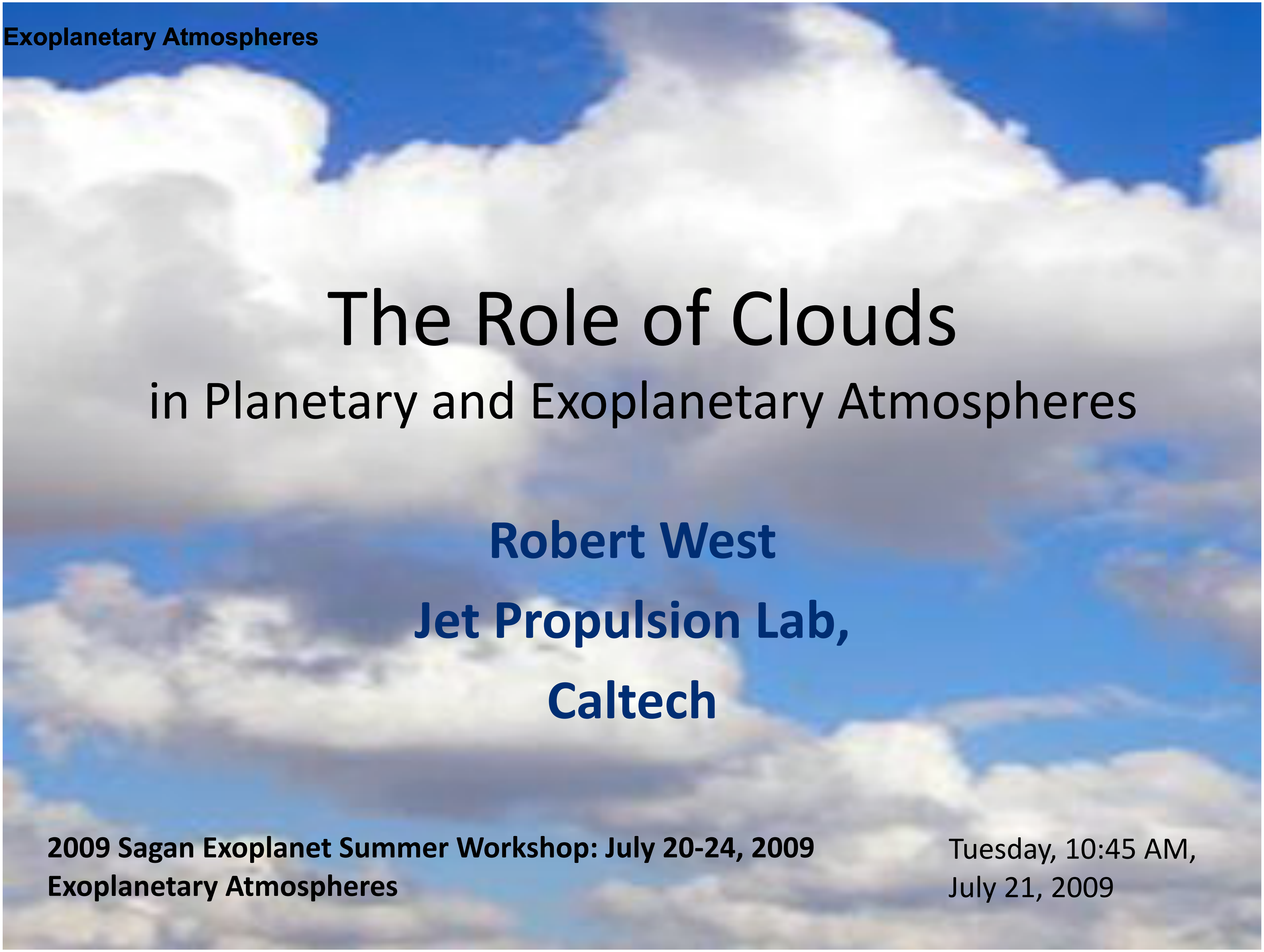


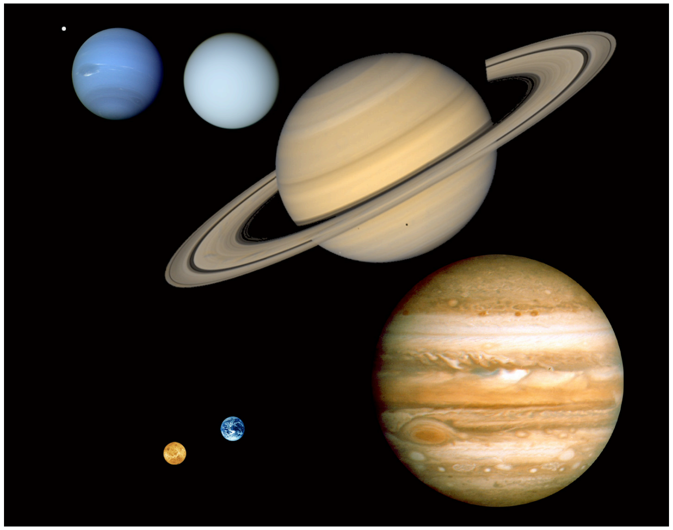
The Role of Clouds

in Planetary and Exoplanetary Atmospheres

Robert West

Jet Propulsion Lab,

Caltech



‘The atmospheres of substellar objects contain clouds of oxides, iron, silicates and other refractory condensates. Water clouds are expected in the coolest objects. The opacity of these ‘dust’ clouds strongly affects both the atmospheric temperature–pressure profile and the emergent flux. Thus, any attempt to model the spectra of these atmospheres must incorporate a cloud model.’ (Ch. Helling et al., *Mon. Not. R. Astron. Soc*. **391**, 1854–1873 (2008)

Outline*

- Thermochemical Equilibrium Theory for Condensates – Chemical abundances, P,T profiles, condensate cloud bases
- Examples from our solar system and beyond
- Beyond the cloud base – Cloud microphysics and dynamics
- Cloud effects on radiative transfer and remote sensing
- Photochemical Haze
- Cloud effects in Cool stars

*See the embedded notes pages for references and notes

Condensation Vapor Pressure

$$\ln(P_V) = \ln(C) + \frac{1}{R_V}\left[-\frac{L_0}{T} + \Delta\alpha \ln T + \frac{\Delta\beta}{2} T + O(T^2) \right].$$

Sánchez-Lavega, Pérez-Hoyos, and Hueso

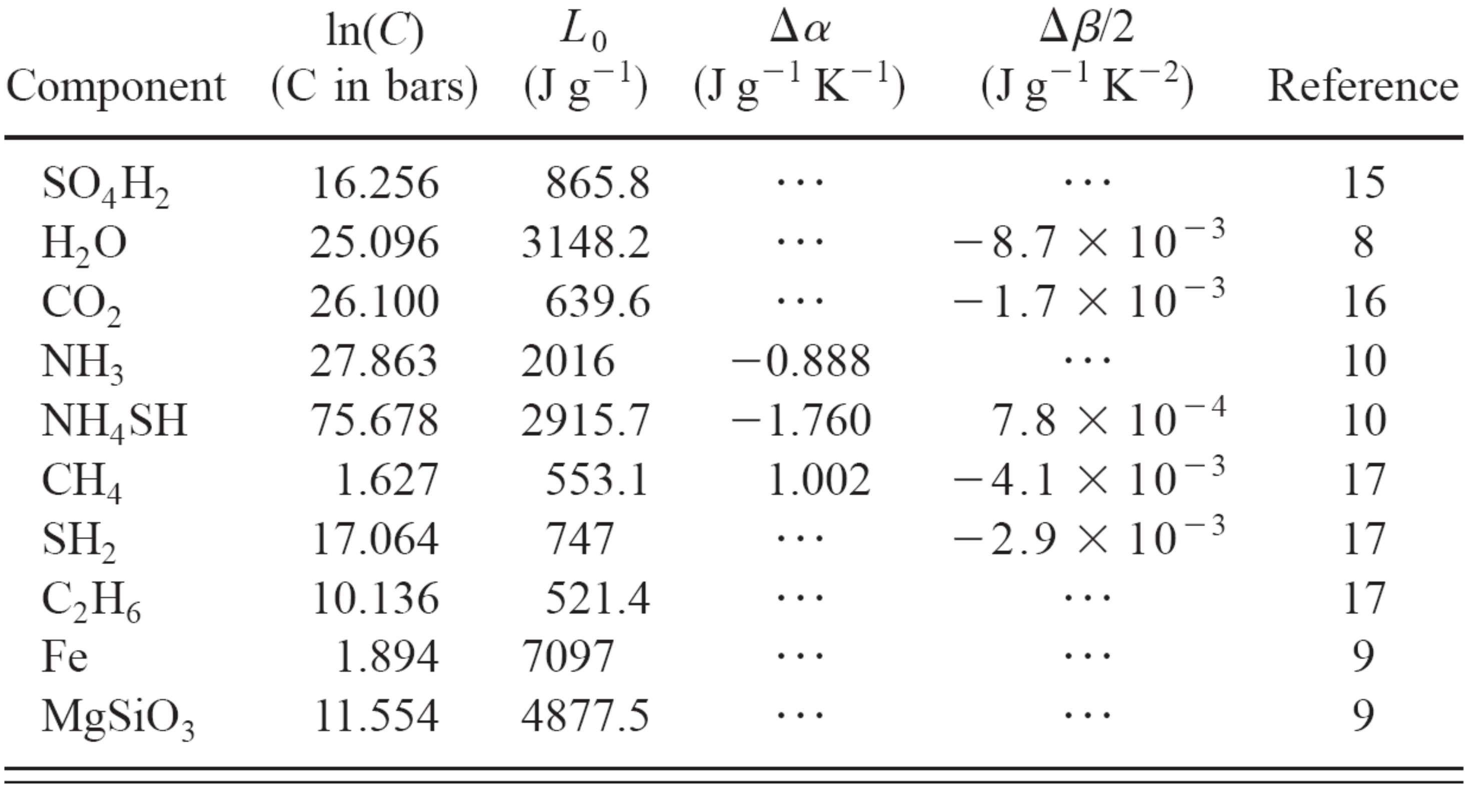
P_V = Vapor pressure in equilibrium with the condensate

