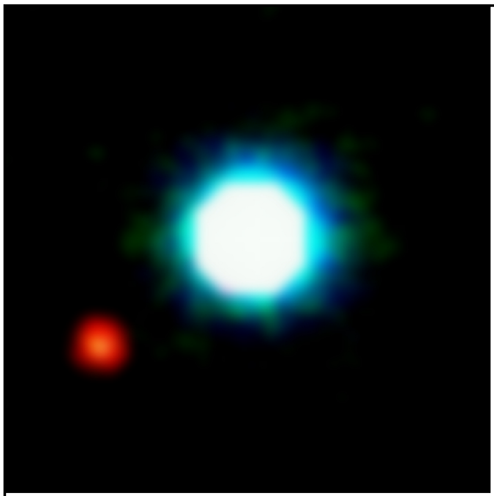

Chavin et al. 2004, 2005

Chemistry of Brown Dwarfs & Exoplanets

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Outline

What are exoplanets & brown dwarfs, and why study them?

Companions to stars - what counts as a planet?

Spectral signatures - atmospheric chemistry

Exoplanets
= Extra-solar system planets;
planets around other stars
defined upper mass limit of 13 Jupiter masses

Why study exoplanets?

Answer the question if the solar is system unique.

Other worlds like Earth?

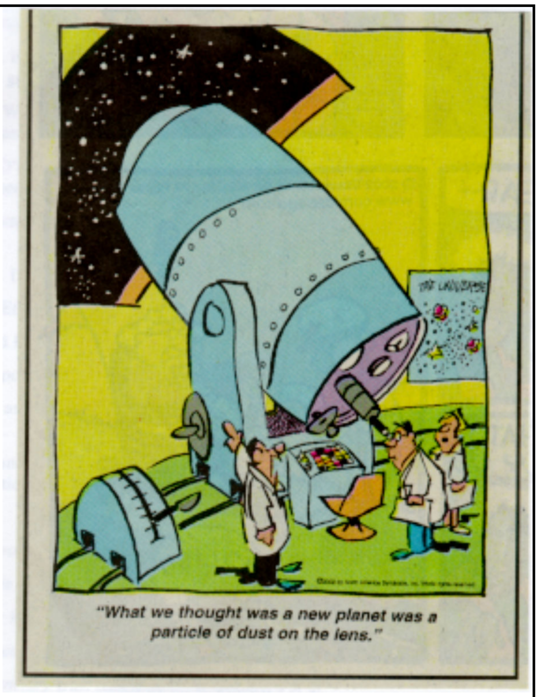
Information about formation processes of planetary systems.

Origin of our solar system

Early 1990s:
No other stars with planets?

No known objects with masses between that of "real stars" and Jupiter
Lowest mass for a "real star"
is ~ 70 Jupiter masses
(~ 0.07 M_{Sun})

Now many cool substellar companions to stars are known
exoplanets & brown dwarfs



"What we thought was a new planet was a particle of dust on the lens."

Direct detection is difficult:

Exoplanets

- far away faint objects around a bright star
- light contrast ratio star/planet 10^{10} (optical), 10^{7} (IR)
- gas giant planets in our solar system reflect visible light from sun and emit mid-infrared radiation

best searched for at infrared wavelengths

planets and brown dwarfs have no lasting internal nuclear energy source like stars

- they release gravitational energy gained during their formation and from contraction
- surface areas are smaller than stars and
- they contain **molecules** that absorb radiation (in far red, IR)

Currently 288 known exoplanets in 249 systems

(9 May 2008)

Jean Schneider, Exoplanet Encyclopedia at http://exoplanet.eu/catalog.php

most planets searched for and found around

other stars like the sun

first detection, 51Peg b, announced in 1995

4 planets around 2 pulsars (supernova remnants)

