Model Atmospheres and Spectra of Brown Dwarfs to Giant Planets

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Abstract.
We review current efforts in modeling the atmospheres of very low mass stars and brown dwarfs, i.e. 3,000 K \( \leq T_{\text{eff}} \leq 200 \) K and solar elemental abundances. In particular, we explore the importance of molecular and grain opacities in their spectra. We also explore the radiation effects of a nearby companion upon the atmosphere of a 1000K atmosphere at 0.05 AU from its parent solar type star.

Very Low Mass Star models and the \( T_{\text{eff}} \) Scale

Very Low Mass stars (VLMs) with masses from about 0.3 \( M_{\odot} \) to the hydrogen burning minimum mass (0.075 \( M_{\odot} \), Baraffe et al. 1995) and young substellar brown dwarfs share similar atmospheric properties. Most of their photospheric hydrogen is locked in H\(_2\) and most of the carbon in CO, with the excess oxygen forming important molecular absorbers such as TiO, VO, and H\(_2\)O. They are subject to an efficient convective mixing often reaching the uppermost layers of their photosphere. Their energy distribution is governed by the millions of absorption lines of TiO, VO, CaH, and FeH in the optical to near-infrared, and H\(_2\)O and CO in the infrared, which leave no window of true continuum. But as brown dwarfs cool with age, they begin to differentiate themselves with the formation of methane (CH\(_4\)) in the infrared (Tsuji, Ohnaka & Aoki 1995, Allard et al. 1996). Across the stellar-to-substellar boundary, clouds of e.g. corundum (Al\(_2\)O\(_3\)), perovskite (CaTiO\(_3\)), iron, enstatite (MgSiO\(_3\)), and forsterite (Mg\(_2\)SiO\(_4\)) may form, depleting the oxygen compounds and heavy elements and profoundly modifying the thermal structure and opacity of their photosphere (Sharp & Huebner 1990, Burrows et al. 1993, Fegley & Loggers 1996, Tsuji, Ohnaka & Aoki 1996ab, Allard et al. 1997b).
Because these processes also occur in the stellar regime where a greater census of cool dwarfs is currently available for study, a proper quantitative understanding of VLM stars near the hydrogen burning limit is a prerequisite to an understanding of the spectroscopic properties and parameters of brown dwarfs and Jovian-type planets. Model atmospheres have been constructed by several investigators over recent years with the primary goals of:

1. Determining the M dwarfs effective temperature scale.

2. Identifying spectroscopic signatures of substellarity i.e. gravity indicators for young brown dwarfs, and spectral features distinctive of cooler evolved brown dwarfs.

3. Providing non-grey surface boundary to evolution calculations of VLMs and brown dwarfs leading to more consistent stellar models, accurate mass-luminosity relations and cooling tracks for these objects.

Table 1. Relevant Model Atmospheres

<table>
<thead>
<tr>
<th>Authors</th>
<th>Grid</th>
<th>$T_{\text{eff}}$ range (K)</th>
<th>Main Opacity Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kurucz 1992</td>
<td>Atlas12 Base</td>
<td>3500 – …</td>
<td>OS</td>
</tr>
<tr>
<td>Allard 1990</td>
<td>zero-metallicity</td>
<td>2000 – 3750</td>
<td>SM+JOLA</td>
</tr>
<tr>
<td>Saumon et al. 1994</td>
<td>zero-metallicity</td>
<td>1000 – 5000</td>
<td>OS</td>
</tr>
<tr>
<td>Tsuji et al. 1995</td>
<td>grainless</td>
<td>1000 – 2800</td>
<td>JOLA</td>
</tr>
<tr>
<td>Brett 1995</td>
<td>MARCS</td>
<td>2400 – 4000</td>
<td>OS</td>
</tr>
<tr>
<td>Allard &amp; Hauschildt 1995</td>
<td>Extended Base</td>
<td>1500 – 4500</td>
<td>SM</td>
</tr>
<tr>
<td>Tsuji et al. 1996</td>
<td>dusty</td>
<td>1000 – 2800</td>
<td>JOLA+Grains</td>
</tr>
<tr>
<td>Allard et al. 1996</td>
<td>NextGen</td>
<td>900 – 9000</td>
<td>OS</td>
</tr>
<tr>
<td>Allard et al. 1997b</td>
<td>NextGen-dusty</td>
<td>900 – 9000</td>
<td>OS+Grains</td>
</tr>
<tr>
<td>Allard et al. 1999</td>
<td>NG-AMES</td>
<td>2000 – 5000</td>
<td>OS+AMES</td>
</tr>
<tr>
<td></td>
<td>NG-AMES-cond</td>
<td>200 – 3000</td>
<td>TiO &amp; H$_2$O same+Grain chemistry</td>
</tr>
</tbody>
</table>

