Highlights of Astronomy, Volume 15
XXVIIth IAU General Assembly, August 2009
Ian F. Corbett, ed.

doi:10.1017/S174392131001063X

SpS1-The evolution of brown dwarf infrared spectroscopic properties

France Allard & Isabelle Baraffe[1]

[1]Centre de Recherche Astrophysique de Lyon, UMR 5574: CNRS, Université de de Lyon, École Normale Supérieure de Lyon, 46 allée dItalie, F-69364 Lyon Cedex 07, France
email: fallard@ens-lyon.fr

Brown dwarfs (hereafter BDs) are formed, like stars, by interstellar cloud collapse, but attaining masses of less then $0.075\,M_\odot$ (Baraffe *et al.* 1998), i.e. too low core temperatures ($<3.5 \times 10^6$ K) to stabilize the nuclear burning of the hydrogen PP chain. Therefore, even the most massive BDs begin cooling after some 10^9 yrs. However, for masses above $0.06\,M_\odot$, core temperatures become hotter than the lithium burning temperature (2.4 x 10^6 K). All BDs above $0.013\,M_\odot$ ($13\,M_{Jup}$) reach core temperatures above the 1.0 x 10^6 K necessary to burn deuterium from about 10^7 yrs. The IAU has adopted the definition of the planetary regime as objects having masses below the deuterium burning conditions. But BDs are likely to form well below this limit into the planetary mass regime down to some $5\,M_{Jup}$. It is therefore convenient, in the absence of indices on their formation mechanisms, to call them planetary mass objects or *planemos*.

While cooling over time, their effective temperature ranges from 3000 K for the most massive or youngest BDs to below 100 K for the least massive and oldest planemos. They therefore encompass several spectral types, extending the spectral classification from M to L, T and eventually Y. Below 1500 K, they become partially electron degenerate, causing their radius to stabilize near a value of 1 R_{Jup}. This causes the surface gravity to reach a maximum value of $\log g$=5.4 at 1500 K before decreasing below even 3.5, towards the planetary mass regime. Too few constraints (eclipsing binaries) are available for these faint objects in the mass-radius diagram, while the stellar regime has been successfully explained by Baraffe *et al.* (1998). For more informations on the core properties and its evolution see the review by Chabrier & Baraffe (2000).

While burning deuterium below some 10^7 yrs depending on their mass, BDs can be fully convective rapid rotators with magnetic spots. The composition of their atmosphere is then typical of M dwarfs stars, with H_2, CO and N_2 the most abundant molecules, and TiO, VO, CO and H_2O the most important opacities. Their spectra also show nearly saturated hydride bands (CaH, CAOH, AlH, MgH, SiH), which play an important role in the spectra of low-metallicity subdwarfs where double-metal molecules deplete faster then hydrides. Pressure broadening is important in these atmospheres. To distinguish M-type BDs from M dwarf stars, one uses indicators of low gravity and of low core temperatures, i.e. the lithium test or the detection of the 6708Å lithium line in BDs.

As a BD cools below 2500K, clouds begin to form in its atmosphere, and the condensation of refractory elements begins to deplete important opacities such as VO, TiO and H_2O, revealing underlying absorption bands (CrH, FeH, water vapor at 0.93 mμ) and atomic lines. The L spectral type occurs when the depletion of refractory elements begins affecting TiO and VO band strengths in the optical. The silicate clouds cause a greenhouse effect (or blanketing effect in astronomy), redistributing flux scattered off of micron-size dust grains to infrared wavelengths, beyond the peak of the spectral distribution ($\geqslant$1.2 μm). Forsterite (Mg_2SiO_4) and enstatite ($MgSiO_3$) provide the strongest dust opacities in these objects. Observations of L dwarfs with *Spitzer* have revealed a corresponding absorption feature around 9 μm (Cushing *et al.* 2006). While clouds affect greatly the atmosphere and spectroscopic properties of BDs, the core evolution and its contraction and cooling history is only negligibly affected. However, their formation history and the magnetic field generation at young age may affect BD evolution more substantially (Baraffe, Chabrier & Gallardo, 2009).

As BDs cool to below 1800 K, silicate clouds sink gradually with the convection zone well below the photosphere. The photosphere, freed of its greenhouse effect and of most of its optical molecular opacities, cools to below the local gas temperature of 1400 K. At such low temperatures, the most stable carbon-bearing molecule is methane. And below 1000 K the most stable azote molecule is NH_3. The detection of these molecules at near-infrared wavelengths is therefore the criteria for the identification of, respectively, T-type and Y-type BDs. The transparent optical wavelengths, allowing line formation into deep and dense atmospheric layers, result in the formation of quasi-molecules (with H_2). This is the case of the resonance doublets of K I at 0.77 μm and Na I D at 0.58 μm, which are broadened to several thousands of angstroms from the line centre. The red wing of the K I doublet defines the shape of the 1.0 μm flux peak. The first Y dwarf could be CFBD0059 with a marginal detection of NH_3 at 1.5 to 1.55 μm in the H bandpass (Delorme *et al.* 2008). The 11 μm band of NH_3 has been detected in T dwarfs.

The coolest, least massive BD known is ULAS 1335 ($T_{eff} = 575$ K (Burningham *et al.* 2008). At such low temperatures, one reaches into the planemo regime and conditions for water vapor condensation. If the mean difference between BDs and planets is their formation mechanism, planets might be distinguished from BDs by an enrichment of elements similar to that measured by the Galileo probe in the atmosphere of Jupiter. However, cloud formation mechanisms in the atmosphere complicate the determination of abundances: the condensation of refractory elements onto grains, and the upwelling of molecules due to convective motions and their generated turbulences and gravity waves (Freytag *et al.* 2009), leads to non-equilibrium chemistry (Saumon *et al.* 2006).

In summary, the evolution of the spectral properties of BDs depends therefore on the details of the cloud formation mechanisms, on the hydrodynamical properties of the atmosphere, and on accurate reaction rates for the molecules involved valid for the density and temperature conditions prevailing in these atmospheres. Model atmospheres rely on detailed and complete (to high J-values) molecular line lists, dissociation energies and oscillator strengths. For the study of M dwarfs, for instance, no line list is yet available for CaOH. For the study of T and Y dwarfs more precise and complete line lists for NH_3, CH_4, H_2S, CO_2 and PH_3 are needed. Refractory indexes as a function of wavelength are also required for condensates LiCl, Na_2S, H_2O, NH_3 and NH_4SH, for example. Model atmospheres (of e.g. Allard *et al.* 2001), synthetic spectra, colors and evolution models are available via the web site (http://phoenix.ens-lyon.fr/simulator).

References

Allard, F. *et al.* 2001, *ApJ* 556, 357
Baraffe, I. *et al.* 1998, *A&A* 337, 403
Baraffe, I. *et al.* 2009, *ApJ* 702, L27
Burningham, B. *et al.* 2008, *MNRAS* 391, 320
Chabrier, G. & Baraffe, I. 2000, *ARA&A* 38, 337
Cushing, M. C. *et al.* 2006, *ApJ* 648, 614
Delorme, P. *et al.* 2008, *A&A* 482, 961
Freytag, B. *et al.* 2009, *A&A* in preparation
Saumon, D. *et al.* 2006, *ApJ* 647, 552