The Birth and Evolution of Brown Dwarfs

Tutorial for the CSPF, or should it be CSSF (Center for Stellar and Substellar Formation)?

Eduardo L. Martin, IfA

Outline

- Basic definitions
- Scenarios of Brown Dwarf Formation
- Brown Dwarfs in Star Formation Regions
- Brown Dwarfs around Stars and Brown Dwarfs
- Final Remarks

Kumar 1963; D’Antona & Mazzitelli 1995; Stevenson 1991, Chabrier & Baraffe 2000

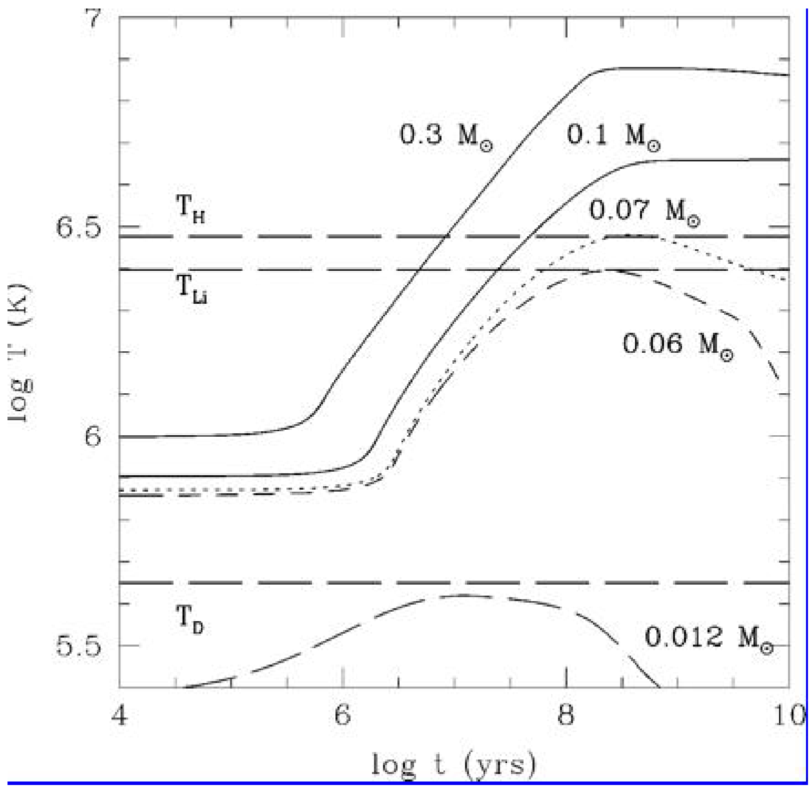
Mass

- A brown dwarf is defined primarily by its mass, irrespective of how it forms.
- The low-mass limit of a star, and the high-mass limit of a brown dwarf, correspond to the minimum mass for **stable** Hydrogen burning.
- The HBMM depends on chemical composition and rotation. For solar abundances and no rotation the HBMM=$0.075M_{Sun}=79M_{Jupiter}$.
- The lower limit of a brown dwarf mass could be at the DBMM=$0.012M_{Sun}=13M_{Jupiter}$.

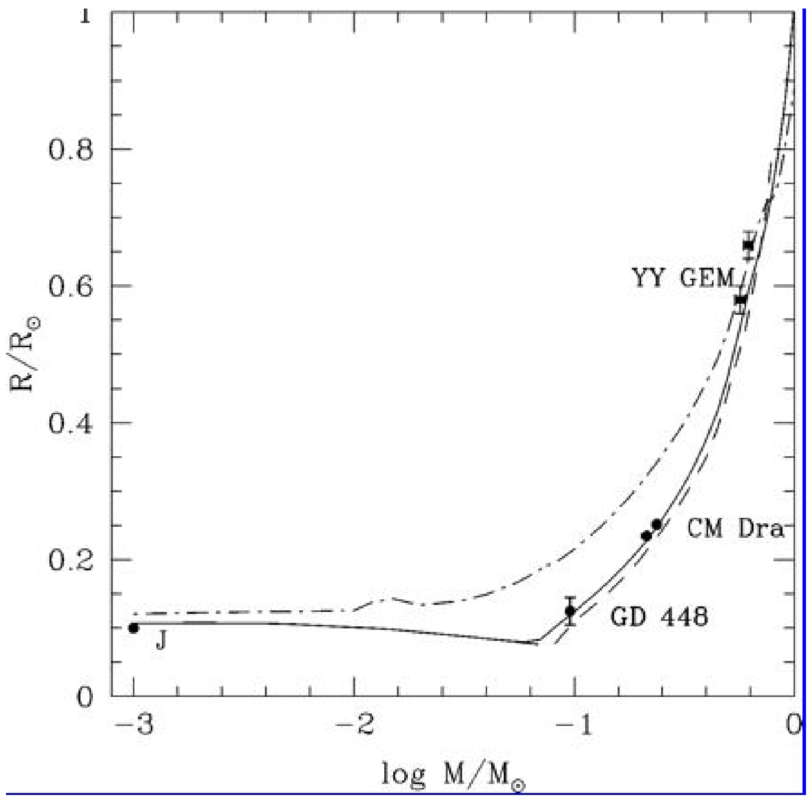
Saumon et al. 1996

Central Temperature

- The central temperature of brown dwarfs ceases to increase when electron degeneracy becomes dominant. Further contraction induces cooling rather than heating.
- The LiBMM is at $0.06M_{Sun}$
- Brown dwarfs can have unstable nuclear reactions.



