



Synthetic spectral libraries*

F. Allard, D. Homeier and B. Freytag

*Centre de Recherche Astrophysique de Lyon, UMR 5574, CNRS, Université de Lyon,
École Normale Supérieure de Lyon, 46 Allée d'Italie, F-69364 Lyon Cedex 07, France*

Abstract. Within the next few years, several instruments aiming at imaging extrasolar planets will see first light. In parallel, low mass planets are being searched around red dwarfs which offer more favorable conditions, both for radial velocity detection and transit studies, than solar-type stars. We review recent advancements and issues concerning the construction of synthetic spectral libraries for very low mass stars, brown dwarfs and exoplanets. The revised solar oxygen abundances and cloud models allow to reproduce the photometric and spectroscopic properties of this transition to a degree never achieved before, but problems remain in the important M-L transition characteristic of the T_{eff} range of characterizable exoplanets.

Keywords : very low mass stars – brown dwarfs – exoplanets

1. Introduction

Since spectroscopic observations of very low mass stars (late 80s), brown dwarfs (mid 90s), and extrasolar planets (mid 2000s) are available, one of the most important challenges in modeling their atmospheres and spectroscopic properties lies in high temperature molecular opacities and cloud formation. K dwarfs show the onset of formation metal hydrides (starting around $T_{\text{eff}} \sim 4500$ K) and oxides (TiO and CO below $T_{\text{eff}} \sim 4000$ K), while water vapor forms in early M dwarfs ($T_{\text{eff}} \sim 2000 - 3900$ K), and methane, ammonia and carbon dioxide are detected in L and T-type brown dwarfs ($T_{\text{eff}} \sim 300 - 1700$ K) and in extrasolar giant planets. Dust aerosols form in the upper atmospheric layers of late-type M dwarfs ($T_{\text{eff}} \leq 2900$ K), with culminating greenhouse and sedimentation effects due to silicate aerosols in L-type brown dwarfs ($T_{\text{eff}} \sim 1700 - 2000$ K). Cloud formation is also an important factor in the detectability of biosignatures, and for the habitability of exoplanets (Paillet, Selsis & Allard

*email: fallard@ens-lyon.fr, or see <http://perso.ens-lyon.fr/france.allard/index.html>

2005, Kasting 2001). Extrasolar planets for which we can currently characterize their atmospheres are either those observed by transit ($T_{\text{eff}} \sim 600 - 2000$ K depending on their distance and the luminosity of the central star) or by imaging (young planets of $T_{\text{eff}} \sim 500 - 2000$ K depending on their mass and age). Several infrared integral field spectrographs combined with coronagraphs and adaptive optics instruments are coming online before 2013 (SPHERE at the VLT, the Gemini Planet Imager at Gemini south, Project1640 at Mount Palomar, etc.). The E-ELT 41 m telescope in Chile due around 2020 will also be ideally suited for planet imaging. M dwarfs are the most numerous stars, constituting 70% of the stellar budget of the Galaxy, and around 600 brown dwarfs and planets are currently known in the solar neighborhood vicinity despite their faintness. Single very low mass (VLM) stars and brown dwarfs are therefore more directly observable and characterizable than exoplanets. They represent, beyond their own importance, a wonderful testbed for the understanding of exo-planetary atmospheric properties, together with solar system studies. Planets can even share the atmospheric composition of brown dwarfs with same T_{eff} (see section 5 below). The models developed for VLMs and brown dwarfs are therefore a unique tool for the characterization of imaged exoplanets if they can explain the stellar-substellar transition. In this paper, we review the ability of recently published models in reproducing observational constraints along the M-L-T spectral transition.

2. Model construction

The modeling of the atmospheres of VLMs has evolved (as here illustrated with the development of the PHOENIX atmosphere code) with the extension of computing capacities from an analytical treatment of the transfer equation using moments of the radiation field (Allard 1990), to a line-by-line opacity sampling in spherical symmetry (Allard, Hauschildt, Miller & Tennyson 1994, 1997 and Hauschildt *et al.* 1999) and more recently to 3D radiation transfer (Seelmann, Hauschildt & Baron 2010). In parallel to detailed radiative transfer in an assumed static environment, hydrodynamical simulations have been developed to reach a realistic representation of the granulation and its induced line shifts for the sun and sun-like stars (see e.g. the review by Freytag *et al.* 2012) by using a non-grey (multi-group binning of opacities) radiative transfer with a pure blackbody source function (scattering is neglected).

