Solar-System Objects as Radiance Calibrators in the Far-Infrared and Submillimeter

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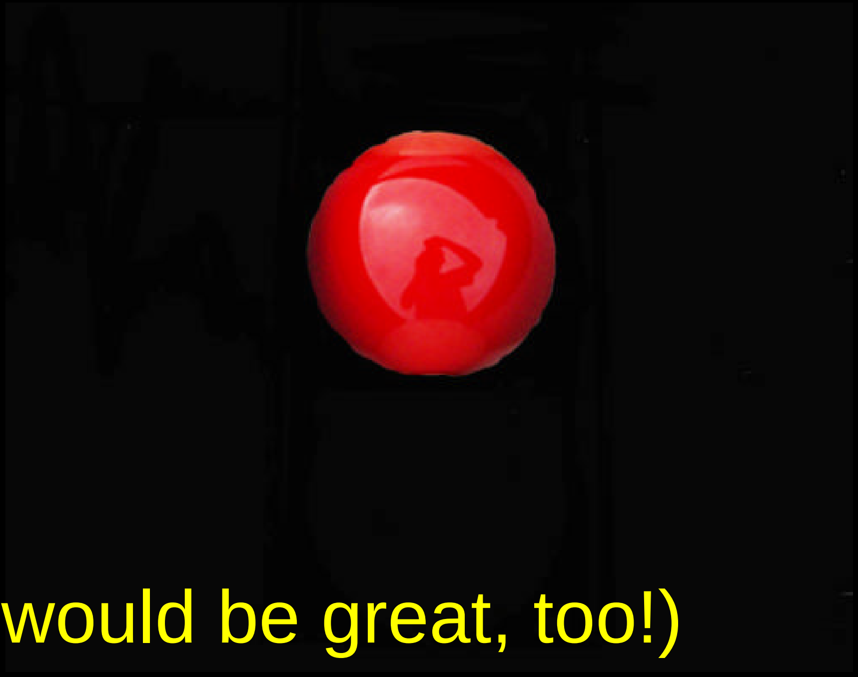
- *Planetary astronomers*: Calibrate planetary flux with stars, not stars with planets! ☹

- But there's a gap between
  - stellar standard spectra which go up to ? = 20 – 30 µm
  - radio standard spectra which go down to ? = 0.5 - 1 cm

- Solar-system objects can bridge this gap

- Ideal calibrator object:

    “moderately bright”
    compact
    non-variable
    (spectrally continuous would be great, too!)



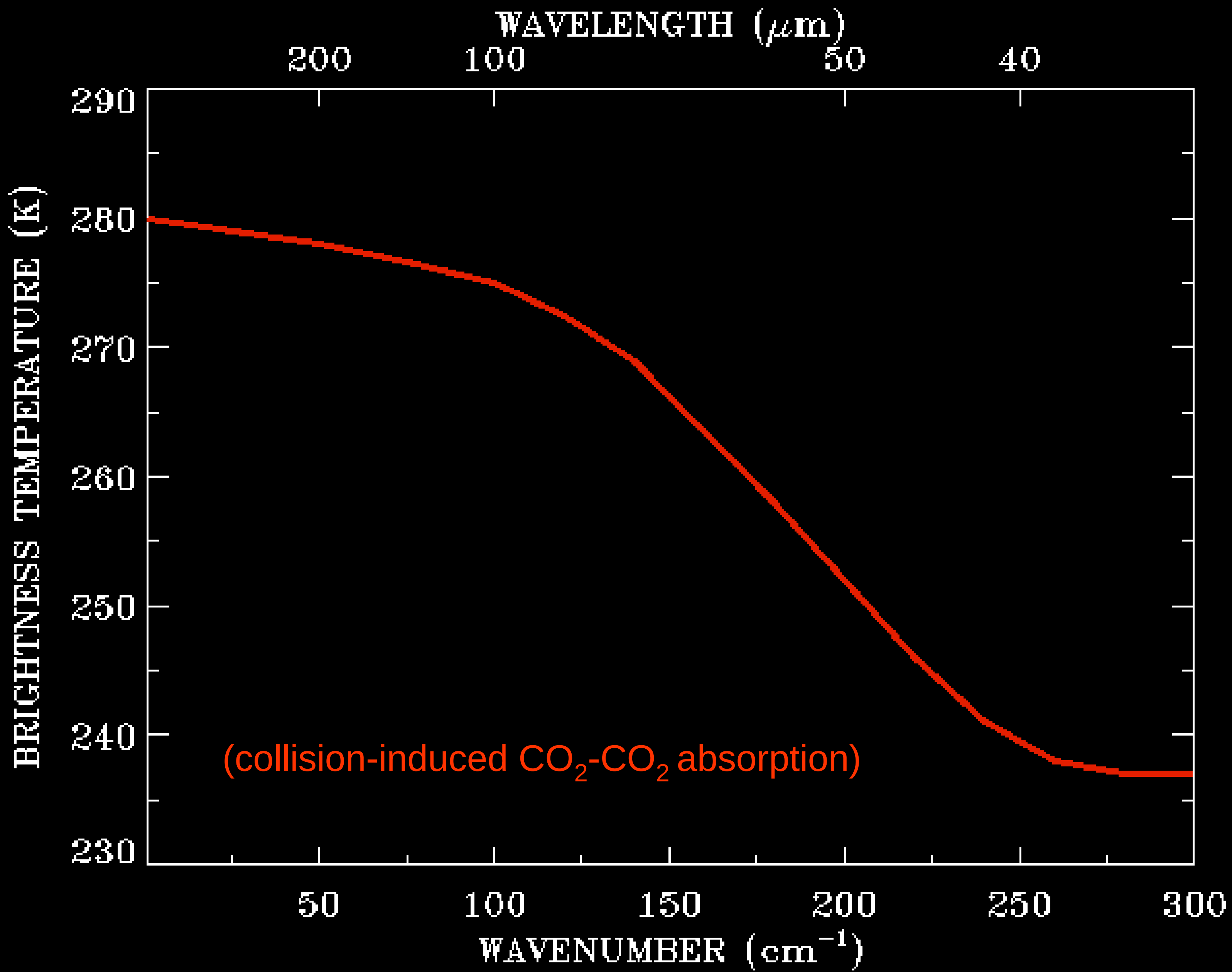
- Such objects do not exist!

- How close do solar-system objects get to the ideal?

One candidate does OK, but has a fatal flaw:

• "moderately bright"?	very bright x PACS,SPIRE
• compact?	up to 40" diameter x HIFI
• non-variable?	probably less than 1%
• spectrally continuous?	CO_2-CO_2 collision-induced absorption (some H_2O, CO, SO_2, HCl lines)

VENUS CONTINUUM SPECTRUM

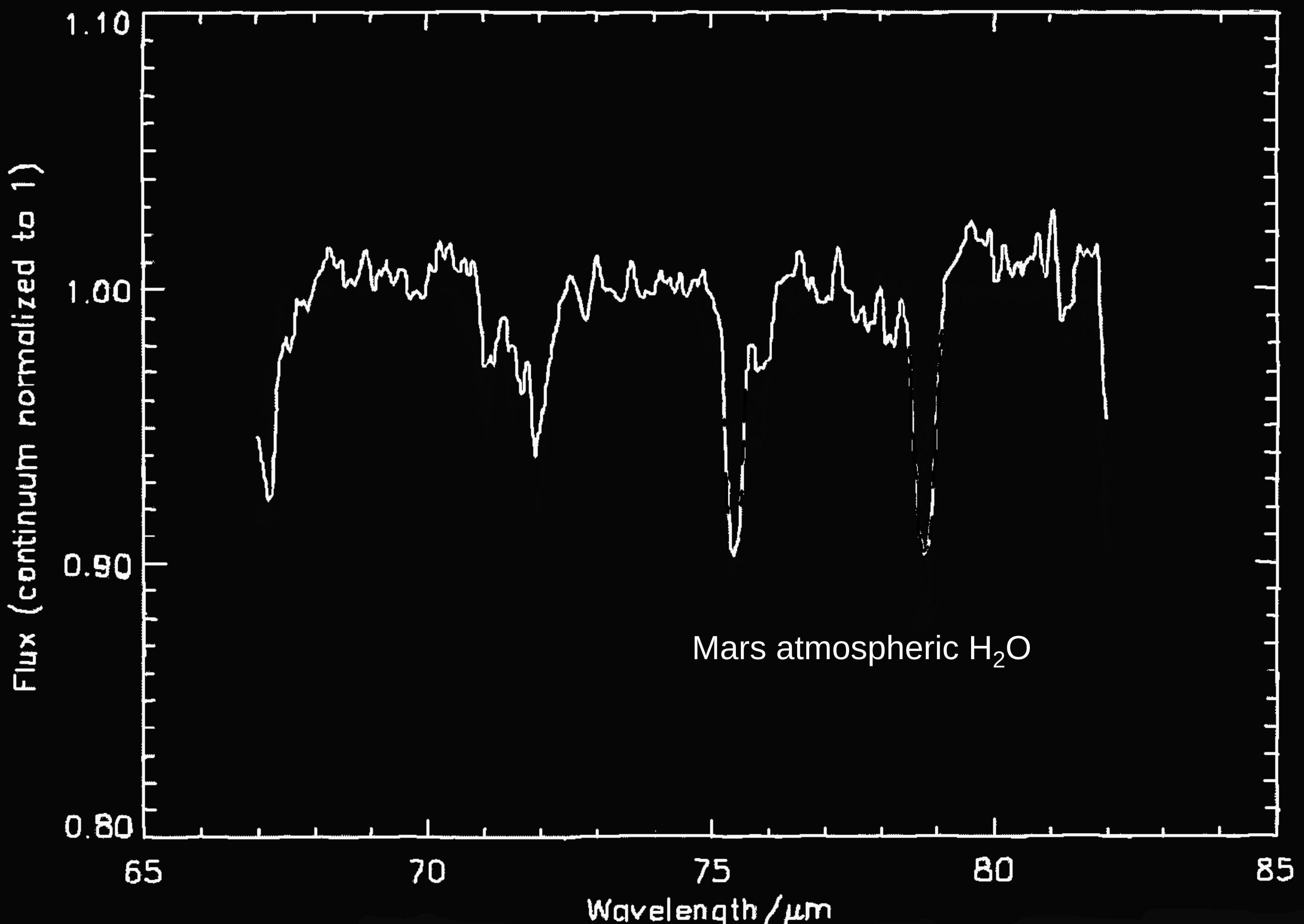


Mars, c’est là!

Mars has been used as a standard for decades

- “moderately bright”? very bright x SPIRE
- compact? ~10 - 20” x HIFI (some ?s)
- non-variable? no, but may be predictable (*e.g.* Rudy et al. 1987 *Icarus* **71**, 159)
- spectrally continuous? surface emission with H_2O vapor absorption lines

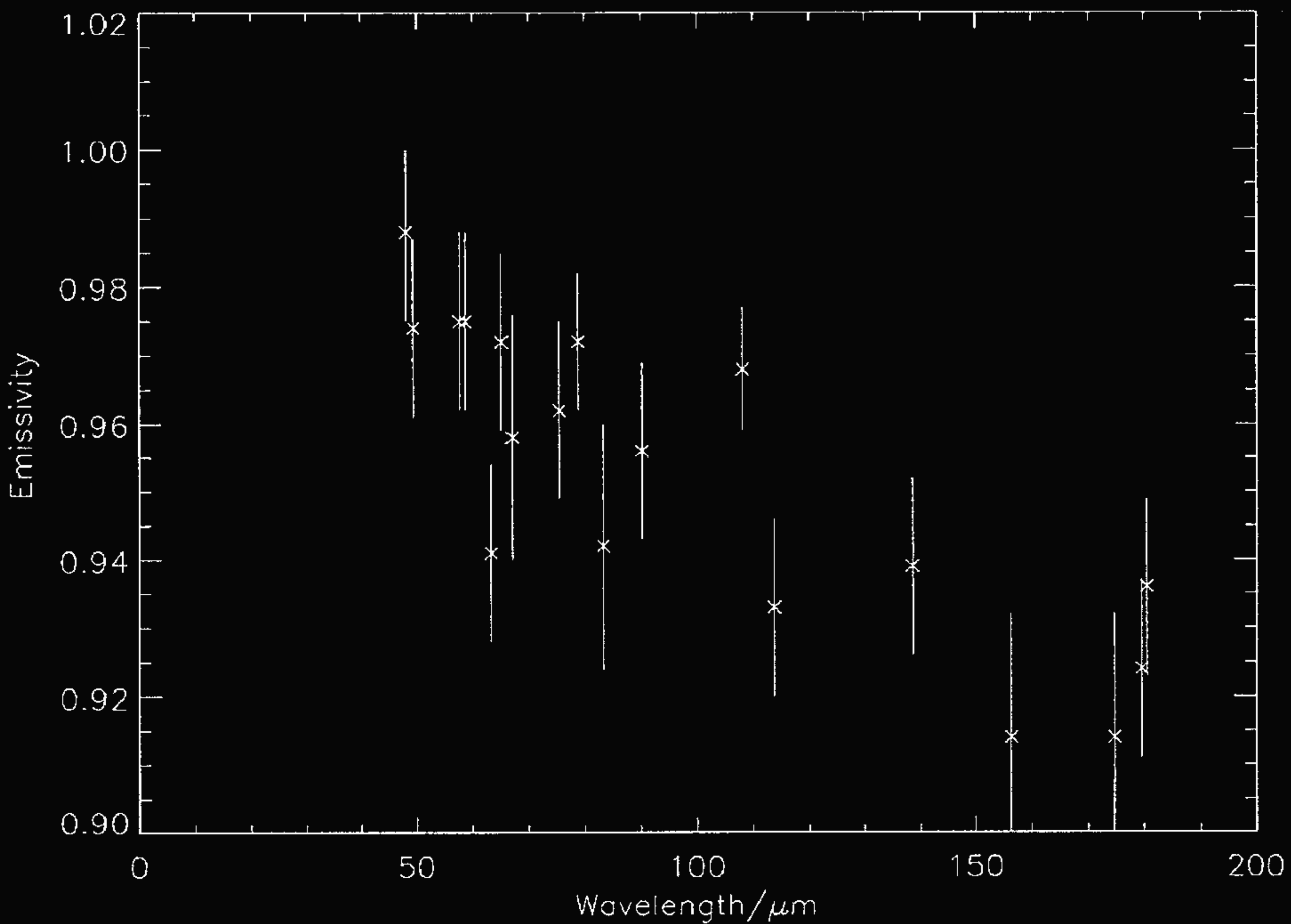
LWS Grating Spectrum of Mars



Burgdorf et al. 2000 Icarus 145, 79.