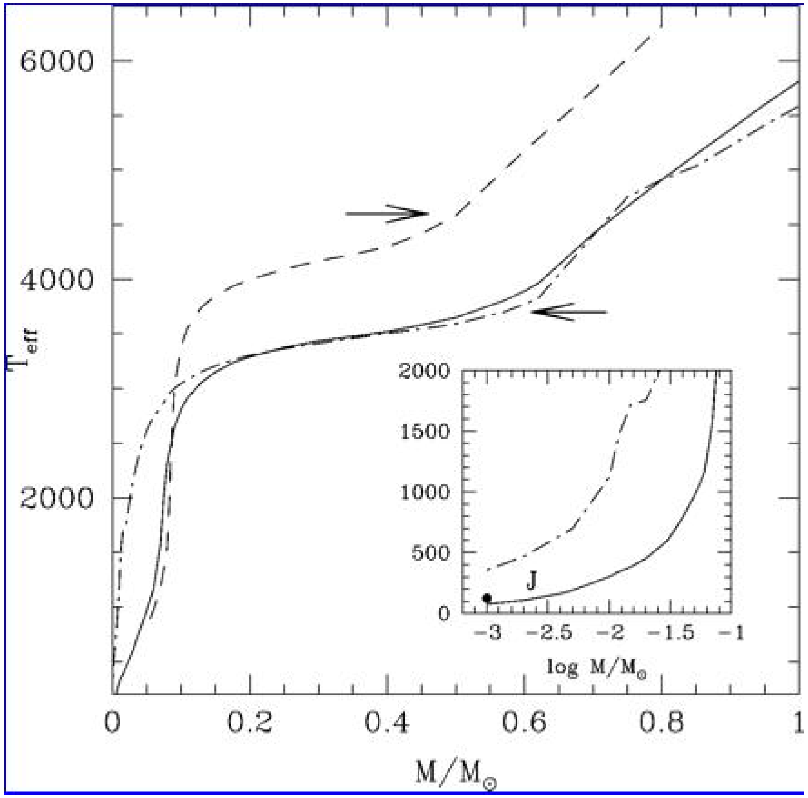
Radius



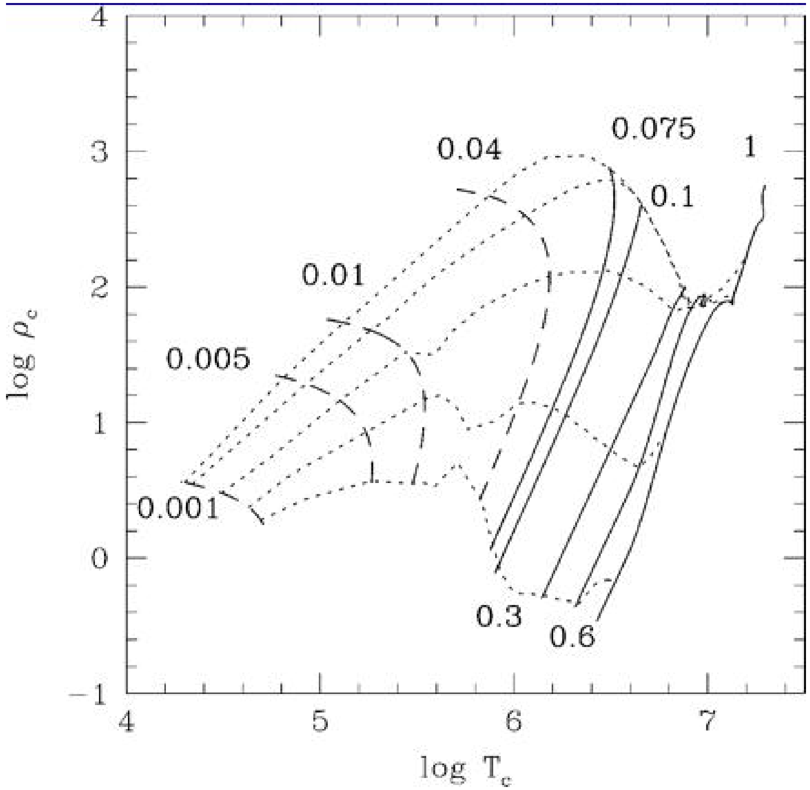
- The radii of brown dwarfs is dominated by the EOS (classical ionic Coulomb pressure + partial degeneracy of e-).
- The mass-radius relationship is smooth $R=R_0m^{-1/8}$.
- Brown dwarfs and planets have similar sizes.

Thermal Properties

- Arrows indicate H_2 formation near the atmosphere. Molecular recombination favors convective instability.
- Brown dwarfs are ultracool, fully convective, objects.
- The temperatures of brown dwarfs can overlap with those of stars and planets.



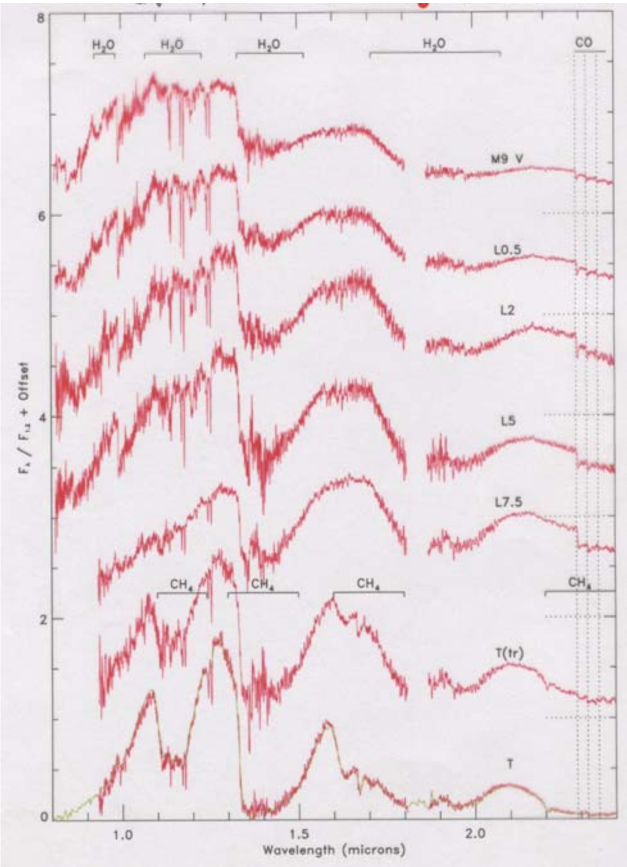
Density



- Brown dwarfs and planets (substellar-mass objects) become denser and cooler with time, when degeneracy dominates.
- The evolution is governed by the release of contraction work .
- Substellar objects keep cooling and contracting very slowly for ever.

Kirkpatrick et al. 1991,1999,2000; Martin et al. 1997,1998,1999; Burgasser et al. 2000,2001; Leggett et al. 2001; Geballe et al. 2002; Cushing et al. 200?