To illustrate the various assumptions made while constructing model atmospheres, let us begin with the description of the equations of ideal magnetohydrodynamics (MHD) — adapted here for the stellar case by specifying the role of gravity, radiative transfer, and energy transport — which are themselves a special case (no resistivity) of the more general equations (see for example Landau & Lifshitz 1960). These are written in the compact vector notation as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\begin{aligned}
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} + (P + \frac{1}{2} \mathbf{B} \cdot \mathbf{B}) \mathbf{I} - \mathbf{B} \mathbf{B}) &= \rho \mathbf{g}, \\
\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v} \mathbf{B} - \mathbf{B} \mathbf{v}) &= 0, \\
\frac{\partial \rho e_t}{\partial t} + \nabla \cdot ((\rho e_t + P + \frac{1}{2} \mathbf{B} \cdot \mathbf{B}) \mathbf{v} - (\mathbf{v} \cdot \mathbf{B}) \mathbf{B} + \mathbf{F}_{\text{rad}}) &= 0.
\end{aligned} \tag{1}$$

The vectors are noted with boldface characters, while scalars are not. For example, P is the gas pressure, ρ the mass density, $\mathbf{g}$ the gravity, and $\mathbf{v}$ is the gas velocity at each point in space. $\mathbf{B}$ is the magnetic field vector, where the units were chosen such that the magnetic permeability μ is equal to one. $\mathbf{I}$ is the identity matrix and $\mathbf{a} \cdot \mathbf{b} = \sum_k a_k b_k$ the scalar product of the two vectors $\mathbf{a}$ and $\mathbf{b}$. The dyadic tensor product of two vectors $\mathbf{a}$ and $\mathbf{b}$ is the tensor $\mathbf{a} \mathbf{b} = \mathbf{C}$ with elements $c_{mn} = a_m b_n$ and the n th component of the divergence of the tensor $\mathbf{C}$ is $(\nabla \cdot \mathbf{C})_n = \sum_m \partial c_{mn} / \partial x_m$. In this case, the total energy is given by

$$\rho e_t = \rho e_i + \rho \frac{1}{2} \mathbf{v} \cdot \mathbf{v} + \frac{1}{2} \mathbf{B} \cdot \mathbf{B} + \rho \Phi, \tag{2}$$

where e_i is again the internal energy per unit mass, and Φ the gravitational potential. The additional constraint for the absence of magnetic monopoles,

$$\nabla \cdot \mathbf{B} = 0, \tag{3}$$

must also be fulfilled.

The first, third, and last equations in Eq. 1 correspond to the mass, magnetic field, and energy conservation, while the second equation is the budget of forces acting on the gas. In the case of stellar astrophysics, gravitational acceleration is an important source term, while the radiative flux participates in the energy budget. Radiation hydrodynamical (RHD) simulations ignore by definition the magnetic field terms in equation 1. This is a good approximation when modeling the neutral photosphere (where most of the emitted flux emerges) of low mass, very low mass stars, and brown dwarfs — with the exception of the ultraviolet and visual spectral range of flaring stars and for the resulting emission lines.

The classical approach for interior and atmosphere models consists in simplifying the problem for a gain of computing efficiency, neglecting the magnetic field, convective and/or rotational motions and other multi-dimensional aspects of the problem, and assuming that the averaged properties of stars can be approximated by modeling their properties radially (uni-dimensionally) and statically. We also assume that the atmosphere does neither create nor destroy the radiation emitted through it. Neglecting motions in modeling the photospheres of VLM stars, brown dwarfs, and planets is acceptable since the convective velocity fluctuation effects on line broadening is hidden by the strong van der Waals broadening prevailing in these atmospheres. But

this is not the case of the impact of the velocity fields on the cloud formation and wind processes (see section 4 below). In this case, equation 1 reduces to the so-called hydrostatic equation and constant flux approximation for the radial or z direction used in classical models:

$$\begin{aligned} \frac{\partial P}{\partial r} &= -\rho g , \\ \frac{\partial F_{\text{rad}}}{\partial r} &= \frac{\partial(\int F_{\lambda} d\lambda)}{\partial r} = 0 . \end{aligned} \quad (4)$$

This allows one to compute the interior evolutive properties of stars throughout the Hertzsprung-Russell diagram, and to solve the radiative transfer in the atmosphere for a much larger number of wavelengths (line-by-line or opacity sampling) or wavelength bins (Opacity Distribution Function or ODF, K-Coefficient) compared to R(M)HD simulations. Classical model atmospheres impose therefore the independent parameter F_{rad} ($= \sigma T_{\text{eff}}^4$, where σ is the Stefan-Boltzmann constant) and compute F_{λ} so that, after model convergence, the target F_{rad} is reached. Other independent parameters are the surface gravity g and the abundances of the elements ϵ_i . This makes it possible to create extensive databases of synthetic spectra and photometry that provide the basis for the interpretation of stellar observations. All the model atmospheres compared in this review are classical models in this sense, and differ mainly in the completeness and accuracy of their opacity database including their cloud model assumptions, and the assumed solar abundances used for the particular grid shown. They must resolve the radiative transfer for the entire spectral energy distribution (as can be seen from Eq. 4) with a good enough spectral resolution to account for all cooling and heating processes.

On the other hand, global RHD simulations are becoming possible even with rotation (Steffen & Freytag 2007). However, these RHD simulations have also to be scaled down significantly in radius to preserve the ability to resolve convective cells and timescales of important processes such as cloud formation. An alternative approach used by many authors is therefore to neglect small scale phenomena and model only larger scales, such as global circulation around the planetary surface (see for example Koskinen, Aylward, Smith & Miller 2007, Showman et al. 2009, Dobbs-Dixon et al. 2010). The challenge of such hydrodynamical simulations is to account for all the most important opacities, in particular scattering, in solving the radiative transfer and hydro equations while keeping the computing time for the model within reasonable limits.