Mars Surface Emissivity Deduced from LWS Flux

(Burgdorf et al. 2000 *Icarus* **145**, 79)



Mars • Global Dust Storm

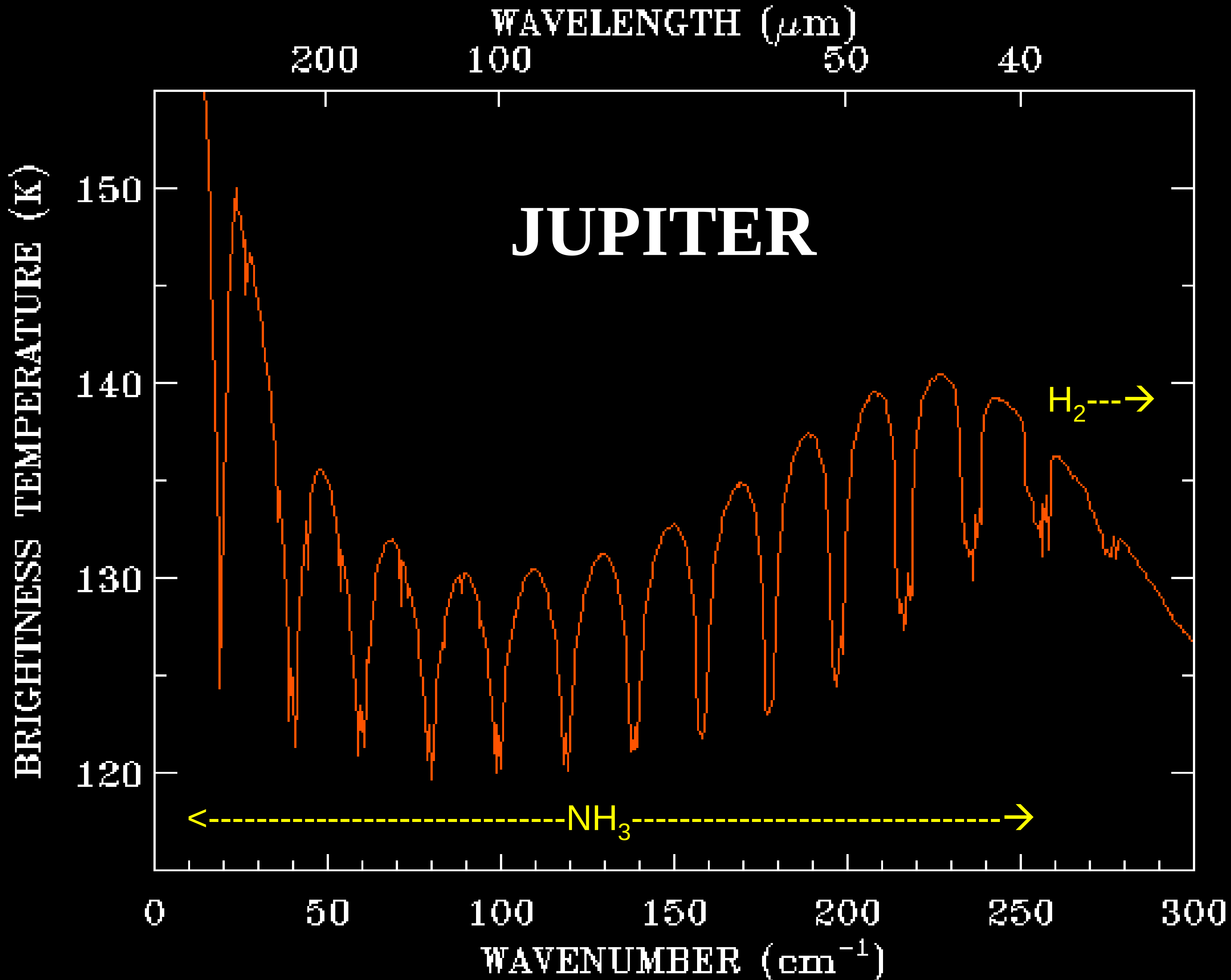
June 26, 2001 — September 4, 2001

Hubble Space Telescope • WFPC2

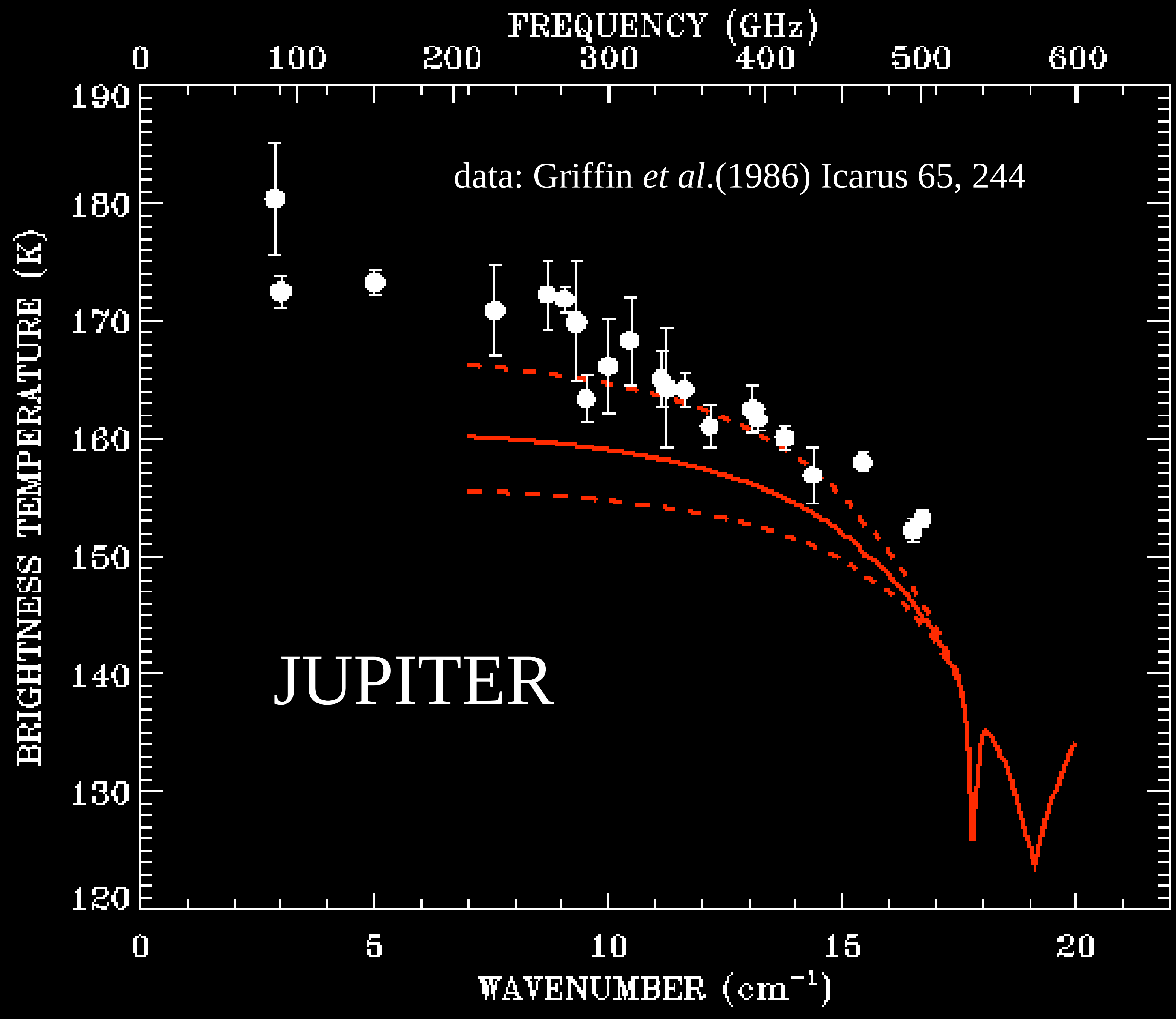
NASA, J. Bell (Cornell), M. Wolff (SSI), and the Hubble Heritage Team (STScI/AURA) • STScI-PRC01-31

Jupiter:

- “moderately bright”? quite bright
  x SPIRE
  x PACS
- compact? 36-42” diameter
  x HIFI
- non-variable?
- spectrally continuous?

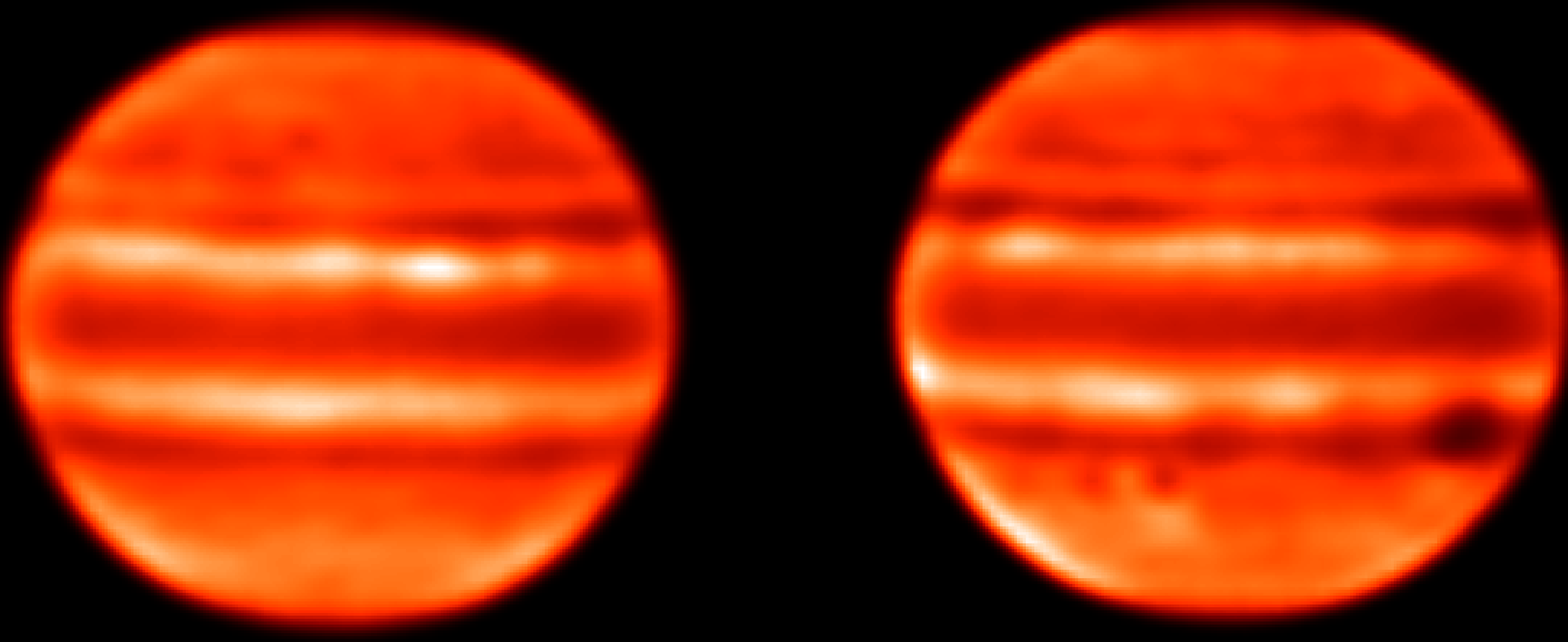


WAVELENGTH (μm)
200
100
50
40
JUPITER
BRIGHTNESS TEMPERATURE (K)
150
140
130
120
H_2--->
<-------------------------NH_3------------------------------->
0
50
100
150
200
250
300
WAVENUMBER (cm^{-1})



