Characterization of Extrasolar Planets

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Characterizing Planets

- Why do it?
- How to measure *M* and *R*?
- Evolution and spectral fitting
- Atmospheric modeling and spectra
- Conclusions

Why Characterize Giant Planets?

Giant Planets are **not** Interesting

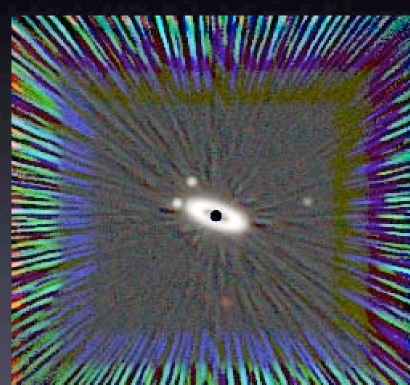
- Radial velocity & SIM will determine masses and orbits
- Giants are not interesting for astrobiology
- Giant planet science provides no heritage for terrestrial planet characterization and is a “niche” field
- Why build specialized instruments?

Giant Planets **are** Interesting

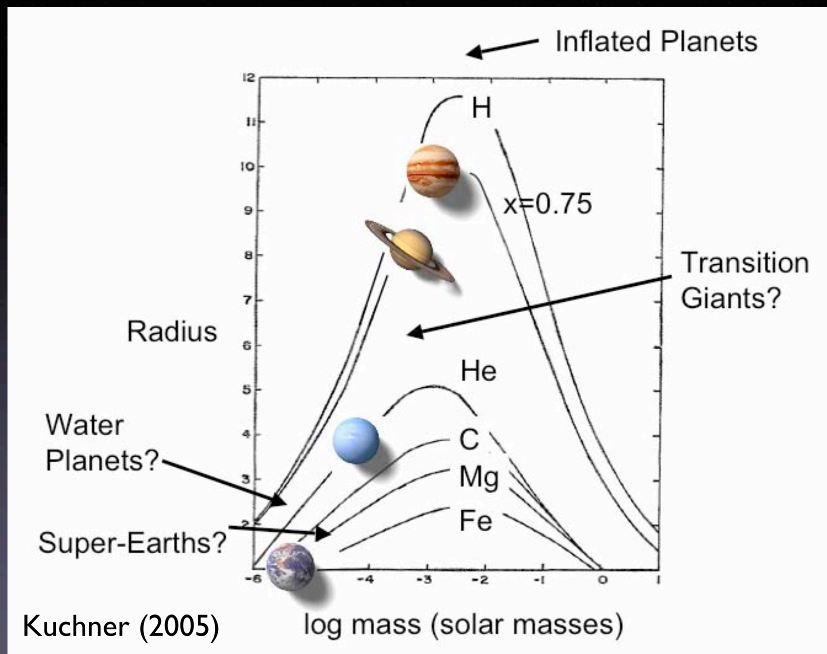
- Radial velocity & SIM will determine masses and orbits: *Planets are more than masses on springs and well characterized planets are fiducials for more distant objects*
- Giants are not interesting for astrobiology: they provide a record of stellar system formation & perhaps volatile transport
- Giant planet science provides no heritage for terrestrial planet characterization: provide end to end experience of planet characterization, heritage for bigger efforts

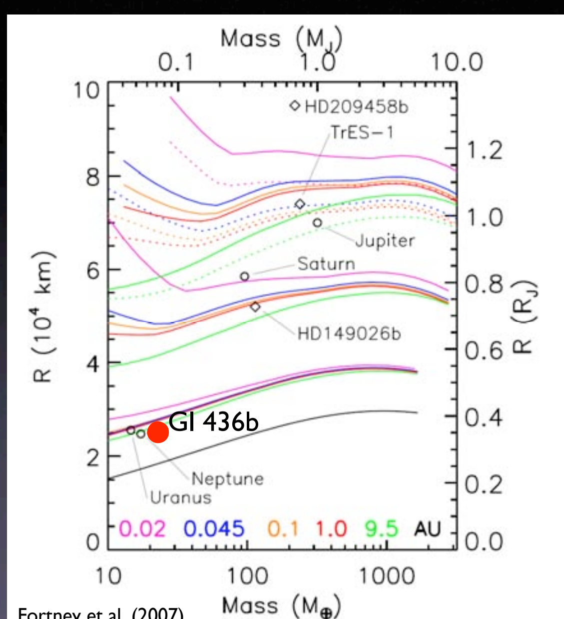
Characterization

- Mass - Images can resolve sin *i*; RV less useful for some groundbased detections (longer *P*, young stars)
- Radius - Scattered light alone does not tightly constrain radius since albedo uncertain - R^2a



Need independent M & R measures





Planet radii yield bulk composition

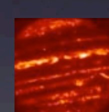
How to Constrain *M* & *R*?

Radius: IR + Visible

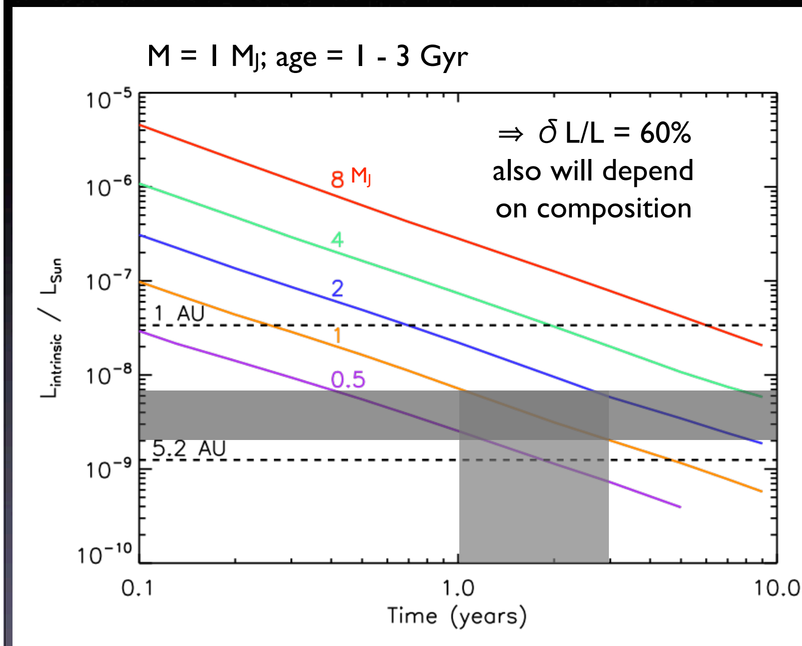
$$L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4 = (1-\Lambda)\pi R^2(\pi\mathcal{F}_\star) + L_{\mathrm{int}}$$

Mid-IR

Visible



R



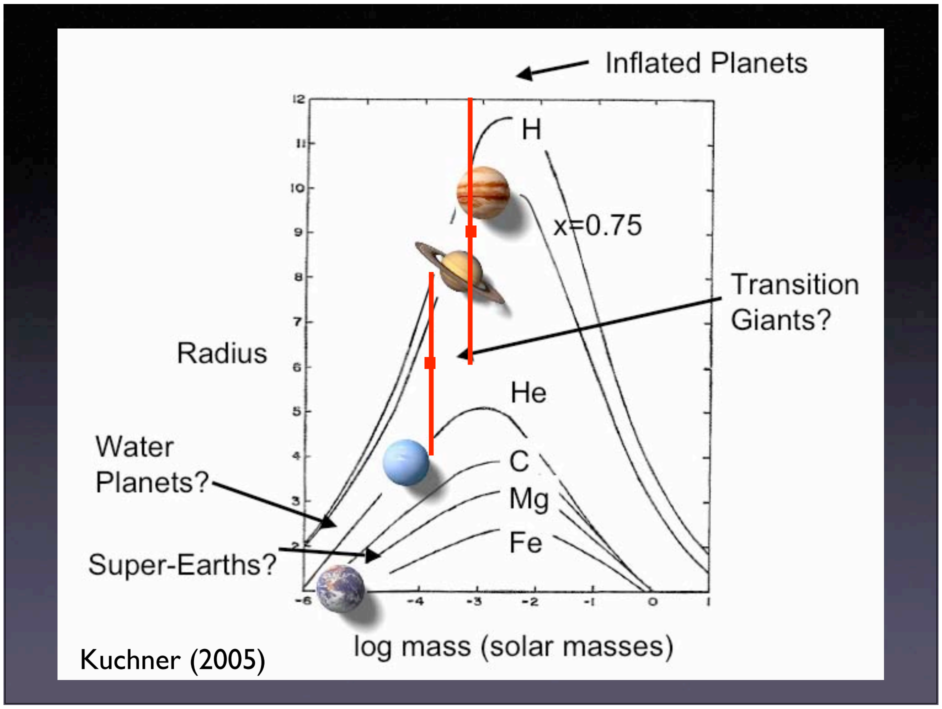
Constraining *R*

$$L = 4\pi R^2 \sigma T_{\rm eff}^4 = (1 - \Lambda)\pi R^2 (\pi \mathcal{F}_\star) + L_{\rm int}$$