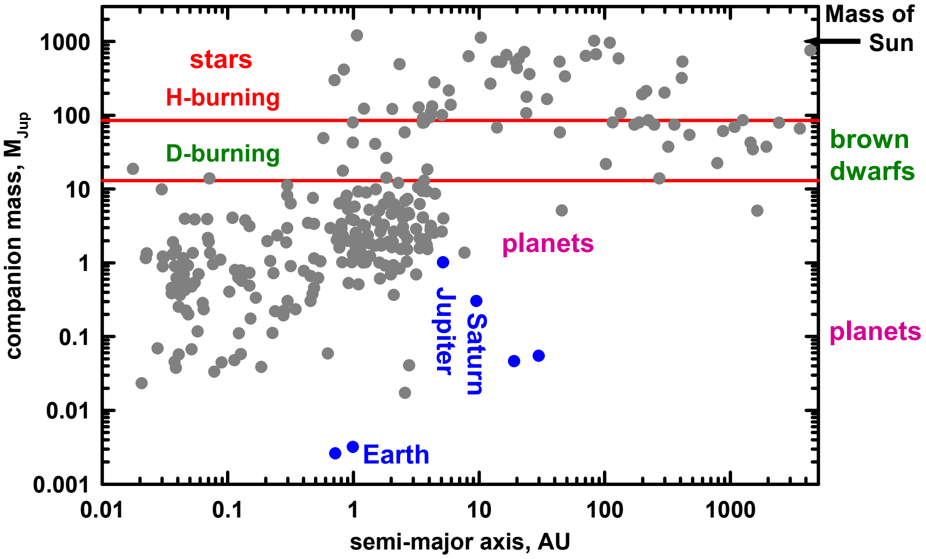
very first exoplanet detection in 1992

also planets around giant stars, white dwarfs

Stars with planets are not rare

but were not easy to detect in the past

Companions to Stars: Planets, Brown Dwarfs, and Stars



Brown dwarfs cannot burn H ("failed stars") but can burn D
Most *known* exoplanets close to host stars; lack of planets at larger orbital distances is observational bias from detection methods

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Many brown dwarfs are companions to "real" stars.
L dwarf GD165B is a companion to a white dwarf star at 120 AU
T dwarf Gl 229B is a companion to a M dwarf star at 44 AU

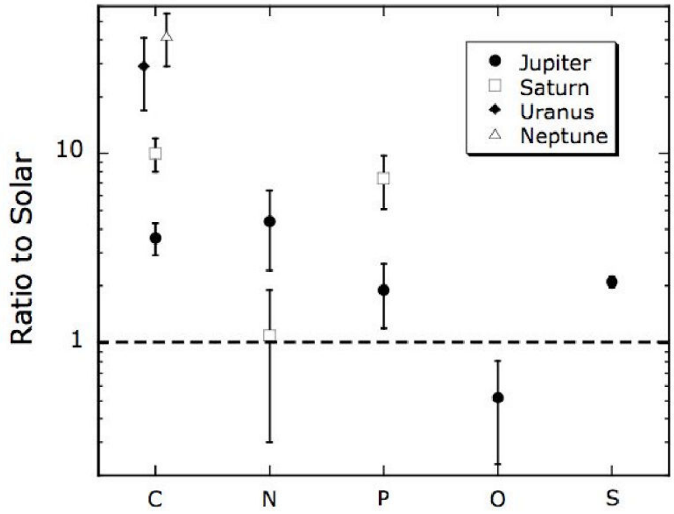
13 M_{jup} from D-burning as lower BD mass limit is a somewhat arbitrary boundary.
Do BDs form like stars or planets?

Principal formation modes:
Stars: Molecular cloud and disk fragmentation

Planets: disk fragmentation:
companion composition = star composition
core accretion:
expect heavy element enrichment

Formation mode leaves imprint on chemistry:
Heavy element enrichments in our gas giant planets when compared to the Sun

Gas giant planets in the solar system are enriched in heavy elements relative to the Sun → Core accretion



exoplanets…

Need to know composition of exoplanets to understand formation mode
→ Need to understand exoplanet spectra
→ Need to understand chemistry

Brown dwarfs: Links in mass between giant planets
and real stars **13 – 75 M_{Jup}**
-cannot burn hydrogen but burn deuterium
-radii are within 15% of Jupiter’s radius
have cool atmospheres (< ~2500 K) that keep cooling
-molecular and condensation chemistry is important

