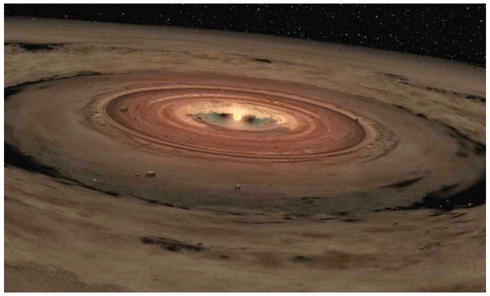
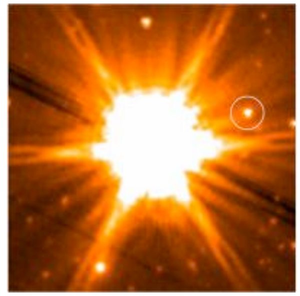
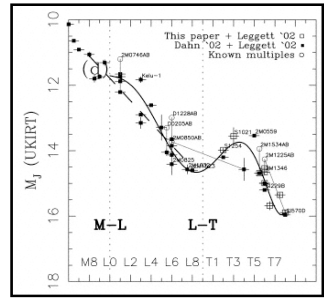
Reminder!

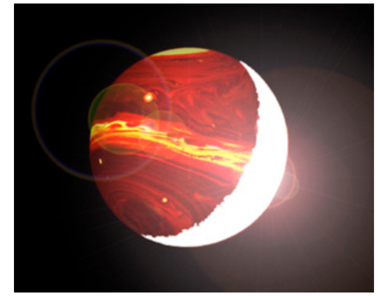
Research paper 1st draft is due to **April 25th** (1 week!)

- You should be done with your reading…
- You should have a working outline…
- You should be writing…



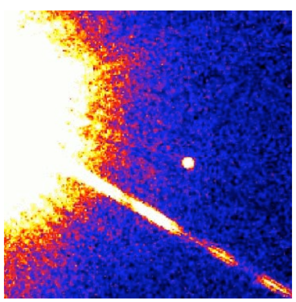


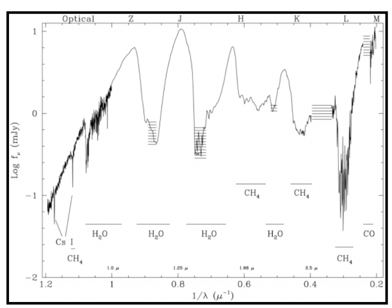


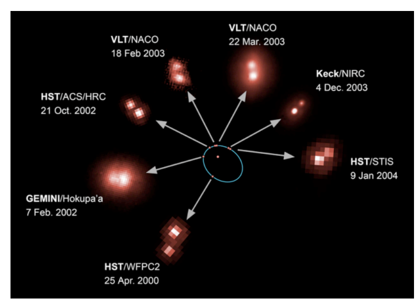


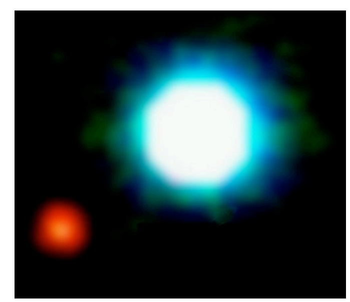
Lecture 11:

