Cloudless Atmospheres for Young Low-gravity Substellar Objects

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Abstract

Atmospheric modeling of low-gravity (VL-G) young brown dwarfs remains challenging. The presence of very thick clouds is a possible source of this challenge, because of their extremely red near-infrared (NIR) spectra, but no cloud models provide a good fit to the data with a radius compatible with the evolutionary models for these objects. We show that cloudless atmospheres assuming a temperature gradient reduction caused by fingering convection provide a very good model to match the observed VL-G NIR spectra. The sequence of extremely red colors in the NIR for atmospheres with effective temperatures from ∼2000K down to ∼1200K is very well reproduced with predicted radii typical of young low-gravity objects. Future observations with NIRSPEC and MIRI on the James Webb Space Telescope (JWST) will provide more constraints in the mid-infrared, helping to confirm or refute whether or not the NIR reddening is caused by fingering convection. We suggest that the presence or absence of clouds will be directly determined by the silicate absorption features that can be observed with MIRI. JWST will therefore be able to better characterize the atmosphere of these hot young brown dwarfs and their low-gravity exoplanet analogs.

Key words: brown dwarfs – methods: numerical – methods: observational – planets and satellites: atmospheres

1. Introduction

Although they represent a small fraction of the entire brown dwarf population, young brown dwarfs (≤150 Myr) largely populate and even dominate the redward part (J − K ≥ 0.8) of the color–magnitude diagram (e.g., Chabrier 2002) and are of great interest because of their large radii and low surface gravity. Their study provides a promising approach to better understanding low-gravity ultracool analog atmospheres such as those of young gas giant exoplanets. Recently, wide-field surveys have led to the identification of large samples of such low-gravity objects (e.g., Gagné et al. 2015a; Aller et al. 2016). This population forms a separate sequence in near-infrared (NIR) color–magnitude diagrams (CMD) from the field objects (Liu et al. 2013, 2016; Faherty et al. 2016). This sequence is typically ∼0.5 mag redder in J − K color and has been interpreted as the presence of thicker clouds with small particles, even though current cloud models struggle to fit these data (e.g., Liu et al. 2016). The models of Saumon & Marley (2008) and Marley et al. (2012) cannot reach the reddest colors at a given magnitude although they have provided reasonable fits and radii for the HR 8799 planets (Marley et al. 2012) and BT-Settl models lead to implausibly small fitted radii (e.g., Liu et al. 2013).

Recently, Tremblin et al. (2016) proposed that the reddening of NIR colors in standard field L dwarfs and exoplanet analogs such as HR8799c is induced by the reduction of the temperature gradient in their atmospheres. The development of fingering convection caused by the mean molecular weight gradient implied by the chemical transition between CO and CH4 could be the origin of this temperature gradient reduction. This mechanism naturally explains why the disappearance of the reddening at the L/T transition is concomitant with the transition between CO and CH4 in the atmospheres of these objects.

In this paper, we show that the same model based on Tremblin et al. (2016) effectively reproduces the spectra of VL-G objects (DENIS J1425-36, 2MASS J2208+29, and PSO J318-22, chosen as late-L members of well-established young moving groups AB Doradus and Beta Pictoris), as well as the sequence in M_J versus J − K CMD. Furthermore, the radii inferred from the spectral fits are in good agreement with the evolutionary models of young objects. The derived ages of DENIS J1425-36 and PSO J318-22 are in good agreement with the ages estimated from their memberships in their respective moving groups. Therefore, these results support the CO/CH4 fingering-unstable interpretation of the L/T transition of standard field objects and VL-G objects.

2. Spectral Models

The spectral models are all done with the ATMO code (Amundsen et al. 2014; Tremblin et al. 2015; Drummond et al. 2016). We kept the same opacity sources as in Tremblin...
et al. (2016) for direct comparison (H₂–H₂, H₂–He, H₂O, CO, CO₂, CH₄, NH₃, K, Na, TiO, VO, and FeH) from the high-temperature ExoMol (Tennyson & Yurchenko 2012) and HITEMP (Rothman et al. 2010) line list databases when available.

