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The spectra of low-temperature atmospheres: Lessons learned from brown dwarfs

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Abstract. Indirect and direct spectroscopic studies of exoplanets are beginning to probe the most prominent chemical constituents and processes in their atmospheres. However, studies of equivalently low-temperature brown dwarfs have been taking place for over a decade. In this review, I summarize some of the results of detailed spectroscopic, photometric and polarimetric studies of brown dwarfs of various effective temperatures, surface gravities and metallicities, highlighting the insight gained into the chemistry and cloud formation of planetary-like atmospheres. Nonequilibrium chemistry and variations in cloud properties are singled out as critical ingredients for interpreting exoplanet spectra. I also discuss recent direct spectroscopic studies of exoplanet atmospheres, both close to and widely-separated from their host star, and propose that the latter are better analogs to isolated brown dwarfs.

Keywords. astrochemistry, stars: atmospheres, stars: low-mass, brown dwarfs, planetary systems

1. Introduction

Our understanding of exoplanet atmospheres is proceeding rapidly, thanks to the fairly recent development of indirect and direct photometric and spectroscopic observational studies of these objects.† Reflectance spectroscopy of transiting planets has revealed key molecular constituents, temperature inversions, and the presence of equatorial jets on the dayside hemispheres of transiting planets (e.g., Charbonneau *et al.* 2005; Deming *et al.* 2005; Burrows *et al.* 2007; Grillmair *et al.* 2007; Knutson *et al.* 2007; Swain *et al.* 2009). Transmission spectroscopy has detected atomic and molecular constituents, hazes, and evaporating exospheres along the termini of transiting exoplanets (e.g., Charbonneau *et al.* 2002; Vidal-Madjar *et al.* 2003; Tinetti *et al.* 2007; Swain *et al.* 2008). Most recently, the detection of young exoplanets through high-contrast imaging has opened up opportunities to directly measure emergent spectral energy distributions, atmospheric compositions and temperatures (e.g., Bowler *et al.* 2010; Hinz *et al.* 2010). The novelty of these investigations have been their ability to overcome the extreme contrast ratio between planet and host star, although results are not without controversy (e.g., Gibson *et al.* 2010).

More easily detectable analogs of warm exoplanets are the brown dwarfs. These "failed stars", with masses insufficient to sustain core hydrogen fusion ($M \lesssim 0.072\ M_{\odot}$; Kumar 1962; Hayashi & Nakano 1963), cool to the point at which their atmospheres have similar temperatures as those of exoplanets. Since their discovery in 1995‡, well over 500 brown

† For recent reviews, see Tinetti & Beaulieu (2009) and Lopez-Morales (2010); also see contributions from M. Swain, G. Tinetti, B. Croll, A. M. Mandell in these proceedings.

‡ On a historical note, the first examples of a hot Jovian planet, 51 Peg, and a cool brown dwarf, Gliese 229B, were reported at the same conference, the 9th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun in Florence, Italy.

dwarfs have been uncovered, mostly isolated sources in the vicinity of the Sun. These objects have temperatures as cool as ≈500 K (e.g., Lucas *et al.* 2010), ages ranging from ∼1 Myr newborns to ∼10 Gyr halo objects, and masses extending from the hydrogen burning limit to below the deuterium burning limit (∼13 M_{Jup}; Chabrier & Baraffe 2000). Their varied and complex spectral energy distributions have given rise to three new spectral classes: L dwarfs, T dwarfs and the still putative Y dwarfs (see Kirkpatrick 2005 for a recent review). Most relevant to this review, the inferred photospheric parameters of known brown dwarfs—pressure, temperature, and to limited degree composition—are equivalent to those for the majority of known exoplanets. As a result, the spectra of exoplanets and brown dwarfs, and the underlying chemistry and atmospheric processes that shape these spectra, are expected to have important similarities.