The computation of these atmospheres requires a careful treatment of the convective mixing and the molecular opacities. The convection must currently be handled using the mixing length formalism while a variety of approximations have been used to handle the millions of molecular and atomic transitions that define the spectral distributions of VLMs and brown dwarfs. The most accurate
of these methods is the so-called opacity sampling (OS) technique which consists in adding the contribution all transitions absorbing within a selected interval around each point of a pre-determined wavelength grid (typically ≈ 22000 points from 0.001 to 100 µm in our models). When the detail of the list of transitions is lacking for a molecule as is the case for the important absorber VO, the Just Overlapping Line Approximation (JOLA) offers an alternative by approximating the band structure based on only a few molecular rotational constants. The straight-mean (SM) and K-coefficients techniques, which consist in averaging the opacities over fixed wavelength intervals chosen smaller than the resolution of typical observations, have also been used in modeling late-type dwarf atmospheres. Their main advantage is to save computing time during the calculation of the models, often at the expense of flexibility and an accurate spectral resolution. The list of recent model atmospheres including those presented at this meeting, and the opacity technique they mostly rely upon is given in table 1. The table accentuates on our own various models grids to stress their different characteristics.

Because they mask emergent photospheric fluxes that would otherwise escape between absorption lines, the JOLA, SM and K-coefficients approximations generally lead to an excessive entrainment of heat in the atmosphere which yields systematically hotter model structures, and higher effective temperature \( T_{\text{eff}} \) estimates for individual stars. Allard et al. (1997a) have reviewed the results of brown dwarfs and VLM model atmosphere calculations with respect to the effective temperature scale of M dwarfs. We reproduce in Figure 1 the \( T_{\text{eff}} - (V - I) \) relation of Allard et al. (1997a) for the models listed in Table 1.

Two double-line spectroscopic and eclipsing M dwarf binary systems, CM Draconis and YY Geminorum, offer some guidance in the sub-solar mass regime and are reported in Figure 1 according to Habets & Heintze (1981). The use of an OS treatment of the main molecular opacities, in particular for TiO, appears to yield a break-through in the agreement of \( T_{\text{eff}} \) scales with these two M dwarfs binary system. The NextGen and MARCS models yield effective temperatures that are coincidently in good agreement with those derived empirically from the \( H_2O \) opacity profile by Jones et al. (1994). Note, however, that the Atlas12 OS models suffer from an inaccurate TiO absorption profile and a lack of \( H_2O \) opacities, and are therefore inadequate in the regime of VLM stars (i.e. below \( T_{\text{eff}} \approx 4500 \) K) where these molecular opacities dominate the stellar spectra and atmospheric structures.

Some uncertainties on the metallicity of the CM Draconis system may eventually disqualify the latter as a member of the disk main sequence (Viti et al. 1997). This stresses the importance of finding other low-mass eclipsing binary systems in the disk. These are hopefully soon to be provided by the 2MASS and DENIS surveys. Much uncertainty remains, therefore, in the lowermost portion of the main sequence. The inclusion of grain formation (as discussed below) and more complete opacities of TiO (now available from the work of Langhoff, 1997 and Schwenke, 1998) now yield a better understanding of the stars and brown dwarfs in the vicinity of the hydrogen burning limit (Allard et al, 1999, Baraffe et al, 1999, in preparation).
Modeling the Infrared Colors of Brown Dwarfs

The DENIS and 2MASS infrared sky surveys have began to deliver large data bases of red dwarfs, brown dwarfs and perhaps extrasolar planets, which necessitate the best possible theoretical foundation. Brown dwarfs and giant planets emit over 65\% of their radiation in the infrared (> 1.0\micron). A proper understanding of their infrared colors is essential in the search for brown dwarfs. Yet the main difficulties met by modelers in recent years has been to reproduce adequately the infrared (1.4 to 2.5\micron) spectral distribution of dwarfs with spectral types later than about M6. All models listed in the central part of table 1 underestimate the emergent flux, most as much as 0.5 mag at the K bandpass, despite the different opacity sources used by the authors. Allard et al. (1994) have explored water vapor opacity data from various sources. Figure 2 summarizes these results. The water vapor opacity profile is quite uncertain and has varied with the degree of completeness and the assumptions used in the construction of the molecular model and its potential surface. The most recent and complete line list of Partridge & Schwenke succeeds for the first time in reproducing the 1.6 \mu m opacity minimum, in the H bandpass, well enough.