Atmospheres II: Chemistry Clouds & Convection

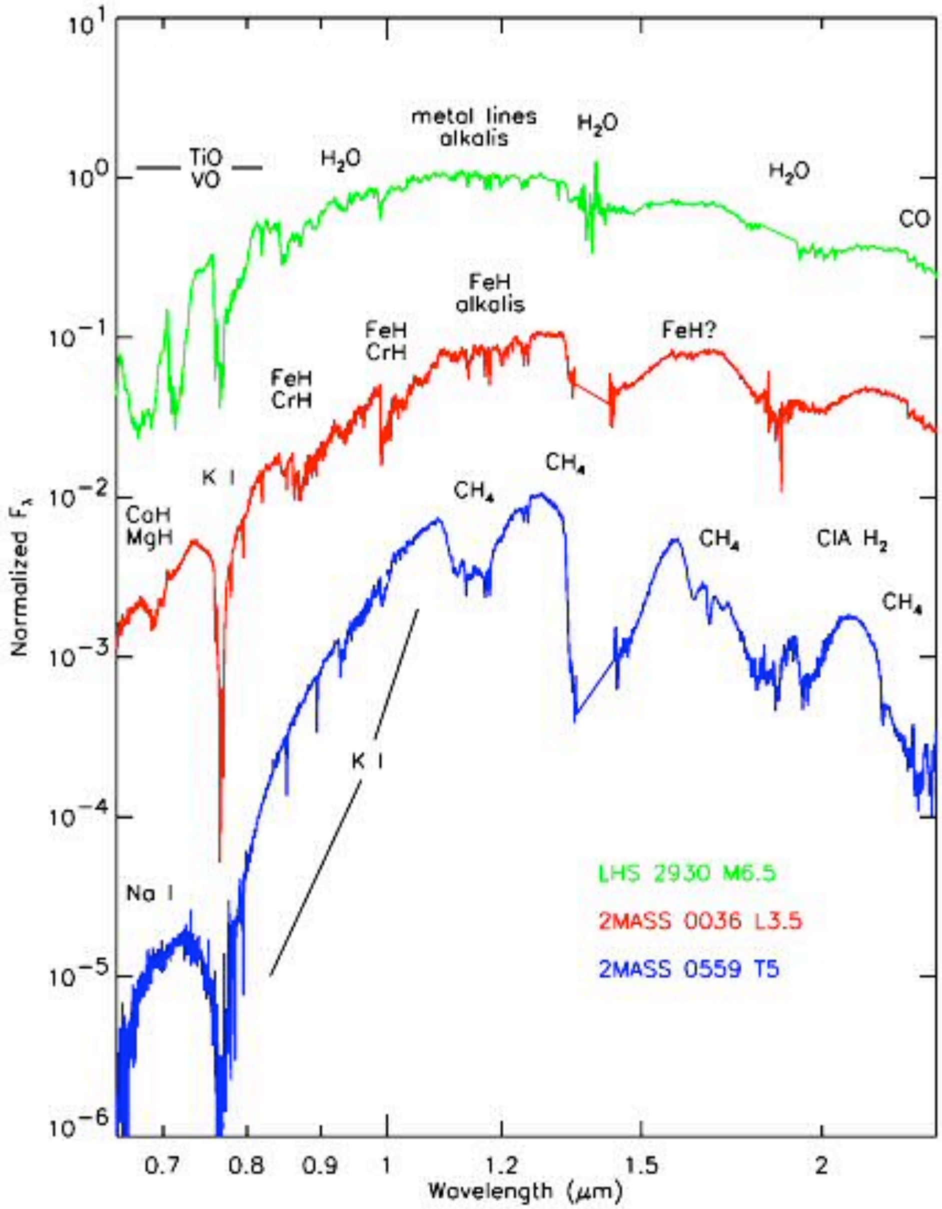








previously in 8.972…

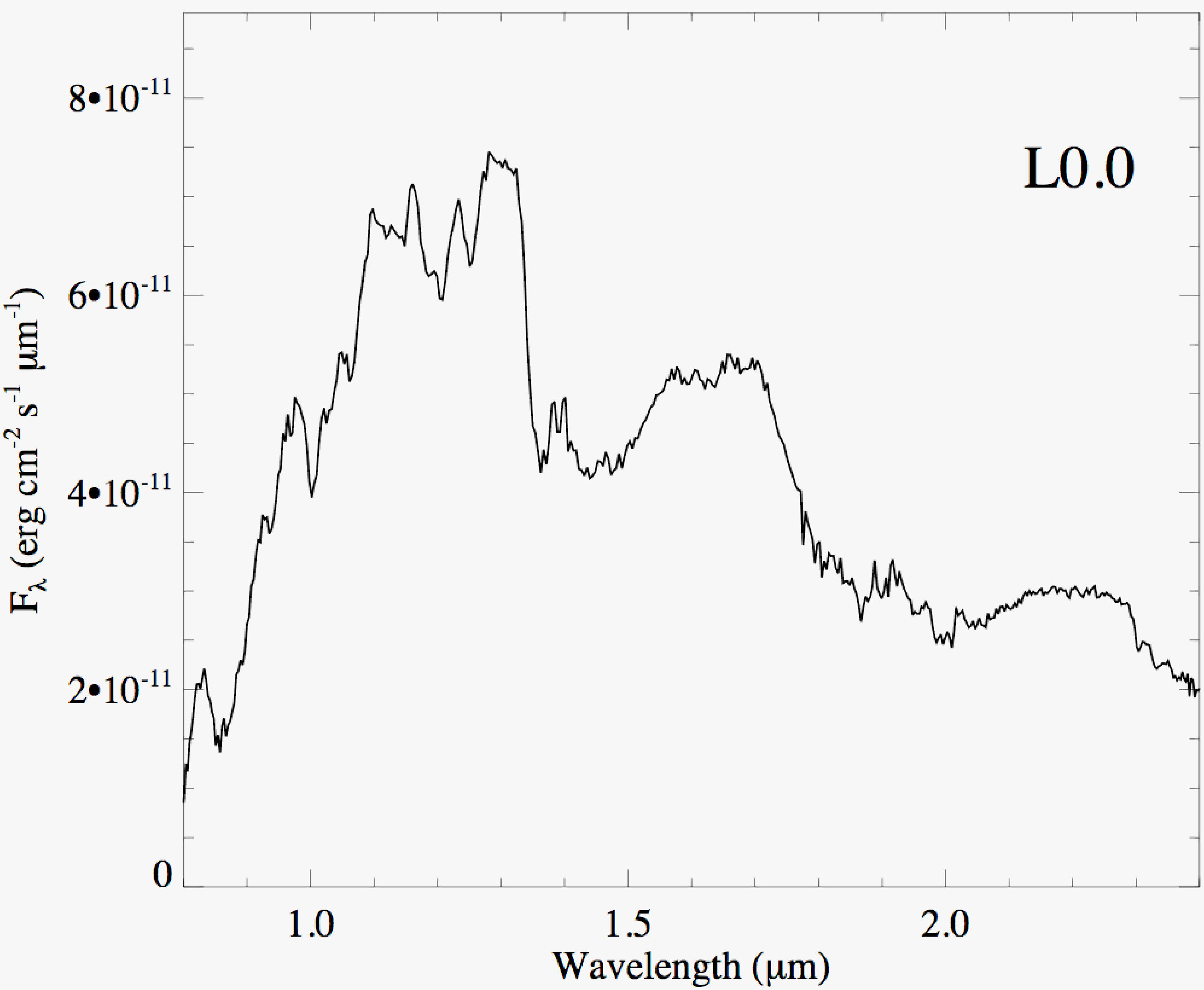


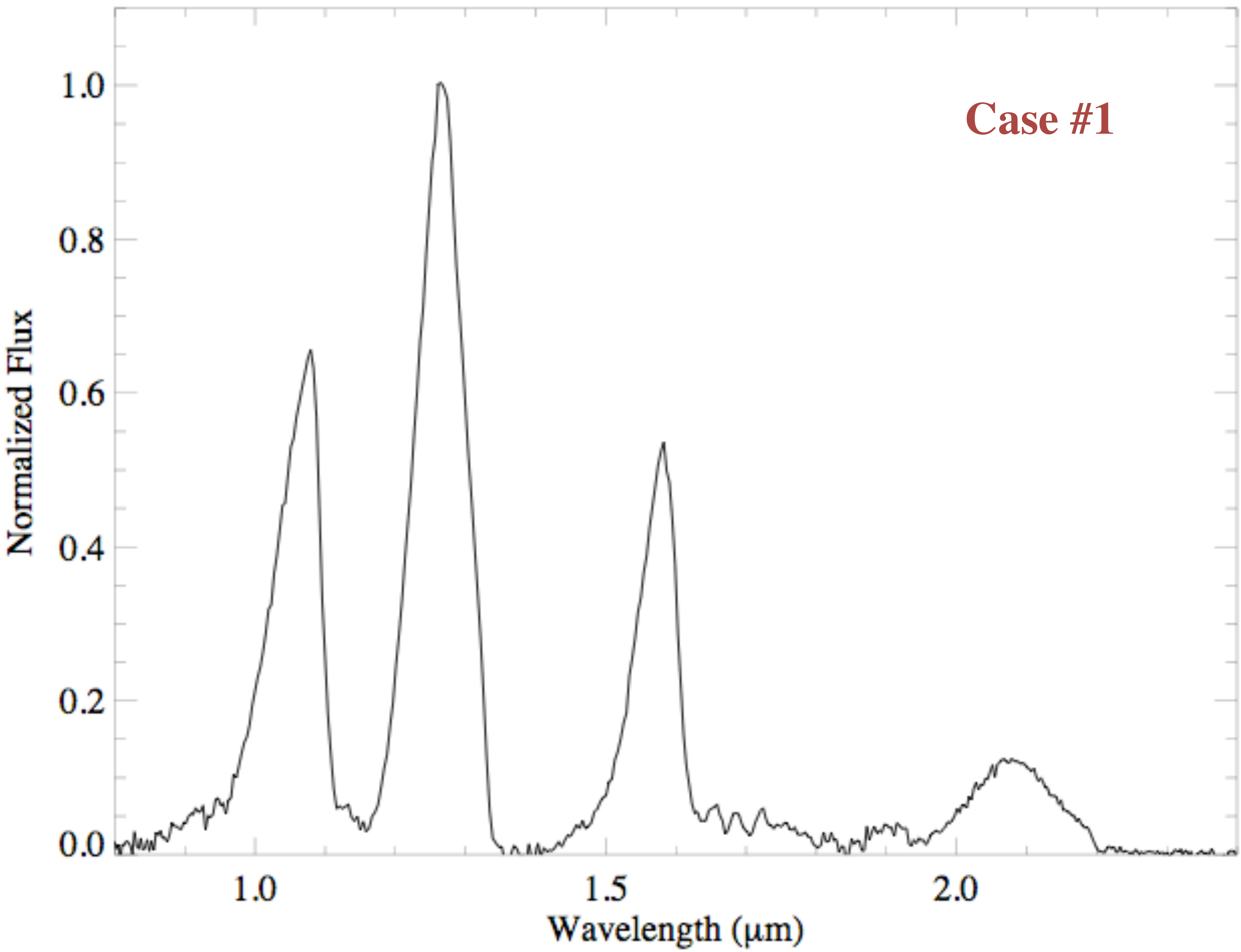
The Spectra of Brown dwarfs

Three spectral types span brown dwarfs: M, L and T

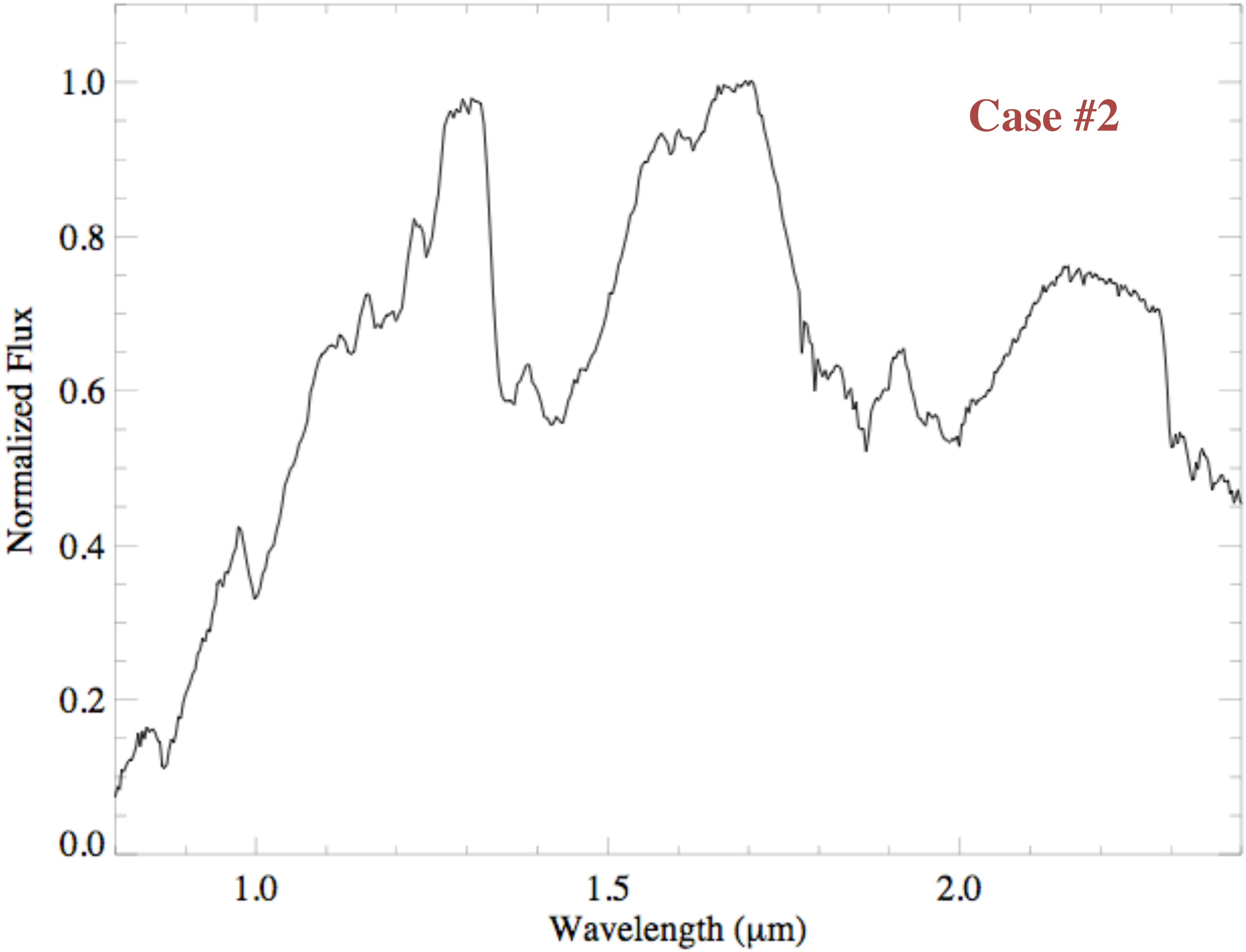
Complex features arise from atomic & molecular absorption, cloud scattering

What features are present depends on local gas pressure & temperature, abundances


L0.0
F_λ (erg cm^{-2} s^{-1} μm^{-1})
8•10^{-11}
6•10^{-11}
4•10^{-11}
2•10^{-11}
0
1.0
1.5
2.0
Wavelength (μm)



Case #1
Normalized Flux
0.0
0.2
0.4
0.6
0.8
1.0
1.0
1.5
2.0
Wavelength (μm)



Case #2
Normalized Flux
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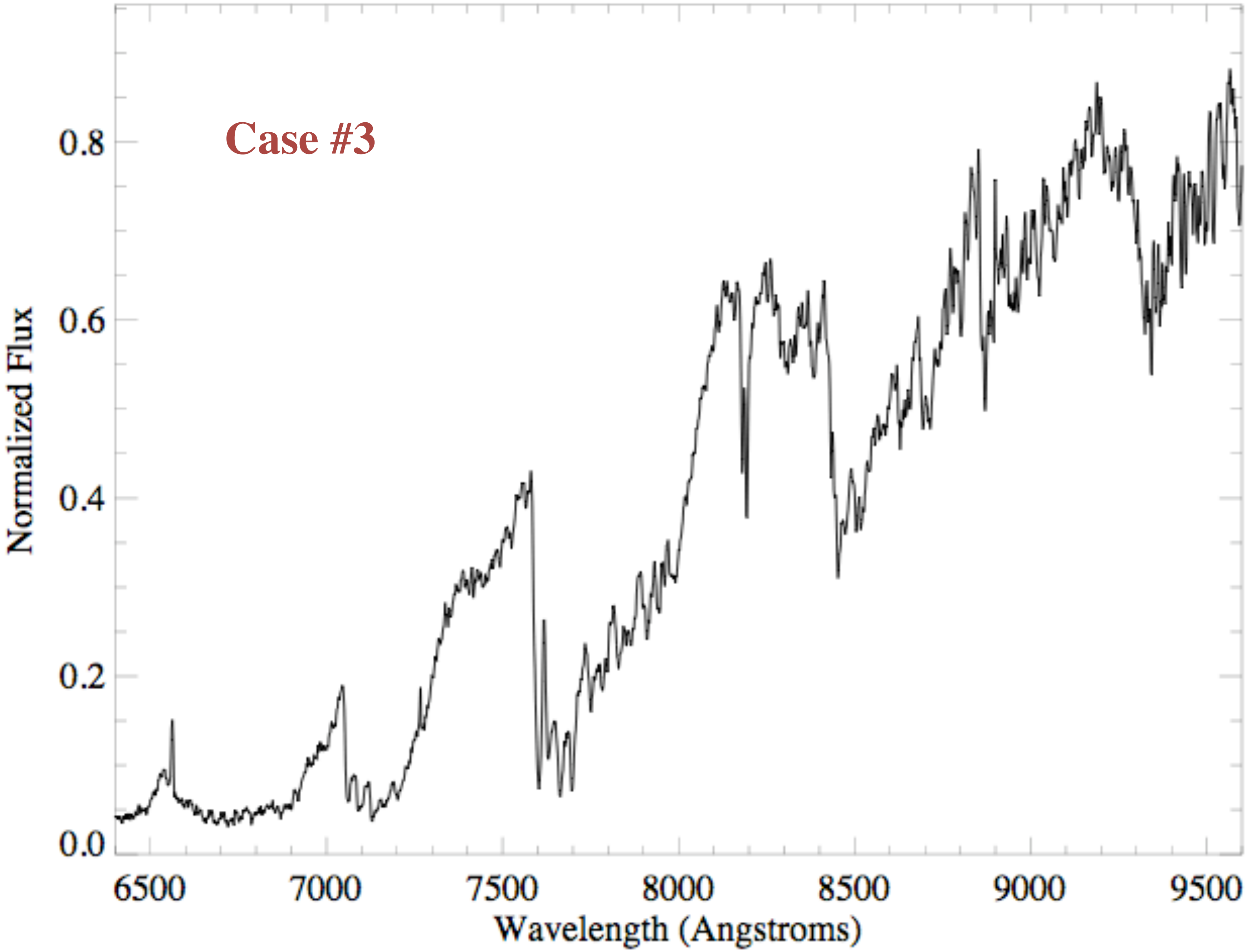
0.2
0.4
0.6
0.8
1.0
1.0
1.5
2.0
Wavelength (μm)



