Prospectives in Exoplanet Model Atmosphere Development

Exo-Abundances : Abundance Measurements in Exoplanetary Atmospheres

Institut de Planétologie et d'Astrophysique de Grenoble
10h45-11h30, Tuesday May 13th 2014

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Isolated Brown Dwarfs and Gas Giant Exoplanets are complex, bound objects are more complex

Seen in isolated brown dwarfs (or planets):

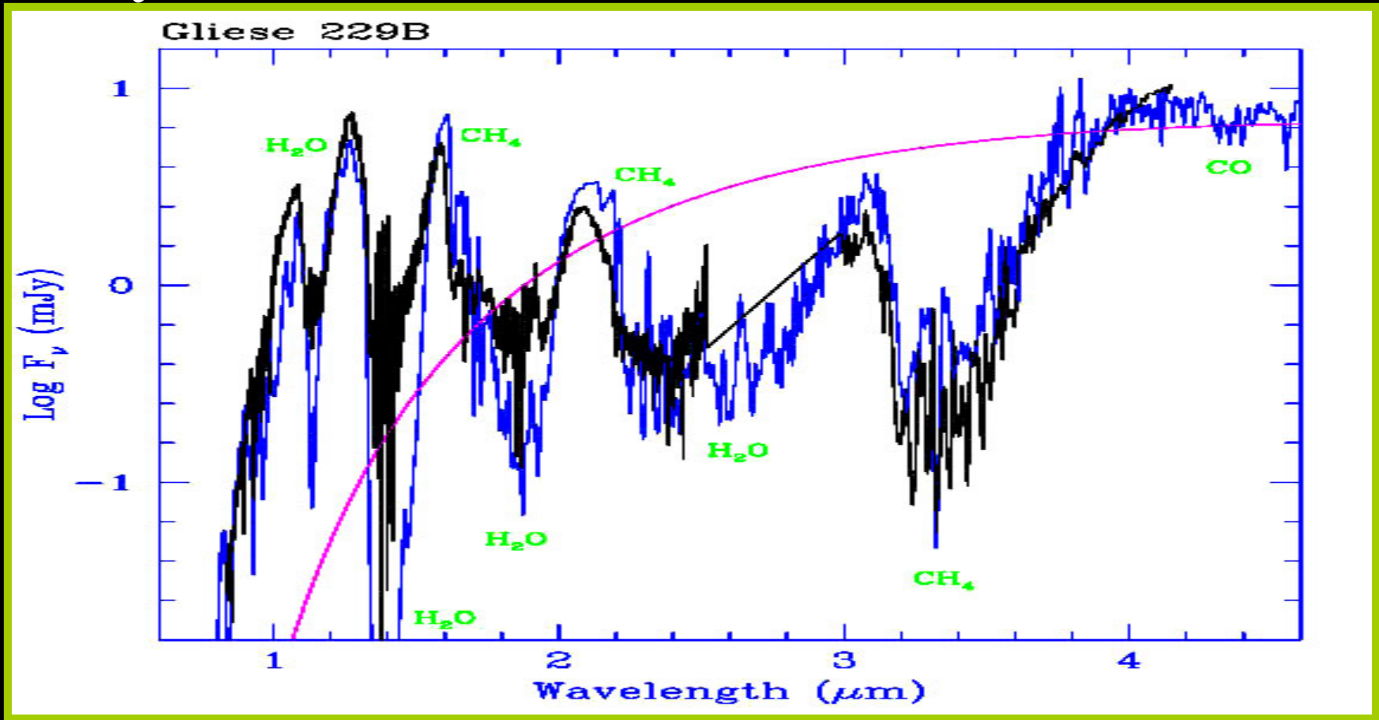
- Molecular formation: FeH, CrH, H_2O, CO, CH_4, NH_3, CO_2, ...
- Quasi-Molecular broadening: KI @ 0.7 mu (Allard et al. '07)
- Disequilibrium chemistry: N_2, NH_3, CO, CO_2, CH_4 (Griffith '00)
- Cloud formation: below T_{eff}=3000K ! (Tsuji et al. '96)
- Carbon enhancement due to sedimentation (60% for Jupiter!)
- Photometric variability (30% of L5 to T6, Buenzli et al. '14)
- Surface inhomogeneities (Crossfield et al. '14)

Additional complexity of bound brown dwarfs and planets:

- Impinging radiation
- Photochemistry, photolysis
- Jets and asymmetric global circulation

The first unambiguous brown dwarf

Nakajima et al. (Nature 378, 463, 1995)



Confirmation, by the detection of the first cool brown dwarf (black curve, *Oppenheimer et al., Science 270, 1478, 1995*), of our model's predictions (*Allard & Hauschildt, ApJ 445, 433, 1995*) that brown dwarfs emit more between molecular bands at 1.1, 1.3, 1.6 et 2.2 μm then a blackbody.

Quasi-molecular K-H_2

Allard, Homeier, Allard et al. (2007)

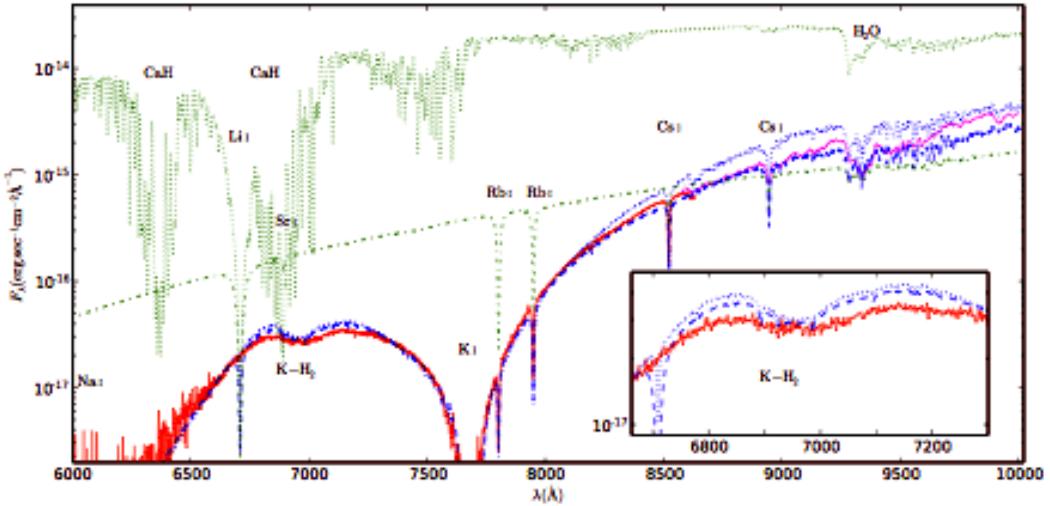
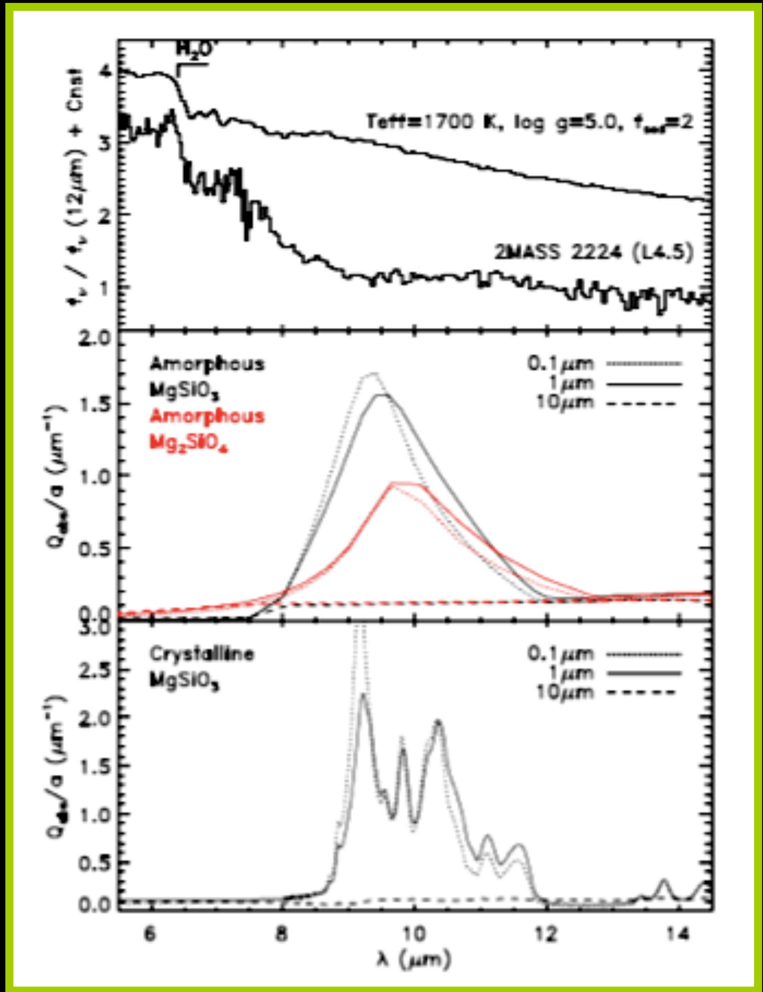