FREQUENCY (GHz)
0
100
200
300
400
500
600
190
180
170
160
150
140
130
120
BRIGHTNESS TEMPERATURE (K)
data: Griffin et al.(1986) Icarus 65, 244
JUPITER
0
5
10
15
20
WAVENUMBER (cm⁻¹)

Jupiter: 17.8 μm, 1996 July 1, 2



(showing tropospheric temperature variability)

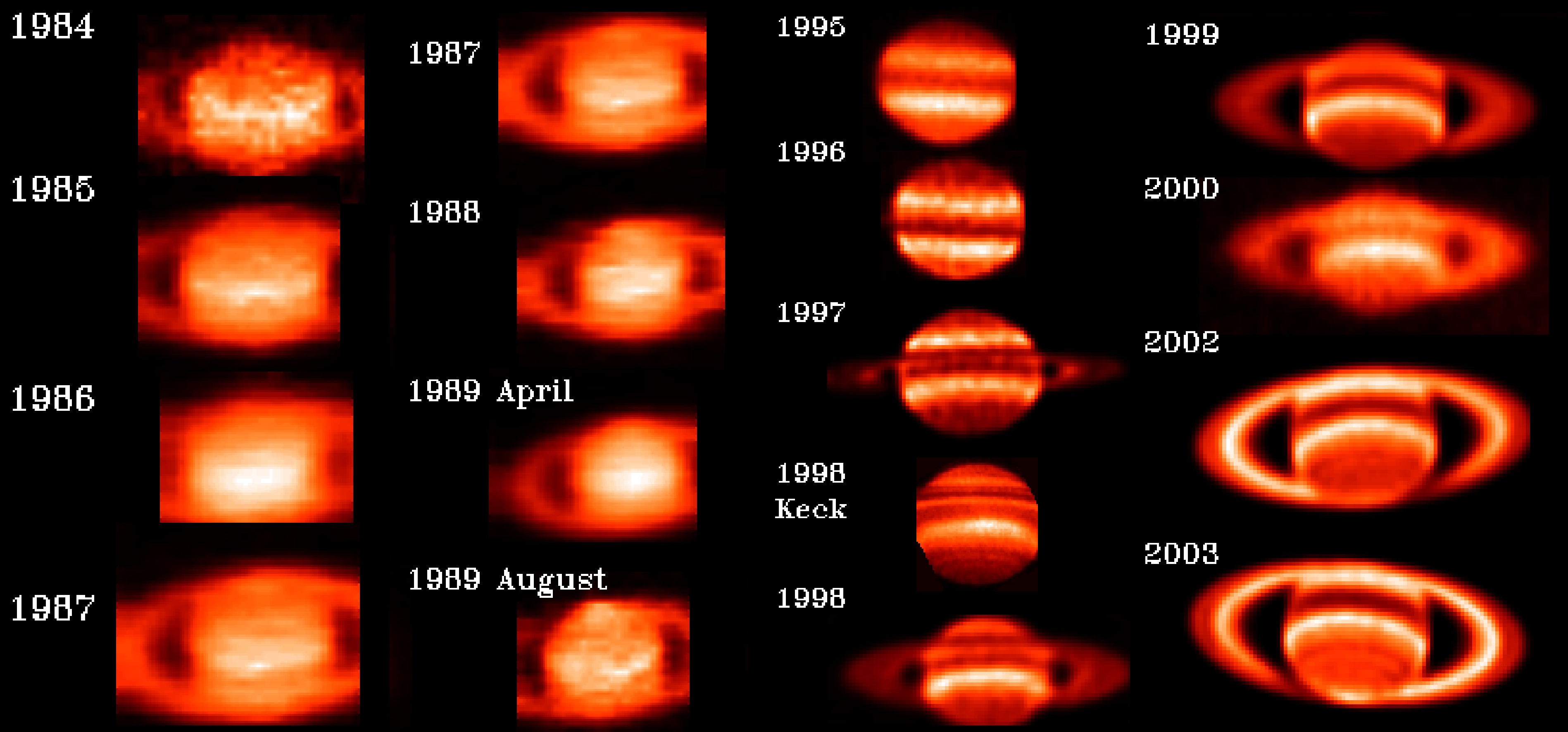
Jupiter:

• “moderately bright”?	quite bright
• compact?	36-42” diameter
• non-variable?	only to within ~5%
• spectrally continuous?	not at all!

Saturn

- Like Jupiter, but with “baggage”
  - Big seasonal changes
  - Comes with substantial ring contributions

17.8-μm H_2 continuum

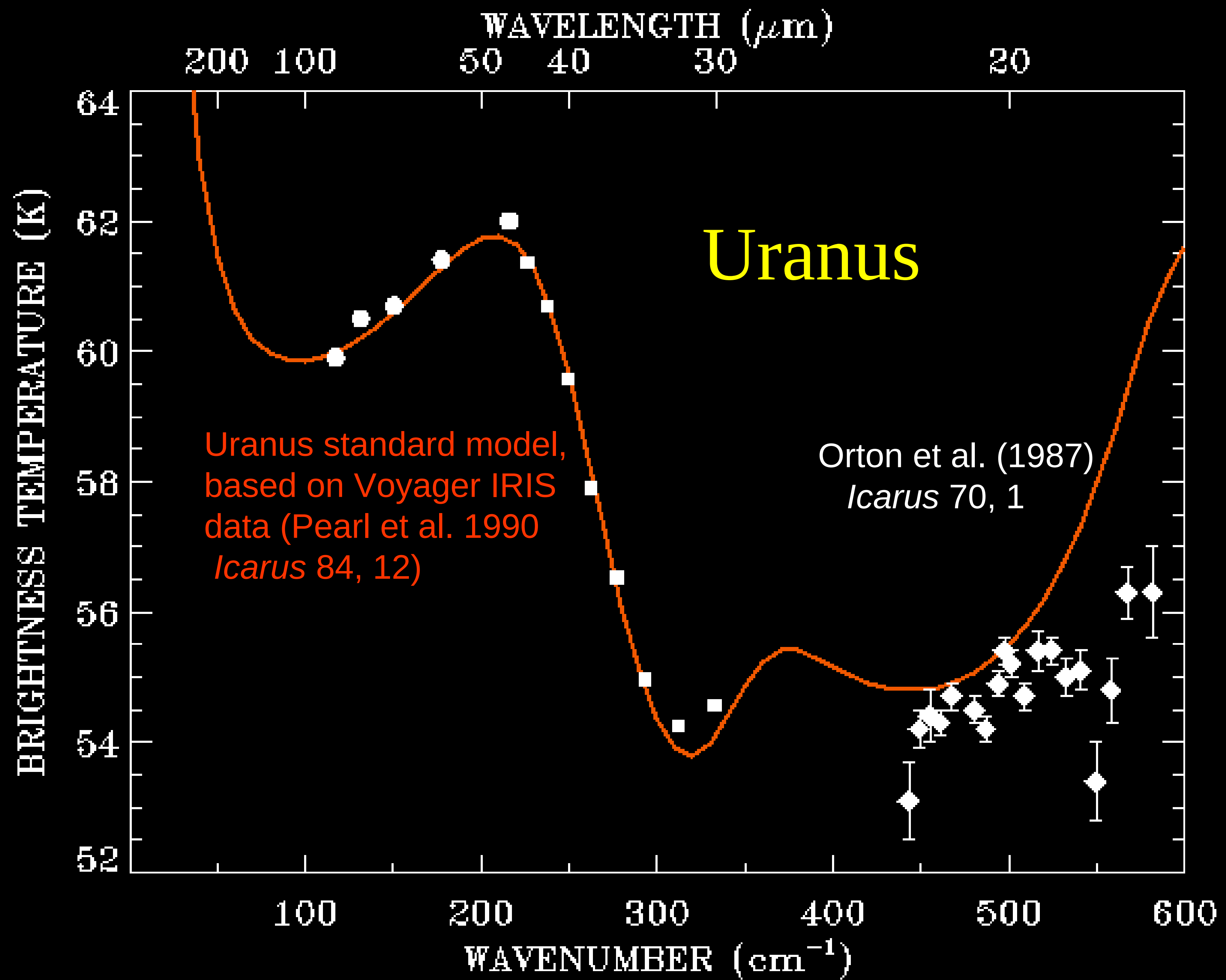


(sensitive to 100- to 200-mbar temperatures in Saturn)

Uranus

Uranus

• “moderately bright”?	yes
• compact?	4” diameter
• non-variable?	maybe
• spectrally continuous?	mostly


WAVELENGTH (μm)
200 100 50 40 30 20
BRIGHTNESS TEMPERATURE (K)
64 62 60 58 56 54 52
Uranus
Uranus standard model, based on Voyager IRIS data (Pearl et al. 1990 *Icarus* 84, 12)
Orton et al. (1987) *Icarus* 70, 1
100 200 300 400 500 600
WAVENUMBER (cm^{-1})

URANUS STANDARD MODEL SPECTRUM

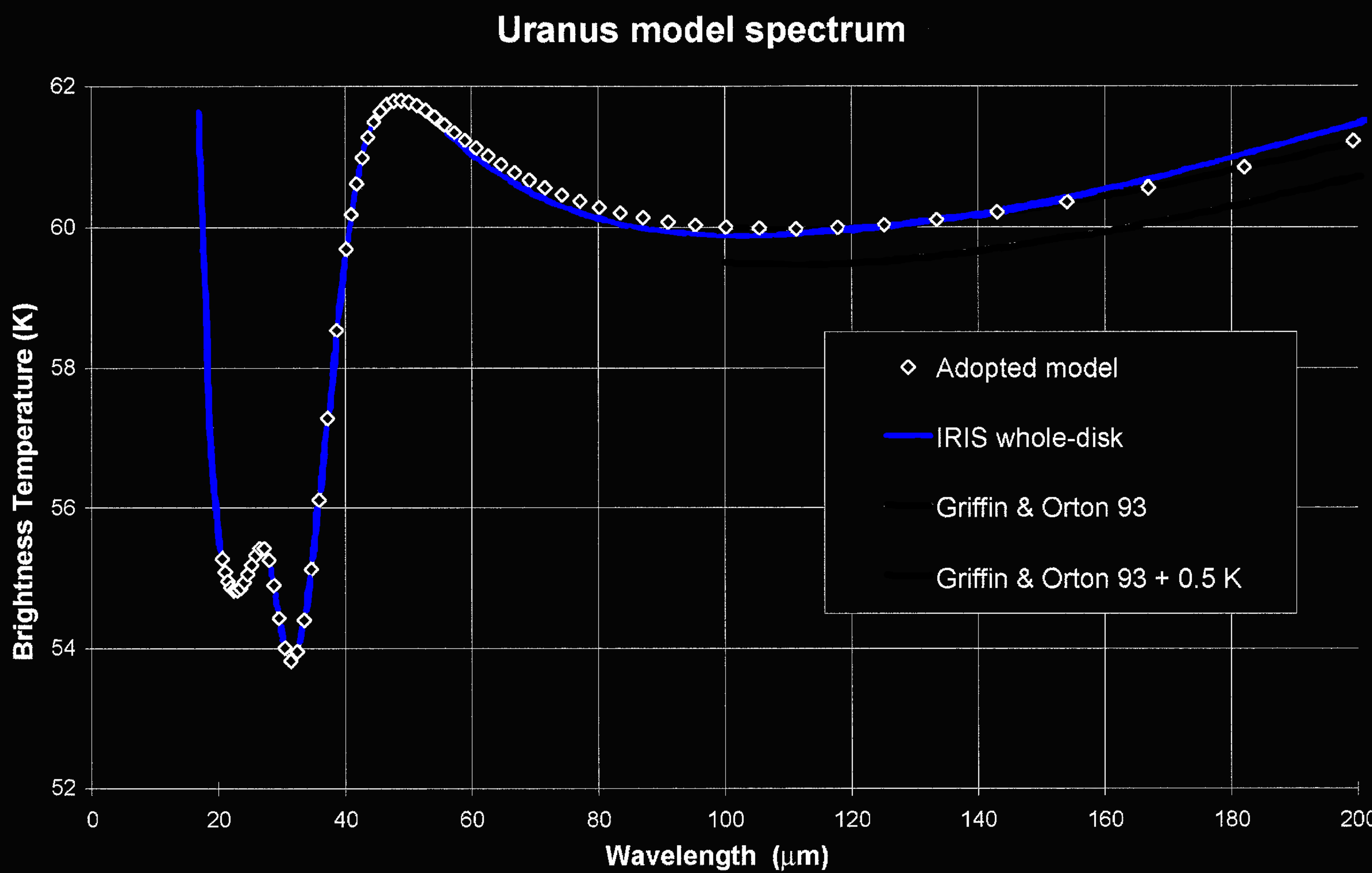
(Griffin and Orton 1993 Icarus 105, 537)

