What do we know about the atmosphere and structure of low mass stars...

...and what do we don’t

Jérémy Leconte
Hertzsprung-Russell diagram
Red dwarfs
Realm of Molecules

Complex molecules with strong IR absorptions form SED peaks in the infrared where these absorptions are.
Mass-Radius diagram

\[ M (M_\oplus) \]

\[ R (R_J) \]

\[ R (R_\oplus) \]

\( M \propto R^3 \)

\( \rho = \text{cst} \)

\[ M_\oplus \]

\[ M_J \]
Mass-Radius diagram
(Sub)stellar evolution equations

\[
\frac{\partial r}{\partial m} = -\frac{1}{4\pi r^2 \rho} \\
\frac{\partial P}{\partial m} = -\frac{Gm(r)}{4\pi r^4} \\
\frac{\partial l}{\partial m} = \epsilon - T \frac{\partial S}{\partial t}
\]

\[
\begin{pmatrix} S \\ P \end{pmatrix} = f(\rho, T) \\
\frac{\partial \ln T}{\partial \ln P} = \nabla_T \\
\epsilon = \chi(\rho, T)
\]

=> Boundary conditions
Mass-Radius diagram
Mass-Radius diagram

\[ M(M_{\oplus}) \]

\[ R(R_{J}) \]

- Water
- Rock
- Iron

H+He+Z

\[ M_c = 10-100 M_\oplus \]

\[ 5 \times 10^8 \text{ yr} \]

\[ 5 \times 10^9 \text{ yr} \]

Chabrier et al. (A&A 1997)
Baraffe et al. (A&A 2008)
Leconte et al. (2009, 2011b)
Mass-Radius diagram: the good news

Chabrier et al. (A&A 1997)
Baraffe et al. (A&A 2008)
Leconte et al. (2009, 2011b)
The core mass of Jupiter

Fig. 7: Jupiter's core mass, as derived by many different authors, at various times since the early 1970s of Uranus and Neptune models, together with this almost-ice shell, resembles a large core. With $0-2 M_\oplus$ central rocks and $9-12 M_\oplus$ of envelope $H_2O$ in Uranus ($12-14.5 M_\oplus$ in Neptune), this gives a central mass of heavy elements of $\sim 11.5 M_\oplus$ for Uranus and $\sim 14.5 M_\oplus$ for Neptune, since larger rocky cores are accompanied by smaller $Z_2$ values. For brevity, we call this mass $M_{23,Z}$, the mass so soft the $Z$-components 2 and 3. It is in agreement with the core mass predicted by the core accretion formation models (CAF) models by Pollack et al. (1996). More recent CAF models however by Alibert et al. (2005) predict significantly smaller core masses of $\sim 6 M_\oplus$ for Jupiter and Saturn. Uranus' and Neptune's $M_{23,Z}$ is larger than Jupiter's core (except if using DFT-MD, which gives 14–18 $M_\oplus$). An obvious consequence is the following hypothesis: All solar system giant planets formed by CAF with an initial core mass of $\sim 5-15 M_\oplus$. A deviation of their present core mass from this value indicates dissolving of initial core material within the deep interior, and does not indicate an inconsistency with CAF.

This dissolving of core material may have happened in the early hot stages of the planet's evolution or within a continuous, slowly progressing process. To explain Jupiter's relatively small derived core, Saumon and Guillot (2004) suggest a large mixing of core material in Jupiter than in Saturn due to a larger gas accretion rate during formation; in this sense, the high metallicity of Uranus' and Neptune's inner envelope implies weak core erosion and thus a small gas accretion rate in agreement with their small derived total gas fraction.

As small Jupiter core today can explain by continuous, slower erosion. If the protocore contained ice, this ice at present Jupiter core conditions of $\sim 20000 K$ and $>40 Mbar$ would be in the plasma phase (French et al. 2009a) which is soluble with hydrogen. However, we do not know how fast such an ice-enriched H/He/ice mixture can be redistributed by convection. Instead, a deep layer of H/He/ice can form which is stable against convection due to a compositional gradient. Note that an extended compositional gradient is not a preferred solution because of Jupiter's large heat flux, which strongly points to large-scale convection.
Uncertainties on the Equation of State (EoS)

[Diagram showing phase transitions and experimental data points for hydrogen under high pressure and temperature conditions.]