2. Brown Dwarf Photospheric Gas Chemistry

The spectra of brown dwarfs are characterized by the forest of atomic and molecular absorption features that reflect their chemistry-rich atmospheres. The evolution of a cooling brown dwarf is matched by the evolution of photospheric gas species, from the strong metal oxide bands (TiO, VO, CO) present in young M dwarfs, to the emergence of metal hydrides (FeH, CrH, MgH, and CaH) and neutral alkali lines in the L dwarfs, to the substantial shift to planetary-like H_2O, CH_4 and NH_3 bands in the T dwarfs; collision-induced H_2 absorption also plays a prominent role in shaping L and T dwarf spectra. Yamamura *et al.* (2010) has recently added CO_2 to this list, detected in the 4.0–4.5 μm spectroscopy of T dwarfs with AKARI. The neutral alkalis play a surprisingly prominent role in shaping cool brown dwarf spectra, through the heavily pressure-broadened Na I and K I doublet lines whose 1000 Å-wide wings effectively suppress all optical emission from these sources (e.g., Burrows & Volobuyev 2003). Hydrogen sulfide (H_2S), phospine (PH_3) and more complex organic molecules are also expected to be present in brown dwarf atmospheres but have not yet been detected. Heavier metals such as Mg, Al, SI, and Fe end up in condensate grain particles in the L dwarfs, and eventually settle below the visible photosphere (Visscher *et al.* 2010, see next section)..

These species are predicted from equilibrium chemistry calculations, but in a few cases the observed abundances are skewed by non-equilibrium chemistry (Griffith & Yelle 1999; Saumon *et al.* 2003; Hubeny & Burrows 2007). Chemical conversions between molecular species have finite rates that are both temperature and pressure dependent. Reactions with long chemical timescales can be slow to adjust to changes in temperature and pressure that accompany vertical mixing in a turbulent photosphere, resulting in locally non-equilibrium abundances. Two key reactions studied in brown dwarf atmospheres are

$$CO + 3H_2 \longleftrightarrow CH_4 + H_2O \tag{2.1}$$

$$N_2 + 3H_2 \longleftrightarrow 2NH_3. \tag{2.2}$$

In both reactions, the products are favored at lower temperatures, but only after breaking double and triple bonds in the reactants. As a result, deep hot gas mixed upward into the cooler photosphere retains enhanced CO and reduced CH_4, NH_3 and H_2O abundances with respect to thermodynamic equilibrium (the symmetric diatom N_2 does not produce a distinct band), with measurable consequences (Noll *et al.* 1997; Saumon *et al.* 2007; Figure 1). Nonequilibrium chemistry appears to be universal in L and T dwarf atmospheres, and hence important for exoplanet spectra (e.g., Fortney *et al.* 2008b).

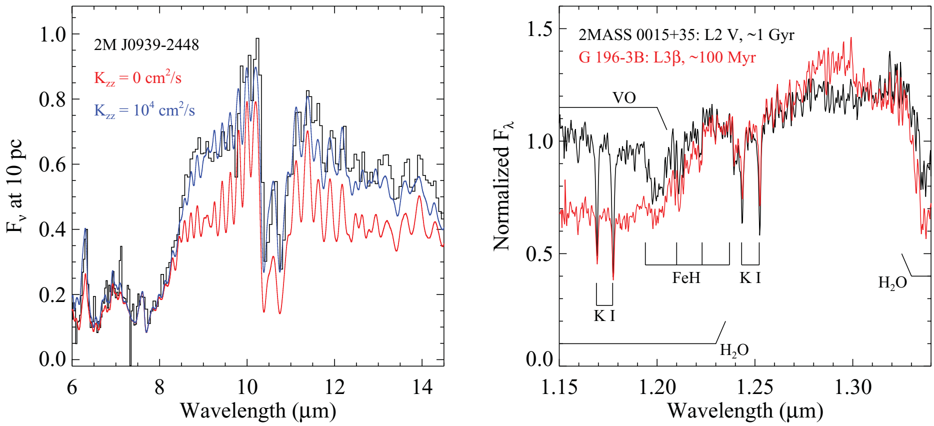

Figure 1. (Left): The mid-infrared spectrum of the T dwarf 2MASS J0939-2448 (black line), compared to two T_{eff} = 700 K, $\log g$ = 5.0 (cgs) from Saumon & Marley (2008), one assuming equilibrium chemistry (red line) and one assuming non-equilibrium chemistry (blue line, with vertical circulation parameterized by a diffusion coefficient K_{zz}). The latter produces weaker NH_3 absorption and an overall better fit to the observational data. (Rght): *J*-band spectra of two early-type L dwarfs, a ∼1 Gyr field source and a ∼100 Myr companion to a nearby young star (G 196-3B; see contribution by M. R. Zapatero Osorio). The spectral deviations seen in the younger source–enhanced VO absorption, weakened alkalis–are a subset of the gravity-sensitive features related to gas pressure effects in brown dwarf photospheres.

