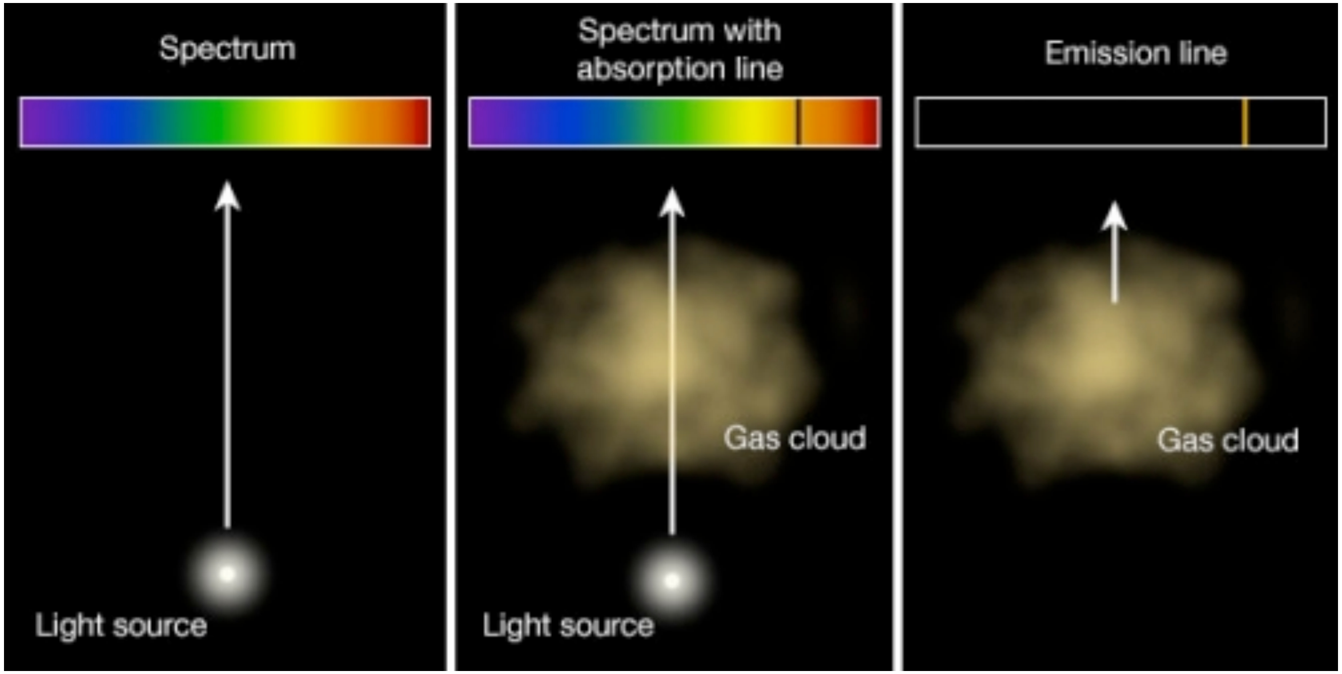
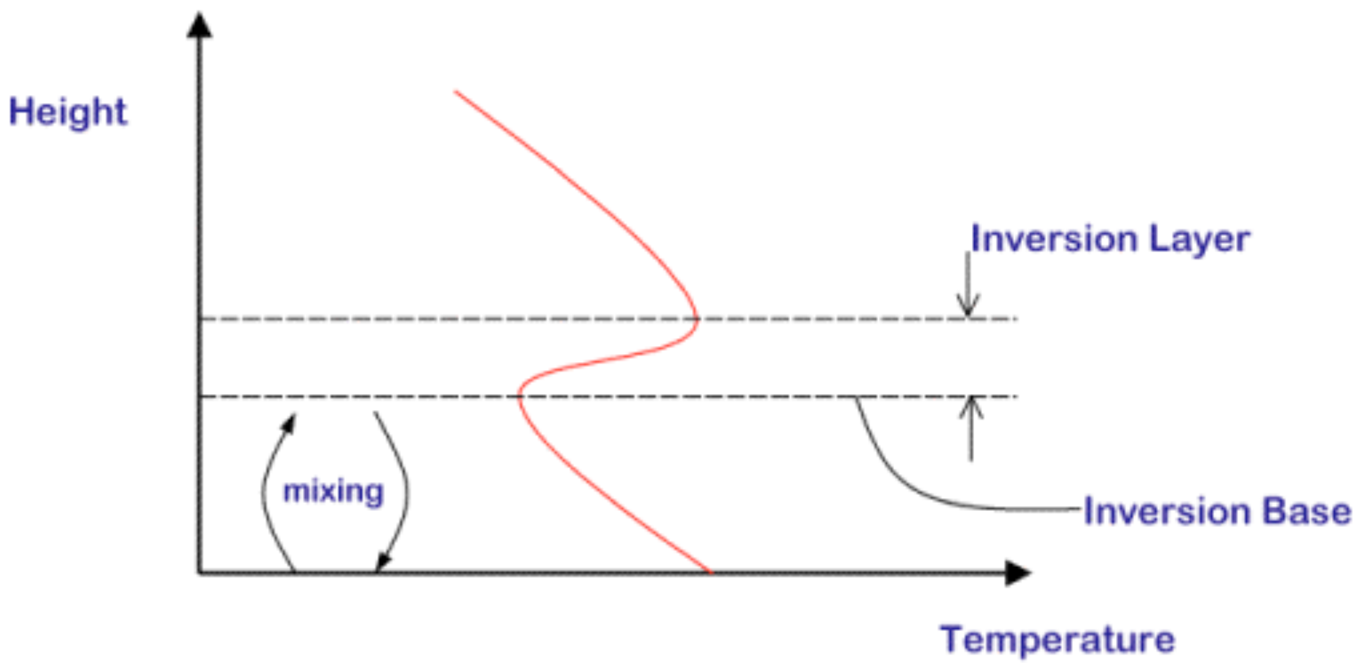
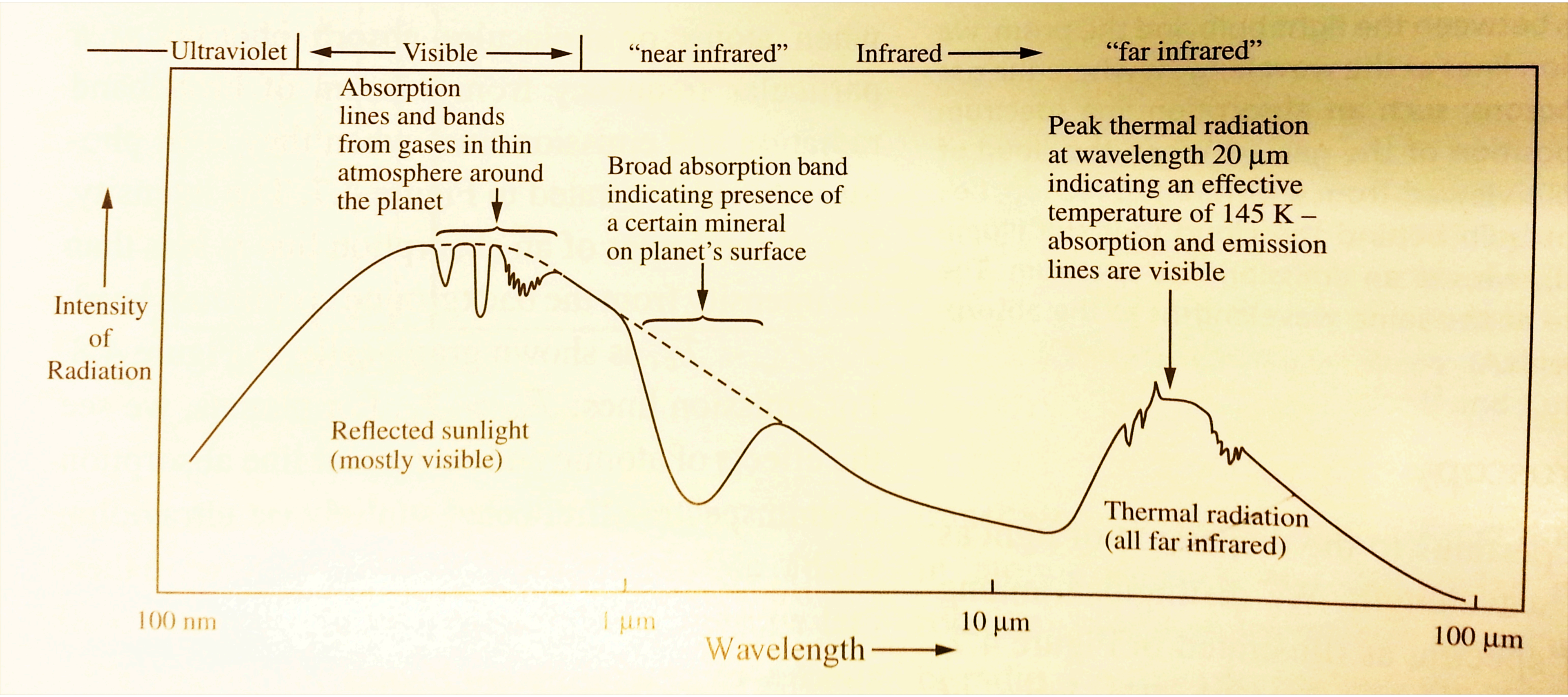