Fig. 1. FORS2 red optical spectrum of the T1 dwarf ε Indi Ba (solid), compared to our synthetic spectra for a 1.3 Gyr (dashed) and 2 Gyr (dotted) model. To highlight the various sources of opacity, spectra obtained when the K and Na D doublets are omitted (dot-dashed), and when dust grains involving Ca and other refractory species are prevented from forming and raining out (upper dotted line) are also shown. All molecular bands but CaH and H_2O have been omitted from the latter spectrum for clarity. The EFOSC spectrum of ε Indi Ba,b is shown from 8600–10 000 Å (light [magenta] solid line) against a composite model of both T dwarfs.

a) Red optical spectrum of the T1 dwarf ε Indi Ba (solid), compared to models for a 1.3 Gyr (dashed) and 2 Gyrs (dotted). Spectra obtained when the K and Na D doublets are omitted (dot-dashed), and when dust grains involving Ca and other refractory species are prevented from forming and raining out (upper dotted line) are also shown. b) Same models where CaH has been remove to show its effect compared to field dwarf spectra from L2 to T.

Forsterite detected in BDs?

Cushing et al (2006)



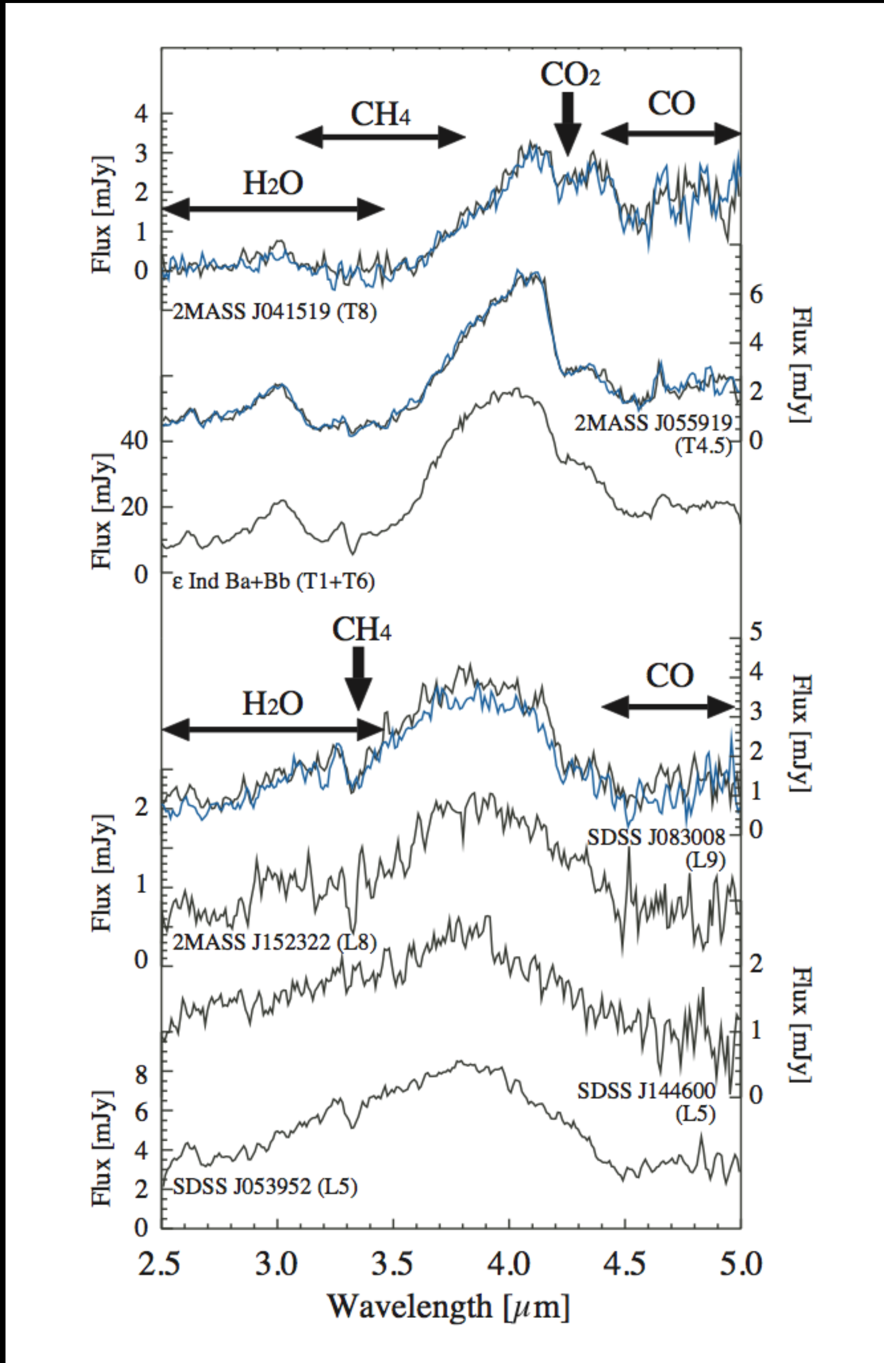
Mid-type L dwarfs, observed with the Infrared Spectrograph (IRS) on board the Spitzer Space Telescope, show an unexpected flattening from roughly 9 to 11 μm. This may be a result of a population of small silicate grains that are not predicted in current cloud models.