![Figure 1. Current model-dependent effective temperature scales for cool stars down to the hydrogen burning limit. Triangles feature results from spectral synthesis of selected stars from the works of Kirkpatrick et al. (1993) and Leggett et al. (1996) as indicated. The new generation of OS models by Brett (1995a) and Allard (1997a), as interpolated onto theoretical isochrones by Chabrier & Baraffe (1997), reproduce closely the independently-determined positions of the eclipsing M dwarf binary system CM Dra and YY Gem, and the empirical T_{\text{eff}} scale of Jones et al. (1994).](image-url)
Figure 2. The observed infrared spectral distribution of the dM8e star VB10 as obtained at UKIRT by Jones et al. (1994) (bold full line) is compared to model spectra obtained using (from bottom to top): (i) the SM laboratory opacity profile of Ludwig (1971), (ii) the 20 million line list by Jorgensen (1994), (iii) the preliminary ab initio line list of 6.2 million transitions by Miller & Tennyson (1994), and (iv) the latest ab initio list of 300 million lines by Partridge & Schwenke (1997). The models (shown as dotted lines) are all fully converged and normalized to the observation at 1.2 μm. Their parameters were determined from a fit to the optical stellar spectra (not shown) and are nearly the same in all four cases. Note that all 300 million lines of the Partridge & Schwenke list have been included in the model construction!

for the atomic NaI resonance line to finally emerge in the synthetic spectrum, matching the observed feature. However, it fails to provide an improvement in the K bandpass where the less complete list of Miller & Tennyson still yield the best match of the models to the observed spectra. The NextGen models of Allard et al. (1997a) are computed using the Miller & Tennyson line list and appear to be the only models to provide a match to the infrared colors of VLMs. This is shown in Figure 3 where the complete series of NextGen models — as interpolated on the Baraffe et al. (1997, 1998) isochrones for 10 Gyrs and 120 Myrs and ranging from metallicities of [M/H] = −2.0 to 0.0 — are compared to the photometric field dwarfs' samples of Leggett (1992), Tinney et al. (1993), and Kirkpatrick, Henry & Simons (1995). Other models series including those of Brett (1995a) and the Extended grid of Allard & Hauschildt (1995) not shown, are distinctively bluer than the observed sequence, while the 10 Gyrs NextGen
models of solar metallicity follow closely the empirical sequence of Kirkpatrick & McCarthy (1994) down to spectral types of M6 (i.e. $J - K \approx 0.85$). Beyond this point, all grainless models fail to reproduce the bottom of the main sequence into the brown dwarf regime as defined by Gl406, VB10, BRI0021 and GD165B. They catch up with observations eventually again at the much lower $T_{\text{eff}}$ of the evolved brown dwarf Gliese 229B, i.e. 900-1000 K (Allard et al. 1996, Marley et al. 1996).

The cause of the model discrepancies at the stellar-to-brown dwarf boundary can only be one that affects the cooler models for Gliese 229B in a far lesser

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1Note that this sequence was defined by stars selected from their optical spectroscopic properties. The somewhat irregular profile of the sequence in this infrared diagram reflects uncertainties in the photometry and age of the selected stars.