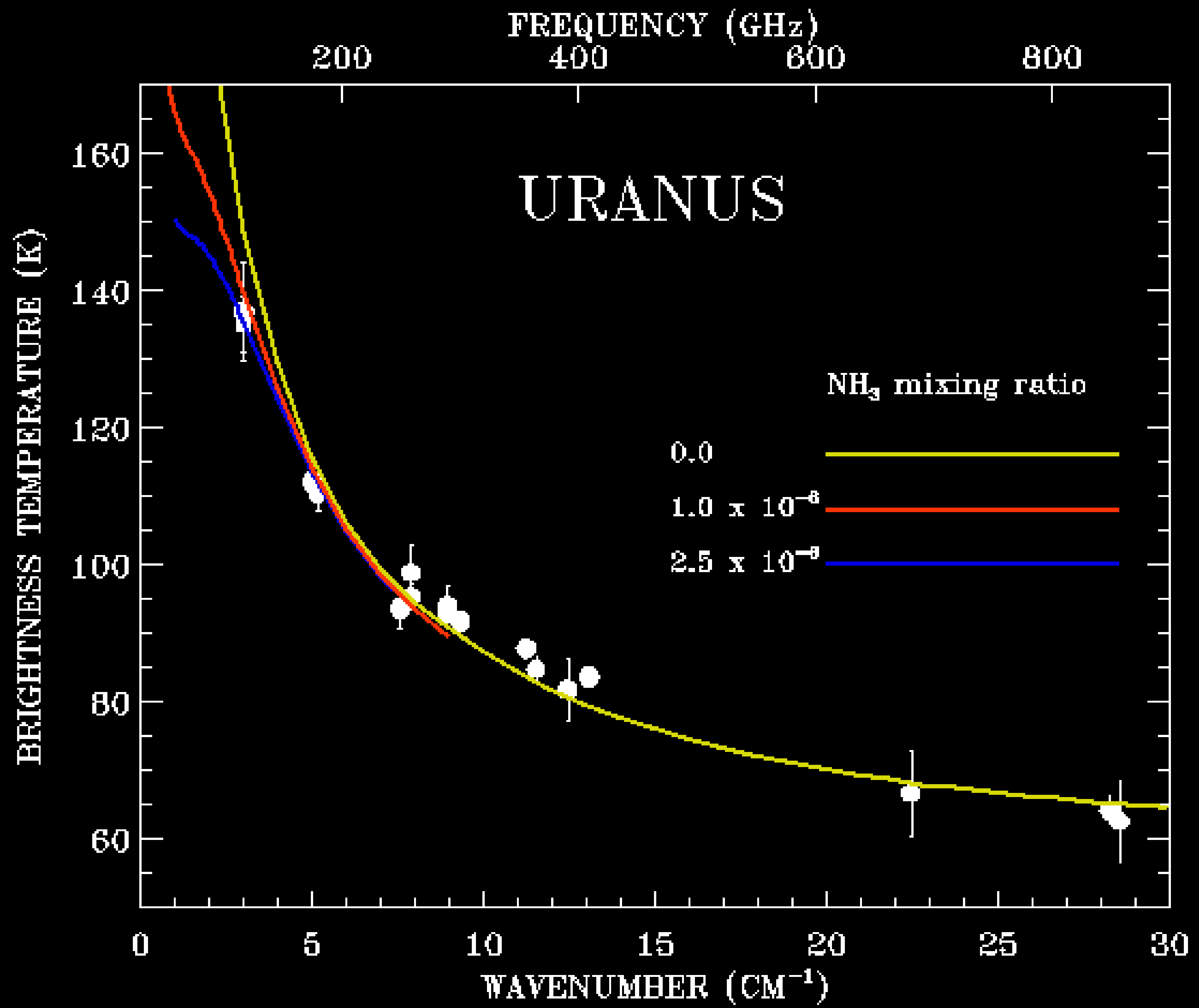
- Based on Voyager-1 IRIS spectra between 200 and 400 cm-1
- Model used to extrapolate spectrum
- Temperature structure derived from 200 – 400 cm-1 spectrum
- Collision-induced H_2-H_2, H_2-He, H_2-CH_4 absorption (equilibrium para/ortho H_2)

  - Molar fraction He = 0.155 ± 0.033
    (Conrath et al. 1987 J. Geophys. Res. 92, 15003)

  - Molar fraction of CH4 = 0.02 ± 0.01
    (Orton et al. 1996 Icarus 67, 289,
    Lindal et al. 1987 J. Geophys. Res. 92, 14987)

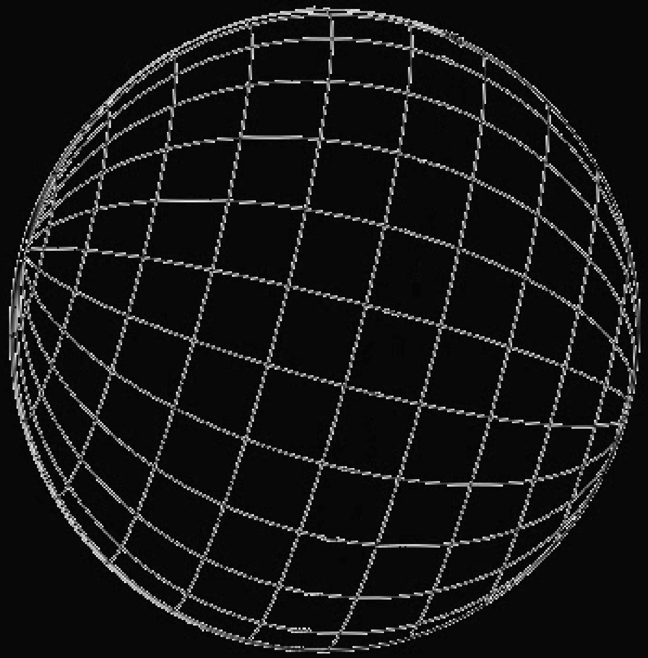
- Uncertainty of radiance ~2% between 50 and 500 cm-1
- Extrapolation to longer wavelengths is less certain.


Uranus model spectrum
Brightness Temperature (K)
62
60
58
56
54
52
0
20
40
60
80
100
120
140
160
180
200
Wavelength (μm)
Adopted model
IRIS whole-disk
Griffin & Orton 93
Griffin & Orton 93 + 0.5 K

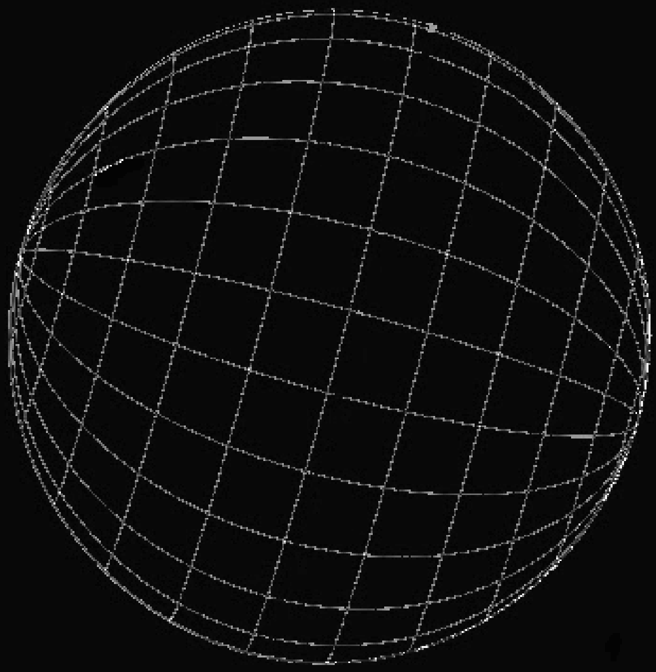


from Griffin and Orton (1993) Icarus 105, 537.

