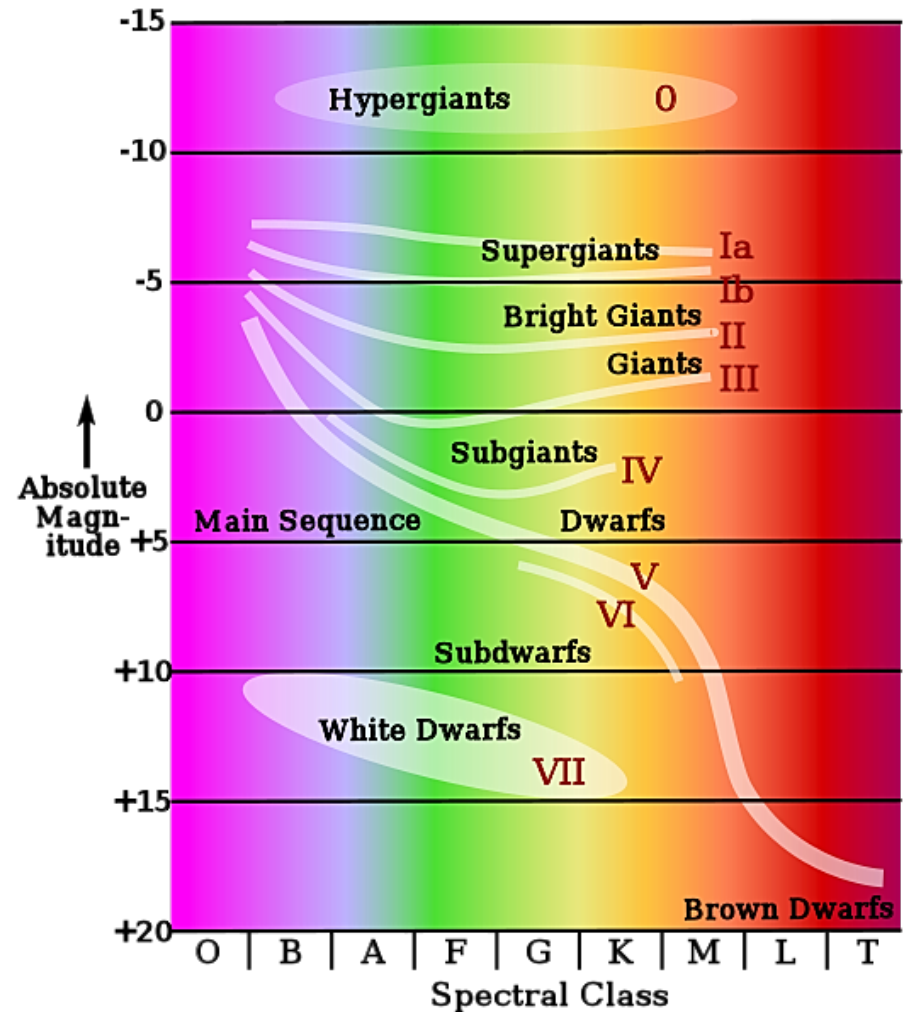


Brown dwarfs: content

- History
- Definition-properties
- Classification (MLTY)
- Interiors
- Evolution
- Atmospheres (rain-out, clouds, HR diagram)
- Formation and young brown dwarfs
- Protoplanetary disk & magnetospheric accretion



Brown dwarfs: history

- Theoretical entity termed a brown dwarf were first theoretically postulated by Kumar (1963) and Hayashi & Nakato (1963) as a low mass by-product of star formation. Long, frustrating but ultimately successful search began.
- Becklin & Zuckerman (1988) discovered a very red companion to a white dwarf GD165 called GD165B which later become a prototype of L sp. type. TiO bands were missing. No CH₄ or NH₃.
- Rebolo et al. (1995) discovery of a young brown dwarf (Teide 1) in the Pleiades cluster, sp.M8, Li test=>BD
- Nakajima et al. (1995) discovered a companion to an nearby M1 dwarf Gl229, dubbed Gl229B. CH₄ in the near infrared resembled Jupiter. It was the first prototype of T dwarfs. It was published in Nature the same year and month as the first exoplanet around the Sun-like star.
- Harvard classification OBAFGKM extended by L-T (Kirkpatrick et al. 1999, Martin et al. 1999, Burgasser et al. 2002)
- Y sp. Type? (WISEP J1828+2650, Cushing et al. 2011)
- Coldest brown dwarf WISE 0855-0714, 250K (Luhman 2014)

Brown dwarfs: definition

- Brown dwarfs (BD) are cool.
- Brown dwarfs are Very Low Mass (VLM) objects.
- VLM stars and BDs are collectively referred to as **VLM objects**.
- Brown dwarfs are not stars by definition.
- BDs are prolongation of the main sequence to lower masses.
- BD is defined as an object without sustained core hydrogen burning (some of them, $>0.065M_{\text{sun}}$, can burn H for some period of time).
- This puts upper boundary on its mass, $0.075 M_{\text{sun}}$ which depends on the metallicity. Higher metallicity triggers blanketing effect, higher core temperatures and hence lower MS edge mass.
- BDs do not burn light hydrogen but can burn deuterium.

Brown dwarfs: definition

- Brown dwarfs and LTY dwarfs are two different things.
- LTY dwarfs are sp.types based on a spectral classification, they are continuation of dwarfs (hot,yellow,orange,red...).
- Objects less massive than stars are also called **sub-stellar** objects (EGP+BD).
- Single (free floating) objects with mass < 13M_{jup} (lower limit of deuterium burning) are called **sub-brown dwarfs** (planetary mass objects), 1M_{sol}=1047M_{jup}.
- The formation history should distinguish between the BDs and planets but it is currently impossible to determine the history and origin of an object.
- L-T **sub-dwarfs**: metal deficient L-T dwarfs formed at very early ages, thick disk or halo, high proper motion.

Brown dwarfs: properties

- Apart from deuterium they can burn lithium.
- It is difficult to determine the mass. Li test is safe for older objects.
- BDs radiate also gravitational energy as they cool and shrink.
- There is a lack of BD in binaries which is a so called 'brown dwarf desert'.
- X-rays similar to low mass stars

- Number of:
 - T dwarfs = $20 \times 10^{-3} / \text{pc}^3$,
 - L dwarfs = $10 \times 10^{-3} / \text{pc}^3$
 - M dwarfs $65 \times 10^{-3} / \text{pc}^3$
 - O-K $30 \times 10^{-3} / \text{pc}^3$

$$t_{KH} = \frac{U/2}{L} = \frac{3}{10} \frac{GM^2}{R} / L = 3 \times 10^{10} \text{ yr}$$
$$(M = 0.050 M_{sol}, L = 10^{-6} L_{sol})$$

- L dwarfs are missing since they cooled to T dwarfs while M dwarfs are stars which did not cool much.

Brown dwarfs: properties

Luminosity function: number of objects per unit absolute magnitude M , per unit volume, $\text{pc}^{-3}\text{mag}^{-1}$.

$$\Phi(M) = \frac{dN}{dM} \quad \vee \quad \frac{dN}{dL}, \frac{dN}{dM_V}, \frac{dN}{dM_I}, \dots$$

Mass function (in linear units) : number of objects per unit mass M , per unit volume.

It is more difficult to get since the mass luminosity relation dL/dM strongly depends on the age contrary to stars . BDs are predicted to contribute about 10% of the mass of stars

$$\Psi(M) = \frac{dN}{dM} = \frac{dN}{dL} \frac{dL}{dM} \quad \xi(M) = \frac{dN}{d \log M} \quad d \log M = \frac{1}{M \ln 10} dM$$

$$\Psi(M) = \frac{dN}{dM} \sim M^{-\alpha}, \quad 1 < \alpha < 2, \quad \text{pc}^{-3} \text{Msol}^{-1} \quad \Psi(M) = \frac{0.4343}{M} \xi(M)$$

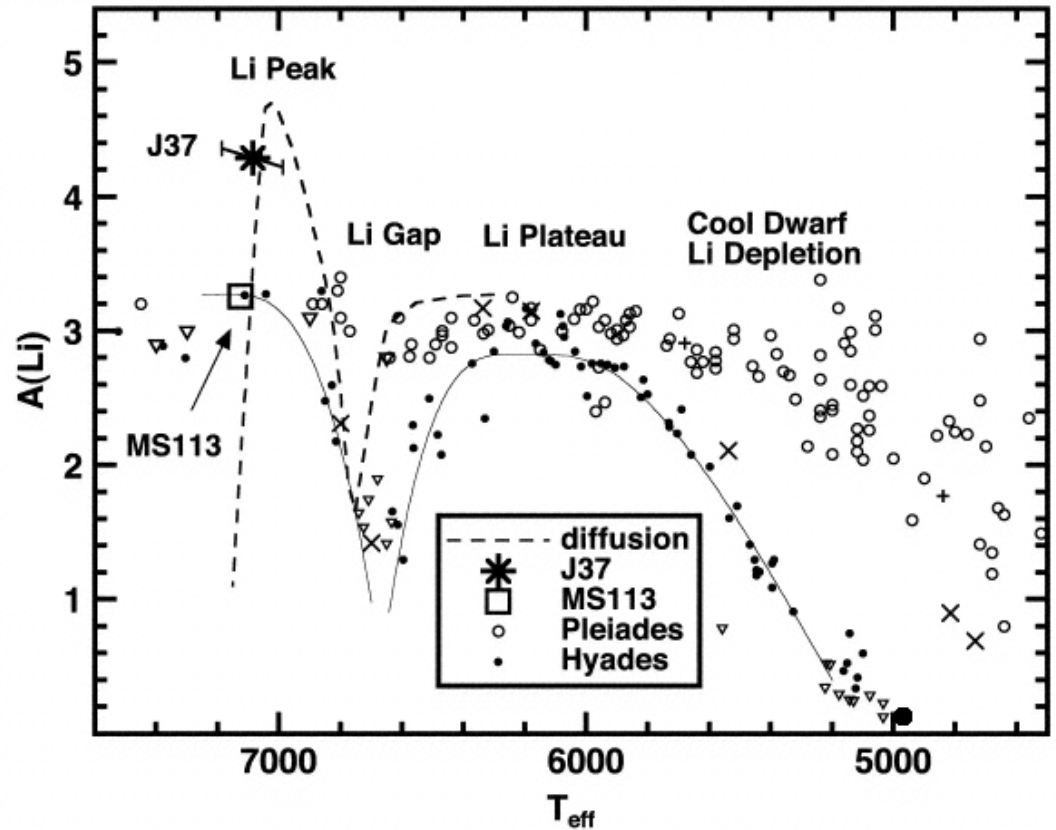
Initial mass function (IMF): is the mass distribution in terms of the initial mass

Salpeter IMF (in linear units) $M > 0.5 \text{Msol}$

$$\Psi(M) \sim M^{-\alpha}, \quad \alpha = 2.35$$

Li test

- Rebolo et al. (1992)
- Light H burns at 3e6K
- Li burns at 2e6K which corresponds to $M > 60M_J$
- Once depleted Li does not produce easily again
- VLM objects are assumed to be fully convective which brings Li down to the furnace and Li depletion is observed at the surface
- So presence of Li in older objects means that they are BDs with $M < 60M_J$
- Cannot be applied to young objects



- Li story and challenges:
- Cosmic, meteoritic Li abundance is low $A(\text{Li})=3$, solar $A(\text{Li})=1.1$ ($\text{Li}/\text{H}=1.3\text{e-}11$)
- Cool dwarfs: conv. zone (CZ) gets deeper into Li burning region, Li abundance decreases with age (Pleiades=100Myr, Hyades=600Myr)
- Li gap: cool edge-increased rotation & mixing, hot edge-diffusion Li settling under CZ
- Li is alkali metal, low 1st ion. potential, is in the form of LiII/LiI in the stellar/BD atmospheres
- LiI has strong resonance line $\text{Li}6708\text{\AA}$, little flux there (big telescope, moderate resolution)
- Li lines is absent at L0, is deepest at L6 and diminishes at later sp. types
- Li line strength depends also on the pseudo-continuum = NaI, KI lines
- For $T < 1500\text{K}$ Li forms LiCl and LiOH