Dynamical Transport

CO_2 detection in brown dwarfs

The NIR spectra of brown dwarfs obtained by the AKARI/IRC. The spectra are ordered in the sequence of their spectral types from bottom (L5) to top (T8). When two observations were made for an object, the data were processed independently and the second spectrum is indicated in blue. The difference between the two observations represents the practical errors. Positions of major molecular bands are indicated.

Yamamura et al. (2010)



Comparative Cloud Model Construction

Parameter-free models

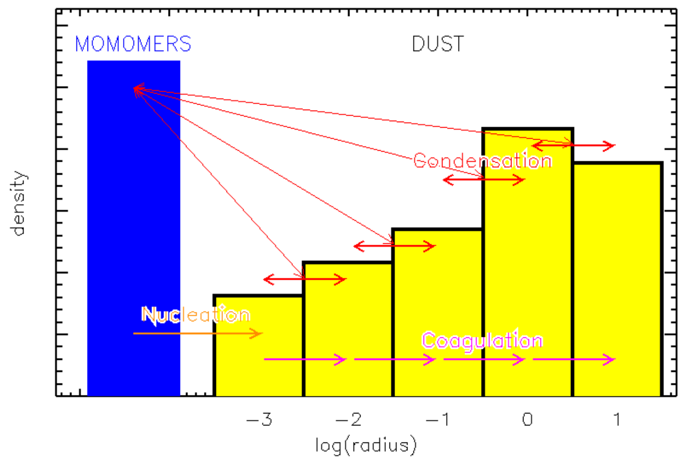
	Phenomenological model: PHOENIX BT-Settl (Allard et al. 2003,2012)	Microphysical model: DRIFT-PHOENIX (Helling et al. 2008)
Seed	= CE (iteration with cloud model*)	= TiO_2
Nucleation	= from cosmic rays (Tanaka 2005)	= DRIFT or 1D hydro (Gail 1984)
Condensation	= Rossow (1978)	= Gail 1984
Coalescence	= Rossow (1978)	= Gail 1984
Coagulation	= Rossow (1978)	= Gail 1984
Sedimentation	= Rossow (1978)	= Gail 1984
Supersaturation	= P_{VS}/Pgas using CE tables for P_{VS}	= Gail 1984
Advective Mixing	= from 2D RHD simulations	= from 2D RHD simulations (without overshoot)
Composition	= 64 types of condensates	= 5 types of condensates
Optical ctes	= pure condensates (Jena database)	= composite optical ctes
Model solved	= Updraft model with solar lowest layer	= up to down (stationary solution of moment equations)

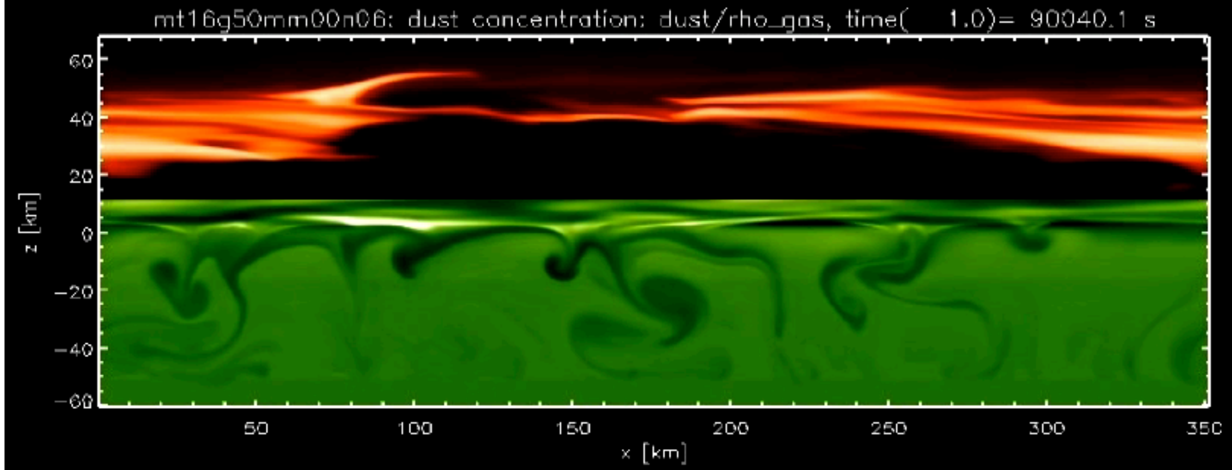
* Cooling history of the gas is preserved

In effect, there isn't much difference between up-to-down and updraft models because grains do not DRIFT or settle through much (within one layer only!) under the conditions of M-L type dwarf atmospheres (Wende, private communication).

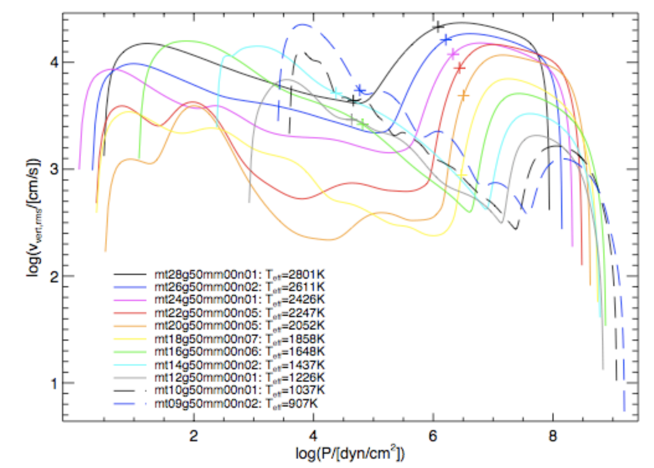
2D HDR simulations of dust cloud formation in brown dwarfs' atmospheres

Freytag et al. (2010)