Similar to Tremblin et al. (2015, 2016) and Drummond et al. (2016), we use the coupling of the radiative/convective code with the CHNO-based chemical network of Venot et al. (2012) for the treatment of the departure from chemical equilibrium in the nitrogen and carbon chemistry. Starting from a converged pressure/temperature (PT) structure at chemical equilibrium, we integrate the time evolution of the abundances of all the chemical species in all the layers of the atmosphere. When the turbulent mixing is faster than the chemical timescales (mixing coefficient $K_{zz}$), the abundances of some molecules are not at chemical equilibrium, and can be controlled by the turbulent diffusion from the deepest layers. The non-equilibrium abundances are computed by solving the time evolution of the continuity equation (see Equation (10) in Drummond et al. 2016) with the LSODE integrator for stiff ordinary differential equations (Hindmarsh 1983). We regularly reconverge the PT structure with the radiative/convective code during the time integration until we reach a steady-state for both the chemistry and energy conservation/hydrostatic equilibrium. We then get a coherent atmospheric structure with out-of-equilibrium chemical abundances. As in Tremblin et al. (2016), we propose that a process similar to fingering convection is responsible for this turbulent mixing and leads to the out-of-equilibrium abundances. Fingering convection can be triggered in the atmospheres of brown dwarfs and exoplanets because of the gradient of mean molecular weight induced by the chemical transitions CO/CH₄ and N₂/NH₃ at chemical equilibrium. Similar to convective motions that lead toadibatic PT structure in the deep atmosphere, fingering convection could impact the PT structure of the atmosphere. As in Tremblin et al. (2016), we propose that fingering-convective motions can induce a temperature gradient reduction, leading to a reddening in the modeled spectrum. This temperature gradient reduction in the atmosphere is modeled using an artificially reduced adiabatic index $\gamma$ in between two pressure levels on top of the convective zone.

In Figure 1, we show the influence of various model parameters at effective temperatures of 1700 and 1300 K, representative of the objects studied in this study. At 1700 K we can see a degeneracy between gravity and metallicity on the spectral shape of the H and K bands. Decreasing gravity or increasing metallicity tends to form a triangular H band and a strong and flatter K band. Decreasing the temperature gradient in the atmosphere by decreasing the effective adiabatic index $\gamma$ increases the reddening in $J - K$. Increasing the surface gravity at an effective temperature of 1300 K has a strong effect on the out-of-equilibrium chemistry and the quenching of CO in the deep atmosphere. At higher gravities, the CO/CH₄ transition is

\[ K_{zz} \] is a free parameter and represents the vertical eddy diffusion coefficient.

\[ \text{https://computation.llnl.gov/casc/odepack/} \]
deeper in the atmosphere, hence it is more difficult to
produce the formation of CH4 (strongly appearing at log g = 4.5) for a
given mixing coefficient $K_{zz}$. Thus, varying $K_{zz}$ would
approximately lead to the same effect as varying gravity for
$T_{\text{eff}} = 1300$ K. For the fitting of the observations we have
probed a similar parameter space, log g in [3.5, 4.5], [M/H] in
[0, 0.5], $T_{\text{eff}}$ in [1200, 1800], and $\gamma$ in [1.01, 1.1].

2.1. DENIS J1425279-365023

DENIS J1425279-365023 was first identified as an L5 dwarf
(Kendall et al. 2004) with a trigonometric distance of
$\sim 11.57 \pm 0.11$ pc (Dieterich et al. 2014). A SpeX Prism
obtained by Gagné et al. (2015a) indicates that the object is a
L4INT-G object based on the index-based classification of
Allers & Liu (2013). Based on the galactic position and space
velocity of the object, Gagné et al. (2015a, 2015b) also concluded that
DENIS J1425-36 is a bona fide member of the
AB Doradus Moving Group (149 ± 30 Myr, Bell et al. 2015).