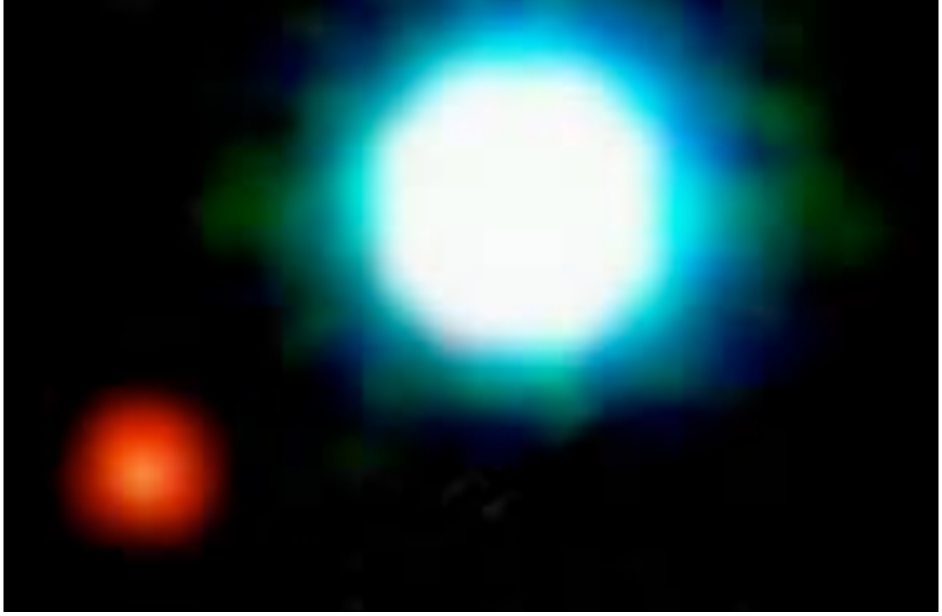
Mid-IR → *R* ← Visible

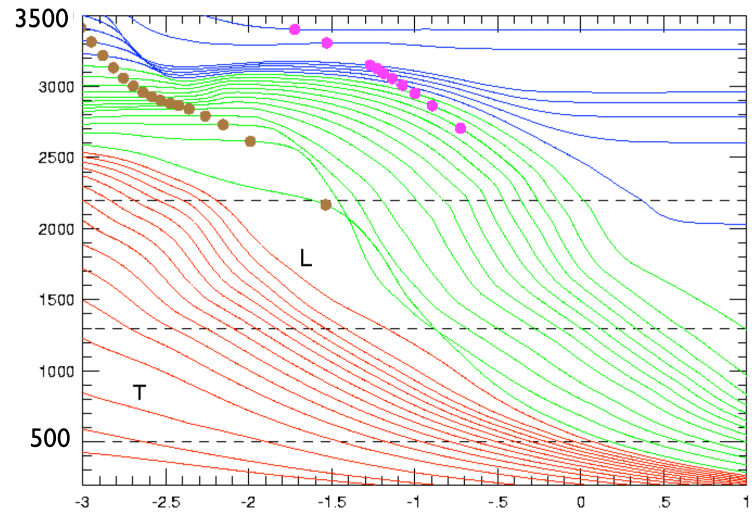
$$\frac{\delta R}{R} > \frac{1}{2}\frac{\delta L_{\rm int}}{L}$$

easily 30% or more



Mass from Evolution





A case study: Gl 570D (T8) - Saumon et al. (2003)

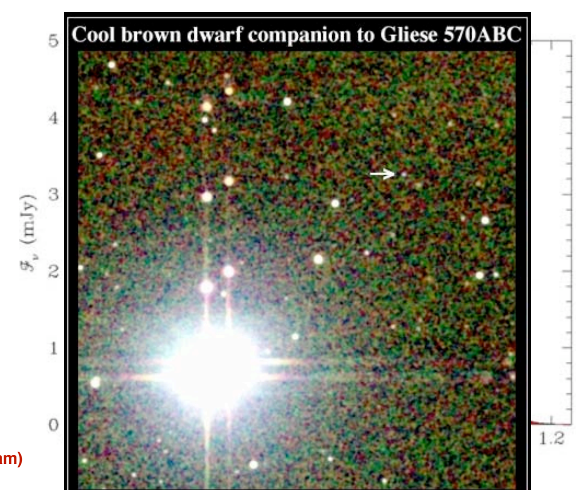
Primary (Gl 570A):

d = 5.91±0.05pc
(Perryman et al. 1997)

[Fe/H] = 0.00±0.12
(Feltzing & Gustafsson 1998)

Age = 2–5 Gyr
(Saumon et al. 2000)

Spectroscopy:
Optical (Burgasser)
Near IR (Leggett)
M' (Geballe)
Mid IRS (Spitzer/IRS Dim Suns team)



~70% of SED has been sampled

Luminosity constrains T_{eff} & g

1) bolometric correction from model spectra

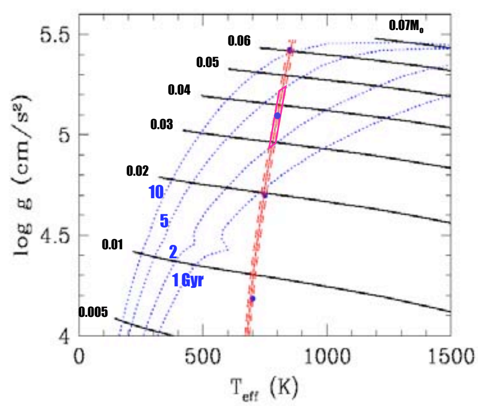
$$L_{bol}^{sp}(T_{eff}, g)$$

2) Evolution

$$L_{bol}^{evol}(T_{eff}, g)$$

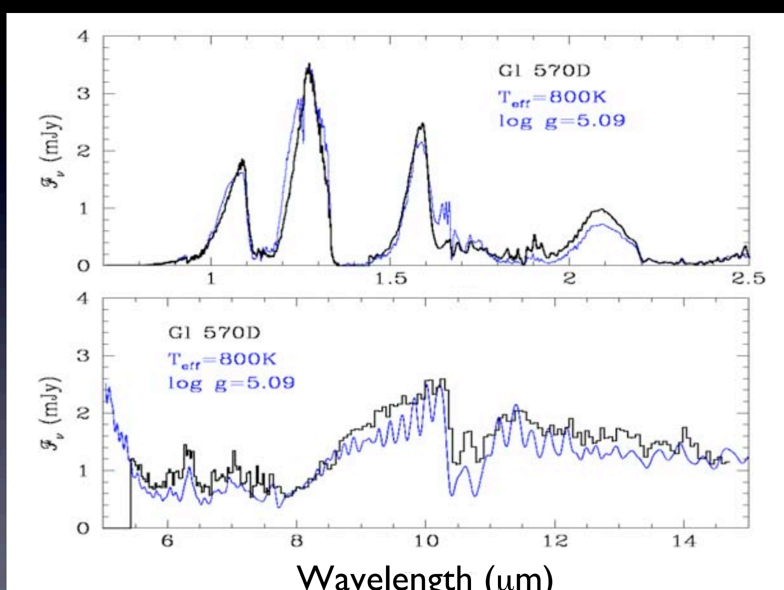
3) $T_{eff}(g)$ follows from

$$L_{bol}^{evol}(T_{eff}, g) = L_{bol}^{sp}(T_{eff}, g)$$



T_{eff}=800 K log g=5.09 L_{bol}/L_o=2.99X10^{-6}

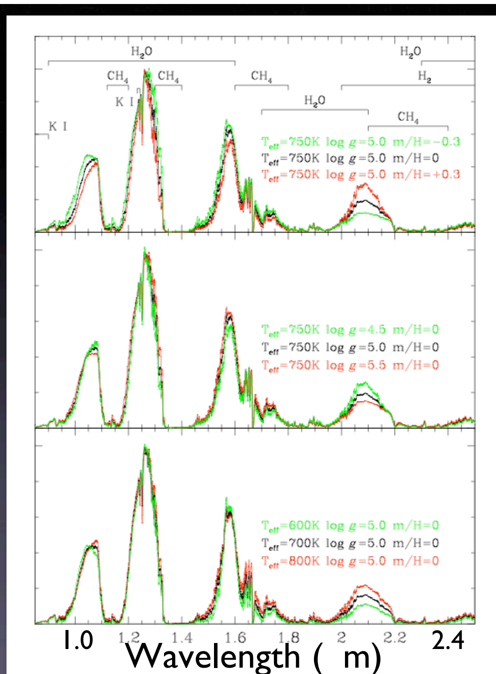
The resulting spectrum (not normalized!)



Evolution Works, But....

- Assumes companion composition = primary
- Substantial wavelength coverage to measure L_{bol}
- Gyr age primary
- Radii of mature brown dwarfs understood
- More challenging at young ages & lower masses
- Spectra most definitive

Leggett et al. (2007)