Chemical abundances are also modulated by gas pressure and metallicity. Photospheric gas pressure is a proxy for surface gravity, which in turn depends on the mass and age of a brown dwarf. As such, young, low-mass brown dwarfs with low surface gravities exhibit distinct spectral peculiarities, including redder near-infrared colors arising from reduced collision-induced H_2 absorption (e.g., Kirkpatrick *et al.* 2006; Allers *et al.* 2007), weakened alkali lines and narrower line wings (e.g., Martín *et al.* 1999; Cruz *et al.* 2009), and modified chemistry arising from pressure effects in conversion reactions†. Metallicity effects can both mimic photospheric gas pressure effects, since $P_{phot} \propto g/\kappa_R$, where g is the surface gravity and κ_R the metallicity-dependent Rosseland mean opacity; and change the overall chemistry through compositional variations. These effects have been studied in a handful of metal-poor ([M/H] = -1...-2) halo L dwarfs (Burgasser *et al.* 2005), which exhibit increased absorption from pressure-sensitive species (H_2, alkalis), higher ratios of metal hydride to metal oxide absorption, and decreased condensate cloud production (Burgasser *et al.* 2003, 2007; Gizis & Harvin 2006; Reiners & Basri 2006). Modestly metal-rich brown dwarfs have been identified as companions to metal-rich stars, and exhibit subtle spectral discrepancies, including a possible enhancement in condensate opacity (e.g., Looper *et al.* 2008).

3. Brown Dwarf Clouds

Equilibrium chemistry at low temperatures includes the formation of condensate (solid and liquid) molecular species. In brown dwarfs, these species appear to be constrained to discrete "cloud" layers by competing processes of vertical upwelling, grain growth and gravitational settling (Ackerman & Marley 2001; Cooper *et al.* 2003; Woitke & Helling

† Both reactions listed above are pressure sensitive, with low pressures favoring the reactants. As a result, the onset of CH_4 absorption, signifying the start of the T dwarf sequence, occurs at lower temperatures for lower surface gravity brown dwarfs—and exoplanets.

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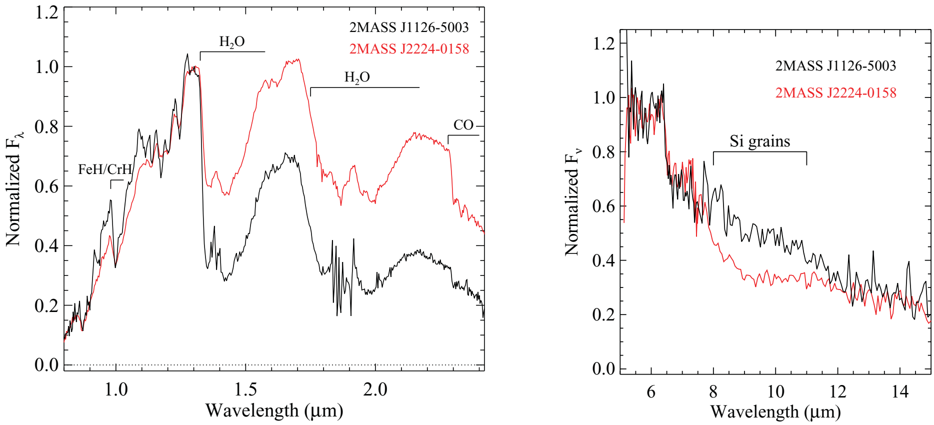

Figure 2. The influence of clouds on brown dwarf spectra. (Left): Near-infrared spectra of two equivalently (optically) classified L dwarfs, illustrating the reddening effects of condensate opacity. The spectra are normalized at 1.25 μm, with the "cloudier" object (2MASS J2224-0158) indicated in red. (Right): Mid-infrared spectra of the same two L dwarfs, highlighting the 8-11 μm silicate grain feature in the cloudier source. These spectra are normalized at 6 μm.

