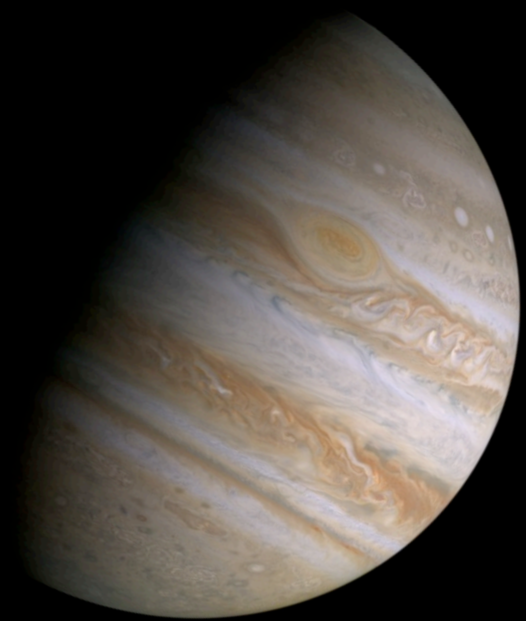
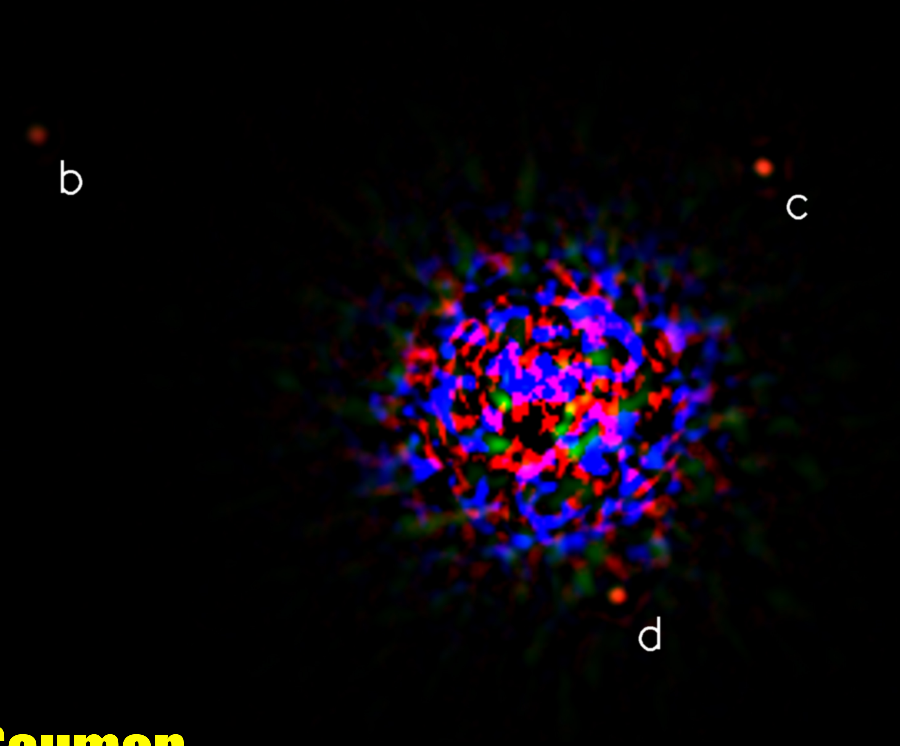
Brown dwarfs and hot young planets





D. Saumon

Los Alamos National Laboratory

Images: Cassini; Marois et al. (2008)

2009 Sagan Exoplanet Summer Workshop, 21 July 2009 LA-UR-09-04365

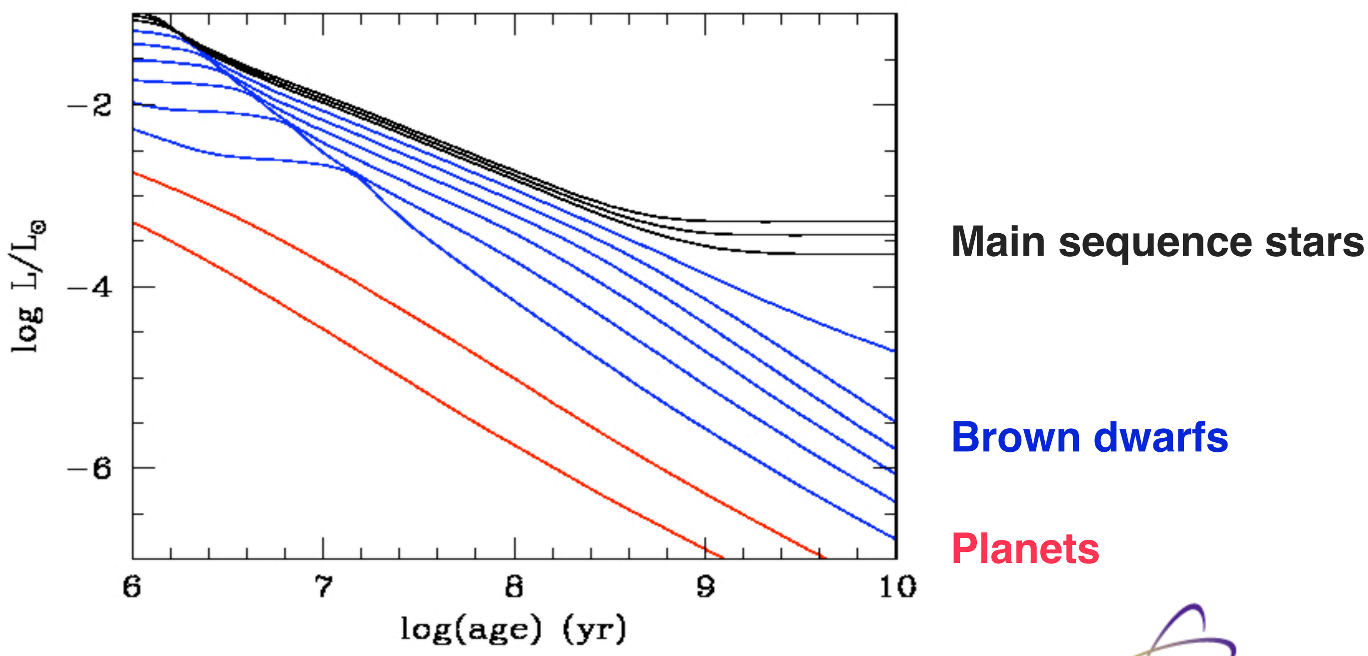
Brown dwarfs and hot young planets

Clouds and the L/T transition

Non-equilibrium chemistry

The basics of brown dwarfs

- **Substellar in mass ~ 12 to 77 $M_{Jupiter}$**
- **Compact! R ~ 0.09 to 0.16 R_{sun} (all ~ size of Jupiter)**
- **No stable source of nuclear energy**
- **Evolution = cooling: T_{eff} decreases with time**
- **The spectral type changes M → L → T (→ Y)**



The basics of brown dwarfs

Two new spectral classes cooler than dM:

L (T$_{eff}$ ~ 2400 →1400K)

T (T$_{eff}$ ~ 1400 → 600K)