URANUS



January 2007



January 2010

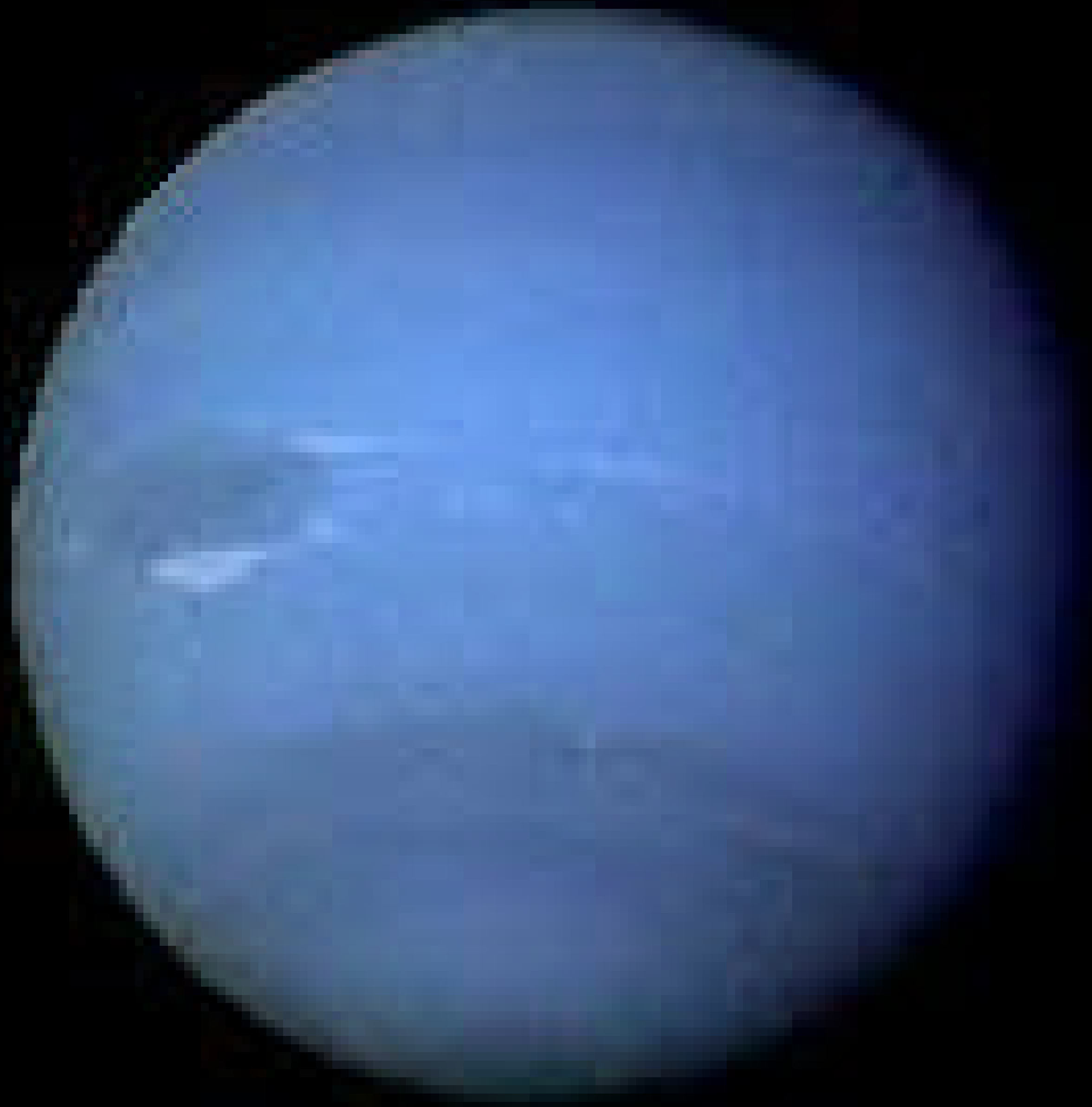
1999

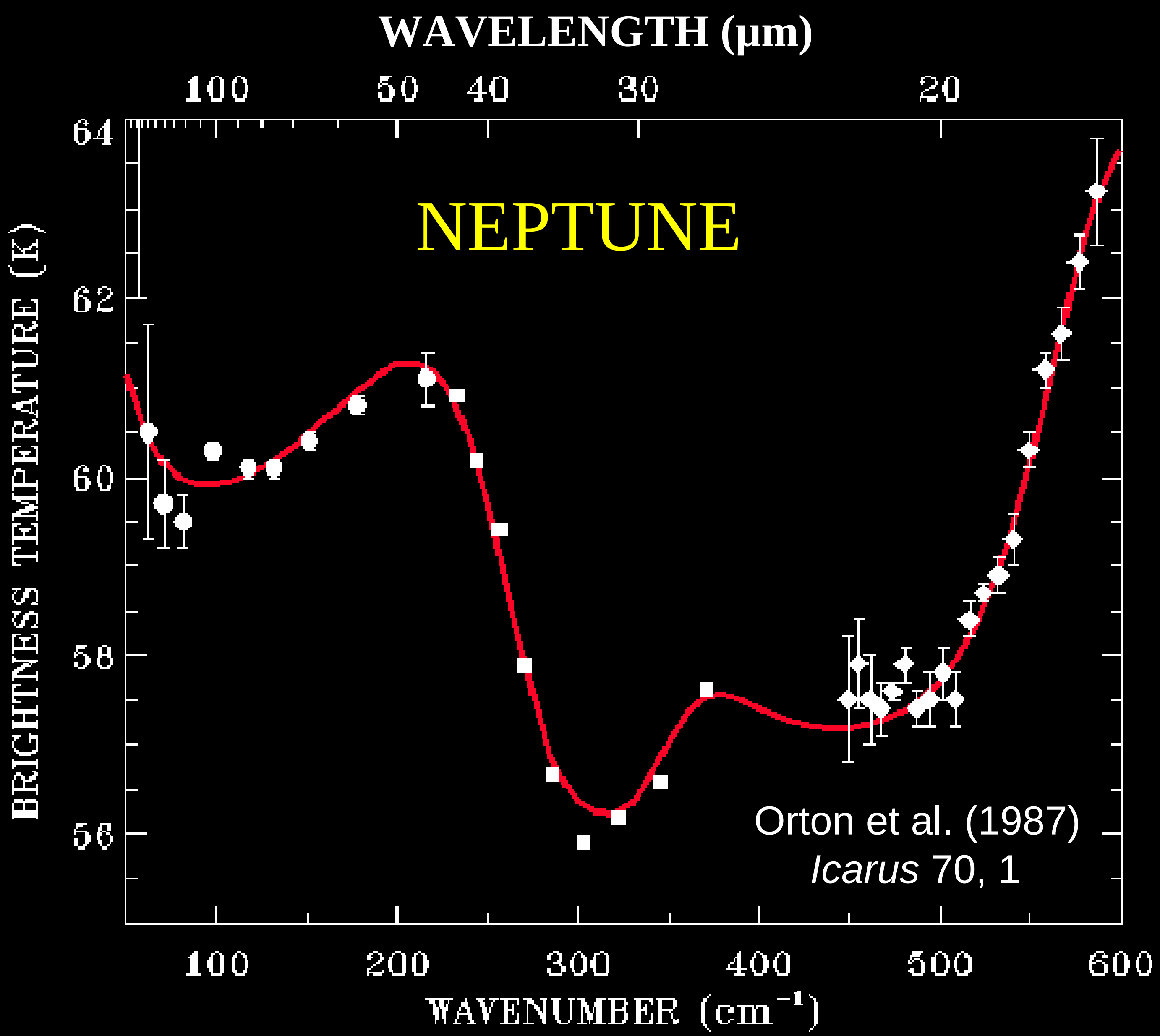
HST: enhanced R, G, B
(Karkoschka, press release)

2004

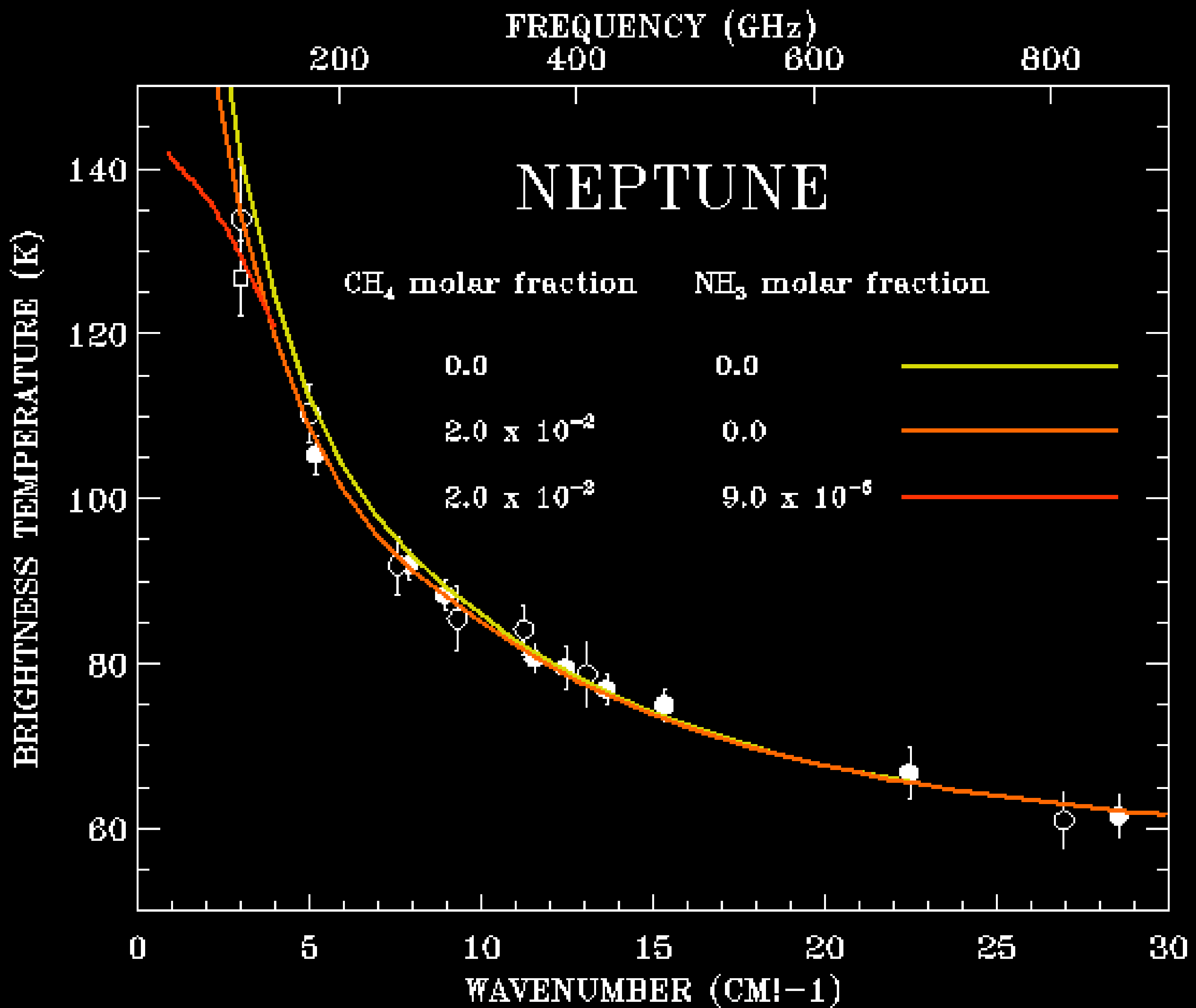
Keck AO: enhanced J, H, K
(de Pater and Hammel, press release)

Neptune: A Viable Alternative?



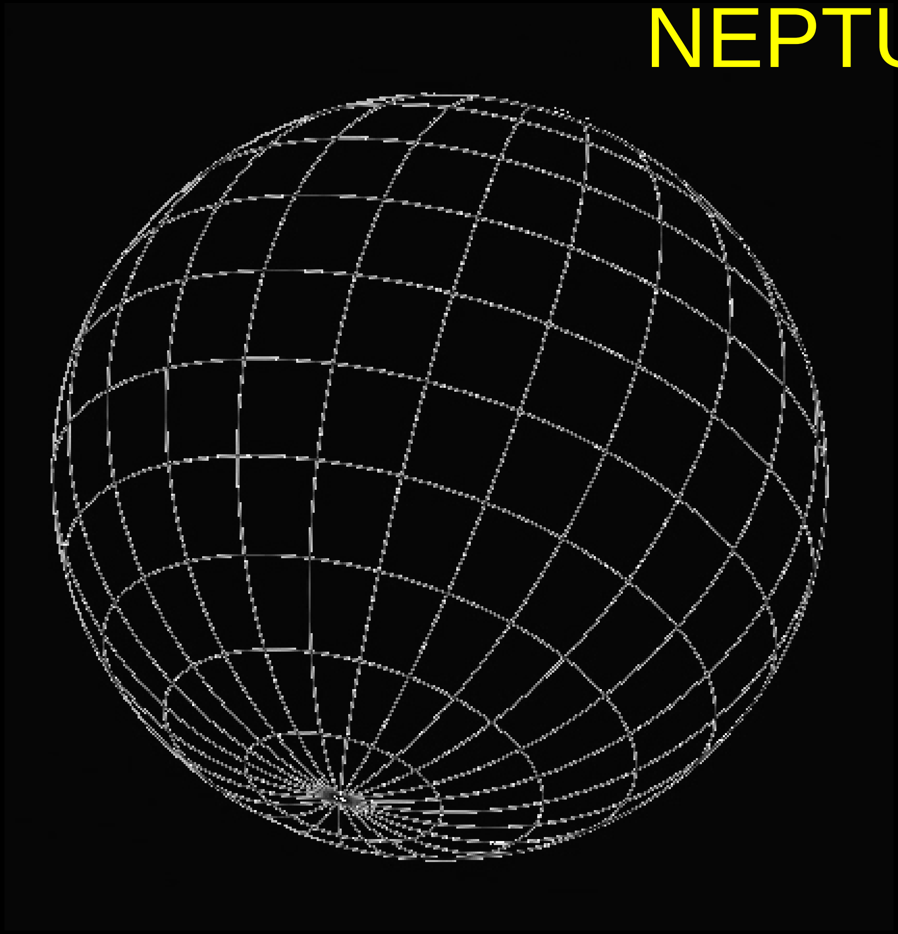


From Burgdorf et al. (2003) *Icarus* **164**, 244.

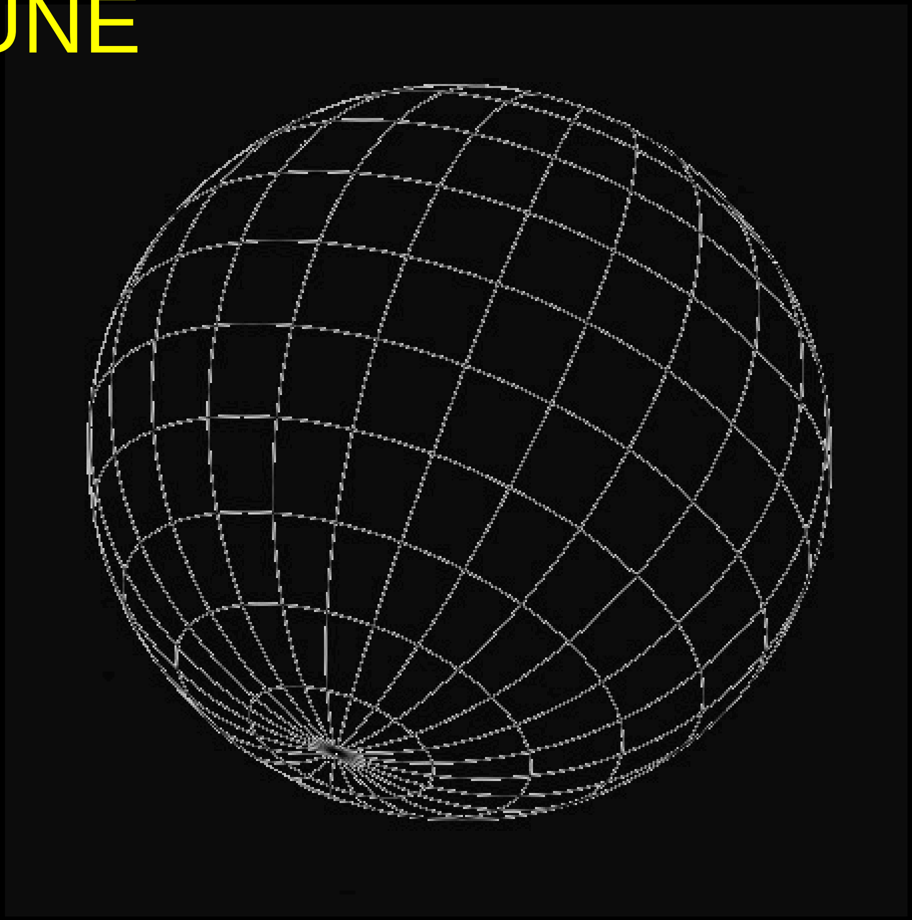


from Griffin and Orton (1993) Icarus 105, 537.

