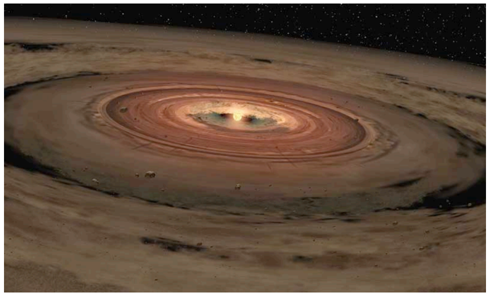
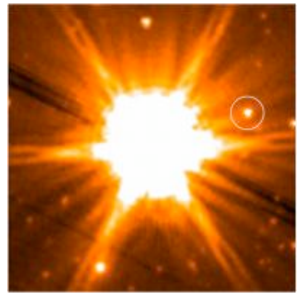
Reminder!

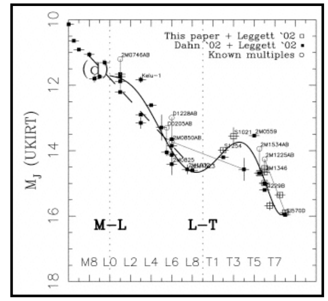
Research paper 1st draft is due to **April 25th** (2 weeks)

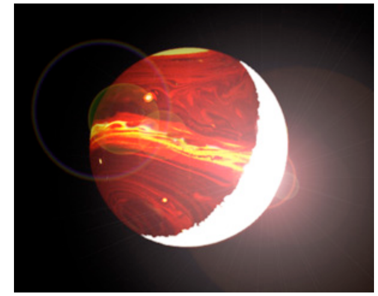
- Have you collected all of your literature?
- Have you read all of your literature?
- Do you have a working outline?
- Have you started writing?

Full information on webpage: **http://web.mit.edu/8.972/www**



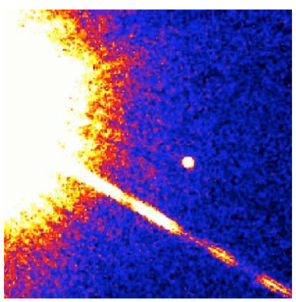


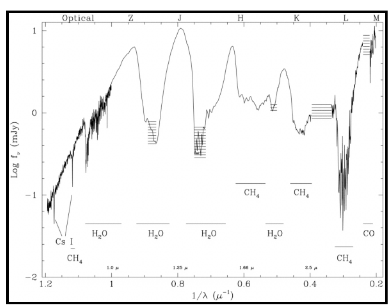


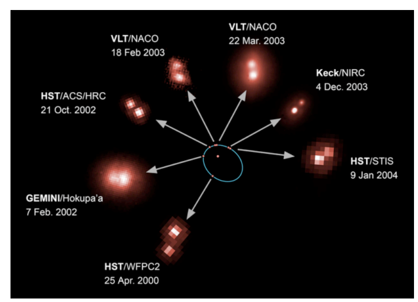


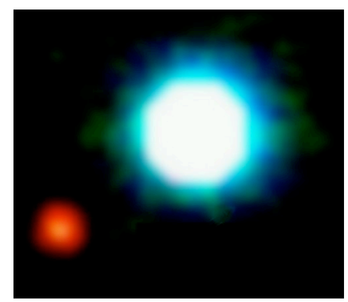
Lecture 10:

Atmospheres I: Brown Dwarf and Exoplanet Spectra









What are the properties of EP/BD atmospheres?

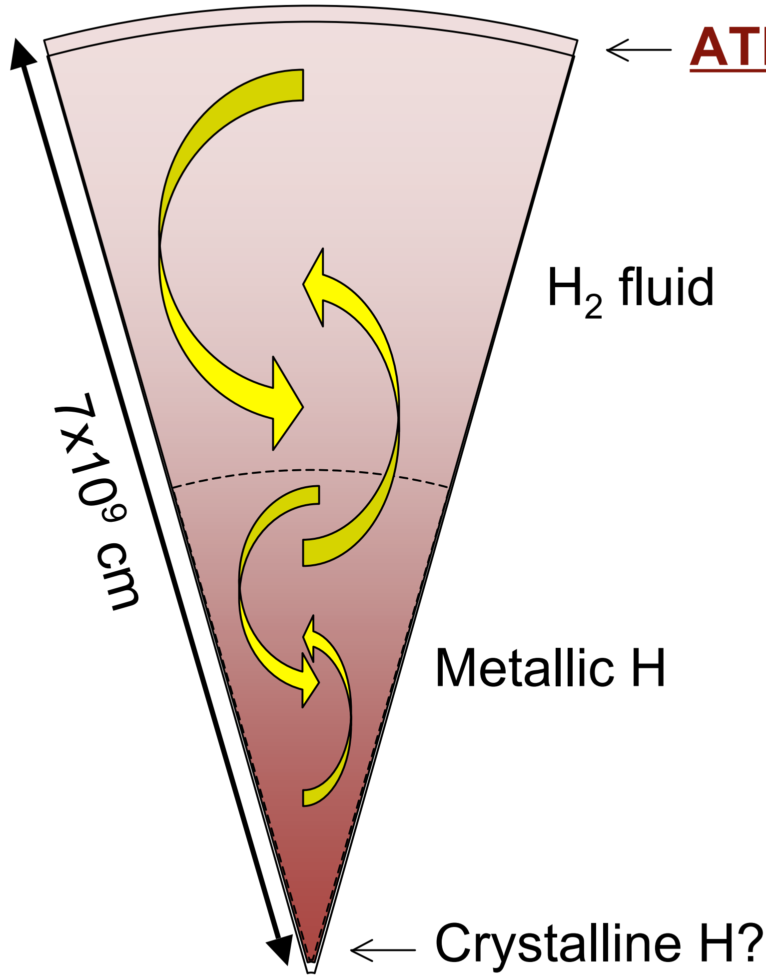
How do we measure EP/BD atmospheres?

How are BD spectra classified?

How are BD spectral types related to their physical properties (temperature, gravity, metallicity)?

How do BD and EP spectra/atmospheres differ?

