The Brown Dwarf - Exoplanet Connection

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What is a brown dwarf?

Low-mass objects with properties intermediate between stars and planets.

“Failed stars” - form like stars, found as isolated systems, can host their own planetary systems.

“Super-Jupiters” - do not fuse hydrogen, sizes comparable to Jupiter, planetary atmospheres.
models from Burrows et al. (2001)

Effective Temperature (K)

Time (Gyr)

Stars

Brown Dwarfs

sustained H-burning

0.075 \( M_\odot \)

(Z dependent)

insufficient H-burning

no fusion of any element

“Planemos”
**spectral types**

**M dwarfs** (3500-2100 K)
magnetically active, only the youngest brown dwarfs are classified M-type

**L dwarfs** (2100-1300 K)
molecule-rich atmospheres contain clouds of “hot dirt” and other condensates

**T dwarfs** (1300-600? K)
coldest known brown dwarfs, atmospheres contain CH$_4$ and NH$_3$ gases
Brown dwarf & Planetary Spectra

Marley & Leggett (2008)
data from Cushing et al. (2005,2007)

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data from Cushing et al. (2005,2007)

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Overview

Similarites between brown dwarf and exoplanet atmospheres

Differences between brown dwarf and exoplanet atmospheres

Focus on condensate cloud formation/evolution
Similarities

Compact radii ($R_{BD} \sim R_{jup}$ for $t > 100$ Myr)

Cool atmospheres ($T_{eff} \sim 3000 - 550$ K)

Similar (but not identical) surface gravities
Chabrier et al. (2008)
models by Baraffe et al. (2003)
Similarities

Compact radii ($R_{BD} \sim R_{jup}$ for $t > 100$ Myr)

Cool atmospheres ($T_{\text{eff}} \sim 3000 - 550$ K)

Similar (but not identical) surface gravities
Cool Brown Dwarfs

- 2000 K
- 1750 K
- 1550 K
- 1400 K
- 1250 K
- 1100 K
- 1000 K
- 950 K
- 850 K
- 750 K
- 575 K

L dwarfs
1300-2100 K

T dwarfs
600?-1300 K

ULAS 1335
(Burningham et al. 2008)

Hot Exoplanets

Fortney et al. (2008)

OGLE-TR-56
OGLE-TR-132
WASP-1
TrES-3
HAT-P-5
TrES-2
TrES-10
HAT-P-3
HD1989458
HD147506
XO-2
HD189733
TrES-2

GJ 436b
HD 17156

Planet Gravity (cm s⁻²)
Cold Brown Dwarfs

2MASS J0939-2448

$T_{\text{eff}} = 600\ K$, $L = 10^{-6}\ L_{\text{sun}}$ brown dwarf binary

(Burgasser et al. 2008)
Similarities

Compact radii \( (R_{\text{BD}} \sim R_{\text{jup}} \text{ for } t > 100 \text{ Myr}) \)

Cool atmospheres \( (T_{\text{eff}} \sim 3000 - 550 \text{ K}) \)

Similar (but not identical) surface gravities
Approximate Brown Dwarf Spectral Type Scale

- OGLE-TR-56b
- OGLE-TR-132b
- HAT-P-2b
- GJ 436b
- CoRoT-Exo-3b
- Beta Pic b
- HR 8799b
- HR 8799c/d
- Gl 618.1B
- Gl 584C
- Gl 570D
- 2M1207B
- AB Pic B
- M9
- L0
- L5
- T0
- T5
- T8
- Y?

Evolutionary models from Burrows et al. (1997, 2001)

Log Surface Gravity (cgs)

Equilibrium/Effective Temperature (K)

VO(g)/V(s)

TiO(g)/Ti-x(s)

Li(g)/LiCl(s)

CO/CH₄

K(g)/KCl(s)

N₂/NH₃

H₂O(g)/H₂O(s)

Planets

Brown Dwarfs

Evolutionary models from Burrows et al. (1997, 2001)

Equilibrium chemical transitions at 1 bar (Lodders & Fegley 2006)

Equivalent chemical transitions at 1 bar (Lodders & Fegley 2006)

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Differences

Metallicities: $[\text{M/H}] \sim -2 \ldots +0.75$ (BDs) vs. $[\text{M/H}] \sim 0.5 \ldots 1.6$ (JSUN)

No external drivers for brown dwarf atmospheres – wind, jets & inversions?