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Figure 3. The most recent models of late type dwarfs are compared to the photometric observations of field stars and brown dwarfs, and to Pleiades objects including the brown dwarfs PPI15, Teide1 and Calar3. Gravity effects are illustrated by three models (open triangles) with log$g$= 5.5, 5.0, and 4.5 from bottom to top. Unresolved binarity is reflected in this diagram by a red excess in $J - K$. The red dwarfs newly discovered by DENIS are also shown, although their photometry is still uncertain at this point. The field brown dwarf Gliese 229B is off the scale to the blue in $J - K$ due to strong CH$_4$ absorption in the $K$ bandpass. Note that H$_2$ opacities depress also in $K$ band flux and cause the NextGen models to turn to the blue at their cool ends. This diagram offers excellent diagnostics to identify brown dwarf candidates of the field (very red in either $J - K$ or $I - J$) or of the halo (very blue in both $I - J$ and $J - K$).
obvious extent. Since the infrared spectral distribution is sensitive to the mixing length, yet without allowing for an improved fit of VLMs spectra, Brett (1995b) suggested that the problem lie in the inadequacy of the mixing length formalism for treating the convective transport in an optically thin photospheric medium. These concerns may also be augmented by uncertainties about the extent of the overshooting phenomenon in VLMs (D’Antona et al. 1997). The convection zone recedes gradually below the photosphere as the mass (and \(T_{\text{eff}}\)) decreases along the isochrones. Fortunately for the lithium test of substellarity (Rebolo et al. 1992) — which relies on the assumption that the brown dwarf is still fully convective and mixing lithium from its core to its photospheric layers after \(10^8\) yrs of age — the photospheric mixing breaks down only well into the brown dwarf regime i.e. for objects always cooler then about 2200K. The presence of lithium in the spectra of a late-type (\(\geq M10\)) field dwarfs, if detected, can therefore only reflect their substellar nature. The shrinking of the convection zone also allows a very good agreement between the models of Marley et al. (1996) (which includes adiabatic convection only for the optically thick layers of the atmosphere) and the models of Allard et al. (1996) (based on a somewhat more careful treatment of convection with the mixing length formalism) for the brown dwarf Gliese 229B (see Figure 5 of Allard et al. 1997a). Yet the maximum radial extent of the convection zone occurs at around \(T_{\text{eff}} = 3000\) K, while the discrepancy with the infrared observations increases steadily towards the bottom of the main sequence.

A more promising answer to the so called “infrared problem” may rather be found in the formation of dust grains in the very cool (typically \(T_{\text{layer}} \approx T_{\text{eff}} - 1000\) K) upper layers of red and brown dwarf’s atmospheres. Tsuji et al. (1996a) proposed, based on their results of including the effects of the formation and opacities of three grain species (\(\text{Al}_2\text{O}_3\), Fe, and MgSiO\(_3\)) in their “dusty” models, that the greenhouse heating of grain opacities, the resulting enhanced \(\text{H}_2\text{O}\) dissociation, and the infrared flux redistribution, can explain the infrared spectra of cool M dwarfs. The formation of perovskite dust grains at the expense of \(\text{TiO}\) may also explain the observed saturation (and disappearance in GD165B and Gliese 229B) of the TiO bands in the optical spectra of late-type red dwarfs (see also Jones & Tsuji 1997). The implications of this result is far reaching.

Known field brown dwarf candidates such as BRI0021 and GD165B can be far cooler and less massive than previously suspected (see e.g. the NextGen-dusty model predictions in Figure 1). If grains also form in the young Pleiades brown dwarfs PP115, Teide1 and Calar3 (\(T_{\text{eff}} \approx 3000, 2800, \) and \(2700\) K respectively), lithium abundances derived from grainless models and synthetic spectra such as those of Pavlenko et al (1995) may be overestimated, and the masses attributed to these objects possibly underestimated. Evolution models of brown dwarfs, which are sensitive to the treatment of the atmospheres (Baraffe et al. 1995), Chabrier & Baraffe 1997), and their predicted Mass-lithium abundance and Mass-Luminosity relations may also be affected.

And indeed, the temperatures and pressure conditions of the outer layers of red dwarfs are propice to the formation of dust grains as demonstrated years ago by Sharp & Huebner (1990). However it was not clear at the time if the inward radiation of an active chromosphere, or the efficient convective mixing from the interior, would heat up these upper photospheric layers and disable grain formation. Another concern is that, under the gravities prevailing in M
dwarfs, gravitational settling may occur that would eliminate large grains and their opacities from the photospheres over relatively short time scales. These possibilities still need to be thoroughly investigated, but clearly, grain formation is a process that must be considered in the construction of M dwarf and brown dwarf model atmosphere.