There are **2 types** of brown dwarfs:
L dwarfs their spectra look more like that of the coolest stars
gases: (TiO, VO) **CrH, FeH, Na, K**
condensate clouds
T dwarfs are the cool brown dwarfs that show **methane** and
resemble gas giant planets like Jupiter

Spectral signatures (= chemistry) of brown dwarfs is a guide for chemistry in exoplanets

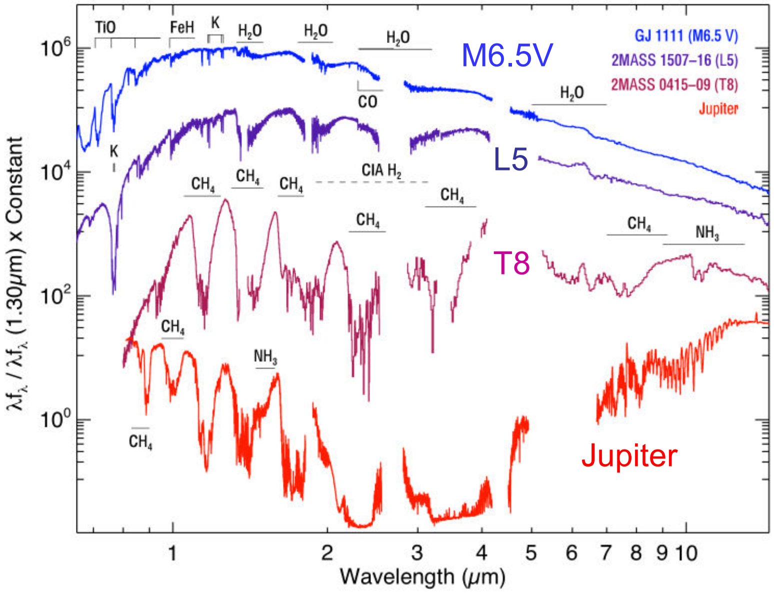


Figure from Mark Marley

> 600 brown dwarfs known & observed

1988: GD165B Becklin & Zuckerman 1988

Now known as the first brown dwarf discovered, but at the time, it looked too much like a very cool M star (TiO, VO)

1995: Gl 229B Nakajima et al. 1995, Oppenheimer et al. 1995

First bona-fide brown dwarf showing ***methane*** absorption

1999: The ***spectral classification*** *of stars* is extended by types **L, T**, and Y for *substellar objects*

(Kirkpatrick et al. 1999, 2000; Martin et al. 1999)

O B A F G K M L T Y
stars brown dwarfs

O B A F G K M L T Y
stars brown dwarfs

Spectral classification from O to T is a proxy for temperature

Subgroup numbers (M0, M1, ..M9) indicate hotter (0) to colder(9)