Experiments:  
- Knudson (Z pinch)  
- Nellis (gas gun)  
- Belov (explosives)  
- Boriskov (explosives)  
- Grishechkin (explosives)  
- Hicks (laser)  
- Knudson (laser)  
- Collins and Da Silva (laser)

Chemical models:  
- Kerley 2003  
- LM Ross  
- SCVH  
- FVT

Ab initio calculations:  
- QMD  
- (p₀ = 0.171 g/cc, T=20 K)  
- (Caillabet et al., 2011)

Classical TCP, fluid H, fluid H₂, solid H₂, HD209458b, Jupiter, Saturn phase transitions and pressure-temperature correlations.
Uncertainties on the Equation of State (EoS)

- **McMahon et al.** (RvMP 2012)
- **Caillabet et al.** (PhRvL 2011)

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**FIG. 12** (color online). Pressure vs temperature along the Hugoniot. On the other hand, the computed optical reflectivity along the Hugoniot reaching a value of the electrical conductivity 

$\sigma = \frac{e^2 n}{m^*}$

where $e$ is the electron charge, $n$ is the electron density, and $m^*$ is the effective mass of the electron. This is because hydrogen, such as technological applications, including inertial confinement fusion (ICF), where hydrogen gas is compressed to H to a transform into a plasma state.

Further, upon increasing temperature, it first melts, and then transforms into a plasma state. This can be seen in the phase diagram of hydrogen, where the melting temperature is seen in other alkali metals, such as sodium and lithium. Further, if hydrogen is a liquid at sufficient pressure, it may remain stable. In fact, a large depression of melting temperature superconductor (TSC) was observed for hydrogen, such as technological applications, including inertial confinement fusion (ICF), where hydrogen gas is compressed to H to a transform into a plasma state.

Unfortunately, simple approximations to account for ZPM (zero-point motion) of the protons in hydrogen can play an important role. For example, the zero-point motion of the protons in hydrogen can lead to a significant correction to the electronic structure.

**FIG. 2**. Hydrogen phase diagram. Solid lines show the boundaries between the gas, liquid, and solid phases. The solid circles show the (approximate) location of critical or triple points. The dashed lines correspond to the noninteracting Fermi liquid transitions.

The properties of hydrogen and helium under high pressure, such as technological applications, including inertial confinement fusion (ICF), where hydrogen gas is compressed to H to a transform into a plasma state.

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Unfortunately, simple approximations to account for ZPM (zero-point motion) of the protons in hydrogen can play an important role. For example, the zero-point motion of the protons in hydrogen can lead to a significant correction to the electronic structure.

**FIG. 3**. Hydrogen phase diagram. Solid lines show the boundaries between the gas, liquid, and solid phases. The solid circles show the (approximate) location of critical or triple points. The dashed lines correspond to the noninteracting Fermi liquid transitions.
Uncertainties on the Equation of State (EoS)

Small effect of metals EoS expected

Chabrier & Baraffe (A&A 1997)
Temperature increases with mass

=> Radiative diffusion more efficient

=> Convection less adiabatic
Uncertainties on Heat transport: Stellar Activity

- Low mass stars can be fast rotators
- Coriolis
- Magnetic field
- Inefficient convection
- Spot coverage

\[ \alpha = \frac{l}{H_p} \quad \beta = \frac{S_{\text{spot}}}{S_*} \]
Uncertainties on Heat transport: Stellar Activity

- Low mass stars can be fast rotators
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\[
\alpha = \frac{l}{H_p} \quad \beta = \frac{S_{\text{spot}}}{S_*}
\]

Transiting binaries are not good calibrators

Late M stars/BD and stellar Activity

• As the mass decrease
  • Effective temperature decreases
    • Ionization decreases
  ➔ Decoupling of convection and magnetic field even at fast rotation
  • reduced activity
  • reduced spot coverage

Uncertainties on Heat transport: Stellar Metallicity

The radiative opacity changes with the stellar metallicity.
Uncertainties on Heat transport: **Stellar Metallicity**

residual effect comes from the atmospheric boundary

\[
\frac{\Delta \rho}{\rho} = \frac{\Delta M}{M} - 3 \frac{\Delta R}{R}
\]
Importance of Atmospheric models: 

$\text{Metallicity}$

$\text{R} (R_\odot)$

$\text{M} (M_\odot)$

$T_{\text{eff}} (K)$

$\alpha_{MLT}=1.5$

$[M/H]=0$

$[M/H]=-0.5$

$\text{Emission level } [M/H] = 0$

$\text{Emission level } [M/H] = -0.5$

$\text{T}_{\text{eff}}$ is not directly observable!
The Brown Dwarf spectroscopy challenge!