Figure 2 shows the SpeX prism spectrum of DENIS J1425-
36 compared to a model obtained with the ATMO code. As in
Tremblin et al. (2016), the reddening of the modeled spectrum
is obtained by a temperature gradient reduction in the
atmosphere using an artificially reduced adiabatic index $\gamma$.
Tremblin et al. (2016) have obtained a very good fit to field
standard L dwarfs with a $\gamma$ value around 1.05 in the region
between $\sim 100$ bars and $\sim 2$ bars. This result has recently been
confirmed by Burningham et al. (2017), although the authors
suggested that sophisticated cloud models could provide a
slightly better fit. For DENIS J1425-36, we show that the same
model provides a good fit to the observed spectrum with a
shallower temperature gradient with $\gamma \approx 1.02$ extending up to
0.25 bars in the atmosphere. As anticipated from the $H$ and $K$
band spectral shapes, we also find a low surface gravity, which
indicates the youth of the object but also a slightly supersolar
metallicity. Most importantly, we have obtained a radius of
$\sim 0.12 R_{\odot}$ for DENIS J1425-36 which corresponds to an age of
100–150 Myr, consistent with evolutionary models (Baraffe
et al. 2003) and the age of the AB Doradus Moving Group.

2.2. 2MASSW J2208136+292121

2MASSW J2208136+292121 was first discovered by
Kirkpatrick et al. (2000) and classified as a peculiar L2. The
peculiarity was later understood as signs of low gravity and the
object is now classified as a L3VL-G with a parallax distance of
47.6 ± 2 pc (Liu et al. 2016). Based on its optical spectrum,
Kirkpatrick et al. (2008) estimated an age of $\sim 100$ Myr for the
object. Gagné et al. (2014) has estimated a probability of only
10% for a potential membership to the Beta Pictoris Moving
Group, which would suggest a younger age of 24 ± 3 Myr
(Bell et al. 2015).

Figure 2 shows the SpeX prism spectrum of 2MASS J2208+
29 compared to a model obtained with the ATMO code. This
object appears to have a CMD position discrepant with its
gravity classification (Liu et al. 2016), with a shift of only
0.1–0.2 mag in $J - K$ relative to the standard field objects. This
fact directly reflects the effective $\gamma$ value of 1.05 found with the
spectral model, a value closer to the one used for a standard
field object (Tremblin et al. 2016). The shape of the spectrum,
e.g., the very peaked $H$ band, clearly indicates a low gravity
and/or a high metallicity for the object, as found with our model.

We have found a radius similar to that of DENIS J1425-36,
around 0.12 $R_{\odot}$. This radius corresponds to an age of
100–150 Myr with evolutionary models. This result confirms the
“optical” age found by Kirkpatrick et al. (2008) and argues against
a membership in the Beta Pictoris Moving Group.

2.3. PSO J318.5338-22.8603

PSO J318.5338-22.8603 has been identified as the reddest
field object ever observed (Liu et al. 2013), with a parallax
distance of 24.6 ± 1.1 pc. Its $J - K$ color is 2.78 mag, which has
been interpreted as a sign of an unusually dusty atmosphere. This interpretation, however, is weakened by the
difficulty of fitting the NIR spectrum with cloud models. A
good fit can be obtained with BT-Settl models (Liu et al. 2013),
but with an implausibly small radius (around 0.08 $R_{\odot}$) for such
a young object. Its membership in the Beta Pictoris Moving
Group suggests an age around 24 ± 3 Myr (Bell et al. 2015).

Figure 2 shows the GNIRS14 spectrum of PSO J318-22
compared to a model obtained with the ATMO code. The
 correspondence between the model and the observed spectrum is
remarkably good and emphasizes the high precision of the
H2O and CO high-temperature opacities derived from ExoMol
(Barber et al. 2006) and HITEMP linelists. Similar to DENIS
J1425-36 and 2MASS J2208+29, the spectral shape of $H$ and $K$
bands points toward a low-gravity and/or high-metallicity
atmosphere, which is indeed indicated by the modeled spectrum.
The reddening is obtained with an effective $\gamma$ of
1.02 up to 0.1 bars in the atmosphere. The out-of-equilibrium
chemistry of CO/CH4 plays an important role in the
atmosphere of PSO J318-22. Unlike DENIS J1425-36 and 2MASS
J2208+29, which have temperatures that are too high,
PSO J318-22 is sufficiently cold for CH4 to dominate the
atmosphere. Out-of-equilibrium processes (that can be linked to
fingering convection Tremblin et al. 2016) are crucial to
preventing CH4 formation and keeping carbon in CO as expected from the observed spectrum, due to quenching of CO
from the deep atmosphere, where it is favored in chemical
equilibrium. In our models, PSO J318-22 is actually right at the
transition of having CH4 as the dominant carbon-bearing
species. The radius we have obtained is around $\sim 0.13 R_{\odot}$
which corresponds to an age between 30 and 50 Myr, in good
agreement with the estimated age of the Beta Pictoris Moving
Group.