M9 dwarfs - the coolest stars

M/L transition T_{eff} ~ 2500 K

TiO, VO disappear condensates

L0 dwarfs - hottest brown dwarfs

L9 dwarfs - coolest L dwarfs

L/T transition T_{eff} ~ 1300 – 1500 K

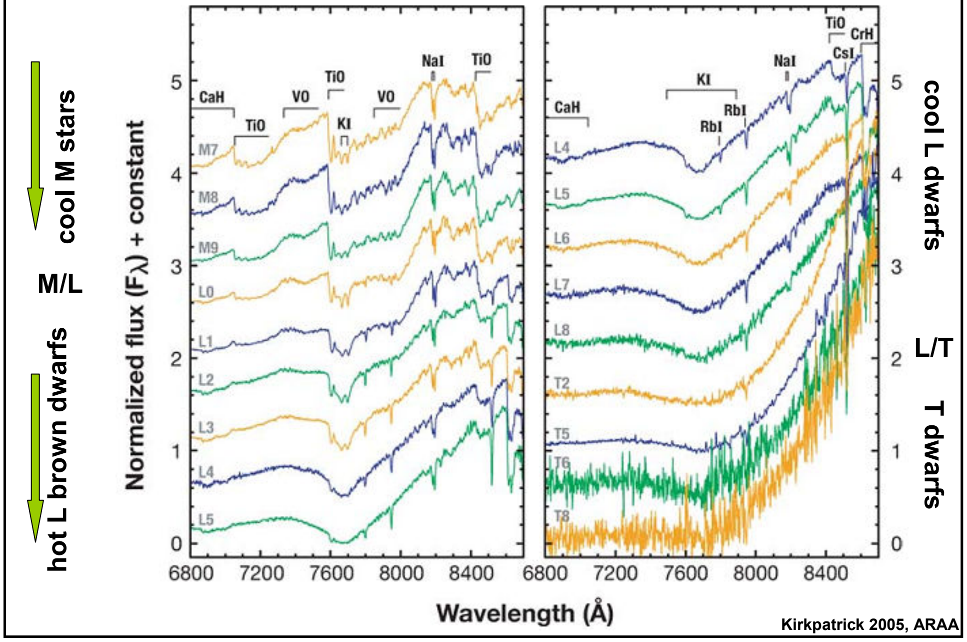
methane appears

T0 dwarfs – brown dwarfs showing **methane**, CH_4, absorption in K & H band

T8 dwarfs - coolest brown dwarfs currently known, T_{eff} ~ 700K

Y dwarfs - without H_2O absorption, T_{eff} <~450 K - not yet found

Optical spectra: M → L → T dwarfs: TiO, VO disappear. FeH, CrH come and go (better in IR) - Na, K, Rb, Cs become strong and go



Kirkpatrick 2005, ARAA

The brown dwarf – exoplanet connection

Brown dwarfs and exoplanets have no internal heat source like stars and cool over time

The cooling time depends on mass and overall composition

Temperatures depend on mass and age

(Burrows et al. 1997, Chabrier et al. 2000, Baraffe et al. 2003)

Spectral types (M, L, T) tracks temperature:
For example, a L0 dwarf with T_{eff} ~ 2500 K could be

A later M dwarf star	**0.085 $M_\odot$**	**age ~ few Ga**
A "young" brown dwarf	**0.075 $M_\odot$**	**age ~ few 100 Ma**
A very young brown dwarf	**0.020 $M_\odot$**	**age <2 Ma**
A very, very young planet	**< 0.013 $M_\odot$**	**age << 2 Ma**

Temperature has largest effect on chemistry, so what we know for brown dwarf chemistry applies to exoplanets as well

Need to understand the chemistry for model atmospheres and model spectra to derive compositions

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What is the chemistry in the atmospheres

Use thermodynamic calculations to find out

Composition of gas and condensates under thermodynamic equilibrium depends on:

- *overall elemental abundances (metallicity, C/O ratio)*
- *temperature*
- *total pressure*

83 naturally occuring elements … many possibilities…

Use solar abundances, focus on more abundant and/or observed elements

- *C, N, O, S, P, Fe, Mg, Si, Ca, Al, Ti, alkalis, …*

Use P-T conditions to encompass atmospheric conditions in giant planets, T, L, and early M dwarfs

- *100 – 3000 K, 0.001 – 1000 bars*

Many exoplanets, brown dwarfs, and low-mass dwarf stars are essentially solar-like in overall elemental composition

***low temperatures* favor molecules and condensates:**

Hot stars	*ionized atoms, neutral atoms*
..	
..	
M dwarf stars	*neutral atoms (alkalis)*
..	*gas molecule formation,*
..	*e.g., TiO, VO, FeH, CrH, CO, H_2O*
Brown dwarfs	
L	*condensate clouds*
T	*CH_4*
Gas giant planets	

Observable atmospheres are strongly influenced by gas and condensation Chemistry

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Carbon chemistry in hot and cool atmospheres