3. Molecular opacities

While earlier work has been developed for the study of red giant stars, the pioneering work on the modeling of VLM atmospheres has been provided by Mould (1975), Allard (1990) and Kui (1991) using a band model or the Just Overlapping Line Approximation (JOLA) opacities developed by Kivel, Mayer & Bethe (1952) and adapted for astrophysical use by Golden (1967). More realistic model atmospheres and synthetic

spectra for VLMs, brown dwarfs, and extrasolar planets using line-by-line or opacity sampling techniques have been made possible thanks to the development of accurate opacities calculated often *ab initio* for atmospheric layers where temperatures can reach 3000 K. The process of improvements was especially remarkable in the case of water vapor line lists. Indeed, the treatment of water vapor, which shapes the infrared part of spectrum, has seen an important evolution through the years from band model approximations to straight means based on hot flames experiments, and then to *ab initio* computations. And *ab initio* water vapor opacities have strongly changed over time with the improvement of computational capacities and a better knowledge of the interaction potential surface. Only the most recent *ab initio* results (Partridge & Schwenke 1997, and the BT2 line list by Barber et al. 2006) confirm the earliest hot flames laboratory experiment results by Ludwig (1971). Nevertheless, a lack of flux persists in the *K* bandpass in the models even using the most recent BT2 opacity profile. Only the UCL line list (Schryber, Miller & Tennyson 1995, due to incompleteness, and with much of its deviations canceling out over the bandpasses) could produce seemingly correct *J – K* colors, and could allow some success of this so-called NextGen (Hauschildt, Allard & Baron 1999) model atmospheres grid in the VLM stellar regime. In the substellar regime, the composition of brown dwarfs varies rapidly with decreasing T_{eff} , and this variation is responsible for the immense change in their SED across T_{eff} regime of the M-L-T spectral transition. If water vapor opacities are now reliable, this is not the case of the more complex methane molecule which is so important in brown dwarfs, and planetary atmospheres. The ExoMol Project supported by an ERC to Jonathan Tennyson (University College London) will allow important advances on molecular opacities in the coming years. A new ammonia line list is already available through this project (Yurchenko, Barber & Tennyson 2011).

4. Mixing

Stars become fully convective throughout their interior and convection reaches furthest out in the optically thin regions of the photosphere in M3 and later dwarfs with T_{eff} below 3200 K (Allard 1990, Chabrier & Baraffe 2000). In most model atmospheres discussed in this review paper, the convective energy transfer is treated using the Mixing Length Theory (or MLT, see Kippenhahn & Weigert 1994), using at best a unique fixed value of the mixing length of 1.0 (1.25 for the ATLAS9 models, 1.5 for the MARCS models, etc). However, since convection becomes efficient in M dwarfs, the precise value of the mixing length matters only for the deep atmospheric structure and as a surface boundary condition for interior models. Ludwig, Allard & Hauschildt (2002) and Ludwig, Allard & Hauschildt (2006) have been able to compare the PHOENIX thermal structure obtained using the MLT with that of RHD simulations. They showed that the MLT could reproduce adequately (except for the overshoot region) the horizontally averaged thermal structure of the hydro simulations when using an adequate value of the mixing length parameter. This value has been estimated for solar type stars to M dwarfs to vary with surface gravity from $\alpha=l/H_p=1.8$

to 2.2 (2.5 to 3.0 for the photosphere). The newer simulations of Freytag, Allard, Ludwig, Homeier & Steffen (2010) suggest that the mixing length decreases down to values as low as 0.5 in the M dwarf to brown dwarfs regime. Models are under construction that account for these revised values. The BT-Settl models use the mass and surface gravity dependent prescription of Ludwig, Freytag & Steffen (1999) for hotter stars, together with an average (2.0) of the values derived for M dwarfs by (Ludwig *et al.* 2002, 2006). They use as well the micro-turbulence velocities from the radiation hydrodynamical simulations (Freytag *et al.* 2010), and the velocity field from RHD simulations from Ludwig *et al.* (2006) and Freytag *et al.* (2010) to calibrate the scale height of overshoot, which becomes important in forming thick clouds in L dwarfs but is negligible for the SED of VLMs and brown dwarfs otherwise. Freytag *et al.* (2010) have indeed addressed the issue of mixing and diffusion in VLM atmospheres by 2D RHD simulations, using the PHOENIX gas opacities in a multi-group opacity scheme, and forsterite with geometric cross-sections. These simulations assume efficient nucleation, using initial monomer densities estimated from the total available density of silicon (least abundant element in the solar composition involved in forsterite). They found that gravity waves form at the internal convective-radiative boundary, and play a decisive role in cloud formation, while around $T_{\text{eff}} \approx 2200$ K the cloud layers become thick enough to initiate cloud convection, which dominates in the mixing.