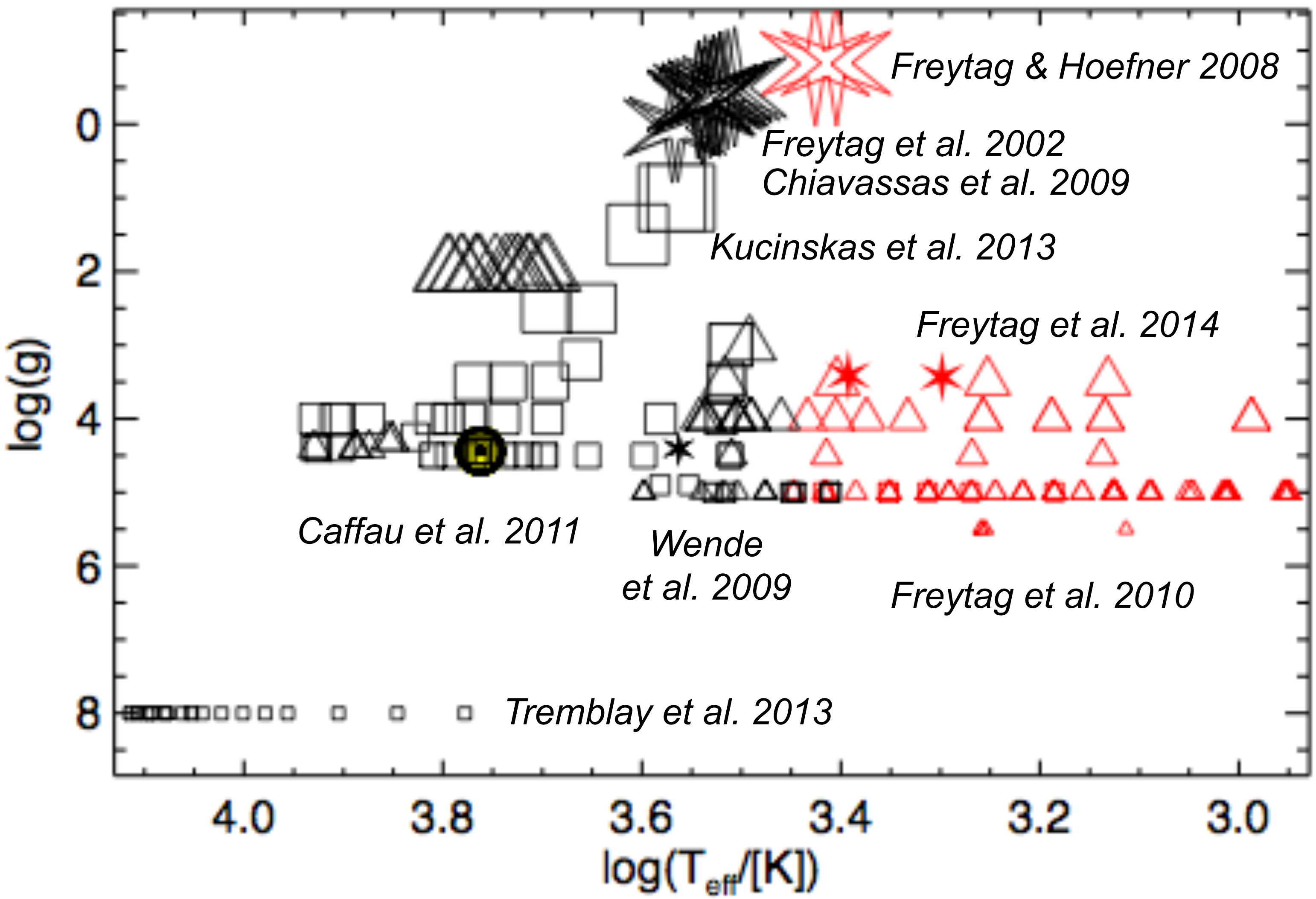


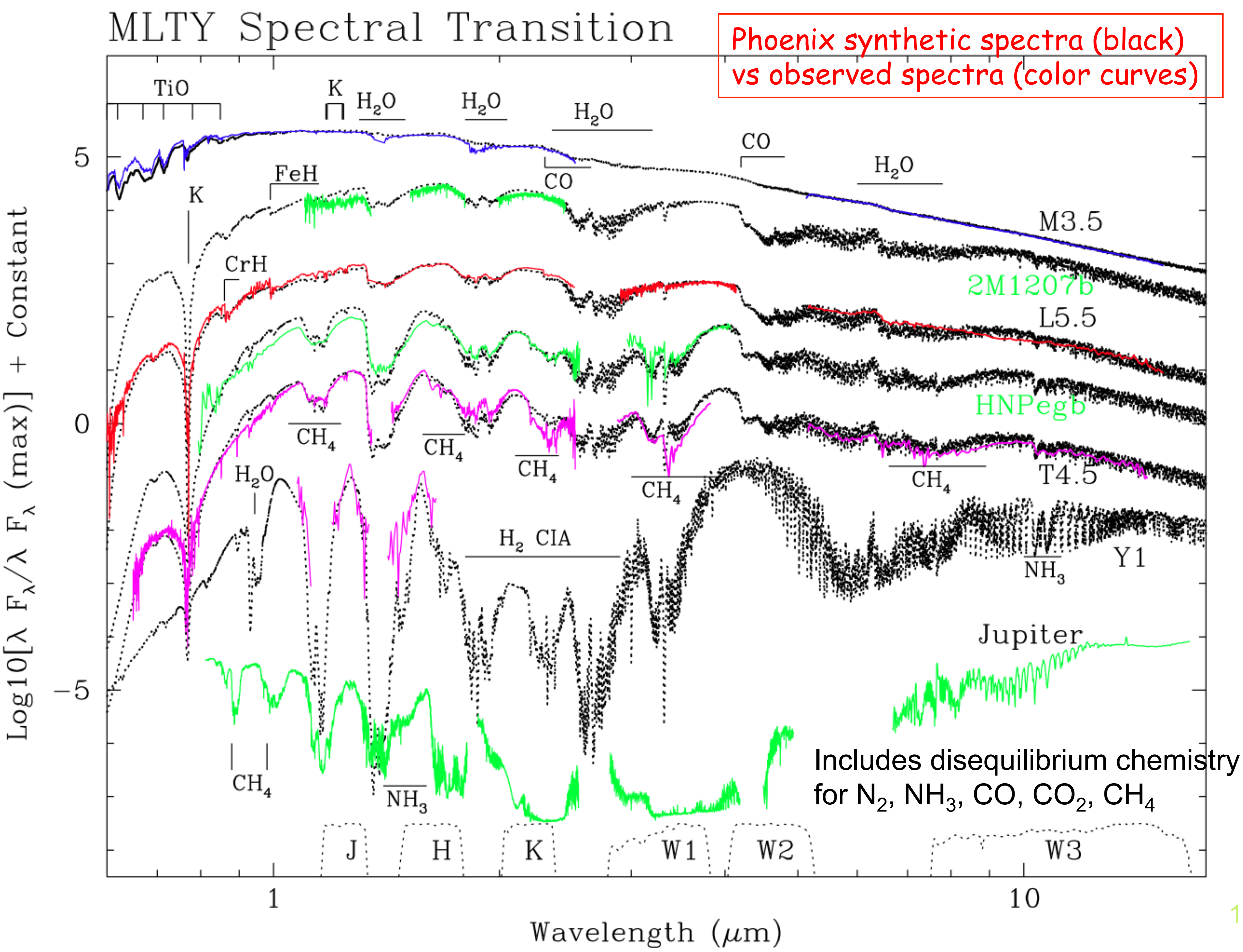
W350 x H80 km² during 36 hrs



CO5BOLD simulations of the gas and forsterite (Mg_2SiO_4) dust based on Phoenix opacities, on a cloud model (dust size bon distribution), and on the nucleation, condensation, coagulation, and sedimentation rates by Rossow (1978). Shown, in red, the dust grain mass density, and, in green, the entropy indicates the convection.