Spectra

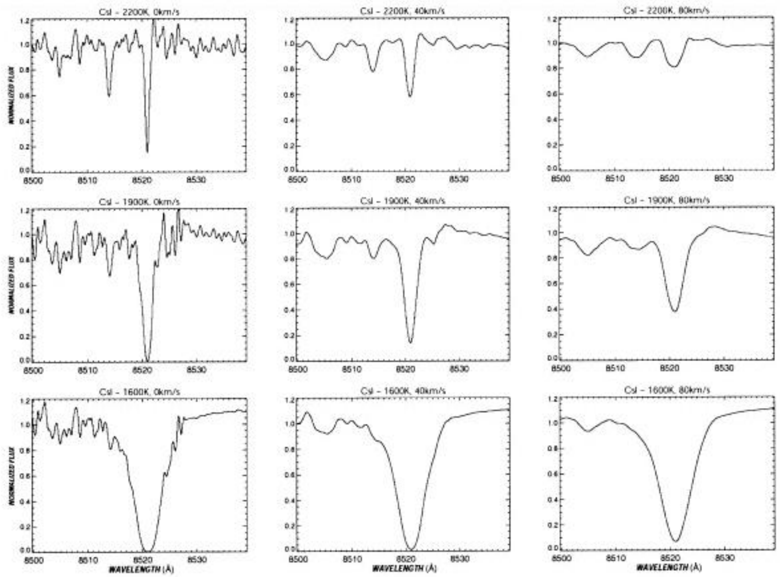


- Two new spectral classes have been defined for ultracool dwarfs.
- The L class is characterized by weak or absent TiO.
- The T class is characterized by CH_4.
- A $35M_{Jupiter}$ evolves from M-type at 10 Myr to T type at 1 Gyr.

Kippenhahn 1970; Basri et al. 2000; Reid et al. 2002.

Rotation

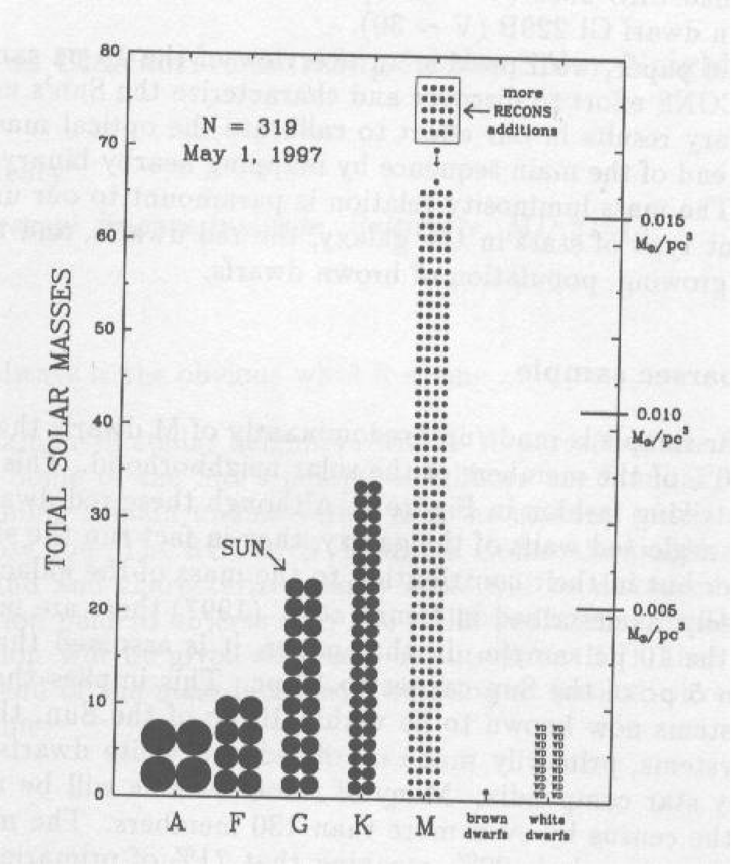
- Projected rotational velocities (vsini) have been measured in 22 field dwarfs M9-L6, using the rotational broadening of atomic and molecular lines.
- Average vsini=21km/s.
- Rotation makes the star more degenerate, and increases the HBMM.



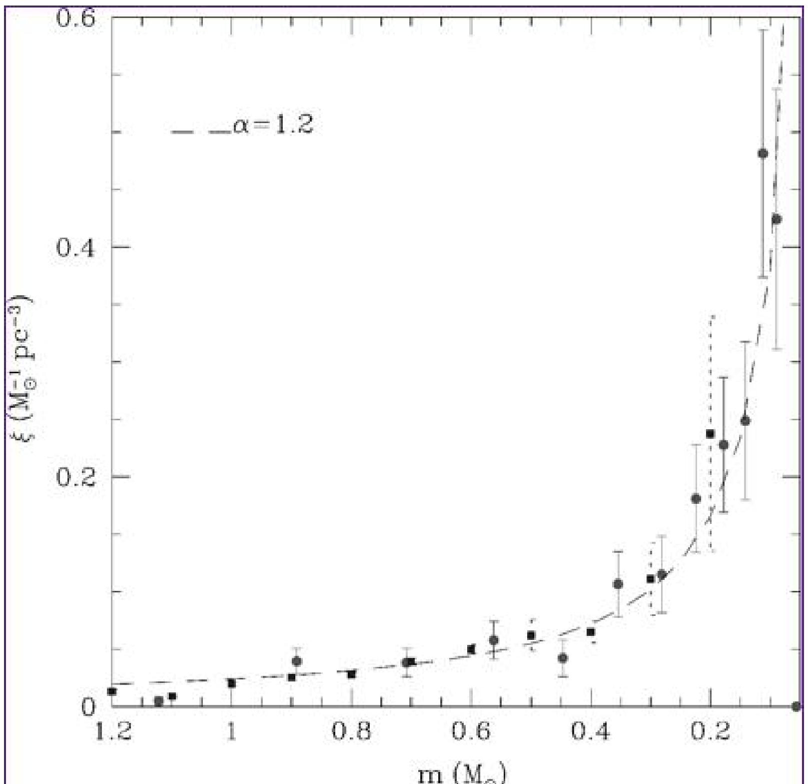
Henry 1998; Martin et al. 1999; Goldmann et al. 2000; Reid et al. 2000; Delfosse et al. 2001; Burgasser et al. 2001

The Solar Neighborhood Census

- In 1997, there were 319 objects in 231 systems known within 10 parsecs of the Sun.
- In ~ 4 years, 8 new objects have been added, 5 isolated and 3 companions to stars. SpT: M9-T8.
- The brightest star in the sample is Sirius (Mv=-1.4), the faintest is Gl570D (Mv~31).



