Lessons from Brown Dwarfs

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Why Brown Dwarfs?

- H$_2$-He objects with masses below H fusion limit (~78M$_J$)
- Same $T_{\text{eff}}$ range as exoplanets
- Atmospheric processes are all generally the same as planets
- Easier to observe & obtain spectra, provide learning and testing ground for exoplanets
- It happened “here” first

adapted from Burrows, Marley+ (1997)
Why Me?

- I’ve been studying brown dwarfs since 1986, before their discovery
- First exoplanet paper in 1999. Seen both fields mature along somewhat different tracks
- Been involved in a lot of “lessons learned”, including my own mistakes
- Have published on Solar Systems giants, exoplanets, and brown dwarfs
Solar Sys. Science

Exoplanets

Brown Dwarfs

• Atmospheric Processes
• Energy transport
• Chemistry
• Clouds
• Photochemistry
• Dynamics
Atmospheric Processes are Central

Energy is absorbed from incident starlight as well as transported up from interior and radiated away to space. The atmosphere is the gatekeeper for evolution, chemistry, clouds, and ultimately all observed spectra.

Brown dwarfs test our understanding of atmospheric processes and connect to solar system and extrasolar giant planets.

Goal is understanding of processes, not just reporting numbers.
Today

• Short reminder on brown dwarf atmospheres and evolution
• A selection of lessons learned
  • Clouds
  • Hazes
  • Chemistry
  • Rainout
  • Disequilibrium chemistry
• Concluding thoughts and advice
Atmospheres in Context

- Sun
- M (3000 K)
- Jupiter (128 K)
- L (1800 K)
- T (1000 K)
Chemical Equilibrium Transition

\[
\text{NH}_3/N_2 \quad CH_4/CO
\]

\[
\{\text{H}_2\text{O}\}
\]

\[
\{\text{NH}_3\}
\]

\[
\{\text{MgSiO}_3\}
\]

\[
\{\text{Fe}\}
\]

\[
\{\text{Al}_2\text{O}_3\}
\]

\[
\{\text{Ca}_4\text{Ti}_3\text{O}_{10}\}
\]

\[
\text{NH}_3/\text{N}_2
\]

\[
\text{CH}_4/\text{CO}
\]

\[
\text{CH}_4 < \text{CO}
\]
Chemical Transition

![Diagram](attachment:image_url)

- NH$_3$/N$_2\quad$CH$_4$/CO
- (H$_2$)
- Sun
- M (3000 K)
- L (1800 K)
- Jupiter (128 K)

$T$ (1000 K)

$P$ (bar)

$\text{CH}_4 > \text{CO}$
LESSONS
Clouds
Clouds

• Long been appreciated that clouds would condense (since 60s)

• Cloud behavior is fundamental aspect of brown dwarf spectra and photometry

• Clouds are intrinsically 3D but need to start with 1D to solve
  • Particle composition, size, distribution matter
  • Possible time variability
  • Easy to see their effects but hard to fingerprint

Gao+ (2021)
Marley & Robinson (2016)
Thermal Emission

$T_{\text{brt}}$ or Flux

Marley & Robinson (2016)

Wavelength
Marley & Robinson (2016)
Cloud Modeling Schools

**Top - Down**
- Helling et al.
- CARMA
- **Fixed**
- Tsuji, Burrows

**Bottom - Up**
- Ackerman & Marley,
- PICASO
- Exo-REM (Charnay et al.)
- **Chemical Equilibrium**
- PHOENIX - DUSTY
- Sedimentation
Cloud Modeling Schools

**Top - Down**

- Microphysics
  - Need seeds up here
- Helling et al.
- CARMA
- Fixed
- Tsuji, Burrows

**Bottom - Up**

- Ackerman & Marley, Eddysed
- Exo-REM (Charnay et al.)

**Chemical Equilibrium**

- PHOENIX - DUSTY

No microphysics, Not really 3D
2MASS 1439 (L1)

$T_{\text{eff}}=2100$ K, $\log g=5.0$, $f_{\text{sed}}=2$
2MASS 1439 (L1)

$T_{\text{eff}} = 2100$ K, $\log g = 5.0$, $f_{\text{sed}} = 2$

$T_{\text{eff}} = 2100$ K, $\log g = 5.0$, $f_{\text{sed}} = \text{nc}$
2MASS 1507 (L5)

$T_{\text{eff}} = 1700$ K, $\log g = 4.5$, $f_{\text{sed}} = 2$

$T_{\text{eff}} = 1700$ K, $\log g = 4.5$, $f_{\text{sed}} = \text{nc}$
DENIS0255 (L8)

$T_{\text{eff}}=1400 \, \text{K}$, $\log g=4.5$, $f_{\text{sed}}=2$

$T_{\text{eff}}=1400 \, \text{K}$, $\log g=4.5$, $f_{\text{sed}}=\text{nc}$

- $f_\nu$ (10$^{-25}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$)
- $\lambda$ (\mu m)
2MASS 0559 (T4.5)

$T_{\text{eff}}=1300$ K, \( \log g=4.5 \), \( f_{\text{sed}}=\text{nc} \)
2MASS 0559 (T4.5)

$T_{\text{eff}}=1300$ K, $\log g=4.5$, $f_{\text{sed}}=nc$

$T_{\text{eff}}=1300$ K, $\log g=4.5$, $f_{\text{sed}}=2$
• Broadband signature is unmistakable
• Silicate absorption more subtle
• Easier with JWST
• Clouds can change dramatically in just 100K. Why?