Case #3
Normalized Flux
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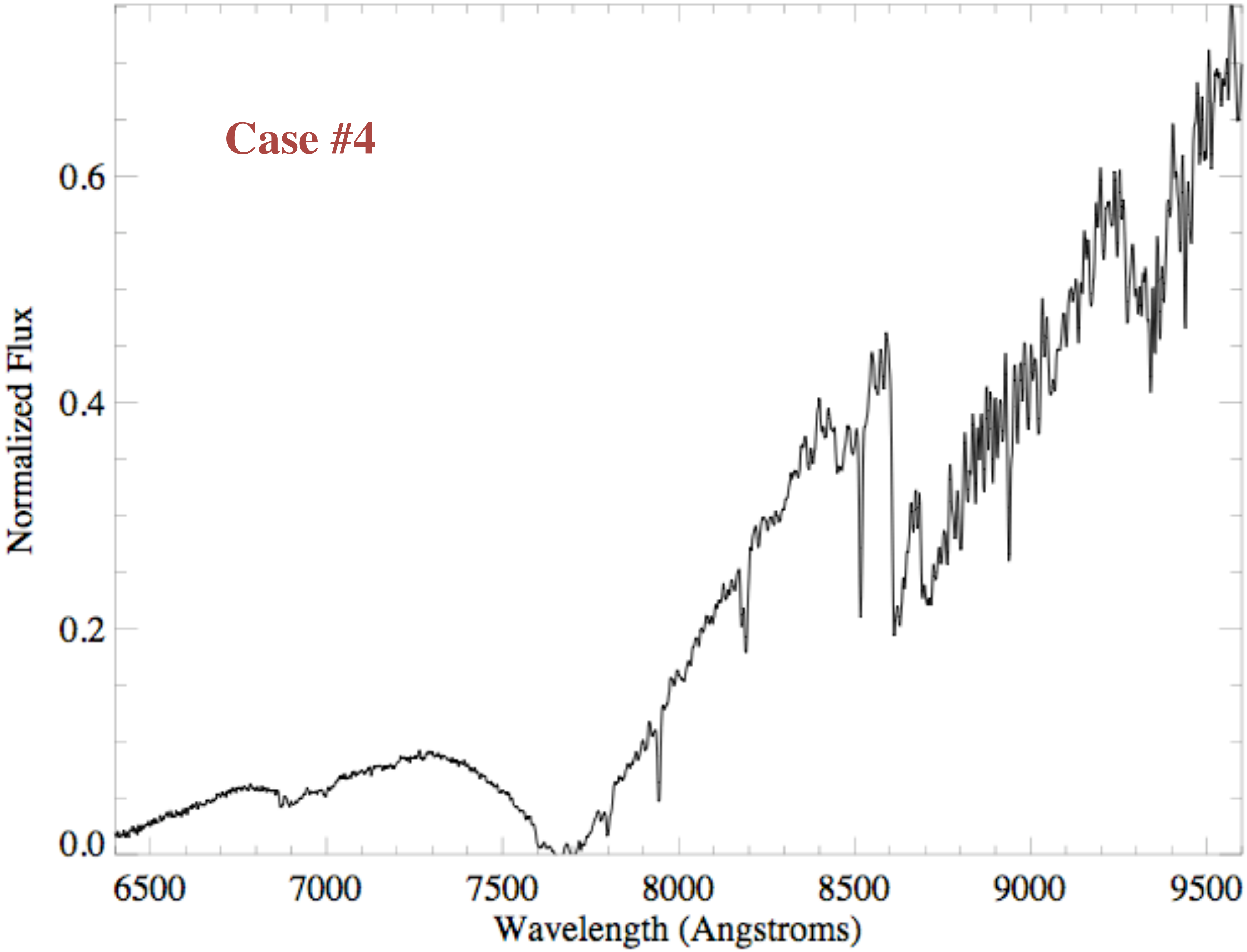
0.4
0.6
0.8
6500
7000
7500
8000
8500
9000
9500
Wavelength (Angstroms)


Case #4
Normalized Flux
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0.4
0.6
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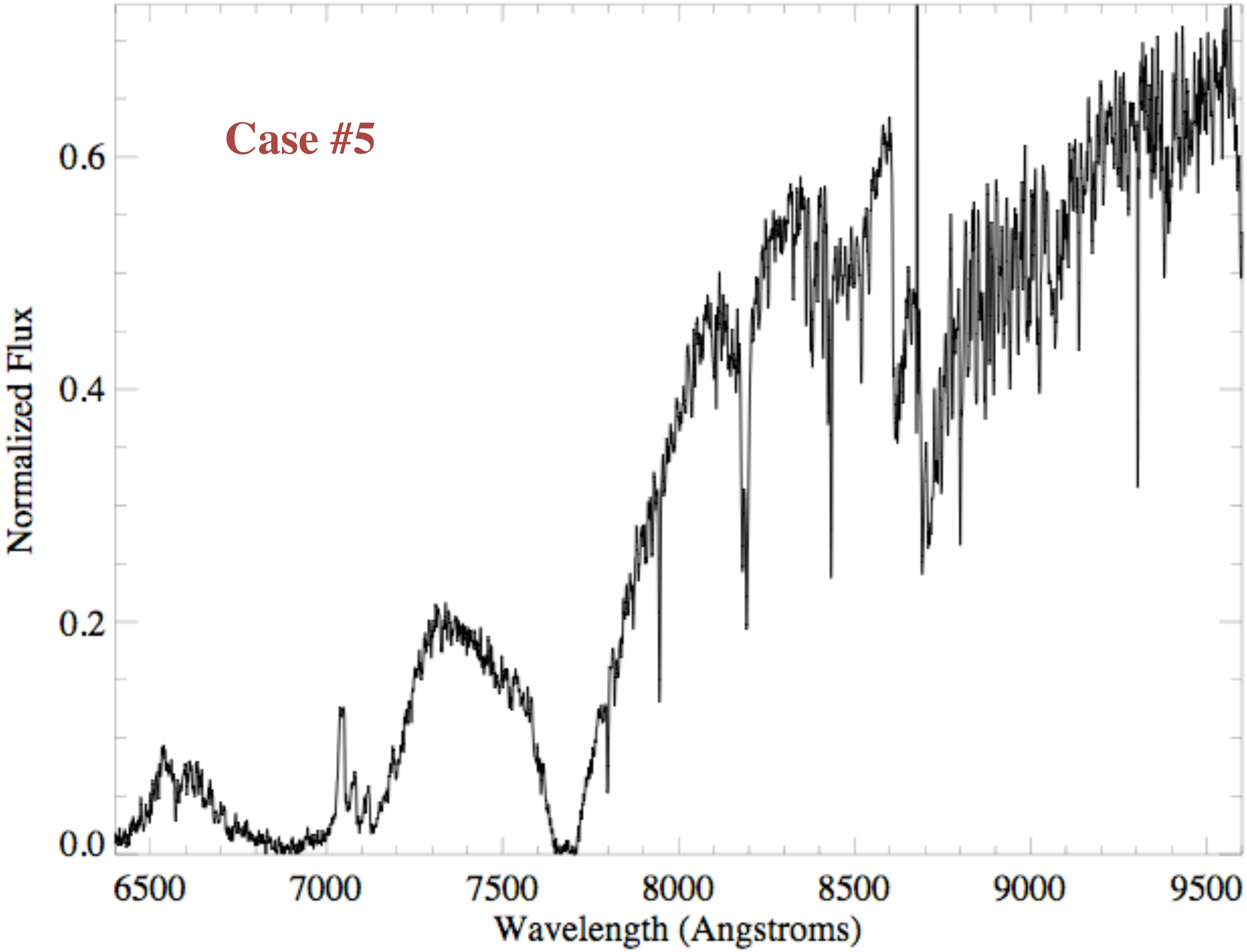
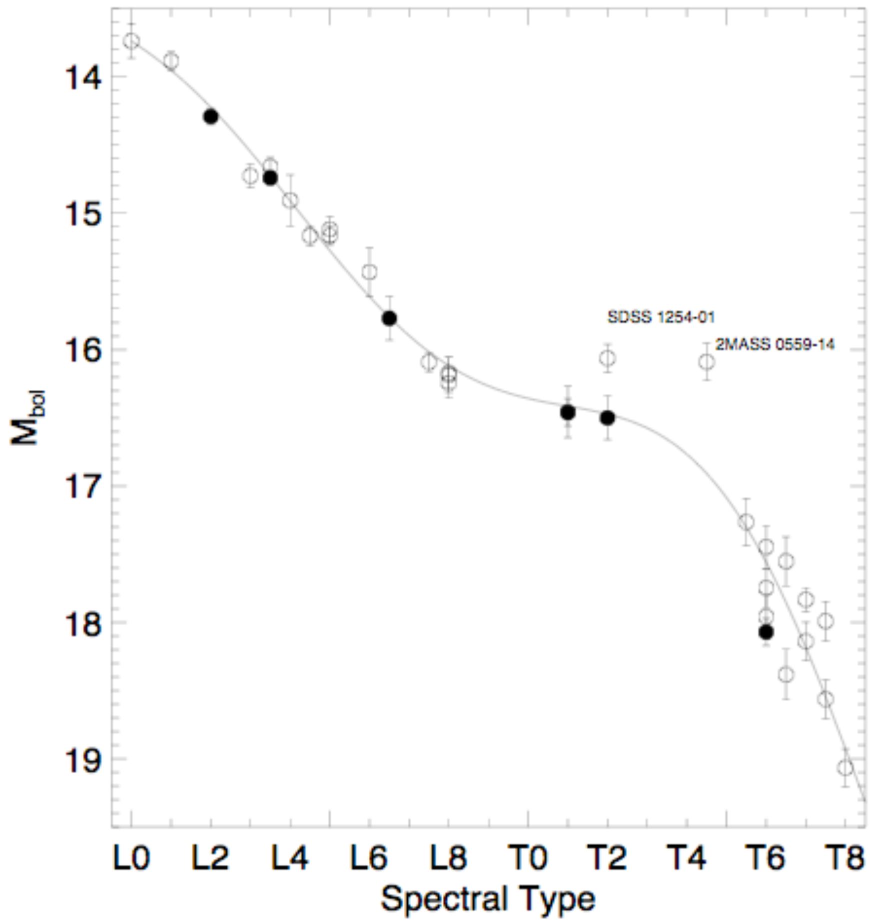
7000
7500
8000
8500
9000
9500
Wavelength (Angstroms)



Case #5
Normalized Flux
0.0
0.2
0.4
0.6
6500
7000
7500
8000
8500
9000
9500
Wavelength (Angstroms)

Spectral Type/Luminosity Relation

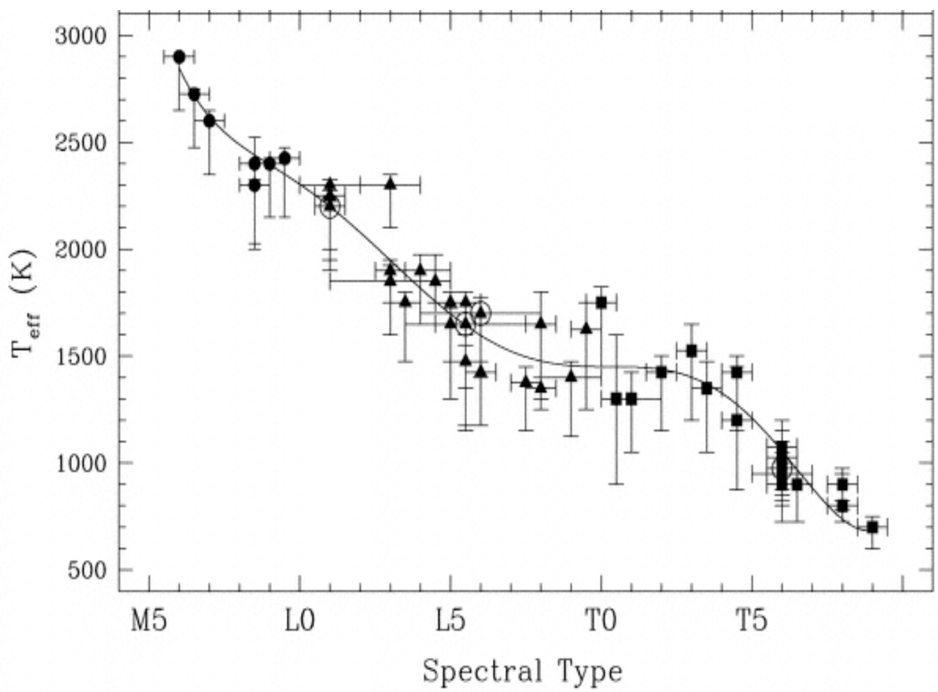


Burgasser (2007)

Overall, luminosity monotonic with spectral type; deviations and variations may arise from "cosmic scatter", unresolved multiplicity

(Golimowski et al. 2004; Vrba et al. 2004)