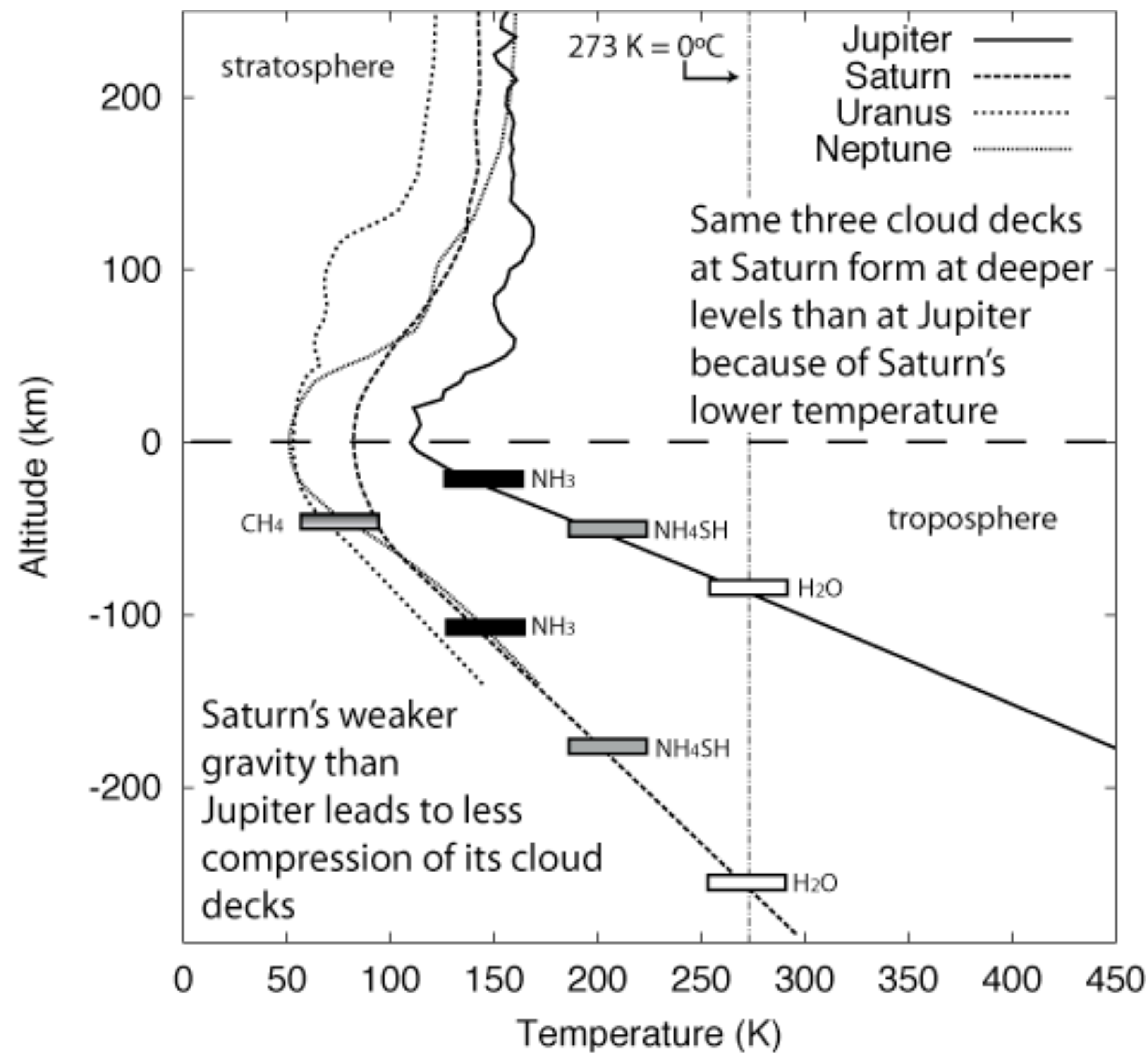
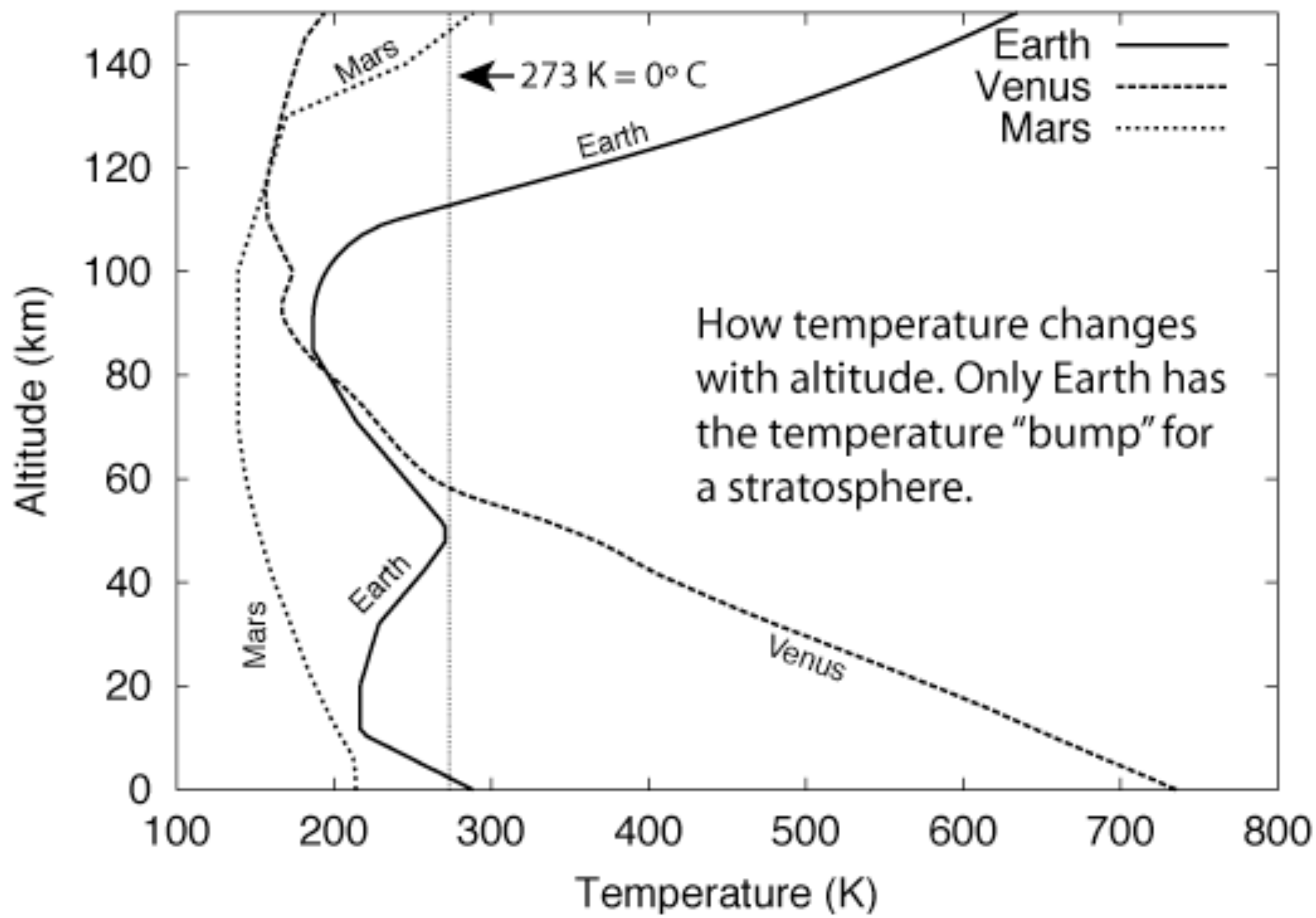

