Modeling UV photo-chemistry and clouds in the atmosphere of exoplanets

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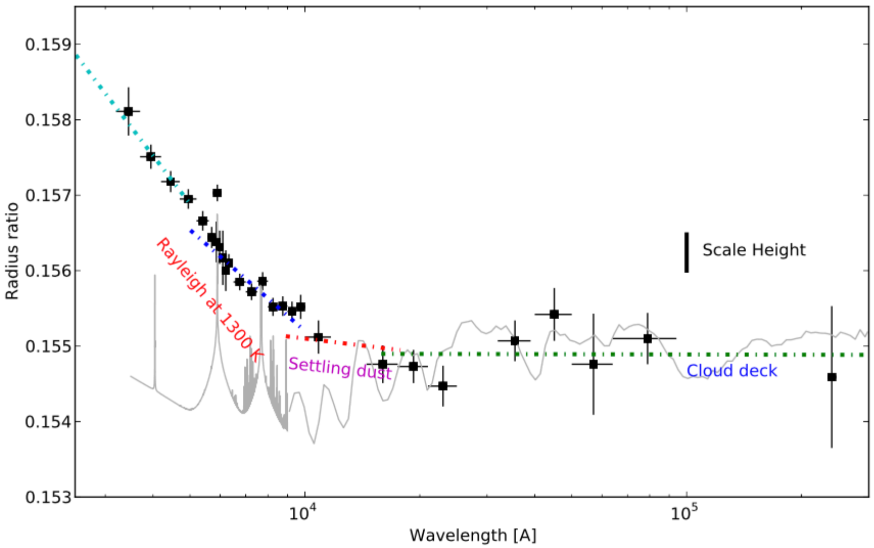
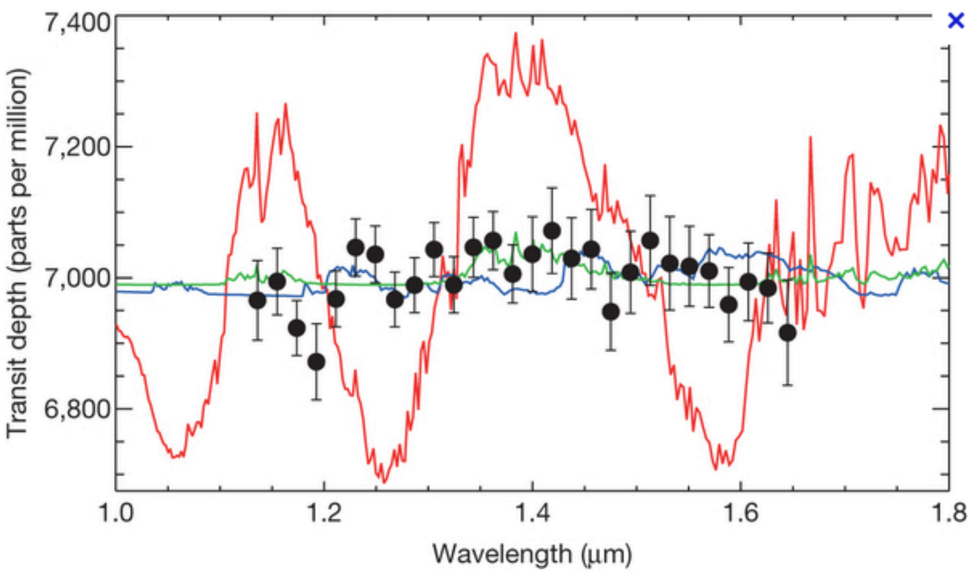
In collaboration with O. Venot (Leuven), F. Selsis (Bordeaux), D. Homeier, G. Chabrier, F. Allard (Lyon)

➢ Transit spectrum of exoplanets example of HD189 (Pont et al 2013) and GJ436b (Knutson et al 2014):





➢ Global strategy:

- Atmo: 1D radiative/convective equilibrium atmospheric model with a complete treatment of (equilibrium and out-of-equilibrium) chemistry and radiative transfer

- UM (Unifed model, UK Met-office): 3D global circulation model with simplified chemistry and radiative transfer

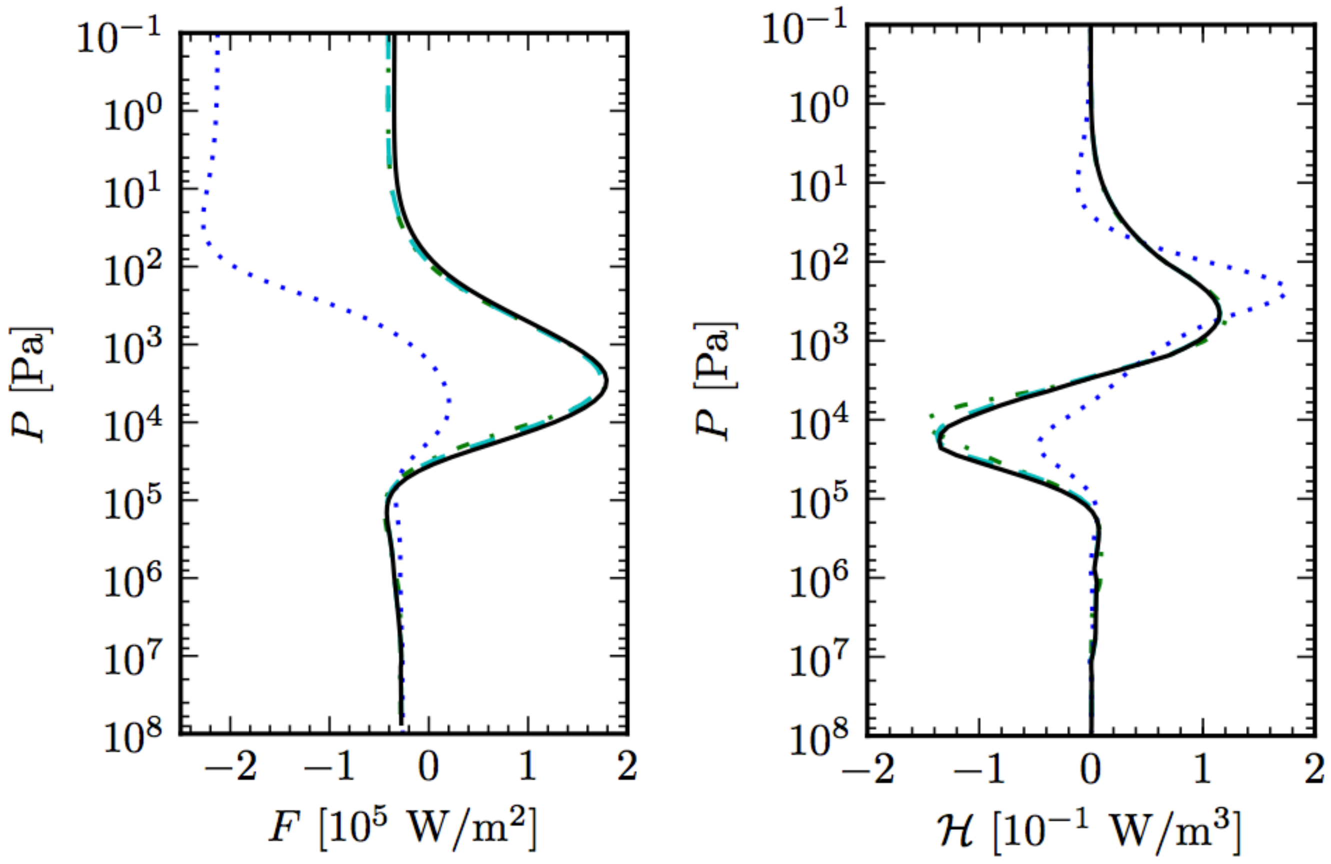
- Radiative transfer (Comparison in Amundsen et al. 2014):

  - Atmo:
    - ✓ Line by line computation at a resolution of 0.001 cm^{-1}: 5E7 frequencies
    - ✓ Discrete ordinate method (Gauss legendre quadrature) with 16 rays

  - UM (Edwards-Slingo scheme):
    - ✓ Correlated-K method with 32 bands and 10 coefficient per band
    - ✓ Two stream approximation

Both includes H2-H2 and H2-He CIA, NH3, CH4 (STDS Exomol), CO, CO2, H2O, TiO, and VO, Na and K. Absorption coefficients are interpolated from a PT table of 800 points.