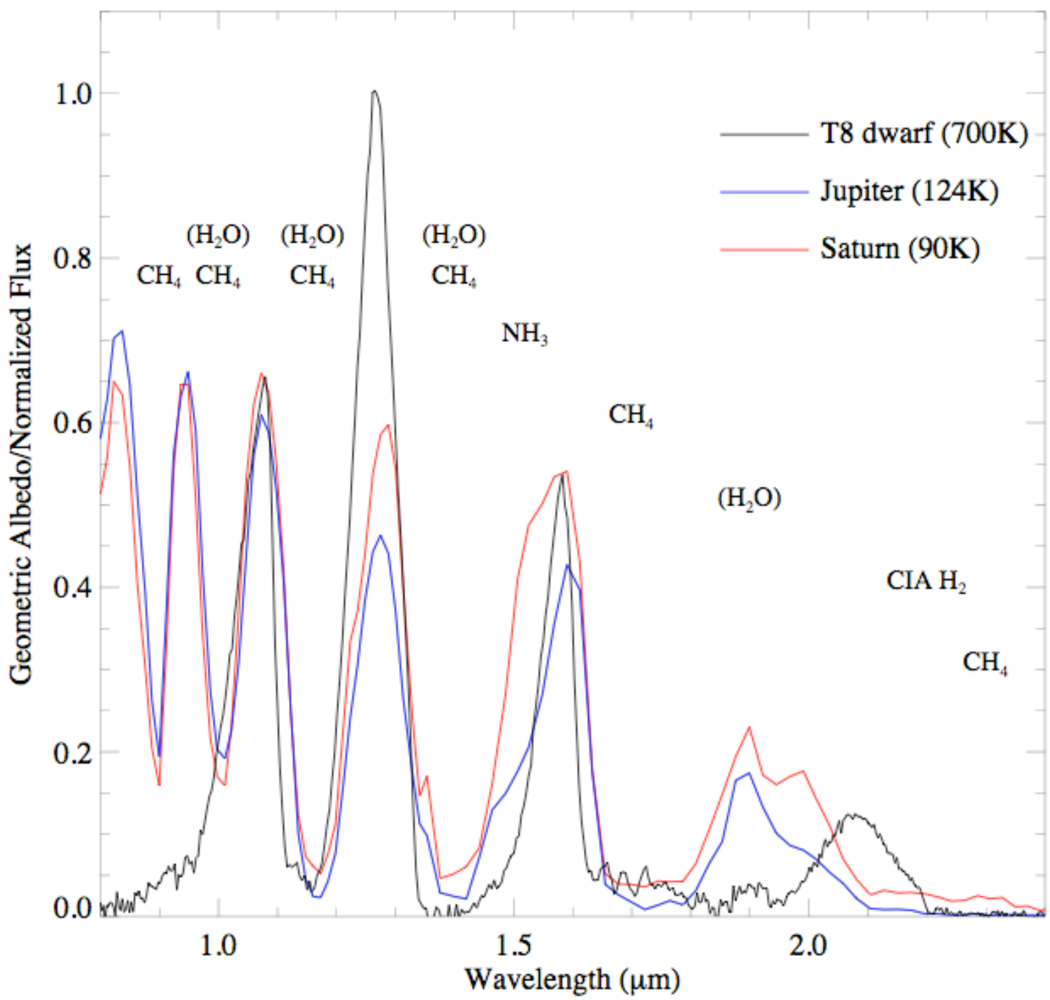
Spectral Type/Temperature Relation



Golimowski et al. (2004)

Again, monotonic relation, with a flattening across L/T transition
(Kirkpatrick et al. 2000; Golimowski et al. 2004; Vrba et al. 2004)

Spectral types appear to track relatively well with bulk properties of sources

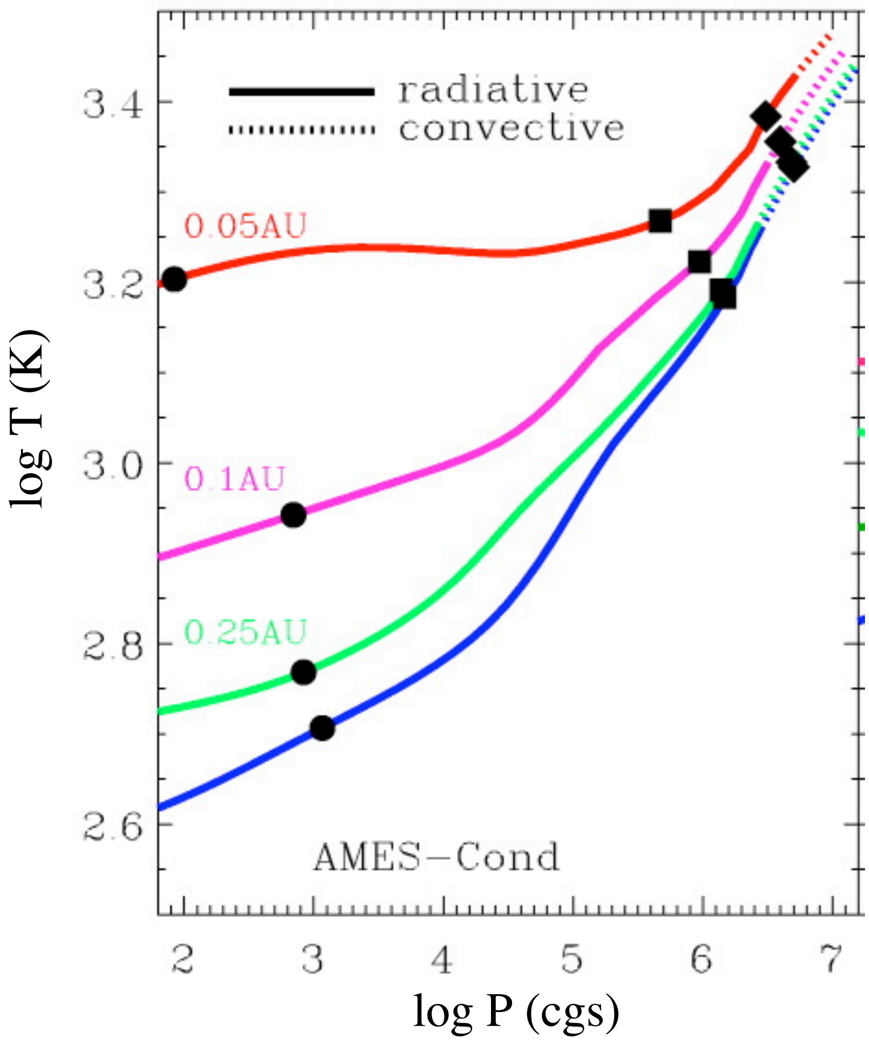


EGP spectra: influenced by external radiation

Short wavelength spectra dominated by reflectance from clouds & hazes

Photochemistry creates non-equilibrium species

Changes T/P profile in upper atmosphere



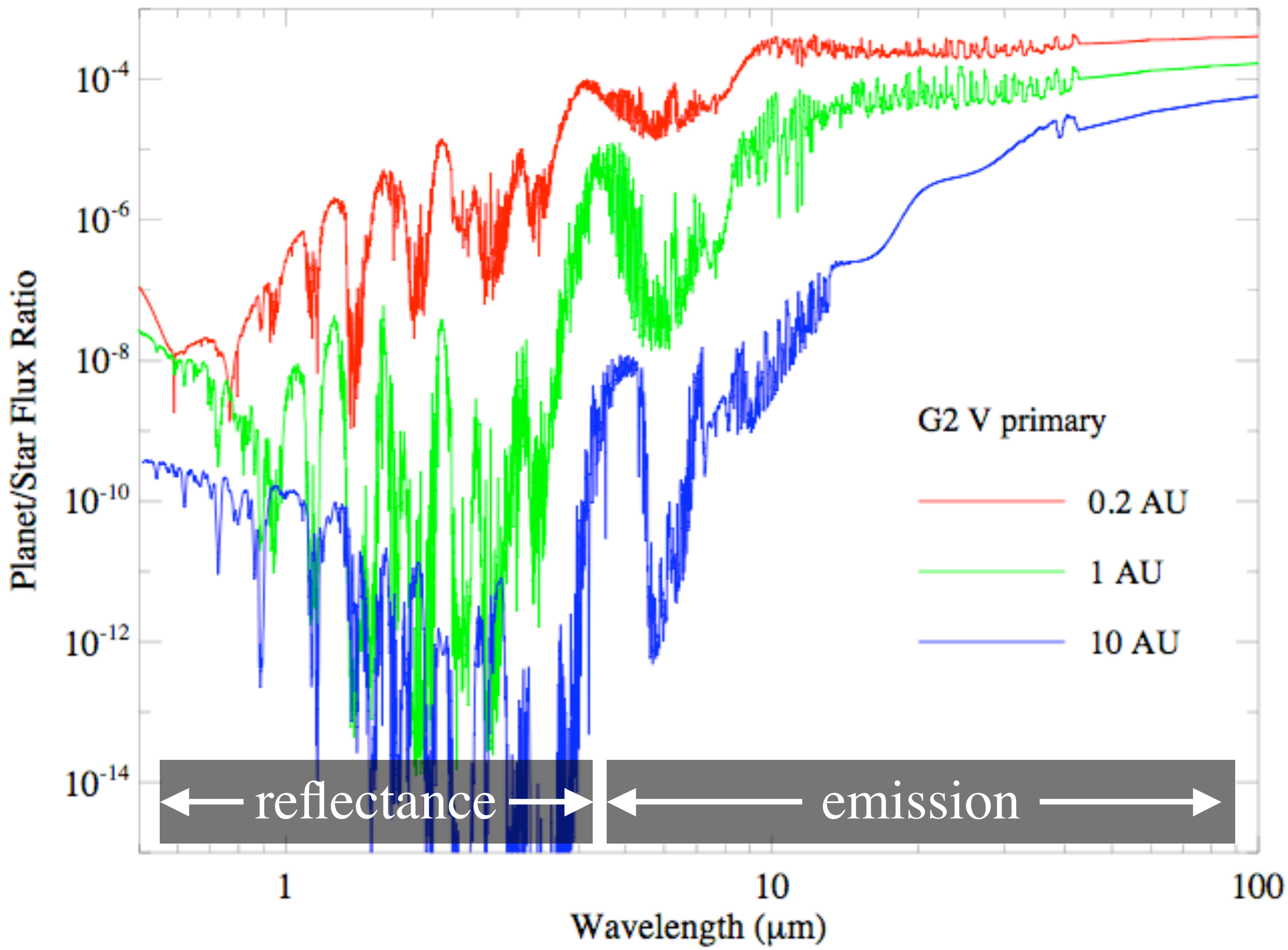
Barman et al. (2004)

EGP T/P profile

Energy deposited into the upper atmosphere by the host star changes its atmospheric T/P profile and creates a **deep upper radiative zone**.