The CO^{5}BOLD GRID

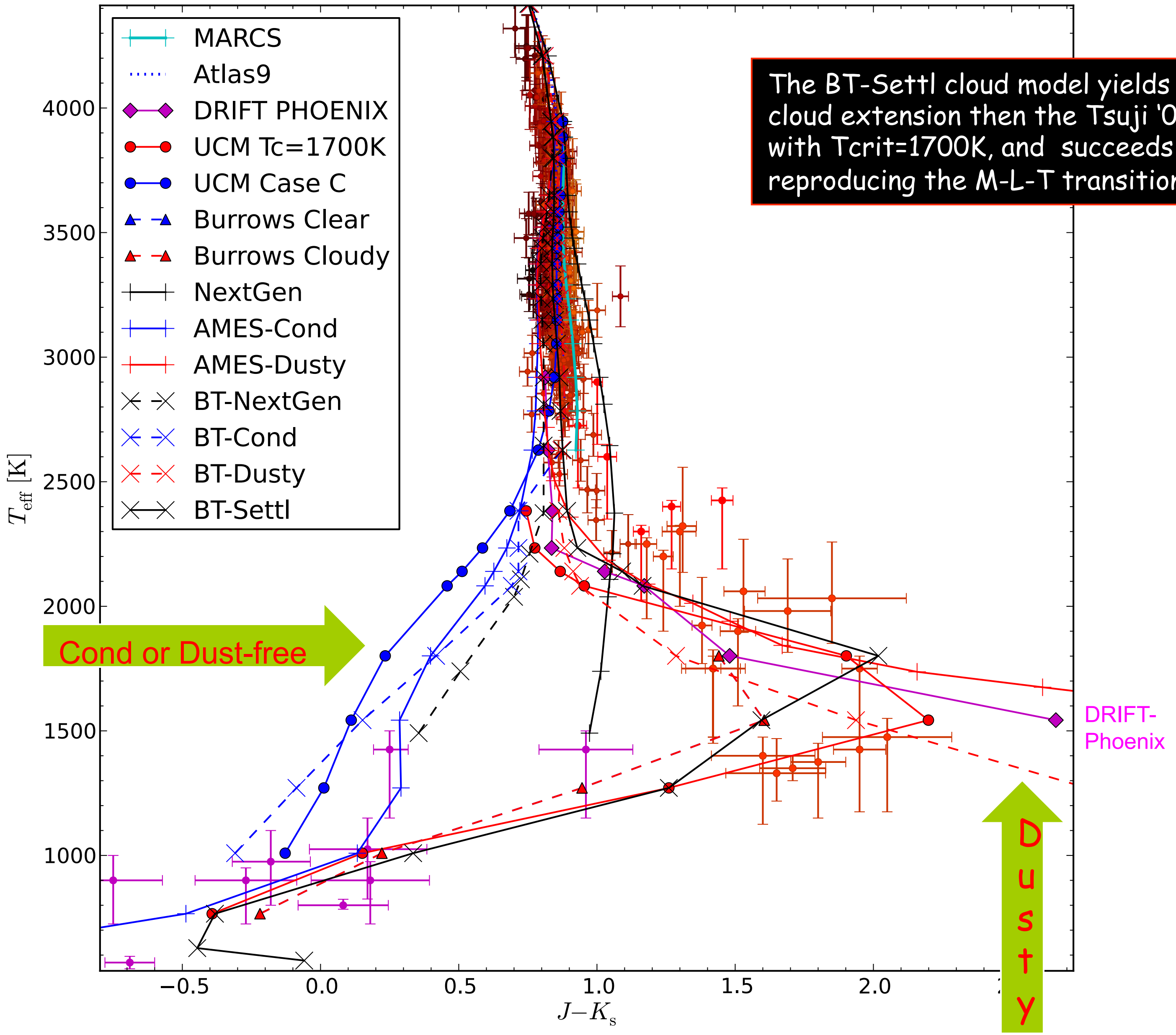




MLTY Spectral Transition
Phoenix synthetic spectra (black)
vs observed spectra (color curves)
TiO
K
H_2O
FeH
CrH
CO
CH_4
H_2 CIA
NH_3
M3.5
2M1207b
L5.5
HNPegb
T4.5
Y1
Jupiter
J
H
K
W1
W2
W3
Log10[λ F_λ/λ F_λ (max)] + Constant
Wavelength (μm)
Includes disequilibrium chemistry
for N_2, NH_3, CO, CO_2, CH_4

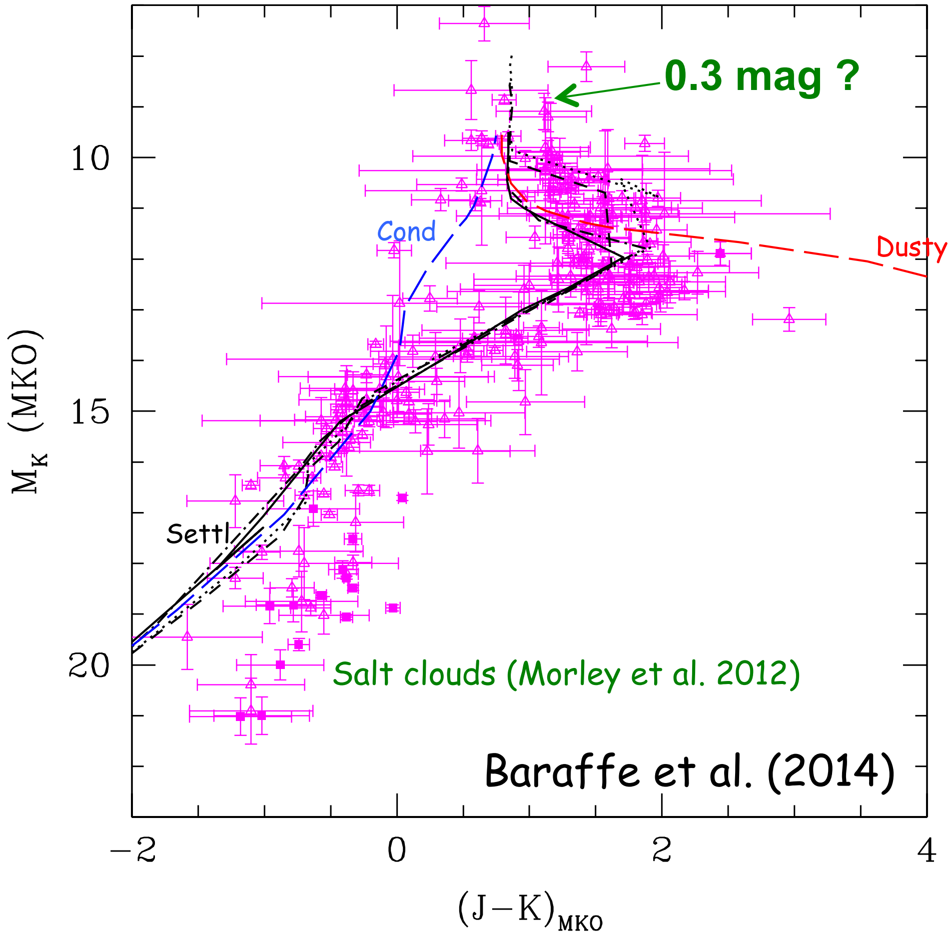
Comparing models from different authors

Estimated Teffs of brown dwarfs by Vrba et al. '04 & Golimowski et al. '04



The BT-Settl cloud model yields similar cloud extension then the Tsuji '02 model with Tcrit=1700K, and succeeds globally in reproducing the M-L-T transition.