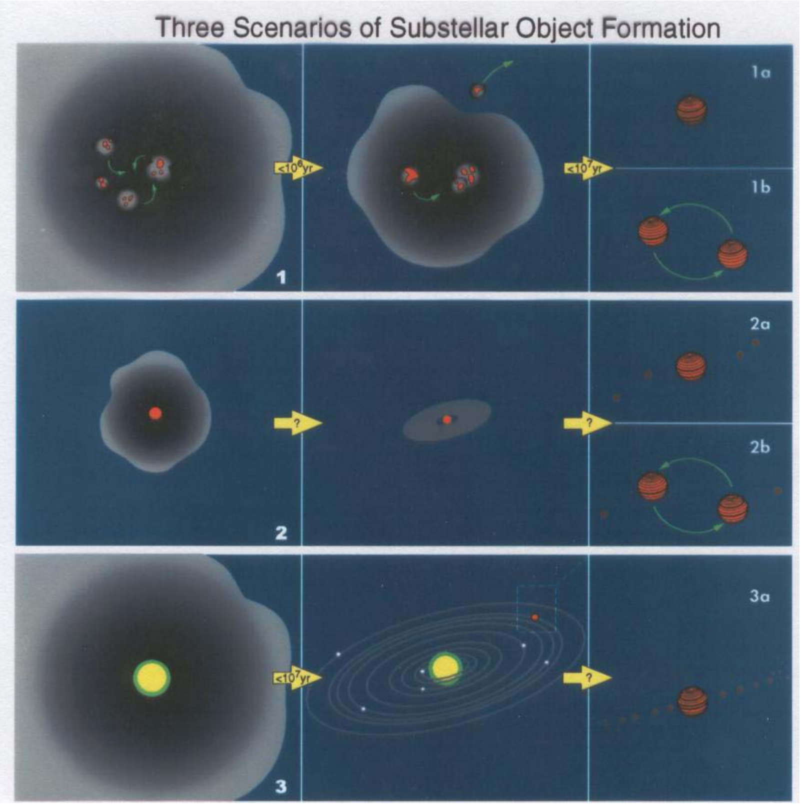
The Mass Function



- The spectrum of masses in the 8 pc sample follows a power law of the form: dn/dm=0.024 $m^{-\alpha}$ $M_{sun}pc^{-3}$ with α=1.2
- Extrapolation of this MF down to 0.01 M_{sun} yields a BD number density comparable to the stellar one (0.1 pc^{-3}), and a factor of 10 lower mass density.

Scenarios of Brown Dwarf Formation

- Brown dwarfs may form in three different environments: 1) In a cluster of objects, where the tend to be ejected. 2) Isolated. 3) Around star, in a disk or envelope.



The Jeans mass

- James Jeans, noted British scientist for his physical analysis of musical sounds, discovered the tendency for a self-gravitating cloud to collapse under its own weight when perturbed by waves with λ longer than $\lambda_{Jeans}=c_S\ (\pi/G\rho_0)^{1/2}$. Shorter λ are propagated away at the speed of sound. $c_S=(\gamma P_0/\rho_0)^{1/2}$.
- The Jeans mass is the mass enclosed in a sphere of radius $\lambda_{Jeans}/2$. $M_{Jeans}=\pi c_S{}^3/6G^{3/2}\rho_0{}^{1/2} \sim T^{3/2}\rho_0{}^{-1/2}$.

The Jeans's instability criterion

- A medium of average density ρ_0 will be unstable to fragmentation at all λ greater than λ_{Jeans} , hence the medium should break up into masses ~ M_{Jeans} .
- During isothermal or cooled collapse M_{Jeans} decreases as ρ_0 increases, leading to hierarchical fragmentation. The process terminates when the fragments become opaque enough to trap their radiation. During adiabatic collapse M_J increases as ρ_0 decreases, leading to opacity limited fragmentation.

Lynden-Bell & Low 1976; Rees 1976; Silk 1977; Boss 1998

Minimum mass of isolated star formation

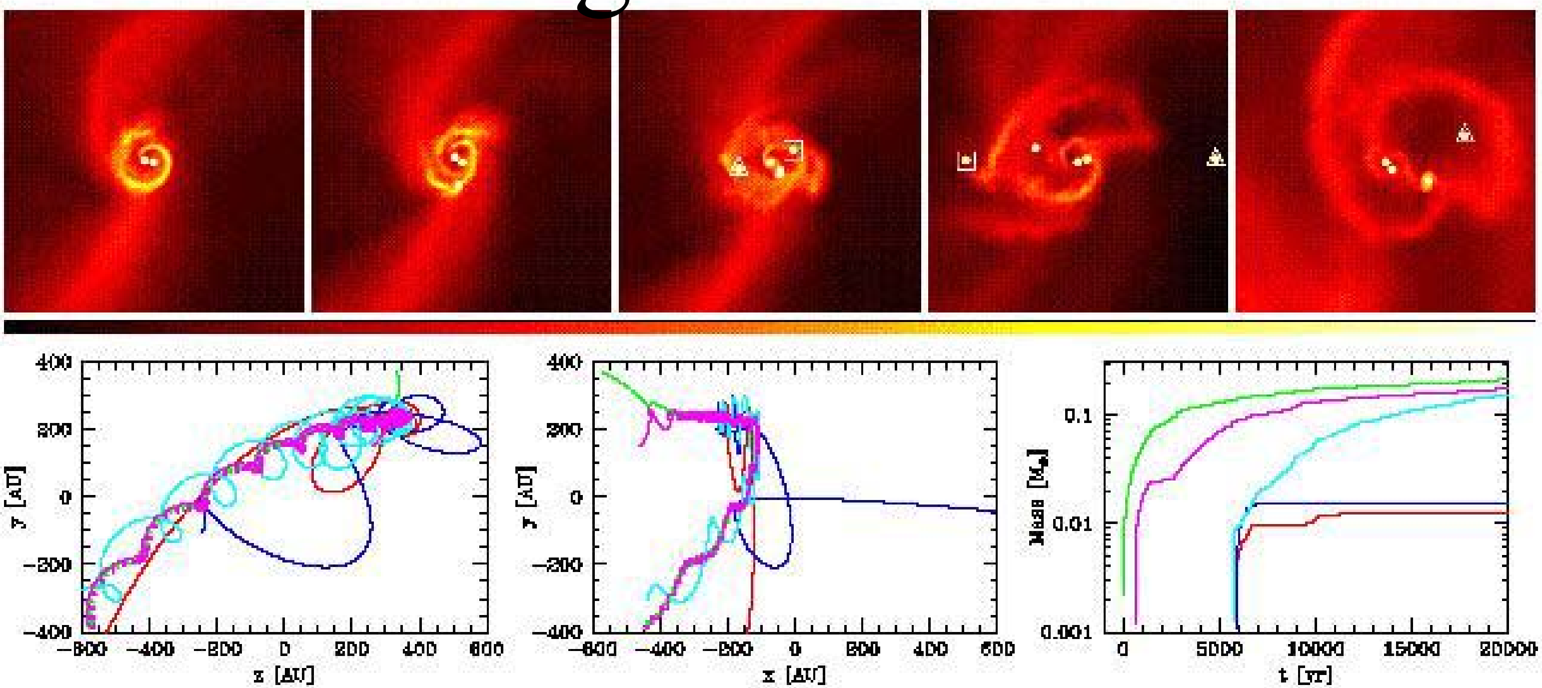
- When the rate at which energy is released by the collapse exceeds the rate at which the gas can cool, the fragment heats up and drives M_{jeans} up. A Jeans-unstable collapsing clump becomes Jeans stable. Rotation and magnetic fields increase the value of M_{Jeans}
- The pressure supported fragment has a radius of ~5 AU and a mass of several $M_{jupiter}$. The fragment is embedded in a collapsing envelope and continues to accrete to $M>10\ M_{jupiter}$