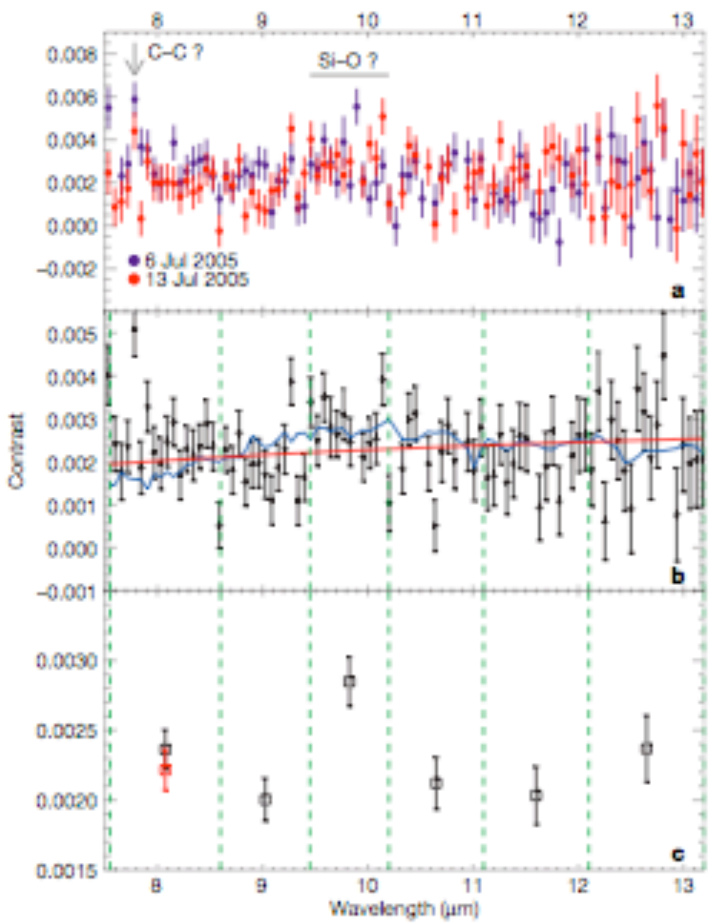
Planet cannot release heat/entropy as effectively ⇒ **changes thermal evolution**

A Hot Jupiter Spectrum (Model)



Data from Burrows et al. (2004)

A Hot Jupiter Spectrum (Observed)



Richardson et al. (2007)

HD 209458B

Emission spectrum in 8-11 micron range

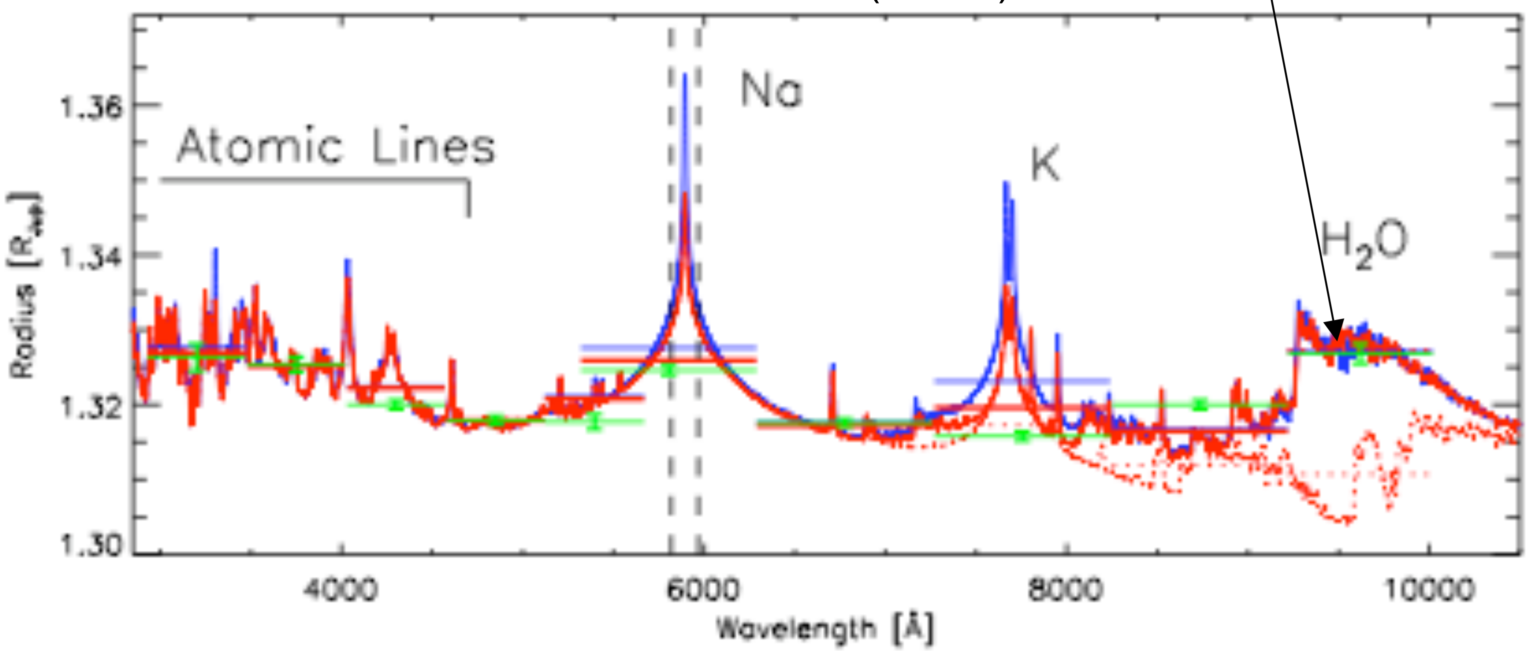
Few features - possible Si-O emission, mystery line (maybe C-C?)

Why is this surprising?

Hot off the press!

Water absorption detected!

HD 209458 (model)



Barman (2007)

The Sudarsky Types

Planet Classifications:

(Sudarsky et al. 2000)

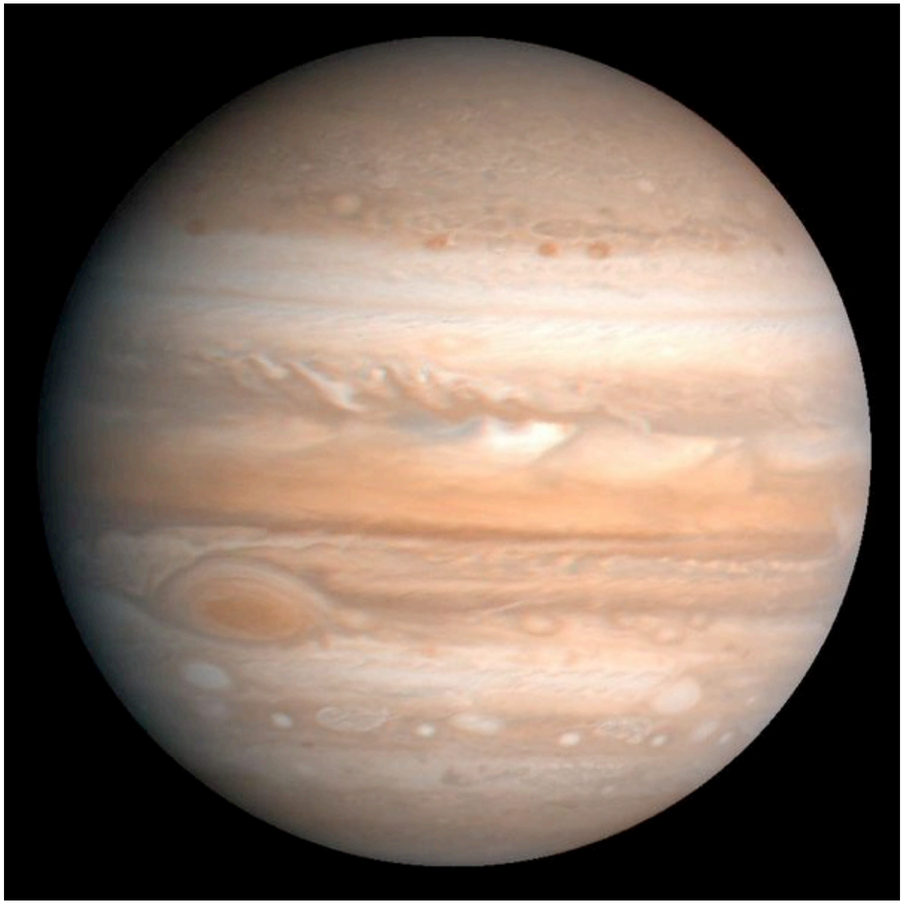
Class I: Ammonia Clouds
($T < 150$ K, $a \approx 5$ AU)

Class II: Water Clouds
($150 < T < 350$ K, $a \approx 3$ AU)

Class III: Clear
($350 < T < 900$, $a \approx 0.5$ AU)

Class IV: Alkali metal absorption
($900 < T < 1500$, $a \approx 0.1$ AU)

Class V: Silicate
($T > 1500$ K, $a \approx 0.04$ AU)



Jupiter, a Class I planet?

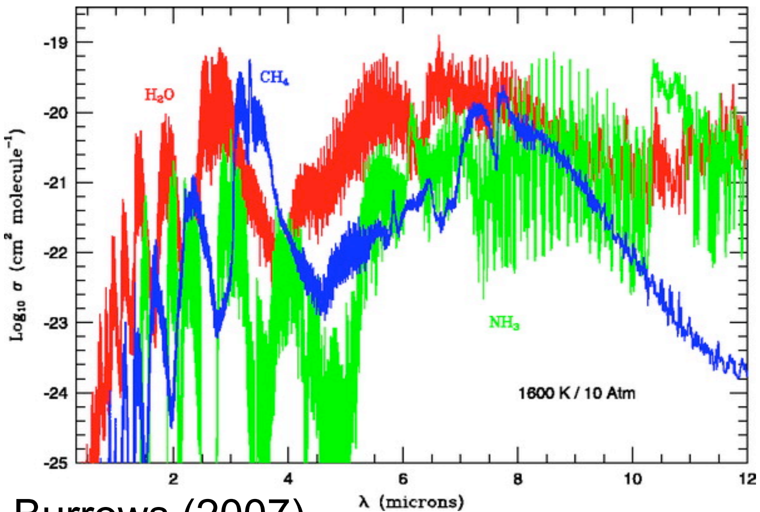
What ingredients go into making a BD/EGP atmosphere?

- Elemental abundances
- Chemistry - LTE, mixing, photochemistry
- Internal heat flow
- Incident flux
- Cloud model - treating solids and liquids
- Gas opacities and particle scattering
- Radiative transfer & energy transport model

⇒ yields thermal structure (T/P profile), emission/reflectance spectrum

A non-trivial problem!

- Large number of molecular lines: **H_2O: 4x10^7 lines**



Sharp & Burrows (2007)

CH_4: 1.7x10^7 lines

TiO: 1.5x10^6 lines

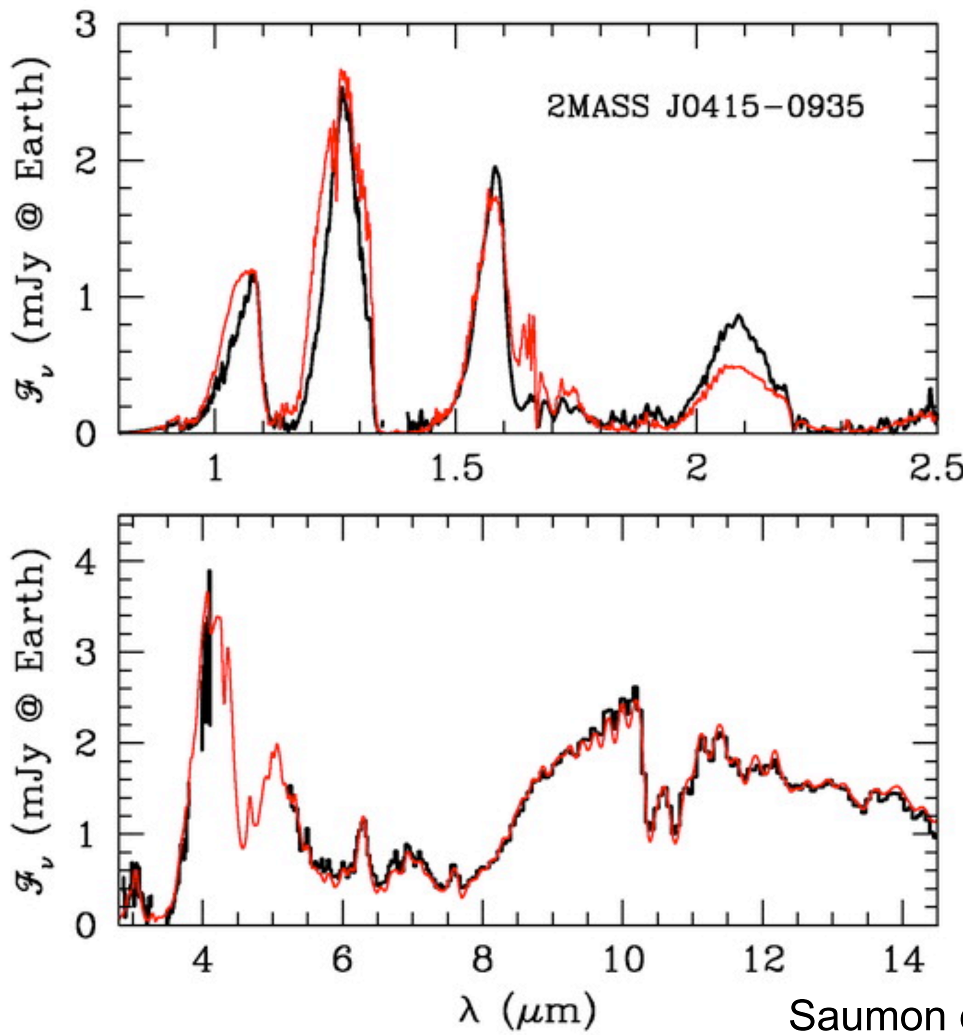
CO: 10^5 lines

NH_3: 10^4 lines

* Many of these not measured for hot EGP/BD temperatures!