BT-Settl in a CMD



New interior and evolution models based on the BT-Settl atmospheres!

Isochrones for 0.05, 0.1, 1 and 5 Gyr are displayed. The Dusty (red) and COND (blue) models at an age of 1 Gyr are also shown for comparison. The data are from Faherty et al. (2012) and Dupuy et al. (2012).

0.3 mag offset in the M-L transition below 2500K !

Currently adding carbonatious molecules and dust species to improve late-T to Y dwarf BT-Settl models.

The BT-Settl models reproduce the Galileo probe measurements of Jupiter abundances !

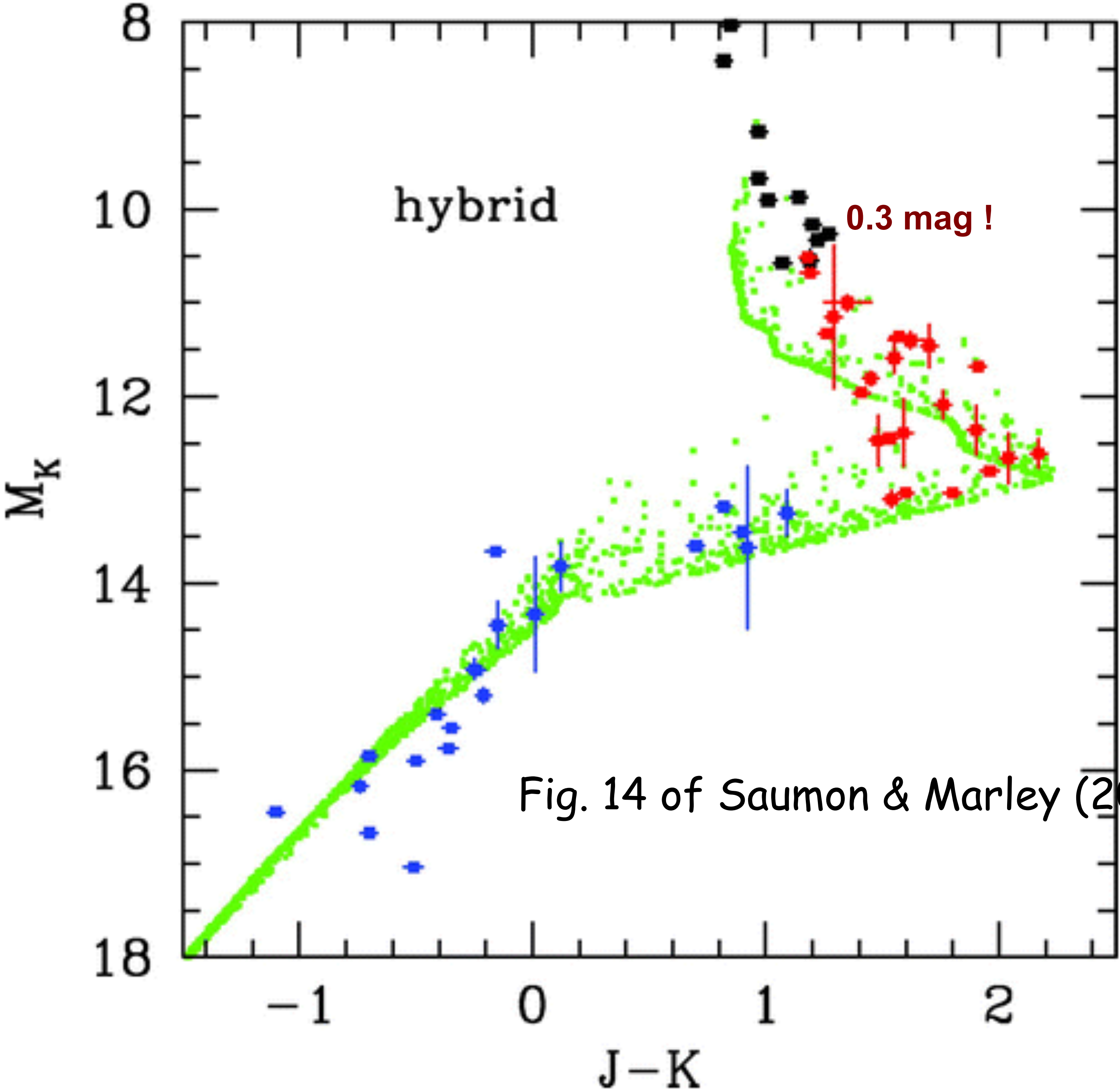


Fig. 14 of Saumon & Marley (2008)

Web Simulator

http://phoenix.ens-lyon.fr/simulator

ONLINE!

- Offers synthetic spectra and thermal structures of published model grids and the relevant publications.
- Computes synthetic spectra, with/ without irradiation by a parent star, and photometry for:

✓ stars

✓ brown dwarfs (1 Myrs - 10 Gyrs)

✓ irradiated stars or planets

✓ telluric exoplanets

- Computes isochrones and finds the parameters of a star by chi-square fitting of colors and/or mags to the isochrones.
- Rosseland/Planck as well as monochromatic opacity tables calculations.

Star, Brown Dwarf & Planet Simulator

Choose the physics required: NextGen '99

MODEL SPECTRA

ISOCHRONE χ^2-fitting

These models are available (via the links below with grey backgrounds) and have been published in the following papers. You will find in this FORMAT file the information needed to understand the content of synthetic spectra files.

• NextGen	Gas phase only, valid for T_{eff} > 2700 K	Allard et al. '97 Baraffe et al. '97 Baraffe et al. '98 Hauschildt et al. '99
• AMES-Dusty	Dust in equilibrium with gas phase, "valid" for Near-IR studies with T_{eff} > 1700 K	Allard et al. '01 Chabrier et al. '00
• AMES-Cond	Same as AMES-Dusty with dust opacities ignored, "valid" for T_{eff} < 1400 K	Allard et al. '01 Baraffe et al. '03
• AMES-Cond-GAIA	Available down to T_{eff} = 2500K	
• BT-Settl	With a cloud model, valid across the entire parameter range	Allard et al. '03 Allard et al. '07 Allard et al. '09
• BT-Dusty	Same as AMES-Dusty with updated opacities	Allard et al. '09
• BT-Cond	Same as AMES-Cond with updated opacities	Allard et al. '09
• BT-NextGen	Same as NextGen with updated opacities	Allard et al. '09

Enstatite ($MgSiO_3$)

Return to France Allard's web page

002620

Web Simulator

http://phoenix.ens-lyon.fr/simulator

ONLINE in Jan. '15 !