2004; Tsuji 2005). There is abundant evidence of for the presence of condensates in brown dwarf atmospheres, including the red near-infrared colors of late-type M and L dwarfs (e.g., Tsuji *et al.* 1996; Marley *et al.* 2002), the disappearance of gas precursors of condensate species (e.g., Kirkpatrick *et al.* 1999; Lodders 2002), the retention of alkali species (e.g., Lodders 1999; Burrows & Sharp 1999), "muted" near-infrared H_2O bands resulting from competing condensate grain opacity (e.g., Jones & Tsuji 1997) the direct detection of the 8-11 μm silicate grain feature (Cushing *et al.* 2006), and spectral model fits indicating the presence of condensate opacity (e.g., Cushing *et al.* 2008; Stephens *et al.* 2009; see Figure 2).

The opacity effects of condensates are most prominent in the infrared spectra of L dwarfs, where they cap the JHK flux peaks, minima in gas opacity (Ackerman & Marley 2001). However, the properties of L dwarf clouds are not universal. Significant source-to-source variations in near-infrared colors (by up to 1.5 mag) and spectral morphology among equivalently classified L dwarfs have been attributed in part to differences in cloud structure and/or particle sizes (Knapp *et al.* 2004; Burgasser *et al.* 2008; Marley *et al.* 2010, Figure 2). Temporal variability observed from magnetically inactive L dwarfs has been attributed to clouds, specifically rotational modulation of cloud structures (e.g., Goldman 2005; Artigau *et al.* 2009; see contribution by J. Radigan). The oblate cloudy atmospheres of rapid rotating L dwarfs can also explain observed linear polarizations of up to 2.5% (Sengupta & Krishan 2001; Ménard *et al.* 2002; Zapatero Osorio *et al.* 2005).

Cloud properties also evolve as a brown dwarf cools into a T dwarf. In general, T dwarf spectra are well-matched to "condensate-free" models, in accord with models of condensate clouds that sink below the visible photosphere (e.g., Marley *et al.* 2002; Burrows *et al.* 2006). What is surprising, however, is that the condensate opacity is observed to disappear more rapidly than models predict, as indicated by a remarkable brightening in 1 μm fluxes across the L/T transition (Dahn *et al.* 2002; Tinney *et al.* 2003; Vrba *et al.* 2004). This brightening has been observed in coeval pairs of L and T dwarfs, ruling out sample heterogeneity arguments (Burgasser *et al.* 2006; Liu *et al.* 2006). The driving mechanism for the sudden loss of photospheric condensates, whether by an onset of patchiness in the global cloud layer (Burgasser *et al.* 2002; Marley *et al.* 2010) or a global

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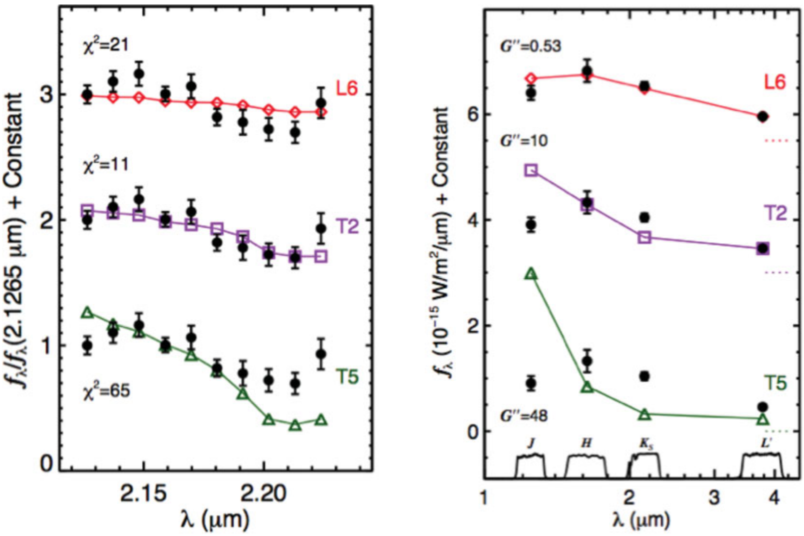

