M-Band Observations of the Coldest Brown Dwarfs

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Brown Dwarfs are Analogs of Directly Imaged Gas Giants

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Things We Want to Know:

• What gases or clouds can we expect to see in gas giant atmospheres at cool temperatures?
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• What wavelength coverage and resolutions are needed for future direct imaging instruments.
Future Directly Imaged Gas Giants Could Resemble Y-dwarfs

51 Eri b (~600K)  Rajan+ 2017

G 204-39B (T6.5), $\chi^2 = 1.22$
The Mid-IR is Essential for Characterizing Colder, Gas Giant Exoplanets

Briesemeister+ 2019 using models from Morley+ 2012, Morley+ 2014
see also Skemer+ 2014
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The Mid-IR is Essential for Characterizing Colder, Gas Giant Exoplanets

- The best star-planet contrast is achieved between 3 to 5 microns.
- Numerous potential opacity sources can be detected/constrained: PH₃, CO, CO₂, CH₄, NH₃, etc (Morley+ 2018)
- Future instruments need to capitalize on this wavelength region (SCALES/KECK)

Briesemeister+ 2019 using models from Morley+ 2012, Morley+ 2014
see also Skemer+ 2014
Wise 0855 (250 K) and Jupiter (126 K) are similar in temperature, but display different molecular features across the M-band.

Figure from Skemer+ 2016 and see Morley+ 2018
M-band Spectral Sequence: 750 K to Jupiter (Miles+ 2020)

<table>
<thead>
<tr>
<th>Name</th>
<th>Temp (K)</th>
<th>Observatory</th>
</tr>
</thead>
<tbody>
<tr>
<td>GI 570 D</td>
<td>750</td>
<td>Gemini/NIRI (Geballe+ 2009)</td>
</tr>
<tr>
<td>2MASS 0415</td>
<td>700</td>
<td>AKARI (Sorahana + 2012)</td>
</tr>
<tr>
<td>WISE 0313</td>
<td>650</td>
<td>Gemini (this work)</td>
</tr>
<tr>
<td>UGPS 0722</td>
<td>550</td>
<td>Gemini (this work)</td>
</tr>
<tr>
<td>WISE 2056</td>
<td>500</td>
<td>Gemini (this work)</td>
</tr>
<tr>
<td>WISE 1541</td>
<td>400</td>
<td>Gemini (this work)</td>
</tr>
<tr>
<td>WISE 0855</td>
<td>250</td>
<td>Gemini (Skemer+ 2016)</td>
</tr>
<tr>
<td>Jupiter</td>
<td>126</td>
<td>ISO (Encrenaz+ 1996)</td>
</tr>
</tbody>
</table>
Water is Predicted to Dominate at Equilibrium

H₂O

Normalized Flux (F_λ)

Wavelength (μm)

200 K
400 K
600 K

Miles+ 2020
M-band Spectral Sequence: 750 K to Jupiter

Normalized Flux ($F_\lambda$) vs. Wavelength ($\mu$m)
Water Can’t Explain the Spectra Alone
CO Mole Fractions Range from $10^{-4}$ to $10^{-7}$
What is Equilibrium Chemistry?
What is Equilibrium Chemistry?

CH$_4$

CO
What is Disequilibrium Chemistry?
What is Disequilibrium Chemistry?
How is Disequilibrium Chemistry Parameterized?

\[ K_{ZZ} = \frac{L^2}{\tau_{mix}} \left[ \frac{\text{cm}^2}{s} \right] \]
How is Disequilibrium Chemistry Estimated?

1. Find where the measured CO abundance occurs along a P-T profile.
2. Calculate the chemical timescale at that pressure and temperature.
3. Calculate the length scale at that pressure and temperature.
4. Repeat for P-T profiles of different surface gravities.

\[ K_{zz} = \frac{L^2}{\tau_{\text{mix}}} \left[ \frac{\text{cm}^2}{\text{s}} \right] \]
Cooler Atmospheres Have Stronger Mixing

$K_{zz}$ (cm$^2$/s) vs. Temperature (Kelvin)

- log(g) = 5.0
- log(g) = 4.7
- log(g) = 4.5
- log(g) = 4.3
- log(g) = 4.0
- log(g) = 3.7
- Jupiter (log(g) = 3.4)

Theoretical $K_{zz}$ upper limit curves log(g) = 3.5 - 5.3
Cooler Atmospheres Have Stronger Mixing

Models predict brown dwarfs and gas-giants colder than 400 K are fully convective, while warmer ones have radiative zones.

Our results show less mixing in the warmer brown dwarfs, which may be due to sluggish convection in their radiative zones.
Conclusions and Looking Forward

- Convection driven disequilibrium chemistry is a common feature of cool brown dwarfs. We should expect to see the same for future, directly imaged gas giant planets.
Conclusions and Looking Forward

- JWST Mid-IR observations will likely expand the types of molecules we can detect in the atmospheres of Y-dwarfs.

- The M-band observations shown in Miles+ 2020 are an early opportunity to understand the gas giants the community will image with HabEx/LUVIOR.