- Offers synthetic spectra and thermal structures of published model grids and the relevant publications.
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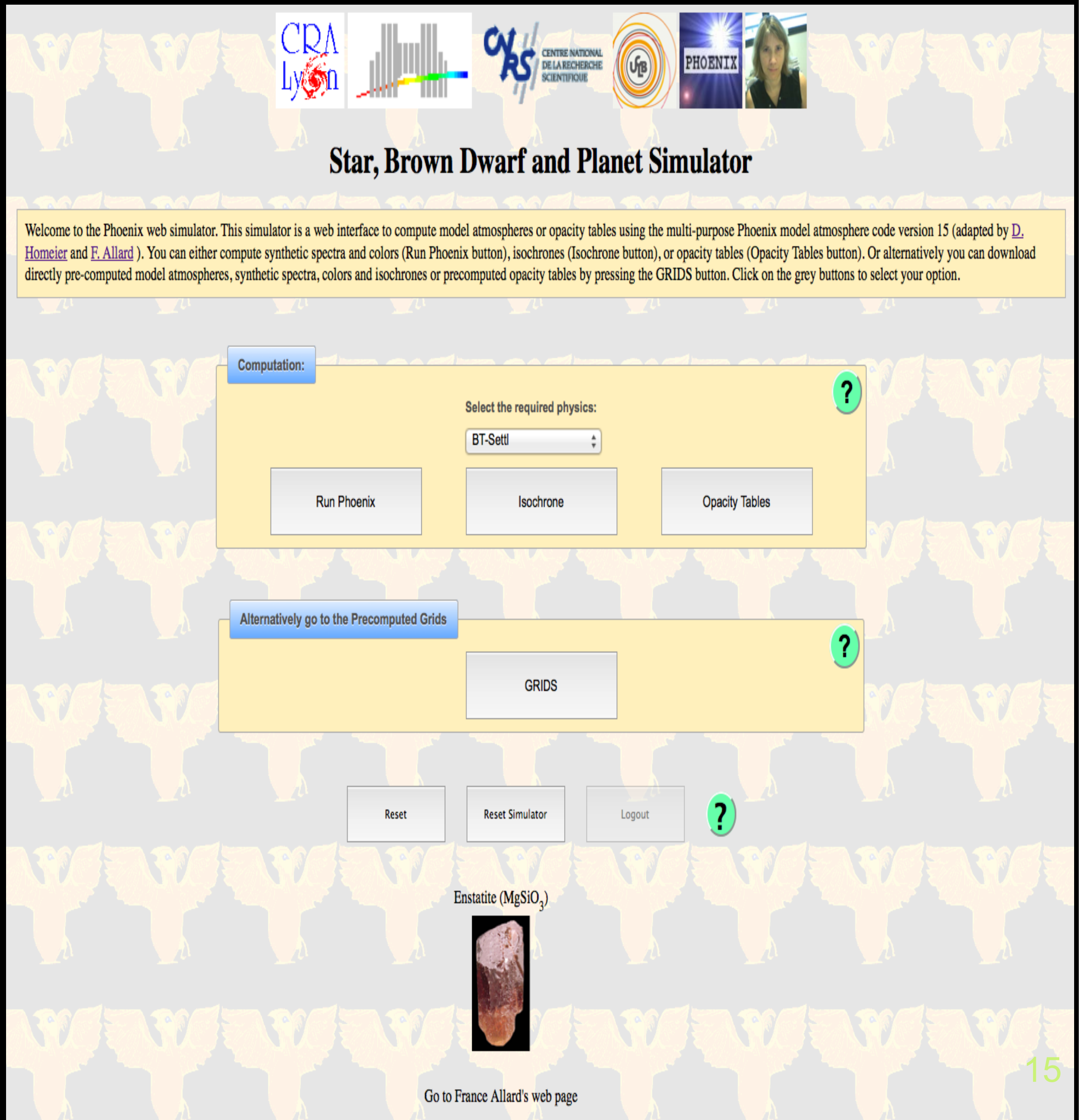


Temperature profile of the Sun

corona

> 350 000 km

$T(r) = 1$ to 3×10^6K

$\rho = 10^{-12}\ \rho_{photosphere}$

Rayon X

chromosphere

2,000 km

T_{eff} =7,000K

Spicules

Protuberances

UV

photosphere

400 km

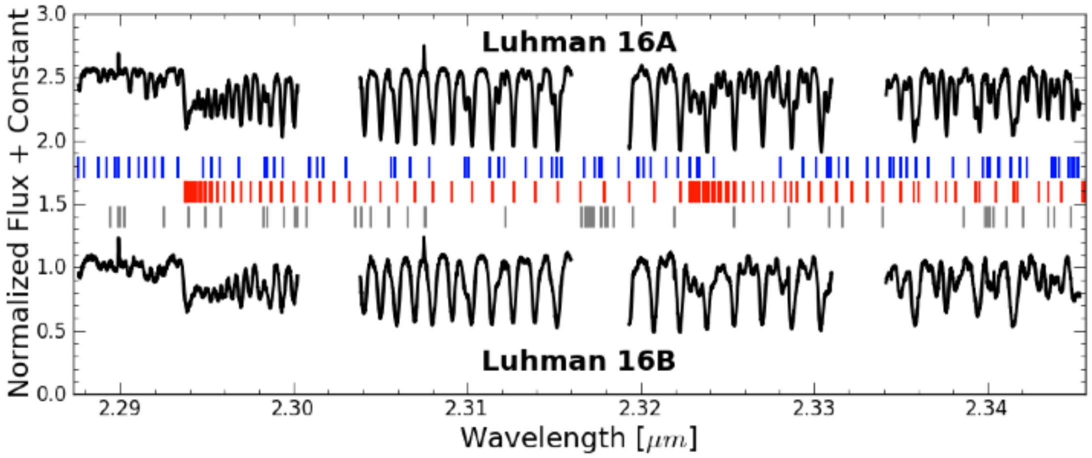
$|T| = 5000K$

T_{eff}= 5,780K

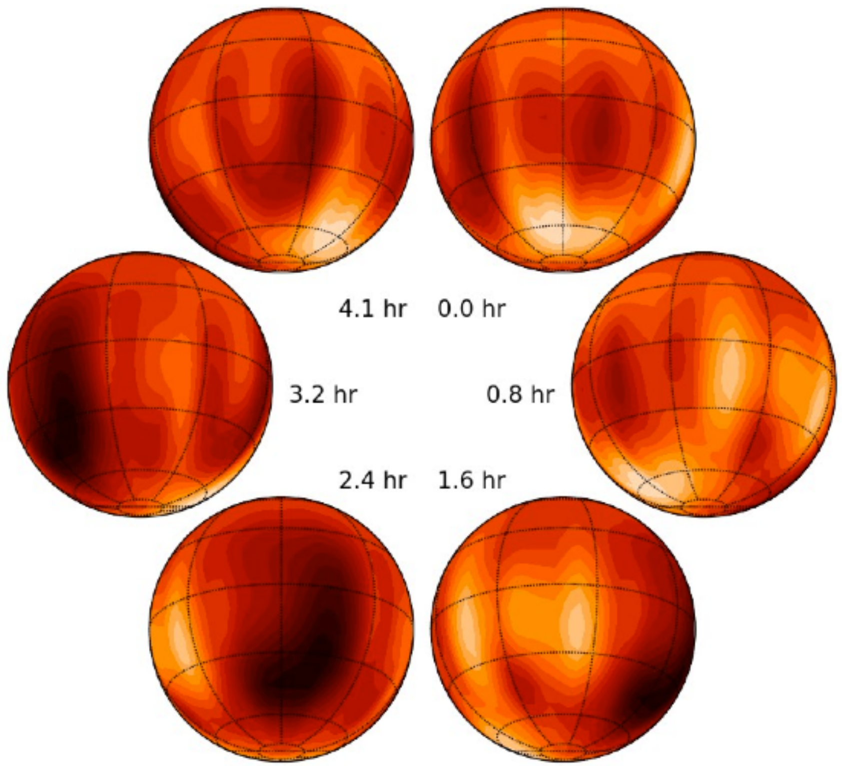
Visual to IR

Surface inhomogeneities revealed by Doppler imaging tomography!