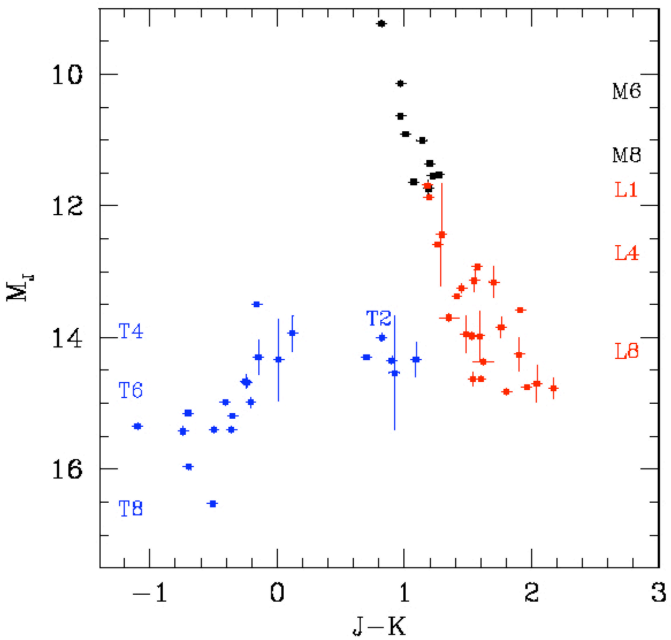
… and soon Y

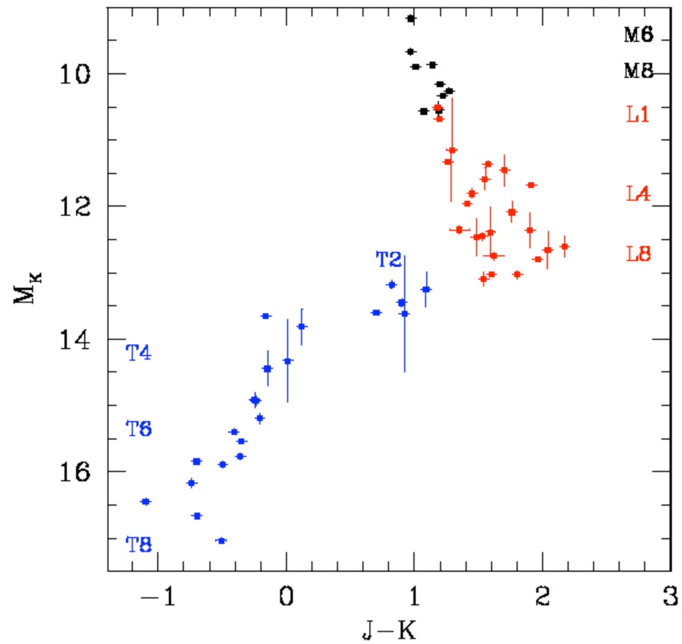
Very strong molecular bands

H_2O, CO, CH_4, NH_3, FeH, TiO

Condensates form in the atmosphere for T$_{eff}$ ≤ 2000K

Near IR color-magnitude diagrams: Brown dwarfs





L dwarfs naturally extend the dM sequence

T dwarfs are "blue" in near-IR colors!

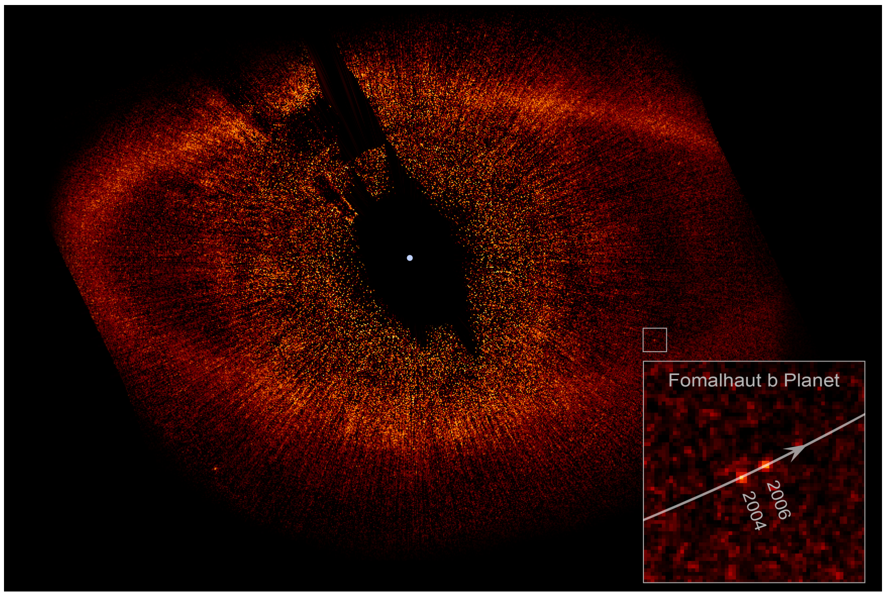
Rapid shift in IR colors at the L/T transition.

Early T's are brighter in *J* than late L's!?

Data from Knapp et al (2004), Burgasser et al. (2006), Liu & Leggett (2005)

Hot young planets

Fomalhaut b



Star:

A3 V 300-500Myr old
dust disk (R=133-160AU)

Planet:

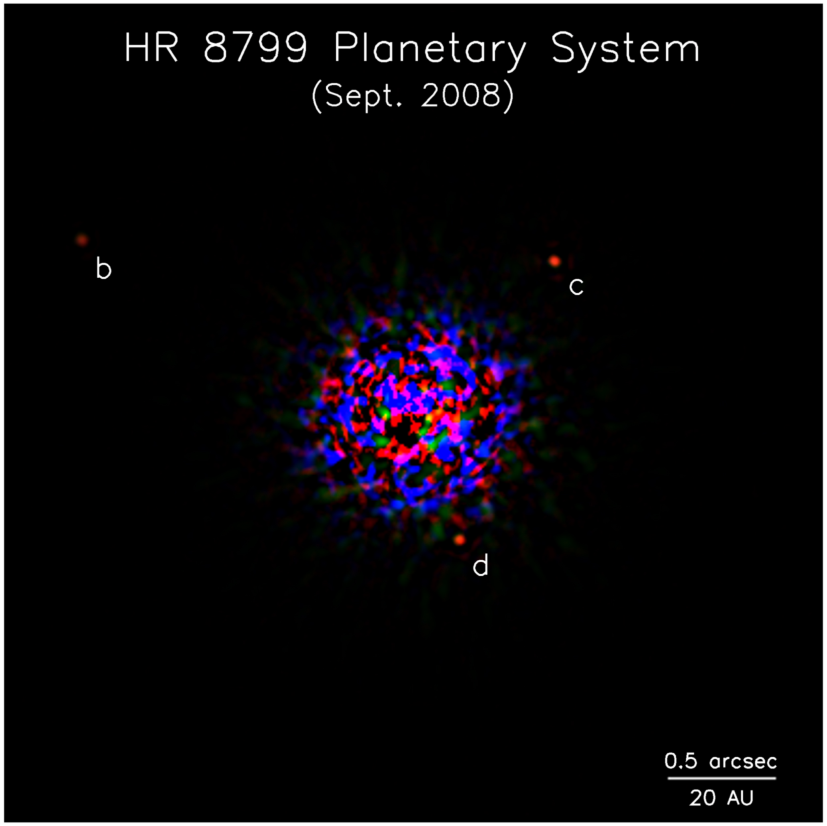
a ~ 115 AU
Mass* ~ 1- 3 $M_{Jupiter}$
T_{eff} * ~ 400K

* Mass and T_{eff} are early estimates

Kalas et al., Science, 322, 1345 (2008)

Hot young planets

HR 8799 b,c,d



Star:

A5 V 30-160Myr old
Inner & outer dust disks
(R ~ 8AU and R ~ 66AU)