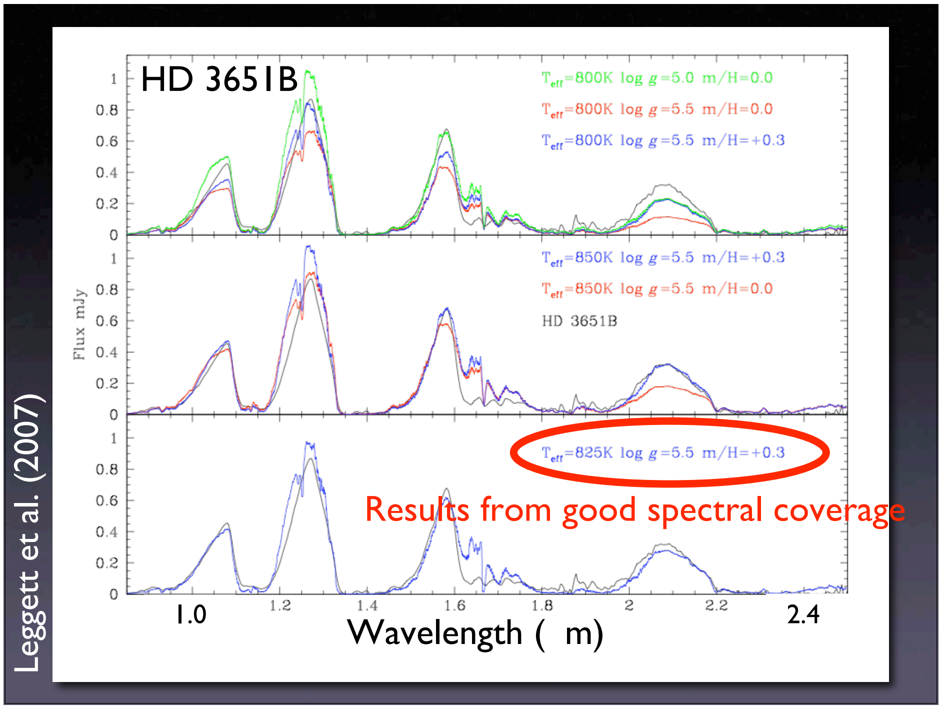
750 K, log g = 5.0, m/H = 0

Metallicity
1/2 to 2 solar

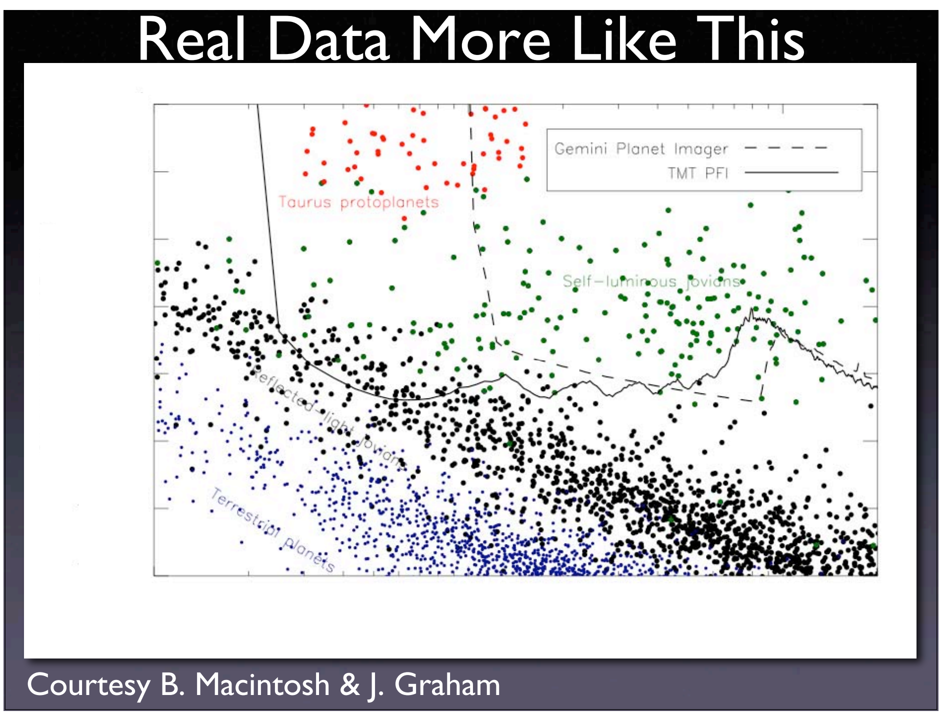
Gravity
15 - 75M_J

T_{eff}
600 to 800 K

R = 400



HD 3651B
Teff=800K log g=5.0 m/H=0.0
Teff=800K log g=5.5 m/H=0.0
Teff=800K log g=5.5 m/H=+0.3
Teff=850K log g=5.5 m/H=+0.3
Teff=850K log g=5.5 m/H=0.0
HD 3651B
Teff=825K log g=5.5 m/H=+0.3
Results from good spectral coverage
Flux mJy
Wavelength (m)
1.0
2.4
Leggett et al. (2007)



Real Data More Like This
Gemini Planet Imager
TMT PFI
Taurus protoplanets
Self-luminous jovians
Reflected-light jovians
Terrestrial planets
Courtesy B. Macintosh & J. Graham

2M1207 Companion

- Companion to ~M8 brown dwarf in TW Hydrae (age ~ 8 Myr)
- red J-K implies late L, T_{eff} ~ 1250 K
- Models give $M = 5 \pm 2\ M_{Jup}$

Chauvin et al. (2004)

Source	SpT	Age (Myr)	J (mag)	H (mag)	K (mag)	L′ (mag)
2MASSWJ1207334−393254	M8	8^{+4}_{-3}	13.00 ± 0.03 [a]	12.39 ± 0.03 [a]	11.95 ± 0.03 [a]	11.38 ± 0.10 [b]
giant planet candidate	L5-L9.5		≥ 18.5 [a]	18.09 ± 0.21 [a]	16.93 ± 0.11 [a]	15.28 ± 0.14 [b]

OPEN **BBC News in video and audio**

Last Updated: Saturday, 30 April, 2005, 15:03 GMT 16:03 UK

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Planet 'seen' around distant sun

European and American scientists say they have photographed a planet outside the Solar System for the first time.

The European Southern Observatory group said the red image is the first direct shot of a planet around another star.

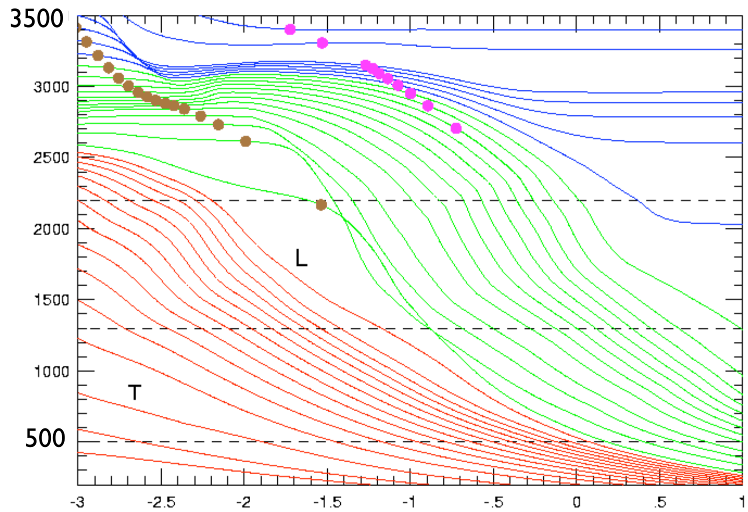
The planet (left) is about five times the mass of our Jupiter

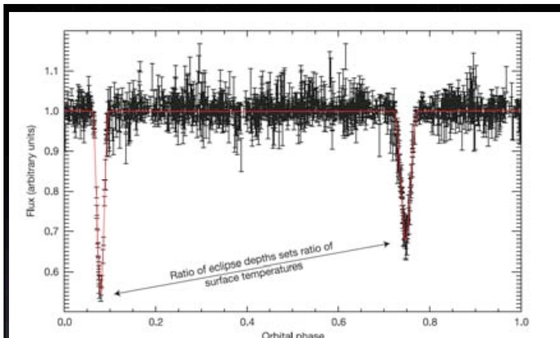
The planet, known as 2M1207b, is about five times the mass of Jupiter and is orbiting at a distance nearly twice as far as Neptune is from our Sun.

Dr Chauvin added: "Given the rather unusual properties of the 2M1207 system, the giant planet most probably did not form like the planets in our Solar System."

"Instead it must have formed the same way our Sun formed, by gravitational collapse of a cloud of gas and dust."

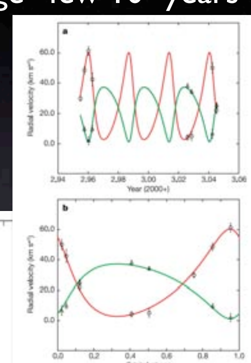
Believable at young ages?





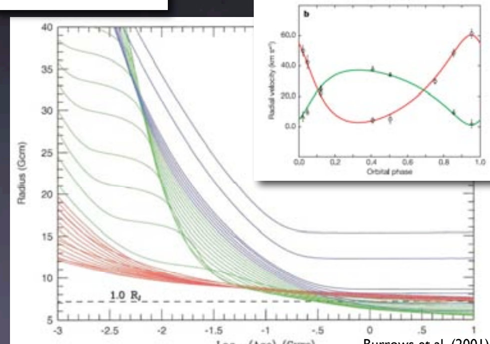
2M0535

eclipsing binary in Orion
age "few 10^6 years"



Stassun et al. (2006)

M_1	$54 \pm 5\ M_J$
M_2	$34 \pm 3\ M_J$
R_1	$6.5\ R_J$
R_2	$5.0\ R_J$

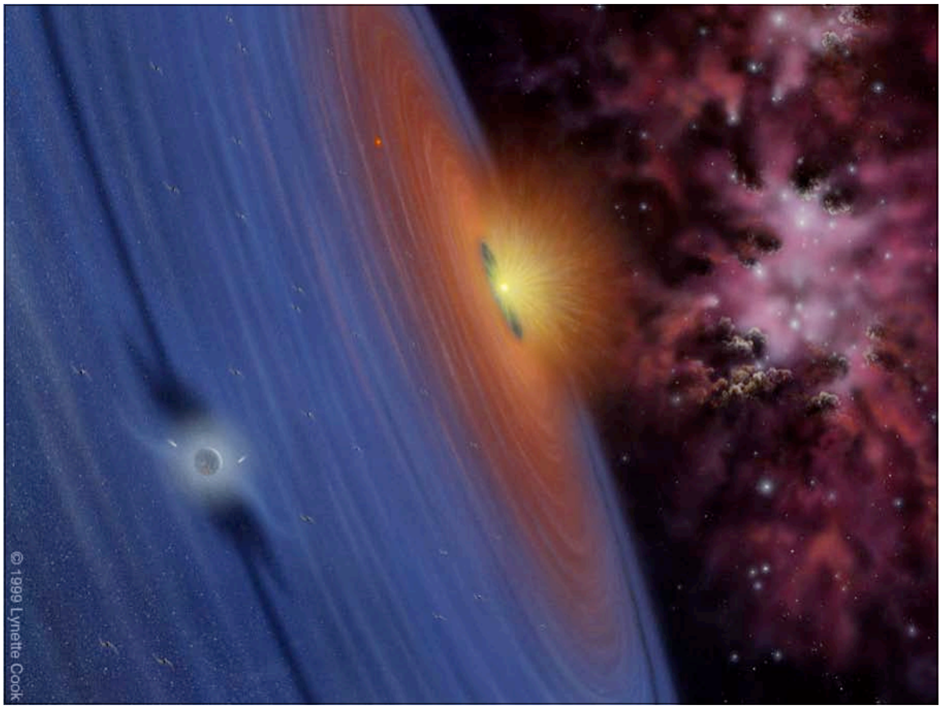


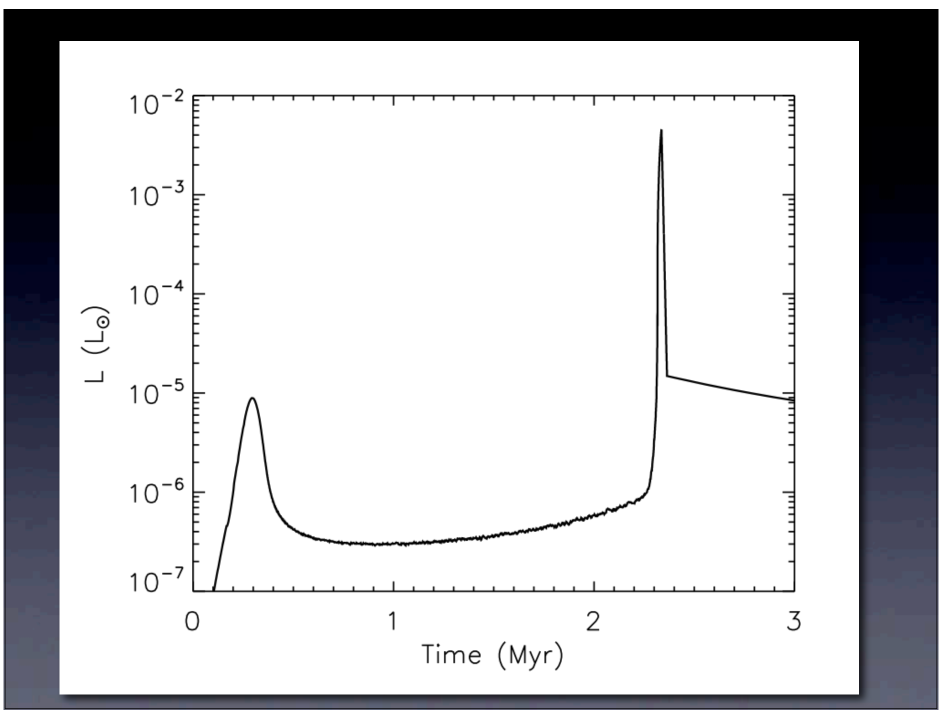
Burrows et al. (2001)