5. Atmospheric composition

The composition of the atmospheres of stars, brown dwarfs, and planets is a function of T_{eff} (radiation either due to internal heat from nuclear fusion and contraction or from irradiation by a parent star), of surface gravity to a lesser extent, and of the elemental abundances of the initial gas from which the star or stellar system is formed. Stellar model atmospheres assume scaled solar abundances for all elements relative to hydrogen. Additionally, some enrichment of α -process elements (C, O, Ne, Mg, Si, S, Ar, Ca, and Ti) resulting from a "pollution" of the star-forming gas by the explosion of a supernova is appropriate in the case of metal-poor subdwarfs of the Galactic thick disk, halo, and globular clusters, and the stars in the high stellar density environment towards the galactic center (Gaidos, Krot & Huss 2009). Important revisions have been made to the solar abundances based on radiation hydrodynamical simulations of the solar photosphere, and to improvements in the detailed line profile analysis. Indeed, two separate groups using independent RHD and spectral synthesis codes (Asplund, Grevesse, Sauval & Scott 2009, Caffau *et al.* 2011) obtain an oxygen reduction of 0.11 – 0.19 dex (up to 34%) compared to the previously used abundances of Grevesse, Noels & Sauval (1993). Since the overall SED of late K dwarfs, M dwarfs, brown dwarfs, and exoplanets is governed by oxygen compounds (TiO, VO in the optical and water vapor and CO in the infrared), the elemental oxygen abundance is of major importance. Fig. 2 of Allard *et al.* (2012) shows an example of these effects, where several models are compared to the optical to infrared SED of the M5.5, M9.5, and L0 dwarfs of the LHS 1070 system. The BT-Settl model by Allard *et al.* (2012) is based on the Asplund *et al.* (2009) solar abundance values, while DRIFT models

by Helling, Dehn, Woitke & Hauschildt (2008b) use the Grevesse et al. (1993) solar abundances, and the MARCS model by Gustafsson, Edvardsson, Eriksson, Jorgensen, Nordlund & Plez (2008) uses the values of Grevesse, Asplund & Sauval (2007). The MARCS model show a systematic near-infrared flux excess, compared both to observations and the other models, which is probably caused by the much lower oxygen abundance values of Grevesse et al. (2007). The oxygen abundances sensitivity of TiO bands is expressed as a reduced line blanketing effect at longer wavelengths, participating in the water vapor profile changes (Allard, Hauschildt & Schwenke 2000). The influence of the solar oxygen abundance can also be clearly seen in Fig. 1 which compares the Casagrande, Flynn & Bessell (2008) T_{eff} and metallicity estimates with the Baraffe, Chabrier, Allard & Hauschildt (1998) NextGen isochrones (assuming an age of 5 Gyrs) using model atmospheres from various authors. The oxygen abundance effects are particularly highlighted by comparing the BT-Settl model based on the Asplund et al. (2009) values with models based on earlier solar abundance values. This is the case of the AMES-Cond/Dusty and BT-NextGen models by Allard et al. (2001, 2012) which are based on the Grevesse et al. (1993) solar abundances. One can see that the higher oxygen abundance causes models to appear too blue by as much as 0.75 mag compared to models based on the Asplund et al. (2009) values. The MARCS models (Gustafsson et al. 2008) based on the Grevesse et al. (2007) values show on the contrary a systematically increasing excess in $J - K_s$ with decreasing T_{eff} . The models are most sensitive on the solar oxygen abundances for M dwarfs around 3300 K, i.e. at the onset of water vapor formation.

6. Cloud formation

One of the most important challenges in modeling these atmospheres is the formation of clouds. Tsuji, Ohnaka & Aoki (1996) had identified dust formation by recognizing the condensation temperatures of hot dust grains (enstatite, forsterite, corundum: MgSiO_3 , Mg_2SiO_4 , and Al_2O_3 crystals) to occur in the line-forming layers ($\tau \approx 10^{-4} - 10^{-2}$) of their models. The onset of this phase transition occurs in M dwarfs below $T_{\text{eff}} = 3000$ K, but the cloud layers are too sparse and optically thin to affect the SED above $T_{\text{eff}} = 2600$ K. The cloud composition, according to equilibrium chemistry, is going from zirconium oxide (ZrO_2), refractory ceramics (perovskite and corundum; CaTiO_3 , Al_2O_3), silicates (e.g. forsterite; Mg_2SiO_4), to salts (CsCl , RbCl , NaCl), and finally to ices (H_2O , NH_3 , NH_4SH) as brown dwarfs cool down over time from M through L, T, and Y spectral types (Allard et al. 2001, Fegley & Lodders 2006). This crystal formation causes the weakening and vanishing of TiO and VO molecular bands (via CaTiO_3 , TiO_2 , and VO_2 grains) from the optical spectra of late M and L dwarfs, revealing CrH and FeH bands otherwise hidden by the molecular pseudo-continuum, and the resonance doublets of alkali transitions which are only condensing onto salts in late-T dwarfs. The scattering effects of this fine dust is Rayleigh scattering which provides veiling to the optical SED, while the greenhouse effect due to the dust cloud causes their infrared colors to become extremely red compared to those of hotter dwarfs. The upper atmosphere, above the cloud layers, is

depleted from condensible material and significantly cooled down by the reduced or missing pseudo-continuum opacities.