Methane - CO equilibrium depends on T and P

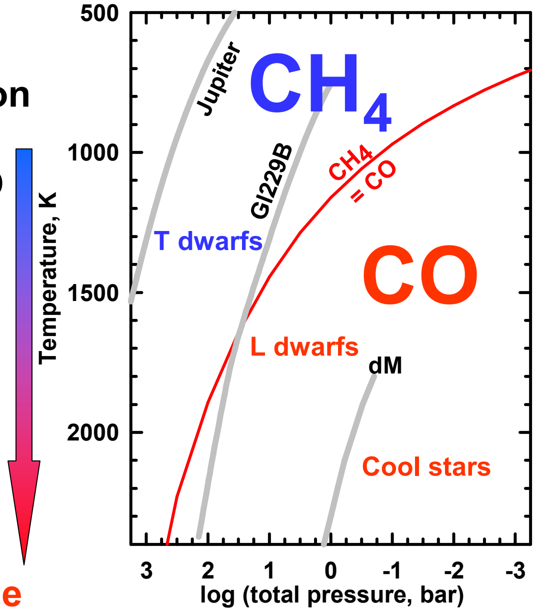
$CO + 3 H_2 = CH_4 + H_2O$

Low T & high P favor CH_4

T dwarfs = Methane dwarfs

High T & low P favor CO, cool M stars

Brown dwarfs of L type



Grey lines are model atmosphere P-T profiles

Exoplanet and Brown Dwarf Atmospheres
Type of compounds formed by the elements depend on temperature and densities in the atmosphere (application of chemical thermodynamics):

In cool Jupiter (~125 K, 1 bar level), reactive elements combine to molecular gases:
molecular hydrogen H_2 methane CH_4
ammonia NH_3 water H_2O
clouds of different rocky and icy condensates

exoplanets in close orbits are hotter (1200 – 1800 K) and different compounds form, e.g.

Cool exoplanet, T dwarf	**Hot exoplanet, L dwarf**
methane, CH_4	**carbon monoxide, CO**

Different compounds have characteristic absorption features in optical and infrared spectra, need to understand chemistry in order to model the spectra

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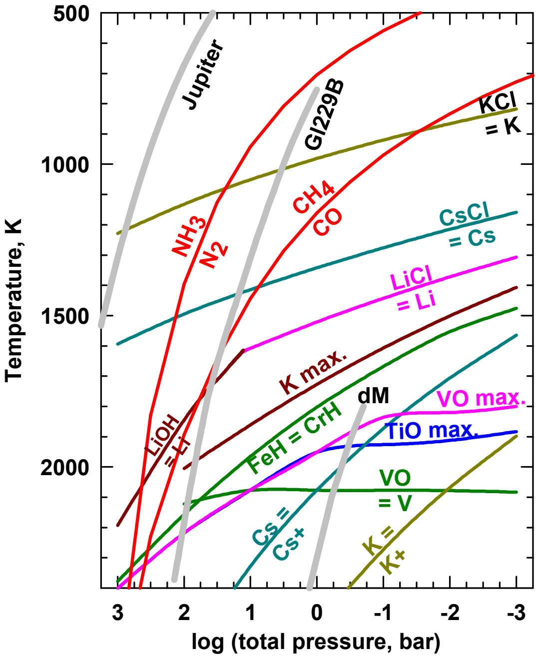
Gas-chemistry in the atmospheres: “Chemical Thermometer”



Gas giant planets and **T dwarfs**: CH_4 & H_2O
Atomic alkalis (K, Cs) disappear into chloride gases and salt clouds

Hot Pegasi Exoplanets and L dwarfs:
CO & H_2O;
TiO, VO → into *ceramics*
FeH, CrH → into metals
Monatomic Na, K, Rb, Cs