2.4. Color–Magnitude Diagram

Figure 3 shows the CMD $M_J$ versus $J - K$ for field objects and
VL-G objects (Liu et al. 2013). The sequence of models has
been computed at a fixed surface gravity of log g = 3.5, radius of
0.13 $R_{\odot}$, vertical mixing at $10^7$ cm$s^{-1}$, effective
adiabatic index of $\gamma = 1.03$, and with solar metallicity. The
range of effective temperature is between 1200 and 2000 K,
which roughly corresponds to objects of masses between 5 and
20 $M_{\odot}$. As shown in Figure 1, the effect of gravity and
metallicity will be relatively small on the $J$ and $K$ band
magnitude, compared to the effect of varying $\gamma$. As expected from the spectral models, this sequence reproduces the
reddening of VL-G objects in the CMD. A sequence with a
higher $\gamma$, e.g., 1.05, as seen for 2MASS J2208+29, would
replicate the field objects with a smaller reddening. Cloud
models are currently struggling to reach the reddening of the

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14 Gemini NIR Spectrometer (Elias et al. 2006).
VL-G objects. Liu et al. (2016) found that the models from Saumon & Marley (2008) and Marley et al. (2012) are systematically too blue. BT-Settl models (Allard et al. 2014) tend to also be bluer than the VL-G objects, and faint red L dwarfs are not reproduced because the cloud-clearing occurs at brighter magnitudes. It is worth stressing that, with the cloud interpretation, these latter models show that there is no correlation between reddening and the CO/CH₄ transition, although observations do show such a correlation both for standard field objects and for VL-G objects.

Figure 2. Spectral models obtained with the ATMO code using a temperature gradient reduction in the atmosphere (Tremblin et al. 2016) compared with the SpeX prism spectra of DENIS J1425279-365023 (Bardalez Gagliuffi et al. 2014) and 2MASSW J2208136+292121 (Allers & Liu 2013), and the GNIRS spectrum of PSO J318.5338-22.8603 (Liu et al. 2013).
3. Discussion and James Webb Space Telescope (JWST) Perspectives

For DENIS J1425-36 and 2MASS J2208+29, the correspondence between the modeled and observed spectra is better in the 1.4–2.4 μm region than below 1.4 μm. This limitation could be caused by our opacity database, which currently contains TiO, VO, and FeH, but may lack other metal hydrides that could be important at high effective temperatures around 1700 K. As seen in Section 2, the spectral shape of the H and K bands clearly indicates a low gravity and/or high metallicity, a degeneracy already observed for other objects (e.g., Delorme et al. 2017). Dedicated studies of the metallicity of moving groups point toward low values, e.g., $[\text{M}/\text{H}] = 0.1$ for AB Doradus (Biazzo et al. 2012). Our models are subject to the same degeneracy and we have generally chosen to keep a metallicity around $[\text{M}/\text{H}] = 0.2$–0.3 to be consistent with the metal Galactic distribution (Anders et al. 2017). Since these evolutionary models are at solar metallicity, the computation of coherent models at higher metallicity might resolve this discrepancy. Following Tremblin et al. (2017), we can write the steady-state energy conservation equation in the following form:

$$

\begin{align*}

u_r,\text{conv} \left( \nabla_T - \frac{\gamma_{\text{ad}} - 1}{\gamma_{\text{ad}}} \right) &= \frac{\gamma_{\text{ad}} - 1}{\gamma_{\text{ad}}} \frac{H_{\text{rad}}}{\rho g} \\

u_r,\text{conv} \left( \nabla_T - \frac{\gamma_{\text{eff}} - 1}{\gamma_{\text{eff}}} \right) &= 0 \\