T = Temperature

R_V = Specific gas constant for the vapor

From Sánchez Lavega et al., 2003

Empirical Constants*

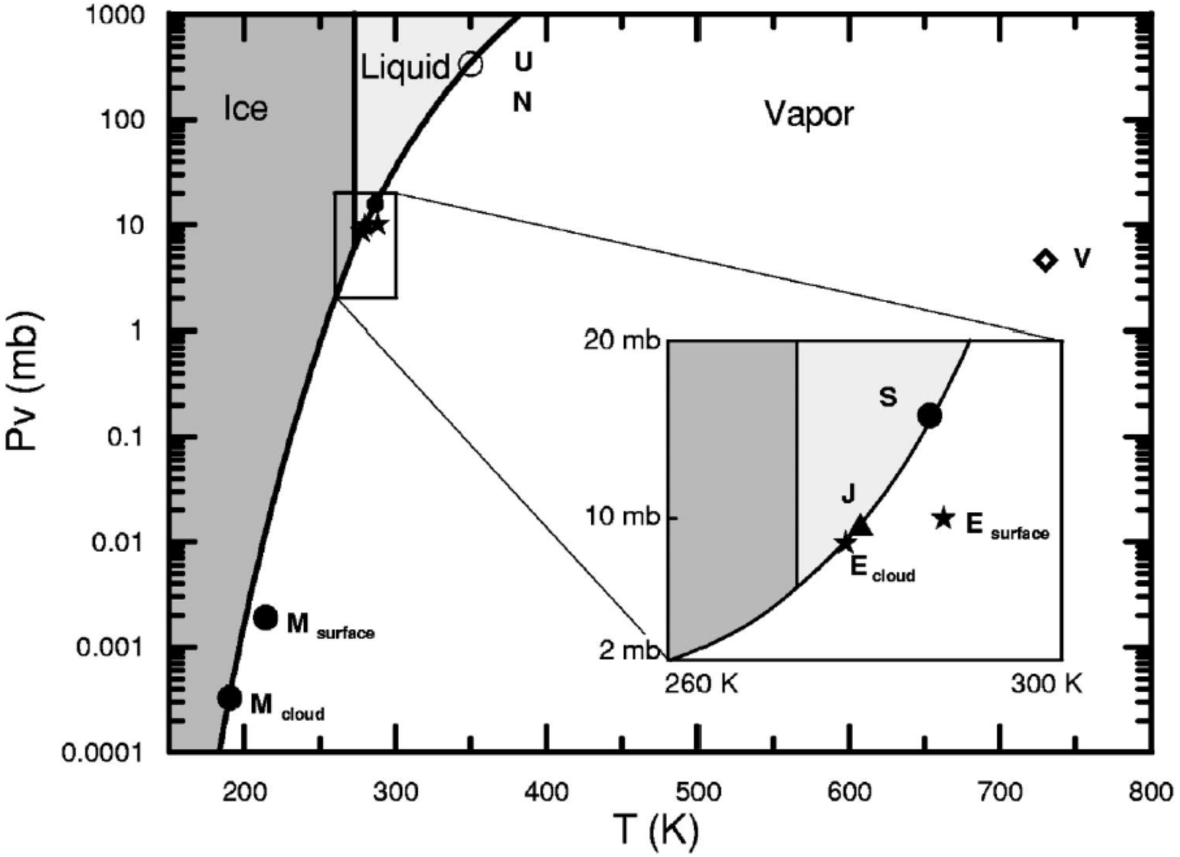


Component	$\ln(C)$ (C in bars)	L_0 ($\mathrm{J\,g^{-1}}$)	$\Delta\alpha$ ($\mathrm{J\,g^{-1}\,K^{-1}}$)	$\Delta\beta/2$ ($\mathrm{J\,g^{-1}\,K^{-2}}$)	Reference
SO_4H_2	16.256	865.8	⋯	⋯	15
H_2O	25.096	3148.2	⋯	-8.7×10^{-3}	8
CO_2	26.100	639.6	⋯	-1.7×10^{-3}	16
NH_3	27.863	2016	−0.888	⋯	10
NH_4SH	75.678	2915.7	−1.760	7.8×10^{-4}	10
CH_4	1.627	553.1	1.002	-4.1×10^{-3}	17
SH_2	17.064	747	⋯	-2.9×10^{-3}	17
C_2H_6	10.136	521.4	⋯	⋯	17
Fe	1.894	7097	⋯	⋯	9
$MgSiO_3$	11.554	4877.5	⋯	⋯	9

From Sánchez Lavega et al., 2003

*For hot Jupiters and cool dwarfs see papers by Lodders and Fegley and colleagues

Phase Diagram – H_2O



From Sánchez Lavega et al., 2003

Planetary Condensates
I. Terrestrial Planets

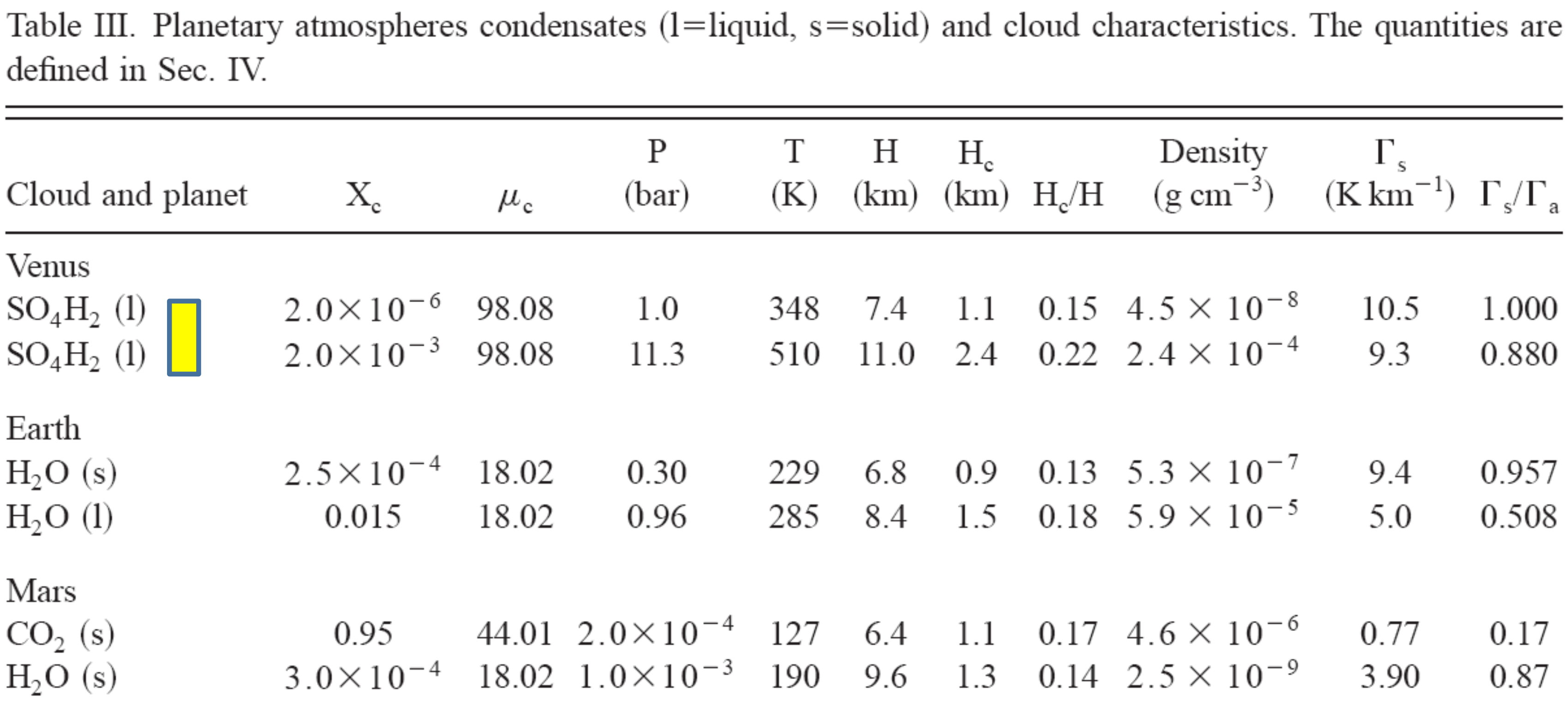


Table III. Planetary atmospheres condensates (l=liquid, s=solid) and cloud characteristics. The quantities are defined in Sec. IV.

Cloud and planet	X_c	μ_c	P (bar)	T (K)	H (km)	H_c (km)	H_c/H	Density (g cm^{-3})	Γ_s (K km^{-1})	Γ_s/Γ_a
Venus										
SO_4H_2 (l)	2.0×10^{-6}	98.08	1.0	348	7.4	1.1	0.15	4.5×10^{-8}	10.5	1.000
SO_4H_2 (l)	2.0×10^{-3}	98.08	11.3	510	11.0	2.4	0.22	2.4×10^{-4}	9.3	0.880
Earth										
H_2O (s)	2.5×10^{-4}	18.02	0.30	229	6.8	0.9	0.13	5.3×10^{-7}	9.4	0.957
H_2O (l)	0.015	18.02	0.96	285	8.4	1.5	0.18	5.9×10^{-5}	5.0	0.508
Mars										
CO_2 (s)	0.95	44.01	2.0×10^{-4}	127	6.4	1.1	0.17	4.6×10^{-6}	0.77	0.17
H_2O (s)	3.0×10^{-4}	18.02	1.0×10^{-3}	190	9.6	1.3	0.14	2.5×10^{-9}	3.90	0.87

Mole Fraction

Molecular weight

Scale height

Lapse rate

From Sánchez Lavega et al., 2003

Planetary Condensates
II. Jupiter, Saturn

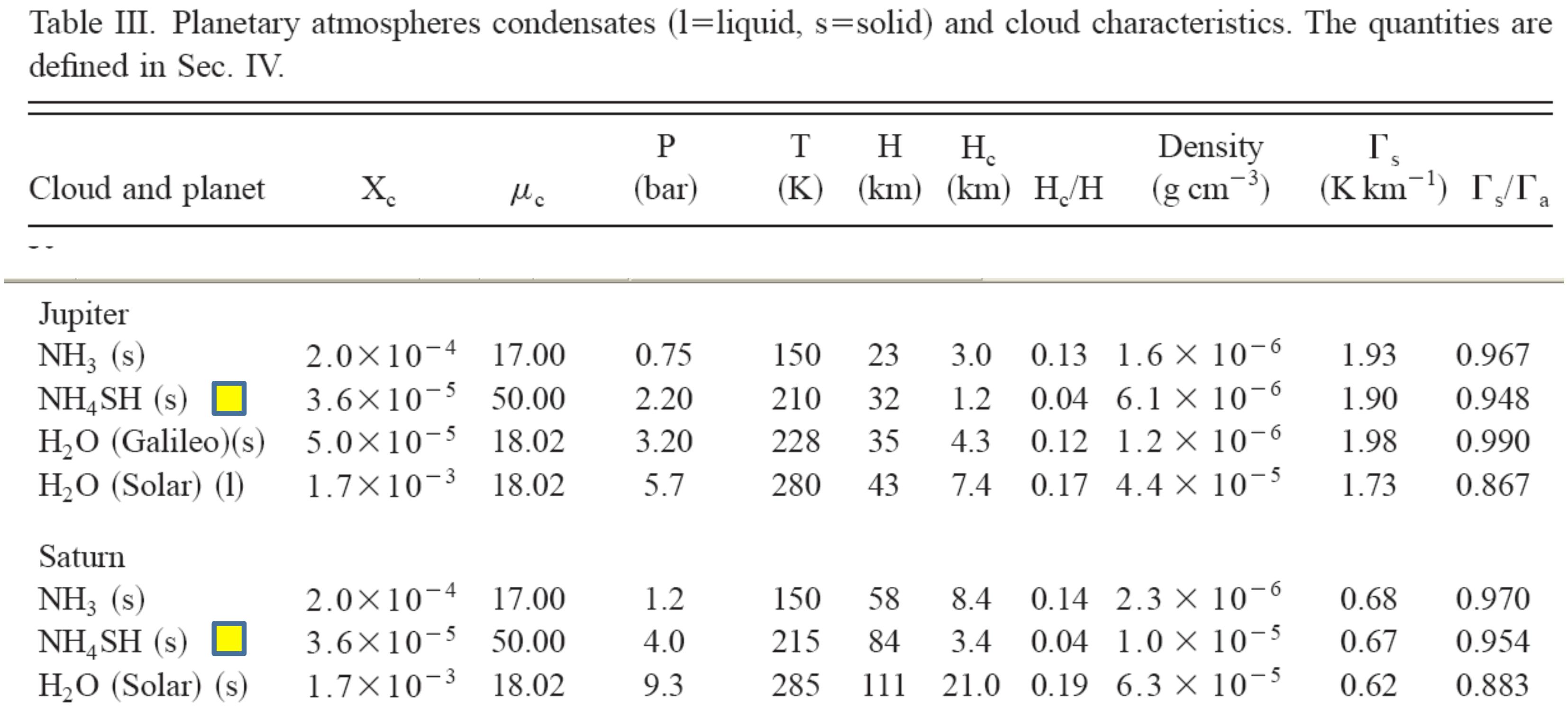


Table III. Planetary atmospheres condensates (l=liquid, s=solid) and cloud characteristics. The quantities are defined in Sec. IV.