- Question of the metallicity
- Need comprehensive line list for many molecules
- Condensates
- Non equilibrium chemistry

Fig. 1: Comparison of the observed spectrum of AB Pic B (black line) with various sets of models. The effective temperature and the surface gravity $\log g$ inferred by such comparison are indicated in each panel for each model used. One notes the large differences between the effective temperatures and gravities inferred from different models. One also notes that none of the models can correctly reproduce the observed spectrum. Figure adopted from [Patience et al (A&A 2012)].

2.1.2 The L/T transition in the colour-magnitude diagram

The description of the L/T transition in a colour-magnitude diagram is a real challenge for theory.
Color-Magnitude diagram: in the optical

Inclusion of a better TiO linelist

Color-Magnitude diagram: in the infra-red

Color-Magnitude diagram: in the infra-red

Secondary Cloud Layers

The colors of the coolest T dwarfs.

Cloud opacity limits the emergent flux most prominently in infrared clear. Flux emerges from deeper, hotter atmospher as the clouds dissipate, the atmospheric windows in the near-infrared clear. Regardless, Td w a r f ss u g e s t st h a tc l o u dp a t c h i n e s sm a yi n d e ep pla y a role (Radigan et al. 2012; Artigau et al. 2009). Regardless, the recent discovery of highly photometrically variable ear tails of the transition are still very much unknown. However, that this transition could potentially be explained by the b ehavior of model near-infrared spectra and reddens the colors of the mod- els.

Importance of Atmospheric models: **Clouds**

Clouds make you redder
Importance of Atmospheric models: Clouds

**Figure 5**

- **Figure 5** shows the flux distribution for different cloud models at various effective temperatures ($T_{\text{eff}}$) and surface gravities ($\log g$).
- The models are color-coded and labeled to indicate their specific conditions.
- The models are divided into two panels: one for $T_{\text{eff}} = 900$ K and another for $T_{\text{eff}} = 1300$ K.
- Each panel contains a cloudless model and cloudy models with different sedimentation efficiencies ($f_{\text{sed}}$).
- The panels also include a cloudless model for comparison.

**Figure 8**

- **Figure 8** indicates the optical depth within the photosphere is largest for higher surface gravity atmospheres.
- The optical depth is calculated using the atmospheric depth at which the optical depth reaches 0.1.
- The figure shows that for all clouds in the indicated temperature range, the optical depth is not necessarily independent of gravity.

**Figure 9**

- **Figure 9** plots the photometric colors in the near-infrared of all brown dwarfs with measured parallaxes and representative surface gravities.
- The figure shows cloudy models from 400-1300 K with several representations of the calculated photometric colors of our suite of cloudless models.
- We also plot the cloudy models larger (redder) than the near-infrared colors of all brown dwarfs with measured parallaxes and representative surface gravities.
- In Section 4.1, we discuss the generation and cloudy models from 400-1300 K with several representations.
- The figure includes a comparison with observations.

**Acknowledgments**

How to explain the L-T transition/continuum

Need 2D/3D modeling!

How to explain the L-T transition/continuum

How to explain the L-T transition/continuum

**BT Settle**

![Diagram showing comparison between models and M-L-T dwarfs data in a (J-K)-M diagram. The photometry is shown from bottom to top. Partly cloudy models (green dots) are for cloud-free fractions (red lines) and cloudy sequence with blue lines, respectively, show model colors for cloudy sequence with h_{eff} and f_{sed}. This is because atmospheres with even a small cloud fraction can be seen across the transition.](Image)

**Patchy clouds**

![Diagram showing comparison between models and M-L-T dwarfs data in a (J-K)-M diagram. The photometry is shown from bottom to top. Partly cloudy models (green dots) are for cloud-free fractions (red lines) and cloudy sequence with blue lines, respectively, show model colors for cloudy sequence with h_{eff} and f_{sed}. This is because atmospheres with even a small cloud fraction can be seen across the transition.](Image)

**Need 3D modeling!**

*Allard et al (2011)*

The variety of clouds

Cooler atmospheres
Importance of Atmospheric models: Chemistry

Fig. 2
Comparison between observations of the planetary mass object 2M1207b (in black) and models assuming equilibrium chemistry (green, labelled LCE) and non-equilibrium chemistry (blue, labelled non-LCE) (top: photometry; bottom: spectroscopy).