➢ Radiative transfer (Comparison in Amundsen et al. 2014):



- Solid black: Atmo
- Dashed green: UM ES code
- Dotted blue: band average

➢ Chemistry:

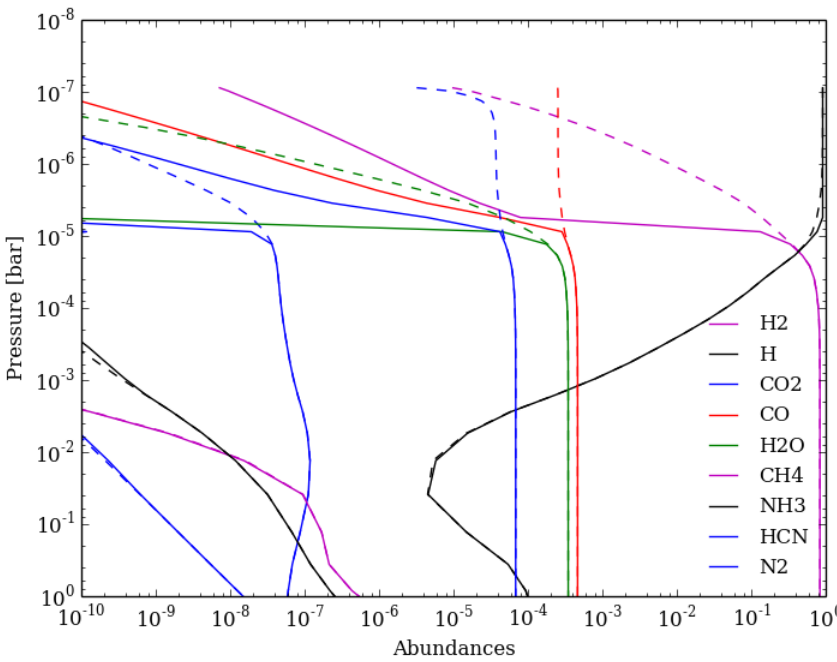
- Atmo:
  - ✓ Equilibrium chemistry by minimization of Gibbs-free energy
  - ✓ Chemical network with photochemistry and mixing from Venot et al. 2012: 109 species ~2000 reactions with C,N,O,H based species up to 2C (+TiO, VO)
  - ✓ Condensation of H2O and NH3 (P. Mourier, ENS undergrad.) and silicates (MgSiO3, KAlSi3O8, etc…, no rainout for the moment)

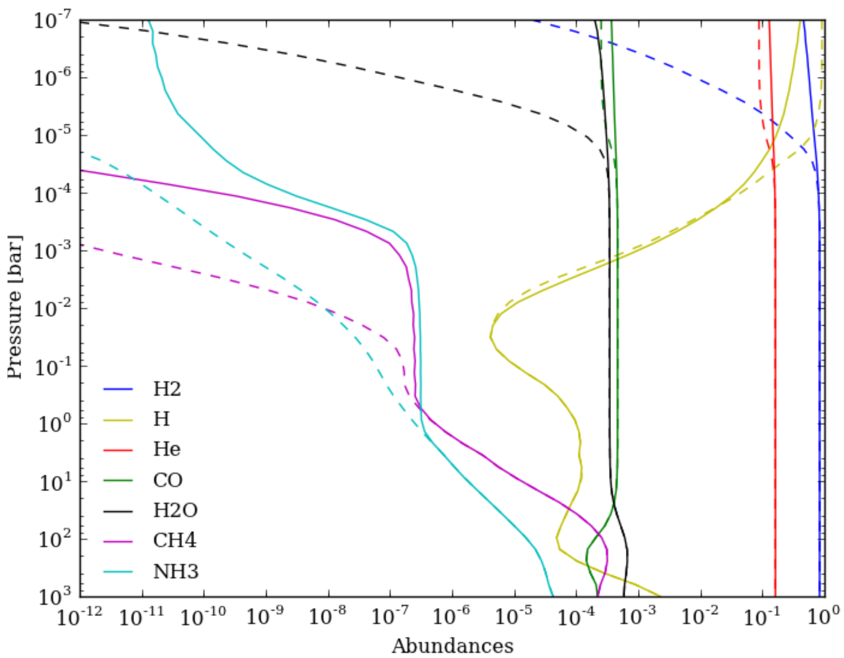
- UM:
  - ✓ Equilibrium chemistry
  - ✓ Reduced network in development from the sensitivity analysis of the full network (see Dobrijevic et al. 2011)

- Out of equilibrium Chemistry (Test on HD209 Venot et al 2012 Moses et al 2011):

Photochemistry:

Mixing using a prescribed Kzz profile:

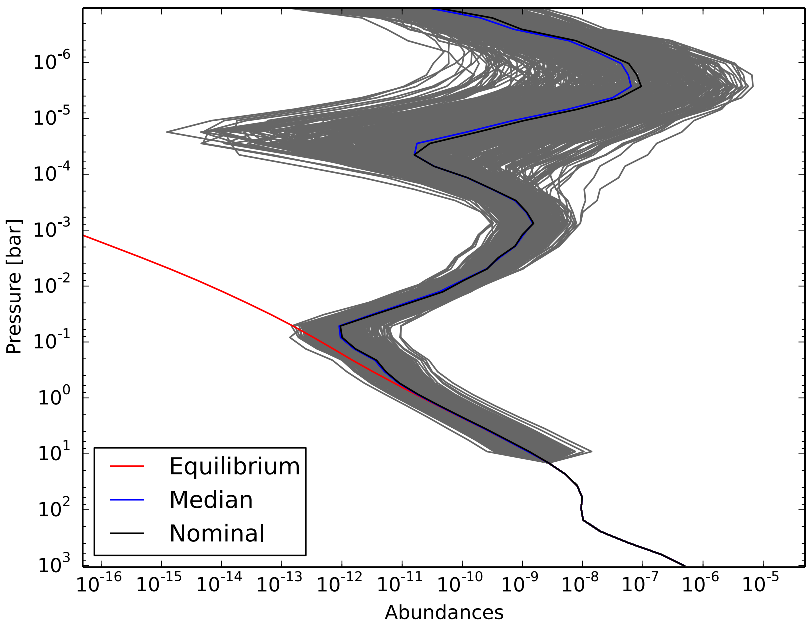




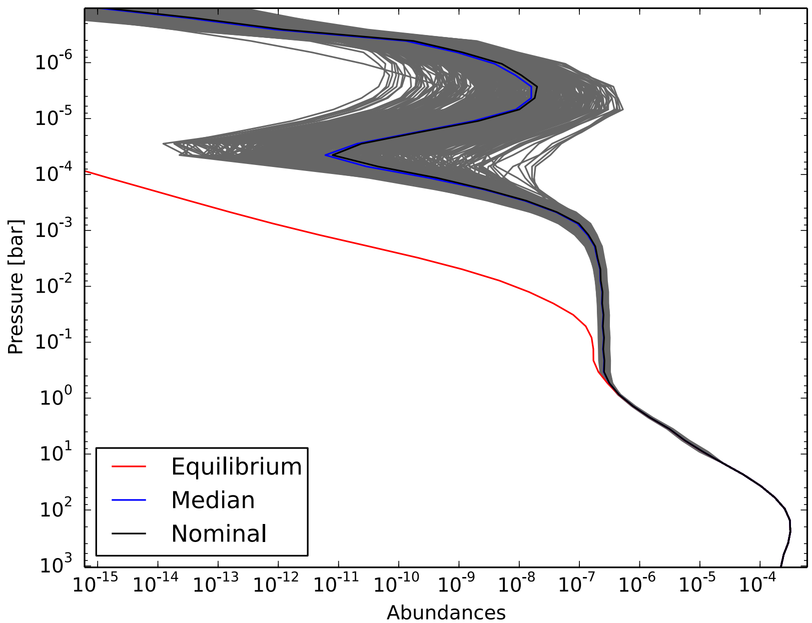
➢ Out of equilibrium Chemistry Sensitivity analysis (B. Drummond):

(See Hebrard 2007 for Titan's atmosphere)