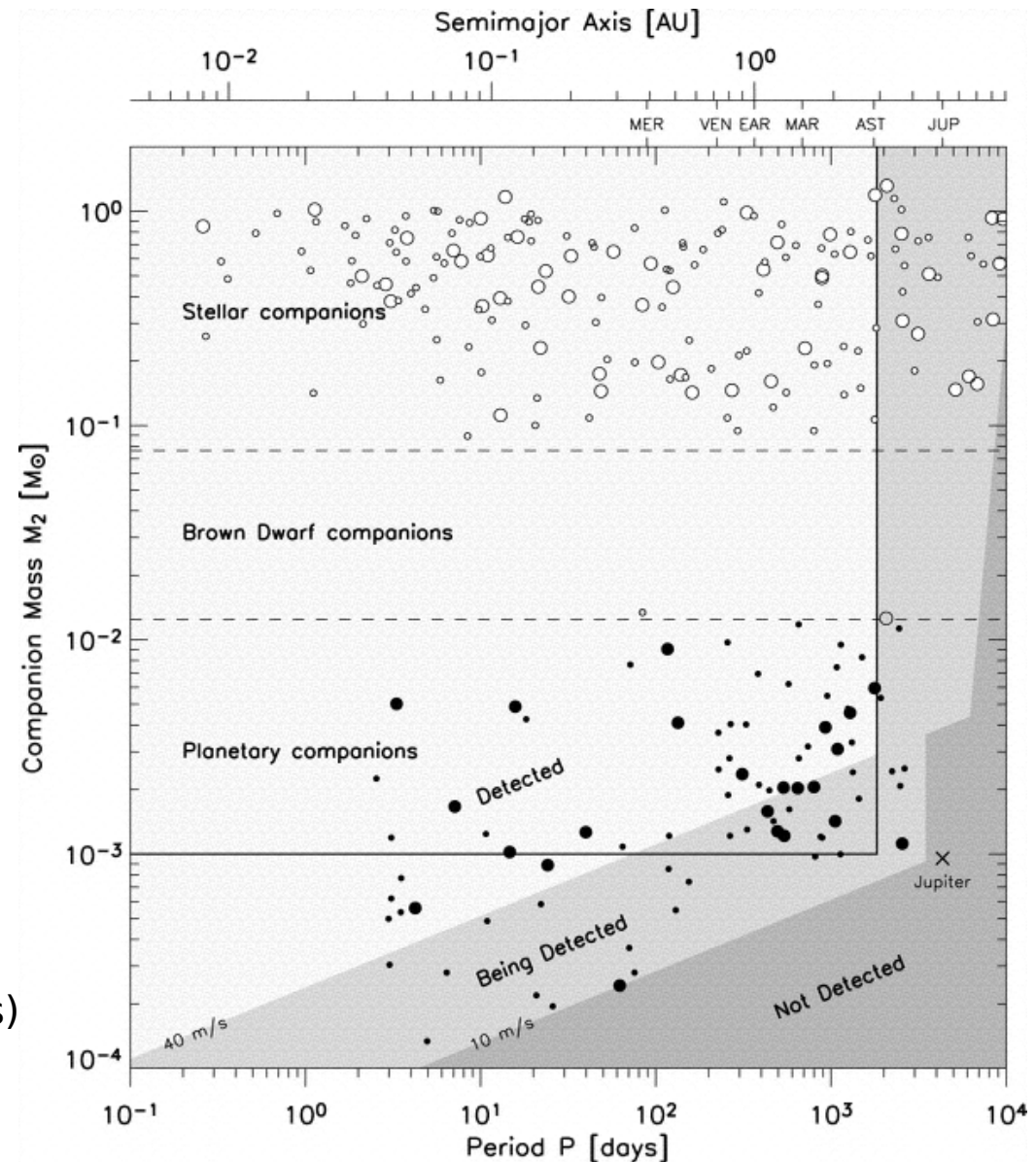
Brown Dwarf Desert

Lack of BD companions (5-80Mj) to F-M stars. Observed frequency only about 1% for separations <3AU (Marcy&Butler 2000)

BD companions to G, K, M stars, 75-300au -> frequency 1%+/-1%
Massive (> 30 MJ) BD companions at 120-1200 au -> frequency 0.7%+/-0.7% (McCarthy & Zuckerman 2004)

No Brown Dwarf Desert at wide separations > 1000au for F-M0 main sequence stars (M>0.5Msun) Gizis et al. (2001)

Grether & Lineweaver (2006), companions to Sun-like stars closer than 25 pc (large symbols)
25-50 pc (small symbols)



Classification: M-L-T-Y

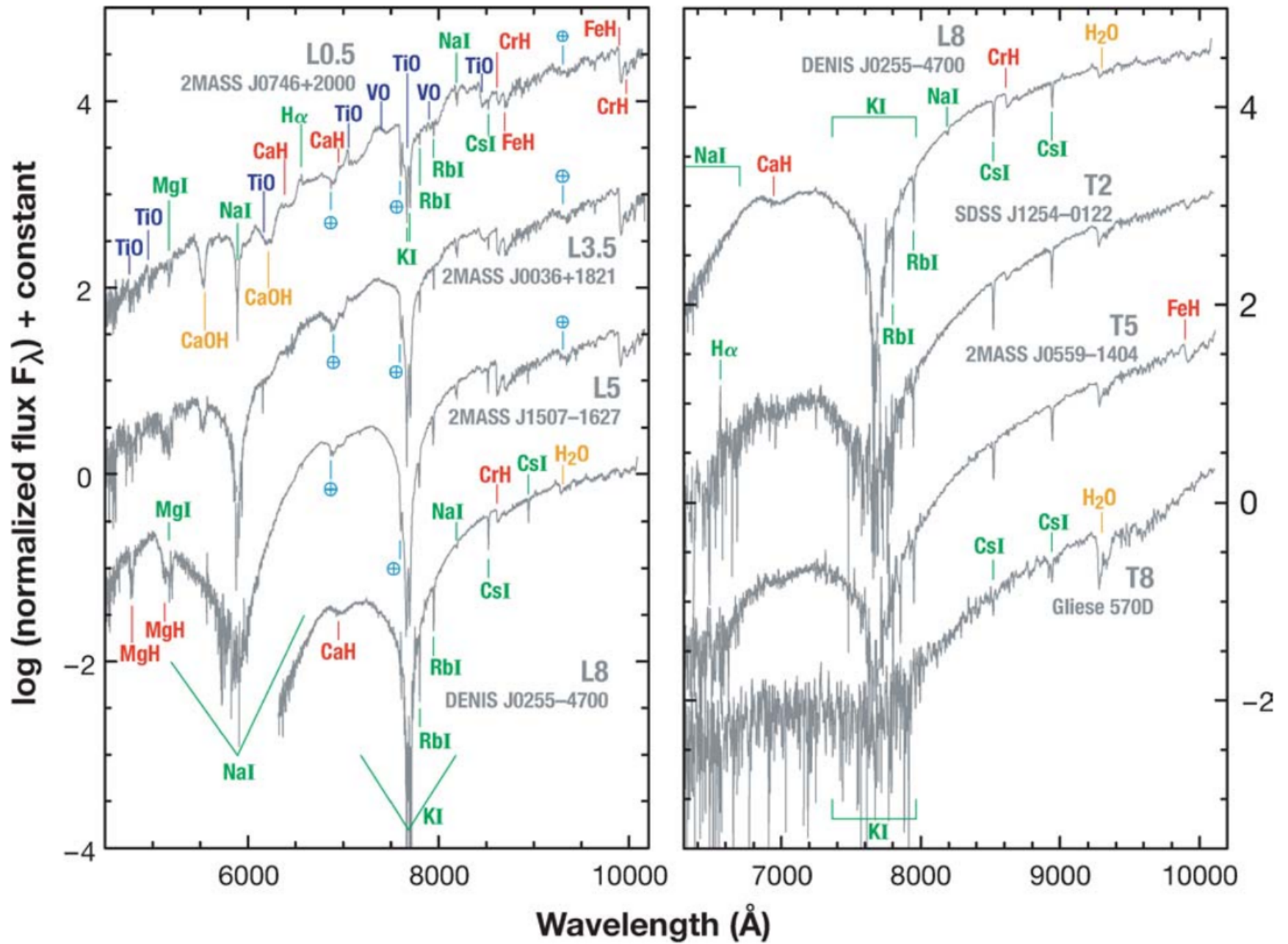
Taxonomy and classification is a backbone of the research. It is defined according to the observed spectral characteristics and not according to the physical properties which may depend upon the current theories which may change with time. Nevertheless, it is certain that sp. types reflect the general trend of decreasing temperature.

M-type: TiO bands get stronger and then weaker. VO behaves in a similar manner but is a little bit less refractory.

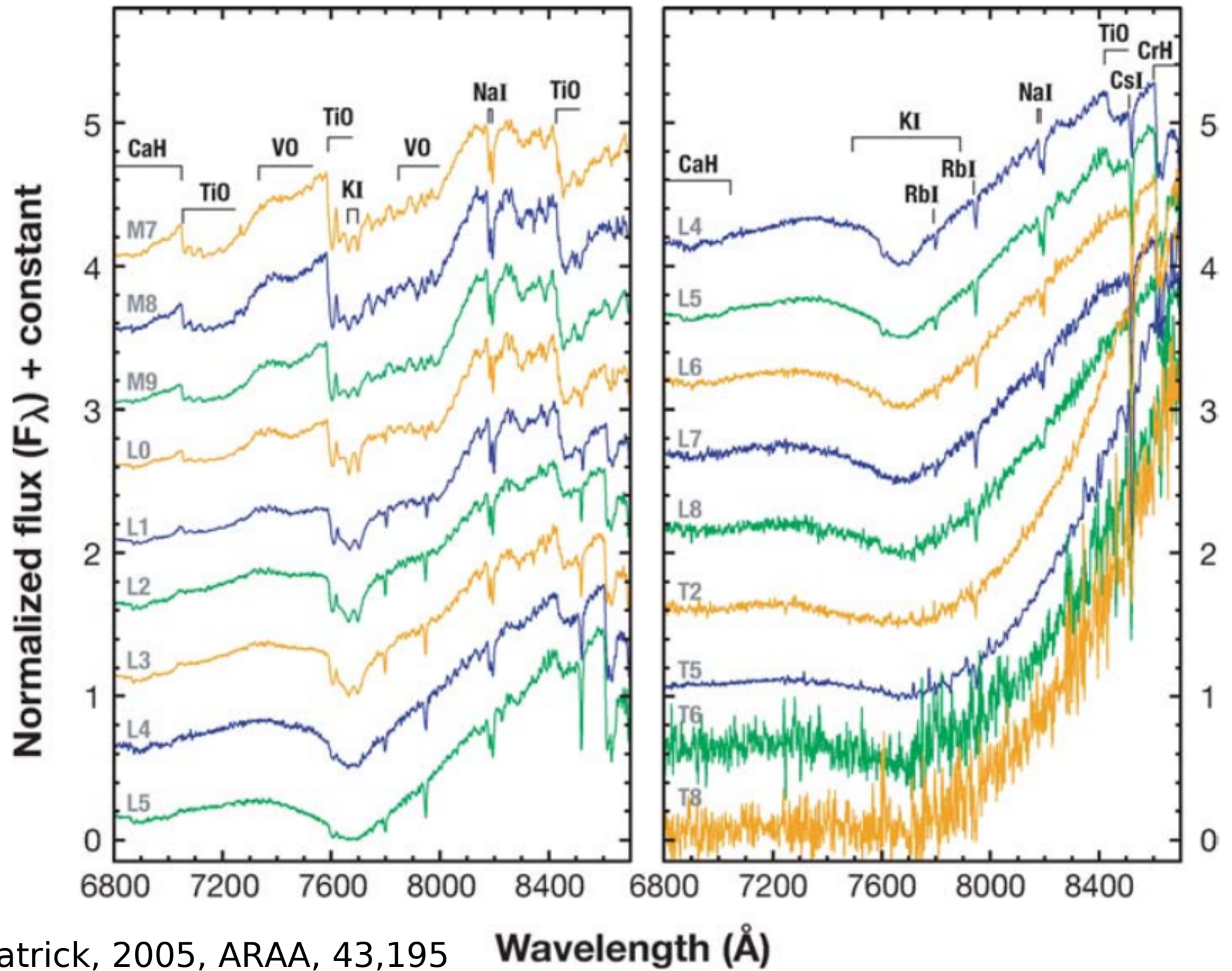
L-type: TiO disappears (TiO_2 , CaTiO_3 =perovskite), lines of alkali metals Na, K get stronger, 2500-1300K, FeH, CrH get stronger and then weaker, onset of CH₄ at 3.3 micron, formation of dust, old stars+young BDs.

T-type: defined by the onset of CH₄ in H-K band, surprise-brightening of FeH (9896)?, dust settling, clearing, J brightening, bluer J-K color index, 1500-500?, they are all sub-stellar.