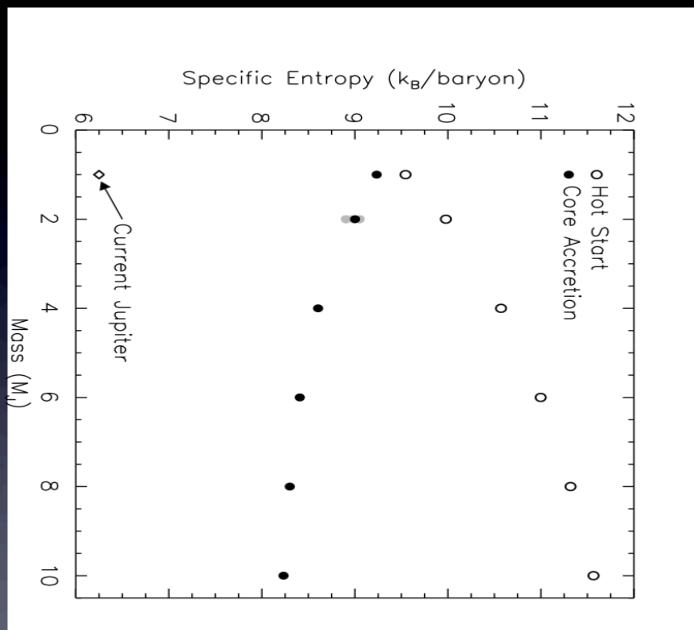
Young Brown Dwarfs

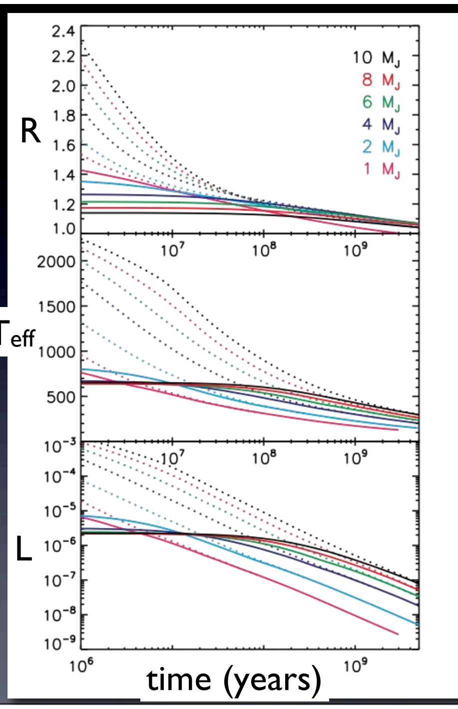
- Evolutionary models passed some tests
- But...early evolution is highly sensitive to initial conditions
- Need more observational tests

Planets remember their formation mechanism, which is likely different from low mass companions.


© 1999 Lynette Cook


L (L☉)
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0
1
2
3
Time (Myr)

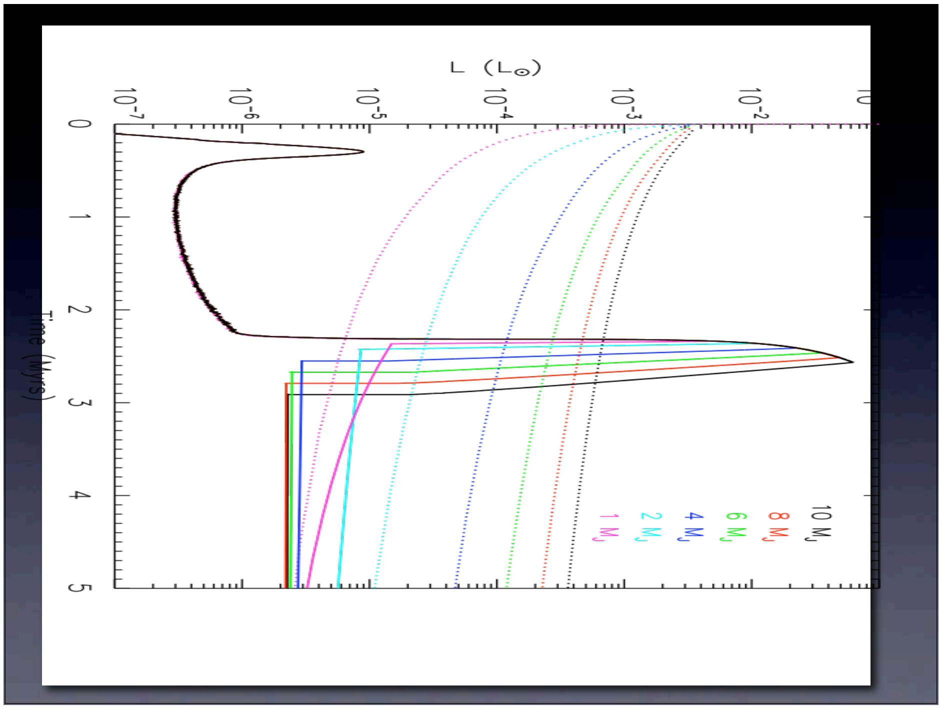


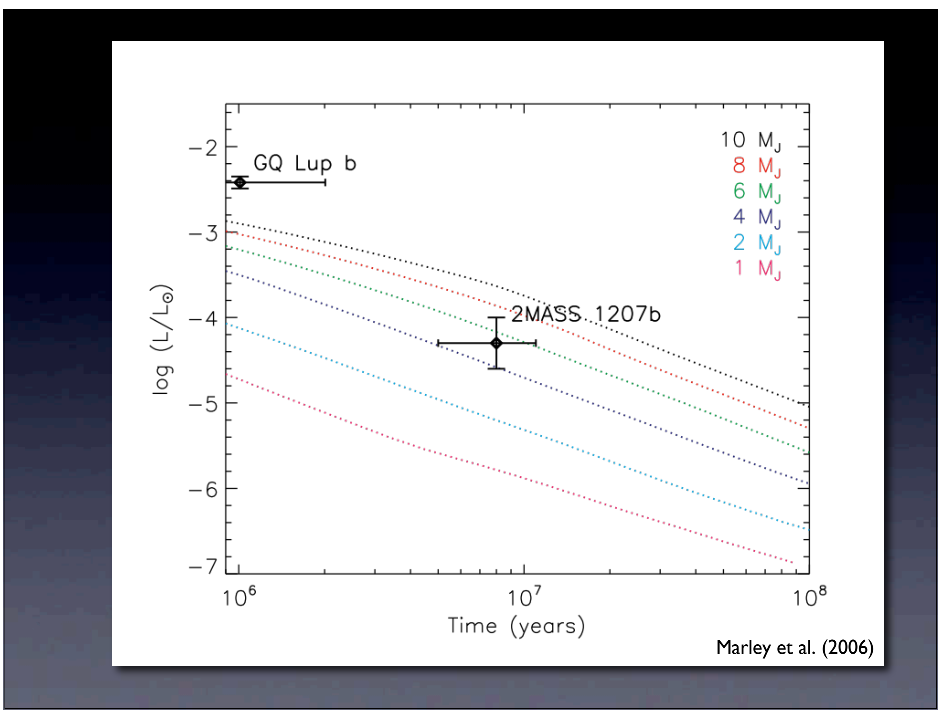


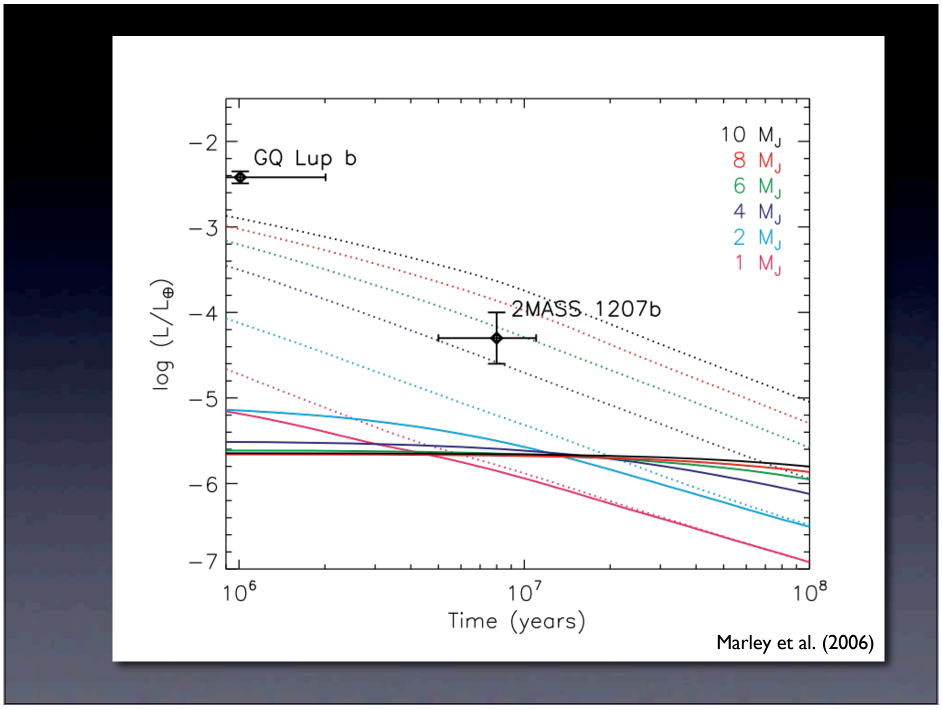
Core Accreted Planets:

- Smaller
- Cooler
- Fainter

Marley et al. (2007)


L (L☉)
Time (Myrs)
10 M_J
8 M_J
6 M_J
4 M_J
2 M_J
1 M_J


GQ Lup b
2MASS 1207b
10 M_J
8 M_J
6 M_J
4 M_J
2 M_J
1 M_J
log (L/L☉)
Time (years)
Marley et al. (2006)