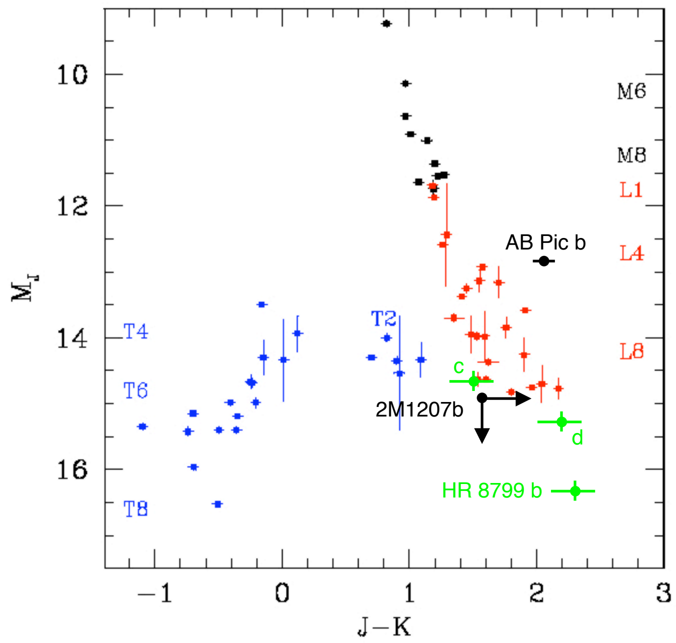
Planets:

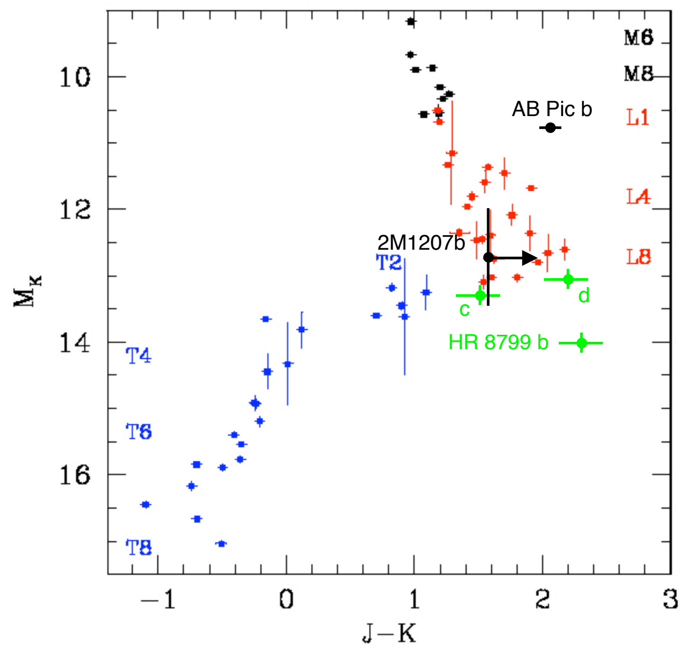
	b	c	d
a (AU)	68	38	24
Mass (M_J)*	5-11	7-13	7-13
T_{eff} (K)*	~900	~1100	~1100

* Mass and T_{eff} are early estimates

Marois et al., Science, 322, 1348 (2008)

Near IR color-magnitude diagrams: Young planets





In the near IR, hot young planets ~ consistent with the brown dwarf sequence

Planet data from Marois et al. (2008) and Neuhäuser (2008)

Los Alamos

Hot young planets compared to field brown dwarfs

Similarities

- Young planets far from their star effectively evolve in isolation
- NIR colors follow the same sequence
- T_{eff} range (L~ 2400-1400K,   T~1400 – 600K)

Differences

- Lower gravity (lower mass, younger)
- Likely metal-rich if formed in a protoplanetary disk
- Hot young planets are more hip

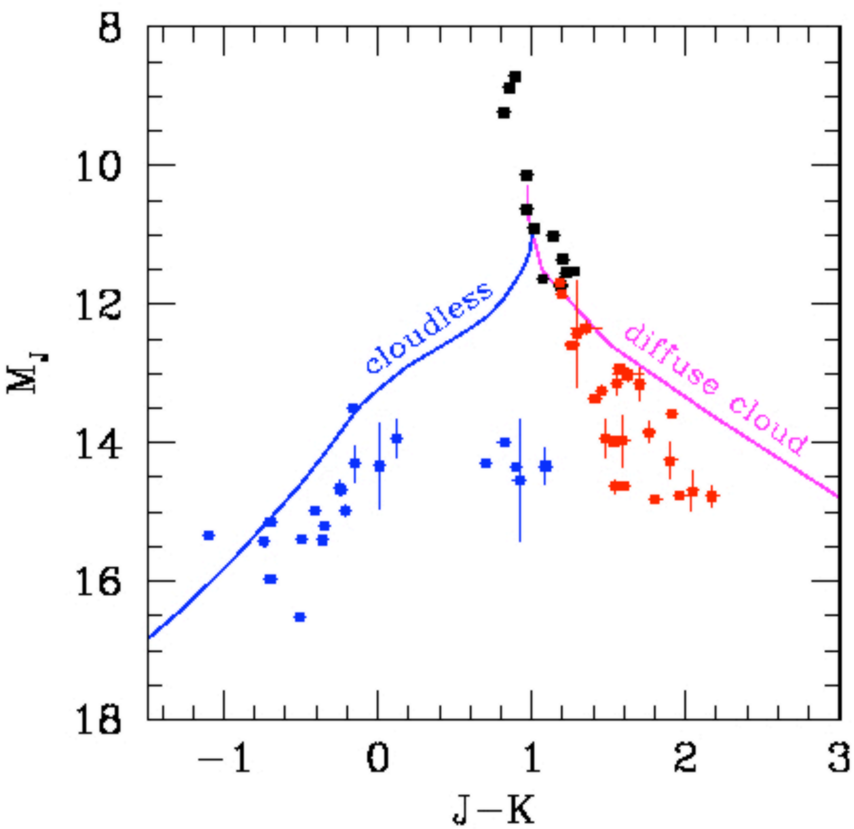
Atmospheric physics & chemistry should be very similar