Atmospheric Properties

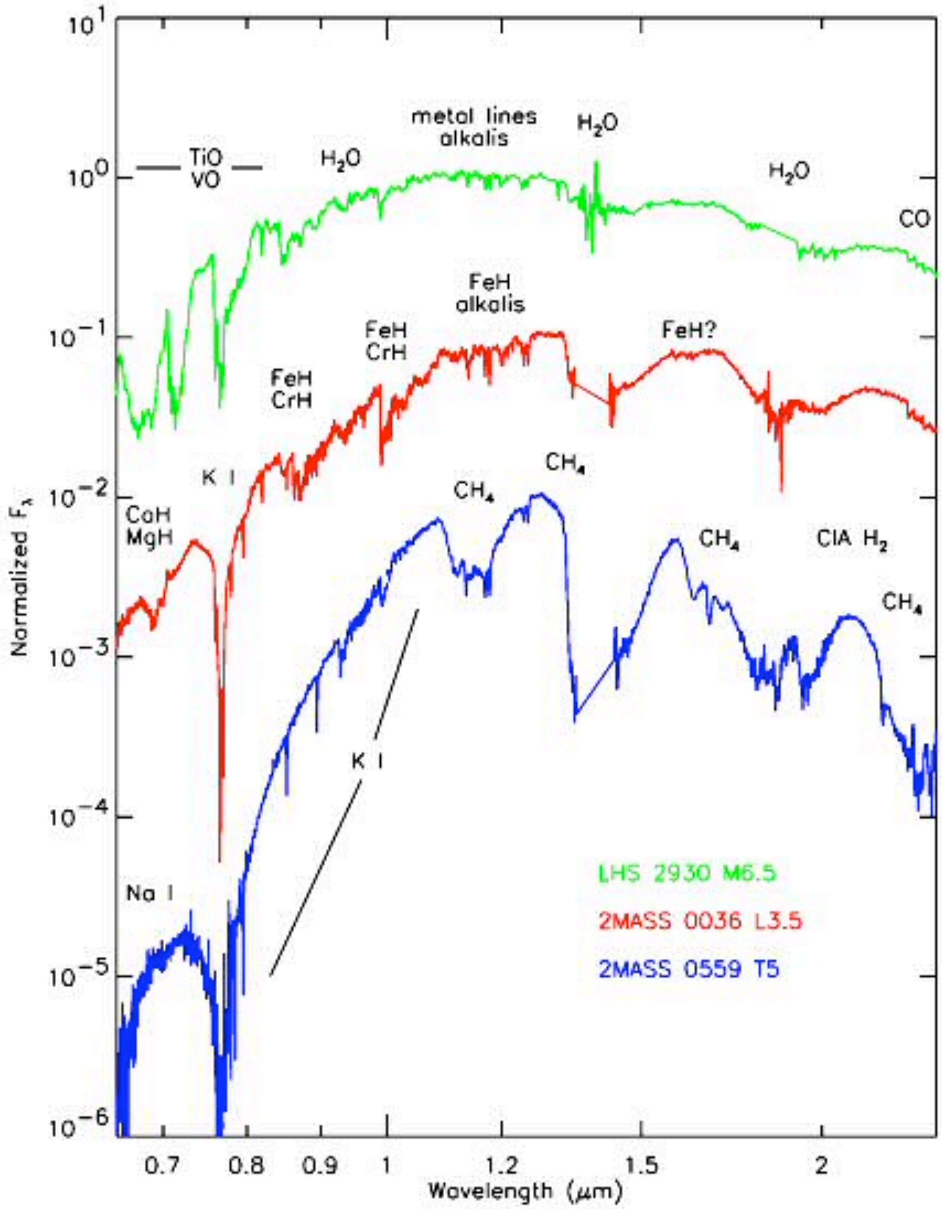


P ≈ 10^{11} bar, T ≈ 10^6 K, ρ ≈ 500 g/cc

Brown Dwarf:	Jupiter:
P ≈ 1-10 bar	P ≈ 0.2-2 bar
T ≈ 1000 K	T ≈ 150 K
$\rho \approx 10^{-4}$ g/cc	$\rho \approx 10^{-3}$ g/cc
$\lambda_P \approx$ 3 km	$\lambda_P \approx$ 25 km

Only observable part of a EP/BD*

"Radiation valve" - heat/entropy loss out, stellar heating in



The Spectra of Brown dwarfs

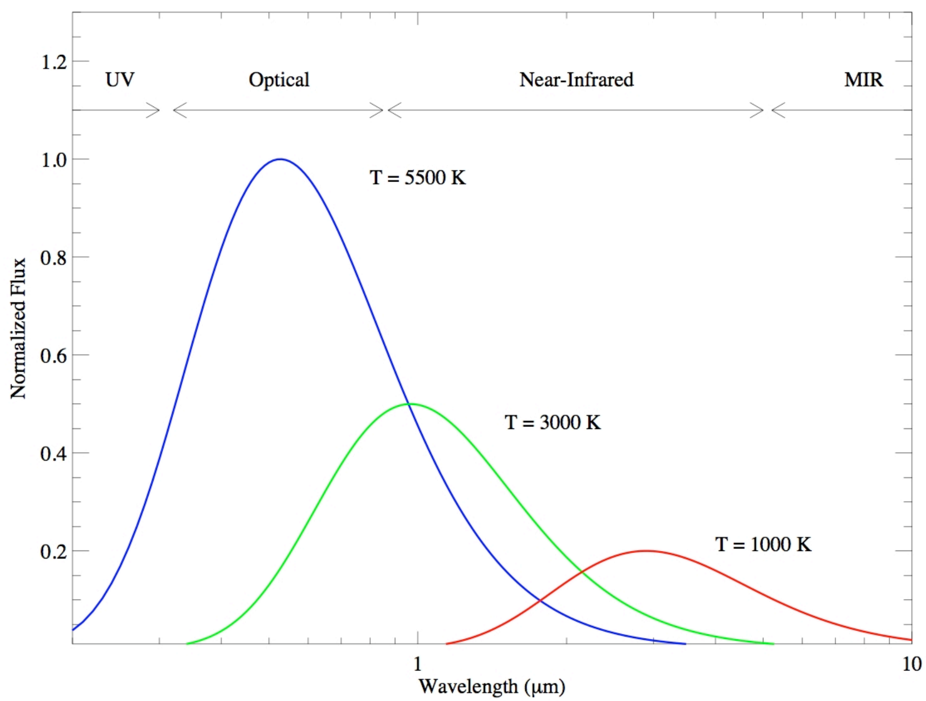
Complex, filled with line and band absorption

Flux peaks at near-infrared wavelengths

What causes this?