Y-type?: may be defined by the onset of ammonia NH₃ for $T < 700\text{K}$ (or condensation of water at 500K?, J-K will reverse to the red again at 400K?, NaI, KI will disappear at 500K?), 500-

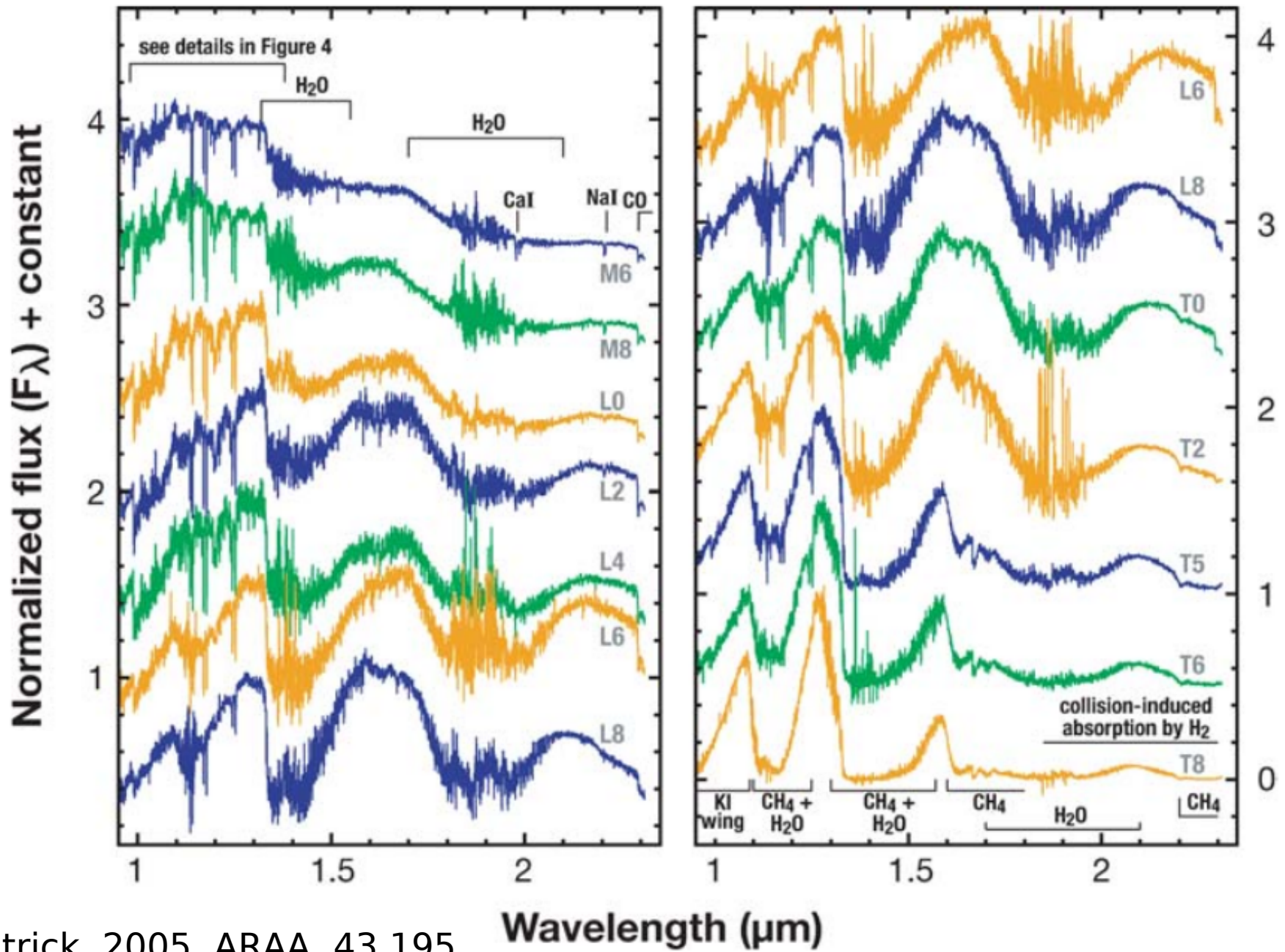


Kirkpatrick, 2005, ARAA, 43,195



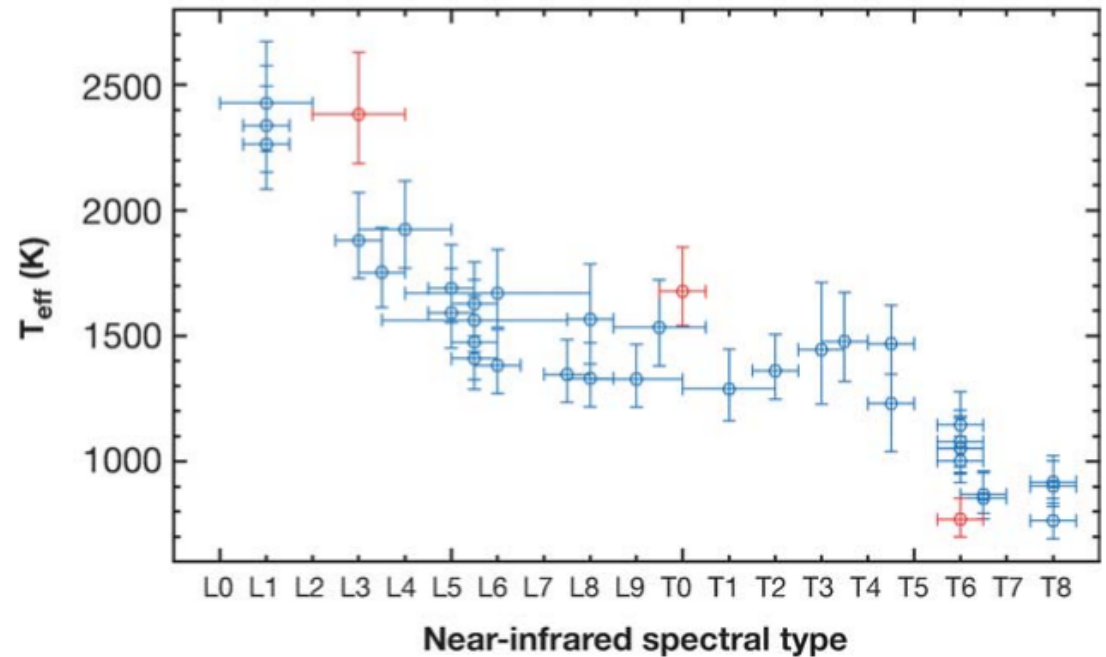
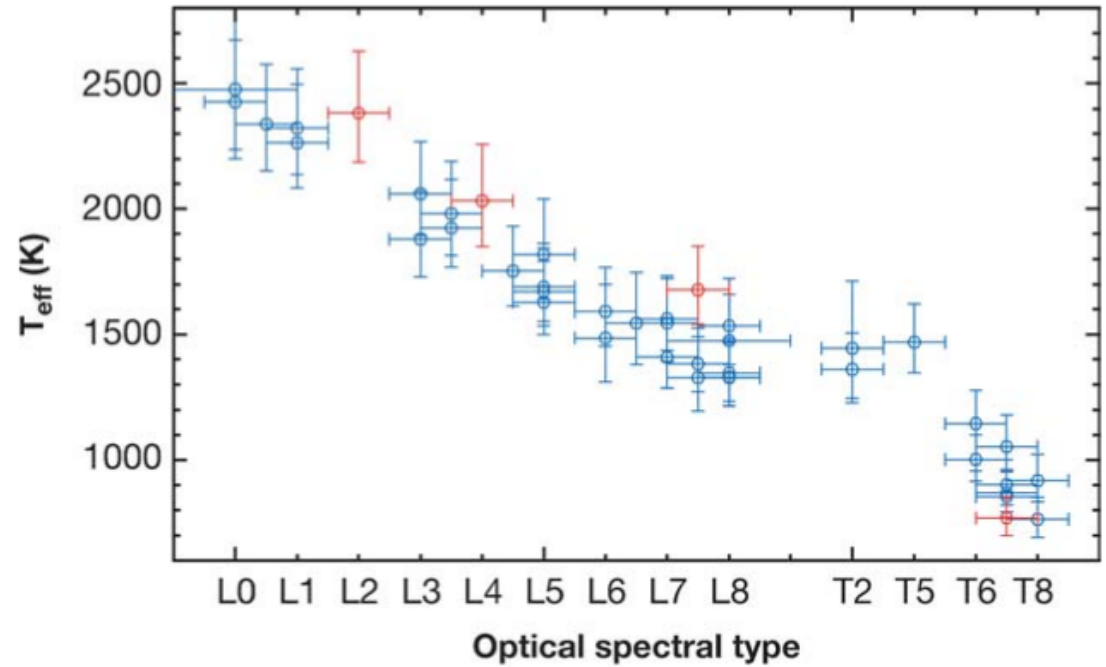
Kirkpatrick, 2005, ARAA, 43,195

Wavelength (\AA)

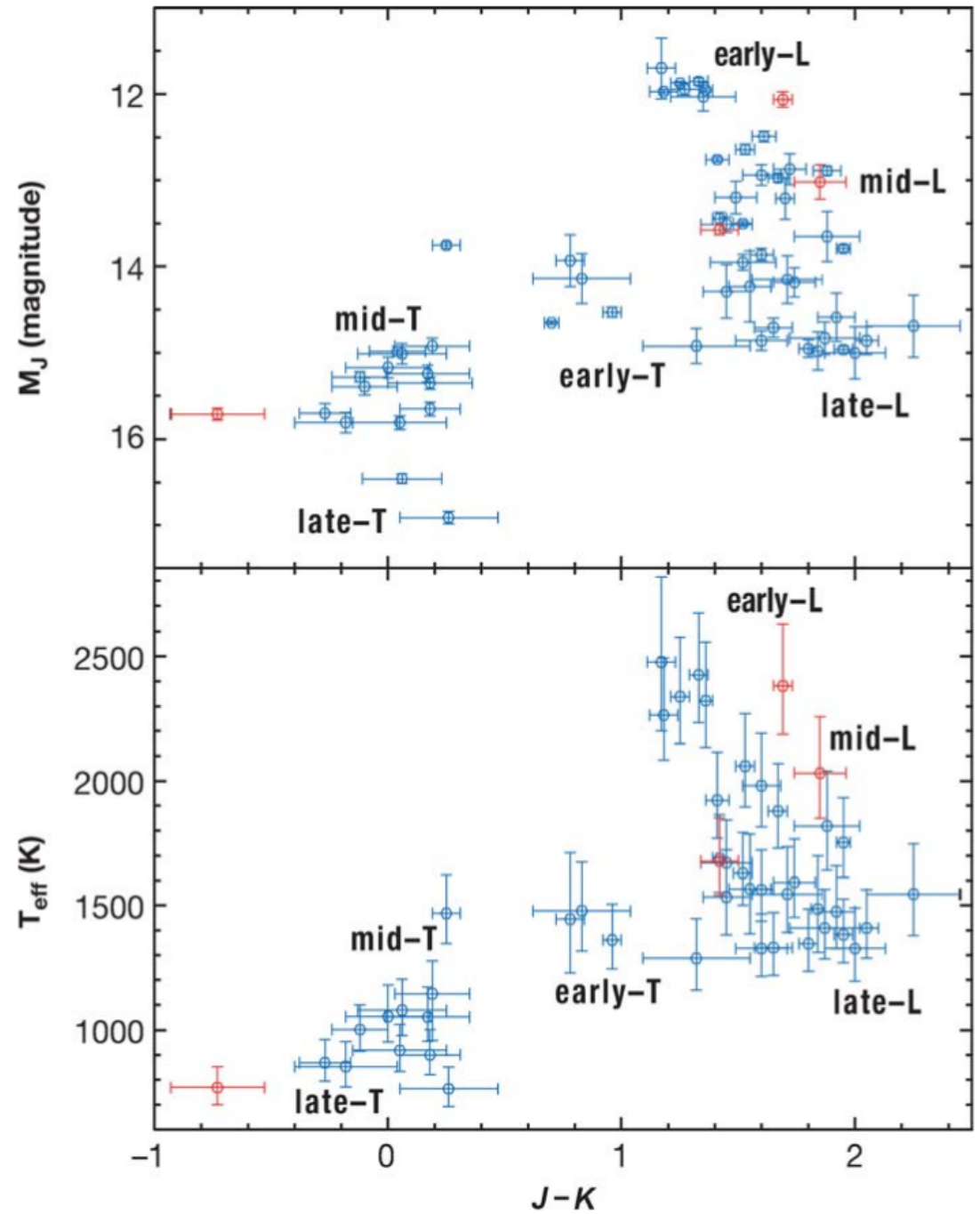


Kirkpatrick, 2005, ARAA, 43,195

$T > 1600\text{K}$ the dust cloud is optically thin.
 $1400 < T < 1700\text{K}$: the dust cloud is getting thicker but moves deeper.
 $T < 1400\text{K}$ cloud is too deep to be observed.