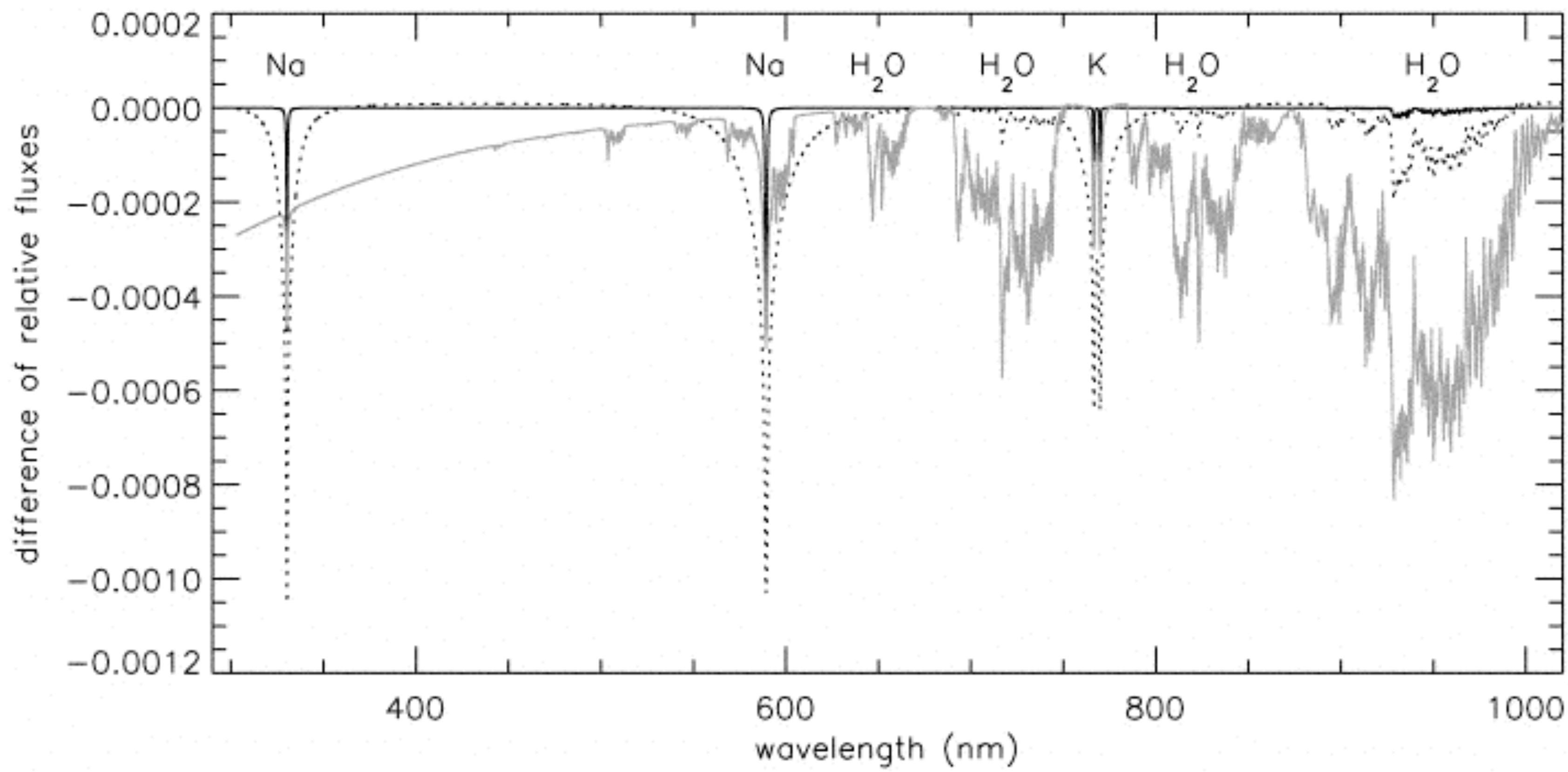
- Pressure broadening (Na I, K I) and interaction potentials (H_2)
- Condensate grain formation & distribution, cloud structure
- Chemistry, especially non-equilibrium mixing

How well do models fit data?



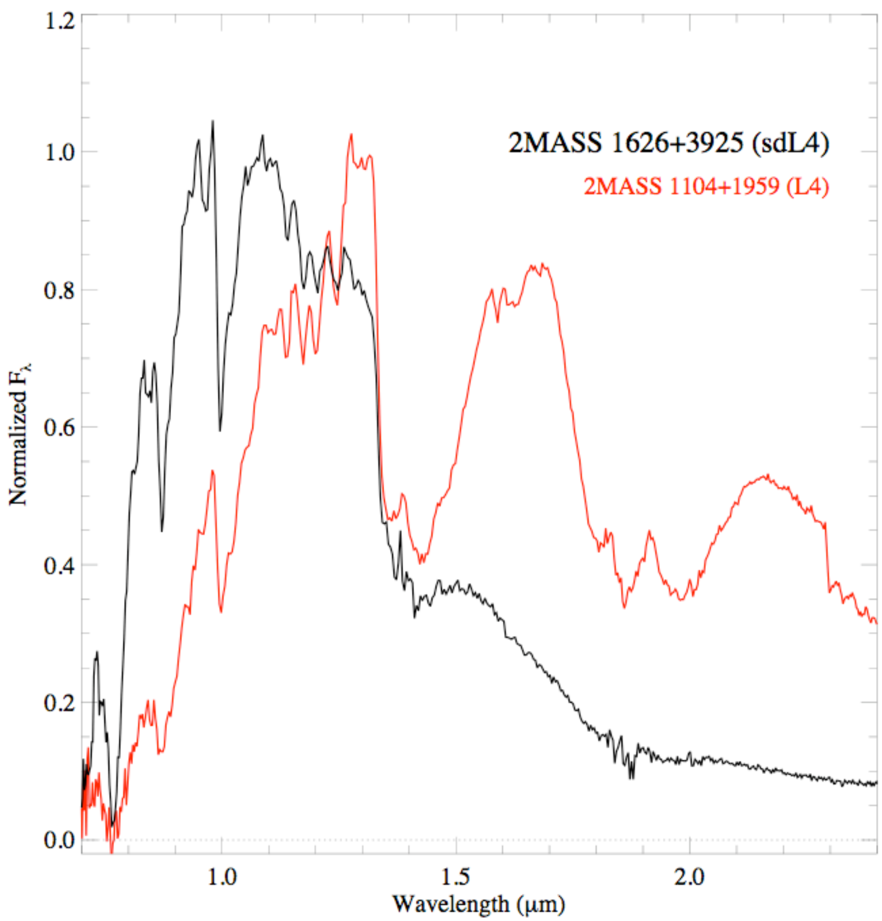
Saumon et al. (2007)

How well do models fit data?



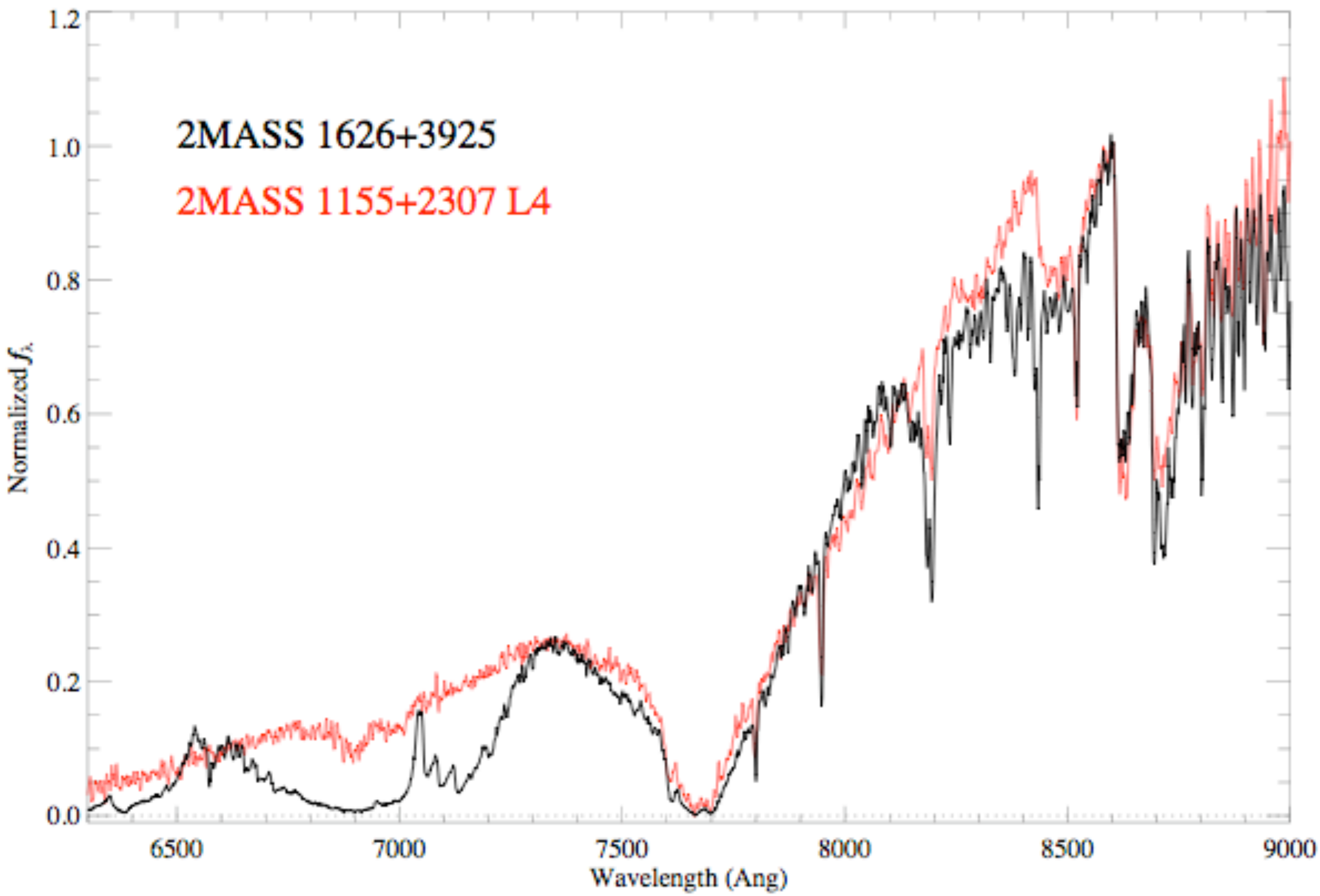
Possible models for Na I absorption in HD 209458b
Charbonneau et al. (2002)