Radiative Transfer 101

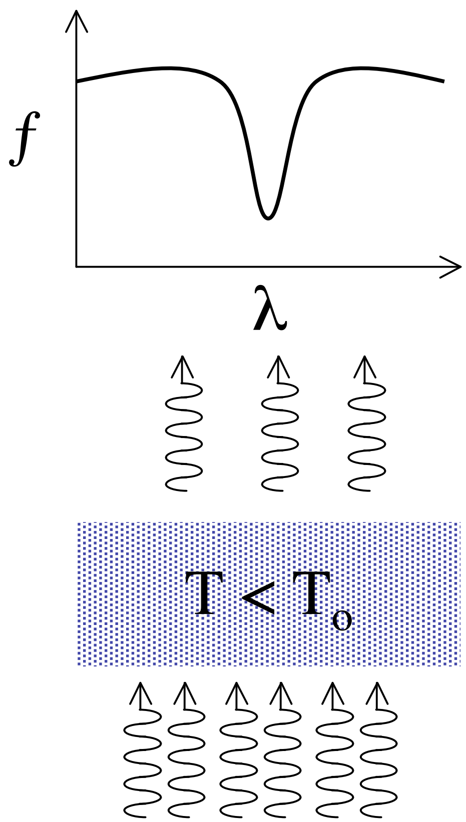
Blackbody flux distribution: $$I_0(\lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k T_{eff}}} - 1}$$



For lowest T_{eff} peak flux moves toward infrared wavelengths (Wein's Law), optical flux minimal.

Explains difficulty in finding these sources early on (poor NIR detector technology)

Radiative Transfer 102



Modifications to blackbody SED: absorption from metals in the atmosphere

$$I(\lambda) = I_0(\lambda)e^{-\tau_\lambda}$$

optical depth

$$d\tau_\lambda = \kappa_\lambda \rho \cos\theta ds$$

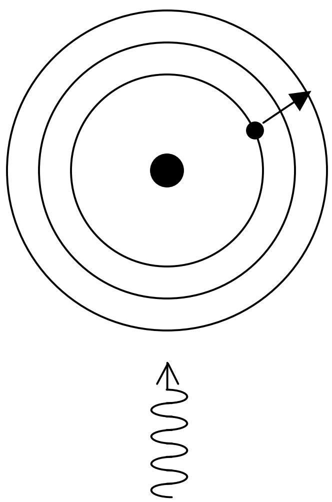
opacity

density

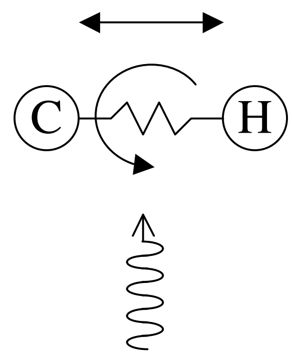
The total optical depth (total absorption) for a given species depends on the column density

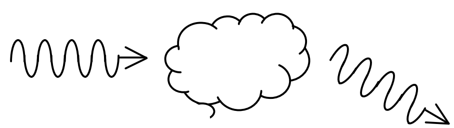
Neutral atoms and molecules are strong, wavelength-dependent absorbers

Electronic transitions (X-ray/UV/optical)



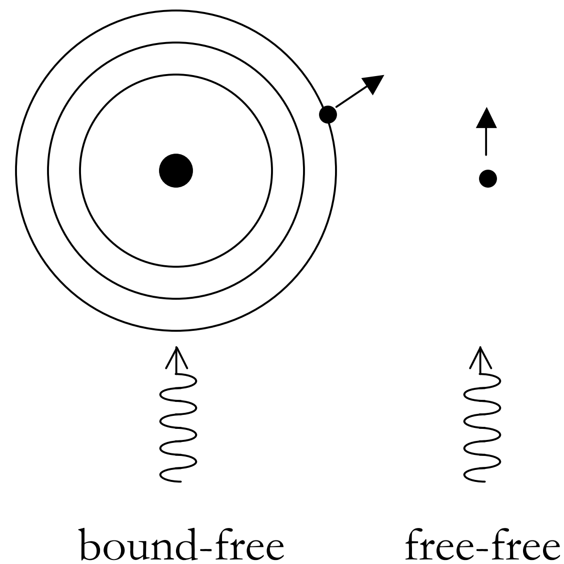
Ro-vibration (optical/infrared)