\gamma_{\text{eff}} &= \frac{\gamma_{\text{ad}} - 1}{\gamma_{\text{ad}}} \left( 1 + \frac{H_{\text{rad}}}{u_r,\text{conv} \rho g} \right)

\end{align*}

$$

with $\nabla_T = \partial \ln T / \partial \ln P$, $u_r,\text{conv}$ as the vertical (overturning or fingering) convective velocities, $H_{\text{rad}}$ as the radiative heating rate, $\rho$ as the density, $g$ as the gravity, $\gamma_{\text{ad}}$ as the standard adiabatic index of the gas, and $\gamma_{\text{eff}}$ as the effective adiabatic index defined by the last equation. In the overturning convective part of the atmosphere, $H_{\text{rad}} \approx 0$ and the

![Figure 3. $M_J$ vs. $J - K$ MKO color–magnitude diagram of field objects (Dupuy & Liu 2012; Faherty et al. 2012), VL-G objects (Liu et al. 2016), and the ATMO model sequence with varying effective temperature.](image-url)
atmosphere are adiabatic with $\nabla T \approx (\gamma_{\text{ad}} - 1)/\gamma_{\text{ad}}$. In the fingering-convective part, the atmosphere is in a zone where the radiative energy transport cannot be ignored, hence $\nabla T \approx (\gamma_{\text{eff}} - 1)/\gamma_{\text{eff}}$ with $\gamma_{\text{eff}} \neq \gamma_{\text{ad}}$. We can give an order of magnitude estimation of the velocities that are needed to obtain $\gamma_{\text{eff}} \approx 1.03$. For the model of PSO J318-22, we estimate that a fingering-convective velocity of the order of $10 \text{ m s}^{-1}$ is required to obtain such a value of the effective adiabatic index (for comparison, velocities in the overturning convection zone are in the range of $30–100 \text{ m s}^{-1}$).

As in Tremblin et al. (2016), we emphasize that this does not mean that clouds are not present in the atmosphere of these objects. Thin high-altitude clouds are likely to form and be driven to the top of the fingering-convective zone in the atmosphere. They could be observed e.g., in the silicate absorption band at $10 \mu\text{m}$ (Cushing et al. 2006). Although we need to expand the fingering-convective zone up to $\sim 0.1 \text{ bar}$ in the atmosphere, it is not clear whether this is sufficient to observe thin high-altitude clouds, since the models reach a $10-\mu\text{m}$ optical depth of $1$ at $\sim 0.01 \text{ bar}$. Key future constraints on these signatures will be obtained by JWST with MIRI (see the indicative location of the absorption feature in the MIRI spectral coverage in Figure 4).

To conclude, we recall that fingering convection induced by the CO/CH$_4$ chemical transition can naturally explain the nature of the L/T transition, a transition between fingering-convective “red” CO-dominated atmospheres to stable “blue” CH$_4$-dominated ones. The reddening of the spectrum of field and VL-G objects can be very well explained by a temperature gradient reduction caused by fingering convection. The estimated radii from the models are in good agreement with the evolutionary models and the estimated ages of moving groups, which strengthens the fingering interpretation.

Nevertheless, as shown in Burningham et al. (2017), both cloud and cloudless models can provide a very good fit to the spectra of field L dwarfs, and cloud models have generally shown good successes in the spectral modeling of field L and T dwarfs in the past 20 years. Young, low-gravity brown dwarfs could provide a good test for distinguishing between the two models if the current limitations of cloudy VL-G models are confirmed by future studies. We provide in Figure 4 the long wavelength ($3–20 \mu\text{m}$) prediction of our full spectral model for PSO J318-22 compared with a BT-Settl cloudy model and simulated observations with NIRspec using the grating G395M with a $\sim 30$ minute exposure time. JWST, with NIRspec, and MIRI observations (SNR $\gtrsim 100$) in the $3–7 \mu\text{m}$ region, and future comparisons with cloud models in that wavelength range, could help us assess which interpretation between clouds and fingering convection is correct.