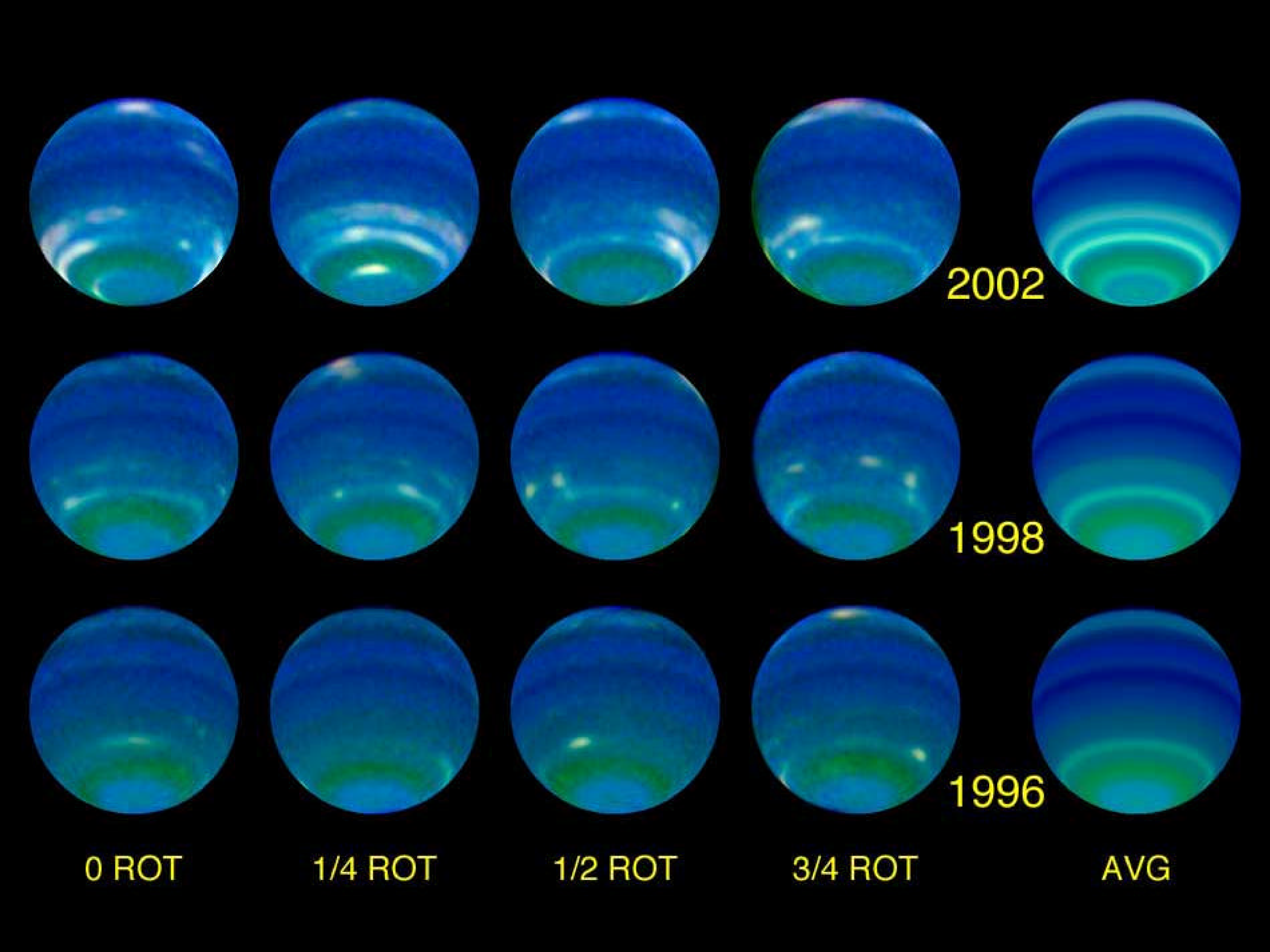
NEPTUNE



January 2007

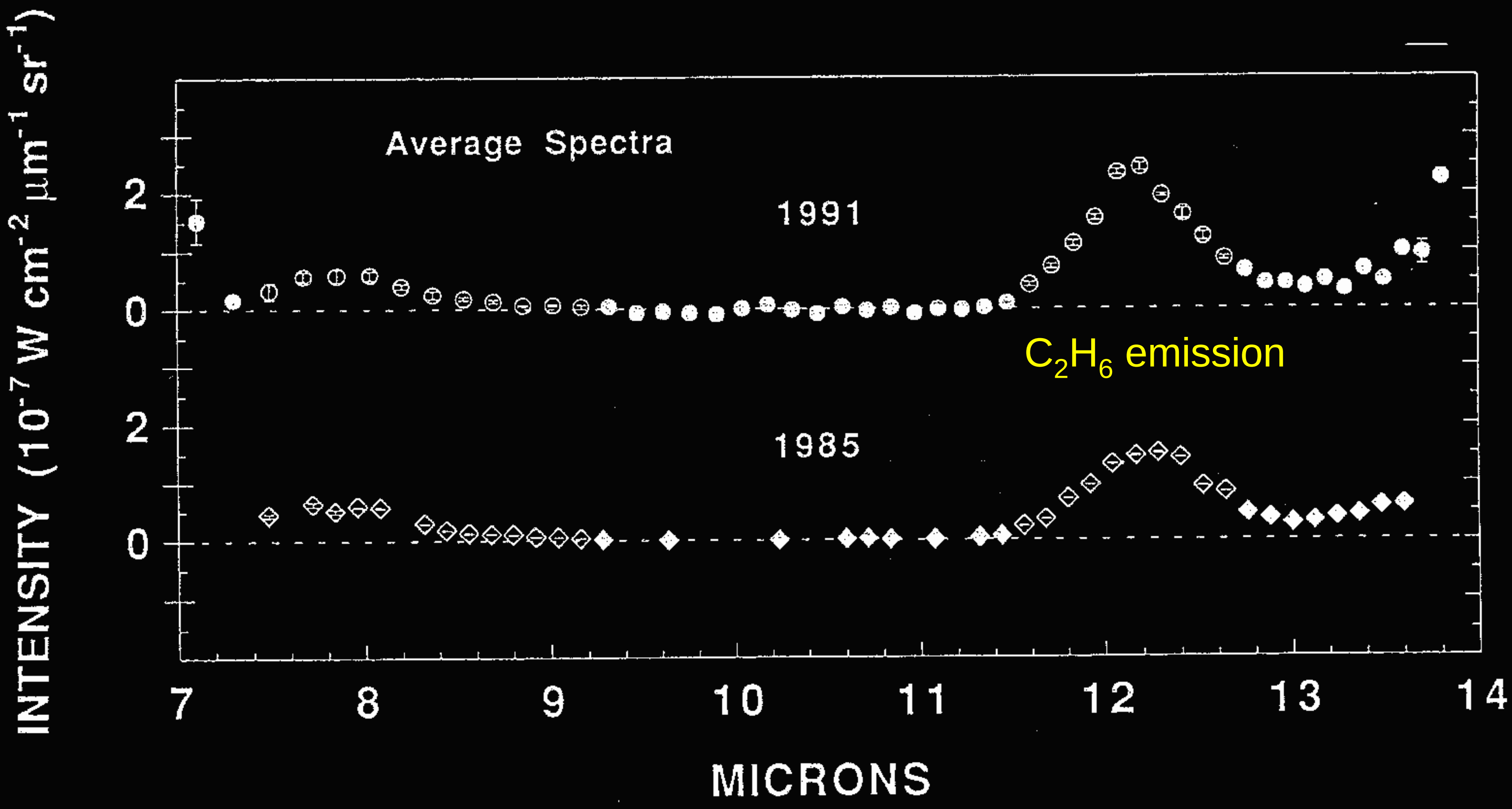


January 2010



2002
1998
1996
0 ROT
1/4 ROT
1/2 ROT
3/4 ROT
AVG

Neptune Long-Term Time Variability



From Hammel et al. (1992) *Icarus* **99**, 347.

pid 3534

prog_name: UN

pi: Glenn Orton

co-is: Martin Burgdorf, Vikki Meadows

Title: The Atmospheres of Uranus and Neptune:
A Time-Resolved Mid-Infrared Assessment of Their Energetic Processes

Abstract: We propose to measure variations of the 3 – 37 micron spectra of Uranus and Neptune to assess the spatial and temporal variations of temperatures, minor constituents, and cloud properties, using the IRS instrument…

Spitzer Space Telescope Nominal Science Operations

TargetName	PI	ProgName	pid	AOT	min_dur	Scheduled_Time(UTC)
Neptune - Lo 899 Neptune	Houck	IRS_MOON	71	irsstare	19.44	2004-05-15 00:58:27.8
Neptune - Lo 899 Neptune	Houck	IRS_MOON	71	irsstare	19.44	2004-05-15 06:16:39.1
Neptune - Lo 899 Neptune	Houck	IRS_MOON	71	irsstare	19.44	2004-05-15 12:12:10.2
Neptune - Lo 899 Neptune	Orton	UN	3534	irsstare	54.01	2004-11-15 22:35:47.4
Neptune - Lo 899 Neptune	Orton	UN	3534	irsstare	54.01	2004-11-16 03:11:40.6
Neptune - Lo 899 Neptune	Orton	UN	3534	irsstare	54.01	2004-11-16 07:50:02.3
Neptune – Lo 899 Neptune	Orton	UN	3534	irsstare	54.01	2004-11-16 12:37:06.0
Uranus - Lon 799 Uranus	Houck	IRS_MOON	71	irsstare	19.50	2004-11-12 20:00:45.4
Uranus - Lon 799 Uranus	Houck	IRS_MOON	71	irsstare	19.50	2004-11-12 20:00:45.4
Uranus - Lon 799 Uranus	Houck	IRS_MOON	71	irsstare	19.50	2004-11-13 02:03:16.6
Uranus – Lo 799 Uranus	Orton	UN	3534	irsstare	54.01	~2005-04
Uranus – Lo 799 Uranus	Orton	UN	3534	irsstare	54.01	~2005-04
Uranus – Lo 799 Uranus	Orton	UN	3534	irsstare	54.01	~2005-04
Uranus – Lo 799 Uranus	Orton	UN	3534	irsstare	54.01	~2005-04

ASTEROIDS and SATELLITES

• **“moderately bright”?**	**Pick bright ones:** **Ceres, Pallas, Vesta,** *Callisto*
• **compact?**	**yes**
• **non-variable?**	**not always**
• **spectrally continuous?**	**most likely**

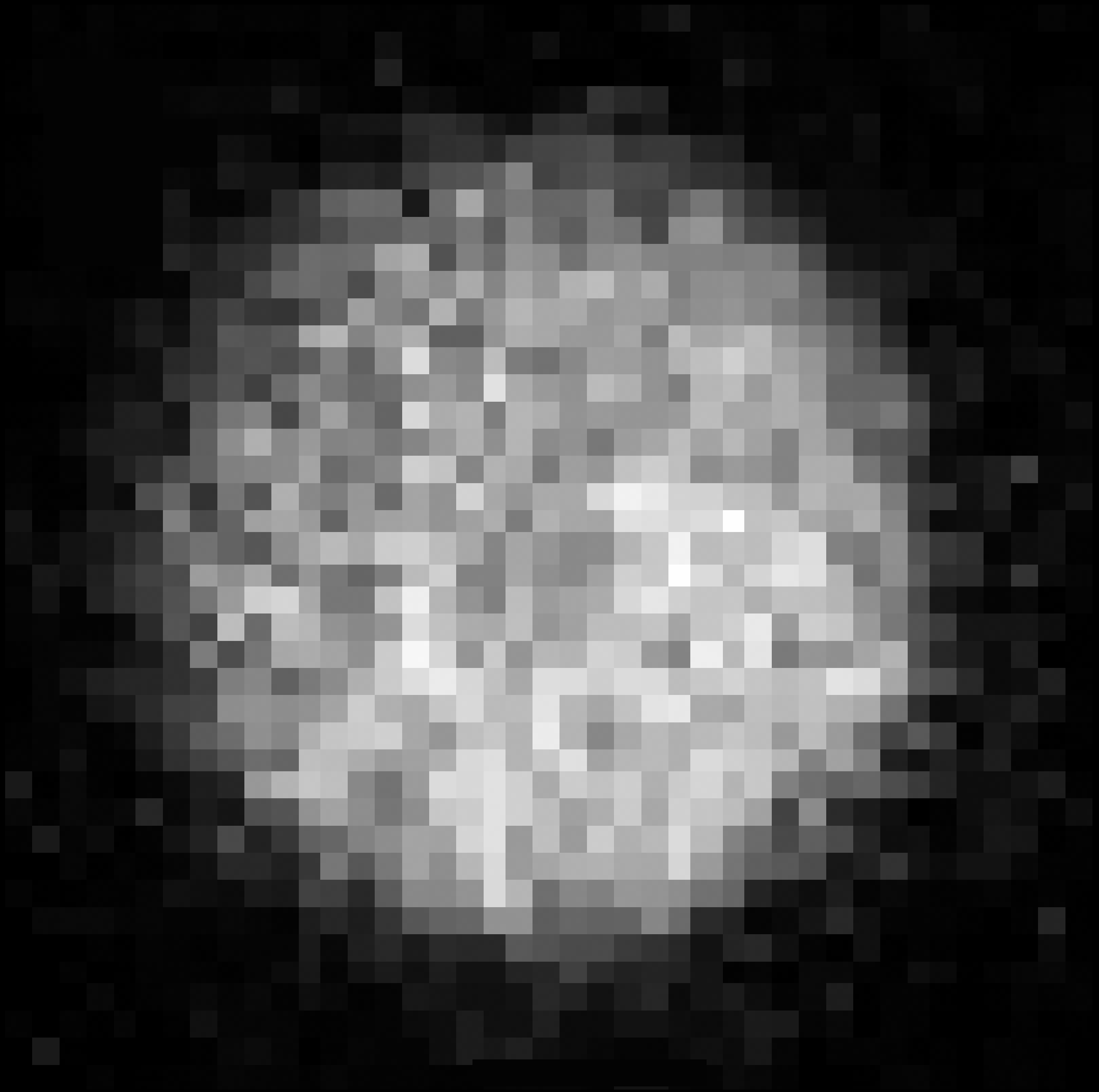
SOLID BODIES (ASTEROIDS & SATELLITES)