Reipurth & Clarke 2001; Boss 2001; Bate et al. 2002

Unstable Multiple Systems

- Most stars form in multiple systems.
- The smaller fragments tend to be ejected from the cloud, cutting them off from the reservoir of gas and dust, and hence preventing them from accreting to a stellar mass.
- Hydrodynamical simulations show that roughly equal numbers of stars and BDs are formed.
- ¾ of the BDs form in discs, and the reminder in filaments. 5% binary fraction. Separation<10AU.

Formation of two BDs via disc fragmentation



Armitage & Bonnell 2002

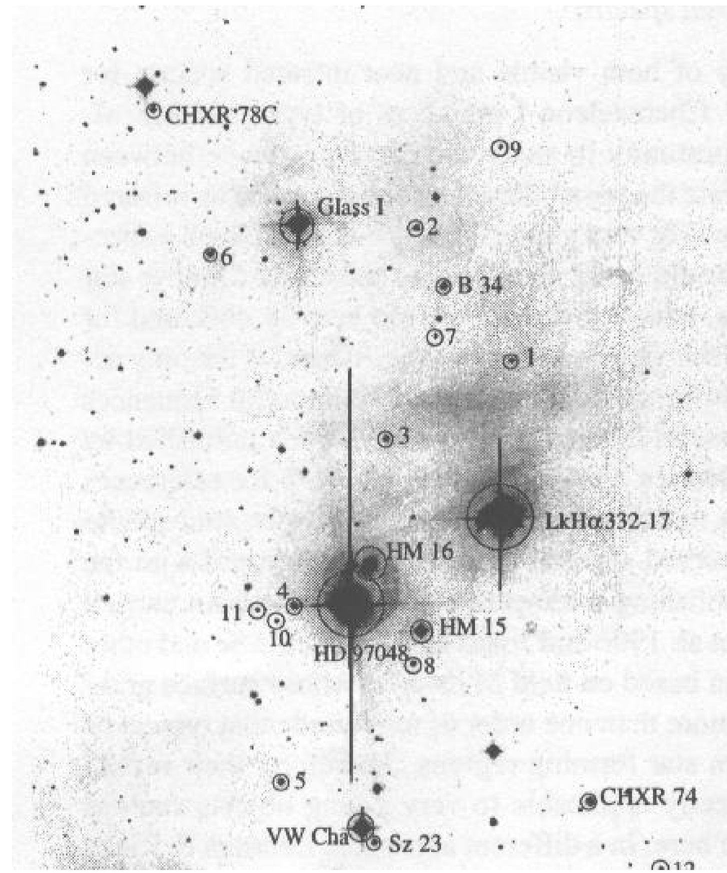
Orbital migration

- When a BD forms within 10 AU of a star, inward orbital migration within the evolving protoplanetary disc make the BD merge with the star, causing significant stellar spin-up.
- For migration to occur, the initial disc mass must be at least comparable to the mass of the BD. Thus, this process should not affect very-low mass stars or brown dwarfs.

Rieke & Rieke 1989; Comeron et al. 1993, 1998, 2000; Lucas & Roche 2000, 2001; Martin et al. 2001; Zapatero Osorio et al. 1999, 2000.

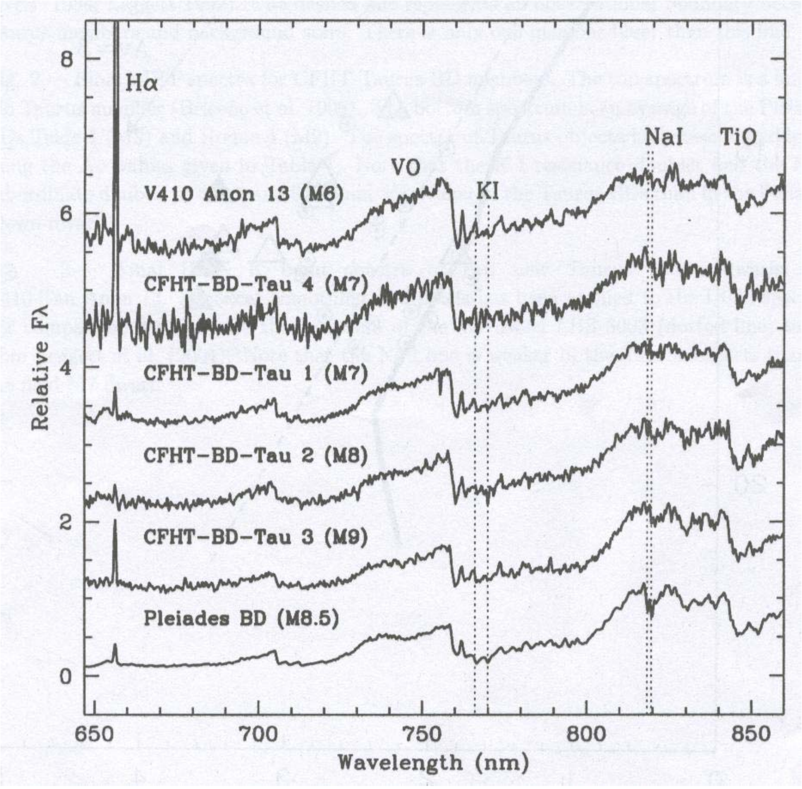
Brown Dwarfs in SFRs

- ~60 BDs have been spectroscopically identified in SFRs, such as Chamaeleon, ρOph, σOrionis, Serpens, Taurus and the Trapezium.
- No wide binaries (separation>1000AU) have been reported.