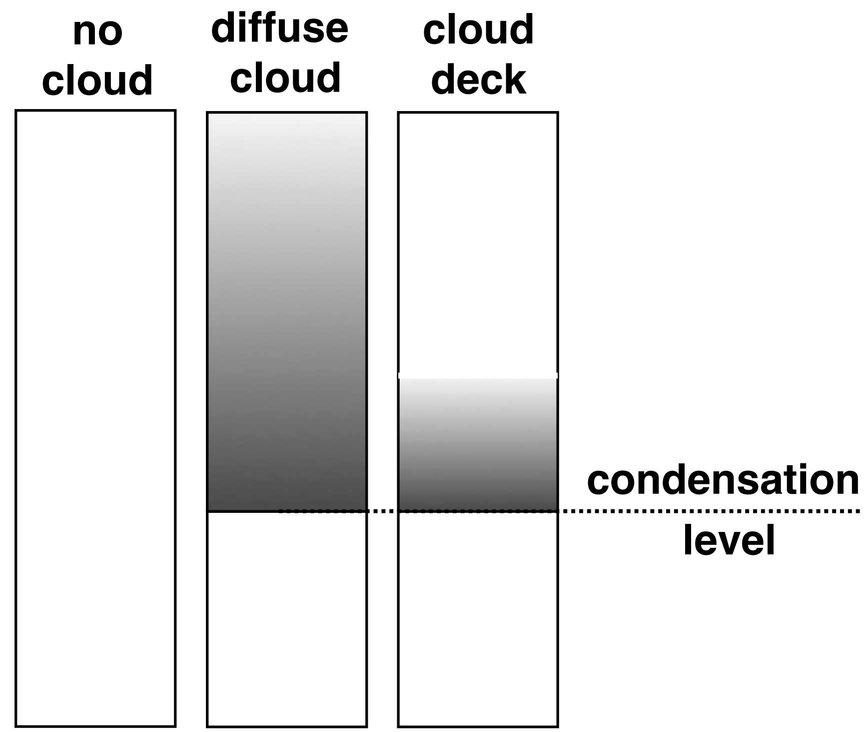
Brown dwarfs and hot young planets

Clouds and the L/T transition

Non-equilibrium chemistry

Color-magnitude diagrams: Limiting cloud models



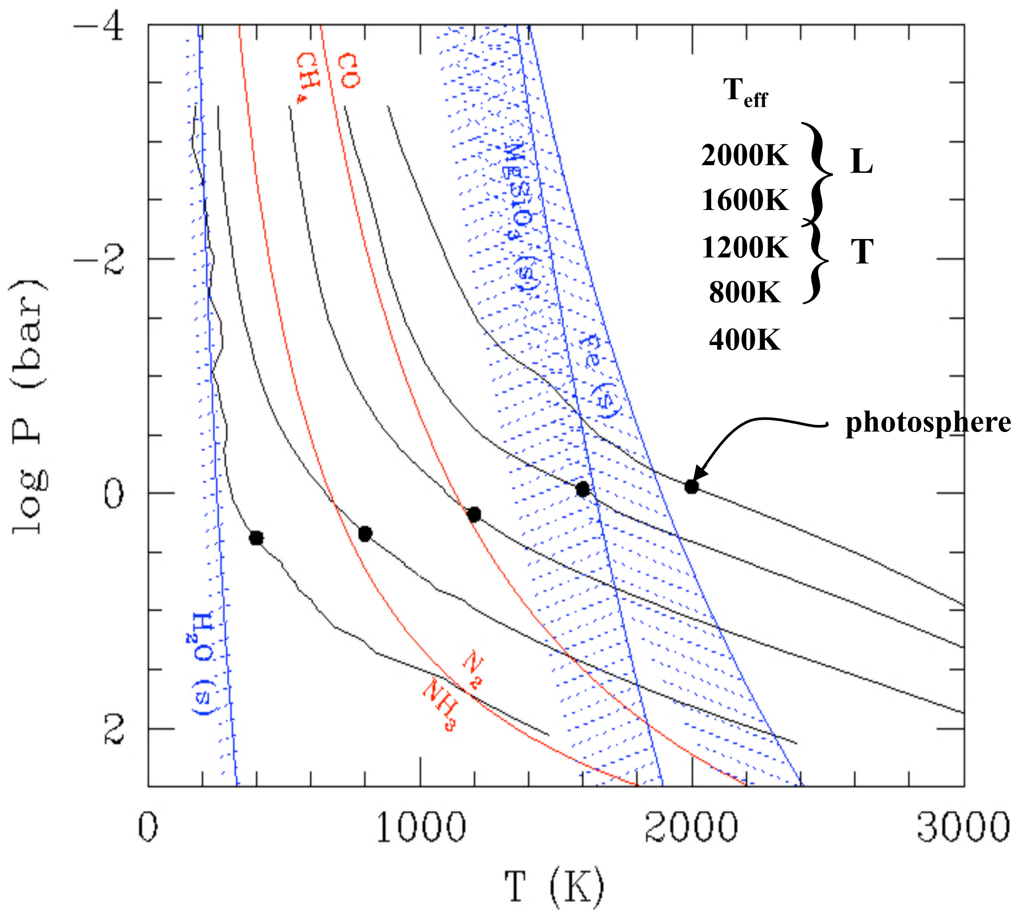


Cloudless models can explain late T dwarfs (>T4)

A diffuse cloud model works for optically thin clouds only (<L4)

→ A more sophisticated cloud model is required (cloud deck)

Condensation and qualitative cloud behaviour



Condensation:

Fe (T$_{eff}$ ~ 2000K)

Silicates (T$_{eff}$ ~ 1600K)

H_2O (T$_{eff}$ ~ 300K)

Main chemical transitions:

$CO \rightarrow CH_4$ (T$_{eff}$ ~ 1200K)

$N_2 \rightarrow NH_3$ (T$_{eff}$ ~ 800K)

A cloud layer will gradually disappear below the photosphere as T$_{eff}$ decreases → cloudless atmosphere!

Los Alamos

A simple cloud model

A minimalist 1-D cloud model* results from a balance between:

1) **Vertical transport of particles (e.g turbulent diffusion)**
2) **Gravitational settling of the particles**

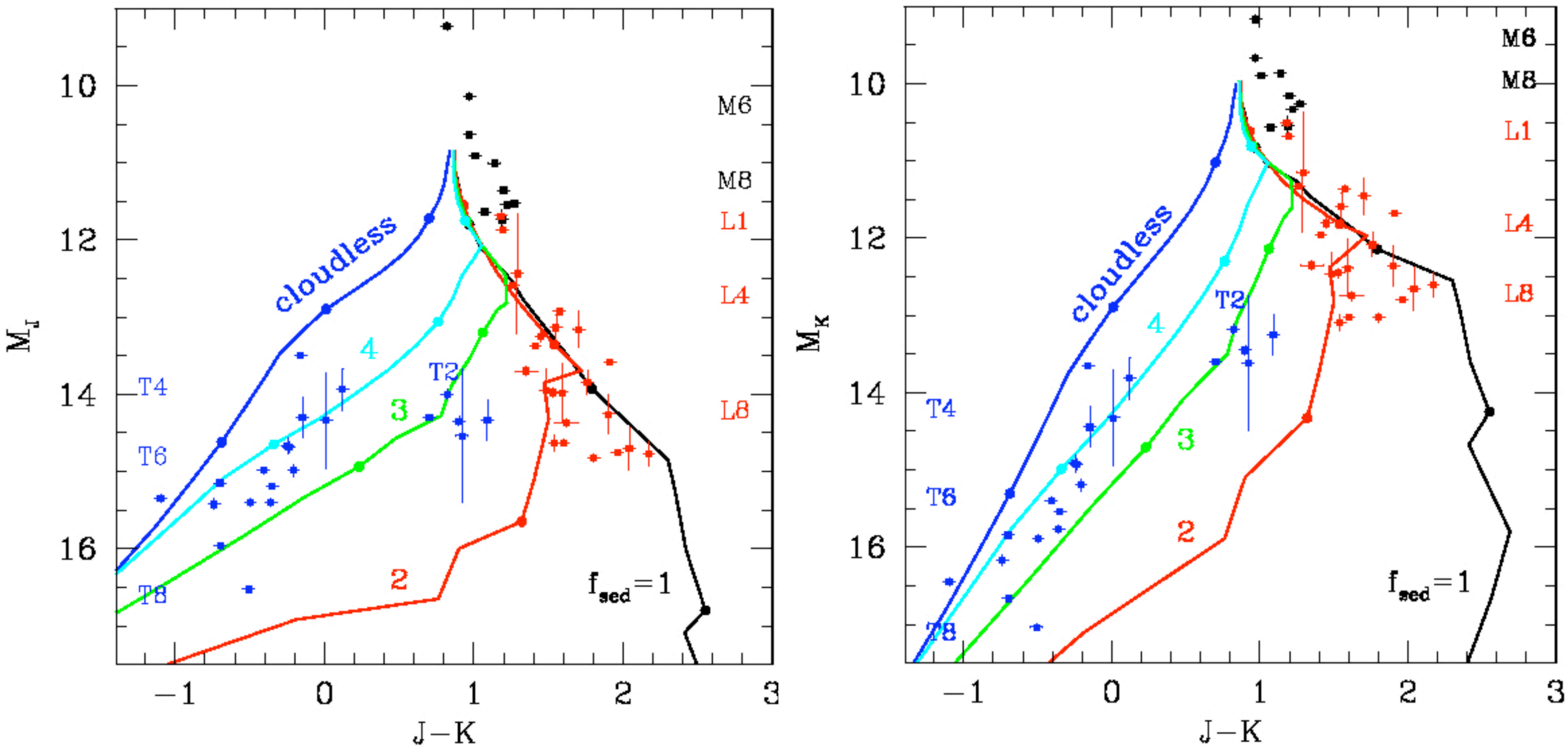
$$-K_{zz}\frac{\partial q_t}{\partial z} - f_{sed} w_* q_c = 0$$