Rotation rates: Jup: 11 hr, BD: $\sim 4$ hr: influences magnetic activity, surface winds
Burgasser et al. (2009)
see also Scholz et al. (2004,2008); Lepine et al. (2003,2005,2007)
Differences

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Harrington et al. (2006); Cowan et al. (2007); Knutson et al. (2007, 2009)
Thermal inversions in exoplanet spectra

Burrows et al. (2007); Fortney et al. (2008)
also Deming et al. (2005); Richardson et al. (2007); Knutson et al. (2008)
exoplanets with & without stratospheres

Fortney et al. (2008)
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Brown Dwarfs are Dizzy

80 km/s max (P<1.5 hr)

30 km/s typical (P<4 hr)

10 km/s “floor” (P<12 hr)
(similar to Jupiter)

3 km/s (P~3d) Hot EPs

Reiners & Basri (2008)

see also Mohanty et al. (2002), Mohanty & Basri (2003), Bailer-Jones (2004); Reiners & Basri (2006), Blake et al. (2007)
Detailed Physics Revealed in Brown Dwarf Atmospheres

- Warm (high J) molecular opacities
- Heavily pressure-broadened line profiles
- Condensate grain and cloud formation
- Vertical mixing and non-equilibrium chemistry
Detailed Physics Revealed in Brown Dwarf Atmospheres

Warm (high J) molecular opacities

Heavily pressure-broadened line profiles

Condensate grain and cloud formation

Vertical mixing and non-equilibrium chemistry
Condensation in BD Atmospheres

At the atmospheric temperatures and pressures of late-M and L dwarfs, several gaseous species form condensates.

e.g.:
- $\text{TiO} \rightarrow \text{TiO}_2(\text{s}), \text{CaTiO}_3(\text{s})$
- $\text{VO} \rightarrow \text{VO}(\text{s})$
- $\text{Fe} \rightarrow \text{Fe}(\text{l})$
- $\text{SiO} \rightarrow \text{SiO}_2(\text{s}), \text{MgSiO}_3(\text{s})$

Marley et al. (2002)
Lodders & Fegley (2006)
Condensation

Disappearance of TiO & VO bands signals transition between M and L spectral classes.

Removal of opacity strengthens other features, notably alkalis
Chabrier et al. (2000)
See also Ackerman & Marley (2001); Allard et al. (2001); Cooper et al. (2003); Helling et al. (2008)

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Direct detection of condensates

Excess absorption at 8-11 μm is coincident with silicate features, grain sizes < 1 μm.

Cushing et al. (2006)
see also Burgasser et al. (2007); Helling et al. (2007); Looper et al. (2008)

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Clouds in L Dwarfs

Ackerman & Marley (2001)
see also Allard et al. (2001); Cooper et al. (2003); Helling et al. (2008)
Cloud Variations

Burgasser et al. (2008)
see also McLean et al. (2003); Knapp et al. (2004); Cruz et al. (2007); Cushing et al. (2008)

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Temporal variations?

While there are clear indications of periodic variability in a few sources, they are weak and often aperiodic.

Clarke et al. (2002); Goldman et al. (2008)
See also Bailer-Jones & Mundt (1999, 2001); Bailer-Jones (2002, 2008); Bailer-Jones et al. (2003); Gelino et al. (2002); Enoch et al. (2003); Koen (2003, 2004, 2005, 2006, 2008); Caballero et al. (2004); Morales-Calderon et al. (2006)

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Chabrier et al. (2000)
See also Ackerman & Marley (2001); Allard et al. (2001); Cooper et al. (2003); Helling et al. (2008)

Cloud-free model

Cloudy model

L dwarfs

T dwarfs

Cloud depletion
Burrows et al. (2006)
See also Dahn et al. (1999); Ackerman & Marley (2001); Marley et al. (2002); Tinney et al. (2003); Tsuji (2003,2005); Saumon & Marley (2008)
Flux-reversal binaries

Liu et al. (2006); Burgasser et al. (2006)
See also Gizis et al. (2003); Cruz et al. (2004); Burgasser (2007,2008); Looper et al. (2008)

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What Drives Cloud Loss?

- Sudden change in sedimentation efficiency?
- “Break-up” of clouds? (cf. Jupiter)
- Compression of clouds?
- Transition $T_{\text{eff}}$ varies with log $g$, [M/H], other…

Several warm EPs have L/T transition $T_{\text{eff}}$s

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**Rhines Length** = $R \times (U/2V_{eq} \cos \Phi)^{1/2} \approx 0.05 \, R$

Scale at which east-west rotation causes elongation of turbulence; **banding scale**

**Rossby Deformation Radius** = $NH/2 \, \Omega \sin \Phi \approx 0.1 \, R$

Scale over which pressure perturbations are tempered by Coriolis forces: **vortex scale**

Jupiter, Saturn << 1; Hot Jupiters ≈ 1

brown dwarfs probably have global structures
Summary

Brown dwarfs & exoplanets share physical properties, but differ in fundamental ways – care must be taken in drawing analogies.

Condensate clouds are prominent in brown dwarf & exoplanet atmospheres, dynamical (mixing) effects must be considered for both evolution & structure.