Cloud and planet	X_c	μ_c	P (bar)	T (K)	H (km)	H_c (km)	H_c/H	Density (g cm^{-3})	Γ_s (K km^{-1})	Γ_s/Γ_a
Jupiter										
NH_3 (s)	2.0×10^{-4}	17.00	0.75	150	23	3.0	0.13	1.6×10^{-6}	1.93	0.967
NH_4SH (s) 🟨	3.6×10^{-5}	50.00	2.20	210	32	1.2	0.04	6.1×10^{-6}	1.90	0.948
H_2O (Galileo)(s)	5.0×10^{-5}	18.02	3.20	228	35	4.3	0.12	1.2×10^{-6}	1.98	0.990
H_2O (Solar) (l)	1.7×10^{-3}	18.02	5.7	280	43	7.4	0.17	4.4×10^{-5}	1.73	0.867
Saturn										
NH_3 (s)	2.0×10^{-4}	17.00	1.2	150	58	8.4	0.14	2.3×10^{-6}	0.68	0.970
NH_4SH (s) 🟨	3.6×10^{-5}	50.00	4.0	215	84	3.4	0.04	1.0×10^{-5}	0.67	0.954
H_2O (Solar) (s)	1.7×10^{-3}	18.02	9.3	285	111	21.0	0.19	6.3×10^{-5}	0.62	0.883

From Sánchez Lavega et al., 2003

Planetary Condensates
III. Uranus, Neptune, HD 209458b

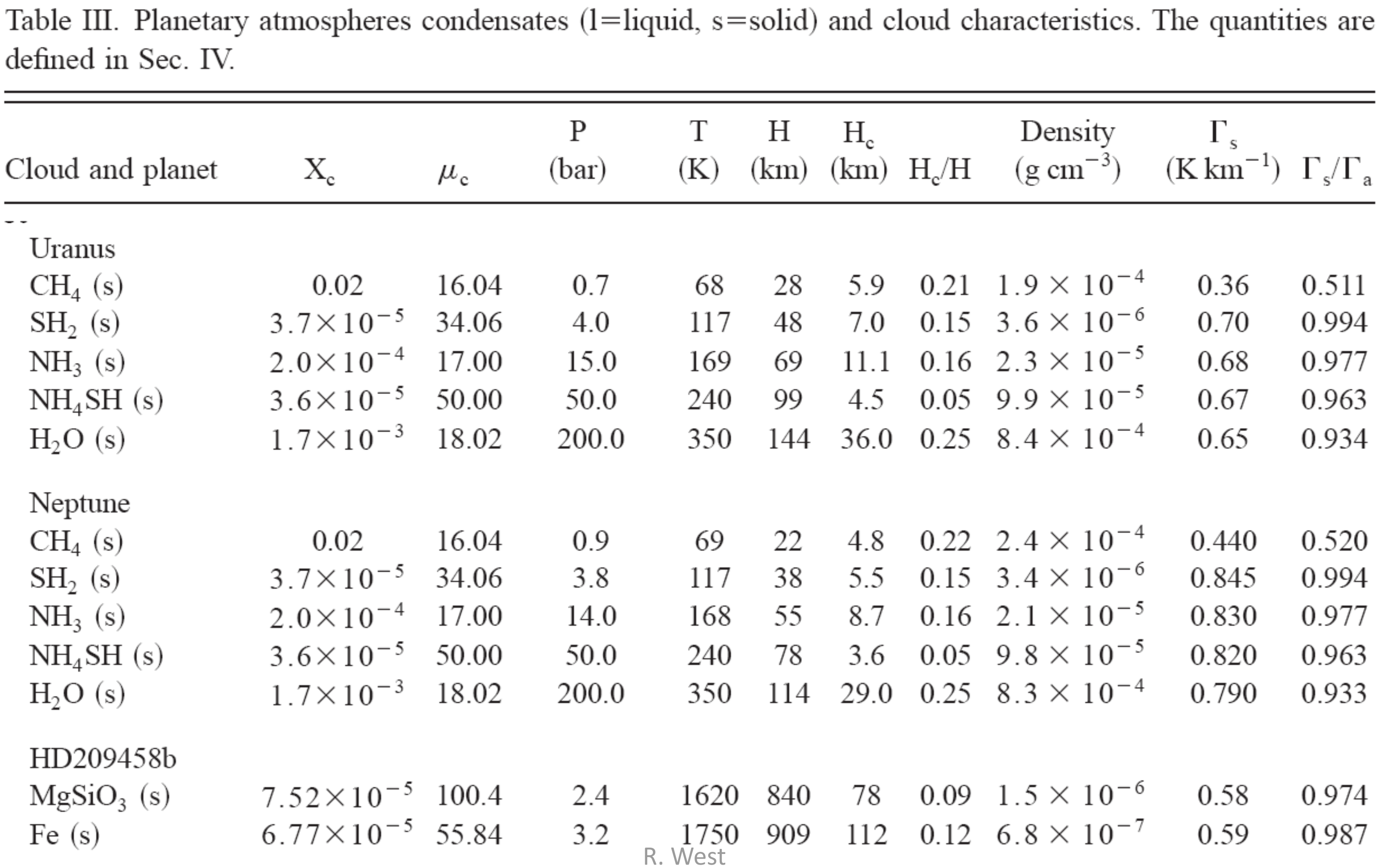
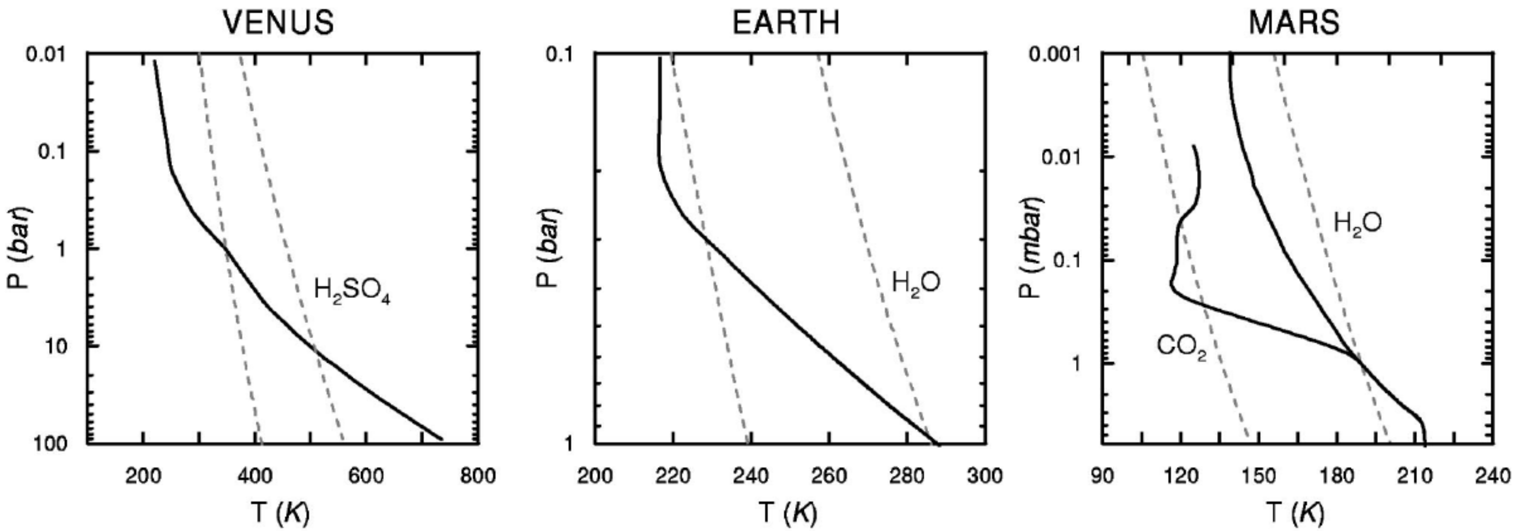


Table III. Planetary atmospheres condensates (l=liquid, s=solid) and cloud characteristics. The quantities are defined in Sec. IV.

Cloud and planet	X_c	μ_c	P (bar)	T (K)	H (km)	H_c (km)	H_c/H	Density (g cm^{-3})	Γ_s (K km^{-1})	Γ_s/Γ_a
Uranus										
CH_4 (s)	0.02	16.04	0.7	68	28	5.9	0.21	1.9×10^{-4}	0.36	0.511
SH_2 (s)	3.7×10^{-5}	34.06	4.0	117	48	7.0	0.15	3.6×10^{-6}	0.70	0.994
NH_3 (s)	2.0×10^{-4}	17.00	15.0	169	69	11.1	0.16	2.3×10^{-5}	0.68	0.977
NH_4SH (s)	3.6×10^{-5}	50.00	50.0	240	99	4.5	0.05	9.9×10^{-5}	0.67	0.963
H_2O (s)	1.7×10^{-3}	18.02	200.0	350	144	36.0	0.25	8.4×10^{-4}	0.65	0.934
Neptune										
CH_4 (s)	0.02	16.04	0.9	69	22	4.8	0.22	2.4×10^{-4}	0.440	0.520
SH_2 (s)	3.7×10^{-5}	34.06	3.8	117	38	5.5	0.15	3.4×10^{-6}	0.845	0.994
NH_3 (s)	2.0×10^{-4}	17.00	14.0	168	55	8.7	0.16	2.1×10^{-5}	0.830	0.977
NH_4SH (s)	3.6×10^{-5}	50.00	50.0	240	78	3.6	0.05	9.8×10^{-5}	0.820	0.963
H_2O (s)	1.7×10^{-3}	18.02	200.0	350	114	29.0	0.25	8.3×10^{-4}	0.790	0.933
HD209458b										
$MgSiO_3$ (s)	7.52×10^{-5}	100.4	2.4	1620	840	78	0.09	1.5×10^{-6}	0.58	0.974
Fe (s)	6.77×10^{-5}	55.84	3.2	1750	909	112	0.12	6.8×10^{-7}	0.59	0.987