Spectrum
Light source
Spectrum with absorption line
Gas cloud
Light source
Emission line
Gas cloud


Height
Inversion Layer
mixing
Inversion Base
Temperature

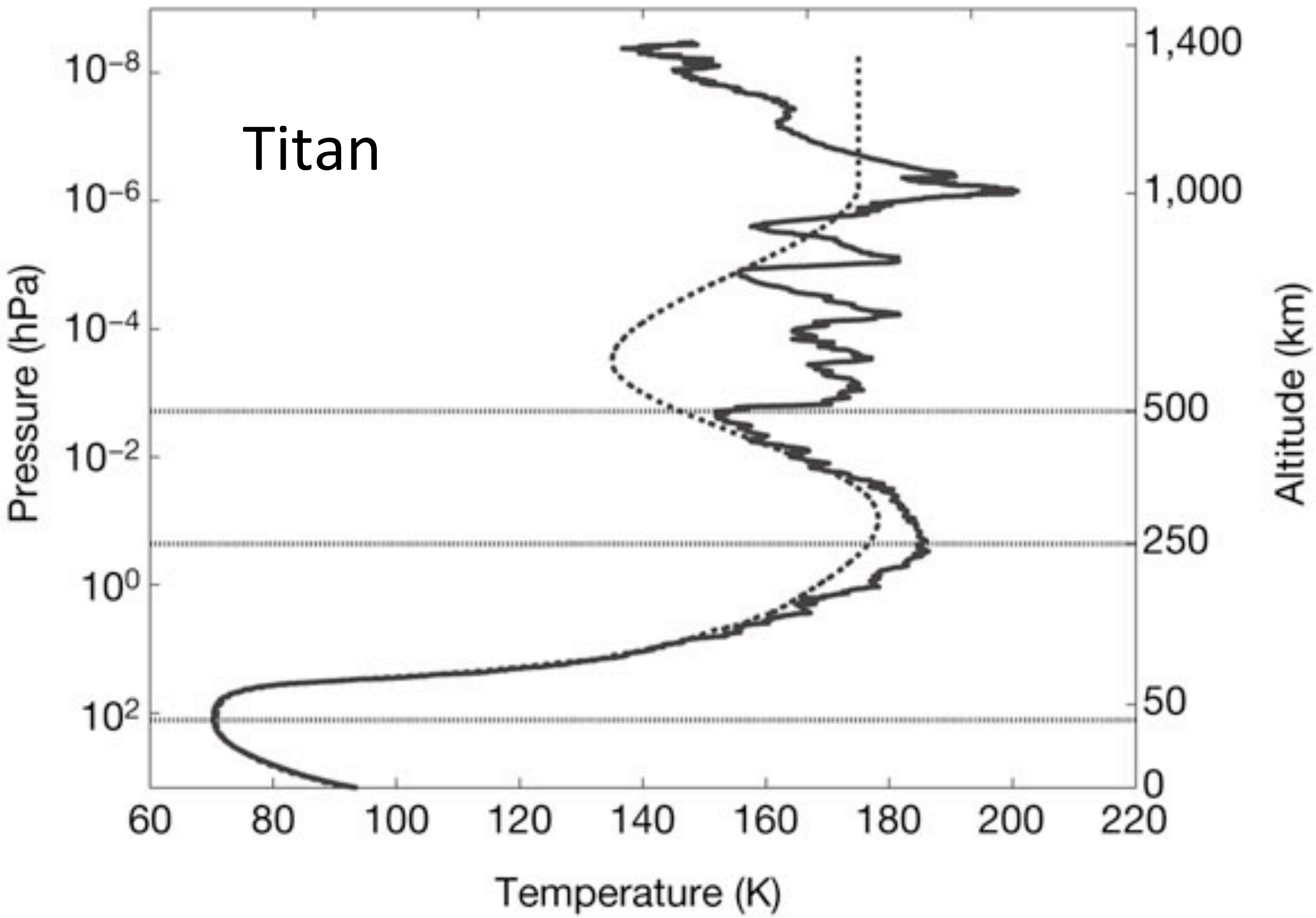
Schematic of Radiation from a Planet



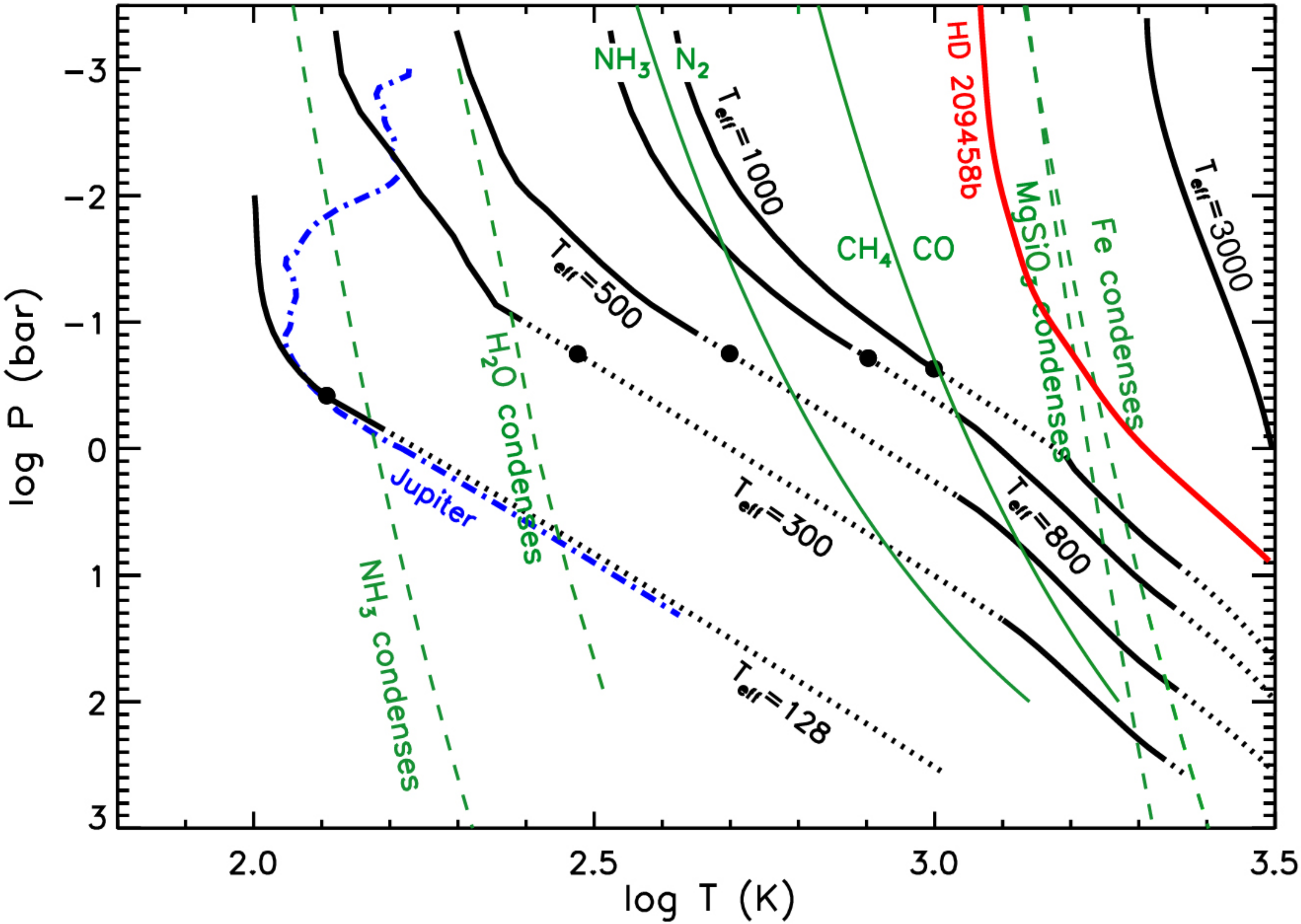

stratosphere
273 K = 0ºC
Jupiter
Saturn
Uranus
Neptune
Same three cloud decks at Saturn form at deeper levels than at Jupiter because of Saturn's lower temperature
NH3
CH4
NH4SH
H2O
troposphere
NH3
Saturn's weaker gravity than Jupiter leads to less compression of its cloud decks
NH4SH
H2O
Altitude (km)
200
100
0
-100
-200
0
50
100
150
200
250
300
350
400
450
Temperature (K)



Earth
Venus
Mars
273 K = 0° C
Mars
Earth
Earth
Mars
Venus
How temperature changes with altitude. Only Earth has the temperature "bump" for a stratosphere.
Altitude (km)
0
20
40
60
80
100
120
140
100
200
300
400
500
600
700
800
Temperature (K)

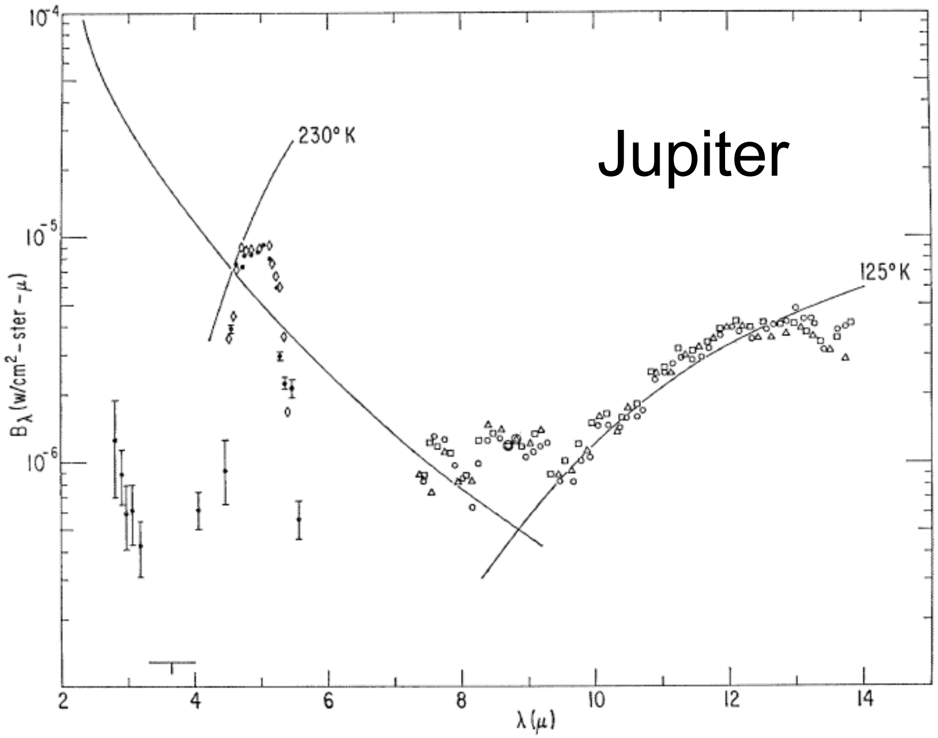


The antigreenhouse effect on Titan reducesthe surface temperature by 9 K whereas the greenhouse effect increasesit by 21 K. The net effectis that the surface temperature (94 K) is 12 K warmer than the effective temperature (82 K). If the haze layer were removed, the antigreenhouse effect would be greatly reduced, the greenhouse effect would become even stronger, and the surface temperature would rise by over 20 K.



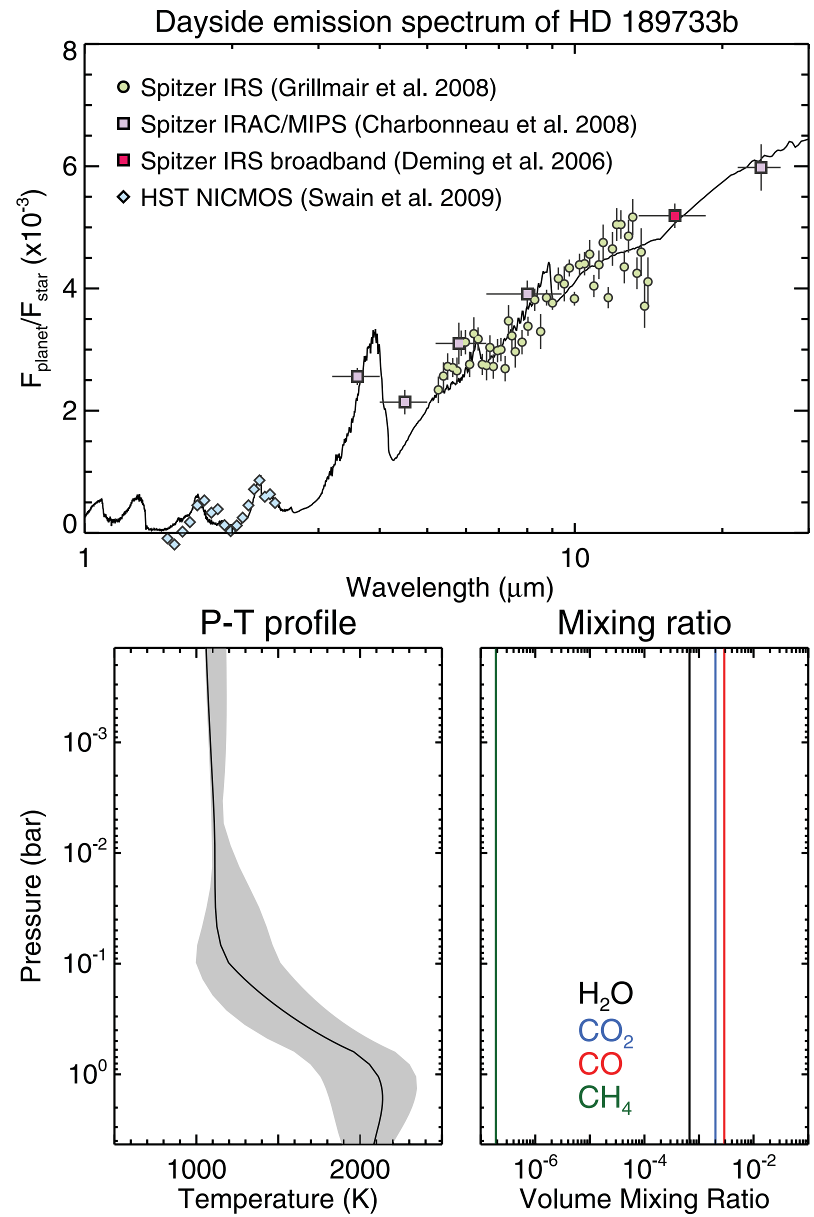
log P (bar)
log T (K)
−3
−2
−1
0
1
2
3
2.0
2.5
3.0
3.5
NH3
N2
CH4
CO
HD 209458b
Teff=1000
Teff=3000
MgSiO3 condenses
Fe condenses
Teff=500
H2O condenses
Teff=300
Teff=800
Jupiter
NH3 condenses
Teff=128

We're 40 years behind work in the Solar System



Gillett, Low, & Stein (1969)

- CH_4 dominant mid IR absorber
- Temperature inversion from 7.8 μm CH_4 band
- Bright at 5 μm – high T_{bright}



Lee et al. (2012)

A scientific case study: 2007-2013

I try to understand what planets around other stars "are like." How hot are they, what are they made of, how do the change with time?