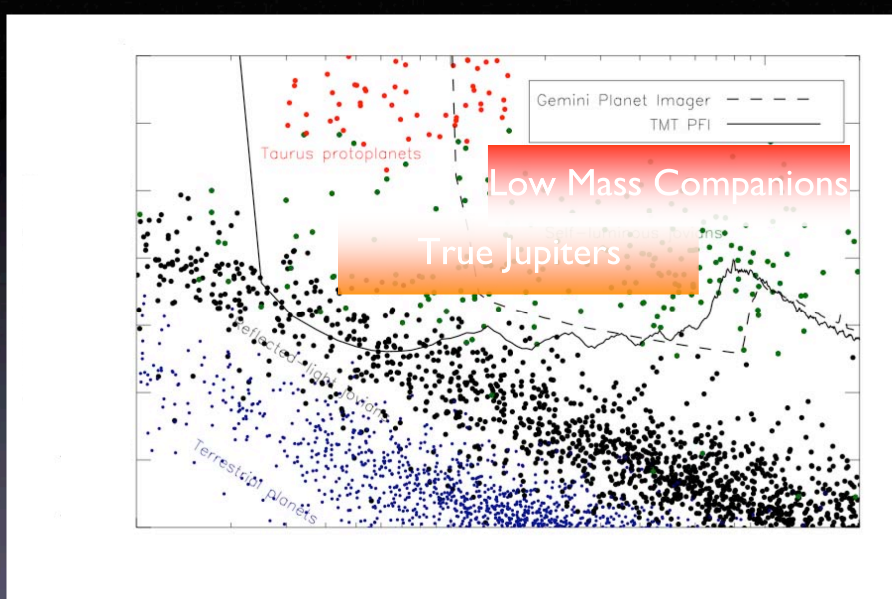


Core Accreted Giants

- Model luminosity depends on treatment of accretion shock
- Many uncertainties (geometry, energy partioning, disk) remain
- Baseline model suggests ***young Jupiters are much fainter than expected***
- Discrepancy increases with mass
- See Marley et al. (2007)

Low Mass Companions can be Distinguished from Planets

- *Formation clues are detectable*
- Composition (different from primary)
- Radius
- Luminosity



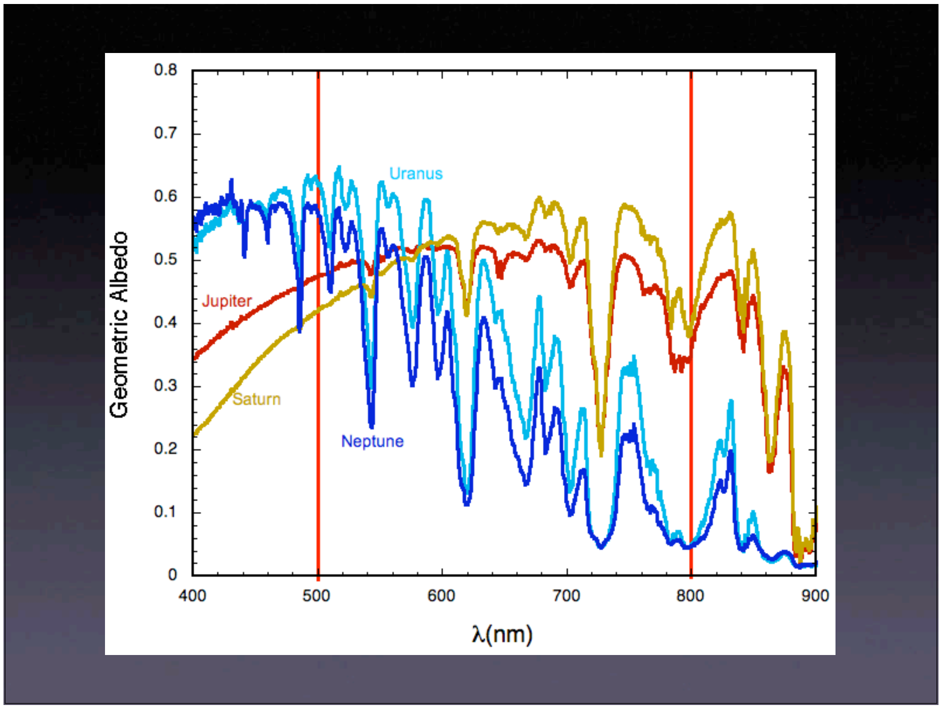
Courtesy B. Macintosh & J. Graham

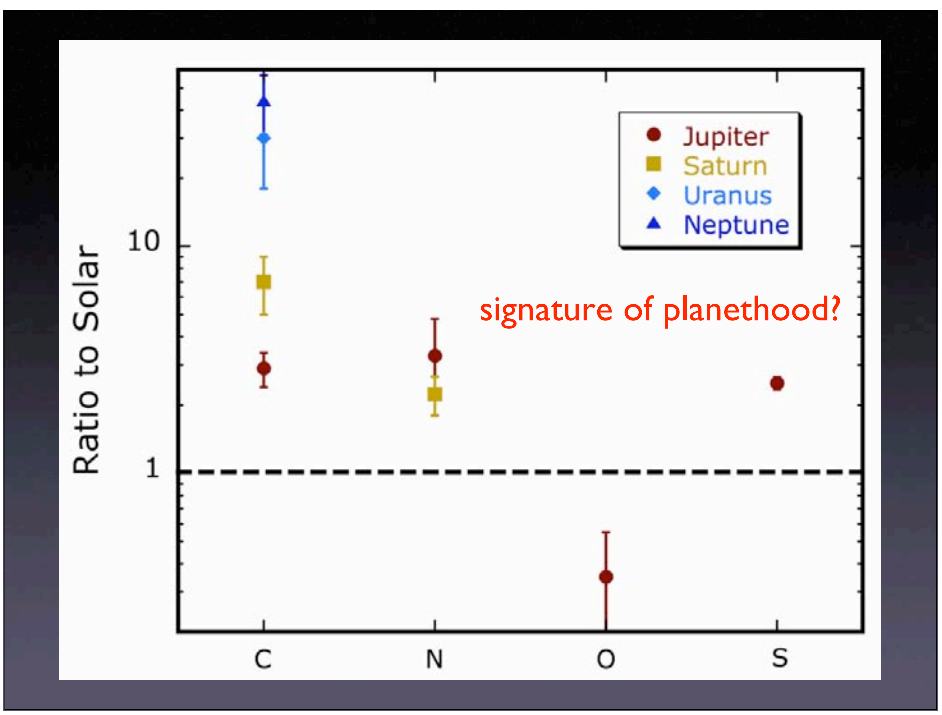
Characterization

- Mass - spectra
- Radius - spectra
- Albedo
- Effective temperature - spectra
  - Equilibrium temperature
  - Internal luminosity

Characterization

- Mass
- Radius
- Albedo
- Effective temperature
  - Equilibrium temperature
  - Internal luminosity
- ***Atmospheric Composition***

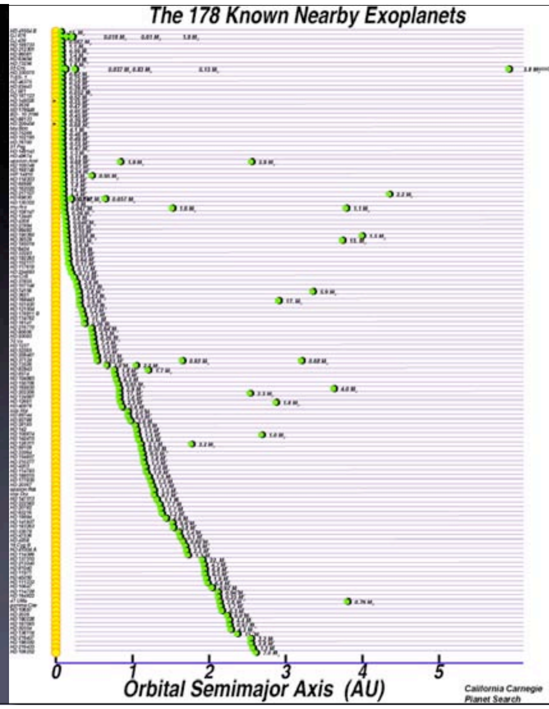

Geometric Albedo
λ(nm)
Uranus
Jupiter
Saturn
Neptune
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
400
500
600
700
800
900


Ratio to Solar
10
1
C
N
O
S
Jupiter
Saturn
Uranus
Neptune
signature of planethood?

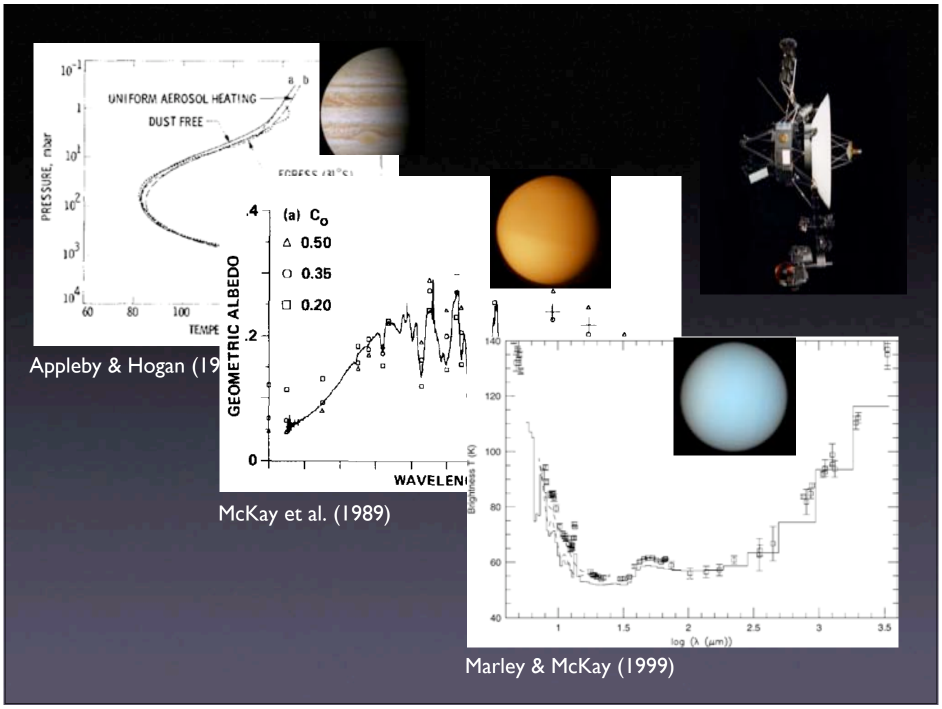
But...