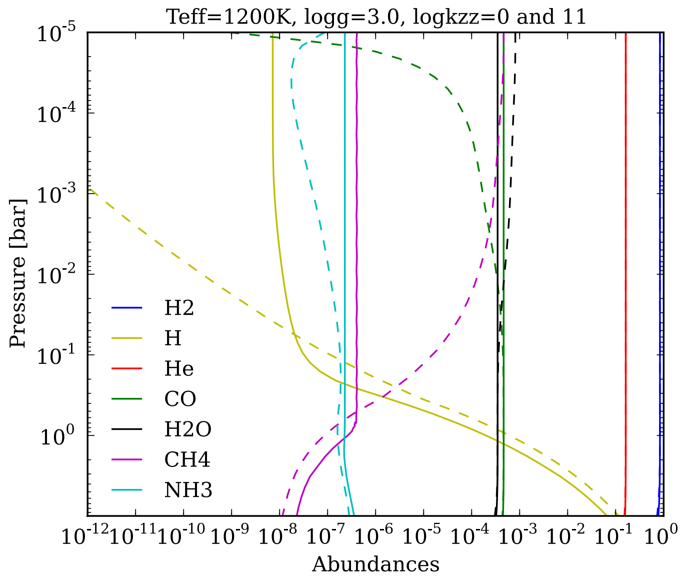
C2H2

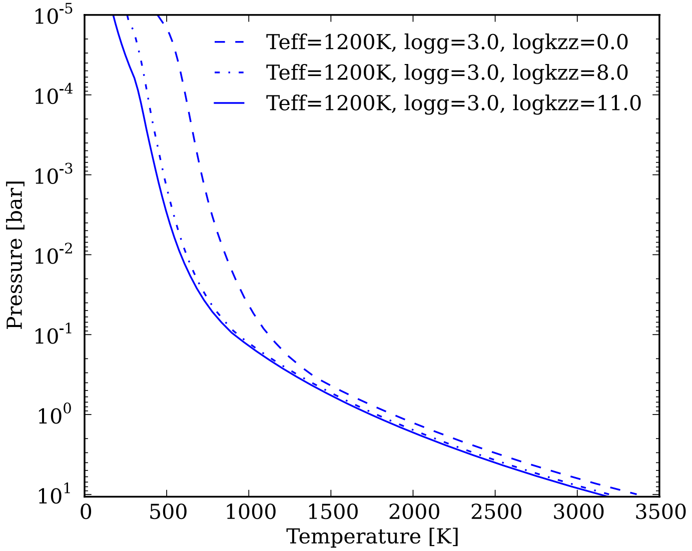


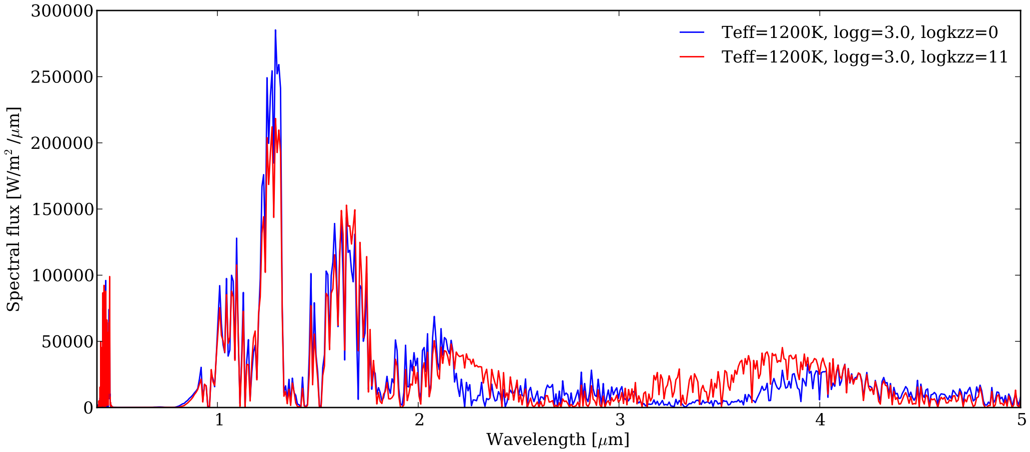
CH4



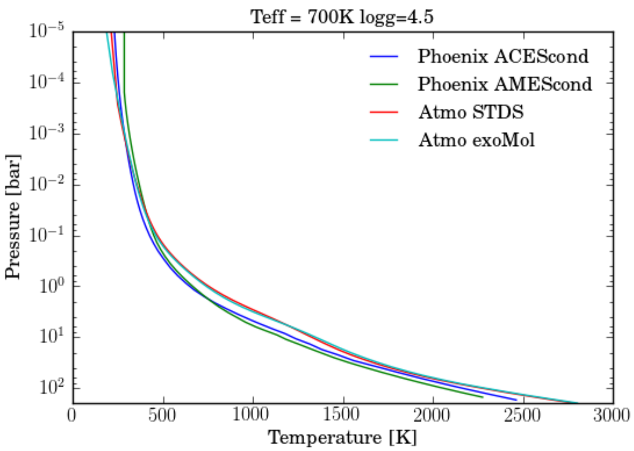
➢ Out of equilibrium Chemistry, effect on PT profiles:

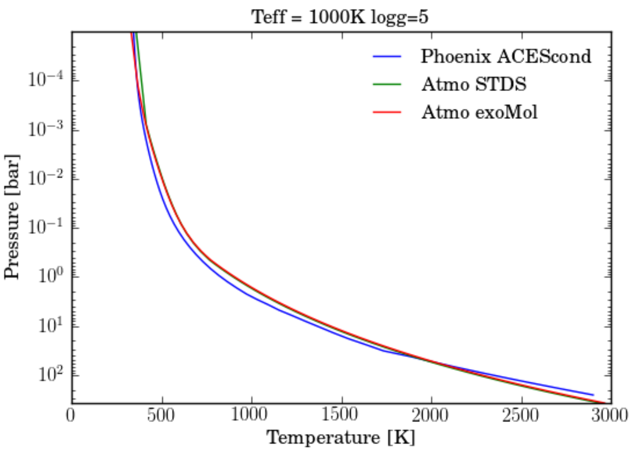




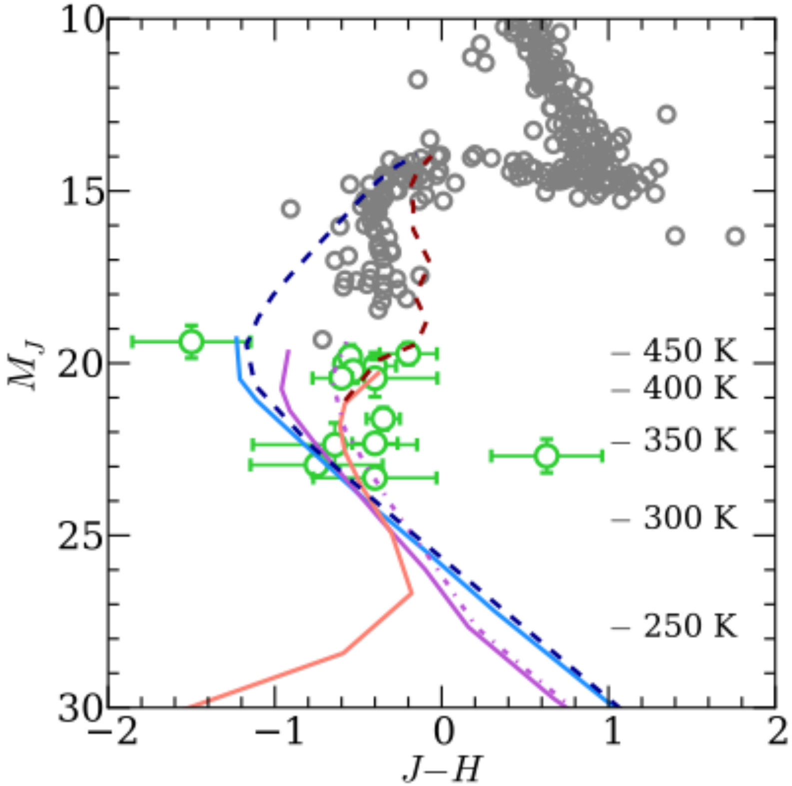


- Radiative/convective equilibrium with Atmo:
- Get a physically consistent pressure temperature profile at hydrostatic and energy equilibrium
  - ✓ Application to Brown Dwarfs and comparisons with Phoenix models
  - ✓ Tests of the new ExoMol linelist for CH_4