Cushing+ (2006)
Clouds

- Silicate spectral signature present in brown dwarfs...will be seeing for exoplanets

- Exactly which species and characteristics still unknown (SiO$_2$, MgSiO$_3$, Mg$_2$SiO$_4$...learn a little mineralogy!). Need to start considering:
  - Mg/Si ratio (when does SiO$_2$ form?)
  - Crystalline/amorphous

- Lots of room for improvement but remember clouds are hard even for Earth’s atmosphere

- Need more powerful & flexible models

- **Advice:** Regardless of which model you use, aim for underlying physical understanding, not just reporting parameters for a model (e.g., $f_{sed}$=2)

_Burningham+ (2021)_
GL 229B the First Brown Dwarf and a Lesson Learned

- H$_2$, He atmosphere w/CH$_4$, H$_2$O
- Jupiter size
- ~60x Jupiter mass
- ~900 K, like young Jupiter

Marley+ (1997)
The brown dwarf Gliese 229B has an observable atmosphere too warm to contain ice clouds like those on Jupiter and too cool to contain silicate clouds like those on low-mass stars. These unique conditions permit visibility to higher pressures than possible in cool stars or planets. Gliese 229B’s 0.85- to 1.0-micrometer spectrum indicates particulates deep in the atmosphere (10 to 50 bars) having optical properties of neither ice nor silicates. Their reddish color suggests an organic composition characteristic of aerosols in planetary stratospheres. The particles’ mass fraction (10⁻⁷) agrees with a photochemical origin caused by incident radiation from the primary star and suggests the occurrence of processes native to planetary stratospheres.
Burrows, Marley, Sharp (2000)

Nope: overlooked opacity

Na

K
“Haze” is often invoked to explain NUV-Visible slopes of exoplanets.

Be careful!

Sedaghati et al., 2017
see also Sing et al., 2015, etc., etc., etc.
Rainout Chemistry

Are condensed species really removed from equilibrium with the gas phase? Lewis termed this “rainout chemistry”. Canonical example is Fe and H₂S in Jupiter.

We test by seeing when Na, K are lost from the atmosphere. KCl vs. albite NaAlSi₃O₈. Does Al₂O₃ sequester Al?
What Happens to Condensed Species?

Retrieval methods test tens of thousands atmospheric composition to find the best fitting abundances.

Lesson Learned:
Rainout – not equilibrium – chemistry is the correct choice. Exemplifies the type of understanding we should be aiming for, trend & process are important not the raw abundances.

Alos an example of the brown dwarf-planetary connection
Disequilibrium Chemistry
Disequilibrium Chemistry

- Observed chemical composition departs from that expected in chemical equilibrium
- Vertical and horizontal transport vs. chemical equilibrium timescales
- 200+ papers on exoplanet disequilibrium chemistry in ADS

Saumon+ 2003
But “Disequilibrium Chemistry” Has a Long History

• Understood since 1970s in Jupiter’s atmosphere
• Fegley & Lodders (1996) predicted for brown dwarfs; Noll et al. (1997) confirmed CO-CH₄ disequilibrium
• Tends to be a focus of BD & exoplanet literature
• But not that surprising for giant exoplanets
  • Both vertical and wind driven expected

• **Lesson Learned:** We don’t need any more simple examples of CO-CH₄ disequilibrium
• Too often used as a crutch for “abundances are not what we expect” or “proposed observations will search for disequilibrium chemistry”

(Lodders & Fegley 1994). However, as noted by Fegley & Lodders, CO in Gl 229B’s upper atmosphere could be present in abundances greater than predicted by thermochemical equilibrium if convective transport is sufficiently rapid compared with the CO-CH₄ equilibrium reaction timescales. This effect is observed in Jupiter’s atmosphere (Prinn & Barshay 1977; Noll et al. 1988). The CO abundance we derive is consistent with equilibrium at T ≥ 1250 K according to Fegley & Lodder’s (1996) models. The presence of CO at qCO > 50 ppm at T ≤ 800 K indicates that some mechanism like convective quenching must be at work in the atmosphere of Gl 229B.

Noll, Geballe, Marley (1997)
Lesson: BDs Point to Better Disequilibrium

- What can we do with it?
- Measure mixing timescales
- Relate to atmospheric structure
- Can we infer $K_{zz}(z)$?
- Does it make sense?
- Feedbacks to structure, spectra?

Upper limits $f(g)$

Inferred $K_{zz}$

- $\log(g) = 5.0$
- $\log(g) = 4.7$
- $\log(g) = 4.5$
- $\log(g) = 4.3$
- $\log(g) = 4.0$
- $\log(g) = 3.7$

Jupiter ($\log(g) = 3.4$)

Theoretical $K_{zz}$ upper limit curves $\log(g) = 3.5 - 5.3$
Some Lessons from Brown Dwarfs

- Most all exoplanet atmosphere topics were studied in brown dwarfs first.
- Worthwhile to take time to look at the literature and see where the BD science went and what it focused on.
- Some specific lessons:
  - Clouds are hard, we are not there yet (don’t trust any models).
    - Don’t focus on model parameters too much yet.
  - Don’t blame clouds and hazes for every shortcoming.
  - Take rainout chemistry seriously.
  - Time to move on with disequilibrium chemistry. What is driving $K_{zz}$?
- Focus on understanding trends and physical processes.