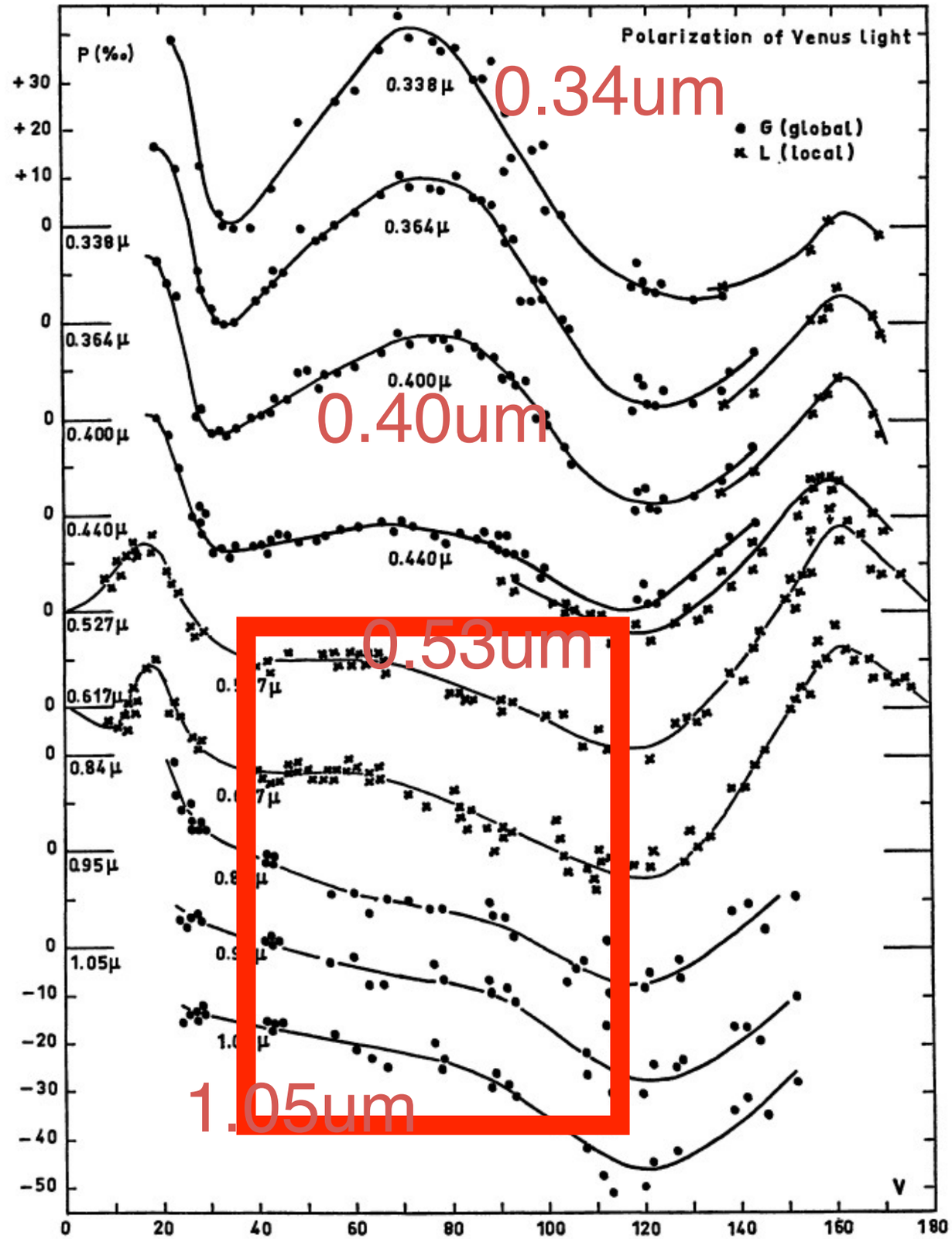

Fig. 1. Polarization of Venus. French Observations. 1950–1970