Barrado et al. 2001; Bejar et al. 1999; Comeron et al. 2001; Luhman et al. 1999; Martin et al. 1996,1999,2001

Optical spectra of young BDs

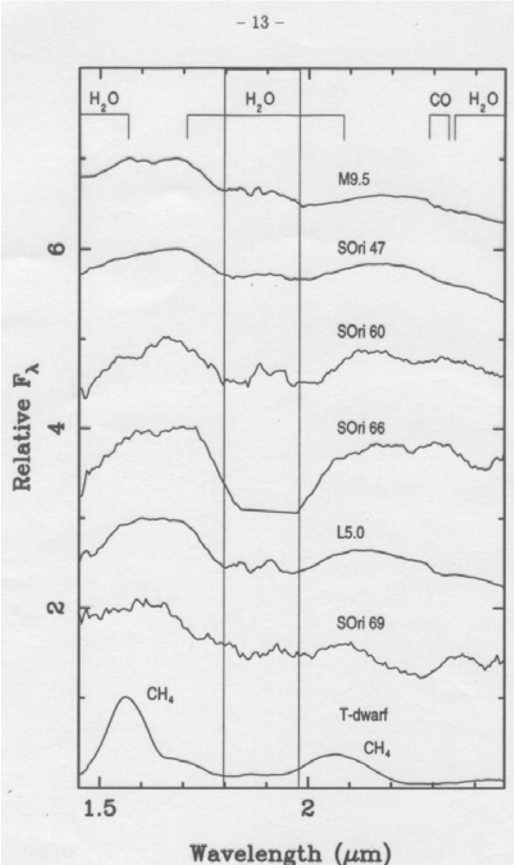


- Spectral types can be derived from the strength of TiO, CaH, and VO molecular bands.
- H_α is typically in emission.
- Alkali lines (KI, NaI) are weakened at low gravity, which can be used as a spectroscopic signature of youth.

Lucas & Roche 2001; Martin et al. 2001

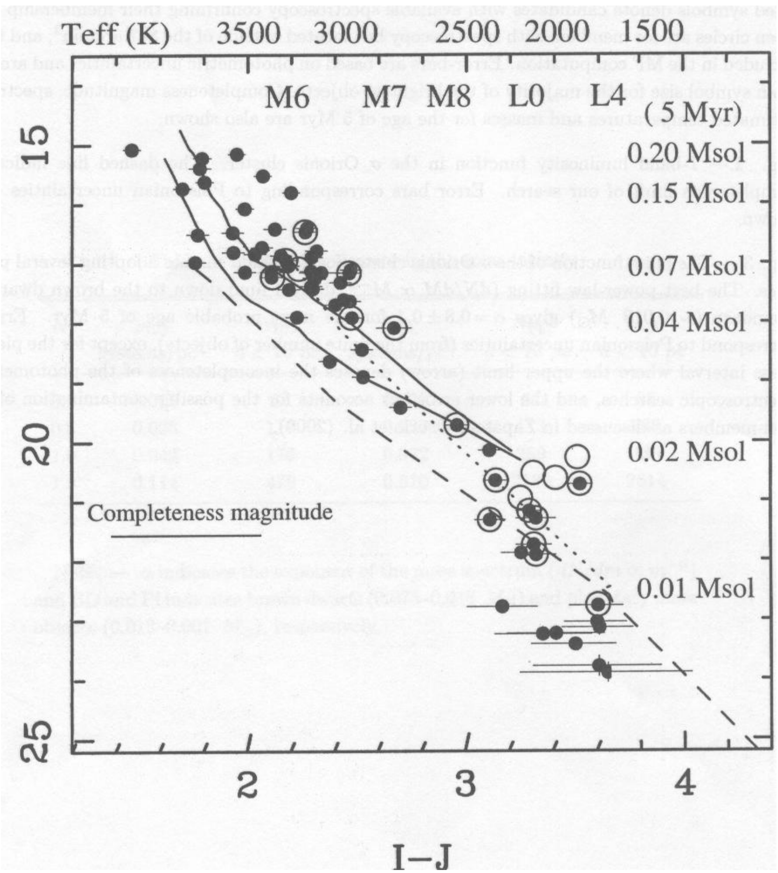
Near-infrared spectra of BDs

- Spectral types can be derived from the strength of H_2O, CO and CH_4 bands.
- Br_γ emission is an indicator of mass accretion onto the central object.
- Alkali lines (KI, NaI) are gravity sensitive.



Bejar et al. 2001; Lucas & Roche 2001

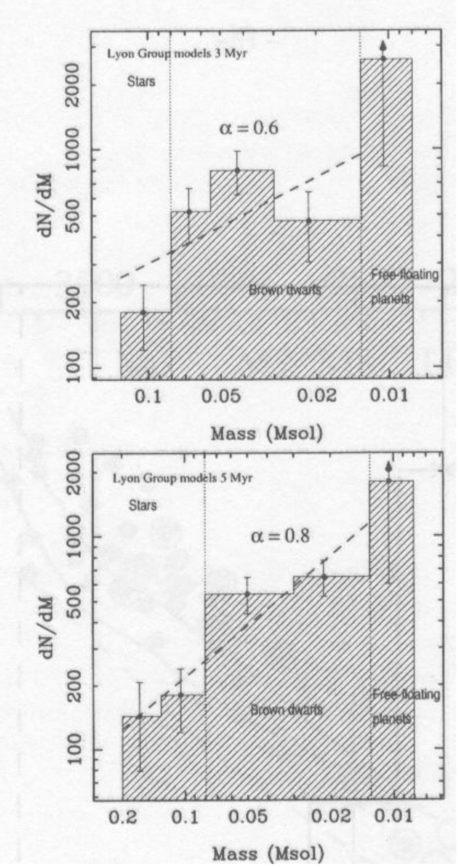
Substellar H-R diagram



- The ages and masses of the young BDs are estimated from comparison with evolutionary models in the Hertzsprung-Russell diagram.
- In σOrionis and the Trapezium, the inferred masses extend down to ~8 $M_{jupiter}$, below the minimum mass for opacity limited fragmentation.