It was known in 2007 that some "hot Jupiters" (gas giant, Jupiter-like planets that orbit very close to their parents) had **hot upper atmospheres** and some had **cold upper atmospheres**

Whether or not the upper atmosphere is hot or cold changes the amount of **infrared light** that these planets emit

In 2008 I thought that I had figured this out

The Astrophysical Journal, 678:1419–1435, 2008 May 10

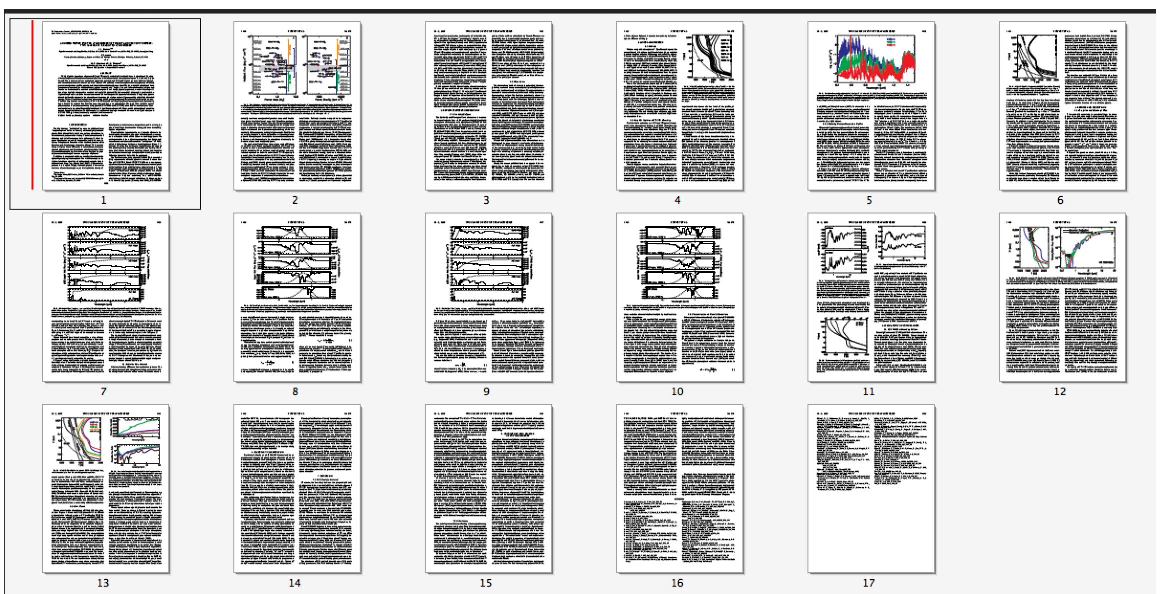
A UNIFIED THEORY FOR THE ATMOSPHERES OF THE HOT AND VERY HOT JUPITERS: TWO CLASSES OF IRRADIATED ATMOSPHERES

J. J. Fortney[1,2,3]
Space Science and Astrobiology Division, Mail Stop 245-3, NASA Ames Research Center, Moffett Field, CA 94035; jfortney@ucolick.org

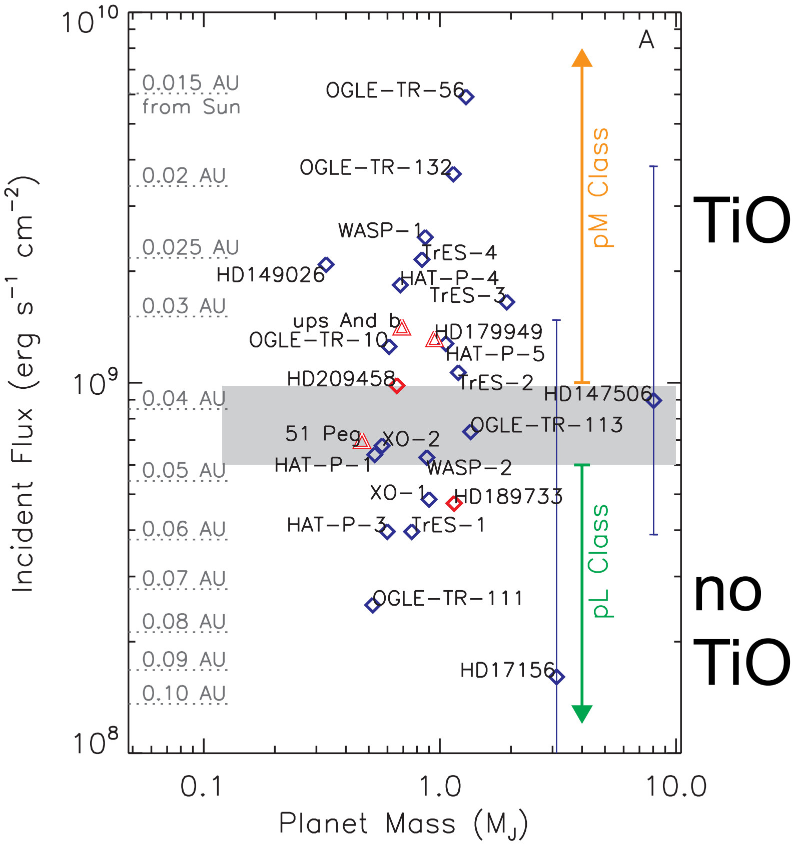
K. Lodders
Planetary Chemistry Laboratory, Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130

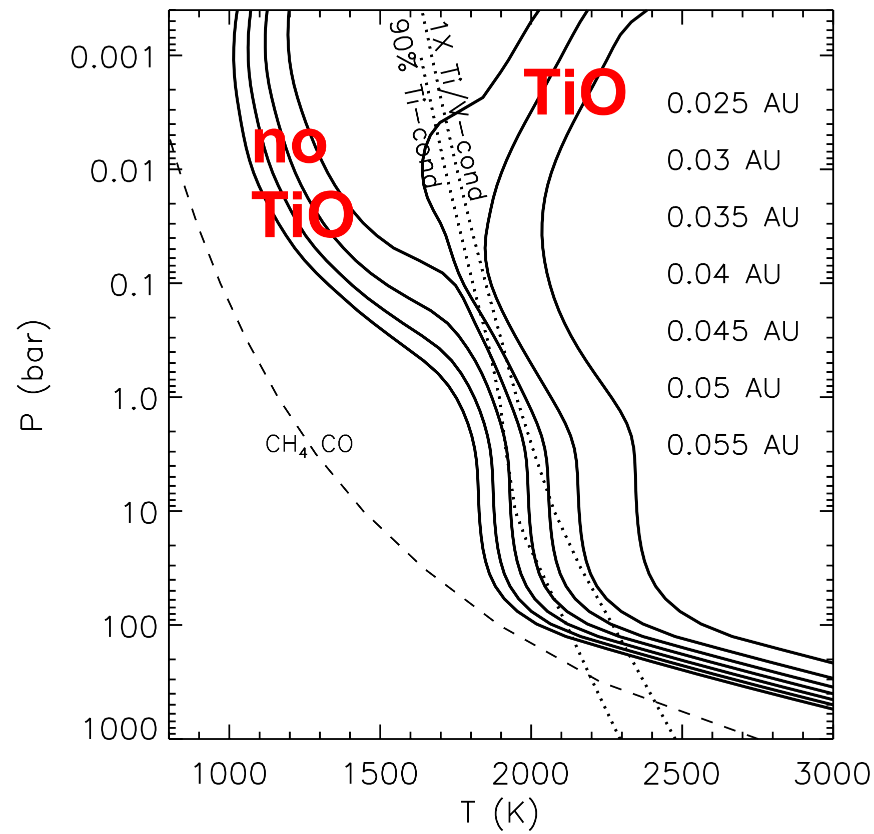
and

M. S. Marley and R. S. Freedman[2]
Space Science and Astrobiology Division, Mail Stop 245-3, NASA Ames Research Center, Moffett Field, CA 94035
Received 2007 September 4; accepted 2007 December 7



I proposed two class of "hot Jupiters"





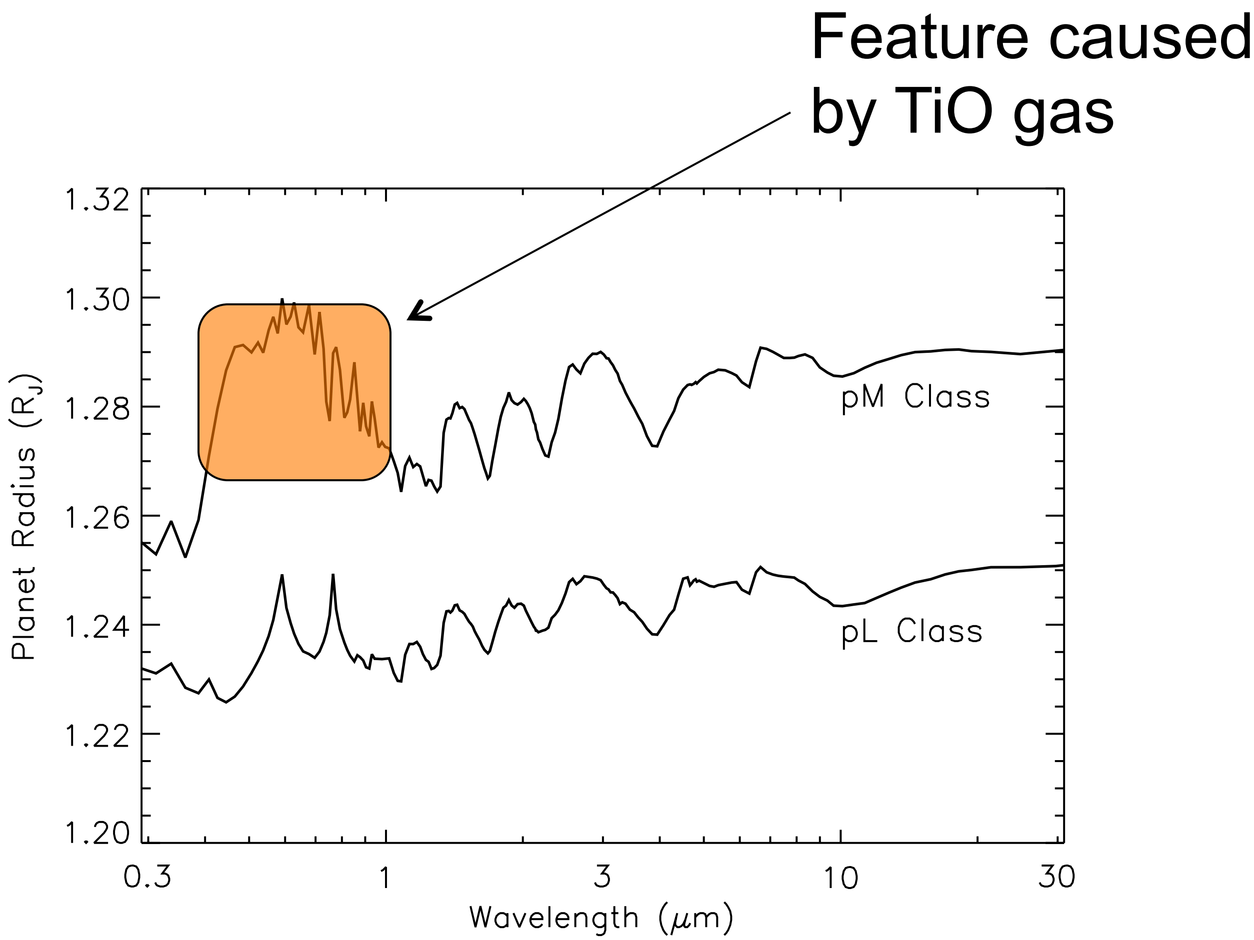
- The hottest planets have **TiO molecules** in their atmosphere, which can strongly absorb starlight at low pressures, which heats the upper atmospheres
- The colder planets should **not have this molecule** in their atmosphere, because at cold temperatures it converts to a different molecule

I discussed in a lot of detail why this theory was consistent with all observational data available at that time

Only about 4 planets had been observed by that time, but since it matched all data, one could probably call it a **theory** rather than a **hypothesis**

If there had been no data, and I had suggested how the planets would behave, then **hypothesis** might have been better