Very hot exoplanets and **M dwarf** stars: TiO, VO
Ionized and neutral alkalis

Clouds in the atmospheres

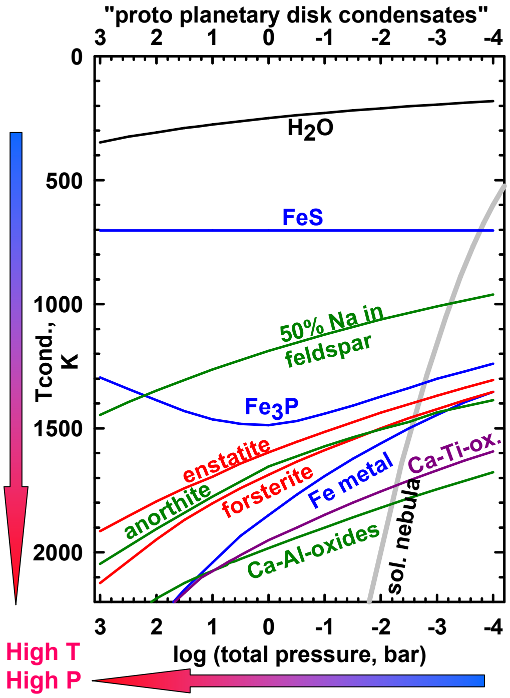
- ***low temperatures* favor molecular and *condensation* chemistry:**

Hot stars	***ionized atoms, neutral atoms***
M dwarf stars	***gas molecule formation***
Brown dwarfs:	
late M, L, & T dwarfs	***condensate formation***
Gas giant planets	

This explains condensates, but not yet the clouds

protoplanetary disks (solar nebula) or stellar winds (M giants) are also near-solar in composition and produce condensates, but in these environs condensates remain dispersed in the gas

- ***Atmospheres are strongly gravitationally bound and gravity causes condensates to settle into cloud layers***



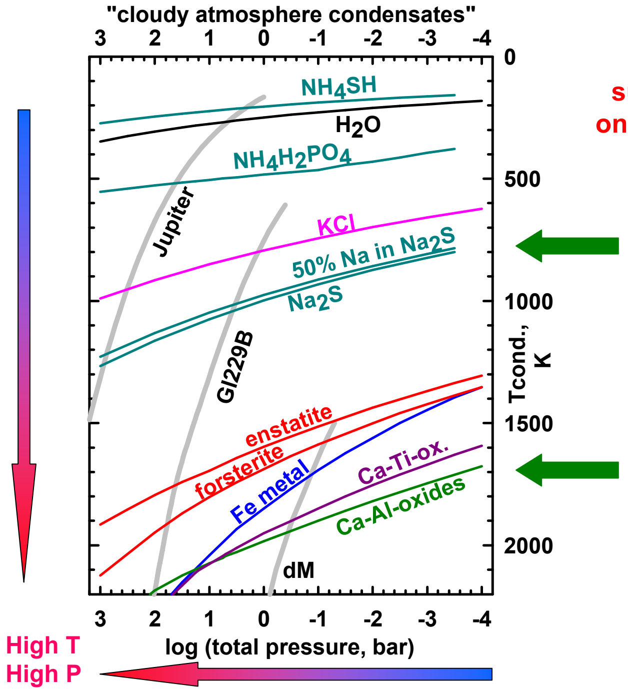
Standard condensation in a solar gas

Fe metal to Fe_3P and FeS
Forsterite to enstatite
Ca-Al-oxides to anorthite, $CaAl_2Si_2O_8$, ino which Na & K condense in solid-solution

Not all of this condensation chemistry happens in brown dwarf and exoplanet atmospheres!

Condensation temperatures decrease with decreasing total pressure. Exceptions: Fe_3P, FeS

Low P << 1 bar applies to proto-planetary disks (solar nebula), high P > 0.1 bar to atmospheres



in brown dwarfs,
alkalis condense as
sulfides and chlorides
only at low temperatures

In the absence of anorthite,
Na condenses as Na_2S
and K as KCl

Ca-Al oxides and anorthite are in a deep cloud layer
No Na and K removal into anorthite
Alkali lines remain in later L & early T

Gas and condensation chemistry in gas-giant planets and brown dwarfs is different than in proto-planetary disks or stellar winds because:

Condensate mineralogy can change at higher pressure.
Condensates settle into cloud layers.