In order to investigate which grains may form in the upper layers of M dwarfs, Allard et al. (1997b) have modified the equation of state used in the NextGen models to include the detailed calculation of some 1000 liquids and crystals, using the free Gibbs energies compiled by Sharp & Huebner. Our results show that, besides the three species considered by Tsuji et al., the M dwarfs atmosphere were rich in condensates with ZrO$_2$, Ca$_2$Al$_2$SiO$_7$, Ca$_2$MgSiO$_7$, MgAl$_2$O$_4$, Ti$_2$O$_3$, Ti$_4$O$_7$, CaTiO$_3$, CaSiO$_3$ and Ca$_2$SiO$_4$ showing up in models as hot as $T_{\text{eff}} = 2700 - 3000$ K (i.e. dM8-dM6)! The preliminary NextGen-dusty models have been computed using a continuous distribution of ellipsoid shapes and interstellar grain sizes (between 0.025 and 0.25 $\mu$m) for the treatment of the opacities of the CaSiO$_3$, Ca$_2$SiO$_4$, Ca$_2$Al$_2$SiO$_7$, Ca$_2$MgSiO$_7$, MgAl$_2$O$_4$, Al$_2$O$_3$, Fe, MgSiO$_3$, and Mg$_2$SiO$_4$ dust grains. This contrasts with the assumption of spherical grains with 0.1 $\mu$m diameters in the dusty models of Tsuji et al. (1996b). Both models are shown in Figures 1 and 3. As can be seen, the dusty models of Tsuji et al. provide the correct tendency of the coolest models to get rapidly very red (as much as $J - K = 1.65$ for GD165B) with decreasing mass for a relatively fixed $I - J$ color. Those models are however systematically too red in $I - J$ by as much as 1 mag and do not reproduce even the most massive M dwarfs while over-predicting the effects of grains in Gliese 229B type brown dwarfs (Tsuji et al. 1996b). The NextGen-dusty models, on the other hand, show the onset of grain formation effects for $J - K \geq 0.85$, bringing an improved agreement with the observed sequence in the region where the grainless NextGen models deviate. A similar behavior is also shown by the models in other colors such as I-J and H-K where the NextGen-dusty models provide an unprecedented match to the observed stars and brown dwarfs colors (Leggett et al. 1998).

Of course, much remains to be improved in the computation of models with dust grains. The size distribution of various grain species, in particular those of the perovskite CaTiO$_3$ which is responsible for the depletion of TiO from the optical spectra of late-type dwarfs and of the calcium silicates which accounts for most of the grain opacities in current models, is unknown for the conditions prevailing in M dwarfs atmospheres. It is conceivable that grains form more efficiently in M dwarfs atmospheres than in the interstellar medium, and present larger sizes are different shapes than interstellar grains do. Fortunately, the total opacity provided by a grain species is little or not affected by our assumptions on the grain sizes. Indeed, a conservation of the total number of element cores requires that the number of grains of a type be inverse proportional to the size of these grains (themselves composed of several core particulates). On the other hand, gravitational settling processes may well be accelerated for larger grains, reducing their local contribution to the total opacity compared to what is now considered in the current “static” dusty models. We may also miss a number of contributors to the opacities from e.g. species for which the scattering profile is not well-known. Further investigations including time dependent grain growth
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analysis will be required to determine the exact contribution of pertinent dust grains to the infrared colors of red and brown dwarfs.

In the meanwhile, diagrams like that of Figure 3 may help in distinguishing interesting brown dwarfs candidates from large data banks of detected objects, and in obtaining an appreciation of the spectral sensitivity needed to detect new brown dwarfs. Models (Tsuji et al. 1995, Allard et al. 1996, Marley et al. 1996) and observations of Gliese 229B have shown that methane bands at 1.7, 2.4 and 3.3 μm appear in the spectra of cool evolved brown dwarfs, and cause their $I - K$ colors to get progressively bluer with decreasing mass and as they cool over time. Yet their $I - J$ colors remain very red which allows to distinguish them from hotter low-mass stars, red shifted galaxies, red giant stars, and even from low metallicity brown dwarfs that are also blue due to pressure-induced $H_2$ opacities in the $H$–to–$K$ bandpasses. Fortunately, uncertainties inherent to grain formation and molecular opacities are far reduced under low metallicity conditions ($[M/H]<-0.5$). Therefore, model atmospheres of metal-poor subdwarf stars and halo brown dwarfs are more reliable than their metal-rich counterparts at this point. This has been nicely demonstrated by Baraffe et al. (1997) who reproduced closely the main sequences of globular clusters ranging in metallicities from $[M/H]=-2.0$ to $-1.0$, as well as the sequence of the Monet et al. (1992) halo subdwarfs in optical color-magnitude diagrams. The colors of halo brown dwarfs as predicted by the NextGen models are therefore expected to be of quantitative quality and await eagerly confrontation with the infrared colors of metal-poor subdwarfs from e.g. the Luyten catalog and the US Naval Observatory surveys. Recently, Pulone et al. (1998) were able to obtain NICMOS photometry of the Ω Cen cluster which shows an excellent agreement with the NextGen models predictions down to the lower main sequence in these filters. This result confirms brilliantly for the first time the quality of the metal-depleted NextGen models in the infrared, and especially that of the important $H_2$ pressure-induced opacity as modeled by Borisow, Jørgensen & Zheng (1997).