Crossfield et al. (Nature 505, 2014)



High-resolution, near-infrared spectra of the Luhman 16AB brown dwarfs (black curves). The vertical ticks indicate absorption features: H_2O (blue) and CO (red), and residual telluric features (gray). The lines of the B component are broader.



Surface map of brown dwarf Luhman 16B, which clearly depicts a bright near-polar region (seen in the upper-right panels) and a darker mid-latitude area (lower-left panels) consistent with large-scale cloud inhomogeneities. The lightest and darkest regions shown correspond to brightness variations of roughly ±10%. The time index of each projection is indicated near the center of the figure.

The rotation significantly modifies the convective properties. The interaction of convection with the overlying, stably stratified atmosphere will generate a wealth of atmospheric waves, and we argue that, just as in the stratospheres of planets in the solar system, the interaction of these waves with the mean flow will lead to a significant atmospheric circulation at regional to global scales.

Global Circulation Model

Case of an L/T dwarf
(T_{eff} of ~650 to 1150K)

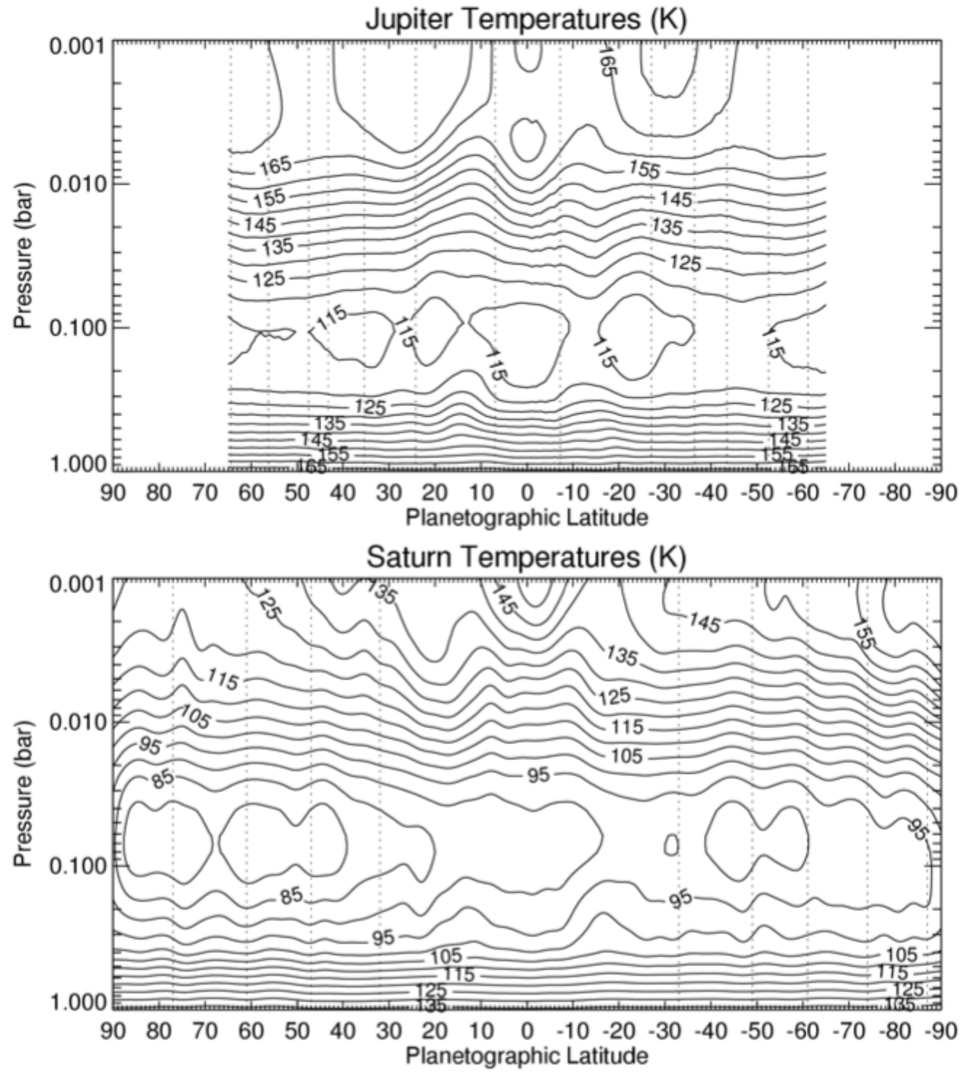
Showman & Kaspi (2013)

Fig. 7. Snapshots at different times of the temperature perturbations at 1 bar in a single model with rotation period of 10 hours.

Temperature perturbations are deviations of temperature from the reference state, in K. Time separation between frames is 4.8 hours.

Fletcher 2011: ATMOSPHERES & WAVES EFFECTIVELY REDISTRIBUTE ENERGY

- **Horizontal redistribution:** efficiency of mixing determines whether species are transported with lon/lat:
  - Dayside/nightside gradients largest where advective timescales >> radiative timescales, photosphere and convective zones well separated (e.g., Showman et al., 2010).
  - Solar system planets have radiation penetrate convective zones, effectively isothermal.
- **No GCM is yet capable of reproducing jovian atmospheric dynamics**
  - Parameterisations of mixing fails to capture the convective dynamics (e.g., H_2O condensation and latent heat release; eddy pumping of jets; vertical structure of thermal winds).
  - Successful in reproducing cloud-top advection of tracers.



Global RHD simulations

Freytag, Schaffenberger & Allard 2014 (in prep.)

T_{eff}= 2200K, logg= 3.5, solar, P=8 Hr

➔

Jupiter

However radius scaled by a factor 20 !
Improvement expected with MPI 2015

Défi

Acronym	**PAP2014**
Titre du projet	**Propriétés Atmosphériques Planétaires**
Proposal title	**Planetary Atmosphere Properties**
Coordinateur scientifique / Scientific Coordinator	France Allard
Laboratory	Centre de Recherche Astrophysique de Lyon
Project duration	48 months
Type of research	☑ Basic Research ☐ Experimental Development ☐ Industrial Research ☐ Technical feasibility study
Grant requested	397,550 €

Type of project	International project
Number of partners	4
Main axis / ~~societal challenge~~	Main: Extrasolar Planets Secondary: The Search for Life on Other Worlds
Main fields of research	*Astrophysics, Model Atmosphere, Spectroscopy*