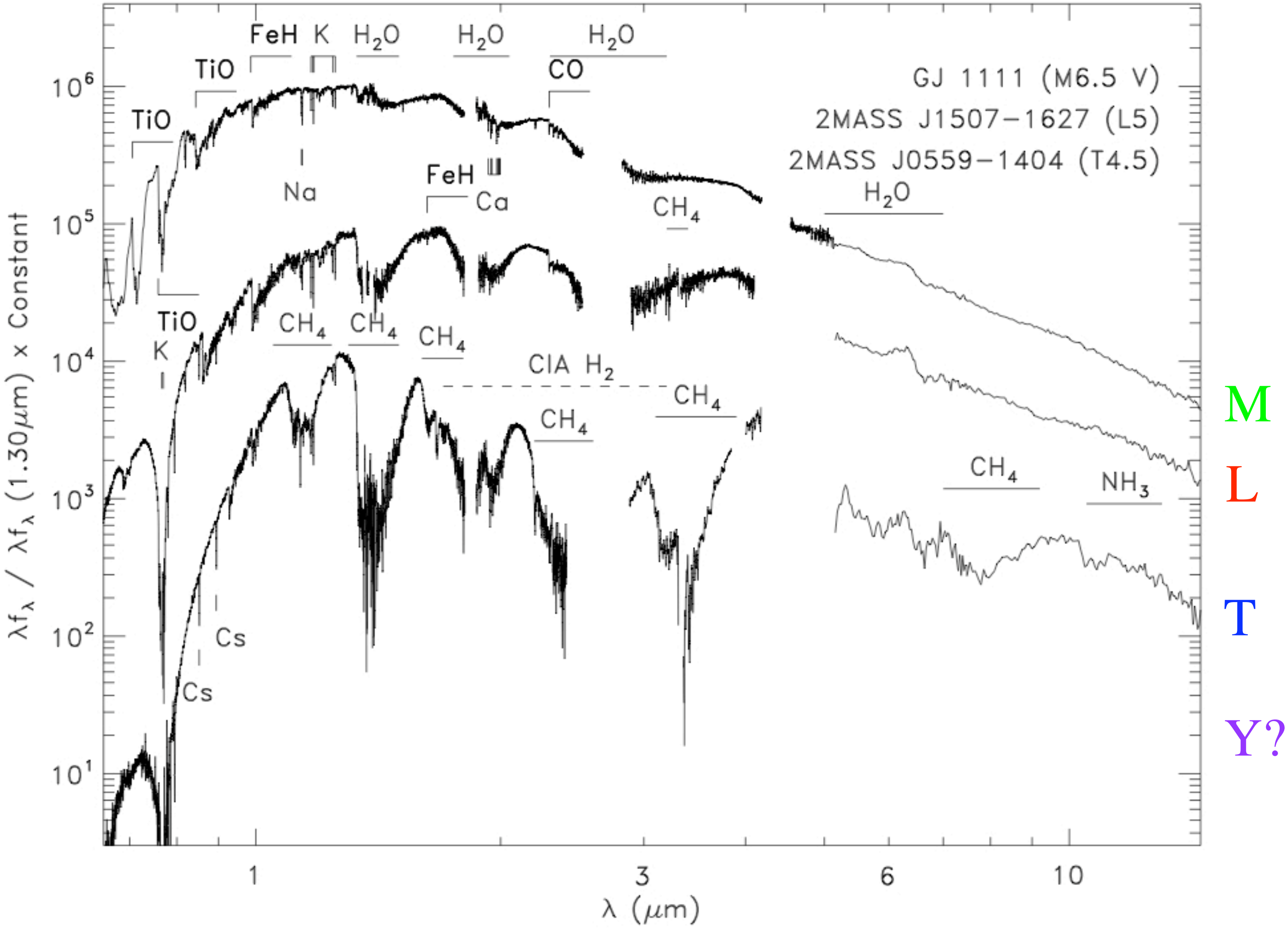




Scattering (optical/infrared)

Continuum sources (optical/infrared/submm/radio)





Cushing et al. (2006)

Spectral sequence: O..B..A..F..G..K..M..L..T..(Y)

Why this letter sequence?

TABLE 5

SUMMARY OF LETTERS TO GUIDE CHOICE OF NEW SPECTRAL TYPE

Letter (1)	Status (2)	Notes (3)
A	In use	Standard spectral class
B	In use	Standard spectral class
C	In use	Standard carbon-star class
D	Ambiguous	Confusion with white dwarf classes DA, DB, DC, etc.
E	Ambiguous	Confusion with elliptical galaxy morphological types E0–E7
F	In use	Standard spectral class
G	In use	Standard spectral class
H	OK	
I	Problematic	Transcription problems with I0 (10, Io) and I1 (11, II, Il)
J	In use	Standard carbon-star class
K	In use	Standard spectral class
L	OK	
M......	In use	Standard spectral class
N	In use	Standard carbon-star class
O	In use	Standard spectral class
P	Problematic?	Incorrect association with planets?
Q	Problematic?	Incorrect association with QSOs?
R	In use	Standard carbon-star class
S.......	In use	Standard spectral class for ZrO-rich stars
T	OK	
U	Problematic?	Incorrect association with ultraviolet sources?
V	Problematic	Confusion with vanadium oxide (V0 vs. VO)
W......	Ambiguous	Confusion with Wolf-Rayet WN and WR classes
X	Problematic	Incorrect association with X-ray sources
Y	OK	
Z	Problematic?	Incorrect implication that we have reached "the end"?

Kirkpatrick et al. (1999)

Spectral sequence:
O..B..A..F..G..K..M..L..T..(Y)

Why this letter sequence?

Mnemonics:

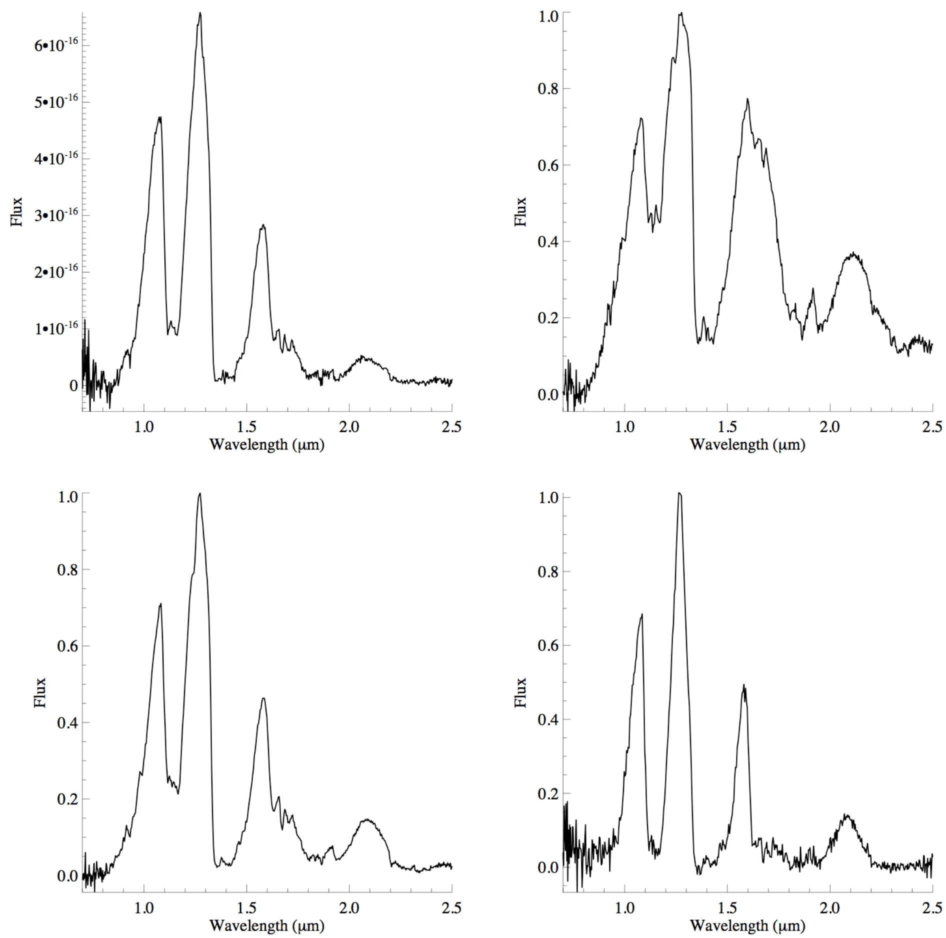
Oh **B**e **A** **F**ine **G**irl/**G**uy **K**iss **M**y **L**ips **T**onight **Y**ahoo!