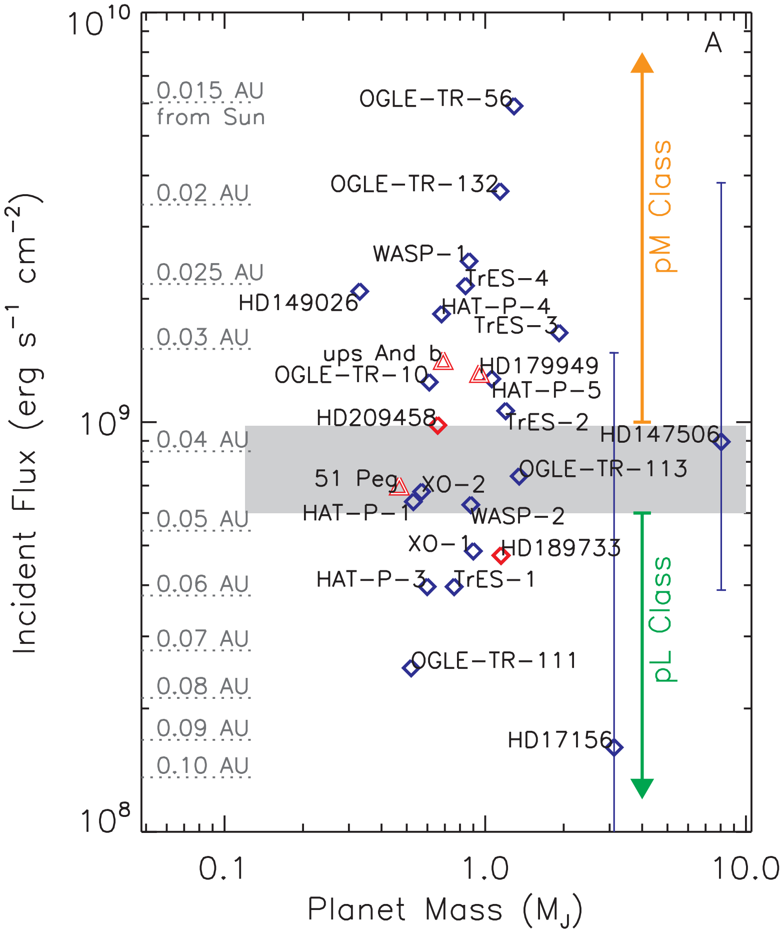
I suggested a variety of different and new observations that could confirm or refute my theory



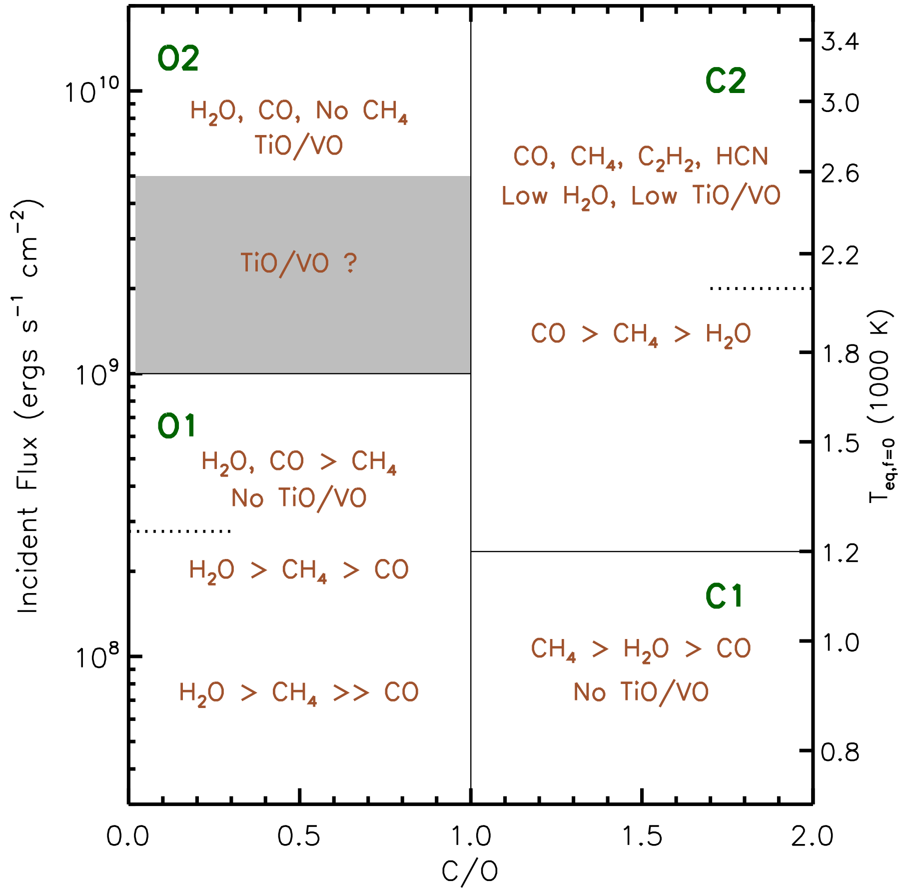
I was wrong.

- Now about 40 planets have been observed, and there is **no evidence for TiO** molecules in any planet!
- However, about 1/3 of the hot Jupiters do have a hot upper atmosphere, and we still don't know why
  - However, some of the hot planets lack hot upper atmospheres
  - Some of the colder planets do have hot upper atmospheres
- Additional classification systems have been proposed

A potential new scheme for classification



Mine (2008)



Another (2012)

We may be stuck for awhile

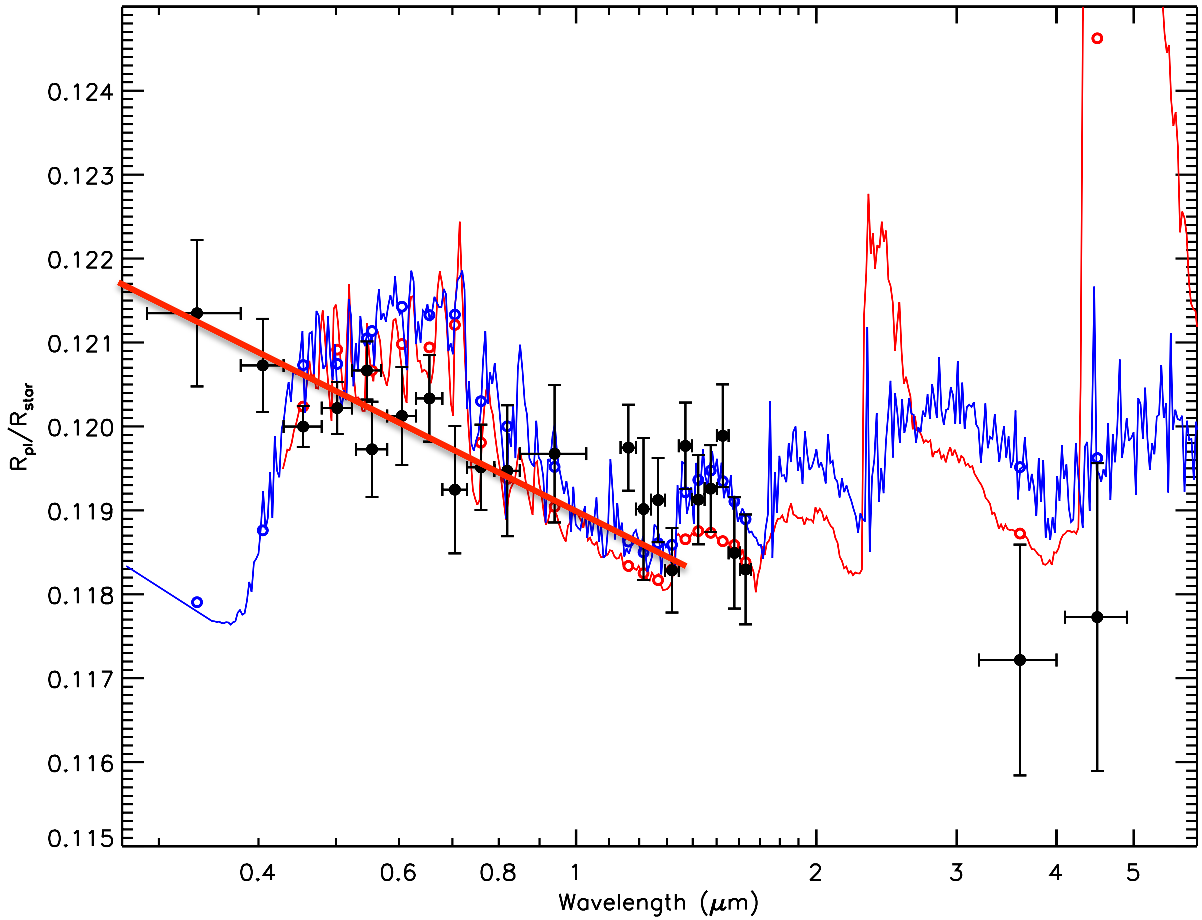
- We probably need better observations to figure out what is really going on in these atmospheres
- Like in much of astronomy, and other sciences, we need new tools (the James Webb Space Telescope, launching 2018) to obtain more and better data

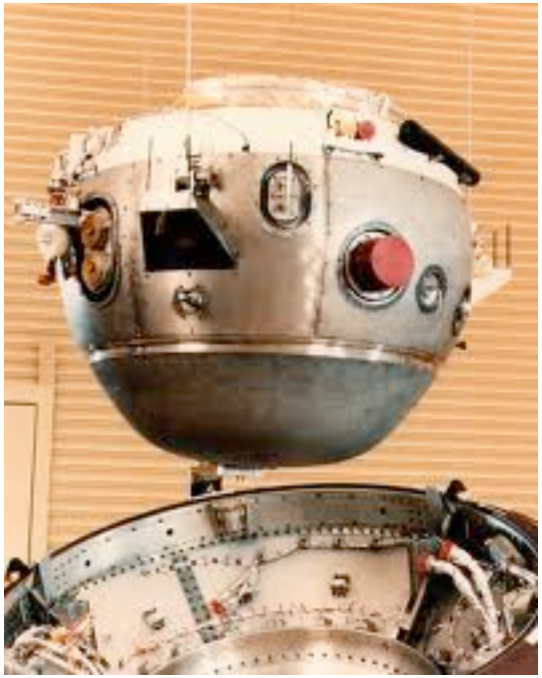
HST hot Jupiter transmission spectral survey: evidence for aerosols and lack of TiO in the atmosphere of WASP-12b