One common approach has been to explore the limiting properties of cloud formation. One limit is the case where sedimentation or gravitational settling is assumed to be fully efficient. This is the case of the Case B model of Tsuji (2002), the AMES-Cond model of Allard et al. (2001), the Clear model of Burgasser et al. (2002), and the Clear model of Burrows, Sudarsky & Hubeny (2006). The other limit is the case where gravitational settling is assumed inefficient and dust, often only forsterite, forms in equilibrium with the gas phase. This is the case of the Case A model of Tsuji (2002), the AMES-Dusty models of Allard et al. (2001), the BT-Dusty models of Allard et al. (2012), the Dusty model of Burgasser et al. (2002), and the Cloudy model of Burrows et al. (2006). To these two limiting cases we can add a third case also explored by several, where condensation is not efficient and the phase transition does not take place. This is the case of the NextGen models of Hauschildt et al. (1999), of the BT-NextGen models of Allard et al. (2012), and the Case B models of (Tsuji 2002, not shown). The purpose of a cloud model is to go beyond these limiting cases and define the number density and size distribution of condensates as a function of depth in the atmosphere, and as a function of the atmospheric parameters. The discovery of dust clouds in M dwarfs and brown dwarfs has therefore triggered the development of cloud models building up on pioneering work in the context of planetary atmospheres developed by Lewis (1969), Rossow (1978), and Lunine, Hubbard, Burrows, Wang & Garlow (1989). The Lewis model is an updraft model (considering that condensation occurs in a gas bubble advected from deeper layers). By lack of knowledge of the velocity field and diffusion coefficient of condensates in the atmospheres of the planets of the solar system, Lewis simply assumed that the advection velocity is equal to the sedimentation velocity, thereby preserving condensible material in the condensation layers. This cloud model did not account for varying grain sizes (these naturally vary as a function of depth in the cloud layers). Rossow, on the other hand, developed characteristic timescales as a function of particle size for the main microphysical processes of importance (condensation, coagulation, coalescence, and sedimentation). The curve intersections gives an estimate of the condensate number densities and mean grain sizes. However, this model made several explicit assumptions concerning the efficiency of supersaturation, the coagulation, etc.

Allard et al. (2003) and Allard et al. (2012) have developed PHOENIX version 15.05 using the index of refraction of 55 condensible species, and a slightly modified version of the Rossow cloud model obtained by ignoring the coalescence and coagulation, and computing the supersaturation consistently. The density and grain size distribution with depth in the atmosphere is obtained by comparing the timescales for nucleation, condensation, gravitational settling or sedimentation, and mixing derived from the Mixing Length Theory for the convective mixing in the convection zones, exponential overshoot according to Ludwig et al. (2002, 2006), and from gravity waves according to Freytag et al. (2010). The cloud model is solved layer by layer inside out (bottom's up) to account for the sequence of grain species

formation as a function of cooling of the gas. Among the most important species forming in the BT-Settl model are ZrO_2 , Al_2O_3 , CaTiO_3 , $\text{Ca}_2\text{Al}_2\text{SiO}_7$, MgAl_2O_4 , Ti_2O_3 , Ti_4O_7 , $\text{Ca}_2\text{MgSi}_2\text{O}_7$, $\text{CaMgSi}_2\text{O}_6$, CaSiO_3 , Fe, Mg_2SiO_4 , MgSiO_3 , Ca_2SiO_4 , MgTiO_3 , MgTi_2O_5 , $\text{Al}_2\text{Si}_2\text{O}_{13}$, VO, V_2O_3 , and Ni. At each step, the gas phase is adjusted for the depletion caused by grain formation and sedimentation. The grain sizes (a unique maximum value per atmospheric layer) are determined by the comparison of the different timescales and thus varies with depth to reach a few times the interstellar values (used in the dusty limiting case models) at the cloud base for the effective temperatures discussed in this paper. While the BT-Settl model assumes dirty spherical grains in the timescales equations to calculate the growth and settling of the grains, it only sums the opacity contributions of each species in each layer as for an ensemble of pure spherical grains.