Departures from the norm: Abundances



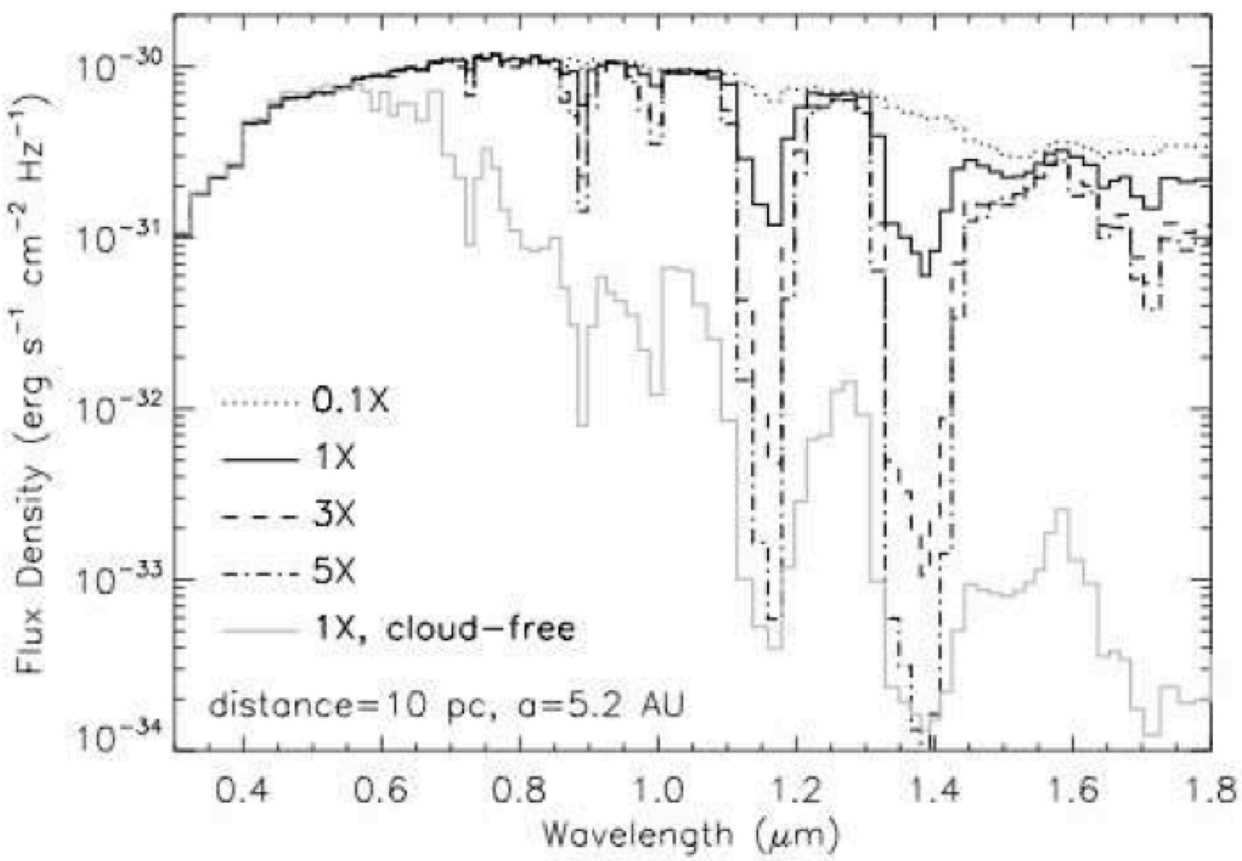
Subdwarfs are metal-poor stars with high space velocities

The depletion of metals changes the ingredients for atmospheric chemistry - thin condensate clouds, strong metal hydrides, strong H_2



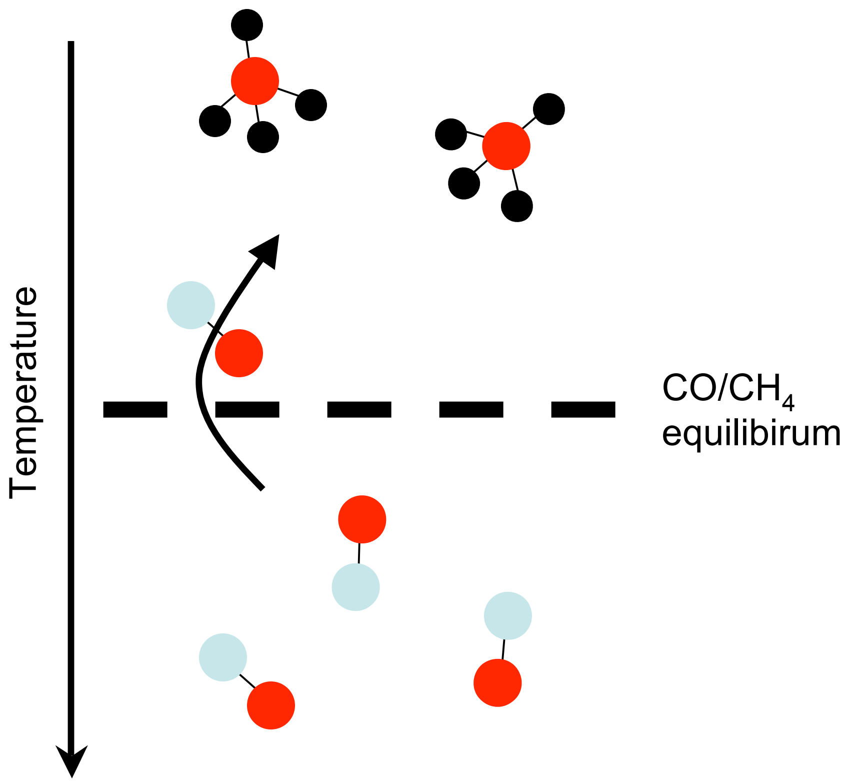
Burgasser, Kirkpatrick & Cruz (2006)

Metallicity effects in EGP spectra



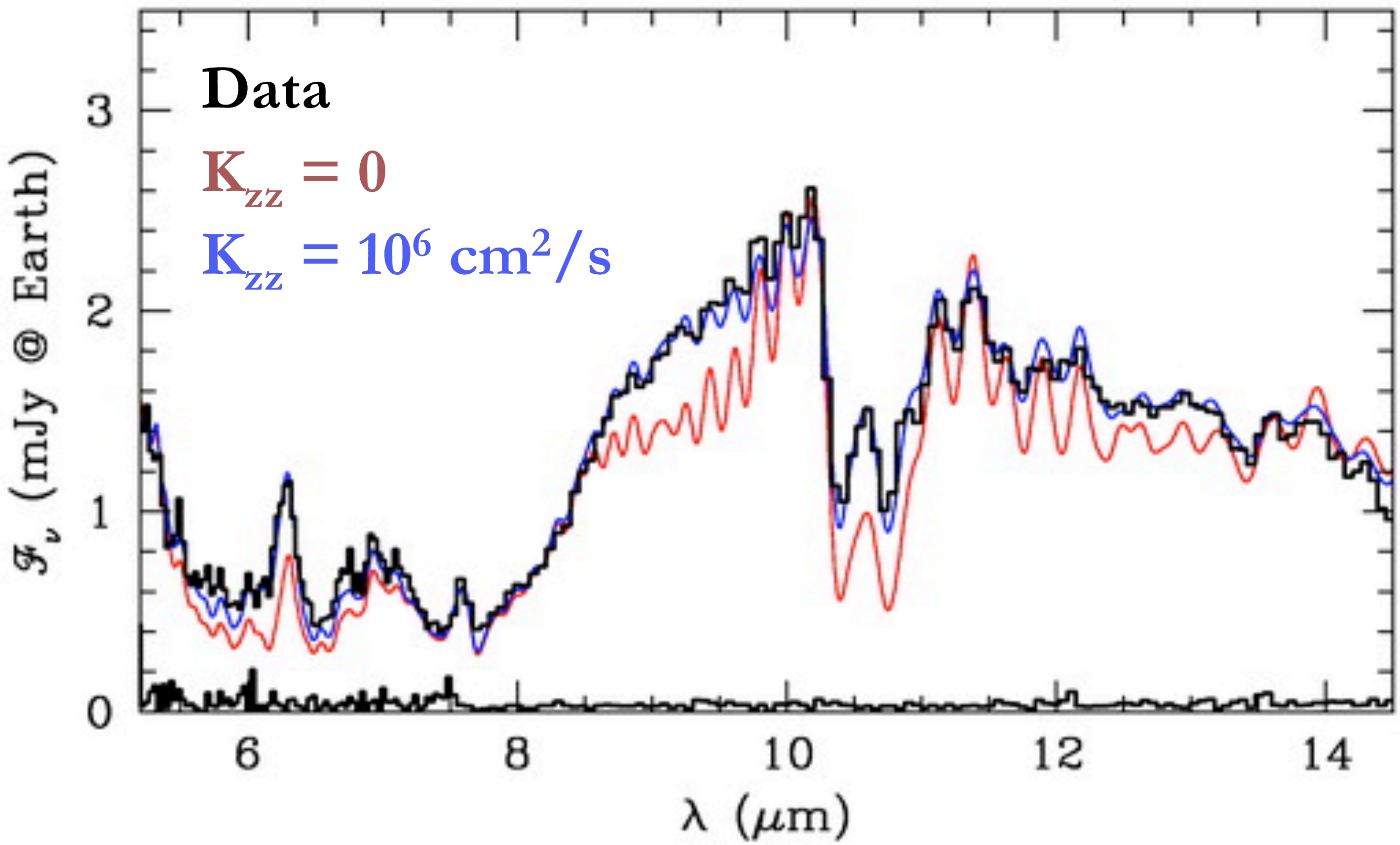
Marley et al. (2007)

Departures from the norm: atmospheric mixing



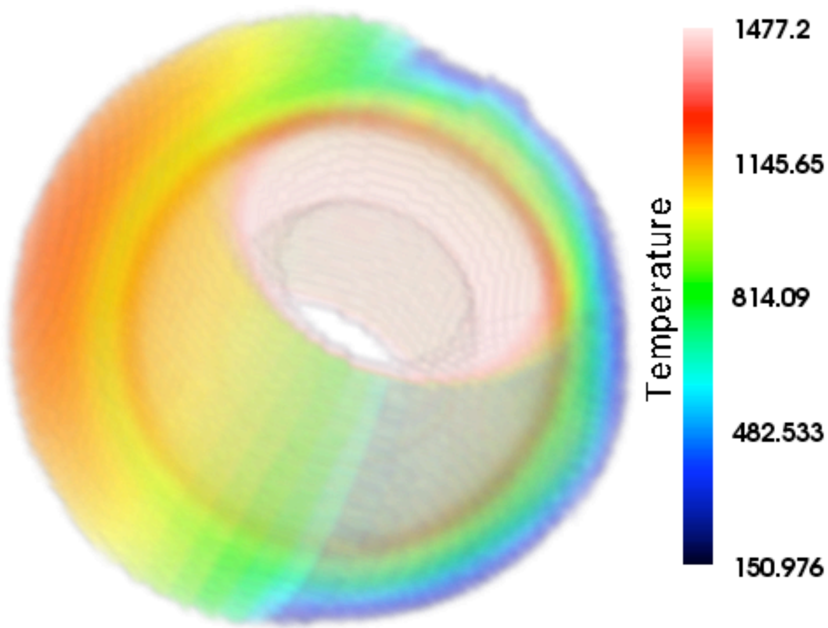
For two species tied by a temperature-dependent chemical reaction (e.g., CO/CH_4), if the **chemical timescale** (reaction rate) is longer than the **mixing timescale** (vertical diffusion velocity), nonequilibrium abundances will be found