Old **B**ill's **A** **F**unny **G**uy **K**issing **M**onica **L**ewinsky (**T**oo **Y**oung)

Only **B**oring **A**stronomers **F**ind **G**rief **K**nowing **M**nemonics **L**ike **T**hese

Our **B**uddy **A**dam **F**eels **G**ood **K**nowing **M**aui **L**ife **T**ops **Y**ours

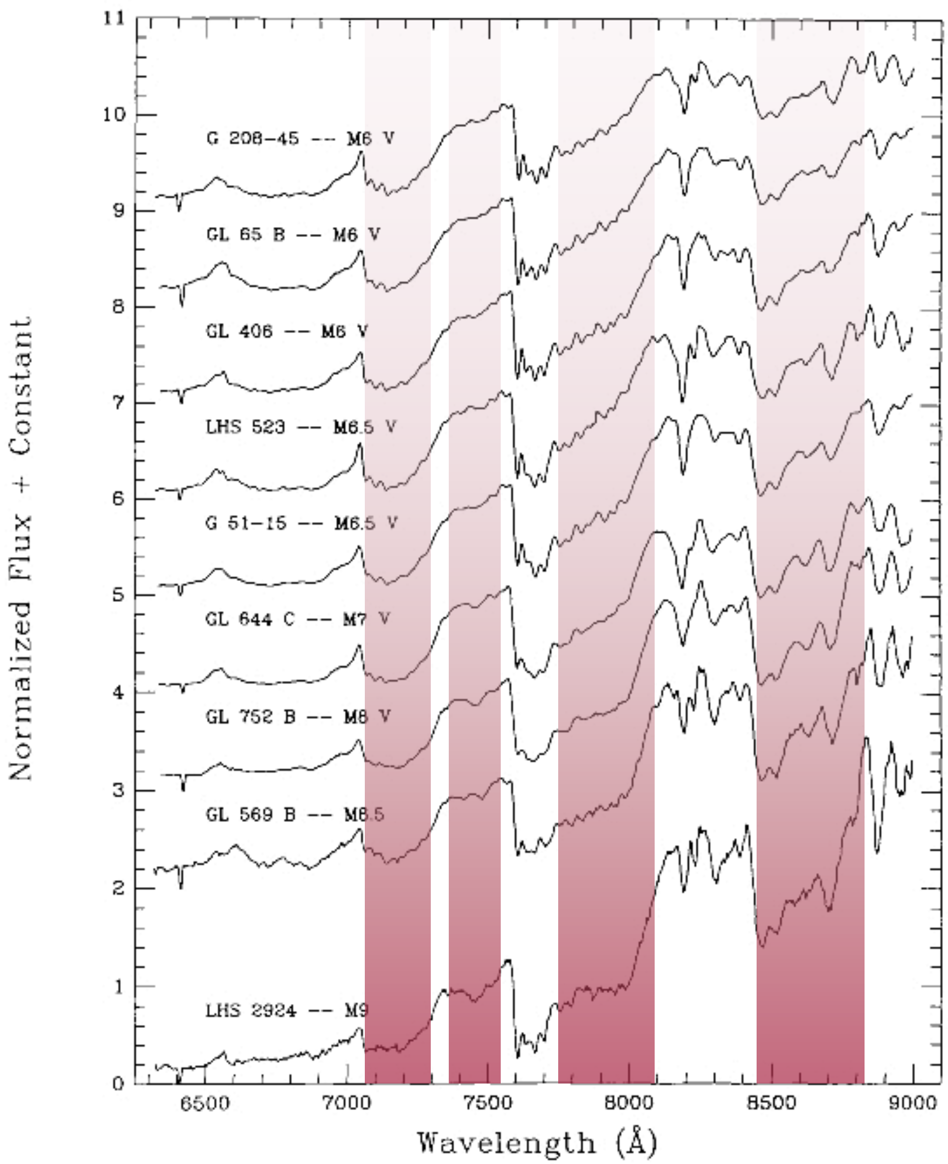
Why classify stars?



A "**standard ruler**" for comparing sources with features in common and variances.

A "**common vernacular**" for comparing sources, different studies.

A good classification system makes use of broadband spectral data and is tied to physical standards.



Kirkpatrick et al. (1991)