K_{zz}: coefficient of diffusive mixing
f_{sed}: dimensionless sedimentation parameter
(as f_{sed} increases, cloud deck becomes thinner)

The location of the bottom of the cloud is determined by the condensation curve

* Ackerman & Marley (2001)

Color-magnitude diagrams: Models with clouds



For L dwarfs, f_{sed} ~ 1-2
The L-T transition occurs over T_{eff} ~ 1400 →1200K
Transition can be accounted for by an increase of f_{sed}

Los Alamos

Clouds in brown dwarfs: Summary

Condensates (Fe & silicates) are present throughout the L spectral class (T_{eff} > 1400K)

The condensates gravitationally settle into cloud decks

Mid- to late-T dwarfs appear to be free of clouds

Clearing of clouds at the L/T transition indicated by CMDs

- An increase of sedimentation efficiency?
- A break up of the cloud layer (partly cloudy weather)?
- Physical mechanism: unknown

There are hints that the L/T transition is gravity sensitive

The L/T transition must occur in hot young planets (e.g. HR 8799 bcd)

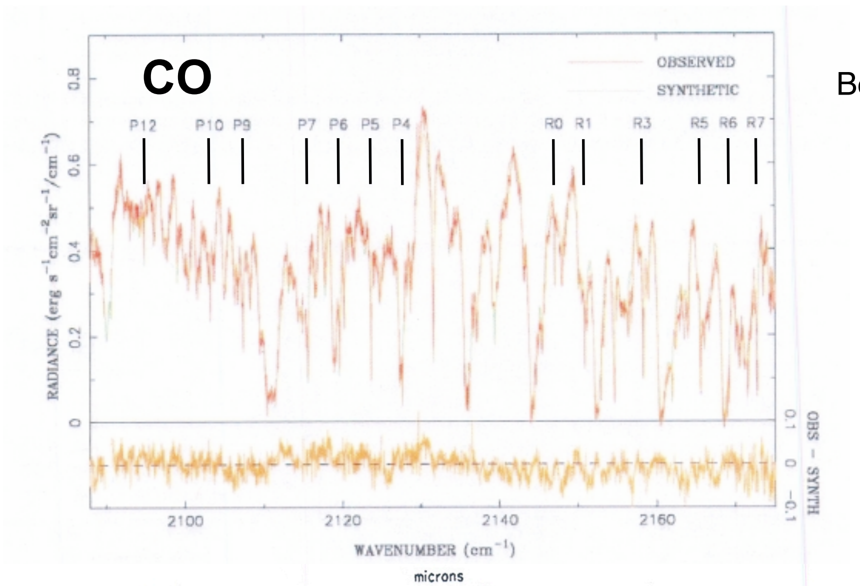
Brown dwarfs and hot young planets

Clouds and the L/T transition

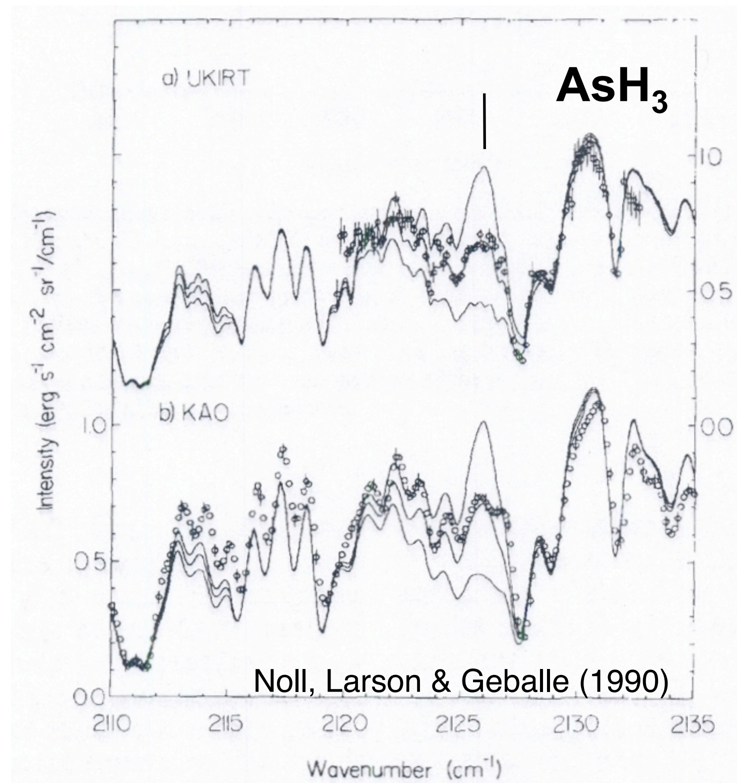
Non-equilibrium chemistry

Los Alamos

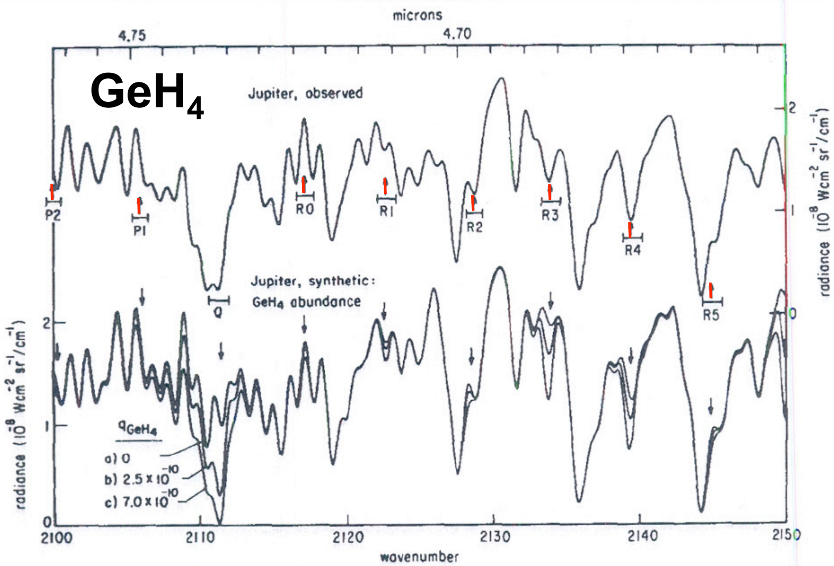
Unexpected species in the atmosphere of Jupiter



Bézard et al. (2002)



Noll, Larson & Geballe (1990)



Bjoraker, Larson & Kunde (1986)

Los Alamos

Chemistry and vertical transport in brown dwarf atmospheres

Chemistry of carbon & nitrogen:

slow →
$CO + 3H_2 \Leftrightarrow CH_4 + H_2O$
← fast

slow →
$N_2 + 3H_2 \Leftrightarrow 2NH_3$
← fast

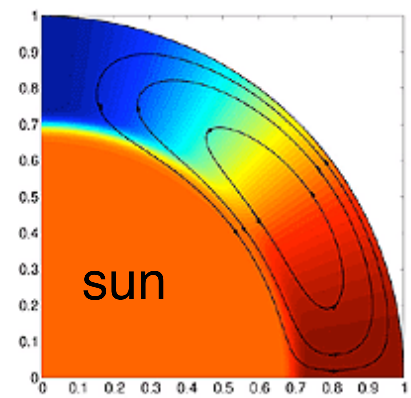
τ_{CO} & τ_{N2}: ms to > Hubble time!