Requiring compostion information turns most of the “Known Exoplanets” into “Known Exoplanet Candidates”

Known Exoplanets:
HD149026b
Gl 436b



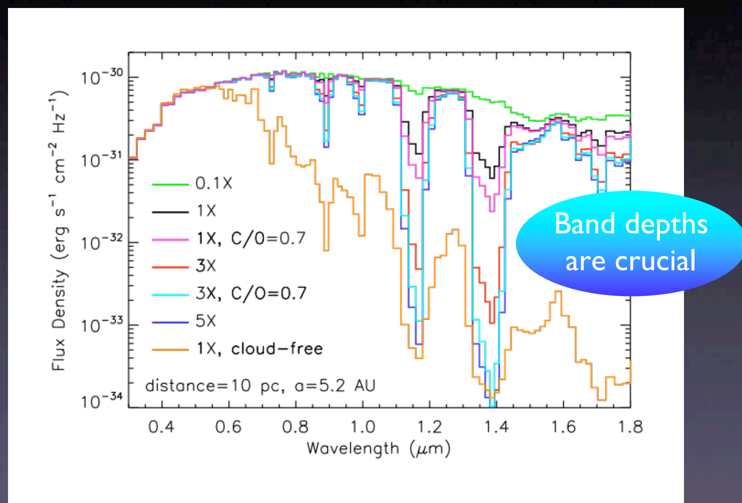
Models

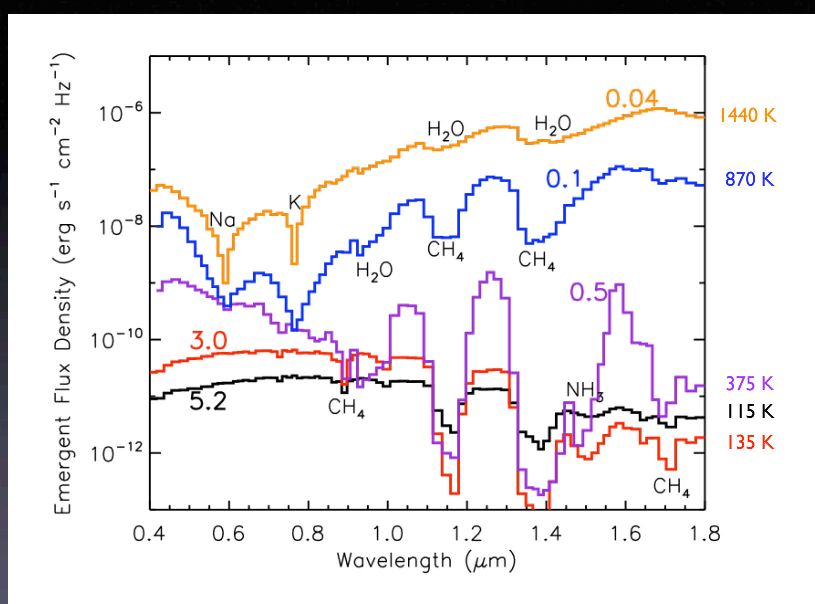


- Composition — Metallicity, C/O, ...
- Chemistry — Sedimentation
- Opacities — High *T* CH_4
- Condensates — Cloud Physics
- \+ Dynamics — Circulation, *f*