Condensation Levels
I. Terrestrial Planets

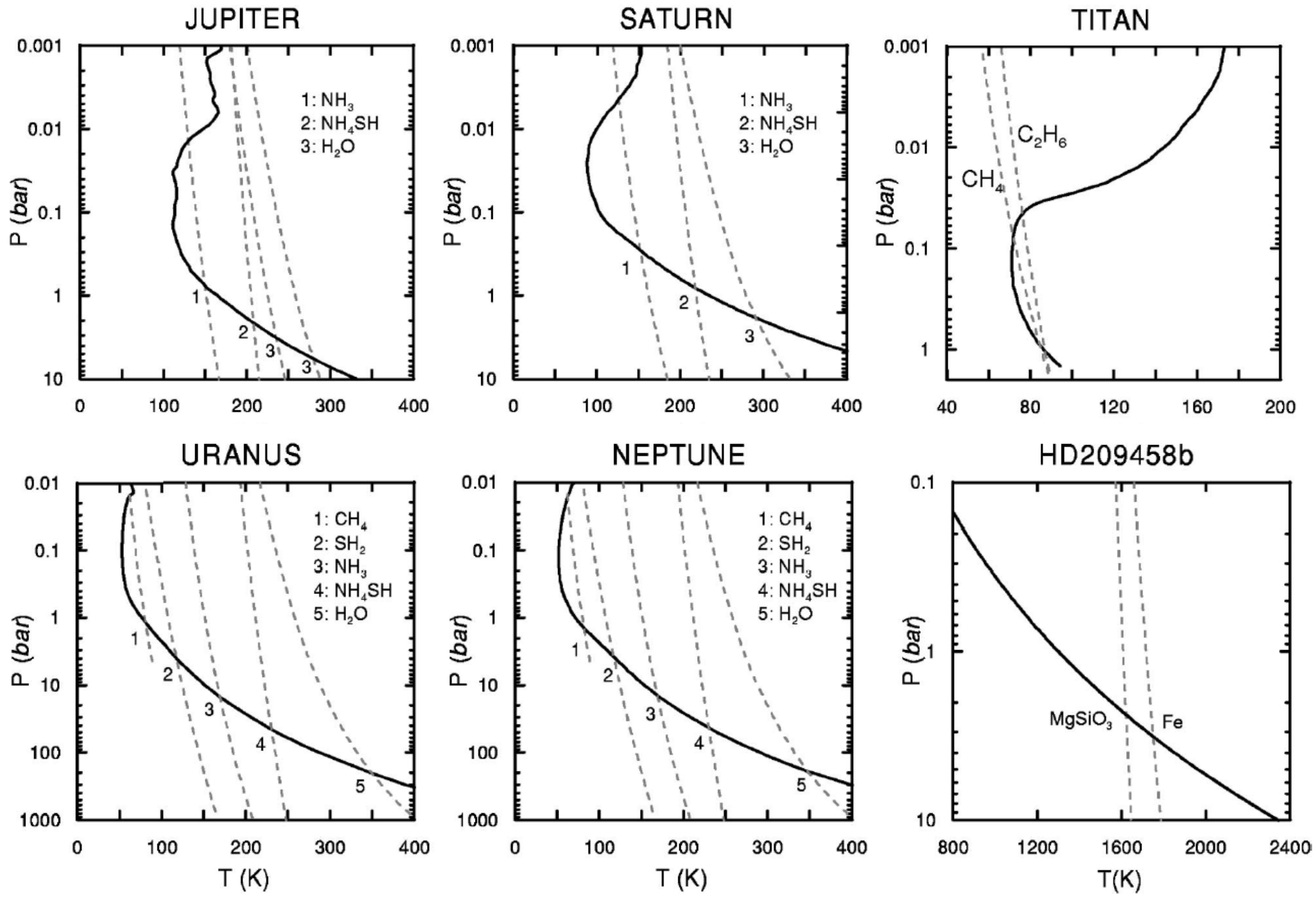


Solid curves: planetary representative P/T relations
Dashed curves: 'Nominal' Pv(T) for noted constituents