Transport:

Convection (τ_{mix} ~ minutes)

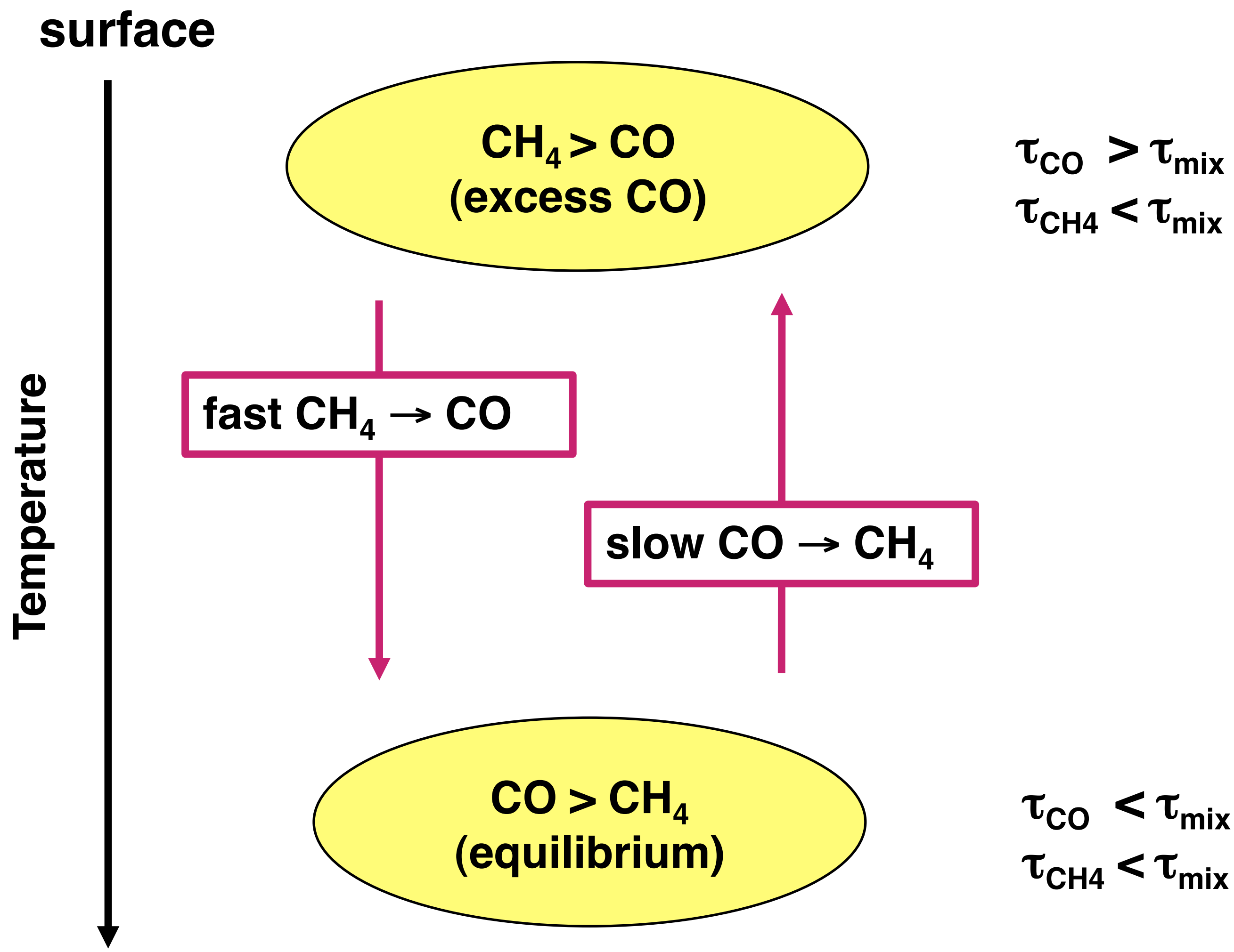
Radiative zone (τ_{mix} ~ hours to years?)

e.g. meridional circulation



Two characteristic mixing time scales in the atmosphere

Chemistry and vertical transport



Effect of mixing on abundances

Net effect:

Excess of CO in the spectrum

Depletion of CH_4, NH_3 and H_2O

} **The most important opacity sources!**

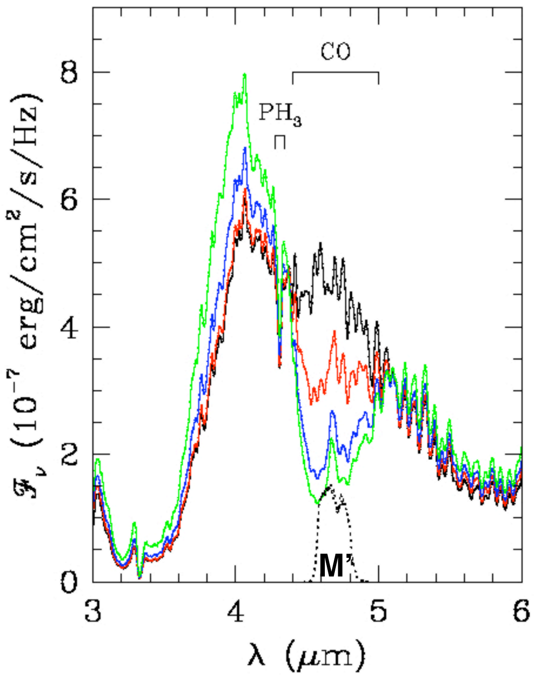
The non-equilibrium abundance of NH_3 is fixed in the convection zone → $\tau_{mix}=\tau_{conv}$

For CO, CH_4 and H_2O, the faster the mixing in the radiative zone, the larger the effect (up to saturation)

A way to measure the mixing time scale in the atmosphere!