Kirkpatrick, 2005, ARAA, 43,195



First Y dwarfs

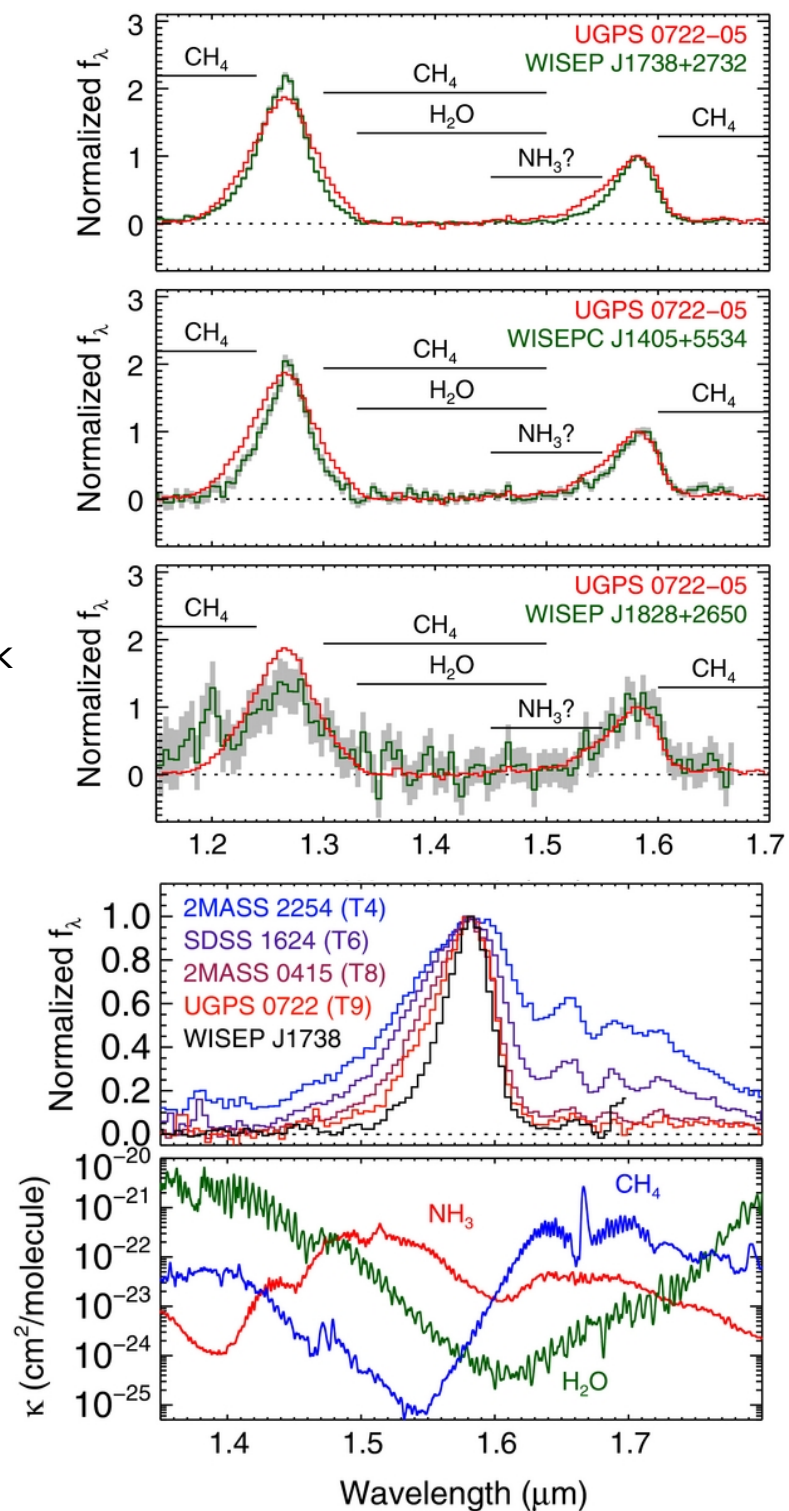
Cushing et al., 2011, ApJ, 743,50

The lower panel of the upper Figure shows the 1.15-1.70 μm spectrum of WISEP J1828+2650 along with the spectrum of UGPS 0722-05 (T9). The spectrum of WISEP J1828+2650, while dominated by the same CH₄ and H₂O absorption bands present in T dwarf spectra, has a feature not seen in any T dwarf: the J- and H-band peaks, when plotted in units of f_λ , are essentially the same height.

Model atmospheres of cool brown dwarfs predict that the near-infrared colors, which are blue for the hotter T dwarfs, turn back to the red at effective temperatures between 300 and 400 K as the Wien tail of the spectral energy distribution collapses.

The spectra were all normalized to unity at the peak of the H band (1.58 μm)

Note that the change in the spectral morphology of the blue wing of the H-band peak is similar between T6/T8 and T8/T9 suggesting a common absorber or set of absorbers. In contrast, the spectrum of WISEP J1738+2732 exhibits excess absorption that matches the position of the NH₃ absorption shown in the lower panel.



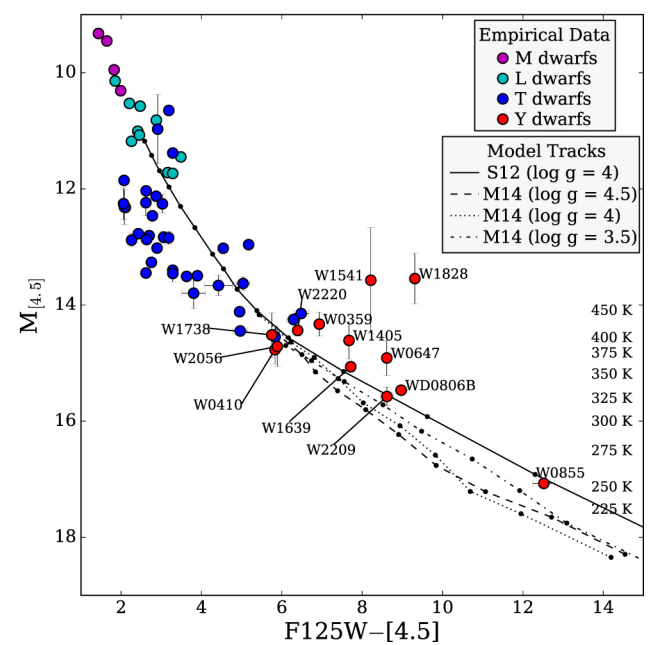
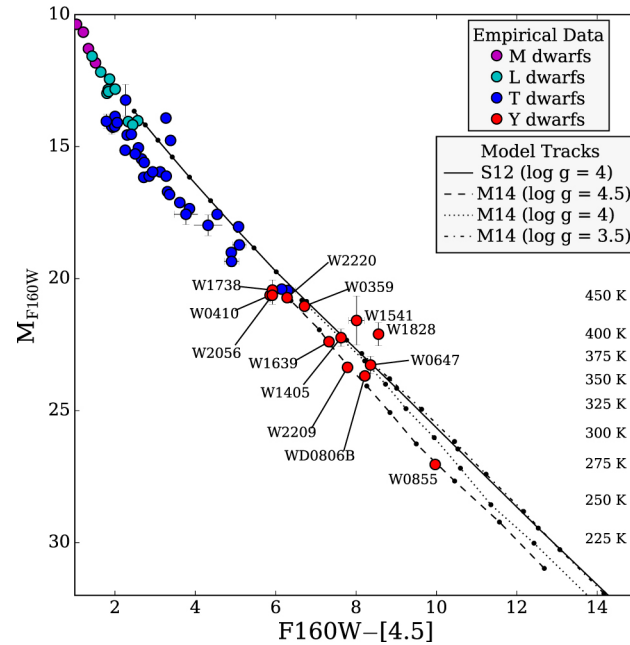
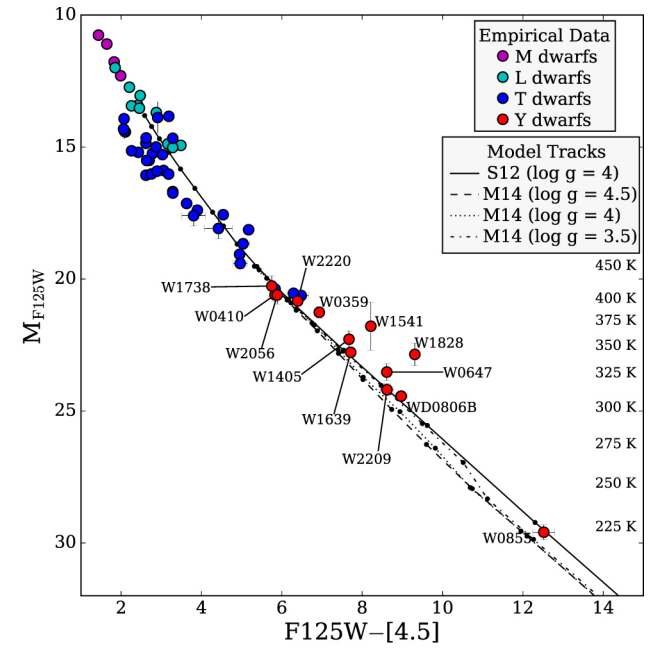
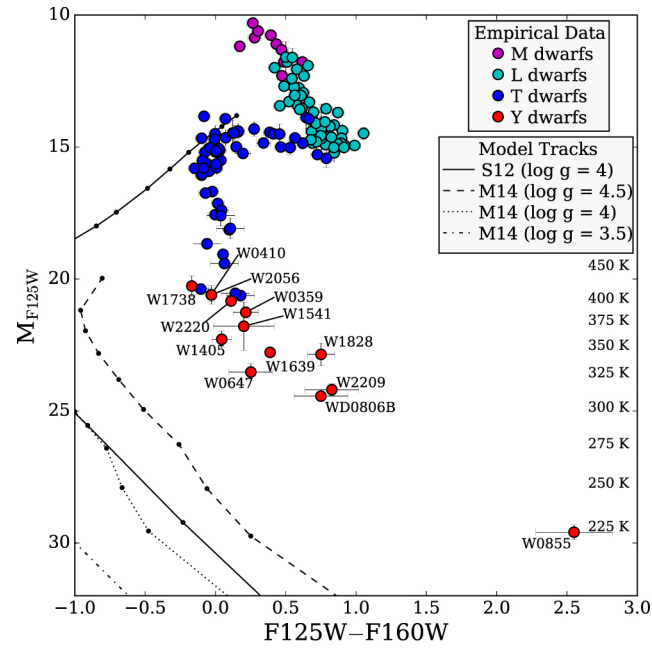
WISE 0855-0714

Discovered by Luhman (2014).

The coldest and faintest brown dwarf known (as of 2026).
Actually, it is a sub-brown dwarf i.e. with a mass in a planet regime.

$T_{\text{eff}}=250\text{K}$. $M_{[4.5]}=17.1\text{ mag}$

Fourth closest system to the Sun. Distance 2pc.



Schneider et al. (2016)

Discovered by Luhman (2013).

Also known as Luhman 16AB.

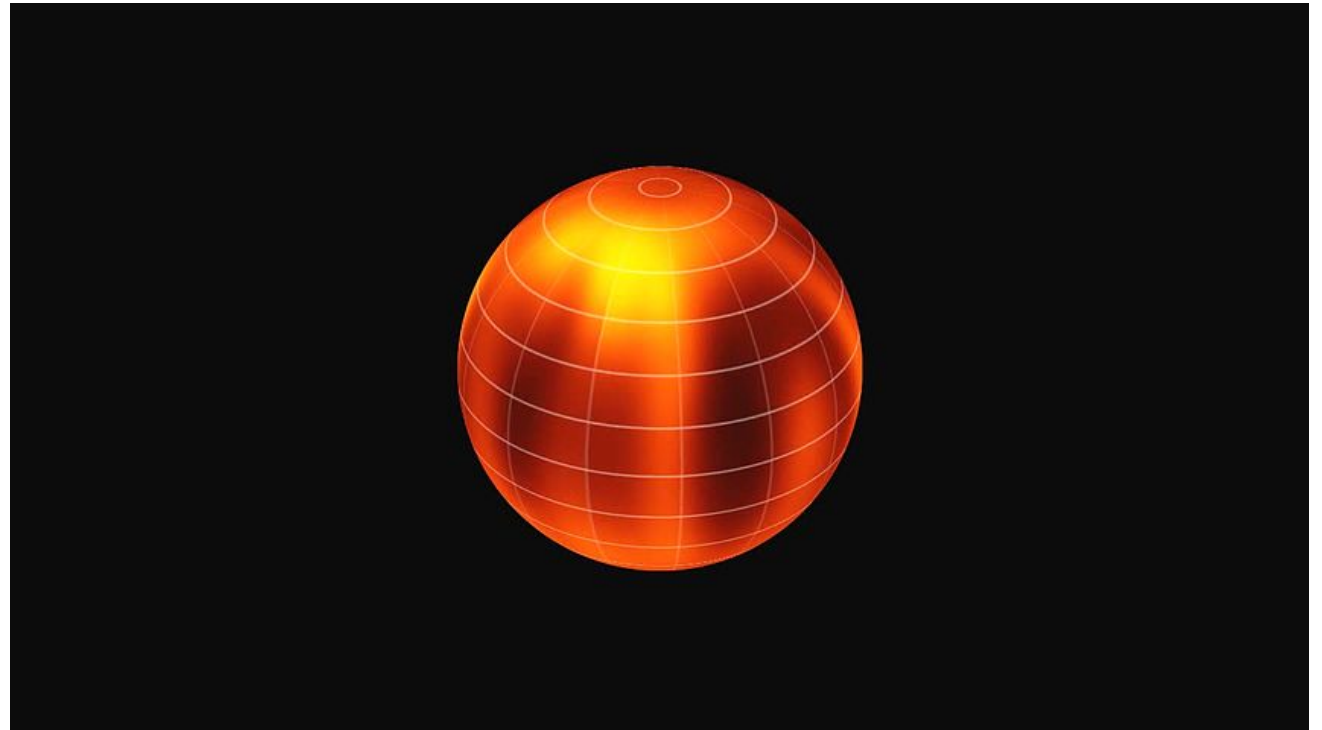
The closest brown dwarfs known.
Distance 6.5 lyr (2.0pc).