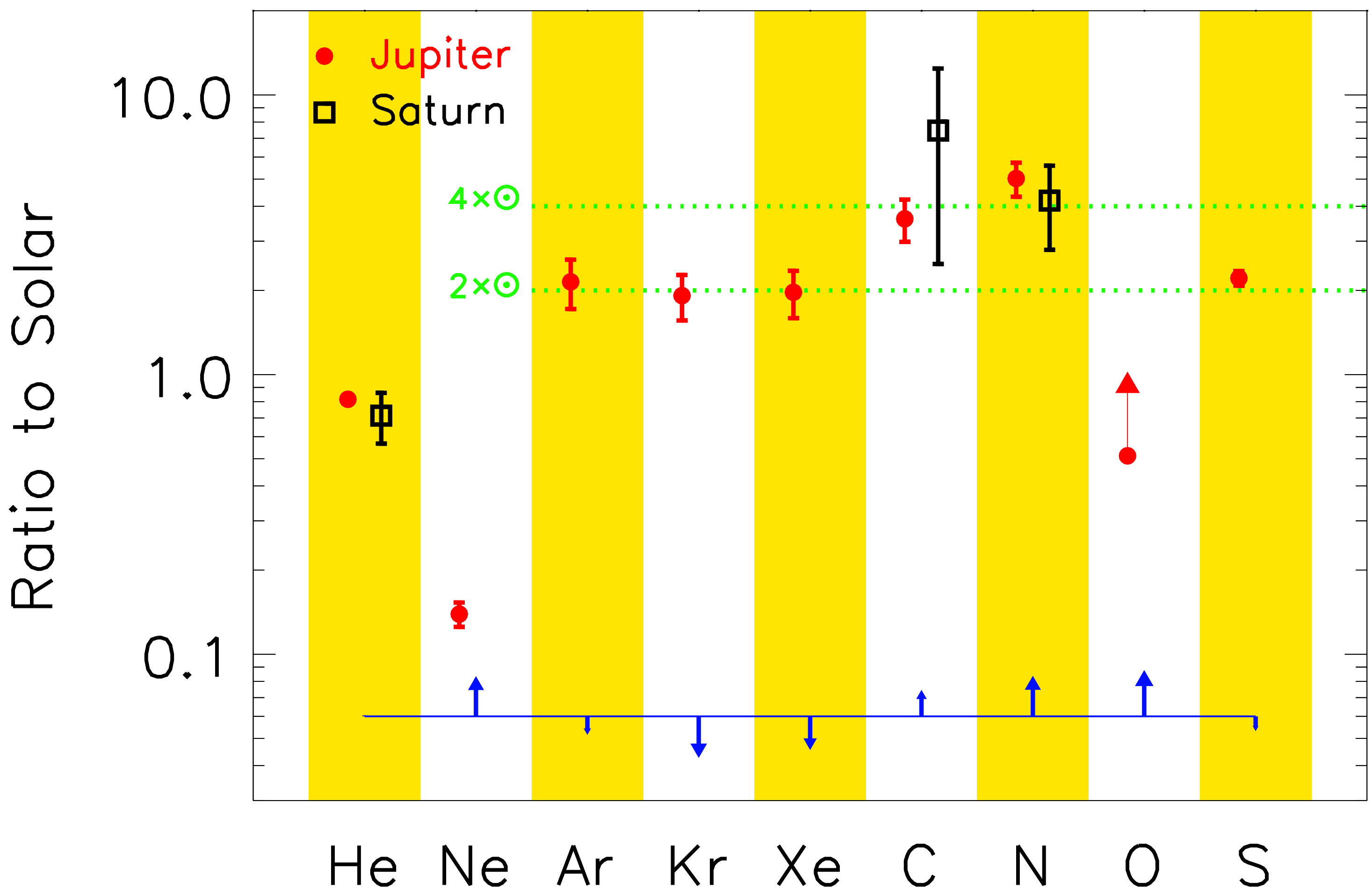
D. K. Sing[1⋆], A. Lecavelier des Etangs[2], J. J. Fortney[3], A. S. Burrows[4], F. Pont[1], H. R. Wakeford[1], G. E. Ballester[5], N. Nikolov[1], G. W. Henry[6], S. Aigrain[7], D. Deming[8], T. M. Evans[7], N. P. Gibson[9], C. M. Huitson[1], H. Knutson[10], A. P. Showman[7], A. Vidal-Madjar[2], P. A. Wilson[1], M. H. Williamson[5], K. Zahnle[11]

HST hot Jupiter transmission spectral survey: evidence for aerosols and lack of TiO in the atmosphere of WASP-12b

D. K. Sing[1⋆], A. Lecavelier des Etangs[2], J. J. Fortney[3], A. S. Burrows[4], F. Pont[1], H. R. Wakeford[1], G. E. Ballester[5], N. Nikolov[1], G. W. Henry[6], S. Aigrain[7], D. Deming[8], T. M. Evans[7], N. P. Gibson[9], C. M. Huitson[1], H. Knutson[10], A. P. Showman[7], A. Vidal-Madjar[2], P. A. Wilson[1], M. H. Williamson[5], K. Zahnle[11]






Jupiter
Saturn
10.0
1.0
0.1
Ratio to Solar
4×⊙
2×⊙
He
Ne
Ar
Kr
Xe
C
N
O
S

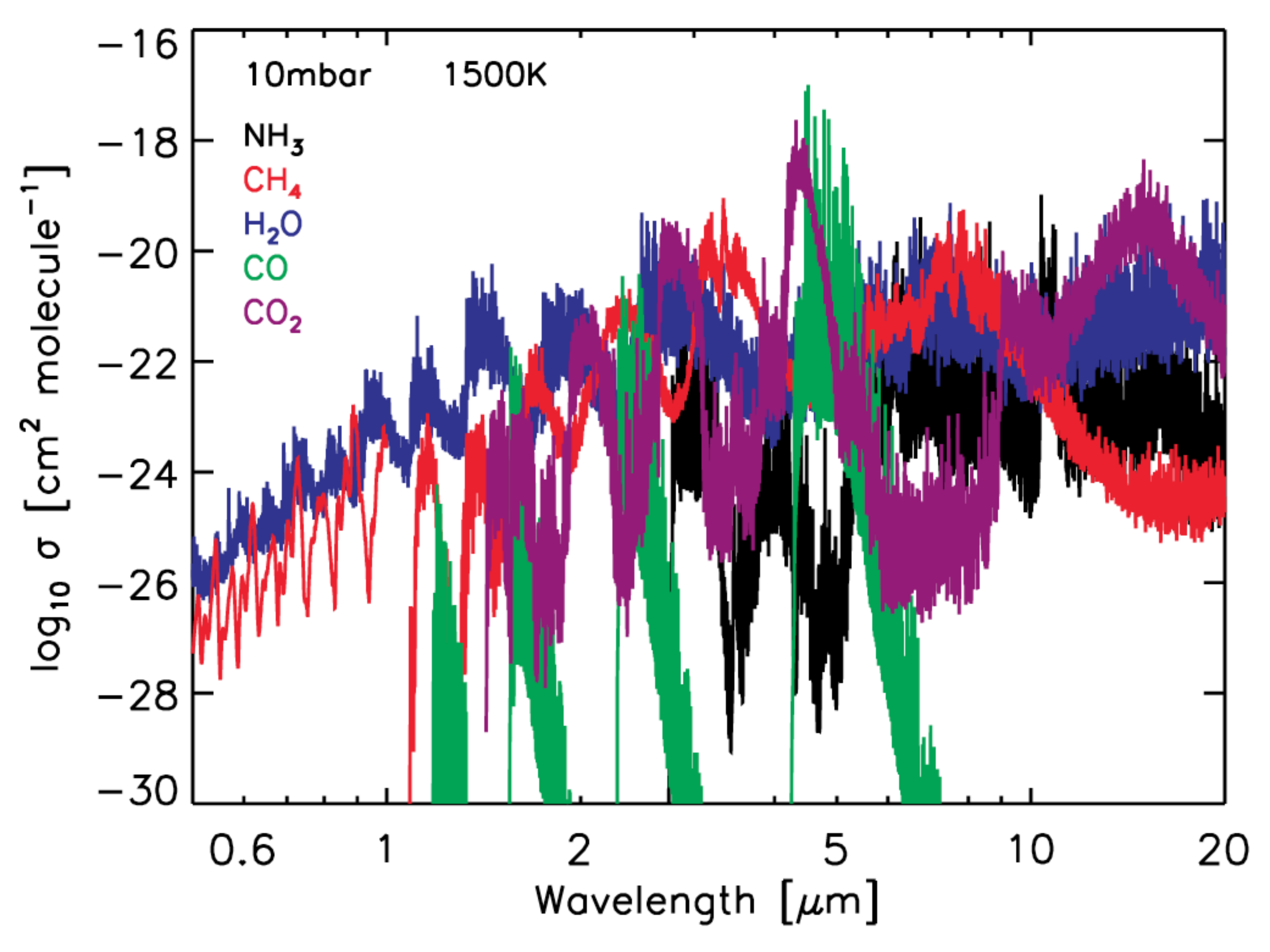
The scientists analysed Huygens' speed, direction of motion, rotation and swinging during descent. The DISR movie includes sidebar graphics that show:

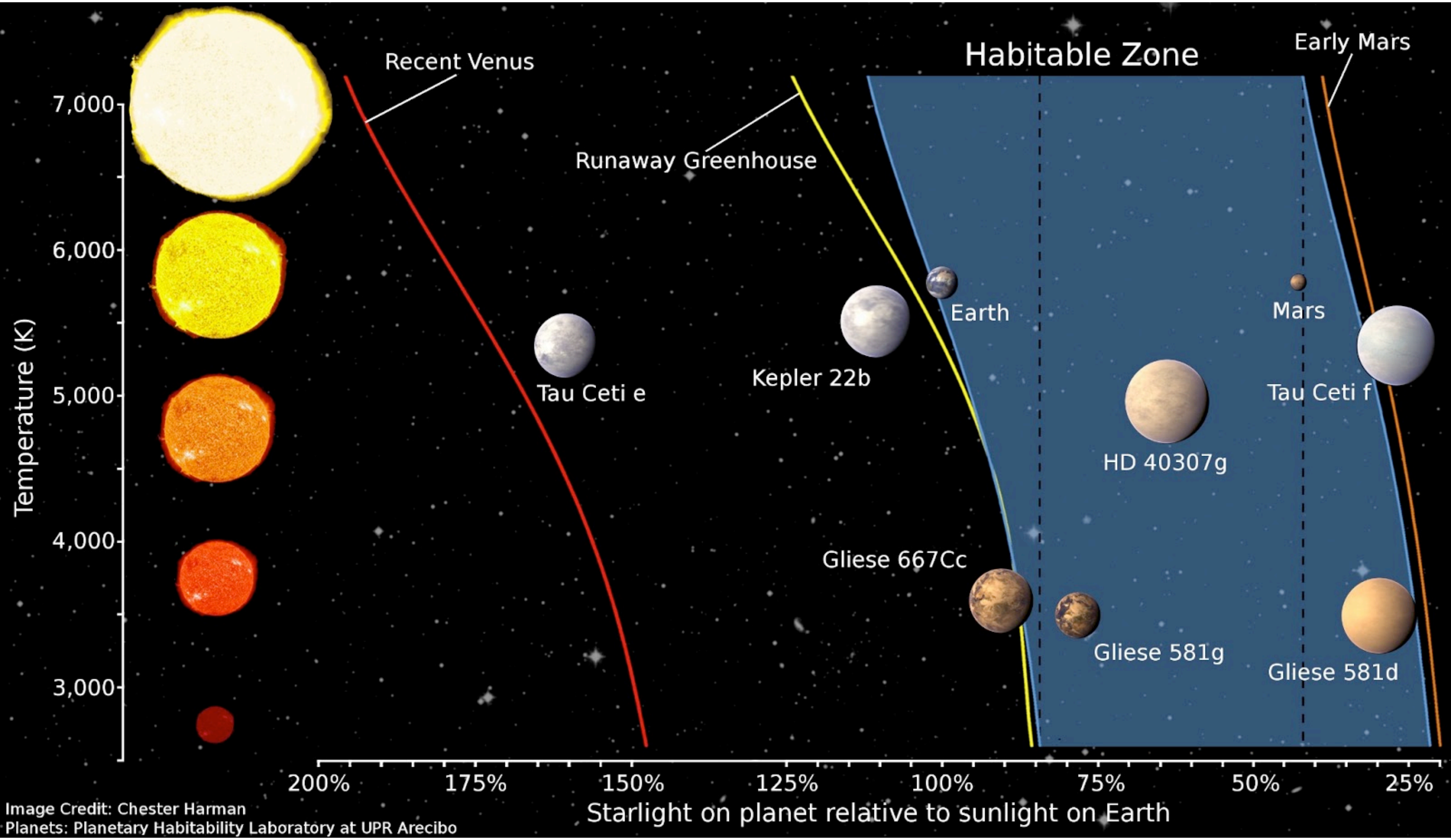
(**Lower left corner**) Huygens' trajectory views from the south, a scale bar for comparison to the height of Mount Everest, colored arrows that point to the sun and to the Cassini orbiter.
(**Top left corner**) A close-up view of the Huygens probe highlighting large and unexpected parachute movements, and a scale bar for comparison to human height.
(**Lower right corner**) A compass that shows the changing direction of view as Huygens rotates, along with the relative positions of the sun and Cassini.
(**Upper right corner**) A clock that shows Universal Time for Jan. 14, 2005 (Universal Time is two hours earlier with respect to Central European Summer Time). Above the clock, events are listed in Mission Time, which starts with the deployment of the first of the three parachutes.