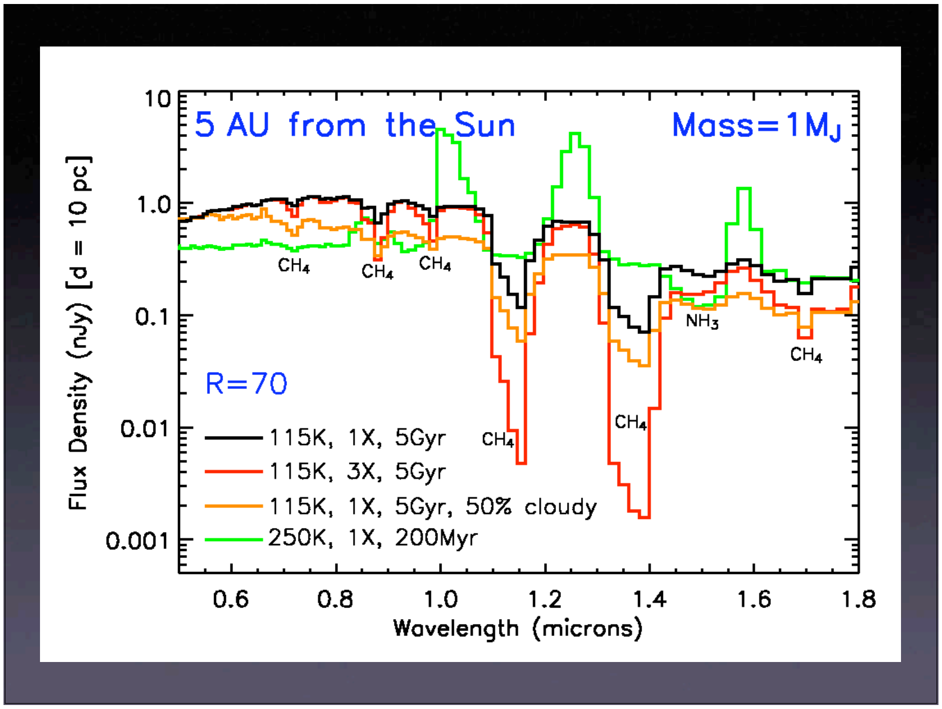
- Thermal Structure & Spectrum

EGP Characterization Requires Spectra

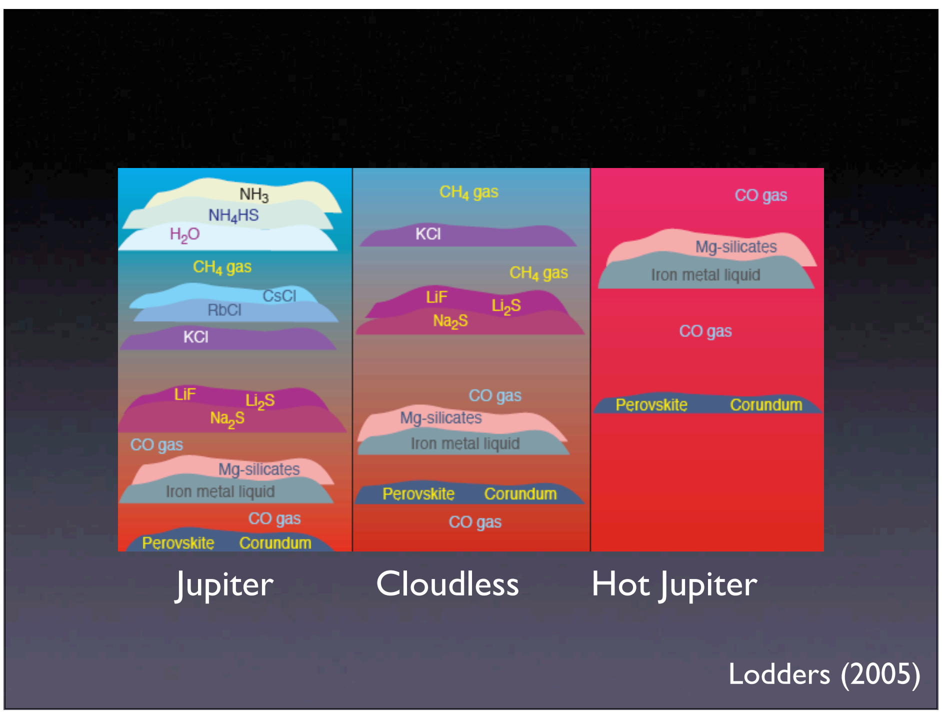




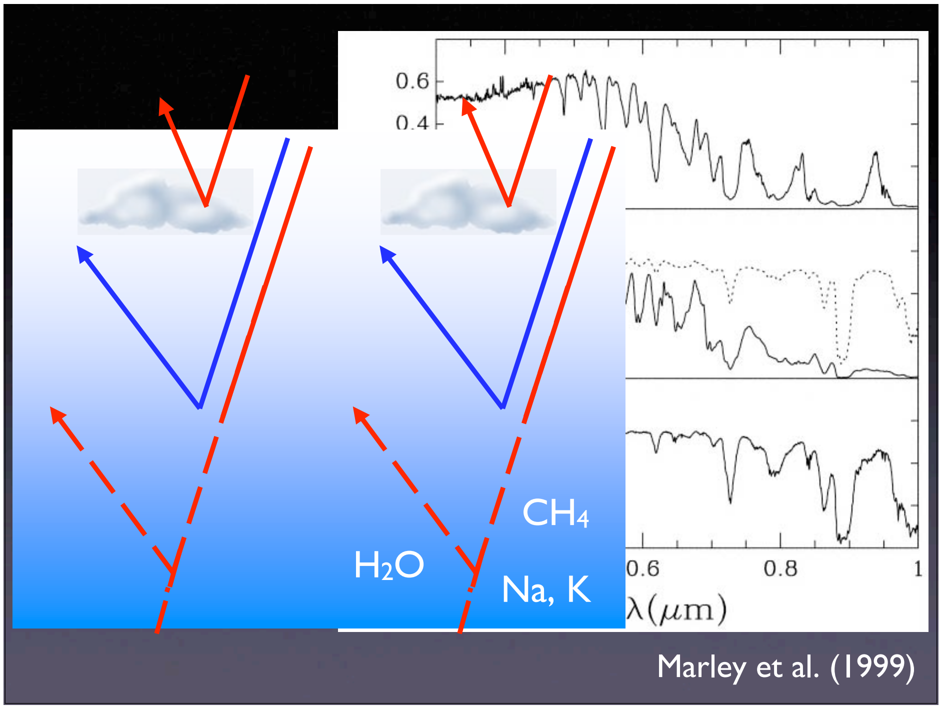
Fortney & Marley

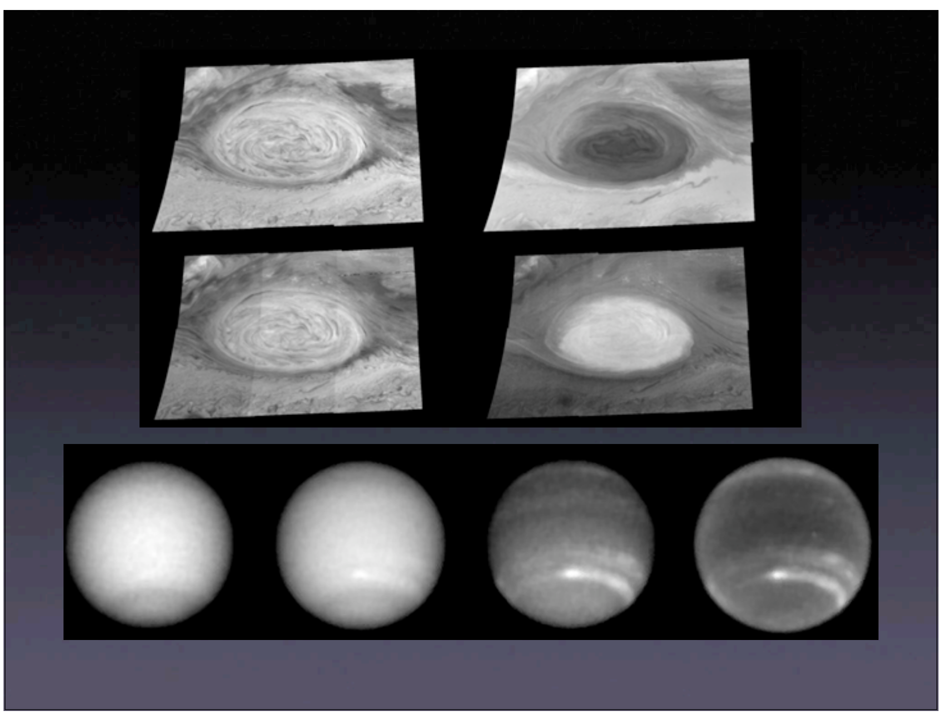


5 AU from the Sun
Mass=1M$_J$
R=70
115K, 1X, 5Gyr
115K, 3X, 5Gyr
115K, 1X, 5Gyr, 50% cloudy
250K, 1X, 200Myr
CH_4
NH_3
Flux Density (nJy) [d = 10 pc]
Wavelength (microns)

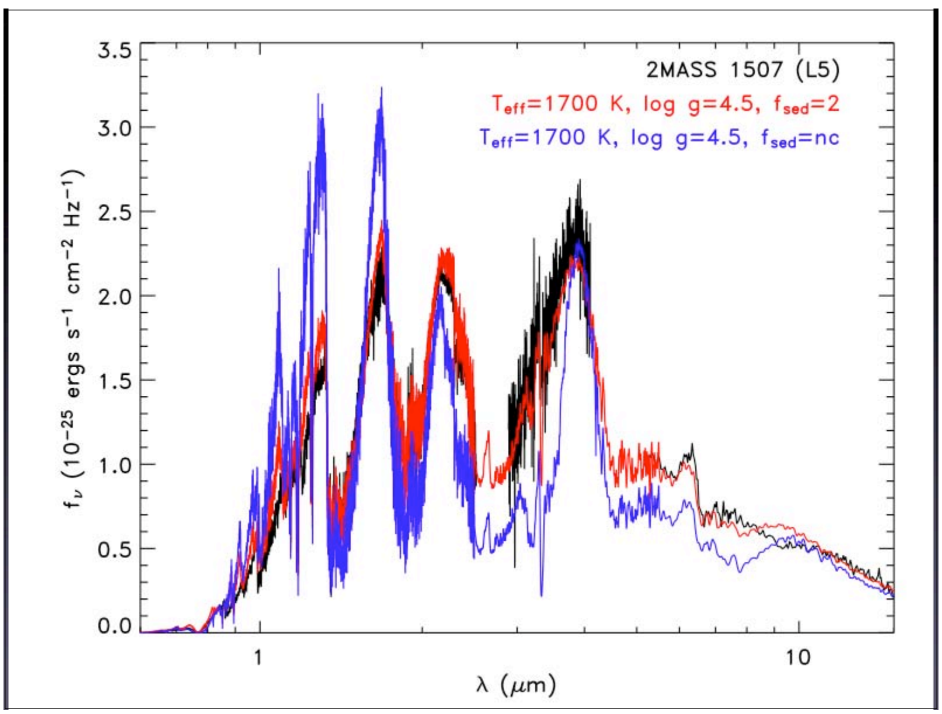


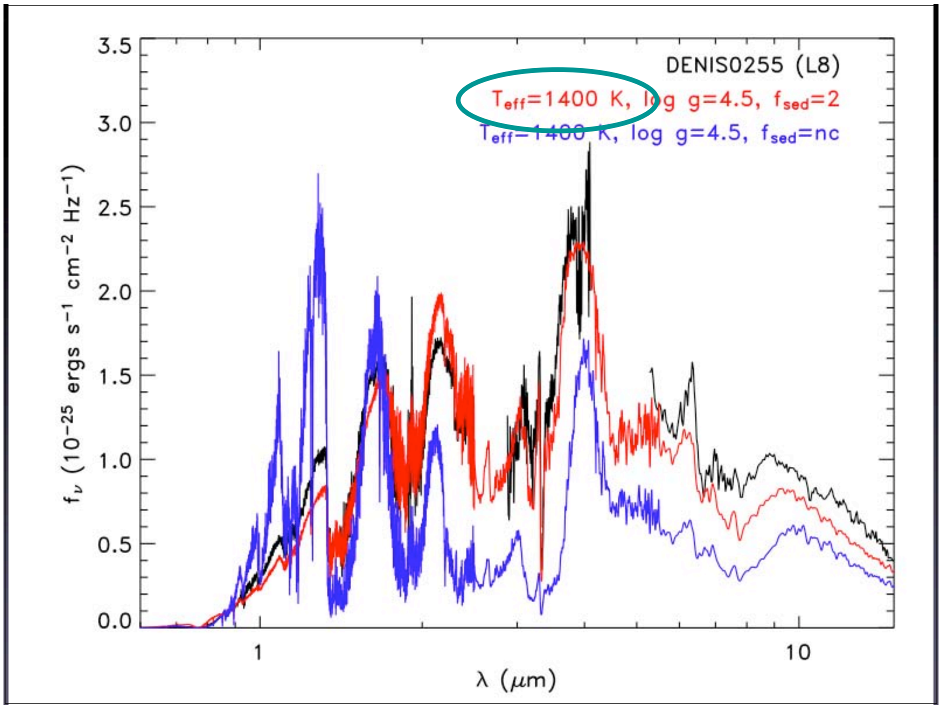
NH_3
NH_4HS
H_2O
CH_4 gas
CsCl
RbCl
KCl
LiF
Li_2S
Na_2S
CO gas
Mg-silicates
Iron metal liquid
Perovskite
Corundum
Jupiter
Cloudless
Hot Jupiter
Lodders (2005)


0.6
0.4
CH4
H2O
Na, K
0.6
0.8
1
λ(μm)
Marley et al. (1999)

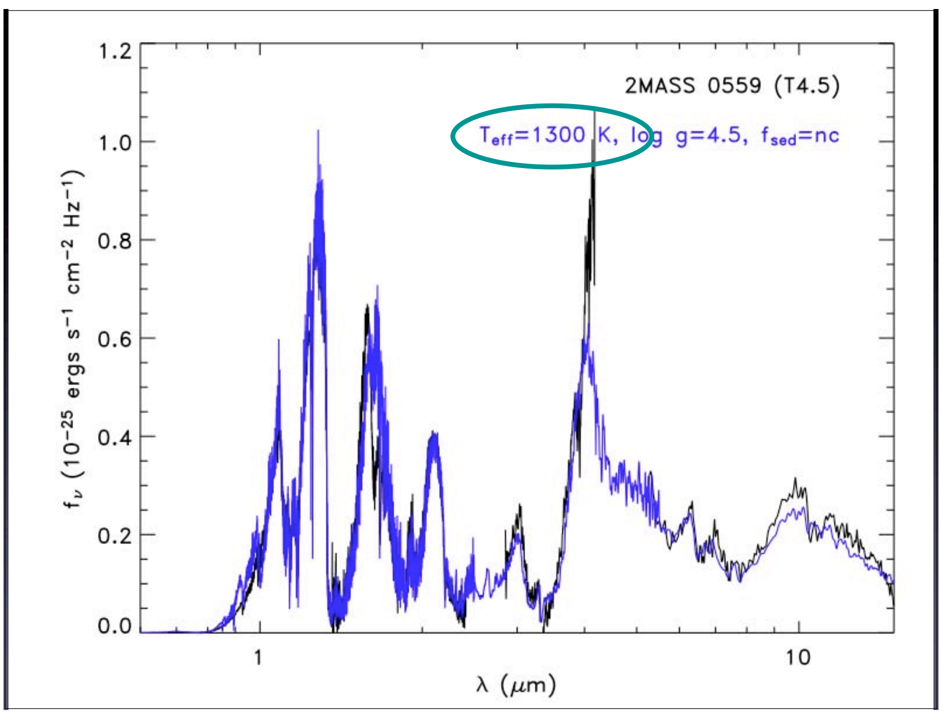


Lessons from Brown Dwarfs

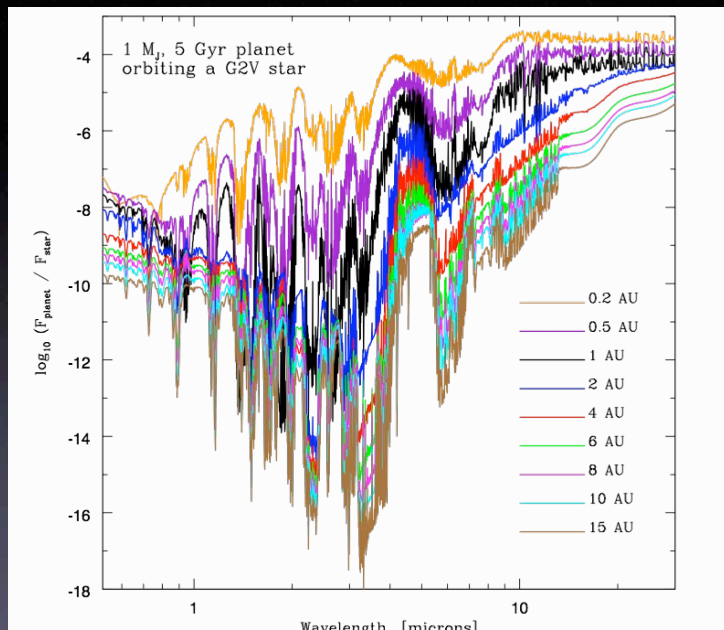




DENIS0255 (L8)
Teff=1400 K, log g=4.5, fsed=2
Teff=1400 K, log g=4.5, fsed=nc
fν (10^-25 ergs s^-1 cm^-2 Hz^-1)
λ (μm)