The sensitivity of the $I - J$ index to the chemical composition of the atmosphere (clearly illustrated by the NextGen model grid) allows to distinguish brown dwarf populations independently of an accurate knowledge of the parallaxes or distances involved. Even young brown dwarfs of lower gravity appear to form a distinct sequence at bluer $I - J$ (and redder $J - K$) values then that of their older field star counterparts as it is also evident from a comparison of the 10 Gyrs and 120 Myrs NextGen models. This gravity effect, and perhaps enhanced grain formation, may explain the scatter of spectroscopic properties observed among field dwarfs at the bottom of the main sequence, as well as the systematic differences between Pleiades brown dwarfs and older field stars of same spectral type (i.e. same VO band strengths) noted by Martin et al. (1996).

Evolved Brown dwarfs

In Figure 4 and 5 we summarizes, the predicted model series absolute fluxes (1999 NG-AMES grids) that 5 Gyr-old free-floating brown dwarfs would have
Figure 4. Spectral sequence of brown dwarfs to EGP model atmospheres at 20 pc. From top to bottom: $T_{\text{eff}} = 2500, 1900, 1800, 1300, 700, 400, 200$K (full curves). These models assume an original solar abundance mix, and settling of dust grains when these exceed the local gas mass density. A model with full dust and no settling at 1800K (bold curve) and a model without dust opacity at 400K (dotted curve) are also shown for comparison. Each model is chosen to match a 5 Gyrs isochrone ($\log g=5.5$ to 3.0) and is calibrated to absolute flux using radii from consistent evolutionary models by Baraffe et al. (1999). The resolution has been reduced from about 2Å to 50Å by boxcar smoothing in order to make comparison of the spectra easier.

at a distance of 20 pc. As can be seen, there is no clear distinction between brown dwarfs and planets; molecular bands most gradually form (dust, H$_2$O, CH$_4$ and NH$_3$) and recede (TiO, VO, FeH, and CO) from the stellar to the planetary regime as the atmospheres get cooler. Atomic lines of alkali elements can develop van der Waaals widths of more then a 1000Åas the atmosphere becomes transparent (see Martin & Basri in this volume). Brown dwarfs remain very bright in the IJK region, and become gradually redder in the near-infrared $I$ to $J$ bandpasses, which allows their detection from ground-based facilities. At 5 µm, the hotter (younger or more massive) brown dwarfs and stars show strong CO bands which cause their flux to drop by nearly 0.5 dex relative to that at 4.5 µm. And between 4.5 and 10 µm, opacities of CH$_4$ (and H$_2$O in the hotter brown dwarfs) cause the flux to drop by 0.5 to 1.0 dex.

For binaries on the other hand, layers of dust in the brown dwarf or planet’s upper atmosphere may increase their albedo sufficiently to reflect the light of a close-by parent star, becoming therefore resolvable in the optical where
Figure 5. Spectral sequence of brown dwarfs to EGP model atmospheres at 20 pc. The models, from top to bottom with $T_{\text{eff}} = 2500, 1900, 1800, 1300, 700K$, and $400K$ (full curves) assume an original solar abundance mix, and settling of dust grains when these exceed the local gas mass density. Models with $T_{\text{eff}} = 400K$ and $200K$ which ignore all dust opacity are shown (dotted curves) for comparison. The hottest models are chosen to match a 5 Gyrs isochrone ($\text{log} g$=5.5 to 3.0) and are calibrated to absolute flux using radii from consistent evolutionary models by Baraffe et al. (1999). The cooler models have been offset fainter, and the resolution has been reduced from about 2Å to 5Å by boxcar smoothing in order to make comparison of the spectra easier.

the clouds are densest and the parent star is brightest. In order to test this hypothesis, we have computed the irradiation of a G2V type star upon a $T_{\text{eff}} = 1000K$ planet at 3 distances from the primary in Figure 6. The models were iterated and converged so as to preserve a constant intrinsic flux in radiative layers, and the dust was allowed according to chemical equilibrium conditions.