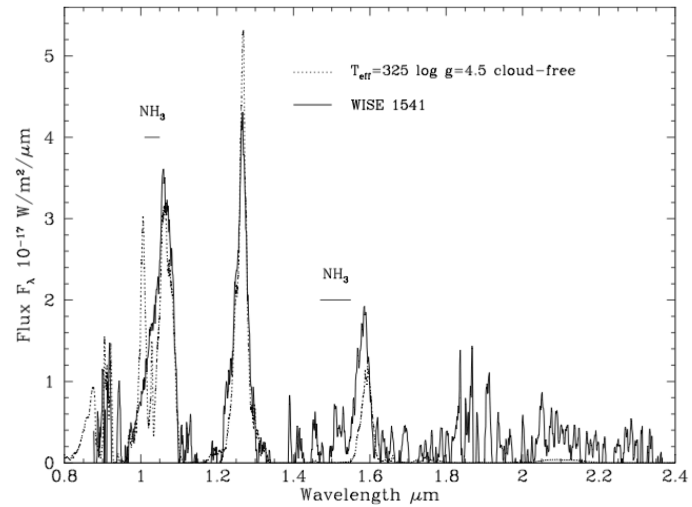


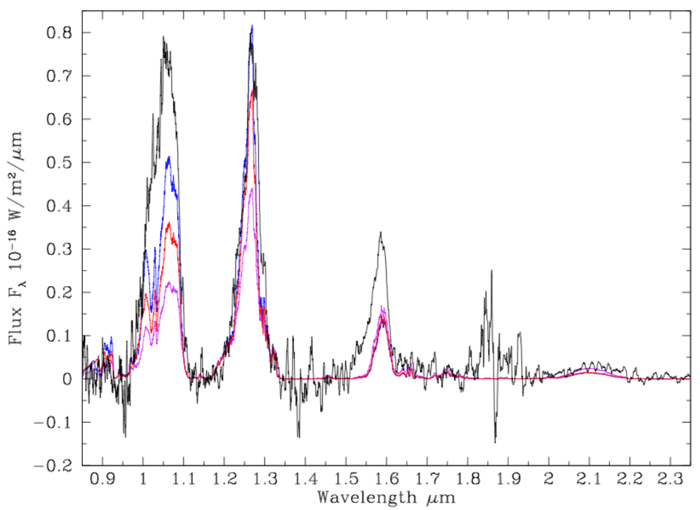


- Radiative/convective equilibrium with Atmo:
- Application to Y dwarfs WISE1541 WISE1217:



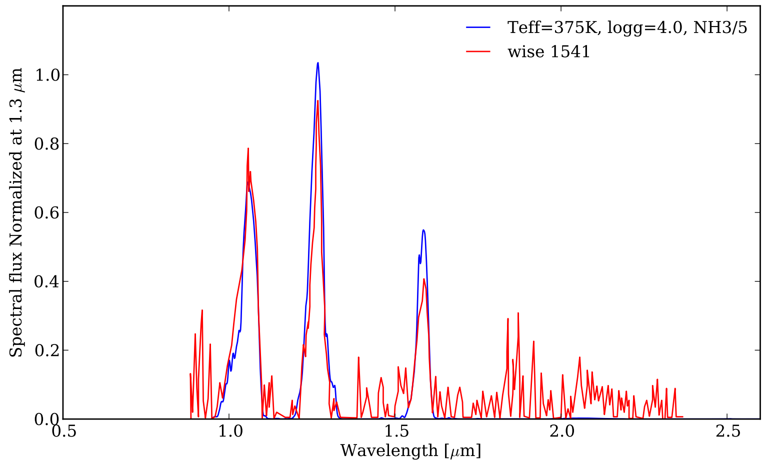
Morley et al 2014

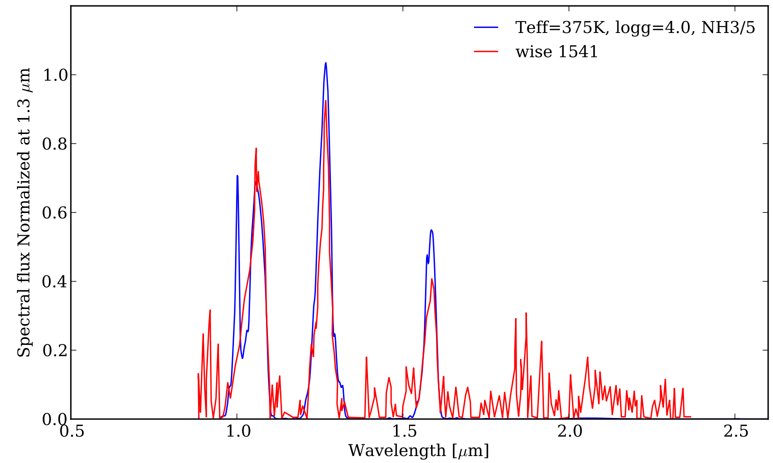


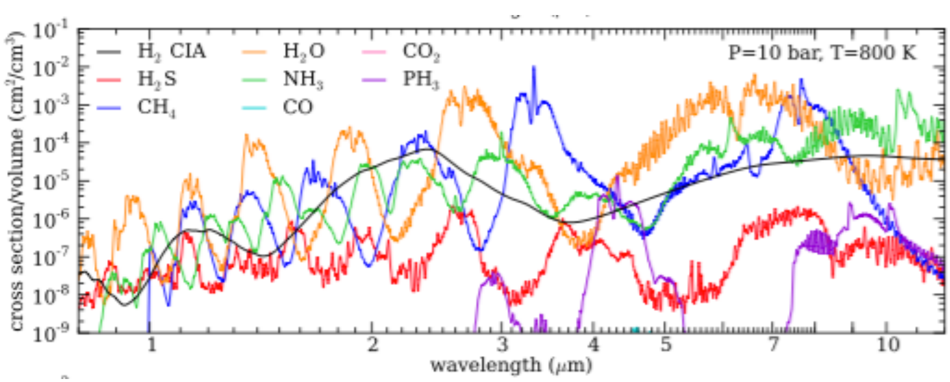


Leggett et al 2013, 2014 (w1217)

- Radiative/convective equilibrium with Atmo:
- Application to Y dwarf WISE1541, spurious effect of STDS CH4 line list