Figure 3. Near-infrared spectrum of the exoplanet HR 8799b, from Bowler *et al.* (2010). (Left): K-band spectrum (circles with error bars) compared to three spectral templates of types L6, T2 and T5. The T2 template provides a reasonable fit. (Right): Broad-band $JHKL$ photometry compared to the same templates, now showing a pronounced mismatch with the T2 template.

phase change in grain sedimentation (Knapp *et al.* 2004), remains an open question. Ongoing theoretical and observational studies are also exploring poorly-constrained grain size distributions and compositions, grain surface chemistry, cloud structure and atmospheric dynamics, and non-equilibrium effects in condensate formation (Helling *et al.* 2008b; Witte *et al.* 2009; Freytag *et al.* 2010).

4. Observed Spectra of Exoplanets: Does Distance Matter?

Much of our understanding of brown dwarf atmospheres comes from the comparison of detailed spectroscopic measurements to theoretical atmosphere models, and the ongoing development of those models (e.g., Burrows *et al.* 2002; Saumon & Marley 2008). Examples of both excellent and very poor model fits to observational data can be found in the literature (e.g., Stephens *et al.* 2009), with problems driven primarily by incomplete molecular opacities, inaccurate treatment of cloud physics, and uncertainties in elemental abundances (see Helling *et al.* 2008a and contribution by A. Becker). The recent direct detection of exoplanets around Fomalhaut (Kalas *et al.* 2008), HR 8799 (Marois *et al.* 2008), and β Pictoris (Lagrange *et al.* 2009, 2010, see contribution by A.-M. Lagrange) has opened to door for direct spectroscopic investigations of these objects as well. Two studies have explored the spectroscopic properties of planets in the HR 8799 system: the mid-infrared spectrum of HR 8799c (Janson *et al.* 2010) and the near-infrared spectrum of HR 8799b (Bowler *et al.* 2010)†. Both studies conclude that current models have difficulty reproducing exoplanet spectra, but in the case of HR 8799b there also appears to be major discrepancies with brown dwarf empirical templates (Figure 3). Does this mean that brown dwarfs are *not* useful analogs for exoplanet atmospheres?

There are in fact several widely-separated ($\gtrsim$100 AU), planetary-mass companions to young stars that show excellent agreement with their brown dwarf counterparts

† There are in addition to several multi-band photometric studies of these and other directly imaged planets.

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(e.g., Chauvin *et al.* 2005a; Lafrenière *et al.* 2010; Chauvin *et al.* 2005b; see contribution by R. Jayawardhana). A case in point is the 650 K, 6-11 M_{Jup} companion Ross 458C (Goldman *et al.* 2010; Scholz 2010), separated by 1100 AU from its 150-800 Myr host binary. The near-infrared spectrum of this object is well-matched to late-type T dwarf field analogs, albeit with spectral discrepancies associated with low surface gravity effects (i.e., reduced H_2 absorption) and evidence of unusually thick clouds (Burgasser *et al.* 2010). While the spectra of these "wide planets" are also poorly reproduced by current theoretical atmosphere models (e.g., Bonnefoy *et al.* 2010; Patience *et al.* 2010), they are at least well-understood within the empirical context of brown dwarf spectroscopy.

Hence, while the HR 8799 planets appear to differ significantly from their brown dwarf counterparts, widely-separated planetary-mass companions appear to be robust brown dwarf analogs. The difference here suggest yet another a potential dividing line between "traditional planets" and "failed stars" (see contribution by A. Nordlund). For closely-orbiting exoplanets, differences may be a consequence of irradiation or tidal heating from the host star, or long-term (and possibly ongoing) interaction with material in the system's debris disk. As such, insight drawn from brown dwarf studies may prove incomplete, as is the case of temperature inversions in highly irradiated planets (e.g. Fortney *et al.* 2008a). Nevertheless, brown dwarf spectroscopy provides a "zeroth-order" empirical calibration for models to which additional physics can be added. Given the rich diversity of brown dwarf atmospheres already observed, it is clear that there is even more to come as exoplanet spectroscopy becomes a more widely employed technique.

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