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**References**

Allard, F., Homeier, D., & Freytag, B. 2014, ASInC,11, 33

Aller, K. M., Liu, M. C., Magnier, E. A., et al. 2016, ApJ, 821, 120

Allers, K. N., & Liu, M. C. 2013, ApJ, 772, 79

Amundsen, D. S., Baraffe, I., Tremblin, P., et al. 2014, A&A, 564, 59

Anders, F., Chiappini, C., Minchev, I., et al. 2017, A&A, 600, A70

Baraffe, I., Chabrier, G., Barman, T. S., et al. 2003, A&A, 402, 701

Barber, R. J., Tennyson, J., Harris, G. J., et al. 2006, MNRAS, 368, 1087

Bardalez Gagliuffi, D. C., Baggett, A. J., Gelino, C. R., et al. 2014, ApJ, 794, 143

Bell, C. P. M., Mamajek, E. E., & Naylor, T. 2015, MNRAS, 454, 593

Biazzo, K., D'Orazi, V., Desidera, S., et al. 2012, MNRAS, 427, 2905

Buenzli, E., Marley, M. S., Apai, D., et al. 2015, ApJ, 812, 163

Burningham, B., Marley, M. S., Line, M. R., et al. 2017, MNRAS, 470, 1177

Burrows, A., Sudarsky, D., & Hubeny, I. 2006, ApJ, 640, 1063

Chabrier, G. 2002, ApJ, 576, 304

Cushing, M. C., Roellig, T. L., Marley, M. S., et al. 2006, ApJ, 668, 614

Delorme, P., Dupuy, T., Gagné, J., et al. 2017, A&A, 602, A82

Dieterich, S. B., Henry, T. J., Jao, W.-C., et al. 2014, AJ, 147, 94

Drummond, B., Tremblin, P., Baraffe, I., et al. 2016, A&A, 594, A69

Dupuy, T. J., & Liu, M. C. 2012, ApJS, 201, 19

Elias, J. H., Joyce, R. R., Liang, M., et al. 2006, Proc. SPIE, 6269, 62694C

**Figure 4.** Top: full spectral model of PSO J318-22 with NIRspec/MIRI spectral coverage. Bottom: NIRspec simulation using the grating G395M with a $\sim 30$ minute exposure time.
Faherty, J. K., Burgasser, A. J., Walter, F. M., et al. 2012, ApJ, 752, 56
Faherty, J. K., Riedel, A. R., & Cruz, K. L. 2016, ApJS, 225, 10
Gagné, J., Faherty, J. K., Cruz, K. L., et al. 2015a, ApJS, 219, 33
Gagné, J., Lafrenière, D., Doyon, R., et al. 2014, ApJ, 783, 121
Gagné, J., Lafrenière, D., Doyon, R., et al. 2015b, ApJ, 798, 73
Hindmarsh, A. C., 1983, IMACS Transactions on Scientific Computation, 1, 55
Kendall, T. R., Delfosse, X., Martin, E. L., et al. 2004, A&A, 416, L17
Kirkpatrick, J. D., Cruz, K. L., Barman, T. S., et al. 2008, ApJ, 689, 1295
Kirkpatrick, J. D., Reid, I. N., Liebert, J., et al. 2000, ApJ, 120, 447
Liu, M. C., Dupuy, T. J., & Allers, K. N. 2016, ApJ, 833, 96
Liu, M. C., Magnier, E. A., Deacon, N. R., et al. 2013, ApJL, 777, L20
Marley, M. S., Saumon, D., & Cushing, M. 2012, ApJ, 754, 135
Rothman, L., Gordon, I., Barber, R., et al. 2010, JQSRT, 111, 2139
Saumon, D., & Marley, M. S. 2008, ApJ, 689, 1327
Tennyson, J., & Yurchenko, S. N. 2012, MNRAS, 425, 21
Tremblin, P., Amundsen, D. S., & Chabrier, G. 2016, ApJL, 817, L19
Tremblin, P., Amundsen, D. S., Mourier, P., et al. 2015, ApJL, 804, L17
Tremblin, P., Chabrier, G., Mayne, N. J., et al. 2017, ApJ, 841, 30
Venot, O., Hébrard, E., Agúndez, M., et al. 2012, A&A, 546, A43