M dwarf spectra

Strong TiO & VO at red optical wavelengths

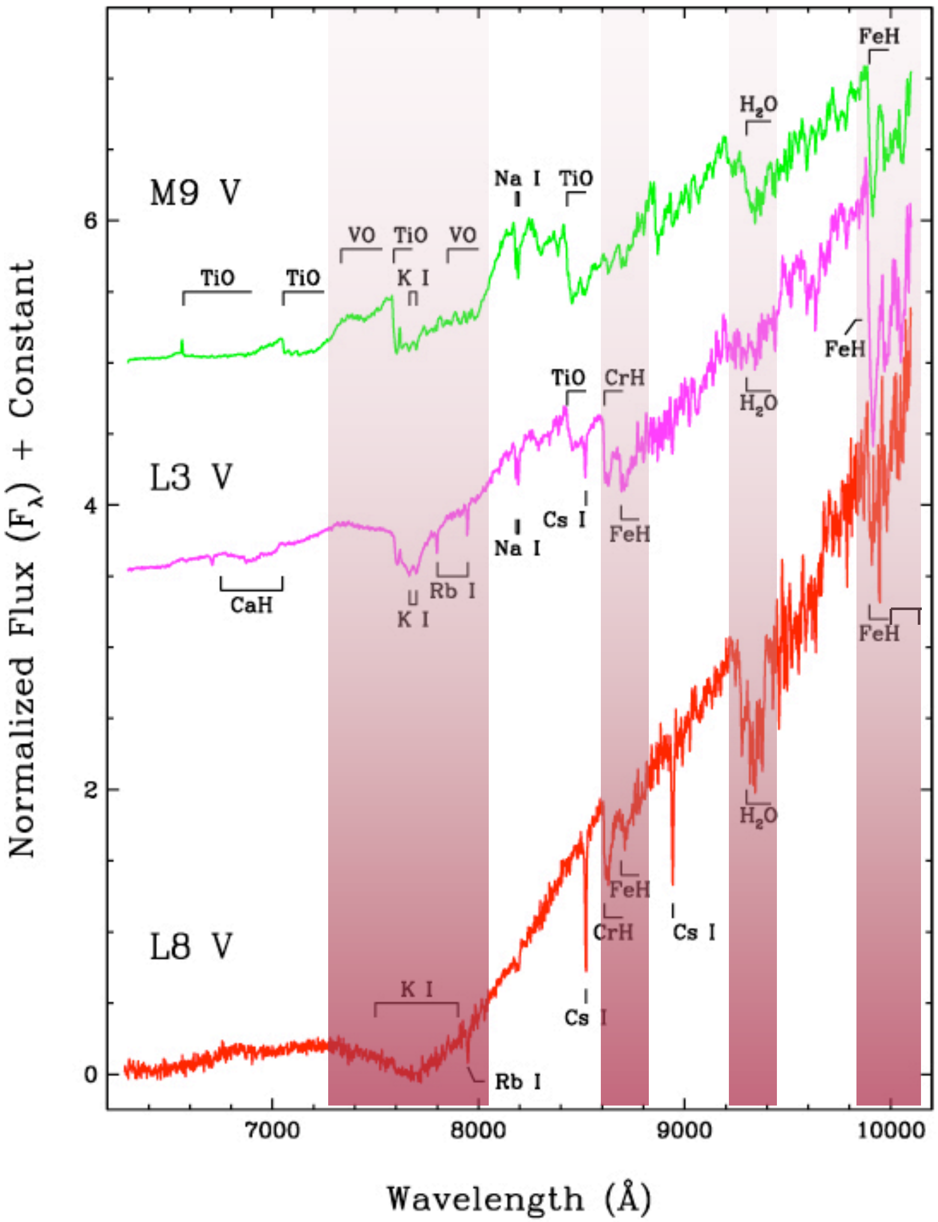
Modest H_2O and CO at near-infrared wavelengths

Alkali & metal lines (K I, Na I, Fe I, Ca I)

Red optical continuum

Red NIR colors

L Dwarf Spectra



Kirkpatrick et al. (1999)

TiO & VO bands disappear

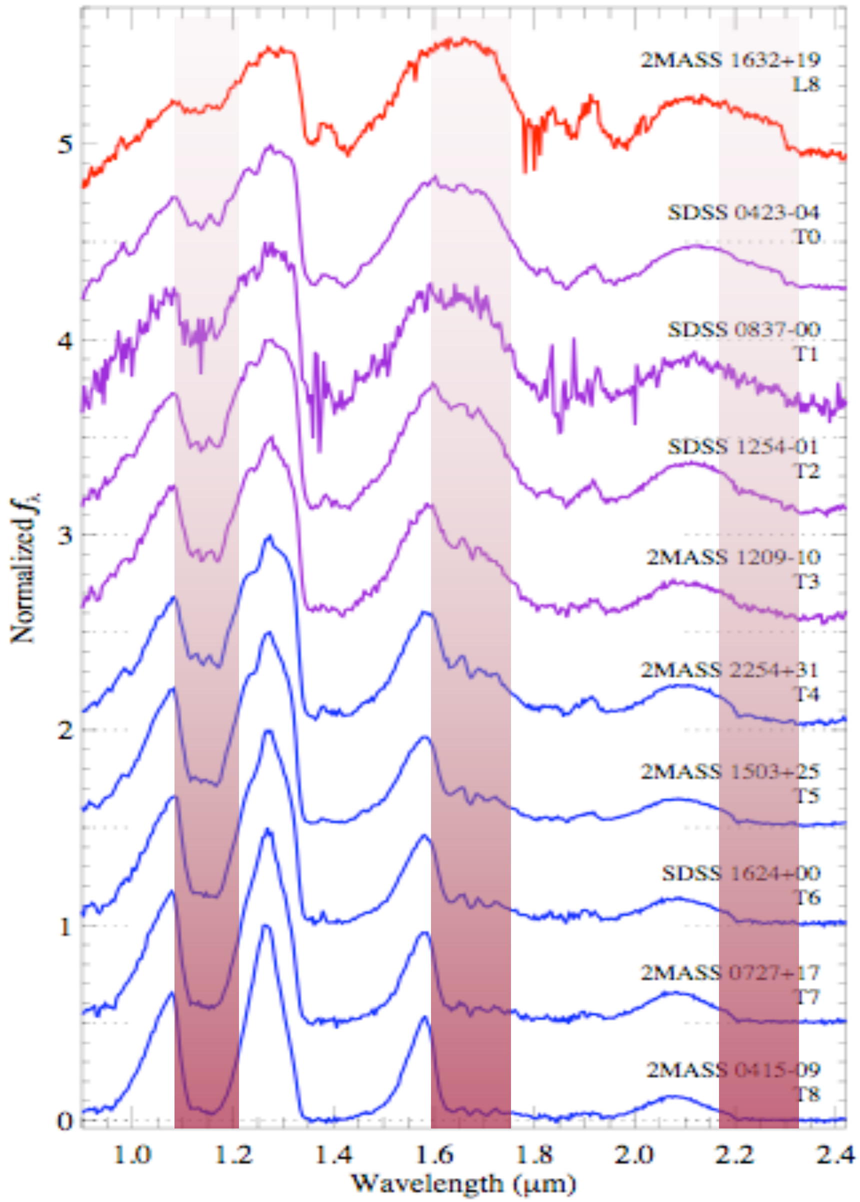
Metal hydrides (FeH, MgH, CaH, CrH) strengthen, then weaken

H_2O, CO strengthen

Prominent alkali lines, esp. K I (7700 Å) & Na I (5500 Å)

Very red optical continuum

Very red NIR colors



Burgasser et al. (2006)

T Dwarf Spectra

Emergence of CH_4 at NIR wavelengths (at expense of CO).