Both models are based on the work of [Barman et al (2011b)] including the cloud model described in [Barman et al (2011a)] (see also Sect. 2.1.1). These comparisons show the important effect of non-equilibrium chemistry on photometry and spectrum of cool objects (the inferred effective temperature in the present case is $T_{\text{eff}} \approx 1000$ K). For comparison, predictions from a model based on a equilibrium cloud model from [Allard et al (2001)] are indicated in red.

Note the large discrepancy between $T_{\text{eff}}$ inferred from the latter model ($T_{\text{eff}} \approx 1600$ K) and the models of [Barman et al (2011b)].

Figure from [Barman et al (2011b)] and reproduced by permission of the AAS.

dust due to sedimentation of condensed species below the photosphere and the formation of CH$_4$, which is the dominant equilibrium form of carbon below a local temperature of $T < 1600$ K while CO dominates at higher temperatures.

The heating of the atmosphere due to the backwarming effect of dust causes IR colors to become very red, as seen in Fig. 4, whereas the formation of CH$_4$, which strongly absorbs near 1.6 $\mu$m yields the characteristic change to bluer (J-H) and (J-K) colors (see the chapter by M. Cushing, his Sect. 7). In addition to this well-known change in colours from the red to the blue characteristic of the L/T transition in the near-IR (see Fig. 4), another major difficulty for models is to describe the scatter of colours for a given magnitude. Several ideas have been suggested to explain this observed property, namely the effect of a single second parameter like gravity [Burrows et al (2006)] or a mixture of effects, namely metallicity, cloud parameters, ages and unresolved binaries [Saumon and Marley (2008)].
All abundance values for C and O in the model grid are given in Tables S1 and S2, respectively. Raising $K_{zz}$ would have no impact and lowering $K_{zz}$ would only increase CH (10 abundance scale where the adoption value z because the adopted value of $K_{zz}$ is 12.0, however, this exercise aids in quantifying the relative detections of CH and CO in HR 8799c and the synthetic spectra shown in the top panel (solid) along with a baseline featureless region of HR 8799c. The central wavelength range is omitted due to lack of strong absorption features. For instance, the large CH absorption feature at 2.32 µm and minimum values of CH (not depicted) always quenches the CO and CH in the spectrum, resulting in the ring-like behavior seen in the spectra of HR 8799c and the synthetic spectra shown in the top panel (solid) along with a baseline featureless region of HR 8799c. A spectrum of a bright speckle, scaled such that the variance is equal to the variance in a cross band spectrum by factors that are easier to detect in the case of CH. The filtered spectrum of HR 8799c (black). The central wavelength range is omitted due to lack of strong absorption features. The CO templates, as expected, the CO: CO templates were performed only over wavelength regions with strong lines (CH - 2.0, 2.1, 2.2, 2.3) and CH - 2.28, 2.30, 2.32 µm). Significant correlations were found with either of the three CH templates: Pure CH, CH templates, as expected. The CO correlation is not required to detect CO: Pure CH, CH templates, as expected. The CO: Pure CH templates, as expected. The CO correlation is not required to detect CO: Pure CH templates, as expected. The CO correlation is not required to detect CO: Pure CH templates, as expected.

**Figure 3:**
- Top: Pure CH templates, as expected. The CO correlation is not required to detect CO: Pure CH templates, as expected. The CO correlation is not required to detect CO: Pure CH templates, as expected.
- Bottom: Pure CH templates, as expected. The CO correlation is not required to detect CO: Pure CH templates, as expected. The CO correlation is not required to detect CO: Pure CH templates, as expected.

**Figure 4:**
- A spectrum of a bright speckle, scaled such that the variance is equal to the variance in a cross band spectrum by factors that are easier to detect in the case of CH. The filtered spectrum of HR 8799c (black). The central wavelength range is omitted due to lack of strong absorption features. The CO templates, as expected. The CO correlation is not required to detect CO: Pure CH templates, as expected. The CO correlation is not required to detect CO: Pure CH templates, as expected. The CO correlation is not required to detect CO: Pure CH templates, as expected.

**Direct imaging Spectroscopy**

*Konopacky, Barman et al (Science, 2013)*
Some Conclusions

★ A lot of uncertainties remain on Stellar Structure!
  • Maybe less critical for M dwarfs
    • EoS should be a minor annoyance
    • Convection/Magnetic field Coupling maybe more important
      • Cannot use Eclipsing Binaries as calibrators

★ Atmospheric modeling is critical to infer properties from colors/SEDs
  • Need better spectroscopy
  • Importance of Clouds and Non-Equilibrium chemistry
  • Need 3D modeling
    ➔ Observations should soon improve that!