Condensate settling changes the chemistry above the clouds

Gas-solid reactions like in the solar nebula do not occur
no Fe + H_2S = FeS + H_2, so H_2S stays in the gas to low temp.

no solid-solution of Na & K in anorthite, Na & K remain to low temperatures. Alkali gases remain in late L and early T

different condensates appear at lower temperatures
e.g., NH_4SH; alkali sulfides and chlorides

Abundant elements are responsible for forming major massive clouds

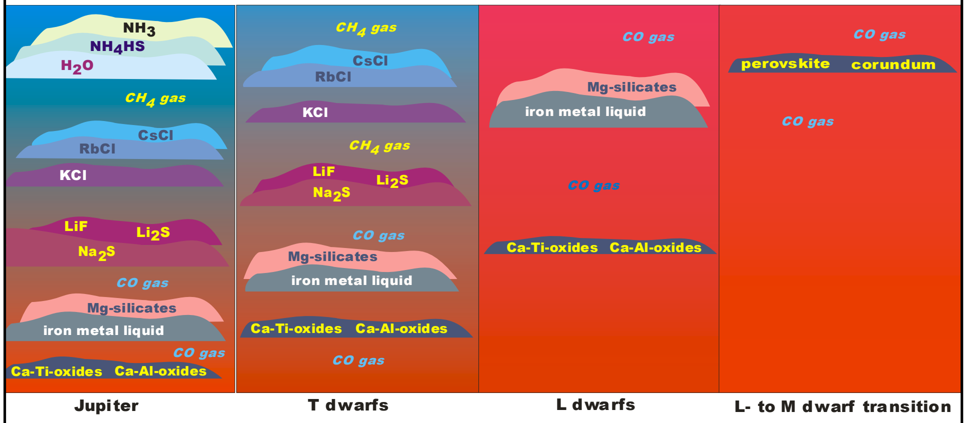
Solar abundance by number		*condenses into*	*Condensation reduces gas abundance of*
$1.4\ 10^7$	**O**	water	**H_2O**
$2.0\ 10^6$	**N**	ammonia	**NH_3**
$1.0\ 10^6$	**Mg**	magnesium silicates	**Mg, MgH**
$1.0\ 10^6$	**Si**	magnesium silicates	**Si, SiO, SiS**
$0.8\ 10^6$	**Fe**	iron metal	**Fe, FeH**
$0.4\ 10^6$	**S**	NH_4SH	**H_2S**

Somewhat less abundant elements form less massive clouds

$6.3\ 10^4$	**Ca**	ceramics	**Ca, CaH**
$8.4\ 10^4$	**Al**	Ca-Al-oxides	**Al, AlH**
$0.2\ 10^4$	**Ti**	Ca-Ti-oxides, TiN	**Ti, TiO**
$5.7\ 10^4$	**Na**	Na_2S	**Na**
$0.4\ 10^4$	**K**	KCl	**K**
$1.3\ 10^4$	**Cr**	Cr metal or Cr_2O_3 (P_{tot}!)	**CrH**
$0.8\ 10^4$	**Mn**	MnS	**Mn**
$0.8\ 10^4$	**P**	$NH_4H_2PO_4$	**PH_3**

Upper-most Cloud Decks:

ammonia ice water ice	salts	Mg-silicates (ol,px) liquid iron	refractory ceramics



Old gas giant planet

Young gas giant planet

At given MASS, the oldest object is the coolest and has the highest number of cloud layers

At a given AGE, the least massive object is the coolest and has the highest number of cloud layers

Upper-most Cloud Decks in gas giant planets:

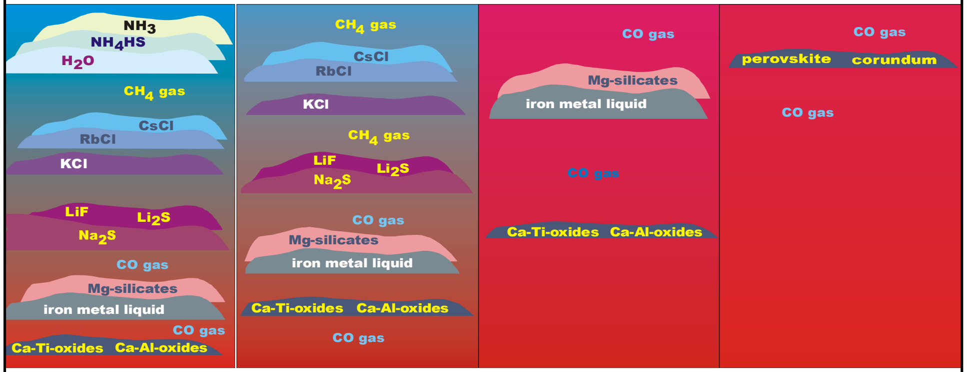
Old -- Young or close to star

ammonia ice
water ice

salts

Mg-silicates (ol,px)
liquid iron

refractory
ceramics



Jupiter

- *The coolest objects are expected to have the largest number of cloud layers*

From Lodders 2004, Brown Dwarfs – Faint at Heart, Rich in Chemistry, Science 303, 323

Summary I

Brown dwarfs: Links in mass between giant planets
and real stars **13 – 75 M_{Jup}**
- cannot burn hydrogen but burn deuterium

-have cool atmospheres (< ~2500 K) that keep cooling
-molecular and condensation chemistry is important

There are **2 types** of brown dwarfs:

L dwarfs their spectra look more like that of the coolest stars
gases: (TiO, VO) **CrH, FeH, Na, K**
Mg-silicates and Fe-metal condensate clouds
near/in the photosphere

T dwarfs are the cool brown dwarfs that show **methane** and
resemble gas giant planets like Jupiter

Spectral signatures (= chemistry) of brown dwarfs is a guide for chemistry in exoplanets

Summary II

Gas giant exoplanets and brown dwarfs can have similar ranges in atmospheric temperatures, overall elemental abundances, and similar chemistry (but different total P)

The ***temperatures*** of brown dwarfs and exoplanets* depend on **mass and age** (cooling time).

→ **Chemistry in gas giant planets resembles that in L or T brown dwarfs, depending on age**

**Complication*: “roaster” exoplanets close to their primary stars are also influenced by the stellar flux that they receive, which depends on distance and type of the host star

→ Giant planets in close orbits look similar to L-type dwarfs

Summary III: Major Chemistry Features

Molecules and condensate clouds appear

Condensation chemistry in brown dwarfs is different than in planetary accretion disks (feldspar vs. KCl condensation)

The gas chemistry tracks atmospheric temperatures and clouds: “Chemical thermometer”

e.g. removal of TiO and VO into refractory ceramic clouds at the stellar-substellar boundary, M/L dwarf transition

CO → CH_4 for hot→ cool brown dwarfs; L/T transition

Cloud formation can be tracked by the depletion of gases (weakening spectral features) that contain the elements sequestered into clouds, e.g., TiO, VO, FeH, CrH, Li, Na, K

For a recent review on this topic, see

Lodders & Fegley 2006, Astrophysics Update 2, Springer, p. 1 ff.

Several figures from this talk and more information on chemistry can be found in our papers available at:

http://solarsystem.wustl.edu

For reference, a list of minerals and their formulas can be found on the last slide.

Minerals & Their Formulas

Oxides

Corundum	Al_2O_3
Periclase	MgO
Rutile	TiO_2
Quartz	SiO_2

Calcium Aluminates

Grossite	$CaAl_4O_7$
Hibonite	$CaAl_{12}O_{19}$

Calcium Titanates

Perovskite	$CaTiO_3$
No name	$Ca_3Ti_2O_7$
No name	$Ca_4Ti_3O_{10}$

Sulfides

Troilite	FeS

Salts

Halite	$NaCl$
Sylvite	KCl

Solid-Solution Series

Melilite

Gehlenite	$Ca_2Al_2SiO_7$
Akermanite	$Ca_2MgSi_2O_7$

Olivines

Forsterite	Mg_2SiO_4
Fayalite	Fe_2SiO_4

Pyroxenes

Enstatite	$MgSiO_3$
Wollastonite	$CaSiO_3$
Ferrosilite	$FeSiO_3$
Diopside	$CaMgSi_2O_6$

Feldspars

Anorthite	$CaAl_2Si_2O_8$
Albite	$NaAlSi_3O_8$
Orthoclase	$KAlSi_3O_8$