Binary: L7.5+T0.5, $a=3\text{AU}$,
 $P=25\text{yr}$

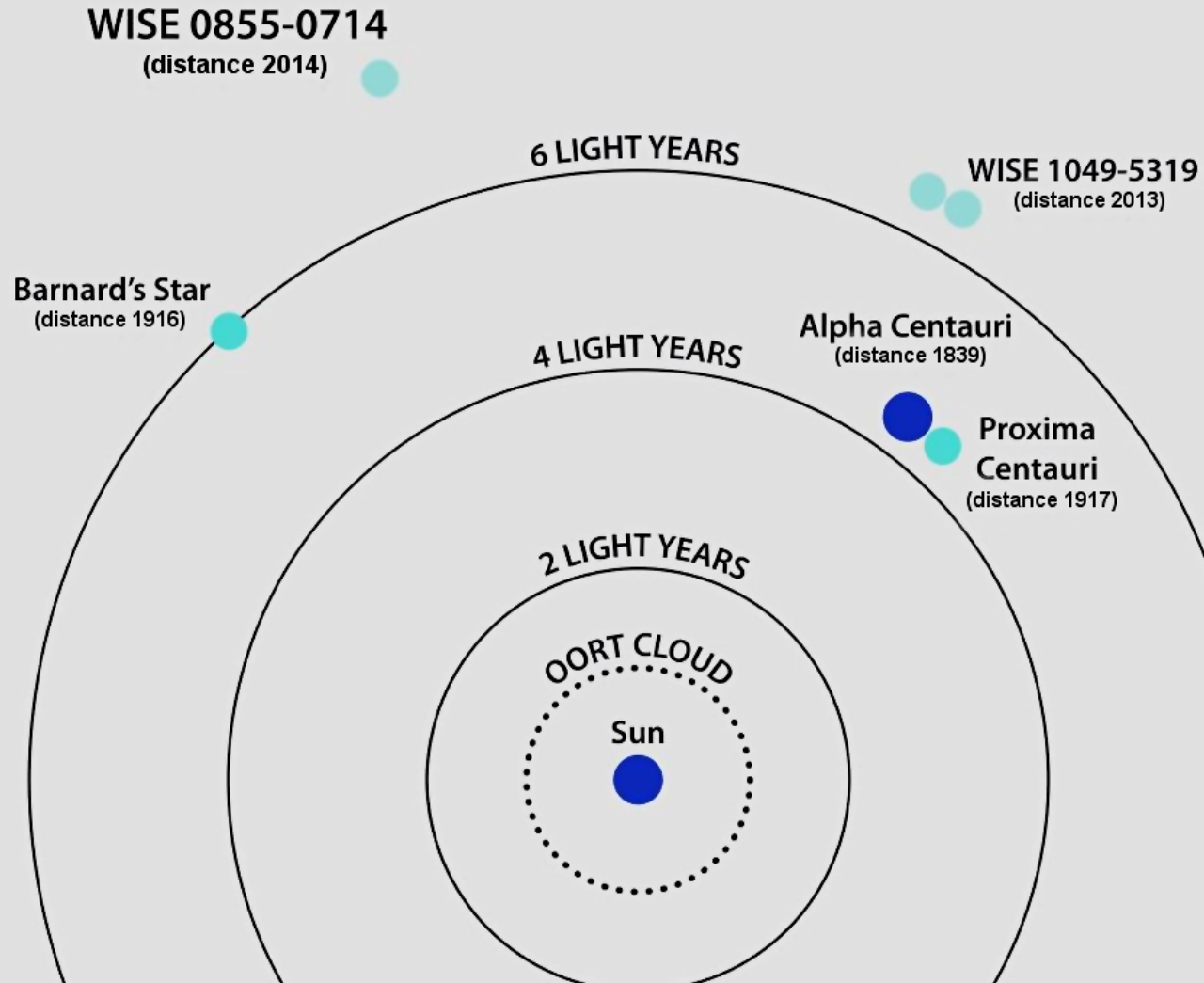
Luhman 16B: patches of clouds
changing on a daily basis.

WISE 1049-5319

Crossfield et al. (2014), VLT



THE SUN'S CLOSEST NEIGHBORS

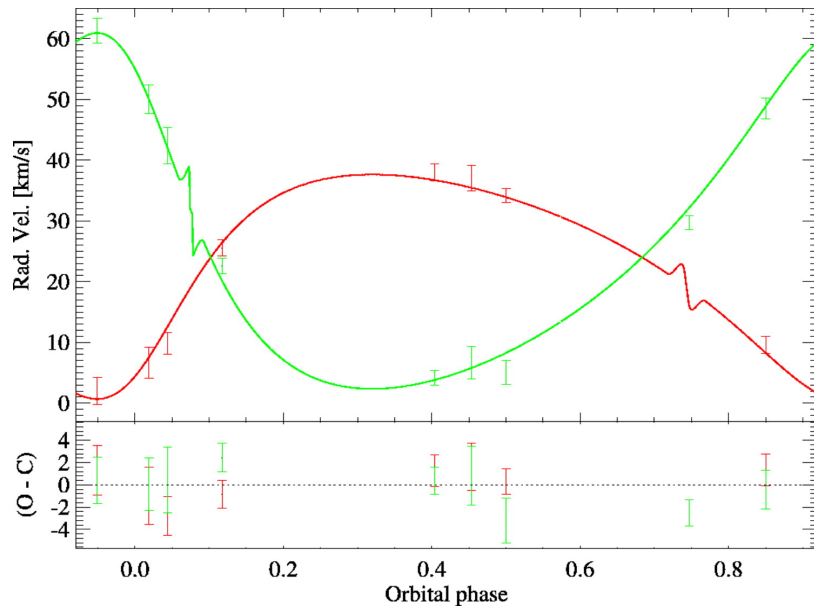


The year is when the distance was measured.

2MASS J05352184-0546085

First eclipsing binary consisting of two brown dwarfs

Stassun, Mathieu & Valenti
2006, Nature, 440, 311



$$P = 9.779556 \pm 0.00002 \text{ d}$$

$$a = 0.040 \pm 0.001 \text{ AU}$$

$$e = 0.323 \pm 0.006$$

$$M_1 = 0.054 \text{ Ms}$$

$$M_2 = 0.034 \text{ Ms}$$

$$R_1 = 0.67 \text{ Rs}$$

$$R_2 = 0.51 \text{ Rs}$$

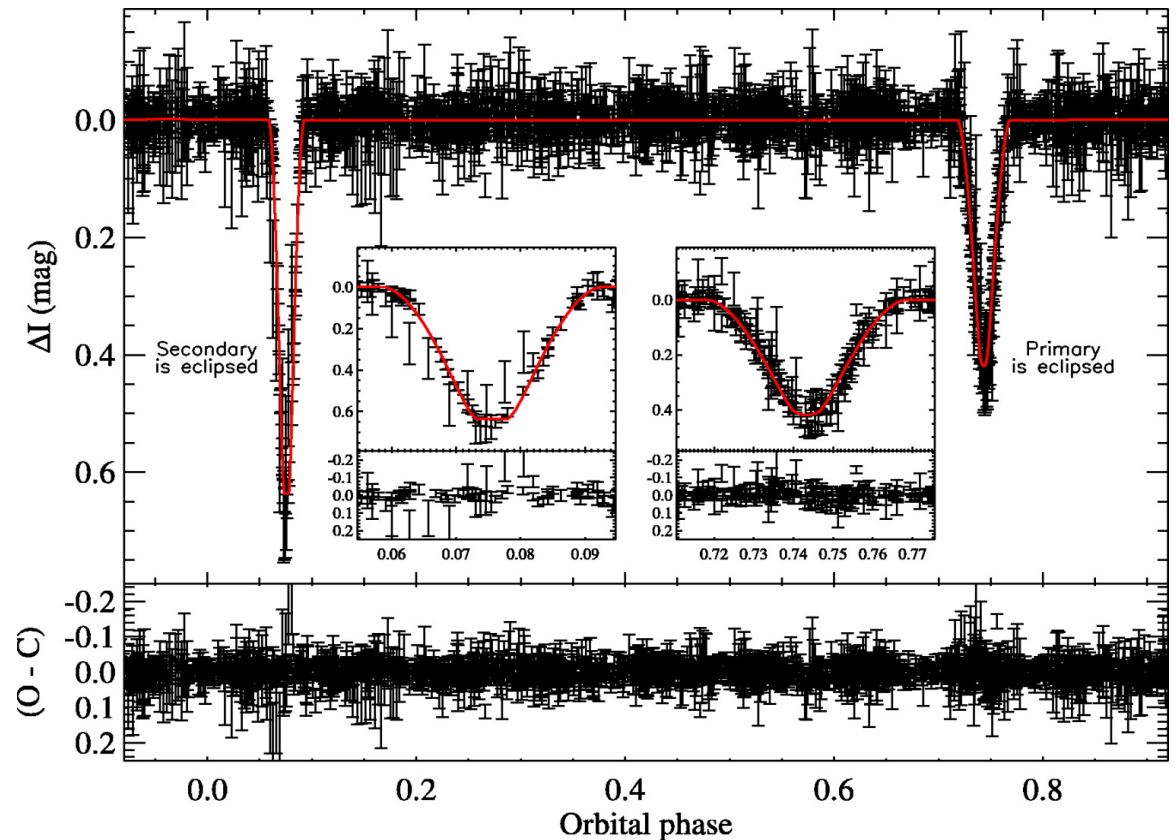
$$T_1 = 2650 \text{ K}$$

$$T_2 = 2790 \text{ K}$$

$$\text{age} = 1 \text{ Myr}$$

$$T(0) = \text{periastron}$$

Problem: masses and radii seem OK but temperature of the secondary is higher!



Formation

$$M_{Jeans} = \left(\frac{5kT}{G \mu m_H} \right)^{3/2} \left(\frac{3}{4 \pi \rho} \right)^{1/2} = 400 \sqrt{(T^3/n)} \quad [M_{sol}, K, cm^{-3}]$$

Traditional formation theory envisage that BDs form as stars. Problem, given a typical T,P in the molecular cloud predicts $M_{Jeans}=1-0.1M_{sol}$.

Nevertheless, there is probably a fragmentation which might stop when the cloud opacity prevents its cooling and it gets heated. This **opacity limited fragmentation** can theoretically produce objects as small as 0.01-0.001 M_{sol} but it assumes ideal smooth environment which is not real and non-homogeneity is likely to be more important than opacity. May be M_{Jeans} has nothing to do or be the same as the mass of the object formed...

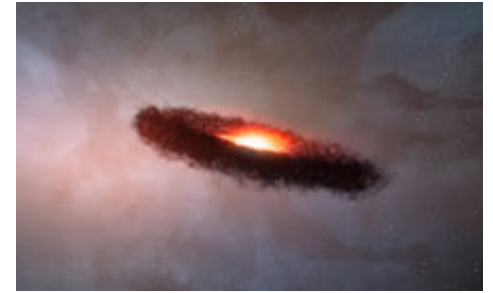
Stars do not form in isolation but interact and compete for mass. BDs could be embryos rejected prematurely from the cloud.

Embryo ejection model predictions (Reipurth & Clarke 2001):

- velocity dispersion of BDs in clusters should be higher than that of stars
- BD-BD binary fraction should be low since they should be disrupted in the ejection process (but there is a significant number of them)
- BDs should have minimal accretion discs (but many of them have)

That is why young brown dwarfs are important.

Young Brown dwarfs



Evidence of accretion processes in young BDs:

- near- and mid-infrared excess
- broad emission lines such as H α (asymmetric, infalling signatures, >200km/s)
- forbidden emission lines (outflows).

Accreting BDs have slow rotation.