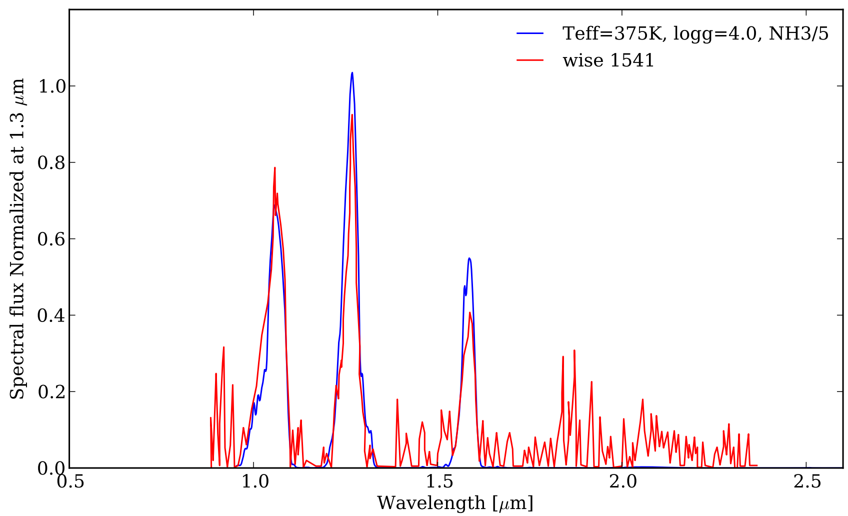


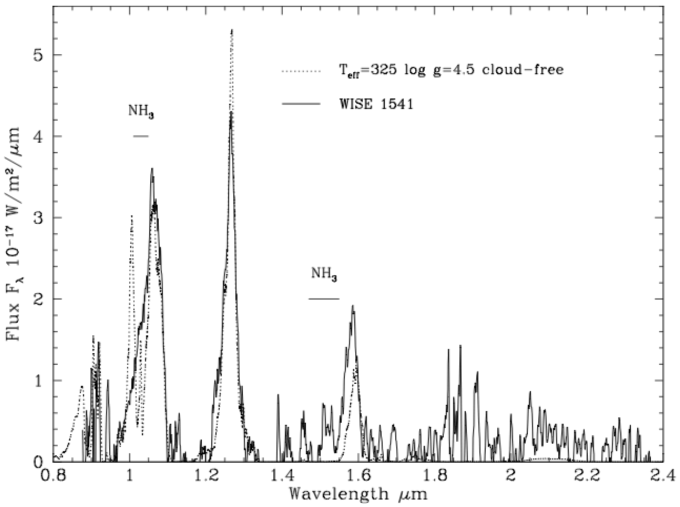


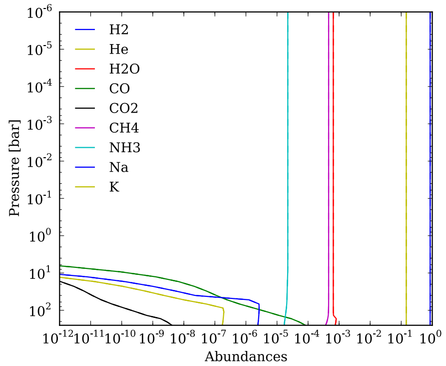


Morley et al 2014

- Radiative/convective equilibrium with Atmo:
- Application to Y dwarf WISE1541, reduction of NH3 by a factor of 5







BIOSIGNATURE GASES IN H_2-DOMINATED ATMOSPHERES ON ROCKY EXOPLANETS

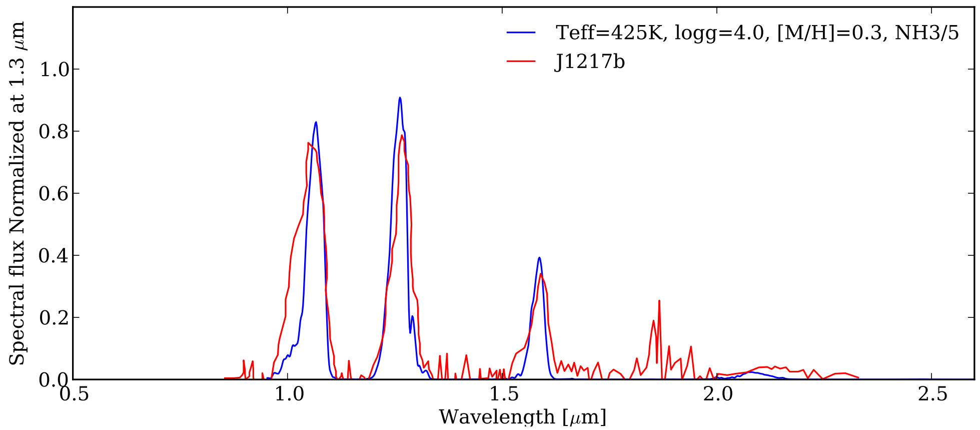
S. SEAGER', W. BAINS[1]', R. HU[1],

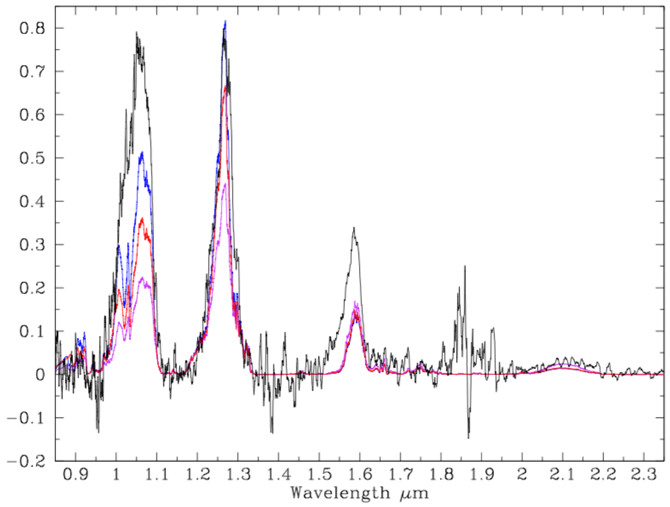
Draft version September 25, 2013

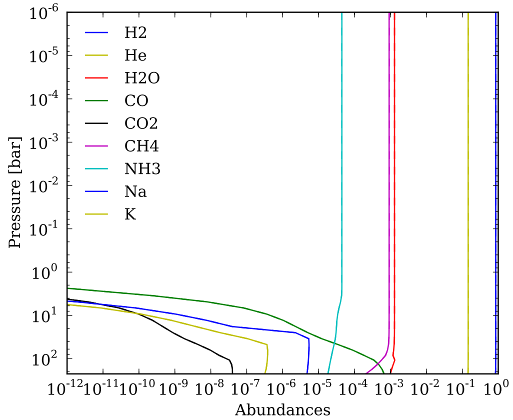
ABSTRACT

Super Earth exoplanets are being discovered with increasing frequency and some will be able to retain stable H_2-dominated atmospheres. We study biosignature gases on exoplanets with thin H_2 atmospheres and habitable surface temperatures, by using a model atmosphere with photochemistry, and biomass estimate framework for evaluating the plausibilty of a range of biosignature gas candidates. We find that photochemically produced H atoms are the most abundant reactive species in H_2 atmospheres. In atmospheres with high CO_2 levels, atomic O is the major destructive species for some molecules. In sun-Earth-like UV radiation environments, H (and in some cases O) will rapidly destroy nearly all biosignature gases of interest. The lower UV fluxes from UV quiet M stars would produce a lower concentration of H (or O) for the same scenario, enabling some biosignature gases to accumulate. The favorability of low-UV radiation environments to accumulation of detectable biosignature gases in an H_2 atmosphere is closely analogous to the case of oxidized atmospheres, where photochemically produced OH is the major destructive species. Most potential biosignature gases, such as DMS and CH_3Cl are therefore more favorable in low UV, as compared to solar-like UV, environments. A few promising biosignature gas candidates, including NH_3 and N_2O, are favorable even in solar-like UV environments, as these gases are destroyed directly by photolysis and not by H (or O). A more subtle finding is that most gases produced by life that are fully hydrogenated forms of an element, such as CH_4, H_2S, are not effective signs of life in an H_2-rich atmosphere, because the dominant atmospheric chemistry will generate such gases abiologically, through photochemistry or geochemistry. Suitable biosignature gases in H_2-rich atmospheres for super Earth exoplanets transiting M stars could potentially be detected in transmission spectra with the *James Webb Space Telescope*.

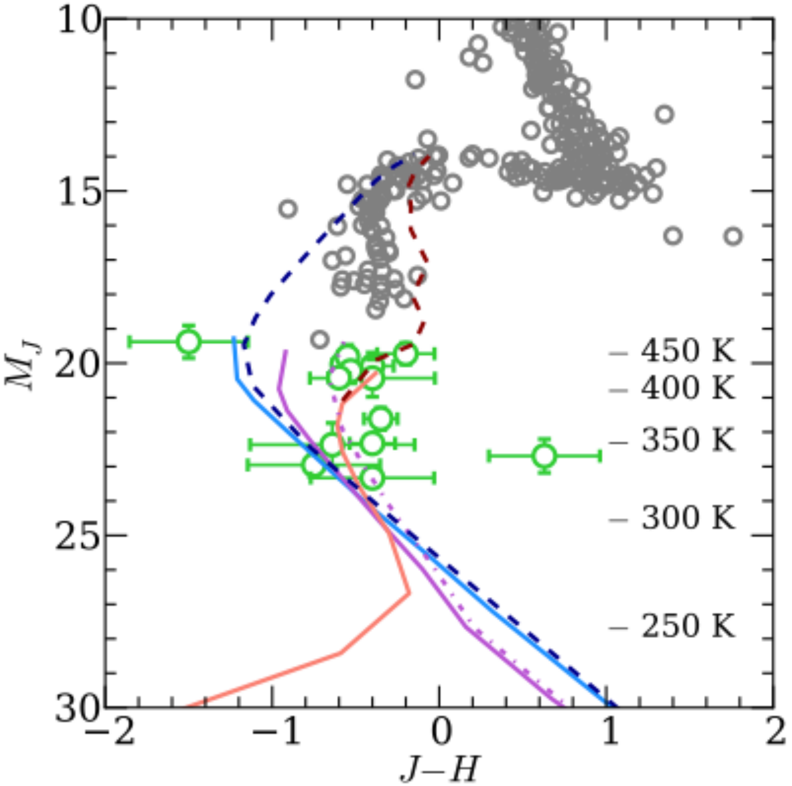
- Radiative/convective equilibrium with Atmo:
- Application to Y dwarf WISE1217, reduction of NH3 by a factor of 5