Helling et al. (2008b) and Witte, Helling & Hauschildt (2009) modified the PHOENIX code to compute the DRIFT-PHOENIX models, considering the nucleation of only seven of the most important solids (TiO_2 , Al_2O_3 , Fe, SiO_2 , MgO, MgSiO_3 , Mg_2SiO_4) made of six different elements. The cloud model is based on resolving the moment equations for the dust density accounting for nucleation on seed particles and their subsequent growth or evaporation, solving from top to bottom of the atmosphere. This model assumes dirty grains mixed according to the composition of each atmospheric layer. It uses composite optical constants resulting in absorption and scattering properties of the grains that are therefore different than those of the BT-Settl models, possibly producing more opaque clouds. However, since the opacities are dominated by atomic and molecular opacities over most of the spectral distribution in this spectral type range, the impact of those differences are difficult to identify. The largest differences between the BT-Dusty, BT-Settl and DRIFT models are the differences in the local number density, the size of dust grains, as well as their mean composition, which are the direct results of the cloud model approach. The DRIFT model includes, similarly to the BT-Settl model, mixing by convection and overshooting by assuming an exponential decrease in mass exchange frequency in the radiative zone. But it neglects the contribution of the gravity waves included in the BT-Settl model.

The models using the limiting cases of maximum dust content describe adequately (given the prevailing uncertainties) the infrared colors of L dwarfs. The cloud-free limiting case models, on the other hand, allow to reproduce to some degree the colors of T dwarfs. But pure equilibrium chemistry models without parametrization of the cloud extension in the atmosphere cannot reproduce the observed behaviour of the M-L-T transition, the dusty models only becoming redder and dustier with decreasing T_{eff} , while dust-free models miss completely the reddening due to the dust greenhouse effects in the L dwarf regime. Fig. 1 shows this situation compared with the effective temperatures estimates obtained by integration of the observed SED (Golimowski et al. 2004, Vrba et al 2004). One can see from Fig. 1 that the late-type M and early-type L dwarfs behave as if dust is formed nearly in equilibrium with the gas phase with extremely red colors in some agreement with the AMES-Dusty models. The BT-Settl

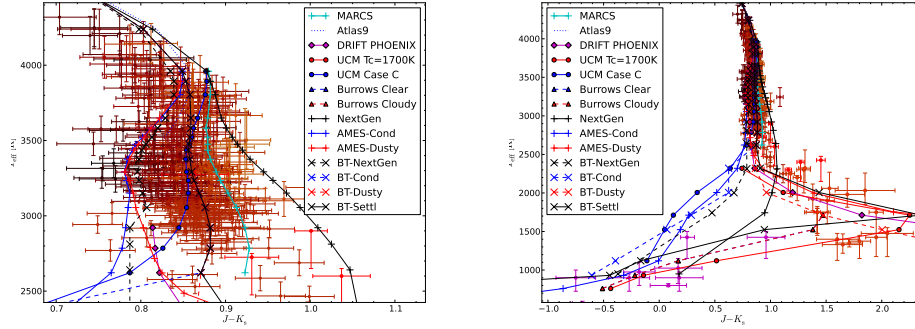


Figure 1. Estimated T_{eff} and metallicity (lighter to darker tones) for M dwarfs by Casagrande et al. (2008) on the left, and brown dwarfs by Golimowski et al. (2004) and Vrba et al. (2004) on the right are compared to the NextGen isochrones for 5 Gyrs Baraffe et al. (1998) using model atmospheres by various authors: MARCS by Gustafsson et al. (2008), ATLAS9 by Castelli & Kurucz (2004), DRIFT-PHOENIX by Helling et al. (2008b), UCM by Tsuji (2002), Clear/Cloudy by Burrows et al. (2006), NextGen by Hauschildt et al. (1999), AMES-Cond/Dusty by Allard et al. (2001), and the BT models by Allard et al. (2012). The region below 2900 K is dominated by dust formation. The dust free models occupy the blue part of the diagram and only at best explain T dwarf colors, while the Dusty and DRIFT models explain at best L dwarfs, becoming only redder with decreasing T_{eff} . The BT-Settl, Cloudy and UCM $T_{\text{crit}} = 1700$ K models describe a complete transition to the red in the L dwarf regime before turning to the blue into the T dwarf regime. The Cloudy model however does not explain the reddest L dwarfs.

models (full black line) reproduce the main sequence down to the L-type brown dwarf regime, before turning to the blue in the late-L and T dwarf regime as a result of the onset of methane formation in the K_s bandpass. The BT-Settl models succeed as good as the limiting case AMES-Dusty (full red curve), BT-Dusty (dashed red curve), and UCM $T_{\text{crit}} = 1700$ K (full red with big dots curve) at explaining the reddest colors of L dwarfs (assuming an age of 5 Gyrs). The fact that a UCM model with T_{crit} value of 1700 K succeeds rather well in reproducing the L-T transition suggests that the cloud extension is somewhat constant through that transition. The DRIFT models, on the other hand, (magenta with diamonds curve) reach slightly less to the red and do not extend low enough in temperature to explain the L-T transition. The M-L transition is not reproduced by any of the different models. This suggests that an additional element neglected thus far is at play, such as non-spherical porous grains for instance. Indeed, all models assume thus far spherical and spherical non-porous grains. The choice of solar abundances and the completeness of the opacity databases used is also somewhat important. One sees in Fig. 1 (on the right) that models based on the Asplund et al. (2009) solar abundances reach to redder colors in better agreement with constraints above 2000 K than other models. The understanding of the M-L transition between $T_{\text{eff}} = 2000$ and 2400 K is an extremely important regime for the study of extrasolar planets...