Thus, BDs share properties in common with classical T Tauri stars and seem to undergo a similar accretion phase.

The best explanation of the BD accretion process is the magnetospheric accretion model (Hartmann, Hewett & Calvet 1994; Muzerolle, Calvet & Hartmann 2001; Muzerolle et al. 2003):

- A large scale magnetic field truncates the accretion disk at some inner radius.
- From that point the accretion is funneled along the magnetic field lines to the magnetic poles.
- An accretion shock and hot spots develop at the surface of the BD.
- The magnetic structures are frozen to the surface and co-rotate with the object. - Moreover, the magnetic axis can be inclined with respect to the rotation axis which would give rise to complicated non-axisymmetric flows and variability due to rotation and hot spots.

Magnetospheric accretion

Star has a dipole magnetic field which increases steeply towards the star:

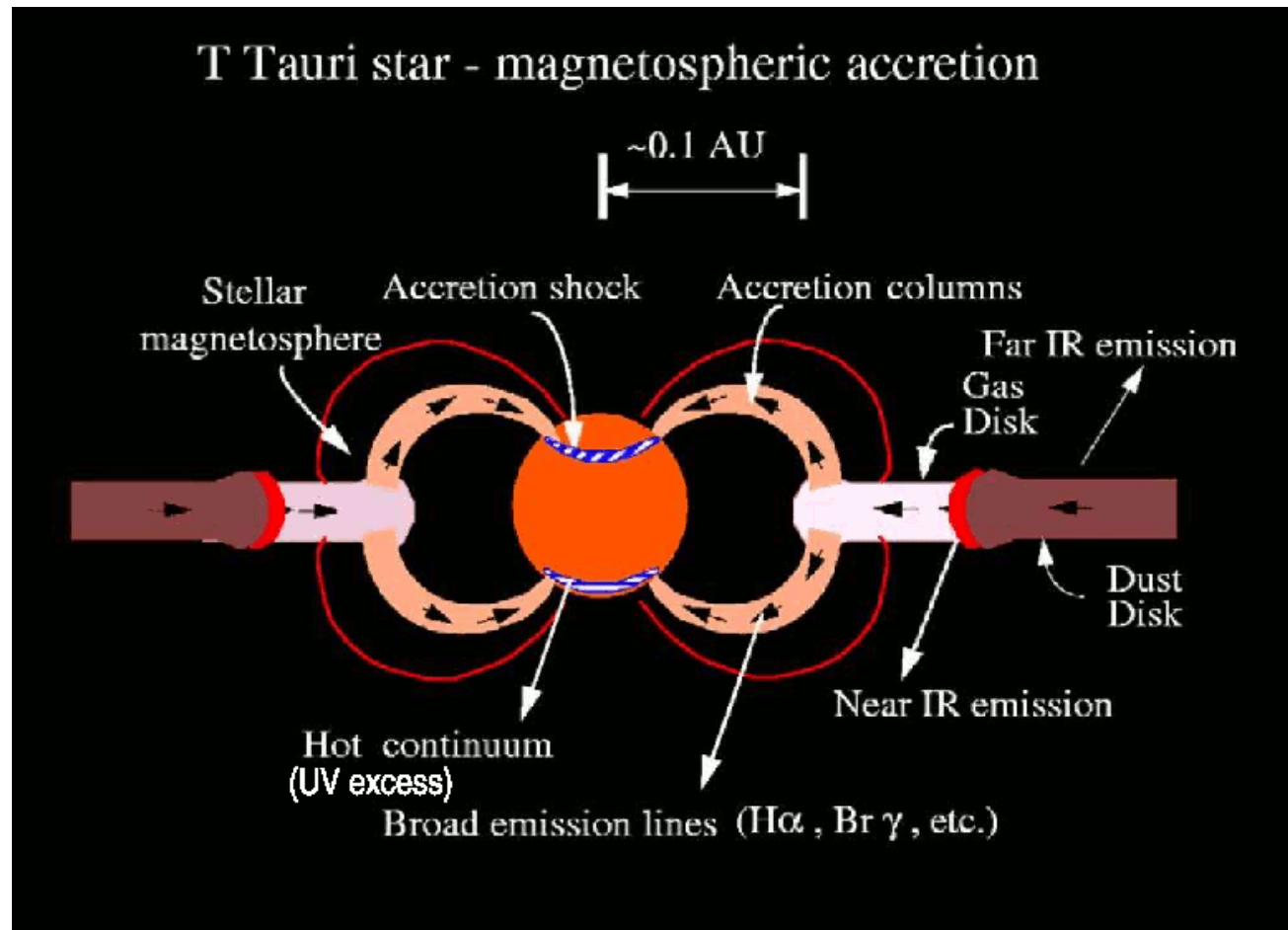
$$B(r) = B_s \left(\frac{R}{r}\right)^3 \quad \longrightarrow \quad B^2(r) = B_s^2 \left(\frac{R}{r}\right)^6$$

When mag. energy density is comparable to the kinetic energy density, the disk is disrupted and the flow follows the mag. field lines:

$$\frac{B^2}{8\pi} = \frac{1}{2} \rho v^2$$

This happens at the distance called the Alfvén radius:

$$r_A$$



Alfven radius

Assuming spherically symmetric accretion:

$$\dot{M} = 4\pi r^2 \rho v \quad \longrightarrow \quad \rho = \frac{\dot{M}}{4\pi r^2 v}$$

free-fall velocity:

$$v^2 = 2 \frac{GM}{r}$$

Dipole field: $B(r) = B_s \left(\frac{R}{r}\right)^3$ \longrightarrow

$$\frac{B^2}{8\pi} = \frac{1}{2} \rho v^2$$

$$B_s^4 \frac{R^{12}}{r^7} = \dot{M}^2 2GM$$

$$\frac{B_s^2}{8\pi} \left(\frac{R}{r}\right)^6 = \frac{\dot{M}}{8\pi r^2} \sqrt{2 \frac{GM}{r}}$$

Solve for Alfven radius:

$$r_A = \left(\frac{B_s^4 R^{12}}{2GM \dot{M}^2} \right)^{1/7}$$

More realistic estimate yields almost the same result for the disruption radius:

$$r_m = \alpha r_A \approx 0.5 r_A$$

Co-rotation and Alfven radii

The disk-magnetosphere interaction depends on the ratio between the Alfven and corotation radii.

Co-rotation radius, r_{cor} , is the radius where Keplerian angular velocity in the disc equals the angular rotational velocity of the star, Ω_{star} .

Keplerian velocity: $m \frac{v^2}{r} = \frac{GMm}{r^2} \quad v^2 = \frac{GM}{r}$

Keplerian angular velocity: $\omega_{disk} = \frac{v}{r} \longrightarrow \omega_{disk}^2 = \frac{GM}{r^3}$

Co-rotation radius: $\omega_{disk}^2 = \omega_{star}^2 \longrightarrow \omega_{star}^2 = \frac{GM}{r_{cor}^3} \longrightarrow r_{cor} = \left(\frac{GM}{\omega_{star}^2} \right)^{1/3}$

$$r_{cor} \geq r_m$$

- a slow rotation of the star
- magnetosphere brakes the inner disc
- momentum transferred to the star
- accretion is favorable

$$r_{cor} < r_m$$

$$r_m = \alpha r_A \approx 0.5 r_A$$

- a rapidly rotating star
- the magnetosphere transfers its angular momentum to the inner disc
- star is in the 'propeller' regime, where accretion is suppressed

Further out is a protoplanetary disk.

Interior and evolution

- Degenerate
- Convective: convective envelope extends in later sp. types. Stars later than M4 become fully convective due to large opacity and ionization
- Metallic H/He mixture
- Molecular atmosphere
- Thermonuclear processes do not govern the evolution

BDs do not produce sufficient energy and cool (gravity, D, Li)

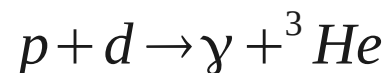
Core temperature, luminosity, effective temperature decrease ($T > 3 \times 10^6 \text{K}$ required for hydrogen fusion, $T > 2 \times 10^6 \text{K}$ for Li, $T > 6 \times 10^5 \text{K}$ for D fusion)

- BD radii shrink with time

Radii of VLM stars increase with mass.

During the evolution, radii of BDs and planets first increase with mass but after some time it reverses and radii decrease with mass. There is a peak radius at 4Mj.

Deuterium burning



Lithium burning



$${}^6\text{Li}/{}^7\text{Li} \approx 0.08, \quad A(\text{Li}) \approx 10^{-9}, \quad d/H \approx 10^{-5}$$

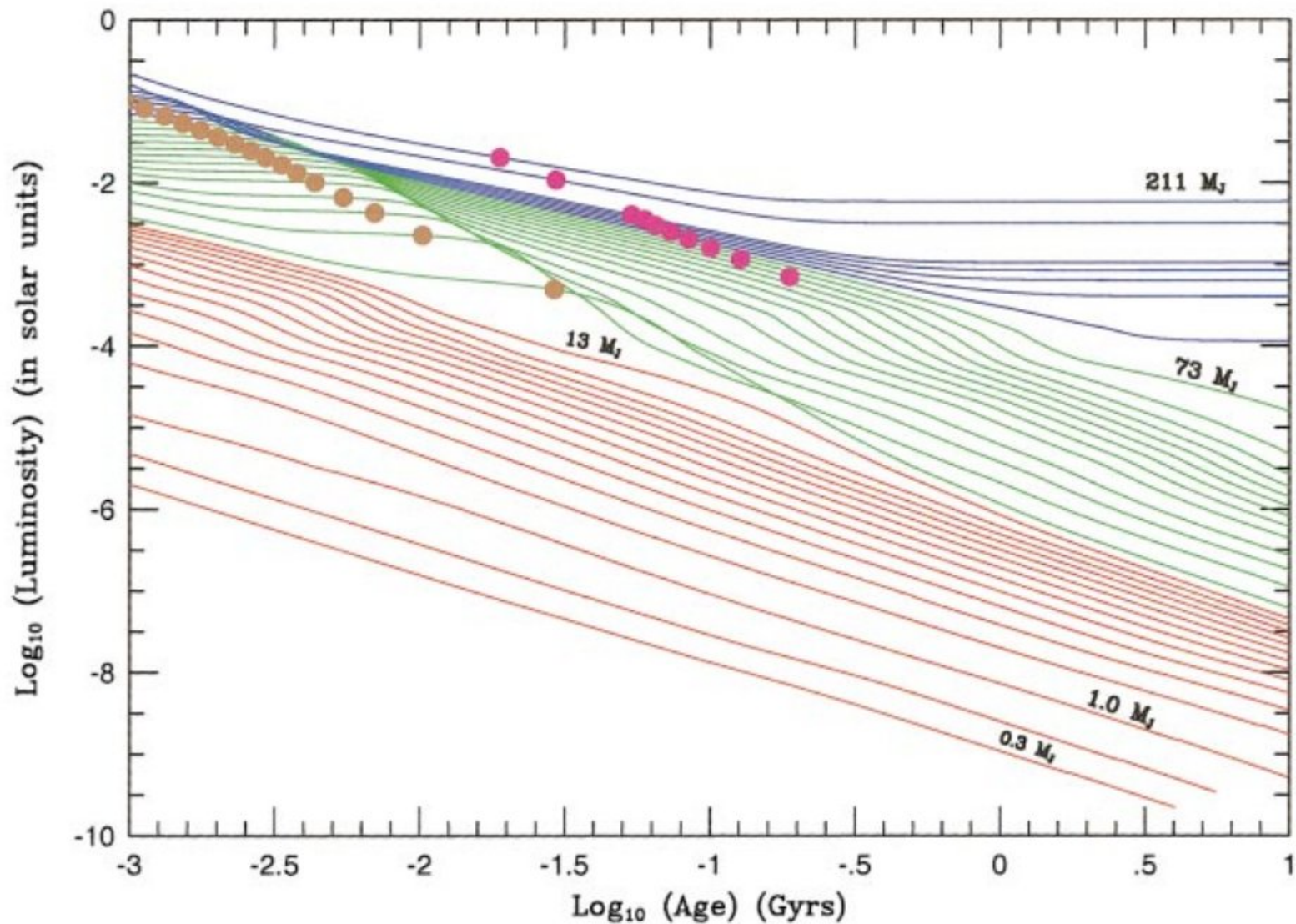


FIG. 1. Evolution of the luminosity (in L_{\odot}) of isolated solar-metallicity red dwarf stars and substellar-mass objects versus age (in years). The stars are shown in blue, those brown dwarfs above $13 M_J$ are shown in green, and brown dwarfs/giant planets equal to or below $13 M_J$ are shown in red. Though the color categories are based on deuterium or light hydrogen burning, they should be considered arbitrary *vis à vis* whether the object in question is a brown dwarf or a planet, sensibly distinguished on the basis of origin. The masses of the substellar objects/stars portrayed are 0.3, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0, 13.0, and $15.0 M_J$ and 0.02, 0.025, 0.03, 0.035, 0.04, 0.045, 0.05, 0.055, 0.06, 0.065, 0.07, 0.075, 0.08, 0.085, 0.09, 0.095, 0.1, 0.15, and $0.2 M_{\odot}$ ($\equiv 211 M_J$). For a given object, the gold dots mark when 50% of the deuterium has burned and the magenta dots mark when 50% of the lithium has burned. Note that the lithium sequence penetrates into the brown dwarf regime near $0.065 M_{\odot}$, below the HBMM. Figure based on Fig. 7 of Burrows *et al.*, 1997 [Color].