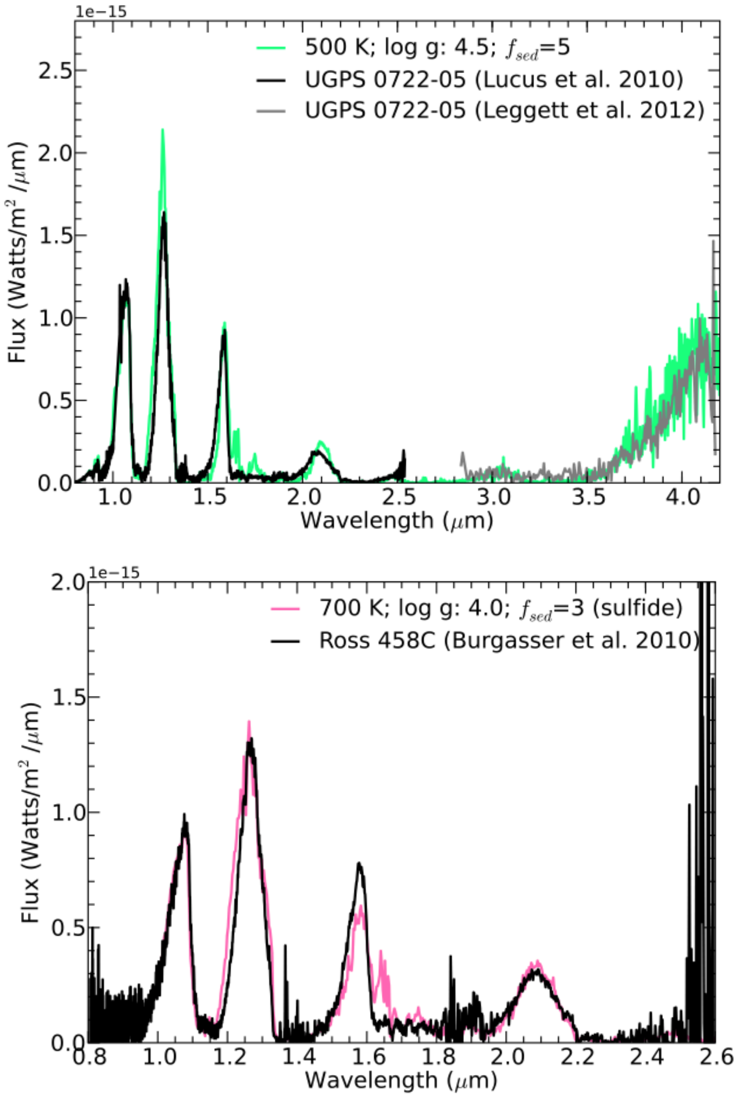




- Radiative/convective equilibrium with Atmo:
- Application to T dwarfs:



Morley et al 2014



Morley et al (2012)

- Radiative/convective equilibrium with Atmo:
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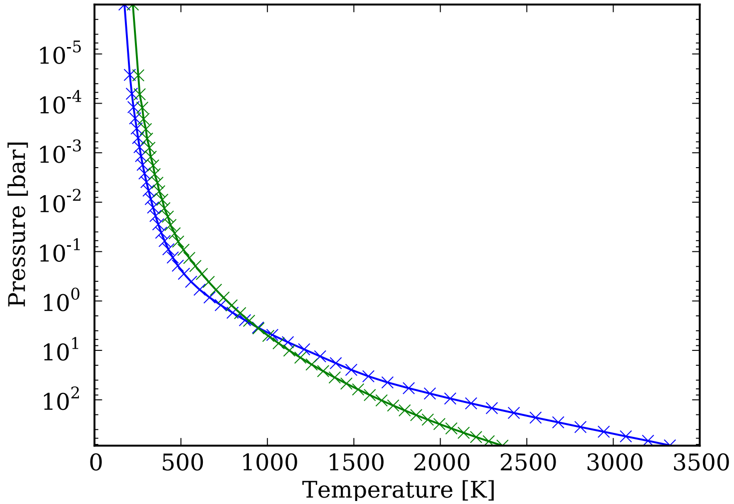