2MASS 0559 (T4.5)
Teff=1300 K, log g=4.5, fsed=nc
fν (10^-25 ergs s^-1 cm^-2 Hz^-1)
λ (μm)



Sudarsky et al. (2003); Burrows (2005)

Photochemistry

Jupiter at 1 AU

- 25x higher UV flux
- H, C, O, N, S, P chemistry
- Many pathways to hazes
- But...Liang et al. (2004) find no hazes in hot Jupiters

Haze Production

- CH_4 + UV

  → C_2H_6

  ↓

  C_3H_8

  ↓

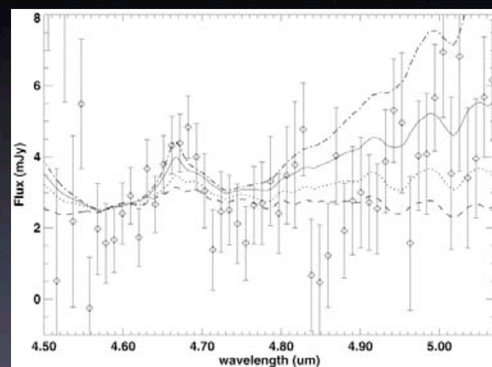
  parafin

Substantially alter spectra and colors of canonical haze-free models

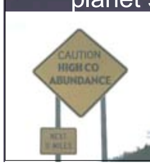
Dynamics & Chemical Equlibrium

Non-equilibrium CO

- Convection or eddy mixing can transport CO
- Strong bond allows dynamical τ << chemical equilibrium τ
- Excess CO observed in Jupiter (Prinn & Barshay 1977)
- Predicted (Fegley & Lodders 1996) and observed (Noll et al. 1997) in Gl229B
- Can CO attenuate EGP 5-μm excess? Relevant for JWST planet search

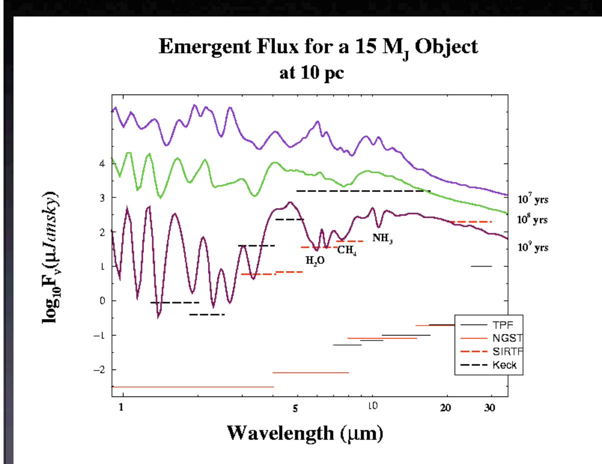


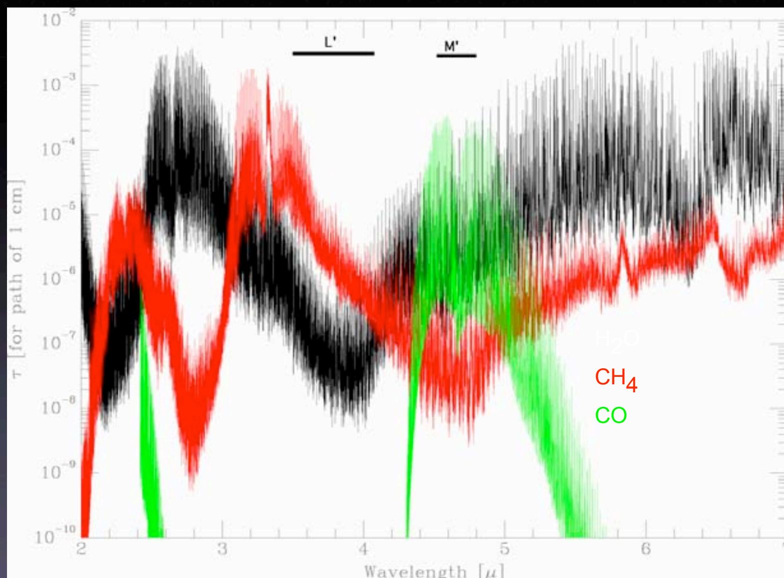
Noll et al. (1997)



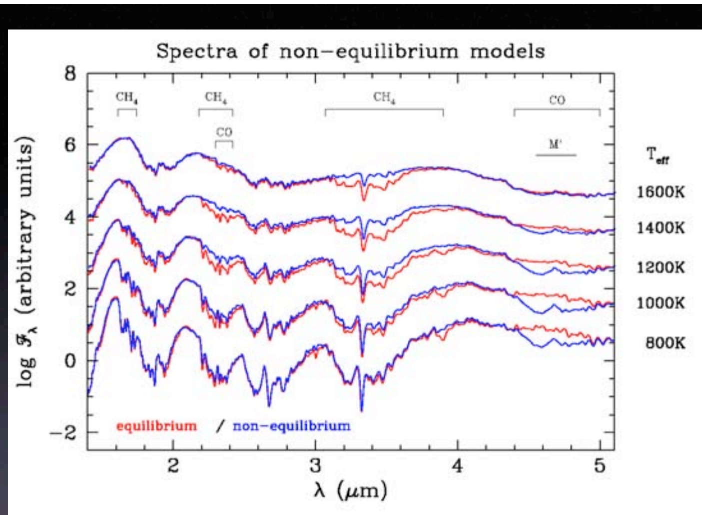
CO and Vertical Mixing

- Models fit observed J, H, K, L' reasonably well
- T dwarfs are generally fainter at M than expected
- Brightness at M band advertised to ease EGP direct detection: "*...we believe that this band is a universal diagnostic for brown dwarfs and jovian planets.*" Marley et al. 1996



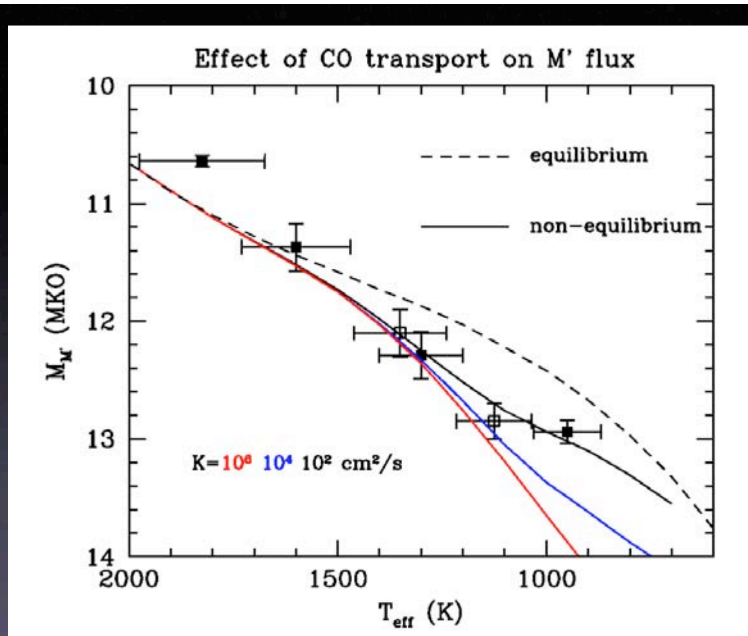


1000 K; 1 bar

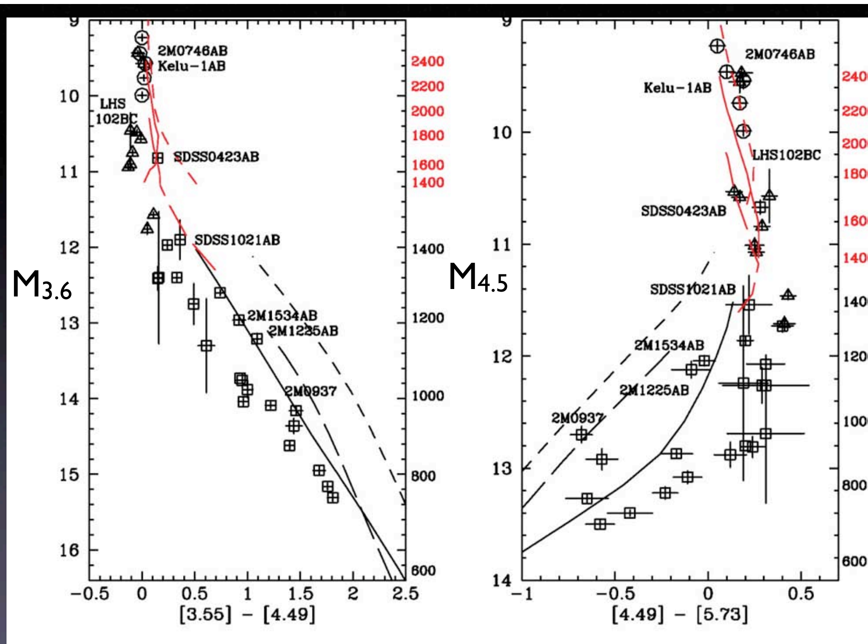


Saumon et al. 2003

Methane arrives late at L, CO hangs in longer



Saumon et al. 2003



Leggett et al. (2007)

M band Less Favorable for Planet Searches

- Up to 40% dimmer than previously expected
- Full phase space of mixing, chemistry not yet explored
- Clouds also major impact
- L’ may be more favorable (lower background, less affected by mixing)

A novel L-band imaging search for giant planets in the Tucana and β Pictoris moving groups ⋆

M. Kasper[1], D. Apai[2,3], M. Janson[4], and W. Brandner[4,5]

At Low Spectral Resolution

- Clouds trump
- Hazes are a concern
- Metallicity
- C/O ratio
- Non-equilibrium chemistry influences search band (L’ vs. M)

Conclusions

- Modeling issues are well understood
- Mass and Radius are just starting points
- For most objects, composition should be major goal of characterization
- Condensates can cloud our vision
- True characterization is challenging, but rewarding