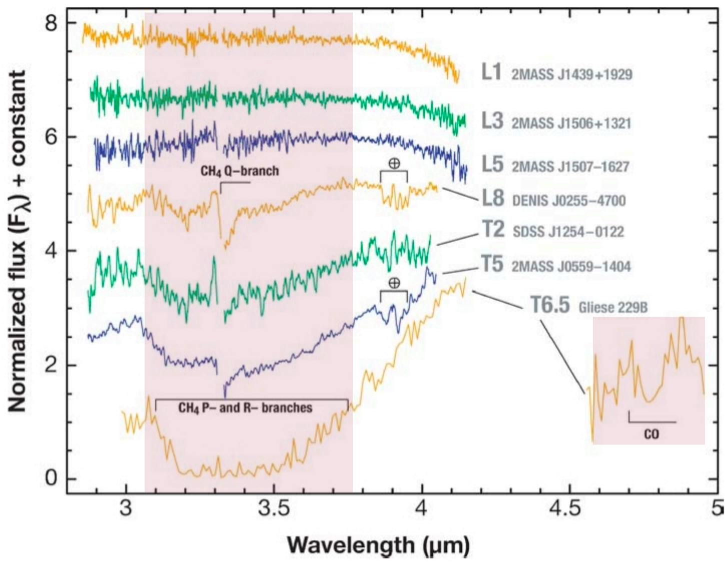
H_2O saturates (very deep)

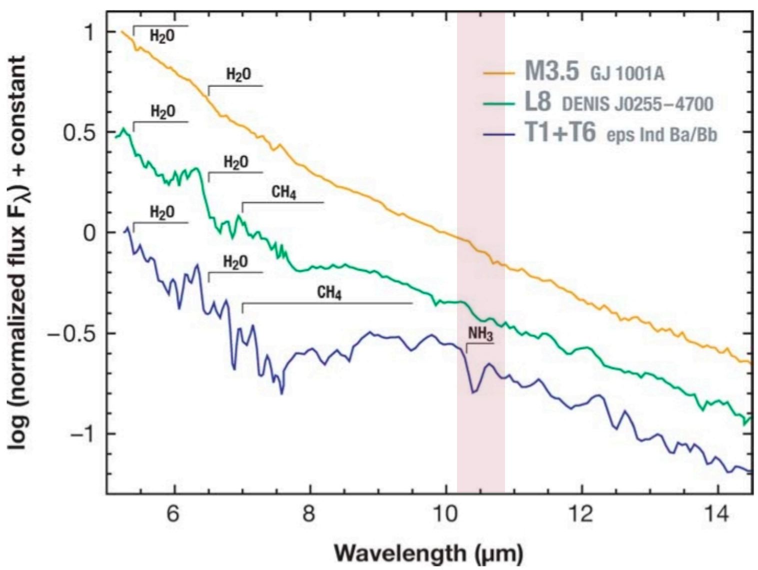
Condensate opacity "disappears"