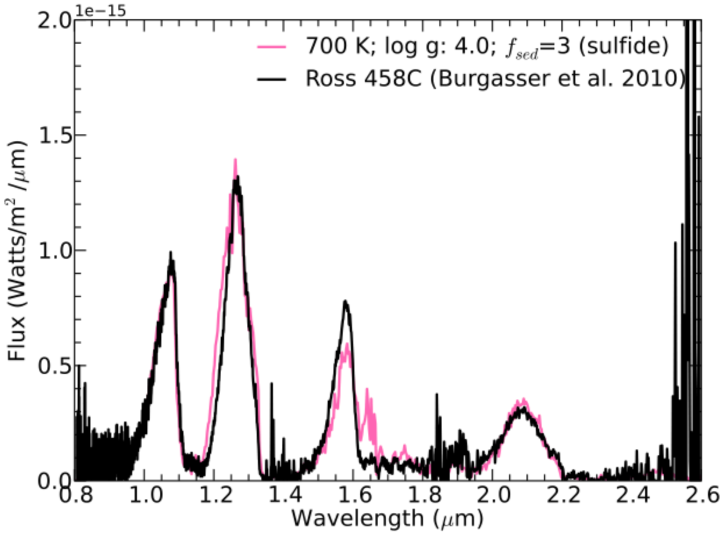

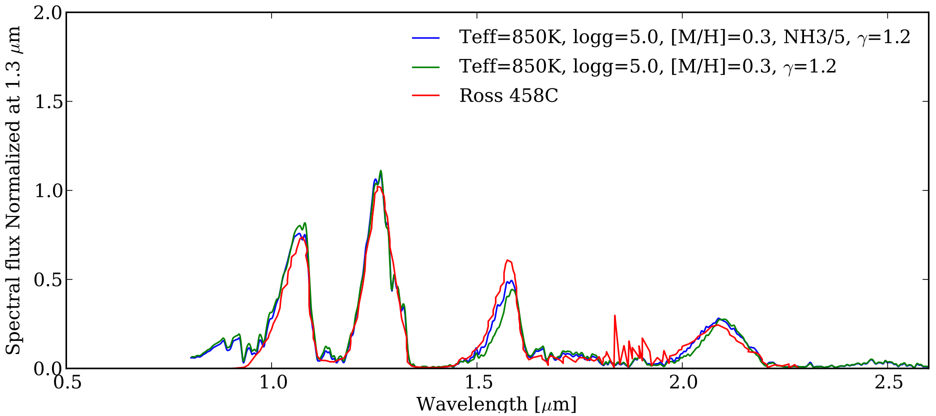

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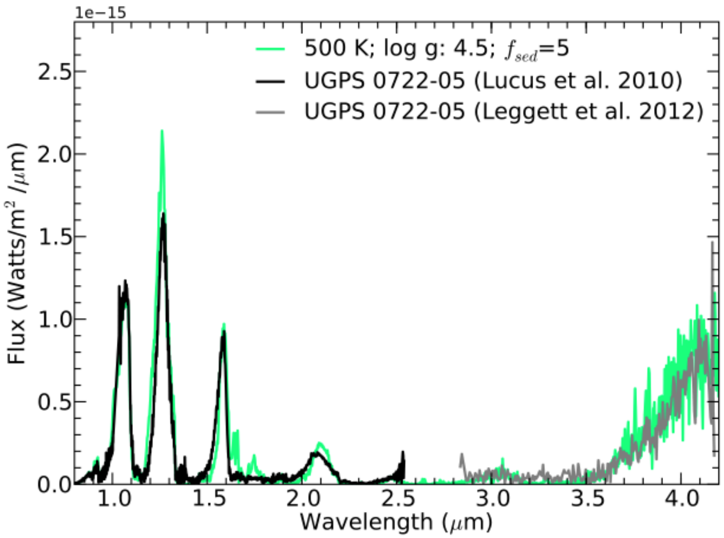
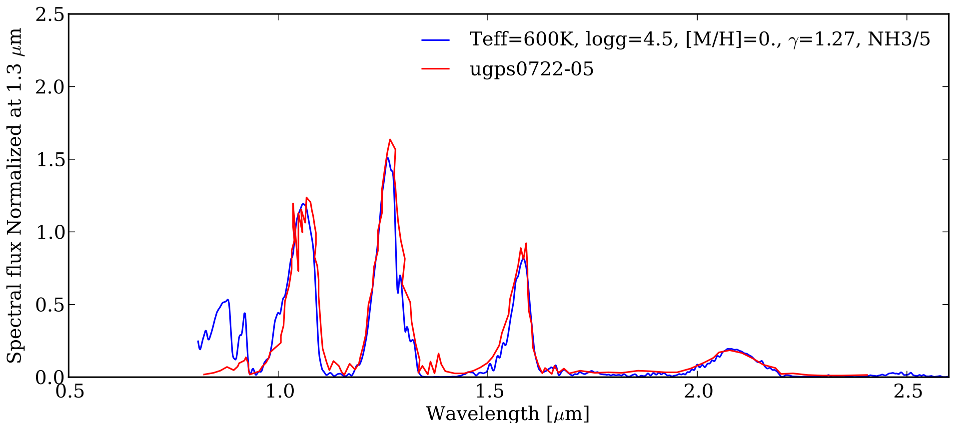


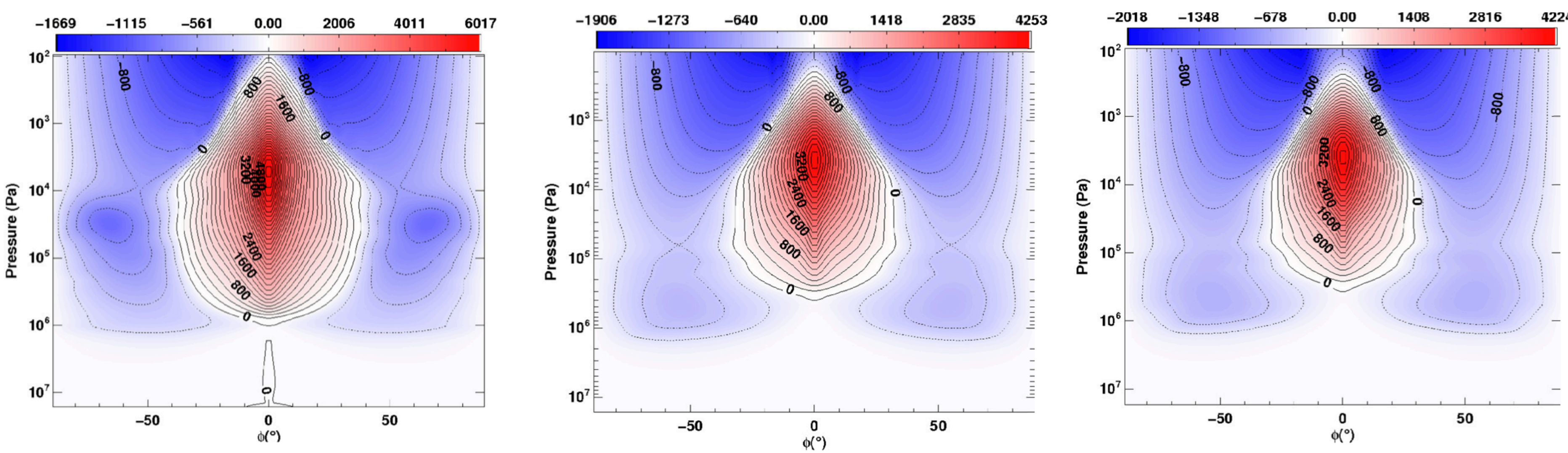


- GCM coupling: The Unified Model

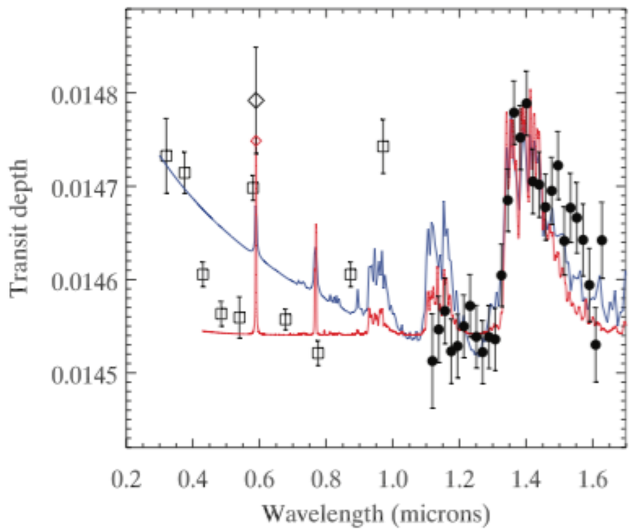
Met Office

- Hydrodynamics with a semi-implicit scheme
- Advection with a semi-lagrangian scheme

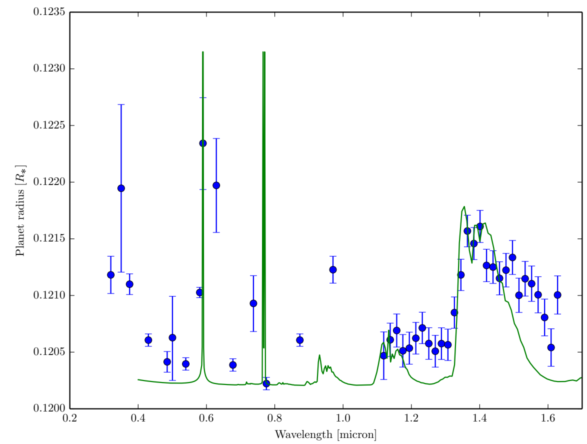
- Averaged zonal wind with shallow, deep, and full equations: Mayne et al. 2014

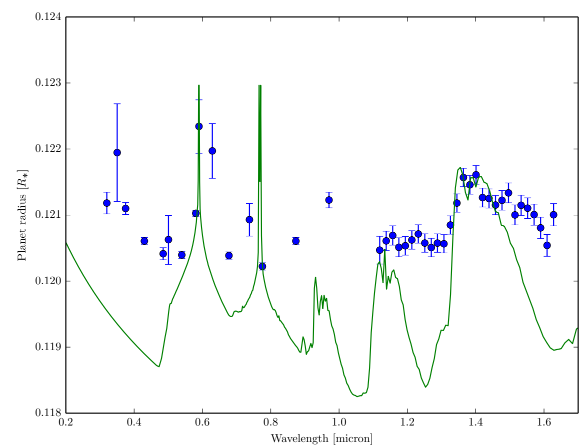


- Coupling the GCM with the radiative transfer scheme:
  - ✓ Under progress by D. Amundsen, J. Manners, N. Mayne