Effect on 4.6μm CO band

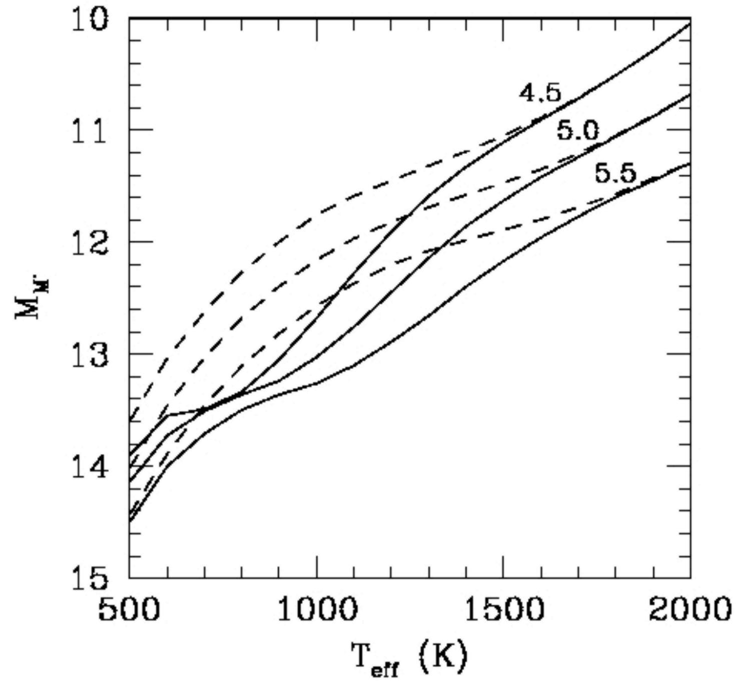
4-5μm



T_{eff}=1000K log g=5

K_{zz}=0, 10², 10⁴, 10⁶ cm²/s

M' flux



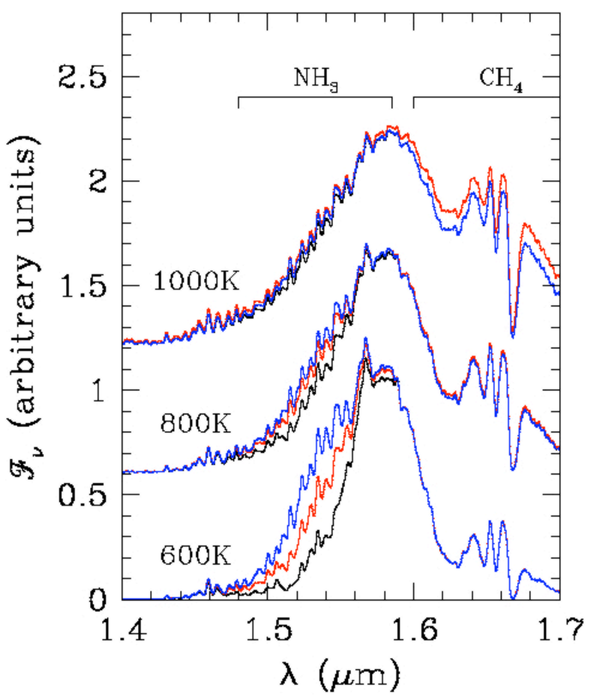
K_{zz}=0, 10⁴ cm²/s

Can affect searches for exoplanets

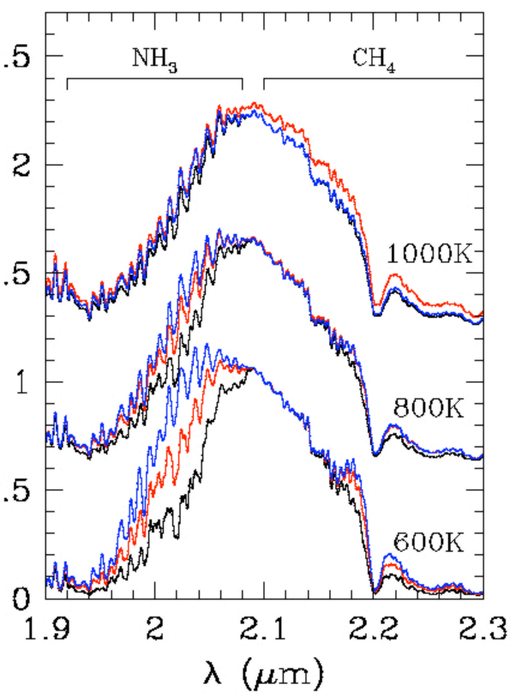
Los Alamos

Effect on NH_3 bands

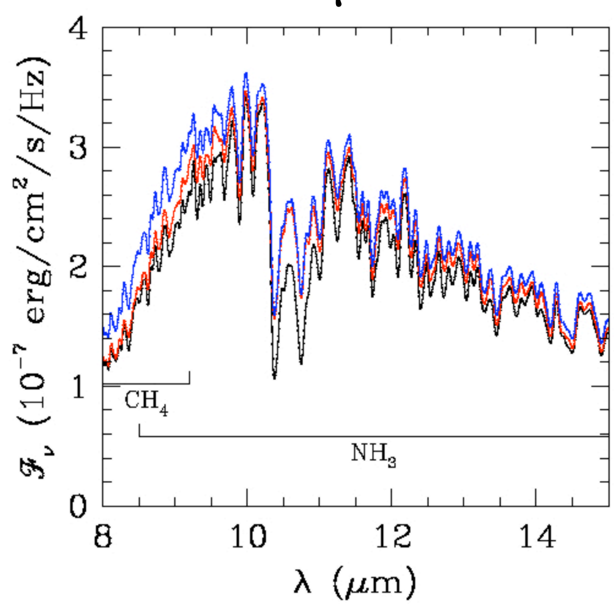
H band



K band



10μm



T_{eff}=1000K log g=5

K_{zz}=0, 10^2, 10^6 cm^2/s

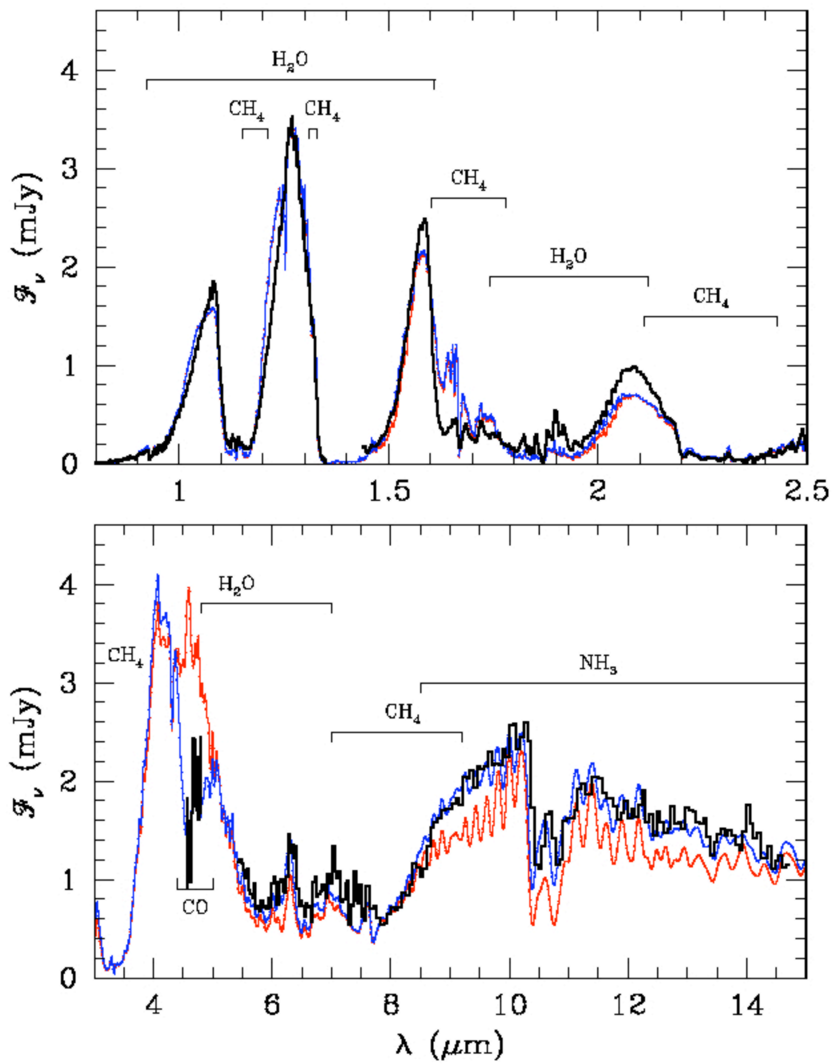
K_{zz}=0, 10^4 cm^2/s & no NH_3

log g=5

Los Alamos

A case study: Gl 570D (T8)