Note: multiple cloud levels
Are expected due to meteorology

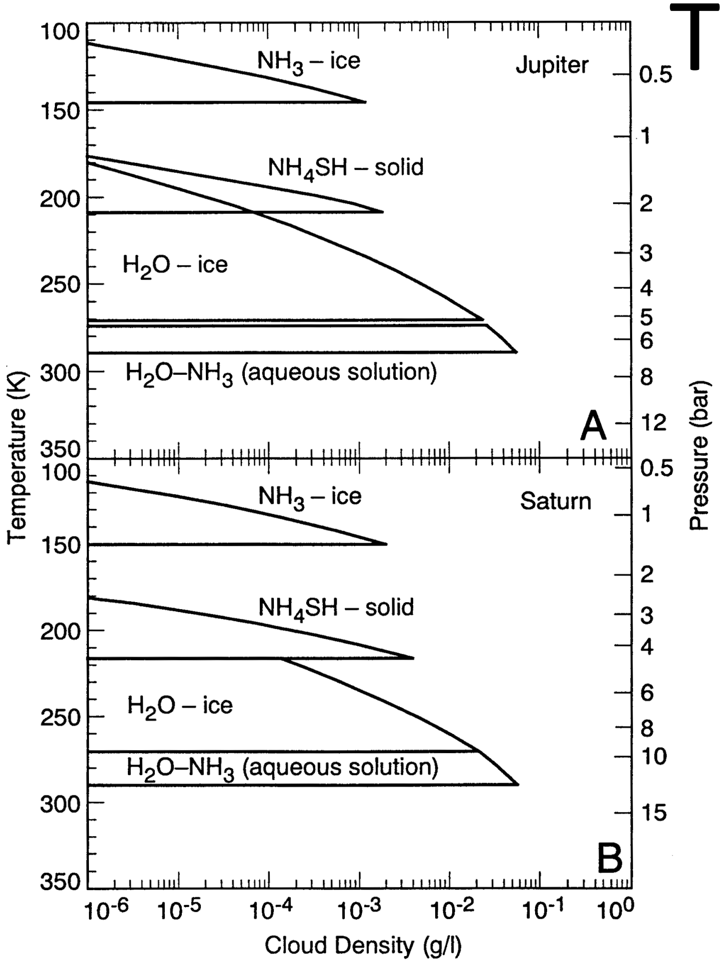
From Sánchez Lavega et al., 2003

Condensation Levels
II. Giant Planets, Titan, HD 209458b

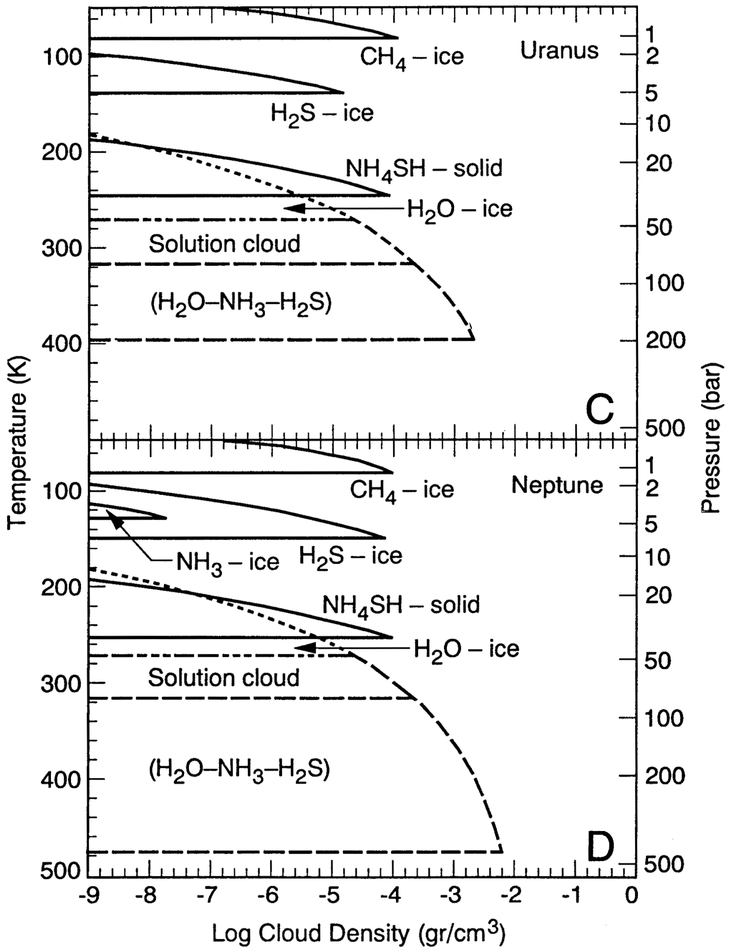


From Sánchez Lavega et al., 2003

Condensate Layers on the Giant Planets – Thermochemical Equilibrium Theory

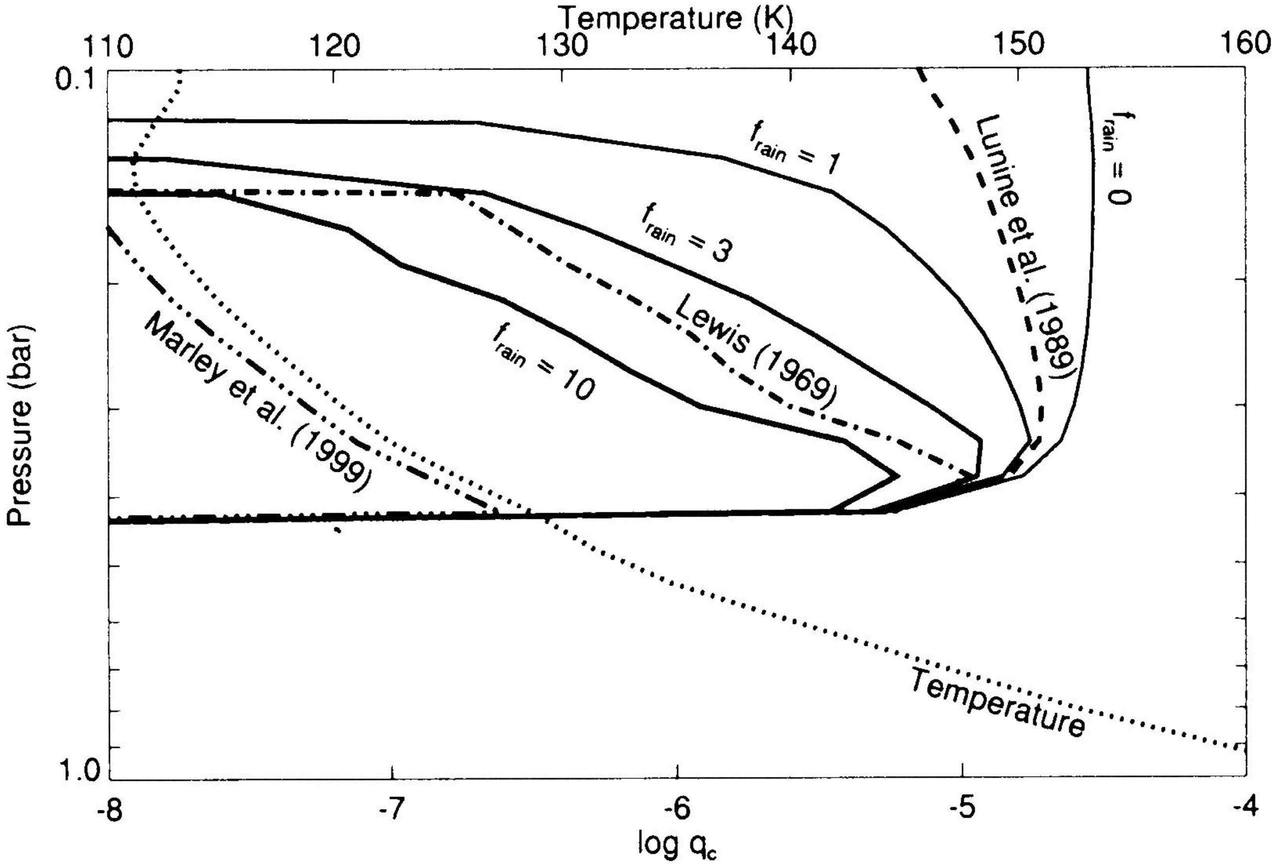


From Atreya and Wong



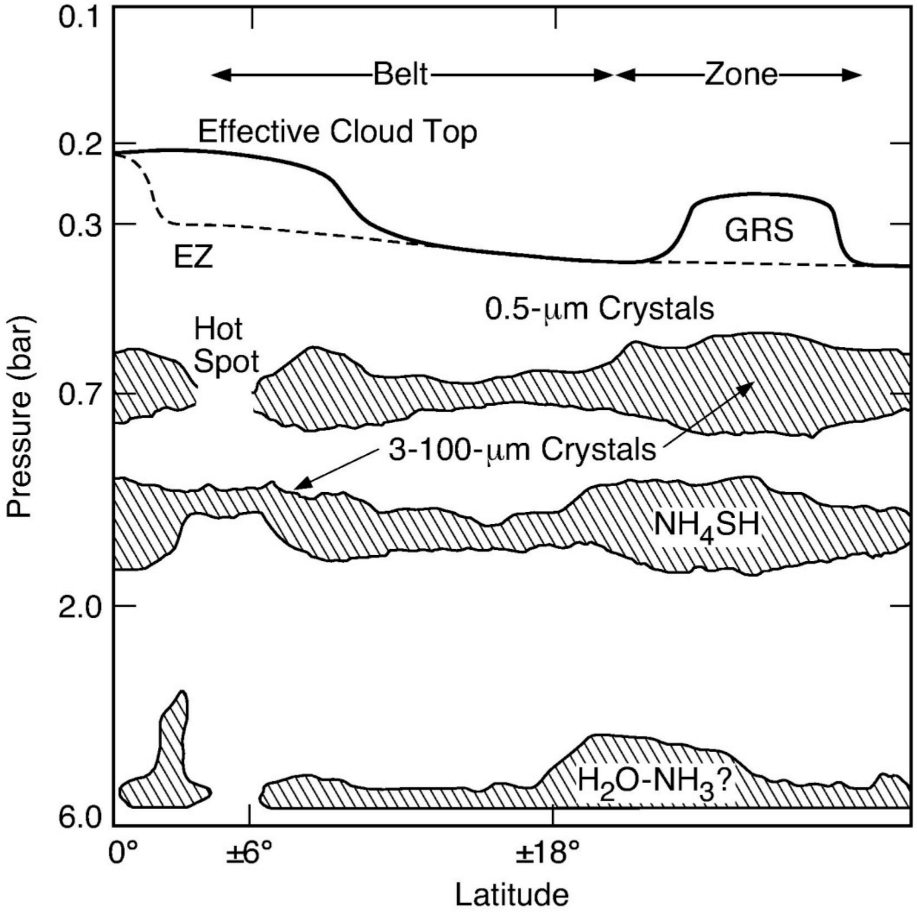
From de Pater et al., 1991

Theoretical Cloud Density Profiles



From Ackerman and Marley, 2001

Observationally Derived Cloud Structure for Jupiter



From West et al., 2004

Particle Nucleation and Growth

The change in Gibbs Free Energy determines if a particle grows or evaporates. For a liquid drop in equilibrium with vapor

$$\Delta G = 4\pi a^2\sigma - \frac{4}{3}\pi a^3 n_l K T \ln(e/e_l)$$

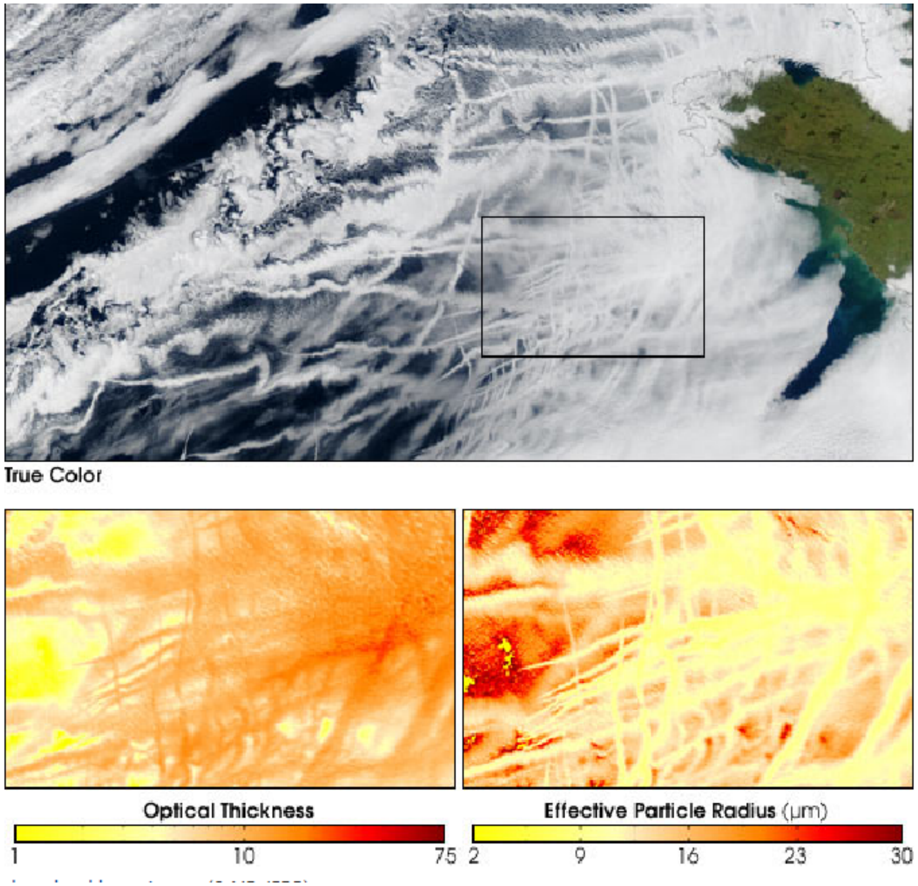
Where a = drop radius
σ = surface tension of the liquid
n_l = number density of molecules in the liquid
e = vapor pressure
e_l = saturation vapor pressure

There is a critical radius where ΔG becomes negative.
If the particle is larger than the critical radius it will grow

Particle Microphysics - I

- Homogeneous and heterogeneous nucleation
- Heterogeneous nucleation requires cloud condensation nuclei (CCN) but these are abundant in most environments
  - Hydrophobic or hygroscopic nuclei influence particle density and size.
  - Abundant hygroscopic CCN lead to a high density of small particles (eg. ship tracks)
  - The opposite is true when hygroscopic CCN are absent

Ship Tracks over the Atlantic

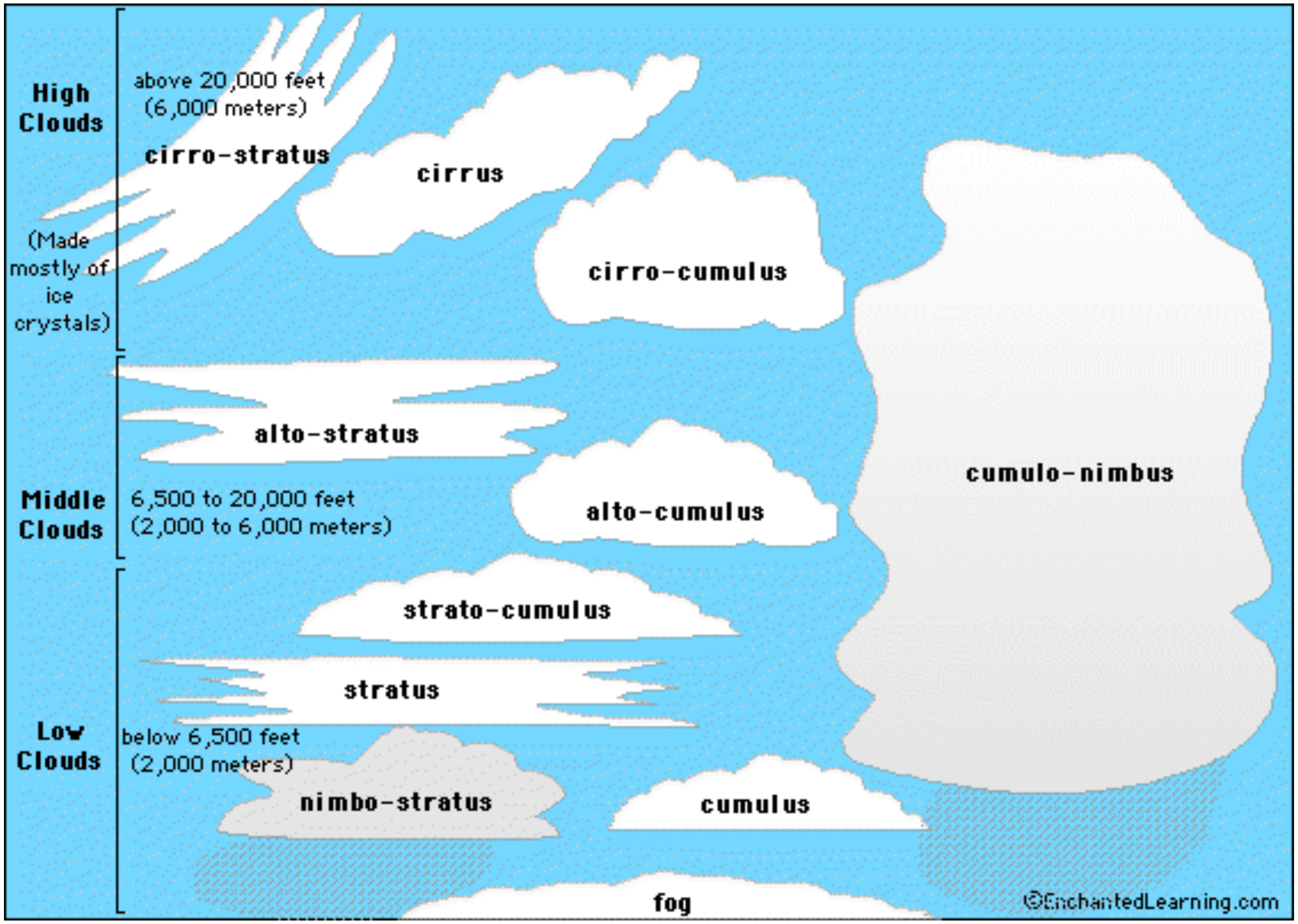


http://earthobservatory.nasa.gov/IOTD/view.php?id=3275

Particle Microphysical Processes

- Growth from vapor (+ CCN)
  - Depends on abundance, contact parameter of CCN and relative humidity of the vapor
- Particle collisions and coagulation
  - Depends on particle size distribution n(r), number density, and sticking coefficient (which in turn depends on particle electrical charge and composition)
  - Modifies n(r,z) where r = radius, z = altitude
- Sedimentation
  - Depends on particle size and density, atmospheric density, gravity
- Transport by advection and eddies
  - Can lead to holes and enormous heterogeneity
  - Cloud particles can be distant from source vapor
- Mixed phase and mixed compositions complicate the simulation