Collision-induced H_2 absorption at K-band important

Optical spectra extremely red and bland

NIR colors are blue



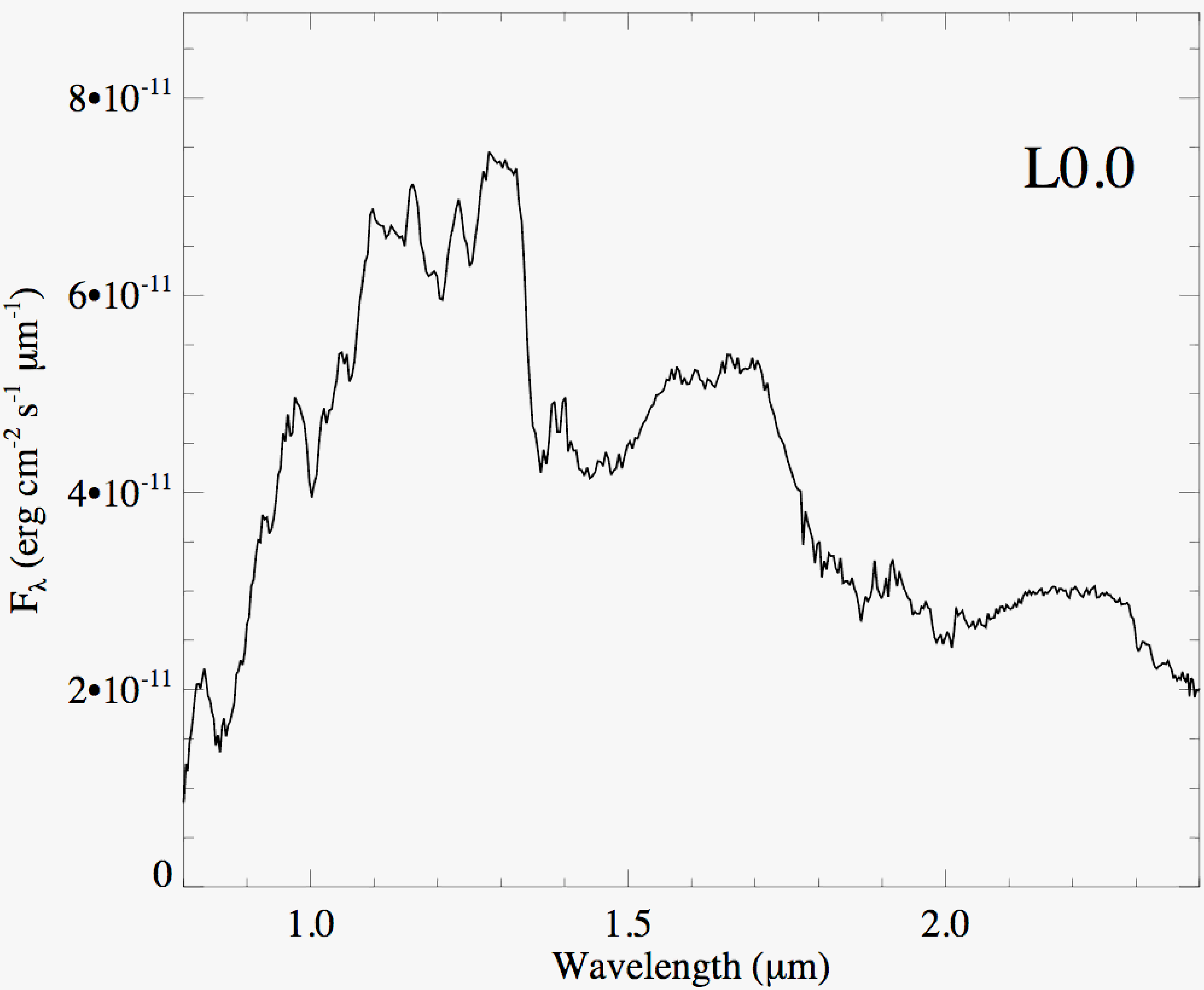


Mid-infrared Spectra

CH_4 at 3.3 μm strong feature even in late L dwarfs; CO enhanced in T dwarfs

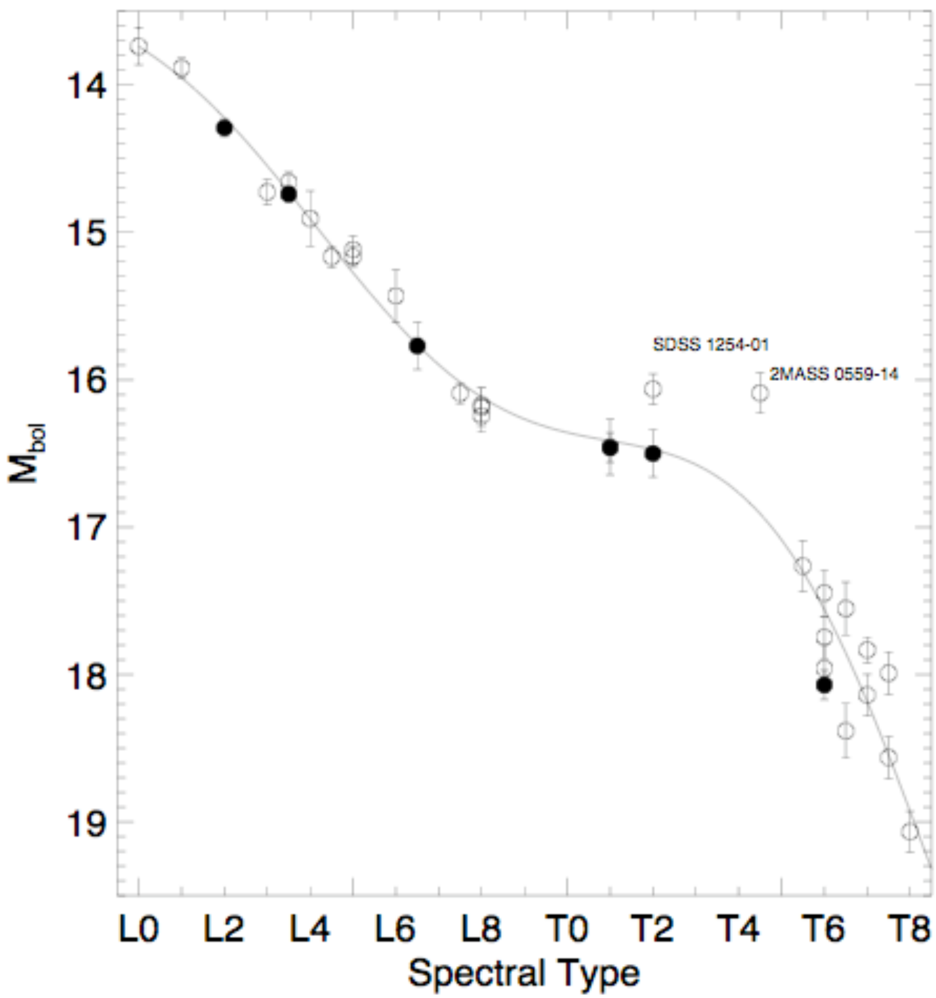
Spitzer IRS spectra (6-14 μm) have revealed **first detection of NH_3** in a non-planetary atmosphere, possible detections of silicate absorption

Oppenheimer et al. (1998); Cushing et al. (2005); Roellig et al. (2005); Kirkpatrick (2005)



L0.0
F_λ (erg cm^{-2} s^{-1} μm^{-1})
8•10^{-11}
6•10^{-11}
4•10^{-11}
2•10^{-11}
0
1.0
1.5
2.0
Wavelength (μm)

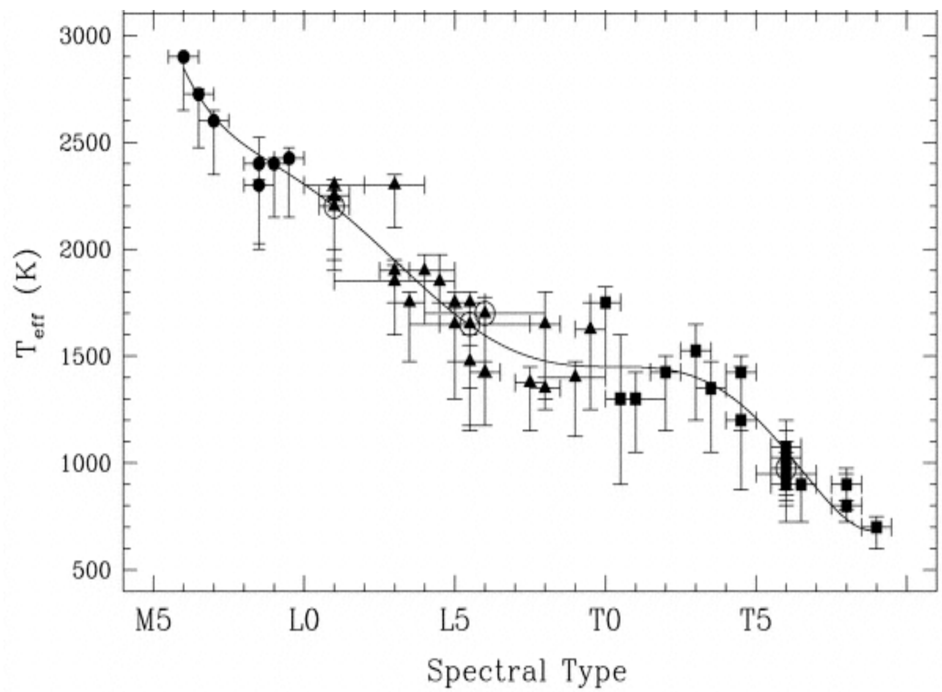
Spectral Type/Luminosity Relation



Burgasser (2007)

Overall, luminosity monotonic with spectral type; deviations and variations may arise from "cosmic scatter", unresolved multiplicity

Spectral Type/Temperature Relation



Golimowski et al. (2004)

Again, monotonic relation, with a flattening across L/T transition

(Kirkpatrick et al. 2000; Golimowski et al. 2004; Vrba et al. 2004)

Some disagreement between L_{bol} and spectral fit values, particularly at young ages: Ongoing problems with spectral models? Radii predictions incorrect?