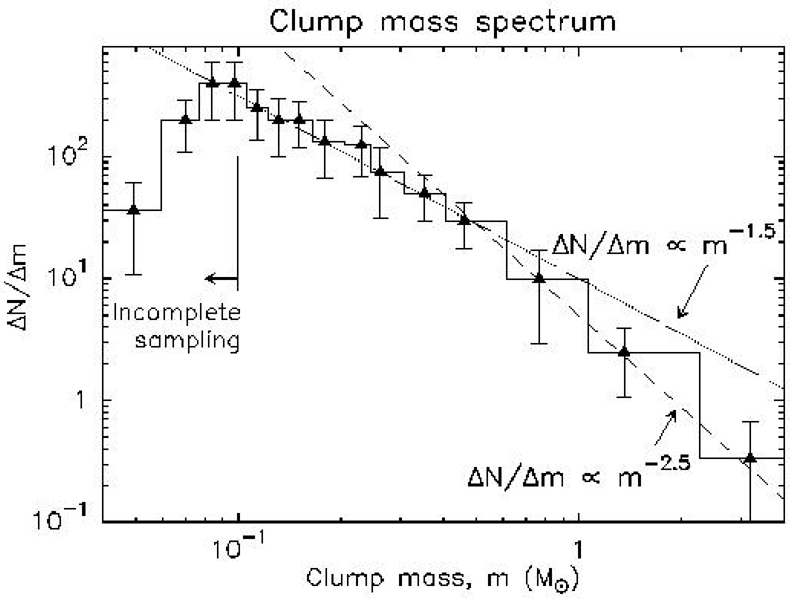
The substellar IMF

- The relative numbers of stars and BDs in SFRs indicate that the IMF does not change abruptly in the substellar regime.
- The low-mass turnoff of the IMF has not been seen yet. It must be at $<8M_{jupiter}$
- The star-formation process does not care about the HBMM or the DBMM.



Motte et al. 1998

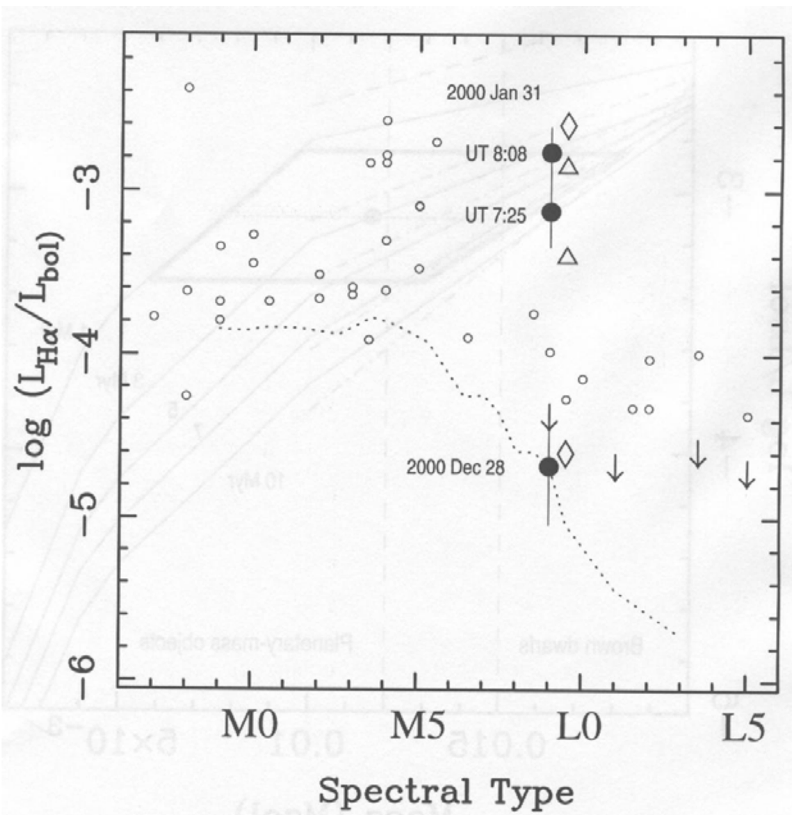
IMF of dusty clumps



- 1.3 mm continuum imaging with IRAM 30-m telescope.
- Dust structures ~ 2000-4500 AU in the ρOph main cloud
- IMF of clumps $dn/dm{\sim}m^{-\alpha}$ with α=1.5 in the 0.1-0.5 M_{Sun} mass range.

Gizis et al. 2000; Zapatero Osorio et al. 2002

H_α activity

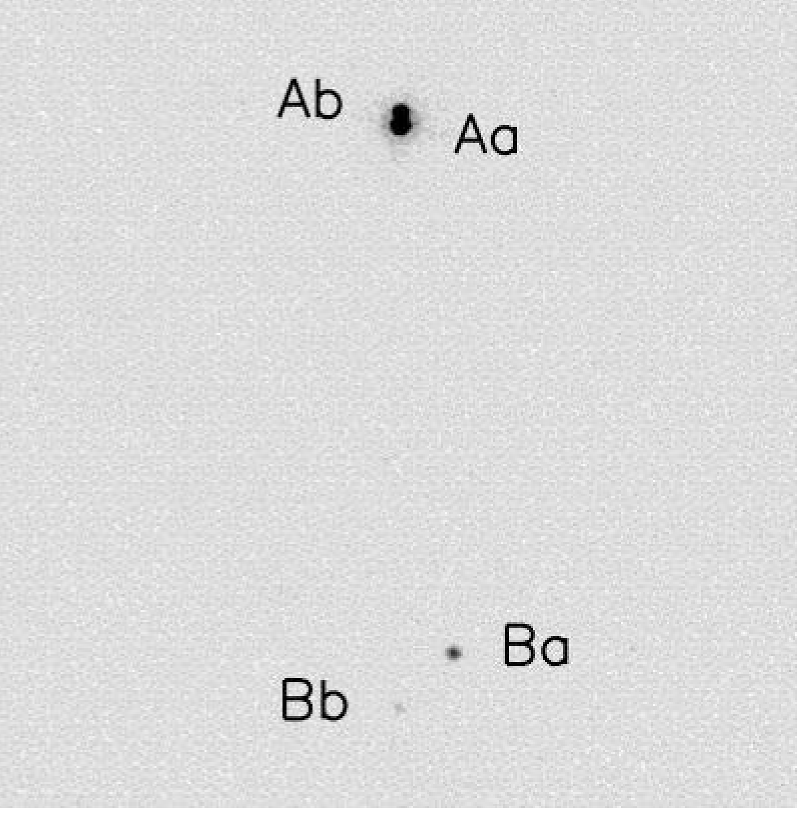


- H_α is a diagnostic of hot plasma. It can be caused by a chromosphere or by an accretion boundary layer.
- The average H_α emission level in young BDs of the σOrionis cluster is higher than in the older counterparts of the solar neighborhood.