Ramifications of Microphysics and Atmospheric Dynamics



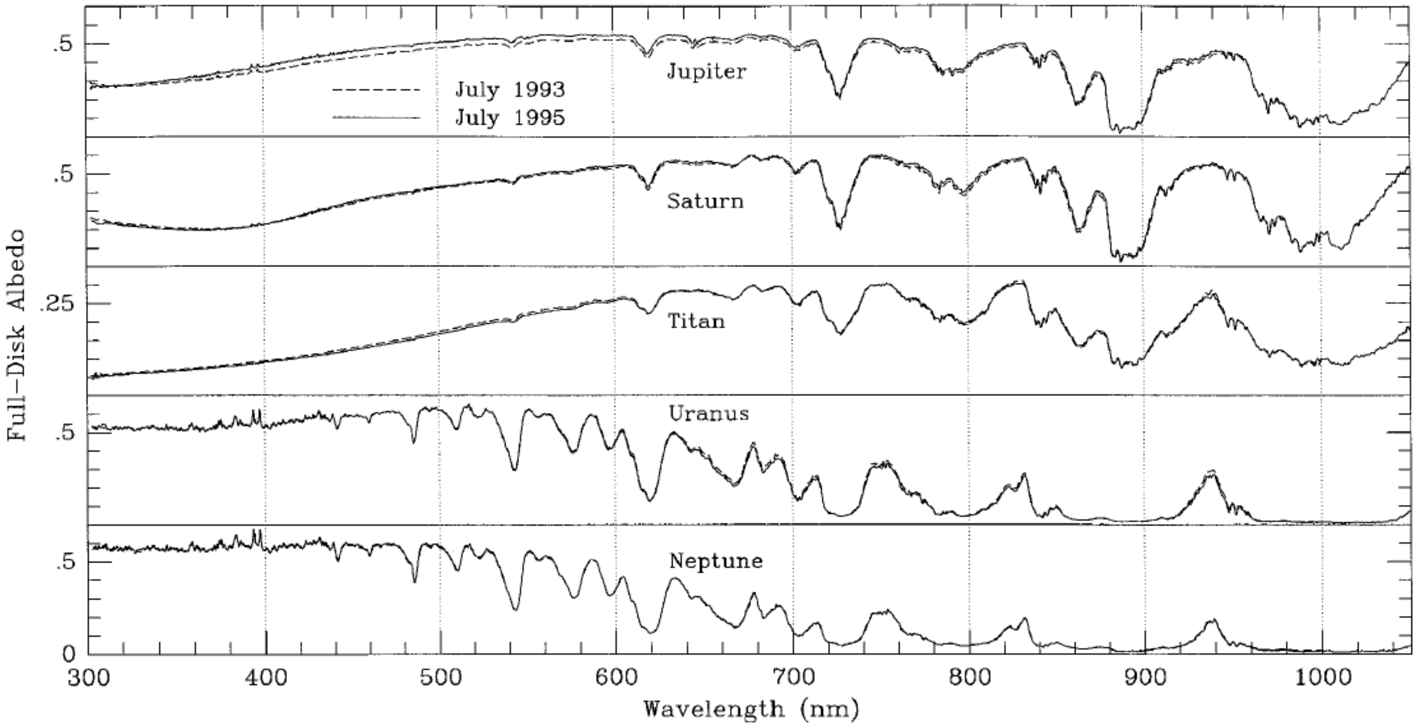
Particle Microphysics: Size and Shape

- Particle size distribution is usually monomodal but can be bimodal, evolves as the cloud evolves
  - Parameters are effective size, and variance
  - Mie theory can be used to calculate optical properties
- Typical mean sizes are sub-micron to 10s of microns, sometimes larger
- If particles are liquid the shape is spherical; if not the shape can be a crystal or aggregates of many small (50 nm) monomers. Most planetary cloud particles are solid

Remote Sensing: Particle Size and Shape Diagnostics: Spectra

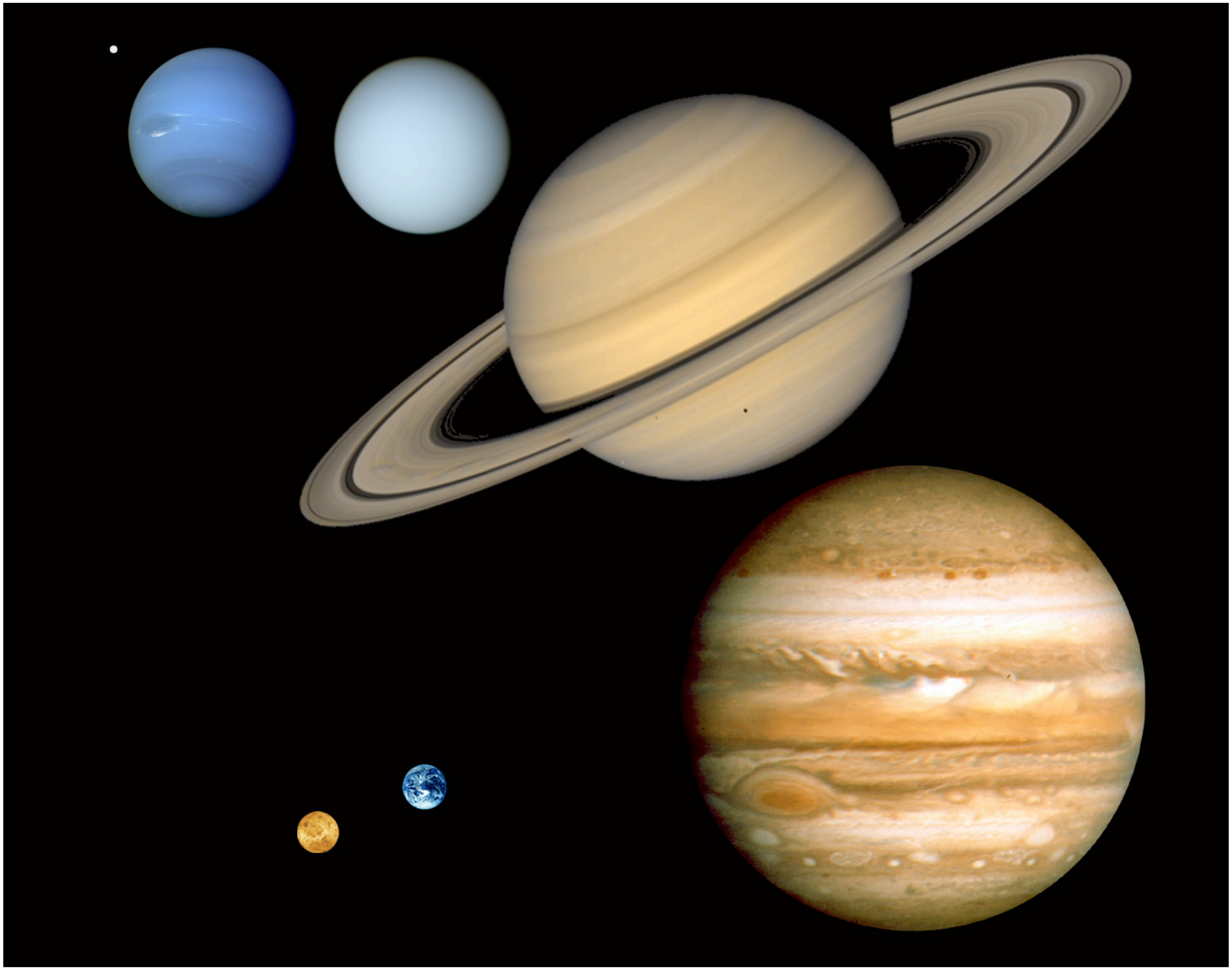
- Spectra of reflected, emitted, or transmitted light
  - Large particles have a flat spectral dependence, except near absorption features
  - Absorption features are broad for large particles, narrow for small particles
  - Mie theory for spheres is sometimes not appropriate

Reflection Spectra of the Giant Planets



Karkoschka, 1998

Note: Spectra of Jupiter and Saturn are much darker than Uranus and Neptune at short wavelengths due to chromophores. The reverse is true at longer wavelengths due to methane absorption.



ISO Spectra – IR Whole Disk

Th. Encrenaz et al. / Planetary and Space Science 47 (1999) 1225–1242 1227

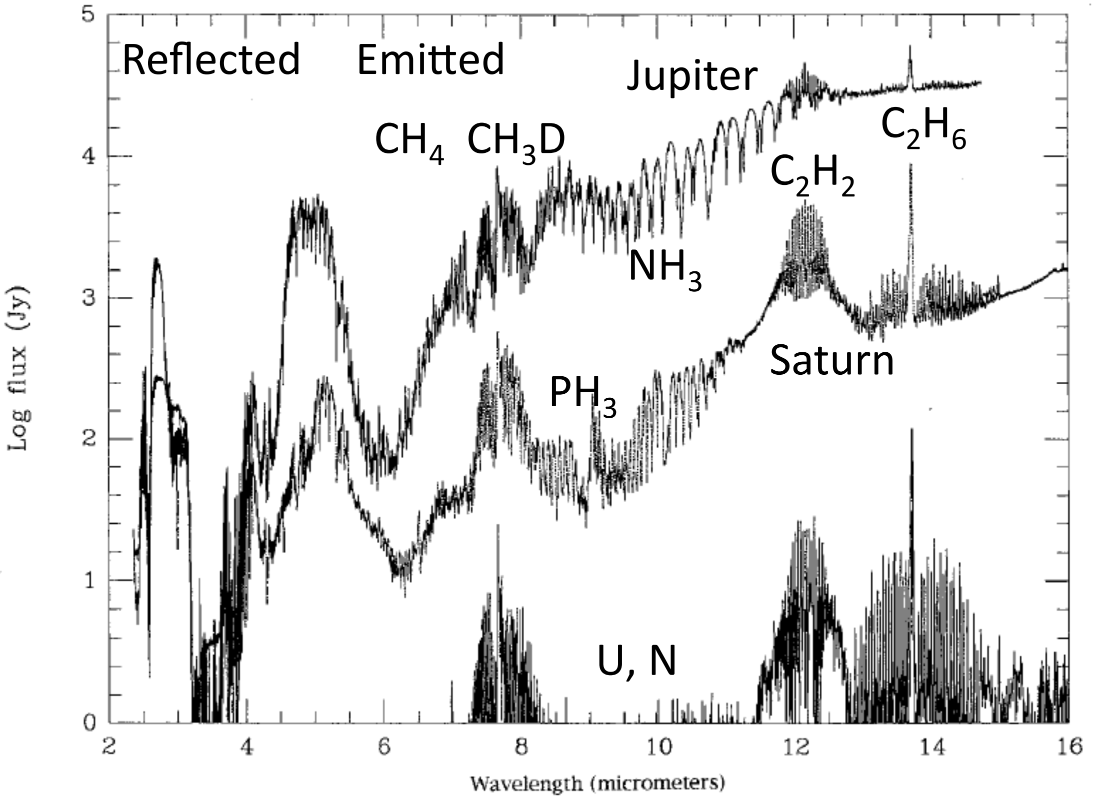
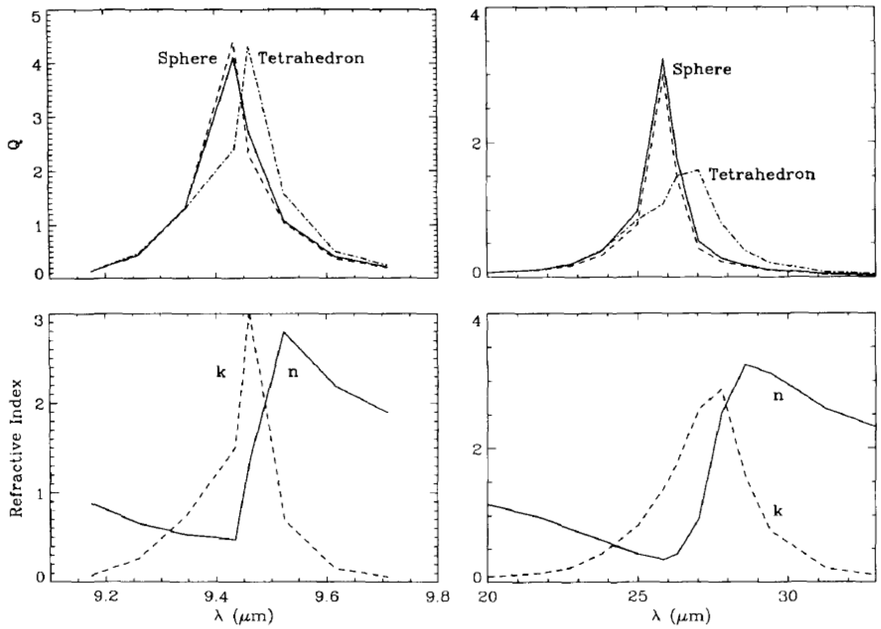


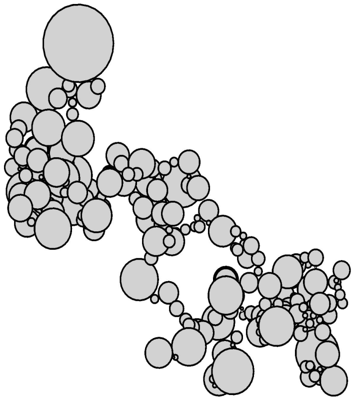
Fig. 1. The SWS grating spectrum of Jupiter between 2 and 16 μm. The resolving power is about 1500. The Uranus spectrum only shows the C_2H_2 band at 13.7 μm, about 3 times weaker than on the Neptune spectrum. Uranus and Neptune are not detected below 7 μm with SWS.