Departures from the norm: atmospheric mixing



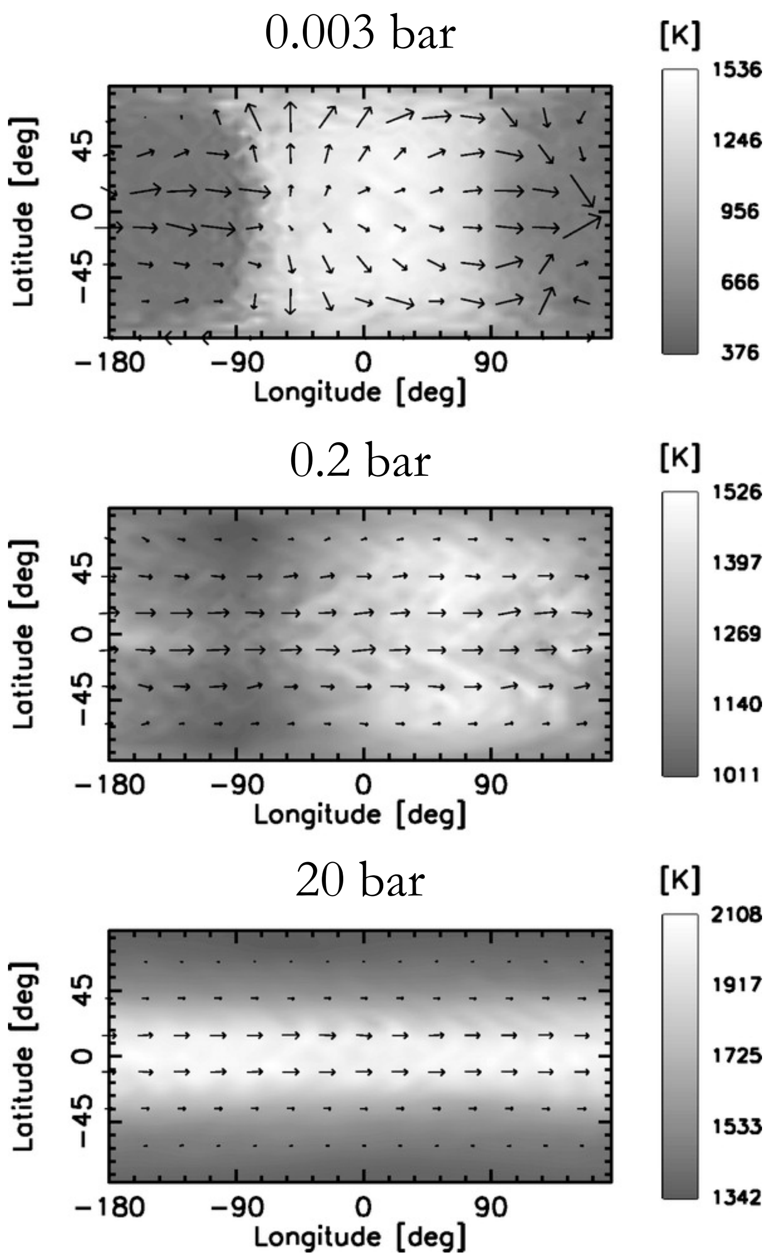
Saumon et al. (2007)

Departures from the norm: horizontal heat flow



Simulation courtesy Ian Dobbs-Dixon (UCSC)

Heating from substellar point in a tidally-locked Hot Jupiter can result in temperature & pressure differentials (winds!) across surface and at deep layers - non-local chemistry

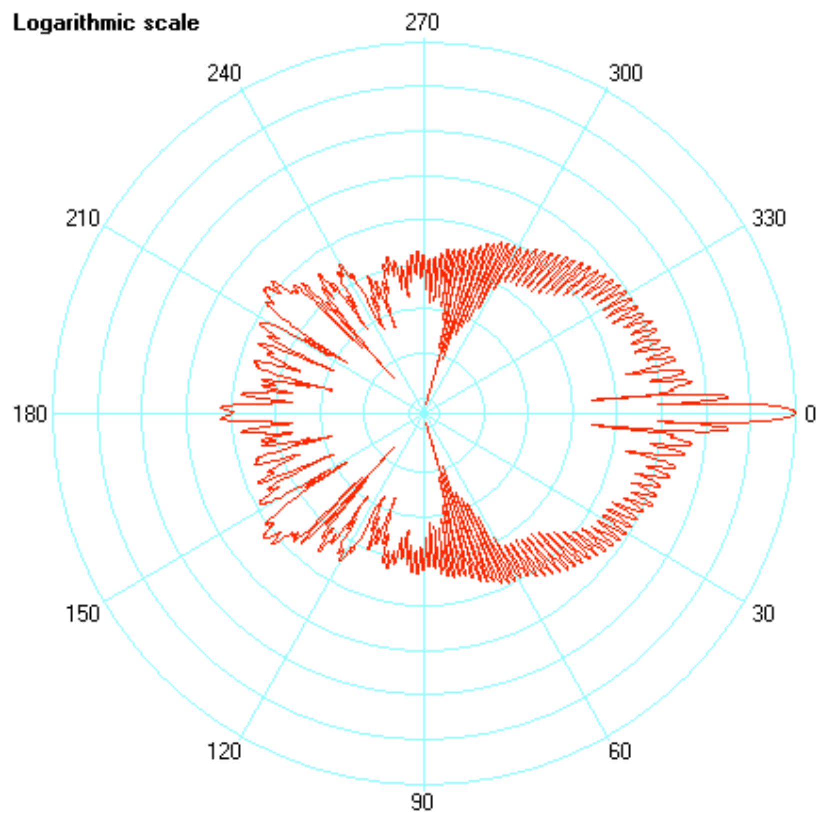


Cooper & Showman (2005)

Departures from the norm:horizontal heat flow

Strong winds (3-9 km/s = 6500-20000 mph) predicted to form under substellar point - offsets hottest point viewed, shifts phase peak

Departures from the norm: scattering



Theoretical scattering function of 0.65 μm light from a water droplet of r = 10 μm (from Phillip Laven and MiePlot)

For planets with significant condensate material, light scattering from particles can affect phase functions and interpretations of secondary eclipse data

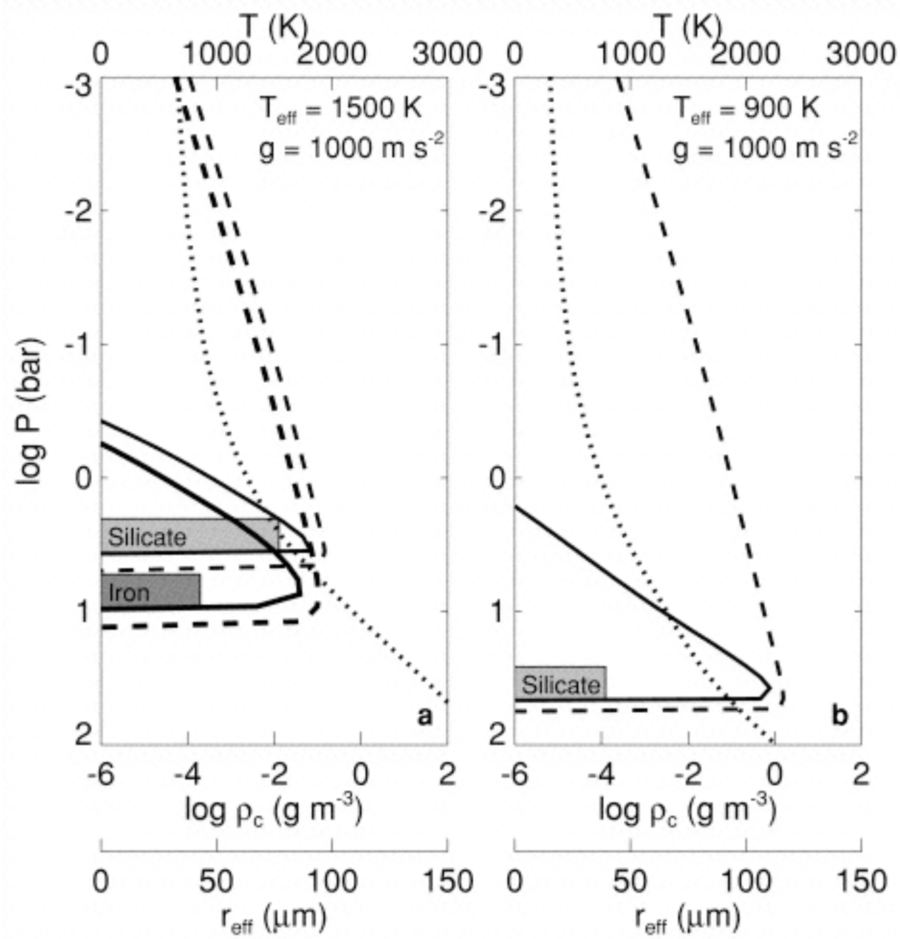
Departures from the norm: photochemistry

UV photolysis produces trace chemical hazes even on distant planets

Directly influences planetary albedo; depends on many poorly known processes

What makes the clouds on Jupiter colorful?

Departures from the norm: clouds

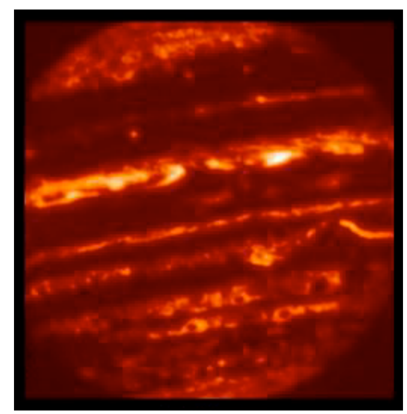


Ackerman & Marley (2001)

Condensate clouds are critical in understanding **L dwarf photospheres** and **planetary albedos**

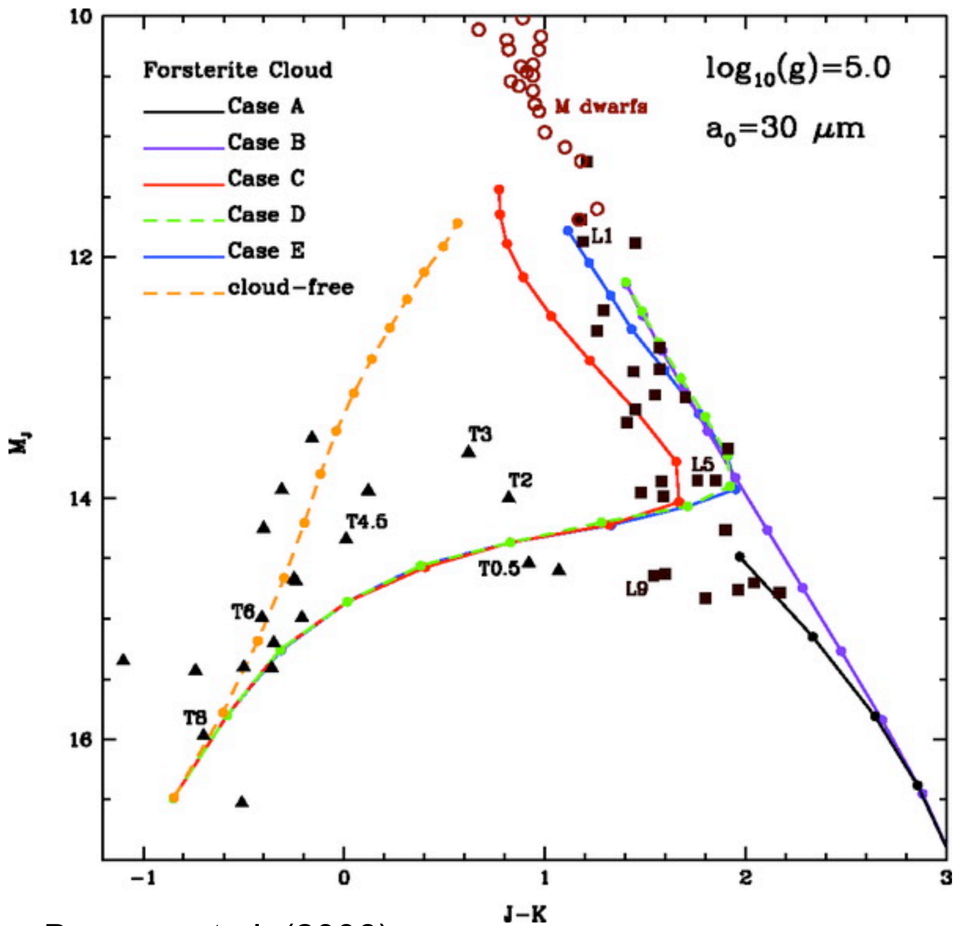
Currently 1D (radial) models are generally employed

Clouds are not 1D! →



Jupiter at 5 μm

Departures from the norm: clouds



Burrows et al. (2006)

Current cloud models are incapable of reproducing L dwarf/T dwarf transition in detail.

This transition may be explained by changes in cloud properties, not temperature/luminosity

Overview

Atmospheres of BDs and EGPs are the gateway to understanding overall physical properties - mass, radius, composition, internal structure, origin, evolution, etc.

Abundant spectral features (atoms, gas molecules, condensates), dynamics (vertical, radiation driven) and chemistry (cloud formation, photolysis) add significant complexity.

How do we (currently) observe EGP atmospheres?

How does the presence of a star change the spectrum of an EGP relative to a BD?

What influences the gas chemistry in BD/EGP atmospheres?

What is the difference between clouds and hazes?

How do clouds affect the spectra of BDs/EGPs?