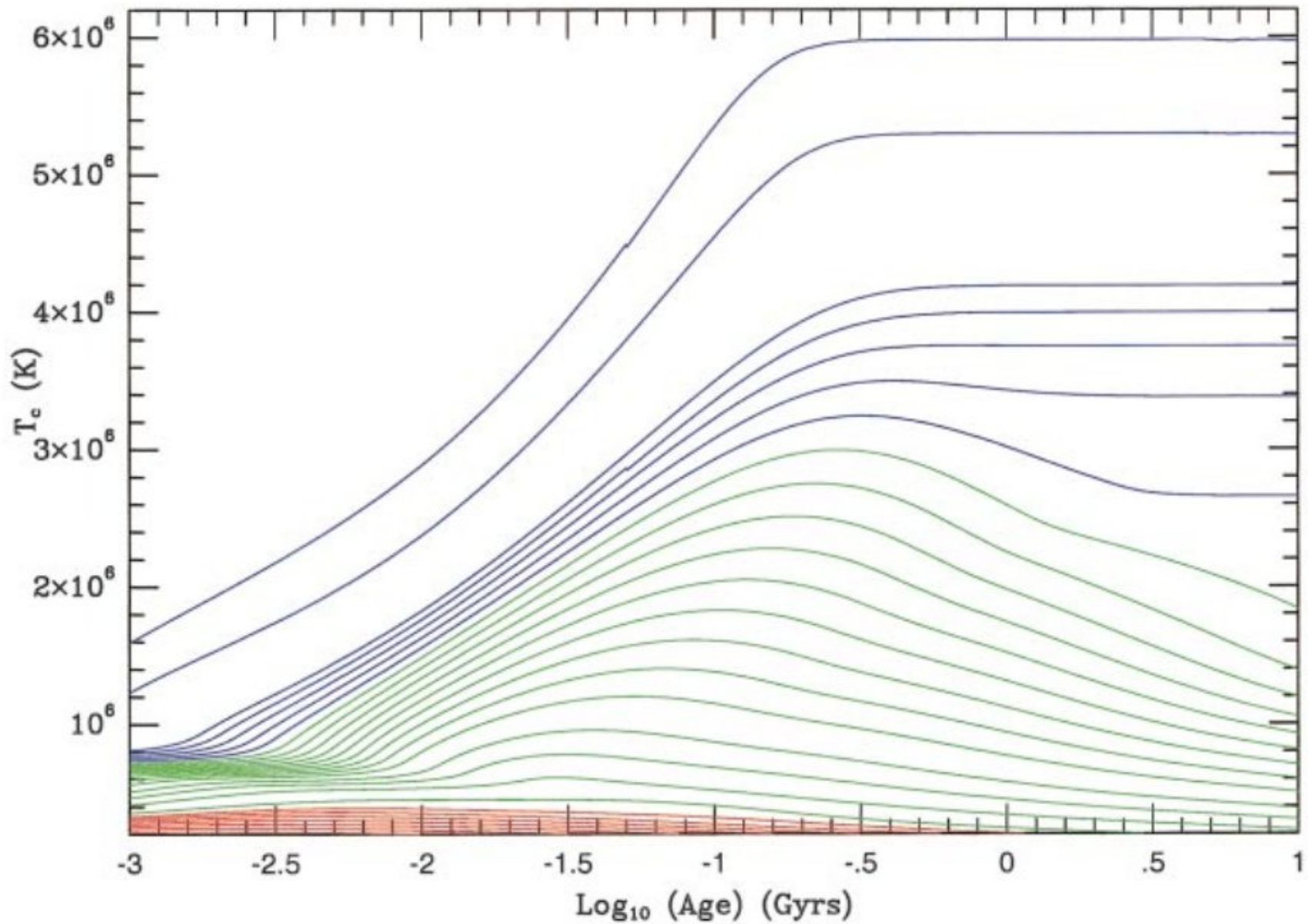


FIG. 2. The central temperature (T_c) in K vs the logarithm (base ten) of the age (in Gyr) for the same mass set of substellar objects presented in Fig. 1. As in Fig. 1, the red lines are for models with masses equal to or below $13 M_J$, the green lines are for objects above $13 M_J$ and below the edge of the main sequence, and the blue are for stars (red dwarfs) up to $0.2 M_{\odot}$. See the text for a discussion of the pertinent features [Color].

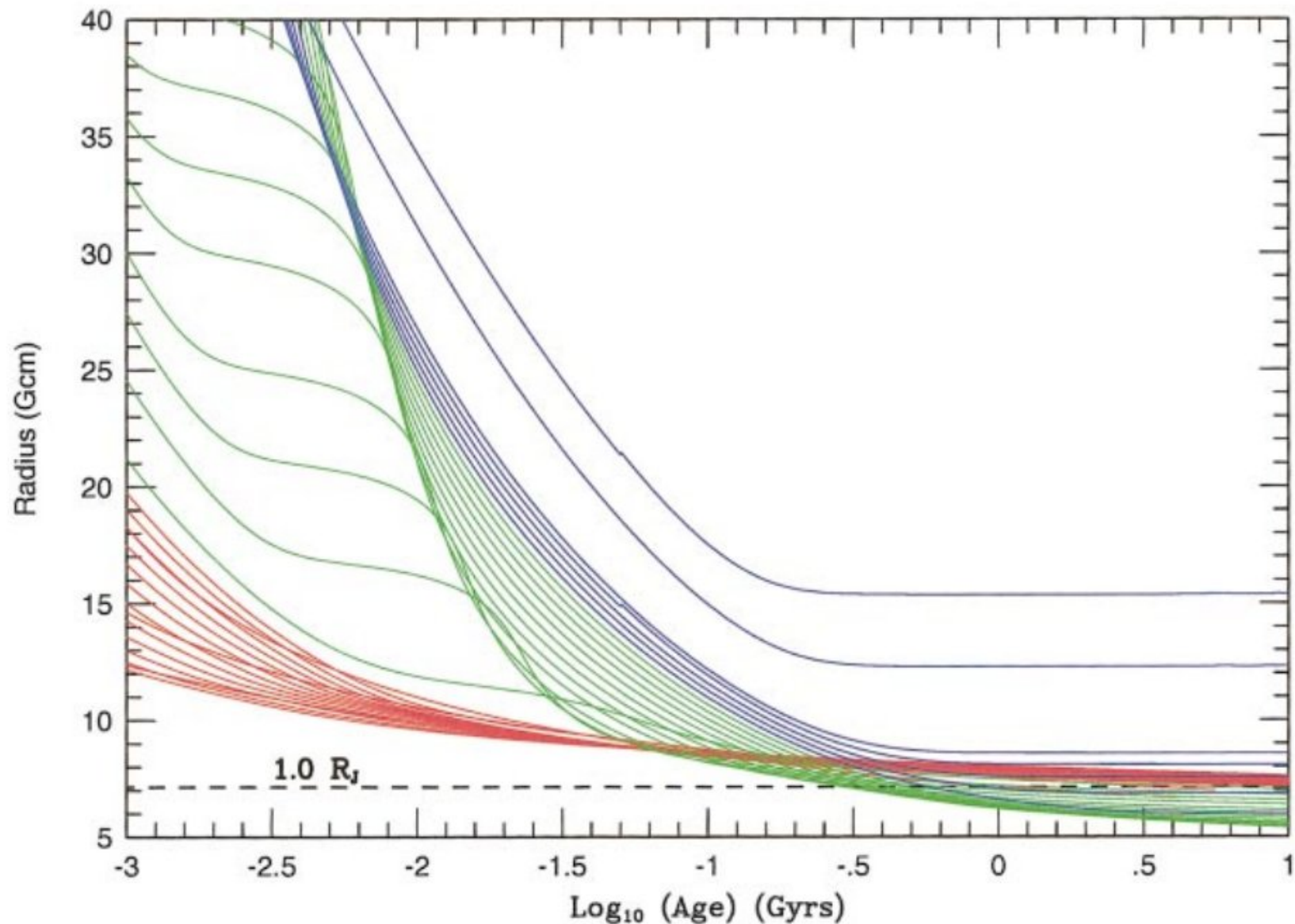


FIG. 3. The radius (in units of $10^9 c$) of substellar-mass objects with the masses given in Fig. 1 vs the \log_{10} of the age (in Gyr). The same color scheme that was used in Fig. 1 is used here. Red is for the low-mass substellar objects, green is for the intermediate-mass substellar objects, and blue is for the stars. Also shown is the radius of Jupiter. Note that the radii are not monotonic with mass and that they cluster near the radius of Jupiter at late times, despite the wide range of masses from $0.3 M_J$ to $0.2 M_\odot$ represented. See text for details [Color].