7. Conclusions

We have compared the behavior of the recently published model atmospheres from various authors across the M-L-T spectral transition from M dwarfs through L type and T type brown dwarfs and confronted them to constraints. If the onset of dust formation is occurring below $T_{\text{eff}} = 2900$ K, the greenhouse or line blanketing effects of dust cloud formation impact strongly ($J - K_s < 2.0$) the near-infrared SED of late-M and L-type atmospheres with $1300 < T_{\text{eff}} < 2600$ K. The BT-Settl models by Allard et al. (2012) are the only models to span the entire regime. In the M dwarf range, the results appear to favor the BT-Settl based on the Asplund et al. (2009) solar abundances versus MARCS and ATLAS 9 models based on other values. In the brown dwarf (and planetary) regime, on the other hand, the unified cloud model by Tsuji (2002) succeeds extremely well in reproducing the constraints, while the BT-Settl models also show a plausible transition. However, no models succeed in reproducing the M-L transition between 2900 and 2000 K. This T_{eff} range is similar to that of young (directly observable by imaging) and strongly irradiated planets (Hot Jupiters).

Acknowledgements

The research leading to these results has received funding from the French “Agence Nationale de la Recherche” (ANR), the “Programme National de Physique Stellaire” (PNPS) of CNRS (INSU), and the European Research Council under the European Community’s Seventh Framework Programme (FP7/2007-2013 Grant Agreement no. 247060). It was also conducted within the Lyon Institute of Origins under grant ANR-10-LABX-66.

References

- Ackerman A. S., Marley M. S., 2001, *ApJ*, 556, 872
- Allard F., 1990, PhD thesis, Ruprecht Karls Univ. Heidelberg
- Allard F., Guillot T., Ludwig H.-G., et al., 2003, in *IAU Symposium*, Vol. 211, Brown Dwarfs, ed. E. Martín, 325
- Allard F., Hauschildt P. H., 1995, *ApJ*, 445, 433
- Allard F., Hauschildt P. H., Alexander D. R., Starrfield S., 1997, *Ann. Rev. Astron. & Astrophys.*, 35, 137
- Allard F., Hauschildt P. H., Alexander D. R., Tamanai A., Schweitzer A., 2001, *ApJ*, 556, 357
- Allard F., Hauschildt P. H., Miller S., Tennyson J., 1994, *ApJL*, 426, L39
- Allard F., Hauschildt P. H., Schwenke D., 2000, *ApJ*, 540, 1005
- Allard F., Homeier D., Freytag B., 2012, *Phil. Trans. A*
- Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, *Ann. Rev. Astron. & Astrophys.*, 47, 481
- Baraffe I., Chabrier G., Allard F., Hauschildt P. H., 1997, *A&A*, 327, 1054
- Baraffe I., Chabrier G., Allard F., Hauschildt P. H., 1998, *A&A*, 337, 403