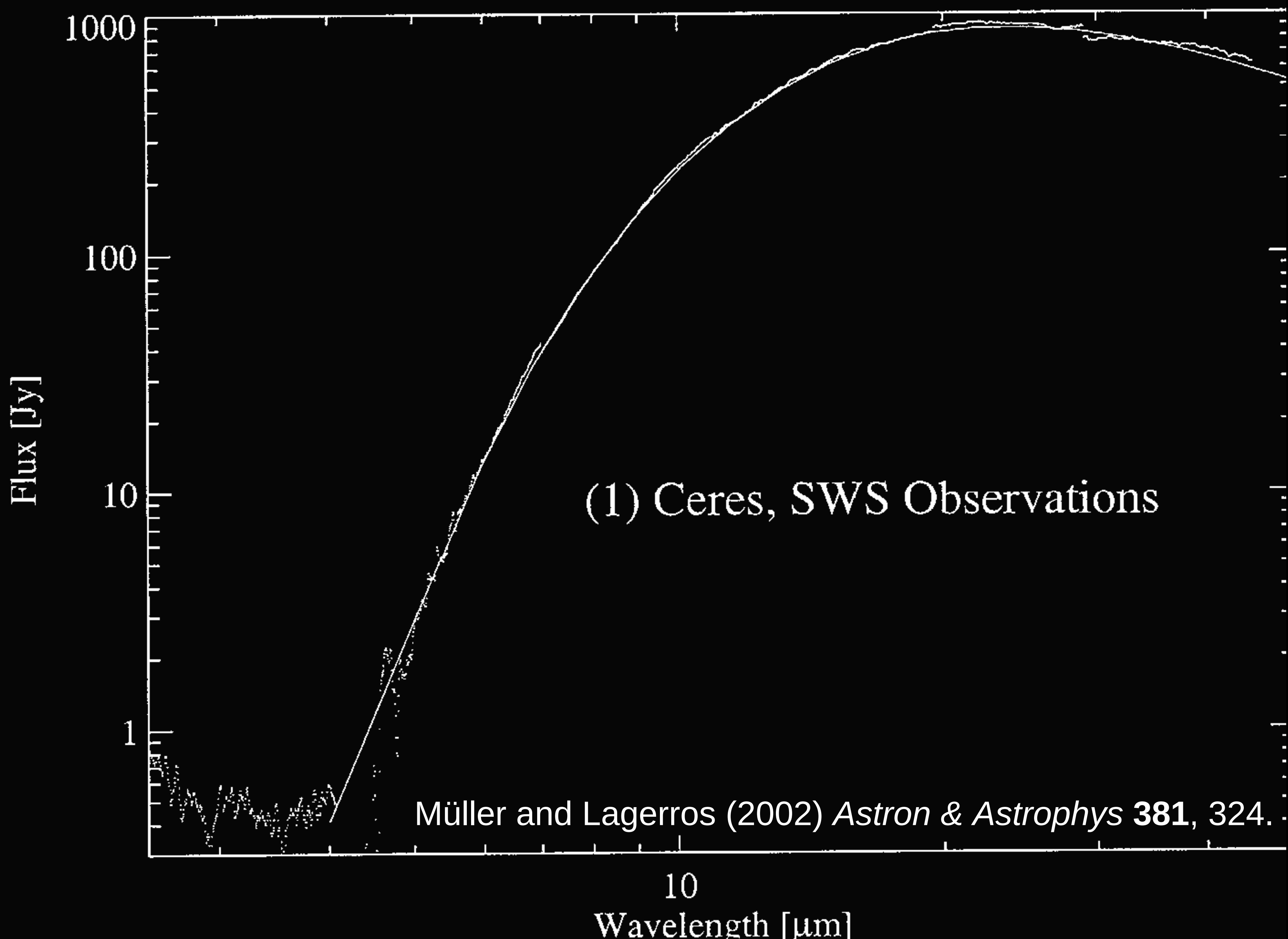
Thermal emission can be predicted from

• Size	known
• Albedo	known or deduced from infrared
• Shape and spin	pick a highly conductive spheroid !
• Observing and illumination geometry	known
• Surface roughness / beaming effect	defined via phase dependence
• Thermal inertia	defined via asymmetry of phase dependence (& probable composition)
• Spectral variation of emissivity • Regolith inhomogeneities (for radiation emerging from longer wavelengths)	require independent spectral calibration

Müller and Lagerros (2002) *Astron & Astrophys* 381, 324.

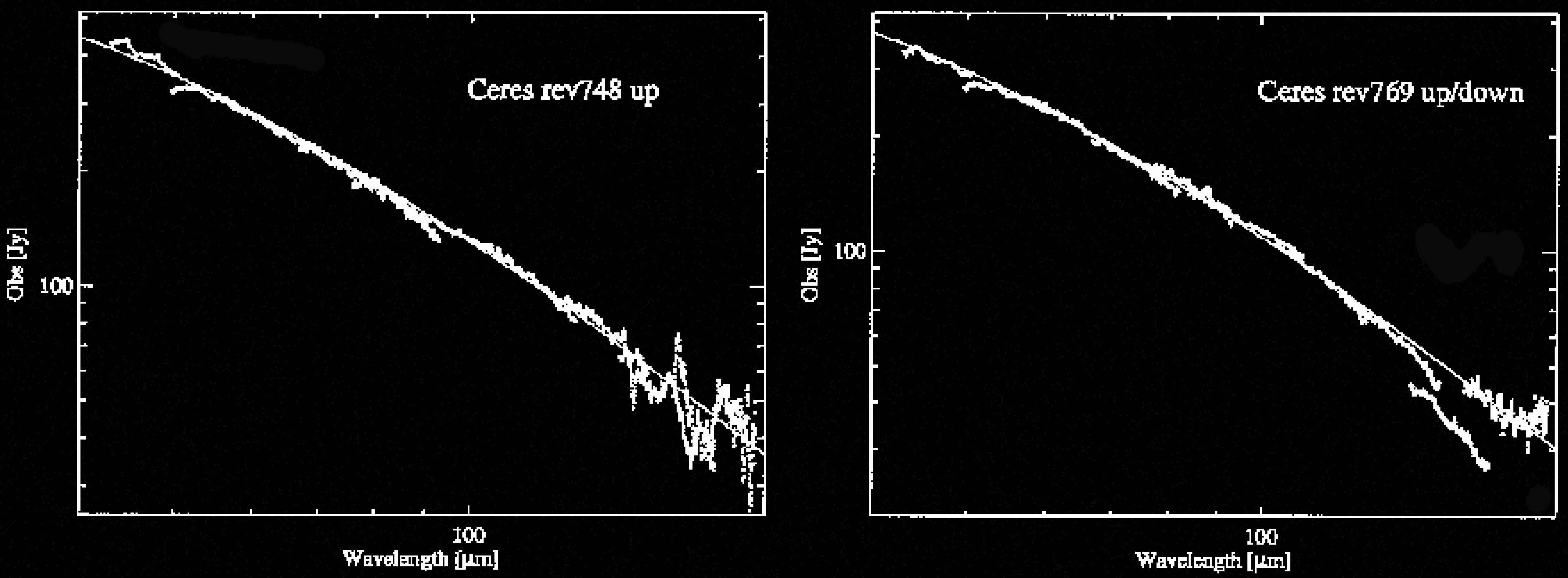
Ceres



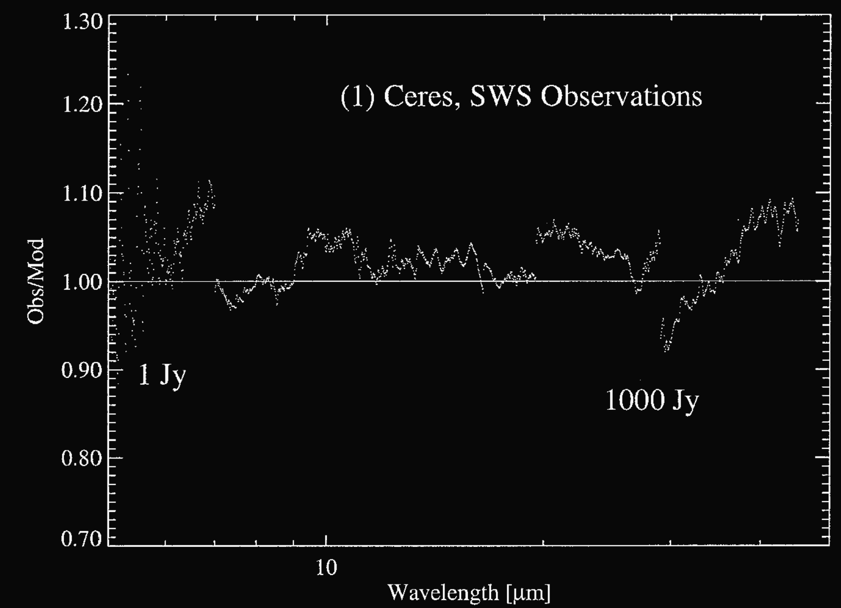


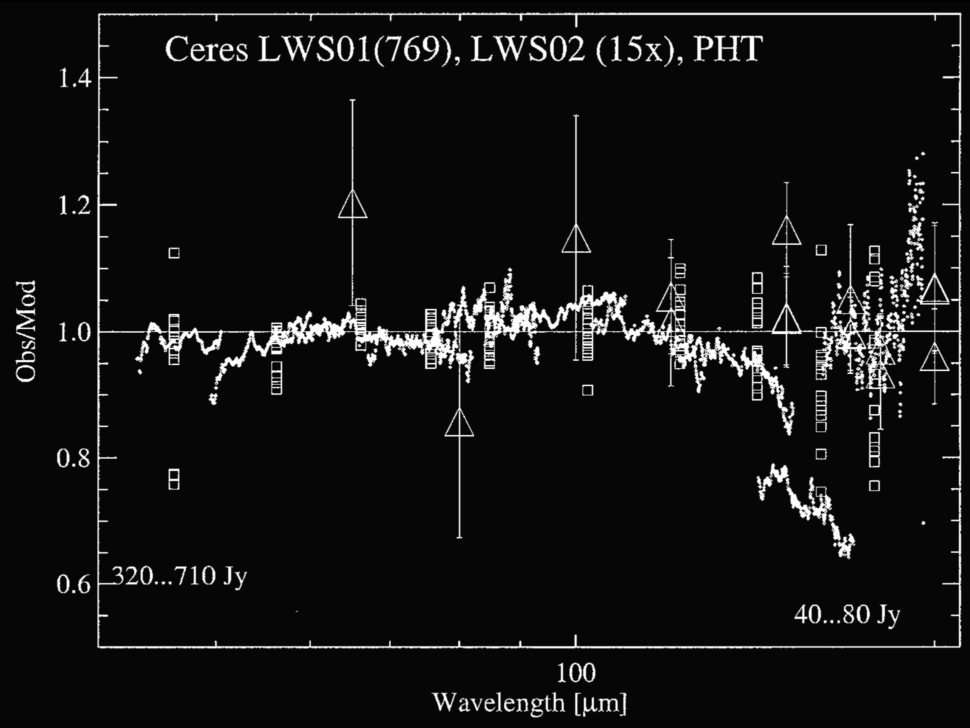
Müller and Lagerros (2002) *Astron & Astrophys* **381**, 324.