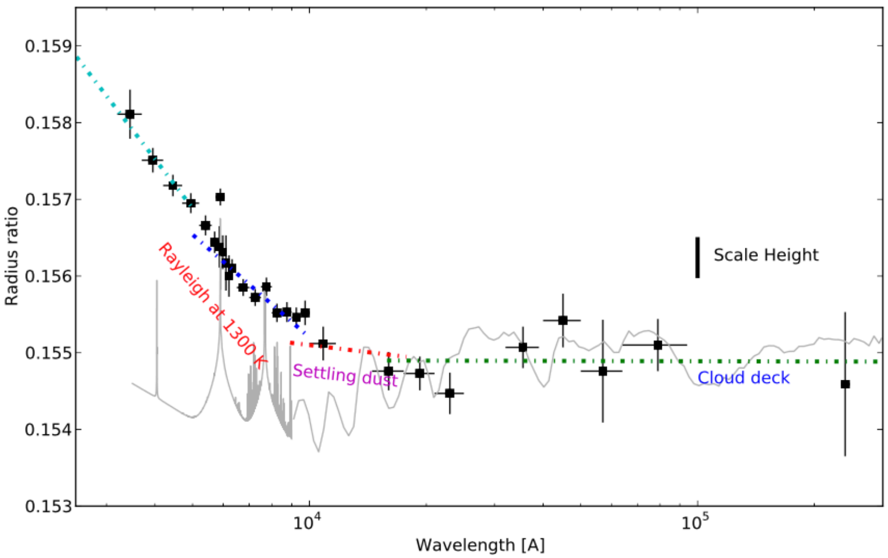


Deming et al 2013, HD209

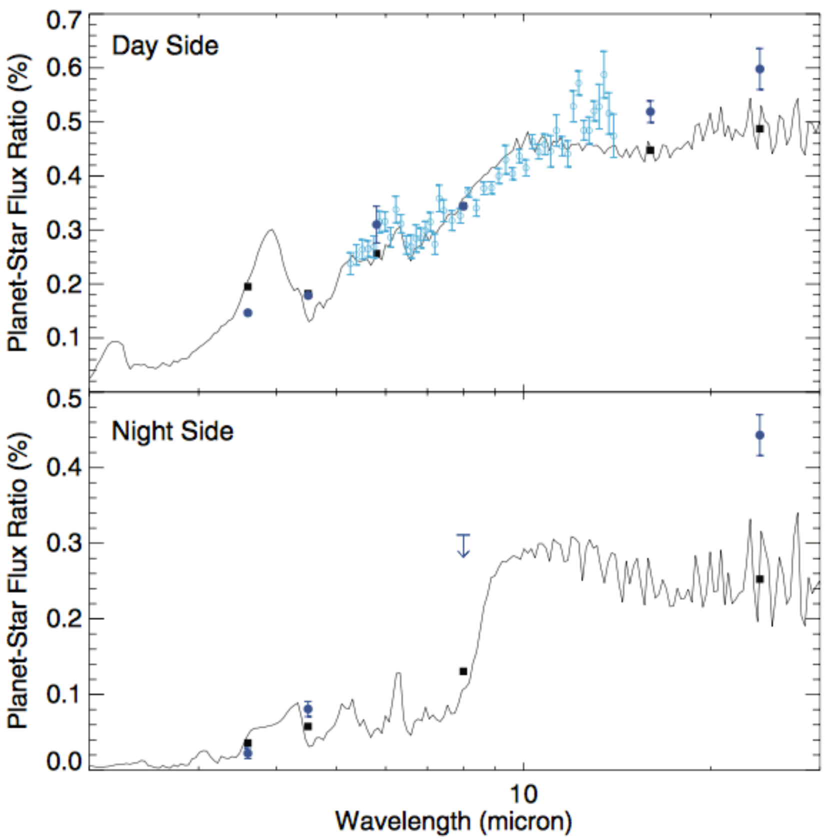




➢ Clouds or not clouds ?

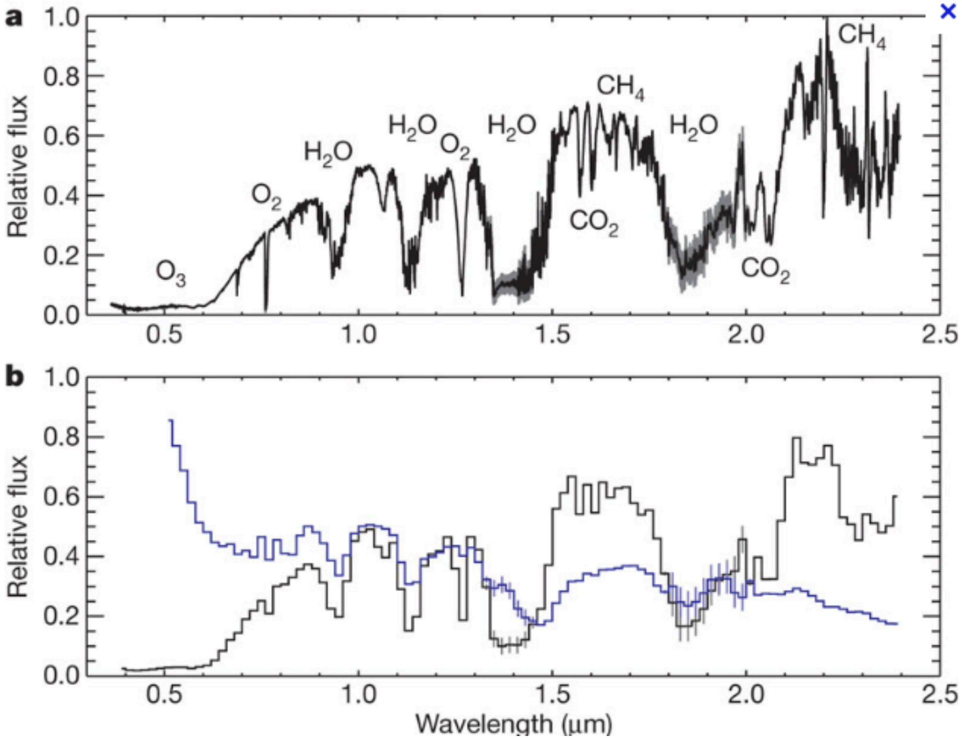


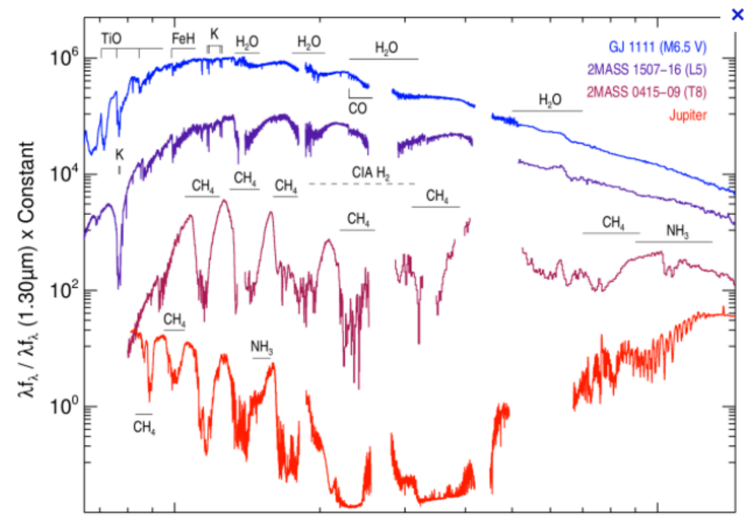
Pont et al 2013, HD189

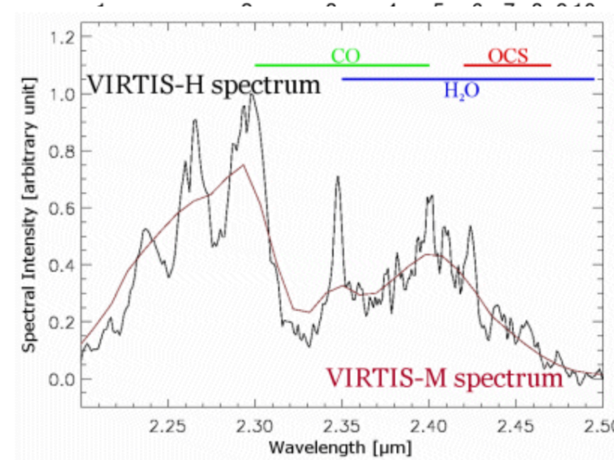


Knutson et al 2012, HD189

- Where are the clouds in the solar system ?
    - Earth Transmission spectrum, Jupiter and Venus emission spectrum







- Global strategy and perspective:

  - Atmo: 1D radiative/convective equilibrium atmospheric model with a complete treatment of (equilibrium and out-of-equilibrium) chemistry and radiative transfer

  - Using the 1D code for converged PT profile with out-of-equilibrium chemistry

  + study the production of haze/clouds to explain exoplanet spectra (transmission/secondary eclispe)

  - UM (Unifed model, UK Met-office): 3D global circulation model with simplified chemistry and radiative transfer

  - Using the coupled model to study the vertical and horizontal quenching of chemical species without assuming a Kzz profile

  + inflated hot jupiters, redistribution of incident stelar flux, shift of substellar point, variability of brown dwarfs…