- Barber R. J., Tennyson J., Harris G. J., Tolchenov R. N., 2006, *MNRAS*, 368, 1087
- Burgasser A. J., 2004, *ApJL*, 614, L73
- Burgasser, A. J., Kirkpatrick J. D., 2006, *ApJ*, 645, 1485
- Burgasser A. J., Kirkpatrick J. D., Burrows A., et al., 2003, *ApJ*, 592, 1186
- Burgasser A. J., Marley M. S., Ackerman A. S., et al., 2002, *ApJL*, 571, L151
- Burningham B., Leggett S. K., Homeier D., et al., 2011, *MNRAS*, 414, 3590
- Burrows A., Sudarsky D., Hubeny I., 2006, *ApJ*, 640, 1063
- Caffau E., Ludwig H.-G., Steffen M., Freytag B., Bonifacio P., 2011, *Solar Physics*, 268, 255
- Casagrande L., Flynn C., Bessell M., 2008, *MNRAS*, 389, 585
- Castelli F., Kurucz R. L., 2004, *A&A*, 419, 725
- Chabrier G., Baraffe I., 1997, *A&A*, 327, 1039
- Chabrier G., Baraffe I., 2000, *Ann. Rev. Astron. & Astrophys.*, 38, 337
- Dobbs-Dixon I., Cumming A., Lin D. N. C., 2010, *ApJ*, 710, 1395
- Freytag B., Allard F., Ludwig H., Homeier D., Steffen M., 2010, *A&A*, 513, A19
- Freytag B., Steffen M., Ludwig H.-G., et al., 2012, *J. Comp. Phys.*, 231, 919
- Gaidos E., Krot A. N., Huss G. R., 2009, *ApJL*, 705, L163
- Golden S. A., 1967, *JQRST*, 7, 225
- Golimowski D. A., Leggett S. K., Marley M. S., et al., 2004, *AJ*, 127, 3516
- Grevesse N., Asplund M., Sauval A. J., 2007, *Space Sci. Rev.*, 130, 105
- Grevesse N., Noels A., Sauval A. J., 1993, *A&A*, 271, 587
- Griffith C. A., Yelle R. V., 1999, *ApJL*, 519, L85
- Gustafsson B., Edvardsson B., Eriksson K., et al., 2008, *A&A*, 486, 951
- Hauschildt P. H., Allard F., Baron E., 1999, *ApJ*, 512, 377
- Helling C., Ackerman A., Allard F., et al., 2008a, *MNRAS*, 391, 1854
- Helling C., Dehn M., Woitke P., Hauschildt P. H., 2008b, *ApJL*, 675, L105
- Kasting J. F., 2001, *AGU Fall Meeting Abstracts*, C1
- King R. R., McCaughrean M. J., Homeier D., et al., 2010, *A&A*, 510, A99+
- Kippenhahn R., Weigert A., 1994, *Stellar Structure and Evolution*, ed. Kippenhahn, R. & Weigert, A.
- Kivel B., Mayer H., Bethe H., 1952, *Ann. Phys.*, 2, 57
- Koskinen T. T., Aylward A. D., Smith C. G. A., Miller S., 2007, *ApJ*, 661, 515
- Kui R., 1991, PhD thesis, National University Australia
- Kurucz R. L., 1973, PhD thesis, HARVARD UNIVERSITY.
- Landau L. D., Lifshitz E. M., 1960, *Electrodynamics of continuous media*, ed. Pergamon Press Ltd.
- Leggett S. K., Burningham B., Saumon D., et al., 2010, *ApJ*, 710, 1627
- Lépine S., Scholz R.-D., 2008, *ApJL*, 681, L33
- Lewis J. S., 1969, *Icarus*, 10, 365
- Lewis J. S., Prinn R. G., 1980, *ApJ*, 238, 357
- Liu M. C., Leggett S. K., Chiu K., 2007, *ApJ*, 660, 1507
- Lodders K., Fegley Jr., B., 2006, *Chemistry of Low Mass Substellar Objects*, ed. Mason J. W. (Springer Verlag), 1
- Ludwig C. B., 1971, *Appl. Opt.*, 10, 1057
- Ludwig H.-G., Allard F., Hauschildt P. H., 2002, *A&A*, 395, 99
- Ludwig H.-G., Allard F., Hauschildt P. H., 2006, *A&A*, 459, 599
- Ludwig H.-G., Caffau E., Steffen M., et al., 2009, *Mem. Soc. Astron. Italiana*, 80, 711
- Ludwig H.-G., Freytag B., Steffen M., 1999, *A&A*, 346, 111
- Lunine J. I., Hubbard W. B., Burrows A., Wang Y.-P., Garlow K., 1989, *ApJ*, 338, 314
- Marley M. S., Saumon D., Goldblatt C., 2010, *ApJL*, 723, L117

- Mould J. R., 1975, *A&A*, 38, 283
Noll K. S., Geballe T. R., Marley M. S., 1997, *ApJL*, 489, L87
Paillet J., Selsis F., Allard F., 2005, in *Protostars and Planets V*, 8341
Partridge H., Schwenke D. W., 1997, *J. Comp. Phys.*, 106, 4618
Pinfield D. J., Burningham B., Lodieu N., et al., 2012, *MNRAS*, 2821
Prinn R. G., Barshay S. S., 1977, *Science*, 198, 1031
Rossow W. B., 1978, *Icarus*, 36, 1
Saumon D., Marley M. S., 2008, *ApJ*, 689, 1327
Saumon D., Marley M. S., Cushing M. C., et al., 2006, *ApJ*, 647, 552
Schaefer L., Fegley B., 2010, *Icarus*, 208, 438
Schryber J. H., Miller S., Tennyson J., 1995, *JQSRT*, 53, 373
Seelmann A. M., Hauschildt P. H., Baron E., 2010, *A&A*, 522, A102
Showman A. P., Fortney J. J., Lian Y., et al., 2009, *ApJ*, 699, 564
Sivarani T., Lépine S., Kembhavi A. K., Gupchup J., 2009, *ApJL*, 694, L140
Steffen M., Freytag B., 2007, *Astronomische Nachrichten*, 328, 1054
Tsuji T., 1965, *Publ. Astron. Soc. Japan*, 17, 152
Tsuji T., 2002, *ApJ*, 575, 264
Tsuji T., Nakajima T., Yanagisawa K., 2004, *ApJ*, 607, 511
Tsuji T., Ohnaka K., Aoki W., 1996, *A&A*, 305, L1
Tsuji T., Yamamura I., Sorahana S., 2011, *ApJ*, 734, 73
Visscher C., Moses J. I., Saslow S. A., 2010, *Icarus*, 209, 602
Vrba F. J., Henden A. A., Luginbuhl C. B., et al., 2004, *AJ*, 127, 2948
Witte S., Helling C., Hauschildt P. H., 2009, *A&A*, 506, 1367
Yung Y. L., Drew W. A., Pinto J. P., Friedl R. R., 1988, *Icarus*, 73, 516
Yurchenko S. N., Barber R. J., Tennyson J., 2011, *MNRAS*, 413, 1828