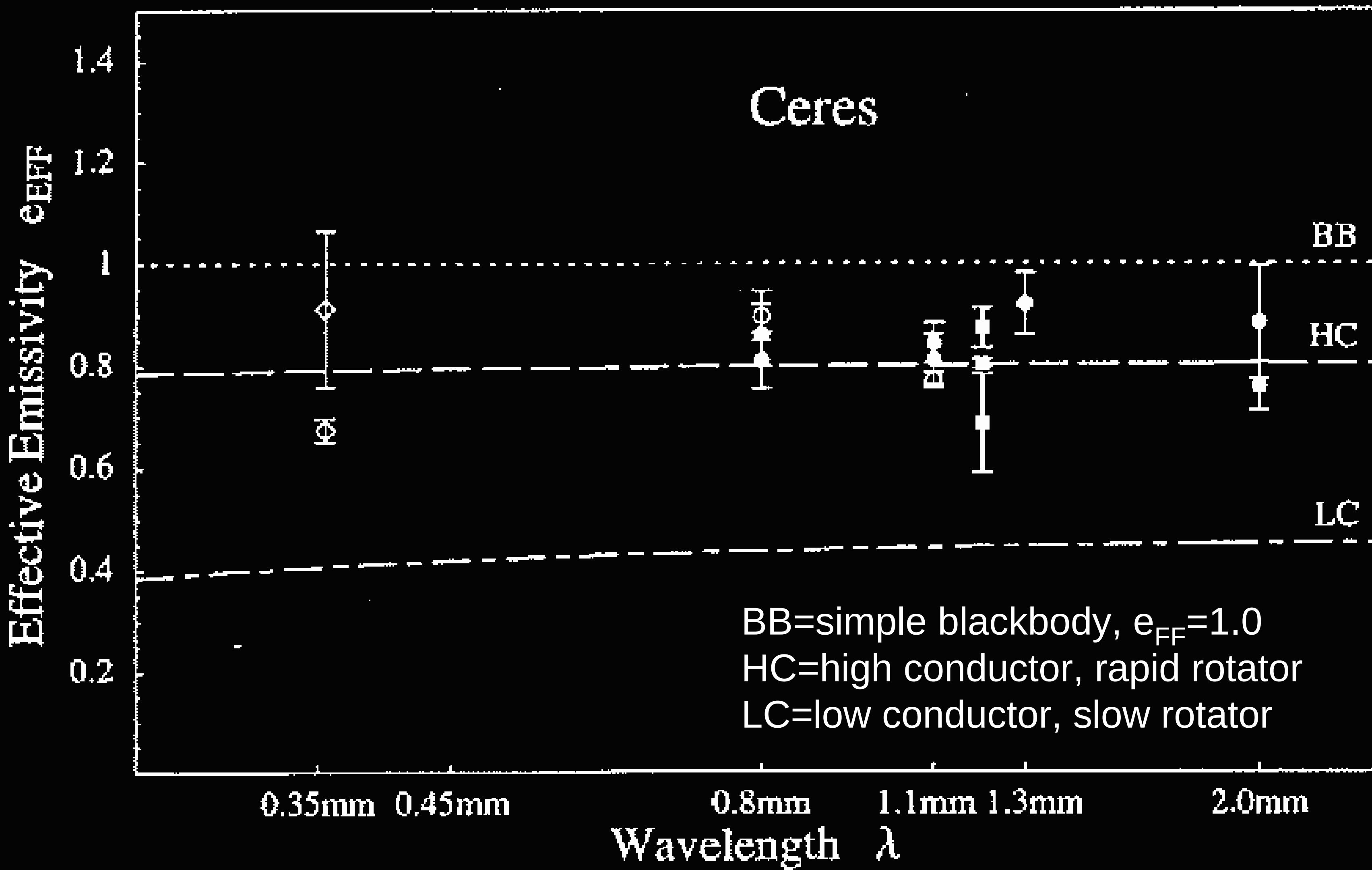
ISO LWS observations of Ceres



Müller and Lagerros (2002) *Astron & Astrophys* **381**, 324.

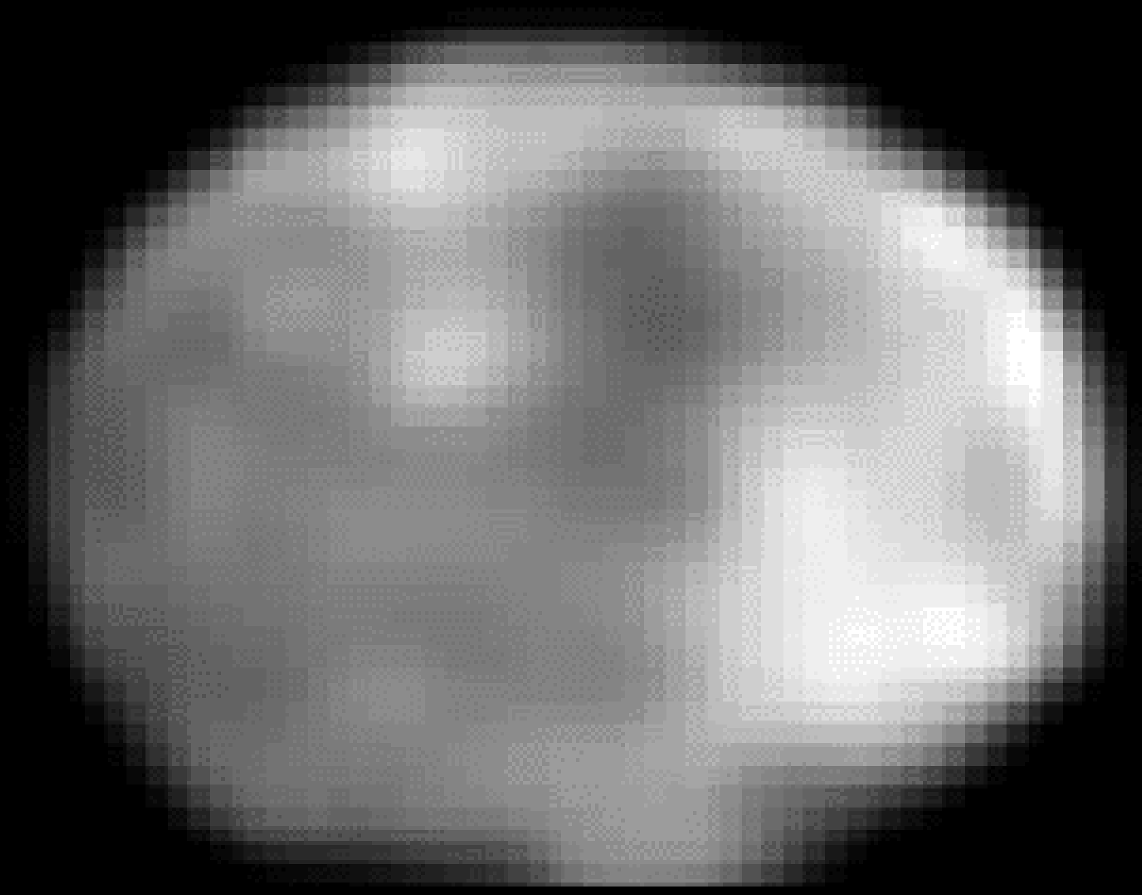

(1) Ceres, SWS Observations
Obs/Mod
1.30
1.20
1.10
1.00
0.90
0.80
0.70
1 Jy
1000 Jy
10
Wavelength [μm]


Ceres LWS01(769), LWS02 (15x), PHT
Obs/Mod
1.4
1.2
1.0
0.8
0.6
320...710 Jy
40...80 Jy
100
Wavelength [μm]



From Redman et al. Astron. J. (1998) 116, 1478

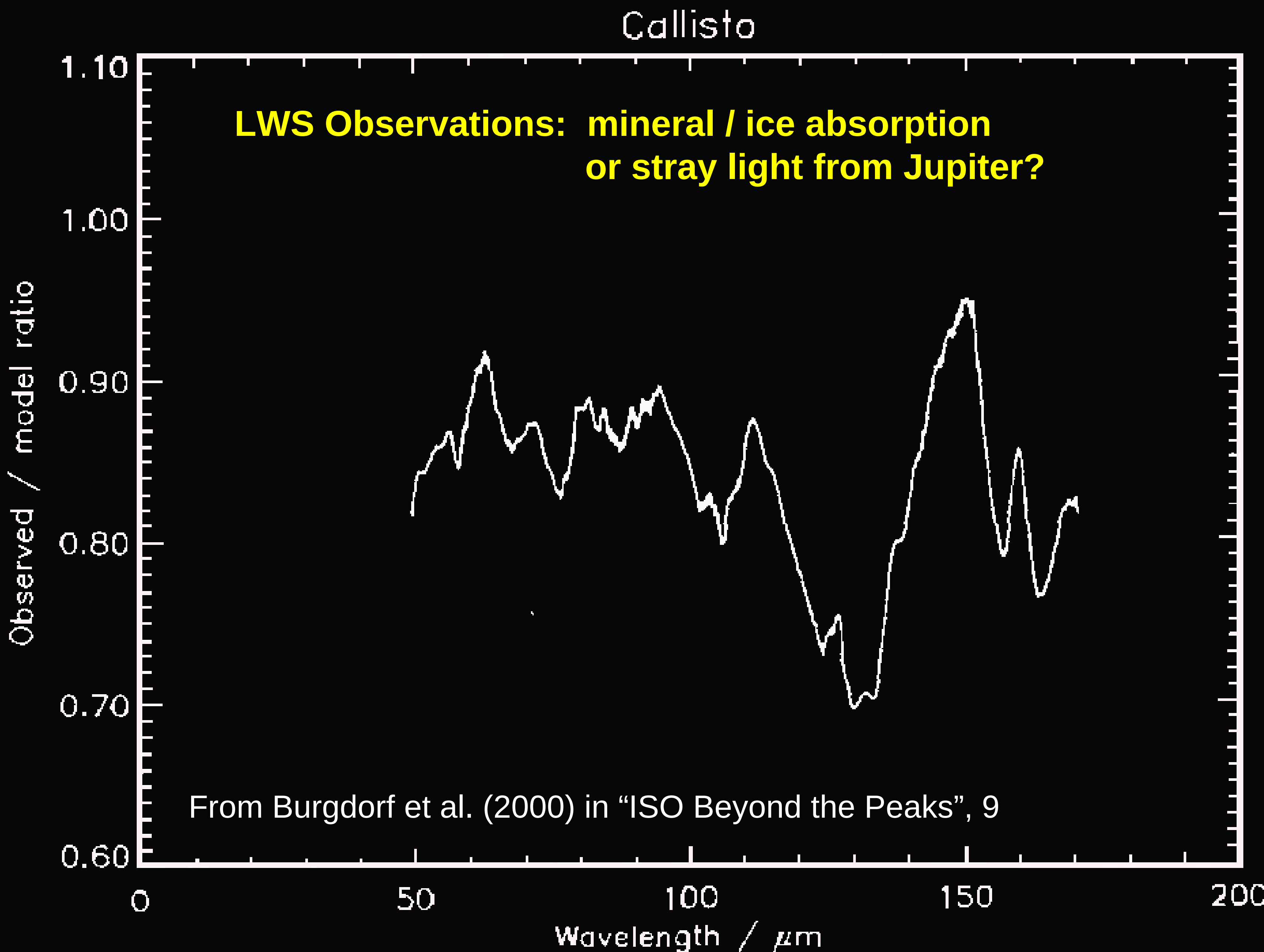
VESTA (HST)



(not exactly a **billiard** ball: how important is spin phase dependence?)

Callisto

← Jupiter
618”


Callisto
LWS Observations: mineral / ice absorption
or stray light from Jupiter?
1.10
1.00
0.90
0.80
0.70
0.60
Observed / model ratio
0
50
100
150
200
Wavelength / μm
From Burgdorf et al. (2000) in “ISO Beyond the Peaks”, 9

Recommendations

Primary Objects

- Uranus (bright, bland, ellipsoidal)
  - assess spatial and temporal variability
  - reassess spectrum in far-infrared through millimeter
- Ceres (bright, bland, spherical)

  …or other spherical asteroids sufficiently bright
  - assess spectrum, spatial variability

Ancillary Objects

- Neptune (possibly more time variable than Uranus)
- Callisto (if Jupiter stray light is not a problem)

If Nothing Else is Available

- Mars (check for dust storms)
- Jupiter (use detailed spectral model, use with ground-based mapping)
- Non-Spherical Asteroids (determine dependence on spin phase)

Develop Calibration System Among Primary and Ancillary Objects