Crystals and Aggregates

Do not use Mie theory

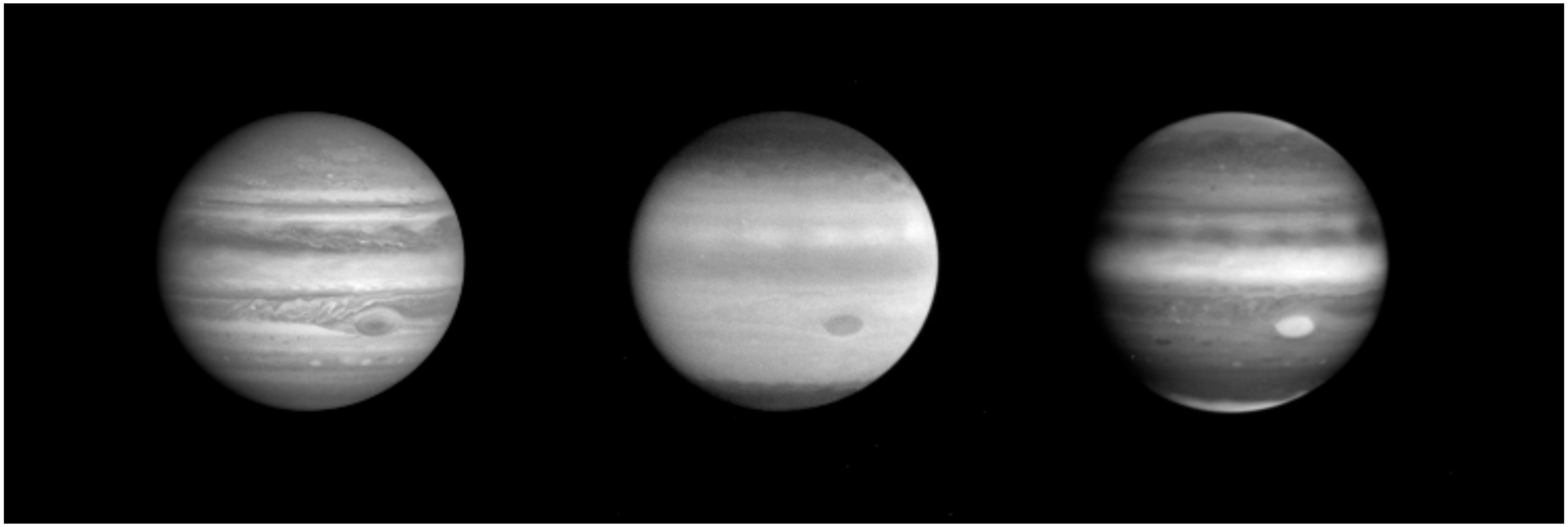


Ammonia Ice absorptions
From West et al., 1989



Photochemical or auroral-generated haze particles in Jupiter/Saturn auroral regions are aggregates

Photochemical/Auroral Haze Revealed by UV and near-IR Images



Blue Near-UV Near-IR Methane

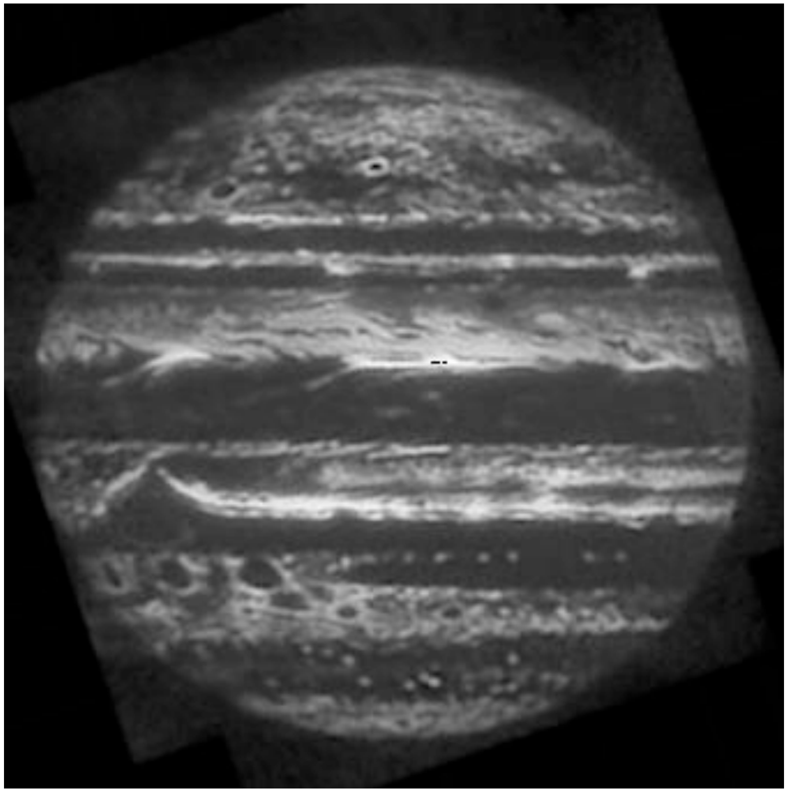
From the Cassini ISS instrument at Jupiter Porco et al., 2003

The polar stratospheric haze Is concentrated near the few-mbar pressure level, well above the condensate cloud deck

Photochemical Haze Production on Planets Near Stars

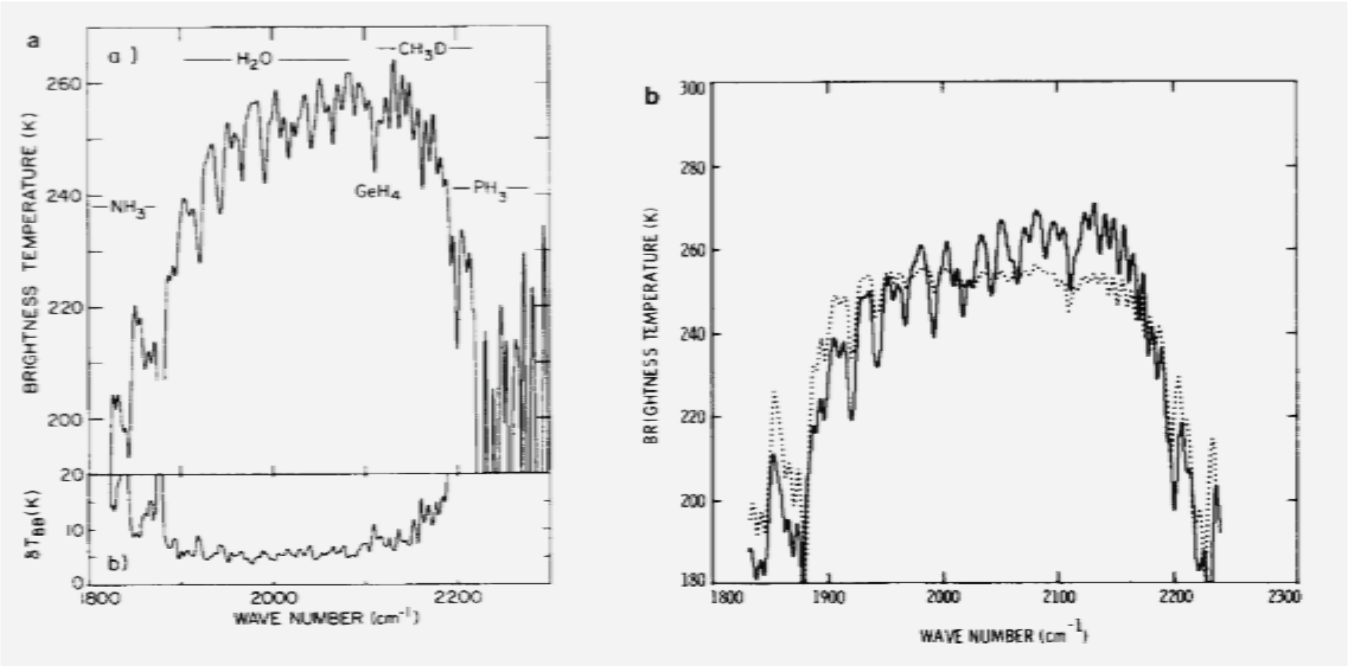
- Stratospheric haze production can be prodigious
- On the giant planets the composition can be organic, N_2H_4 (hydrazine), P_2H_4 (diphosphene)
- Tidal locking will influence static stability, photochemical production rates and lifetimes
- Dynamical regime will be unfamiliar probably leading to a highly asymmetric distribution of absorbing haze.
- Does this explain the low albedo for HD 209458b? See paper by Rowe et al., *Ap. J*. **689**, 2008