From this test it appears that the impinging radiation can heat efficiently the outer layers of the planet’s atmosphere which then become rapidly to hot to allow the formation of dust clouds and even molecules in its spectrum. Intrinsically cooler, less massive planets and/or further away from their parent stars can preserve their molecular features. However reflection effects remain small for such a hot i.e. massive planet due to the nature of the dust clouds (silicates) prevailing at high temperatures, leaving the peak flux emerging as in the case of free-floating objects around the J and K bandpasses.

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Figure 6. Spectrum of a young EGP (T\text{eff} = 1000K) irradiated by a G2V primary at four orbital distances: 0.05 AU, 0.10 AU, 0.20 AU, and infinite. The plot shows the incident spectrum (topmost curve), the spectrum emitted by the irradiated planet (curves with more flux and shallower water and methane bands) and the non-irradiated spectrum of the EGP (lowermost curve). In this simple test case, the irradiation is assumed to be isotropic. The dashed line is the blackbody spectrum for T\text{eff} = 1000K. The EGP model includes atomic and molecular spectral lines as well as dust formation and the resulting dust opacities. The resolution has been reduced from about 2Å to 30Å by boxcar smoothing in order to make comparison of the spectra easier.

Conclusions

In these exciting times where discoveries of brown dwarfs are finally breaking through, model atmospheres are also rapidly becoming up to the task of interpreting the observations and deriving new search strategies. Uniform grids of dwarf stars and brown dwarfs model atmospheres exist that extend from the tip to the toes of the main sequence – and beyond: 9000K to 200K, logg= 3.0-6.0, and [M/H]= 0.0 to −2.0 for the NextGen and NG-AMES models. These large model grids allowed the construction of consistent interior and evolution models for VLMs that yield unprecedented agreement with globular cluster main sequences observed to 0.1 M\odot with HST. They led to the mass-luminosity relation for low mass stars, which is of primary importance for the derivation of the stellar mass function of both the halo and the disk populations. This allows now to constrain the brown dwarf density with the help of the microlensing experiments (OGLE, EROS, MACHO, etc.), and leads to the important realization that brown dwarfs cannot make up a significant fraction of the halo missing mass.
The effective temperature scale of K to M type dwarfs with spectral types earlier than M6 is now unambiguously established, with only small uncertainties remaining from a possible incompleteness of existing TiO line lists. Grain formation has been identified as an important process in M dwarfs and brown dwarfs atmospheres which could explain the long-standing difficulties of the models to reproduce the spectral distribution of dwarfs later than about M6. The results of the models indicate that it may no longer be assumed that the convection zone extends to the photosphere of late-type red dwarfs and brown dwarfs. But their photospheric lithium abundance nevertheless always reflect the substellar nature of young, hot brown dwarfs such as those found in the Pleiades cluster. Fortunately, if the lithium test cannot identify transition objects and brown dwarfs of the field, the Opacity Sampling treatment and grain formation have introduce new gravity (hence age) effects in the NextGen models that were not seen in the previous Extended models and that will potentially allow to separate younger transitional objects from field stars as readily as from their location in color-color diagrams. For this the colors of late-type red dwarfs need to be known with good accuracy i.e. better than about 0.05 magnitude, which we find is not the case of many known late M dwarfs.

As cooler dwarfs are being discovered, spectral types are stretching far beyond the classical Morgan & Keenan scheme. The lack of TiO bands in the optical, and the emergence of CH$_4$ opacities in the infrared in GD165B and Gl229B call for an extension of the MK system beyond M9 to two other spectral classes (L and T). In any case, studies of the optical spectra of Gliese 229B, GD165B, the DENIS and 2MASS objects and other late-type dwarfs will soon allow to determine the stellar surface coverage of dust clouds if such are present, and to verify if intrinsic spectral-type variability afflict cool dusty dwarfs. Models will be the subject of further investigations relative to grain formation and its effect on late-type dwarfs until they can predict the behavior of brown dwarfs from the hot, red and dusty L dwarfs to the cold, blue and nearly dust-free T dwarfs in a natural cooling sequence.

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