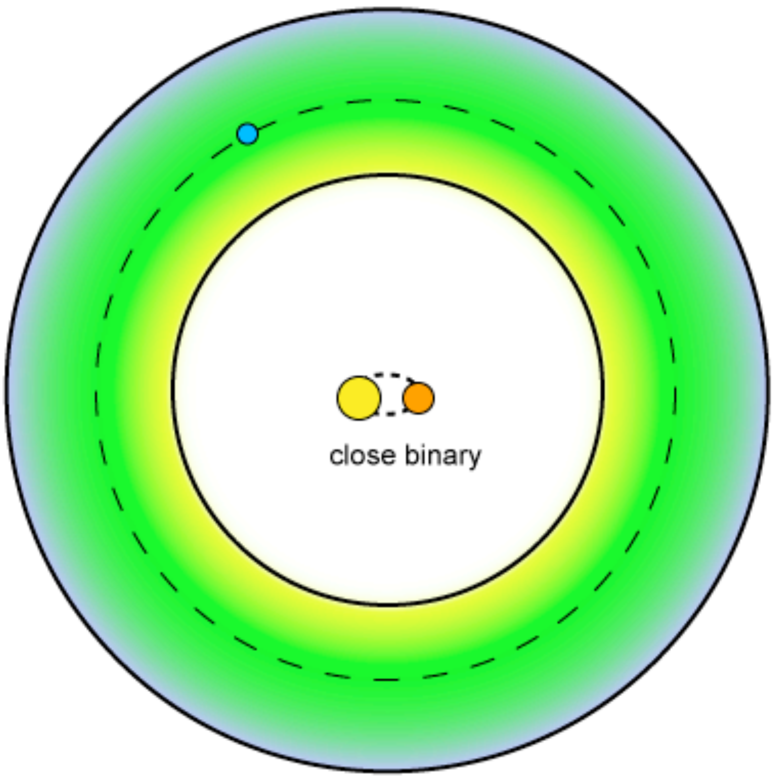
Sounds from a left speaker trace Huygens' motion, with tones changing with rotational speed and the tilt of the parachute. There also are clicks that clock the rotational counter, as well as sounds for the probe's heat shield hitting Titan's atmosphere, parachute deployments, heat shield release, jettison of the DISR cover and touch-down.

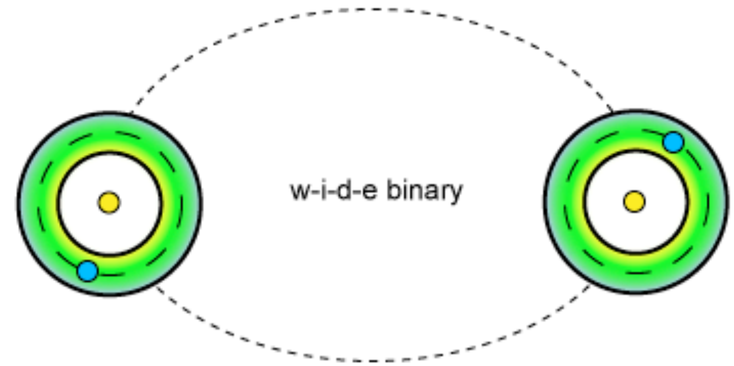
Sounds from a right speaker go with DISR activity. There's a continuous tone that represents the strength of Huygens' signal to Cassini. Then there are 13 different chimes - one for each of DISR's 13 different science parts - that keep time with flashing-white-dot exposure counters.

During its descent, DISR took 3500 exposures.


10mbar
1500K
NH3
CH4
H2O
CO
CO2
−16
−18
−20
−22
−24
−26
−28
−30
log10 σ [cm2 molecule−1]
0.6
1
2
5
10
20
Wavelength [μm]


Habitable Zone
Early Mars
Recent Venus
Runaway Greenhouse
7,000
6,000
5,000
4,000
3,000
Temperature (K)
Earth
Mars
Tau Ceti e
Kepler 22b
Tau Ceti f
HD 40307g
Gliese 667Cc
Gliese 581g
Gliese 581d
200%
175%
150%
125%
100%
75%
50%
25%
Starlight on planet relative to sunlight on Earth
Image Credit: Chester Harman
Planets: Planetary Habitability Laboratory at UPR Arecibo



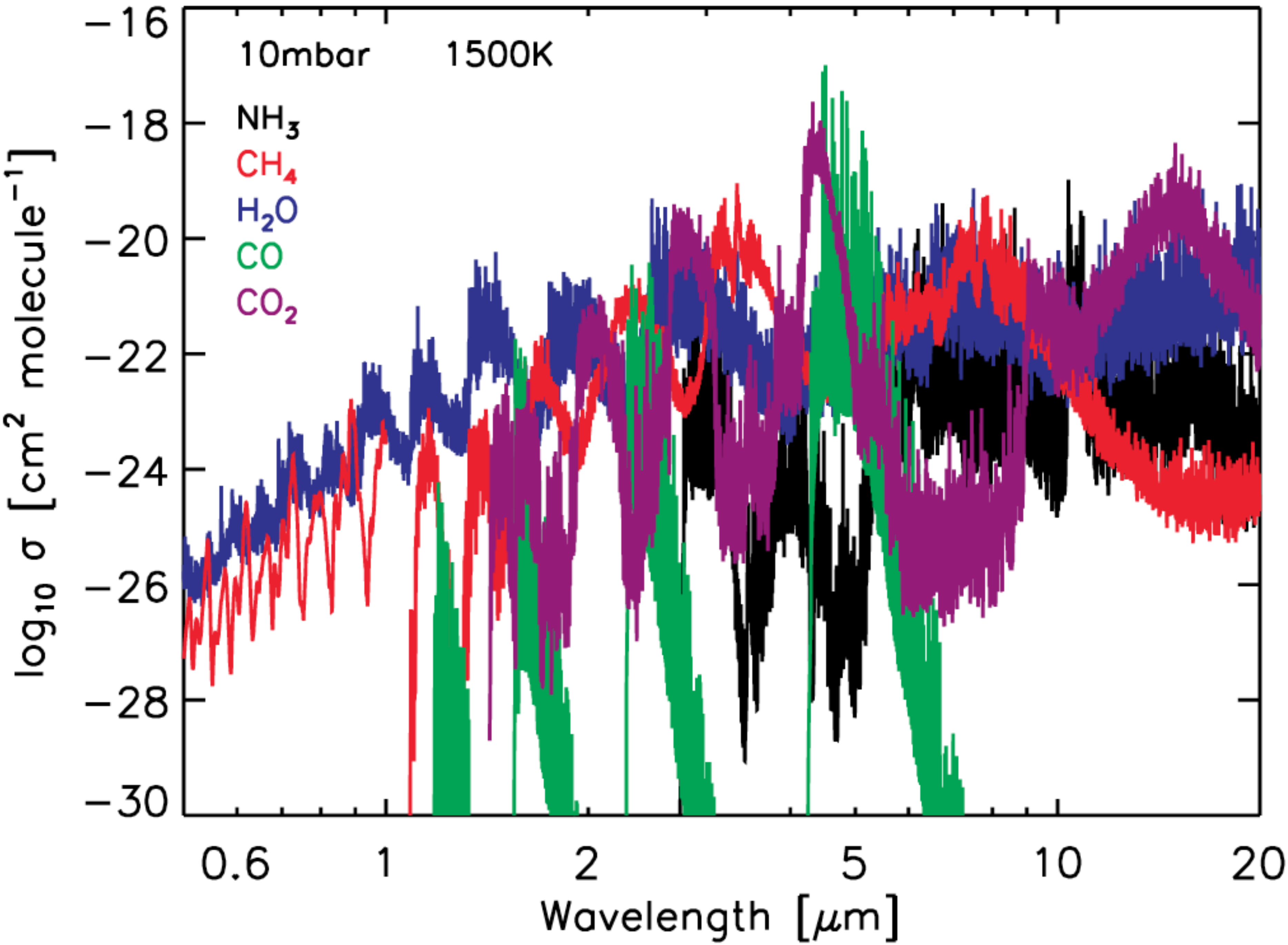


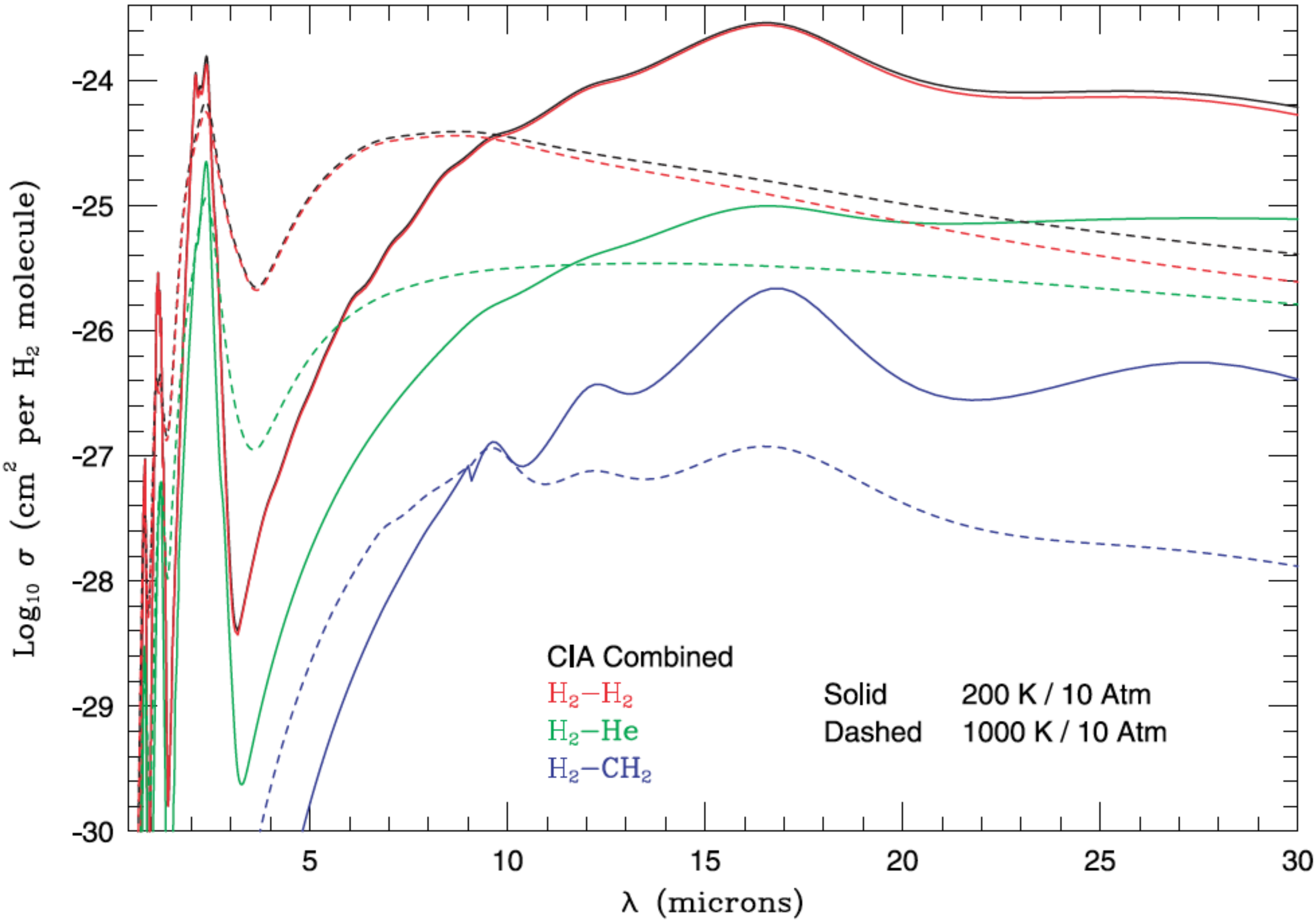
Habitable zones for stable planet orbits in binary systems