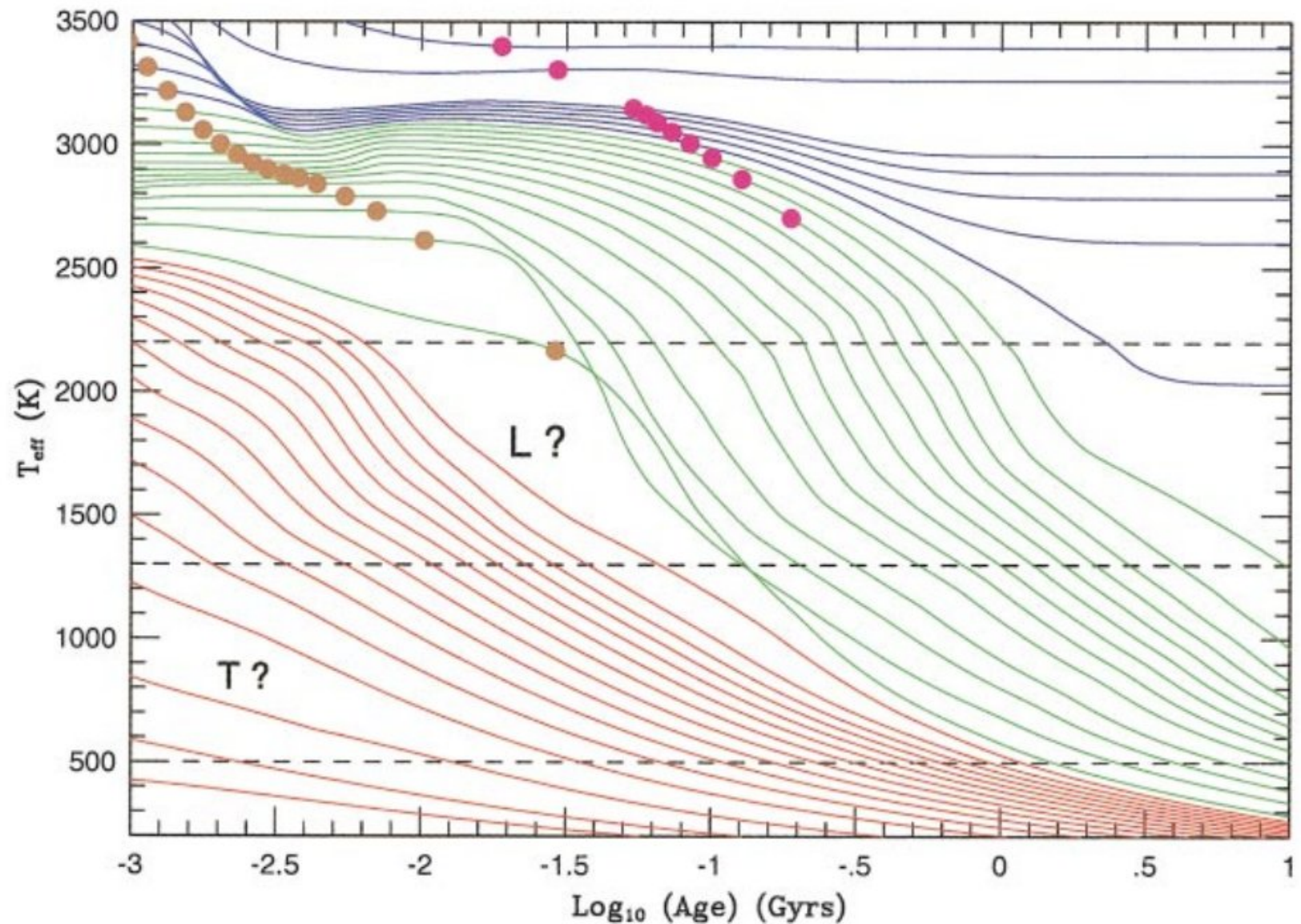
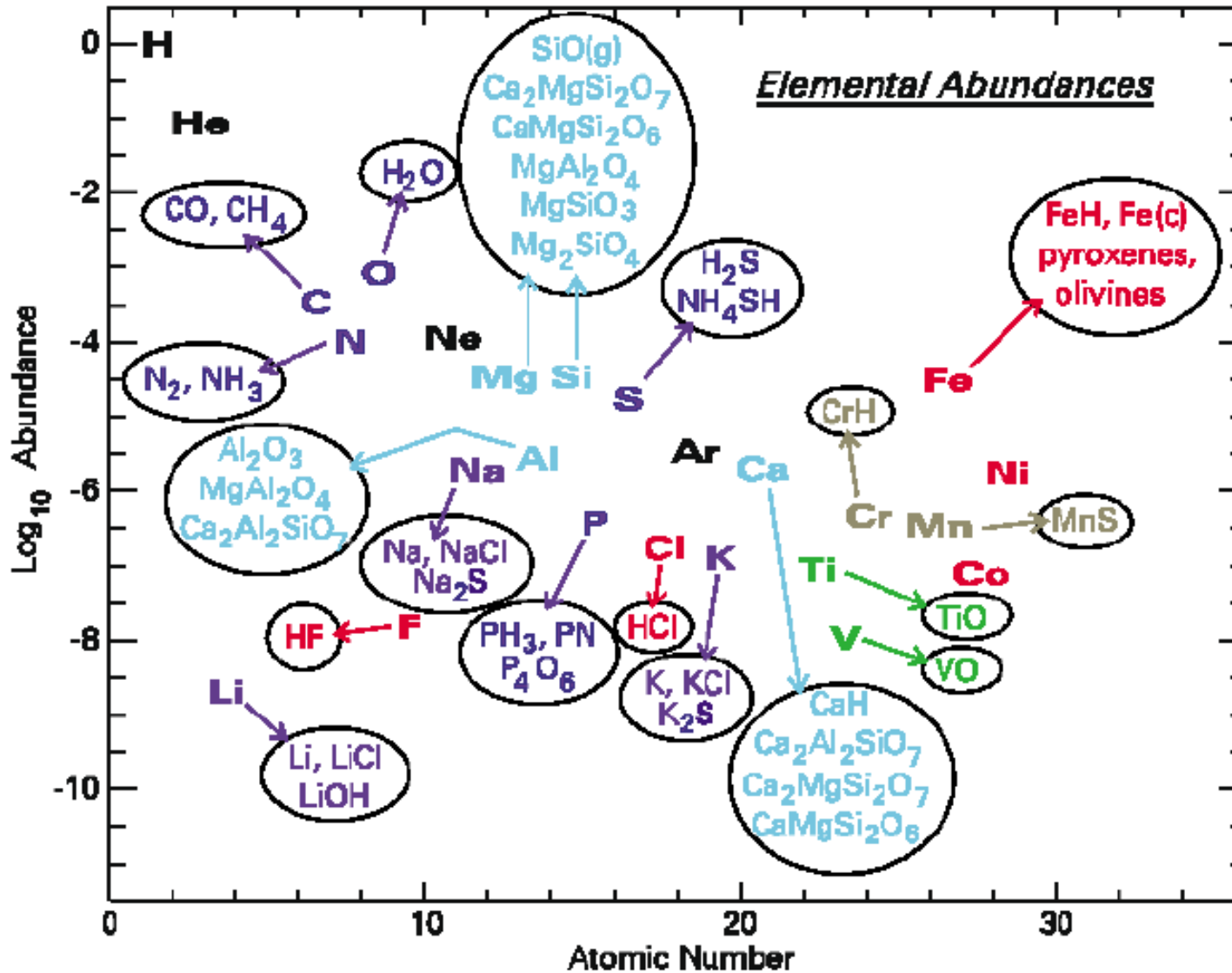


FIG. 8. This figure depicts the evolution of T_{eff} (in K) with age for the mass set used in Fig. 1 and with the same color scheme. Superposed are dots which mark the ages for a given mass at which 50% of the deuterium (gold) and lithium (magenta) are burned. Though the L and T dwarf regions are as yet poorly determined and are no doubt functions not only of T_{eff} , but of gravity and composition, approximate realms for the L and T dwarfs are indicated with the dashed horizontal lines. The spectral type M borders spectral type L on the high-temperature side. Note that the edge of the hydrogen-burning main sequence is an L dwarf and that almost all brown dwarfs evolve from M to L to T spectral types [Color].

Atmospheres: chemistry



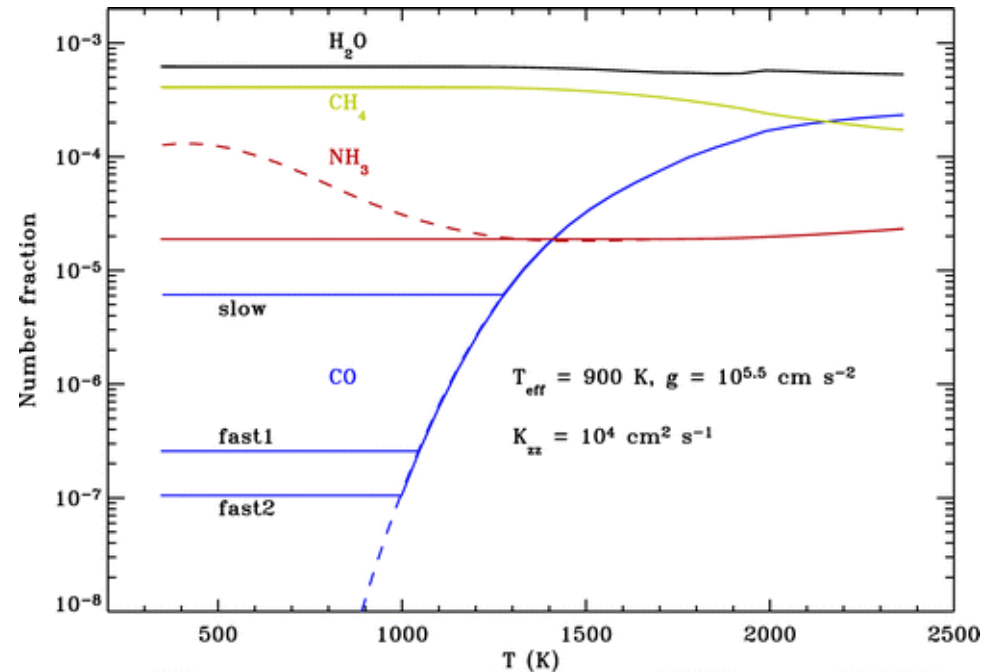
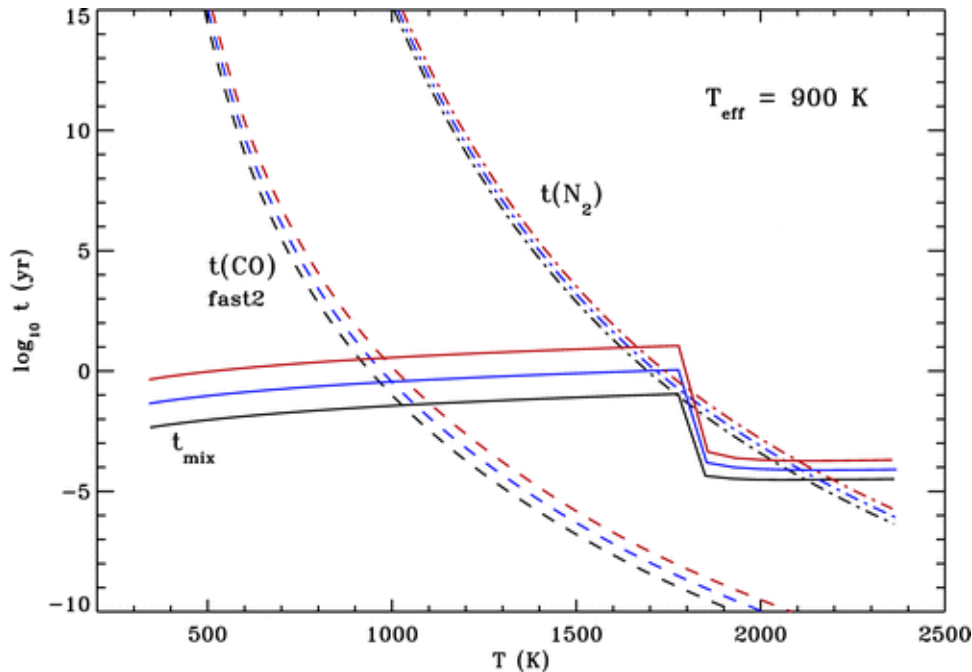
Atmospheres: non-LCE

Hydrostatic equilibrium, radiative+convective equilibrium, LTE, LCE, dust, clouds, rain-out

LCE can be violated e.g. due to:

- Presence of clouds and rain out
- Photo chemistry
- Characteristic times of chemical reactions $>$ mixing time scale

Dashed line- equilibrium abundance
Solid line -nonLCE abundance

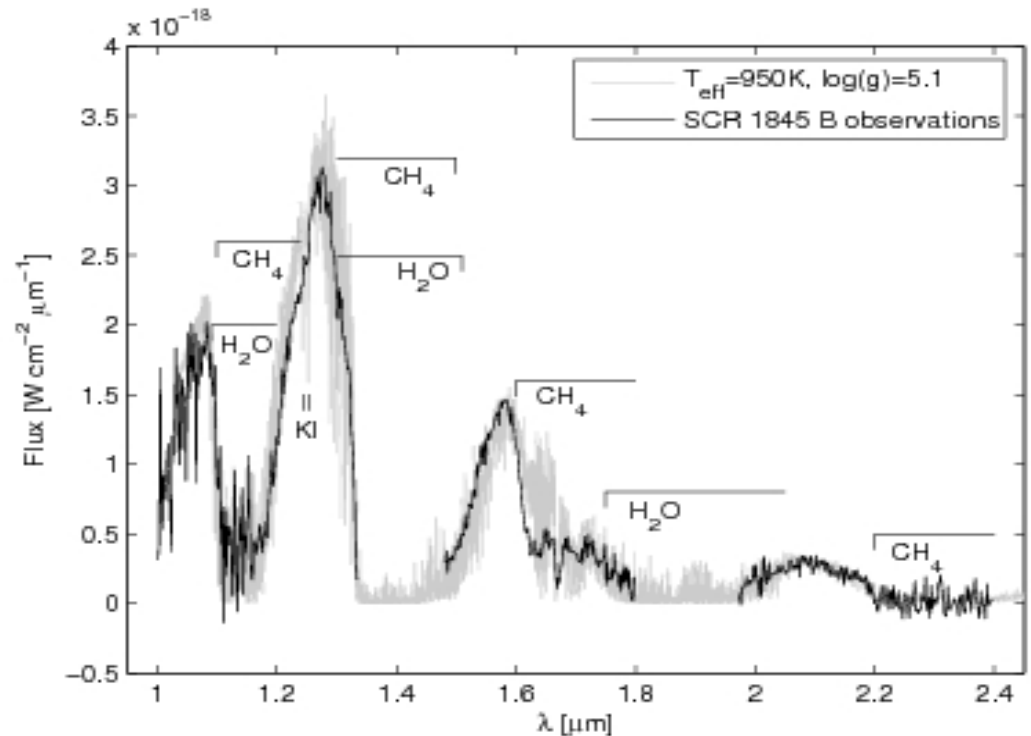


Hubeny & Burrows (2007)

The very nearby M/T dwarf binary SCR 1845-6357

History

- SCR 1845= very red nearby star, 3.5pc, Hambly et al. (2004)
- Deacon et al. (2005), parallax 282 ± 23 mas
- Henry et al. (2006), 3.85 ± 0.02 pc (24th closest star)
- SCR 1845 B discovered by Biller et al. (2006), first late M/T dwarf binary
- Separation $1''.064$, 4 AU,
- proper motion: RA $2''.444/\text{yr}$, Dec $0''.696/\text{yr}$
- Brown dwarf binaries are important => masses



Spectroscopy: black line - observed spectrum of the brown dwarf; gray line - best fitting synthetic spectrum for $T_{\text{eff}}=950\text{K}$, $\log g=5.1$ (cgs).

Kasper M., Biller B.A., Burrows A., Brandner W., Budaj J., Close L.M. 2007, A&A 471, 655
Proved that it is a brown dwarf, sp.type T6, and that it is gravitationally bound to SCR1845A.

Thank you!