Cloud Heterogeneity is Important for Emitted Radiation



Ground-based 5-µm image from J. Spencer

Jovian Hot Spot Spectra and Models

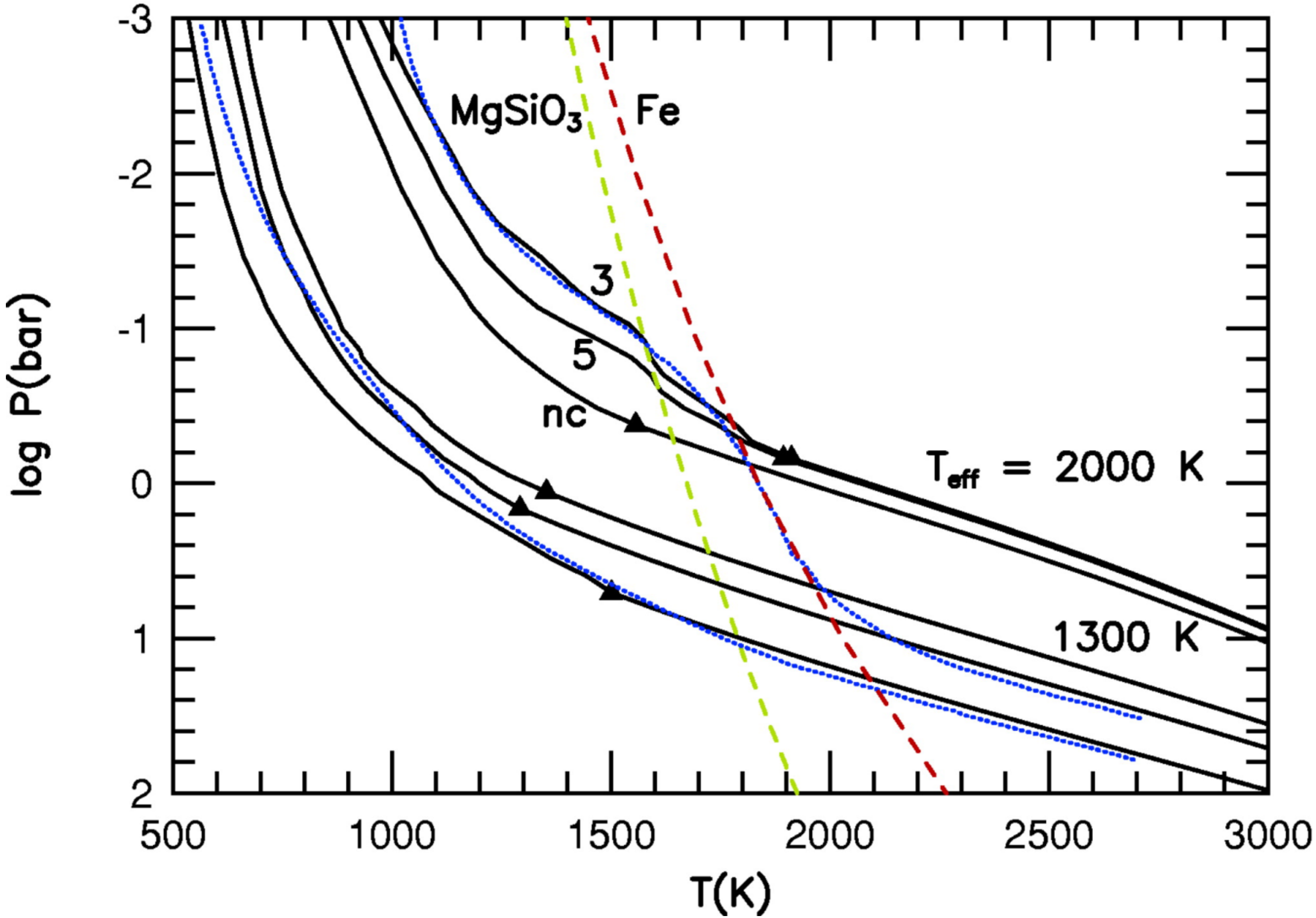


Data from the Voyager IRIS instrument .

Models having cloud opacity at the water base or high above the water base. If the cloud is at the water base the spectrum is much too flat

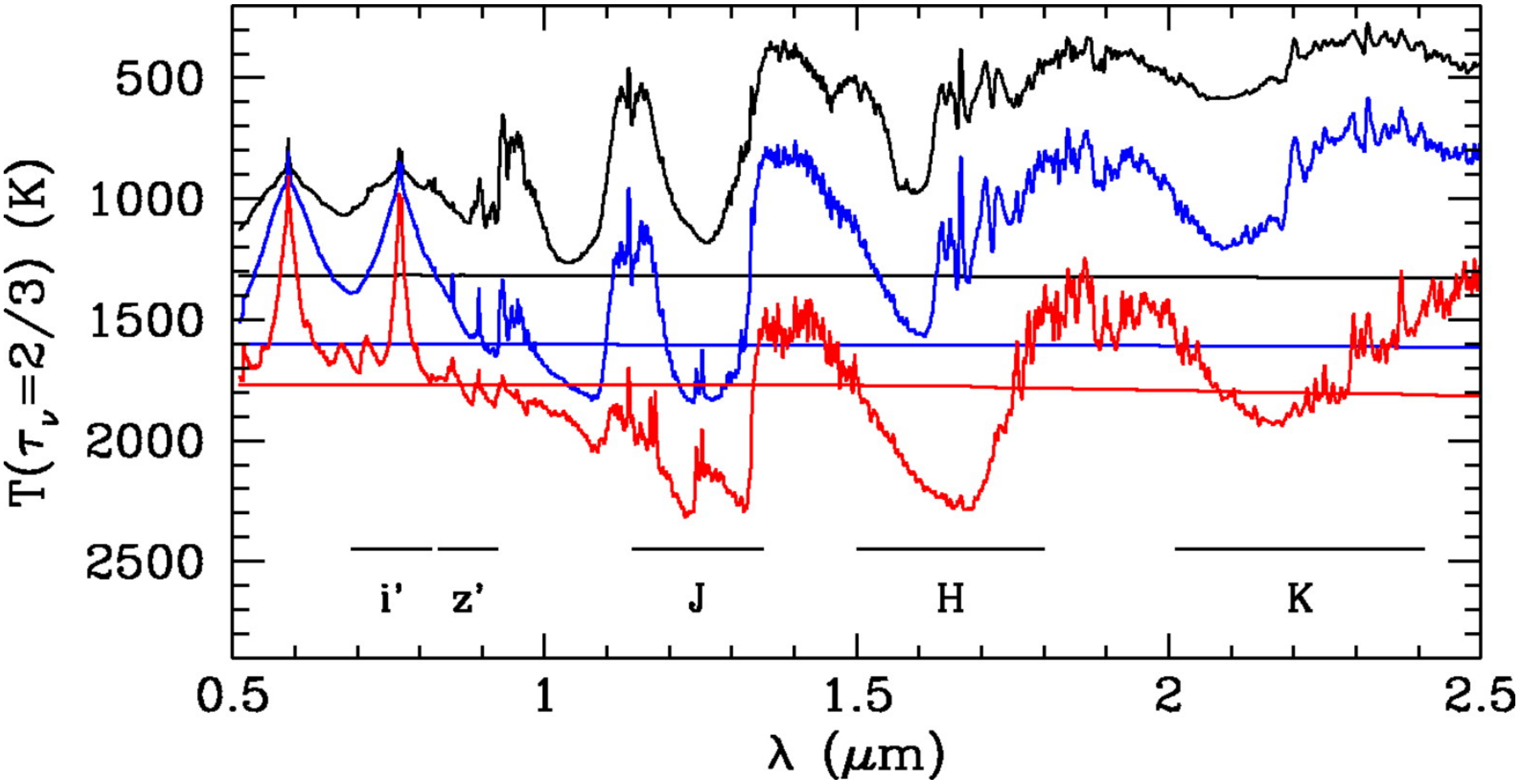
From West et al., 1986.

Clouds in Dwarf Stars



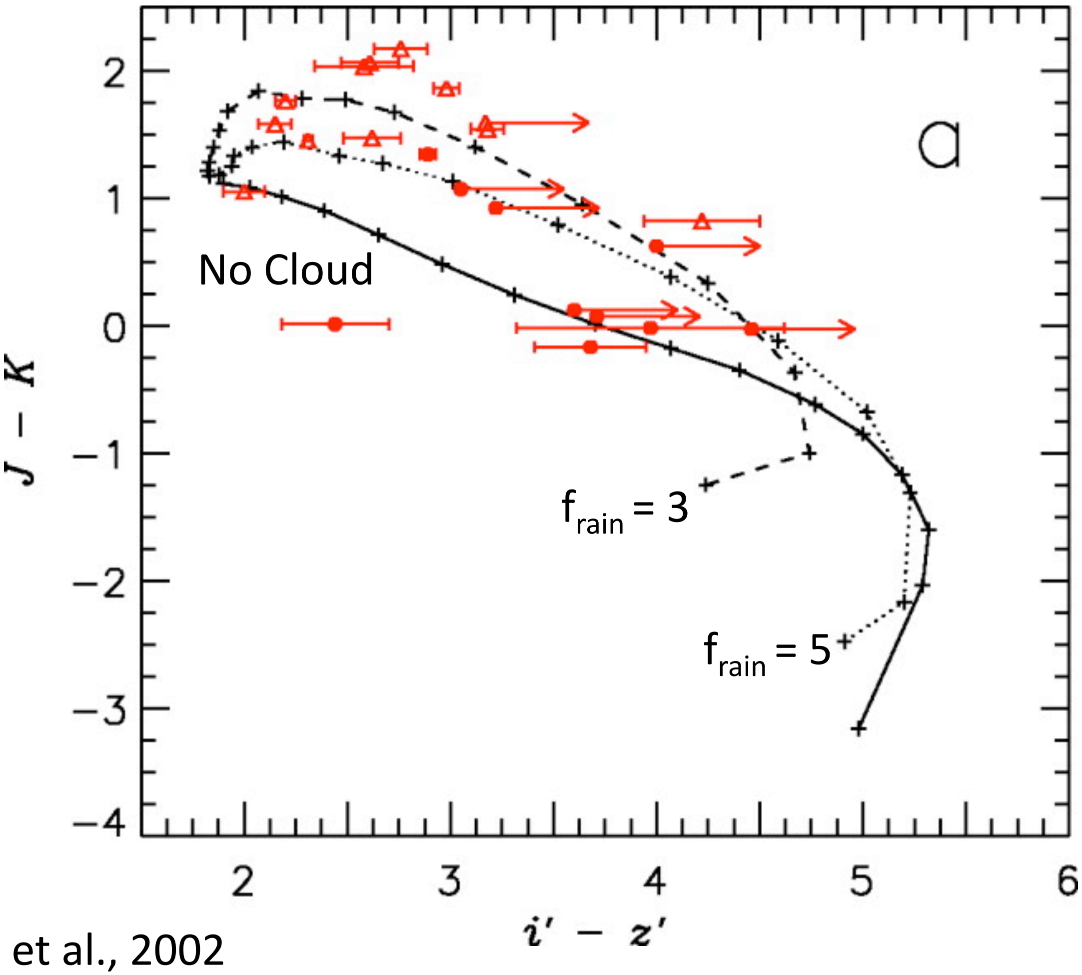
Marley et al., 2002

Effective Temperatures for Three Models – Cloud or no Cloud



Marley et al., 2002

Color Diagram for L, T Dwarfs with/without Clouds



Marley et al., 2002

Conclusions from Cool Star Models

- Condensate layers have a profound effect on the P/T profile, and models would be in disagreement with observation if all available cloud opacity were in play. Sedimentation and/or cloud heterogeneity are important in limiting cloud opacity. (Marley et al., 2002)
- Condensate layers have a significant effect on on the observed spectrum (as much as 2 magnitudes in the color diagram)

Further reading*

- West, R. A., “Clouds in Planetary Atmospheres”, in Encyclopedia of Astronomy and Astrophysics. Institute of Physics Publishing and Grove Publishers Ltd. (2001)
- West, R. A., K. H. Baines, and J. B. Pollack, “Clouds and Aerosols in the Uranian Atmosphere.” in Uranus. J. T. Bergstralh and M.S. Matthews, Eds., Univ. of Arizona Press (1991)
- West, R.A., “Condensates in Jovian Atmospheres,” in From Giant Planets to Cool Stars, C. Griffith and M. Marley, Eds., Astron. Soc. Pacific Conference Series (1999)
- West, R. A., K. H. Baines, A. J. Friedson, D. Banfield, B. Ragent, and F. Taylor, “Jovian Clouds and Haze”, in Jupiter - The Planet, Satellites and Magnetosphere. F. Bagenal, T. Dowling and W. McKinnon, Eds., Cambridge University Press, 2004.
- West, R. A., K. H. Baines, E. Karkoschka and A. Sanchez-Lavega. “Clouds and Aerosols in Saturn’s Atmosphere”, submitted to Saturn after Cassini/Huygens, M. Dougherty et al. Eds., Springer, due fall, 2009.

*A separate text file bibliography, including abstract for dwarf stars is available