Left: A *circumbinary planet* (orbiting both stars in a close binary system).
Stable planet orbit is very large in comparison to binary star separation.

Right: A wide binary system, where star-star distance remains very large in comparison to stable orbits of the planets.

(These drawings are NOT to scale!)


10mbar
1500K
NH_3
CH_4
H_2O
CO
CO_2
$\log_{10}\sigma$ [cm^2 $molecule^{-1}$]
−16
−18
−20
−22
−24
−26
−28
−30
0.6
1
2
5
10
20
Wavelength [μm]

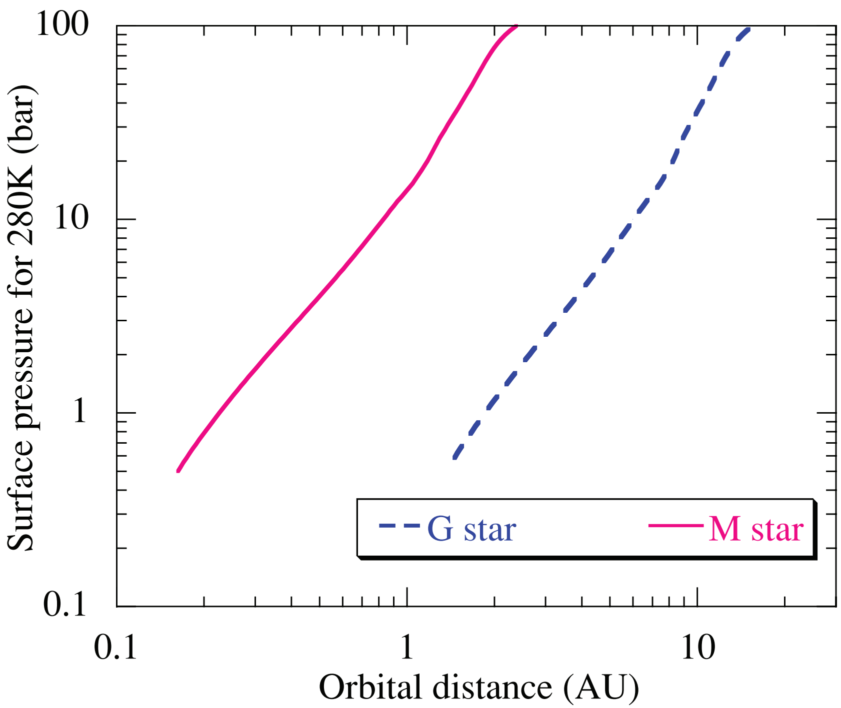


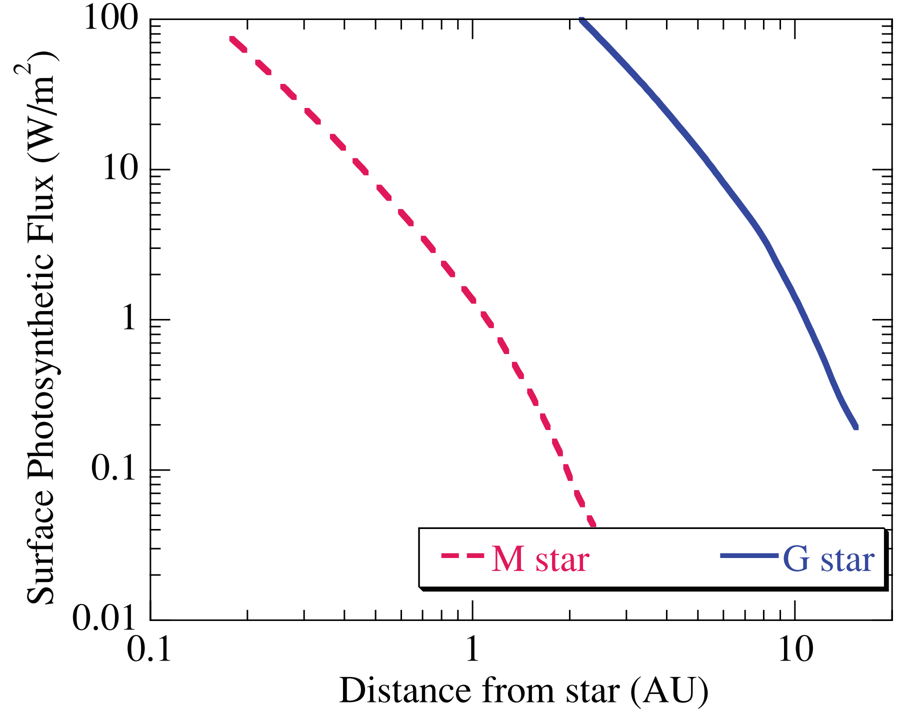
CIA Combined
H_2–H_2
H_2–He
H_2–CH_2
Solid 200 K / 10 Atm
Dashed 1000 K / 10 Atm
$Log_{10}\ \sigma$ (cm^2 per H_2 molecule)
λ (microns)
-24
-25
-26
-27
-28
-29
-30
5
10
15
20
25
30

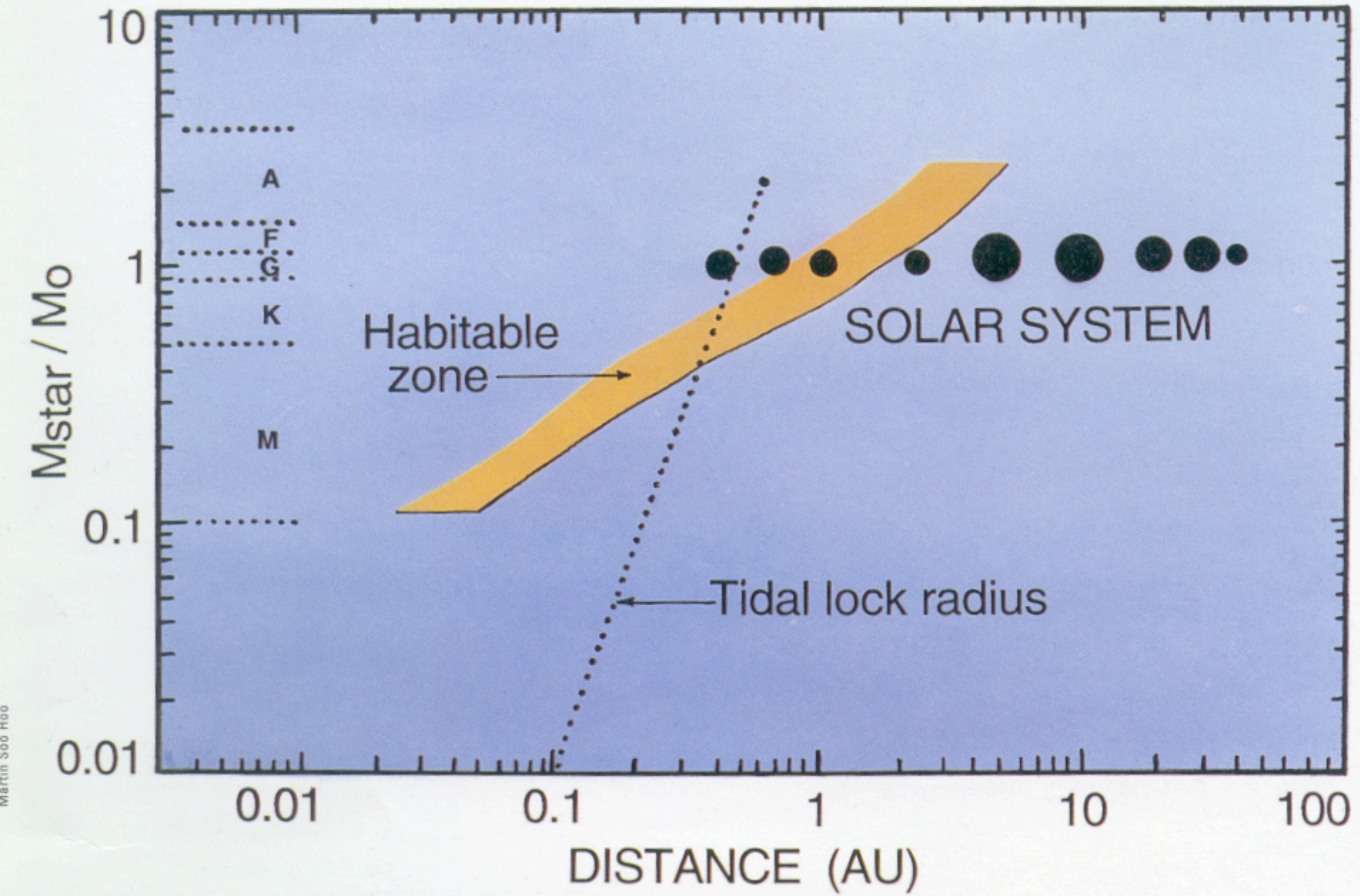
cal Journal Letters, 734:L13 (5pp), 2011 June 10 doi:10.1088/2041-

HYDROGEN GREENHOUSE PLANETS BEYOND THE HABITABLE ZONE

Raymond Pierrehumbert[1] and Eric Gaidos[2]
[1] Department of the Geophysical Sciences, University of Chicago, Chicago, IL 60637, USA; rtp1@geosci.uchicago.edu
[2] Department of Geology and Geophysics, University of Hawaii at Manoa, Honoulu, HI 96822, USA; gaidos@hawaii.edu
Received 2011 April 3; accepted 2011 April 29; published 2011 May 19






10
1
0.1
0.01
A
F
G
K
M
Mstar / Mo
Habitable
zone
SOLAR SYSTEM
Tidal lock radius
0.01
0.1
1
10
100
DISTANCE (AU)
Martin Soo Hoo