Model fluxes are computed at Earth



T_{eff}=820K log g=5.23

[M/H]=0

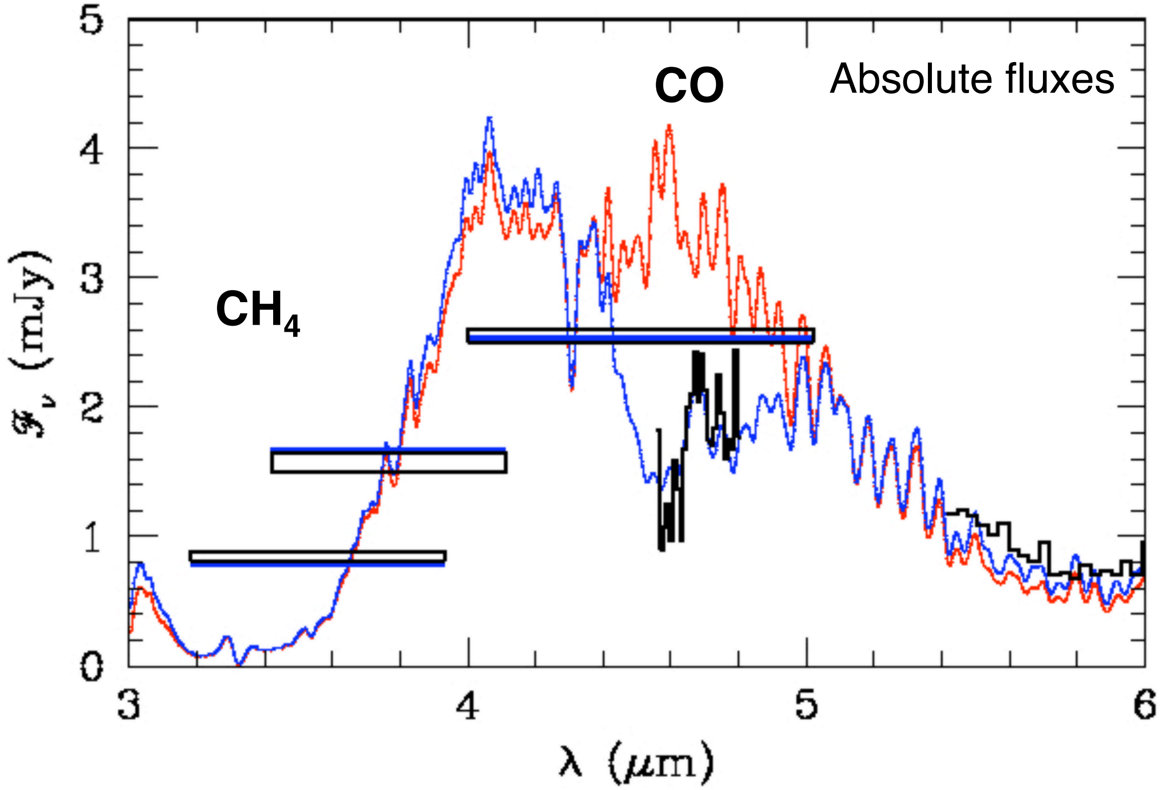
Equilibrium model

Model with mixing: τ_{mix} =14d

Saumon et al. (2006)

Los Alamos

Gl 570D: 3-5μm spectrum and photometry



T_{eff}= 820K log g=5.23 [M/H]=0

Equilibrium (no CO) With mixing: τ_{mix}=14d

Geballe et al. (2009)

Departure from chemical equilibrium: Summary

The consequence of very basic considerations (“universality”)

Important at low T_{eff}: late L dwarfs and T dwarfs

Affects CO (↑), CH_4 (↓) , H_2O (↓) and NH_3 (↓), all important sources of opacity

CO excess observed in all 5 T dwarfs subjected to detailed analysis (e.g. Gl 570D)

NH_3 depleted in the IRS spectra of 3 T dwarfs analyzed so far

Additional evidence shows that departures from equilibrium chemistry (i.e. vertical mixing) are common in brown dwarfs

An opportunity to measure the mixing time scale in the atmosphere

Mixing mechanism not known (parametric models only)

Los Alamos

What have we learned from brown dwarfs?

Hot young planets are very similar to field brown dwarfs and can be modelled with the same tools and physics

Two well-studied features that are relevant to hot young planets:

Clouds:

- **Form cloud deck(s) of iron and silicate particles**
- **Clouds present for T_{eff} > 1400K (L), absent for T_{eff}<1200K (late T). Gravity dependent?**
- **Clouds disappear over only 200K of cooling in T_{eff} . Mechanism?**

Vertical transport:

- **Drives abundances of CO, NH_3, H_2O and CH_4 away from chemical equilibrium values. Mixing mechanism in radiative zone? Time scale?**
- **Apparently "universal" among the cooler brown dwarfs**
- **Decreases M' flux significantly: Can affect searches of exoplanets**

Los Alamos

Brown dwarfs and hot young planets: Essential reading

Reviews on brown dwarfs

Chabrier & Baraffe 2000, ARAA, 38, 337
Burrows et al. 2001, Rev. Mod. Phys., 73, 719
Kirkpatrick 2005, ARAA, 43, 195

Hot young planets

HR 8799:
- Marois et al. 2008, Science, 322, 1348
- Lafrenière et al. 2009, Ap. J., 694, L148
- Fukagawa et al. 2009, Ap. J., 696, L1

Fomalhaut:
- Kalas et al, 2008, Science, 322, 1345

β Pic:
- Lagrange et al. 2009, A&A, 493, L21

AB Pic:
- Chauvin et al. 2005, A&A, 438, 29

GQ Lup:
- Seifahrt et al. 2007, A&A, 463, 309
- Marois et al. 2007, Ap. J., 654, L151

2MASS 1207:
- Chauvin et al. 2005, A&A, 438, L25
- Mohanty et al. 2007, Ap. J., 657, 1064

Cloud models and the L/T transition

Ackerman & Marley 2001, Ap. J., 556, 872
Allard et al. 2001, Ap. J., 556, 357
Tsuji 2002, Ap. J., 575, 264
Burgasser et al. 2002, Ap. J., 571, L151
Tsuji & Nakajima 2003, Ap. J., 585, L151
Knapp et al. 2004, A. J., 127, 3553
Golimowski et al. 2004, A. J., 127, 3516
Helling et al 2006, A&A, 455, 325
Burrows et al. 2006, Ap. J., 640, 1063
Saumon & Marley 2008, Ap. J., 689, 1327
Helling et al. 2008, MNRAS, 391, 1854

Brown dwarfs and hot young planets: Essential reading

Non-equilibrium chemistry

In brown dwarfs

Lodders & Fegley, 2002, Icarus, 155, 393
Saumon et al. 2000, Ap. J., 541, 374
Saumon et al. 2006, Ap. J., 647, 552
Saumon et al. 2007, Ap. J., 656, 1136
Leggett et al. 2007, Ap. J., 655, 1079
Hubeny & Burrows 2007, Ap. J., 669, 1248
Geballe et al. 2009, Ap. J., 695, 844

In exoplanets (hot Jupiters)

Cooper & Showman 2006, Ap. J., 649, 1048
Fortney et al. 2006, Ap. J., 652, 746