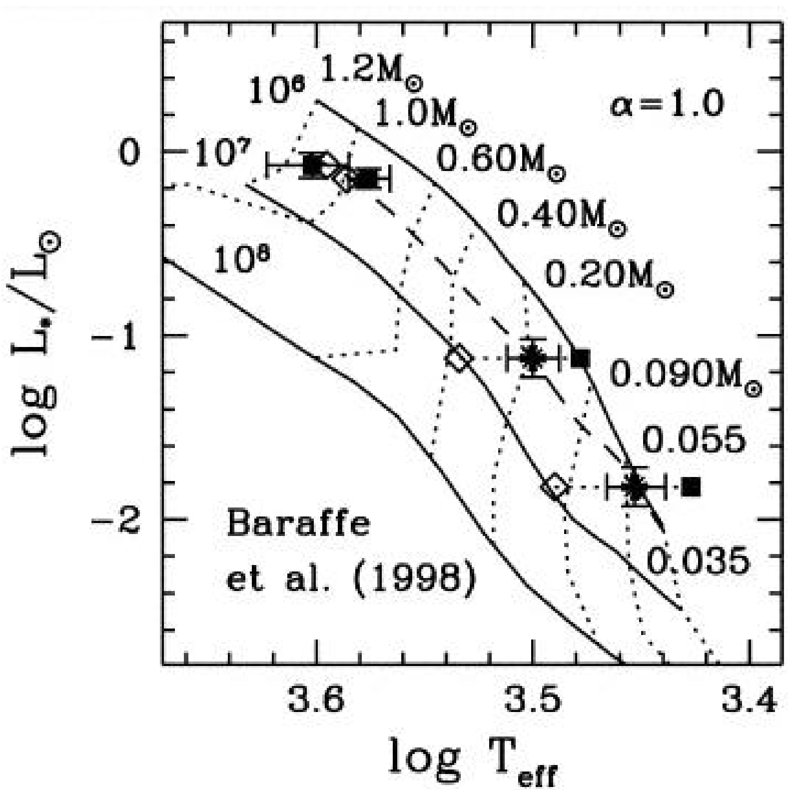
Roddier et al. 1996, White et al. 1999

The GG Tau quadruple system

- GG Tau is comprised of four components shown in this HST/WFPC2 image.
- Two pairs separated by 10”.1 (1400 AU). The brighter pair is a 0”.25 (35 AU) binary. The fainter pair is a 1”.5 (207 AU) binary. Circumbinary disk.
- SpT: K7/M0 for the brighter pair. M5/M7 for the fainter pair.



GG Tau in the H-R diagram

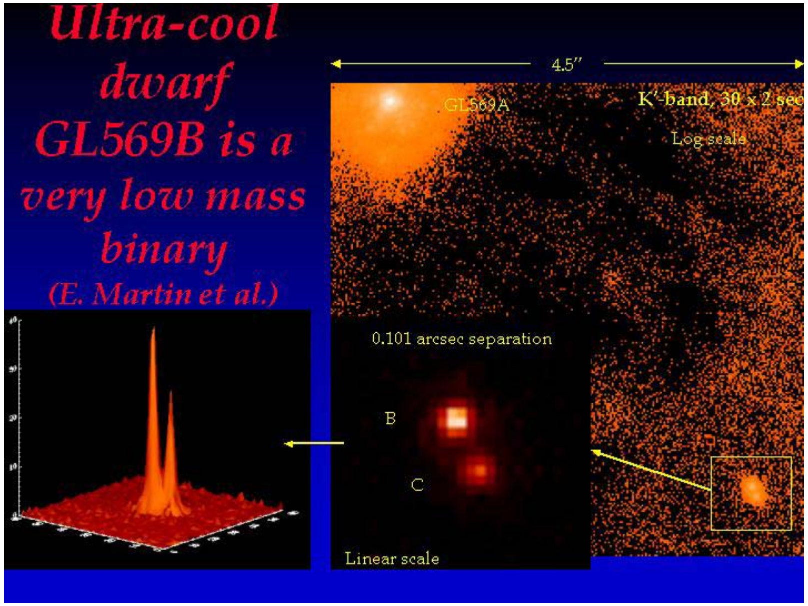


- The four components define an isochrone with which the Teff scale and evolutionary models can be tested.
- Consistent solution with the Baraffe et al. (1998) models and age 1.5 Myr. 0.78,0.68,0.12,0.04M_{Sun}

Martin et al. 2000

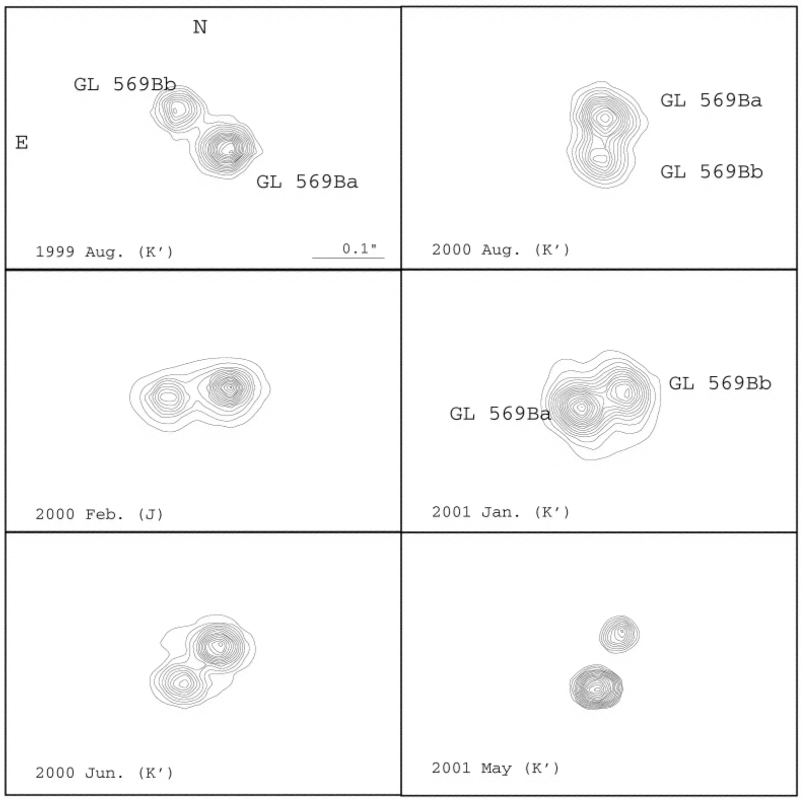
A Double Brown Dwarf

- Using Keck/AO, the M8.5 companion to the nearby star Gl569 was found to be double, with a separation of 0.1”, corresponding to a projected semi-major axis of ~1 AU for a distance of 9.8 parsec.



Lane et al. 2001

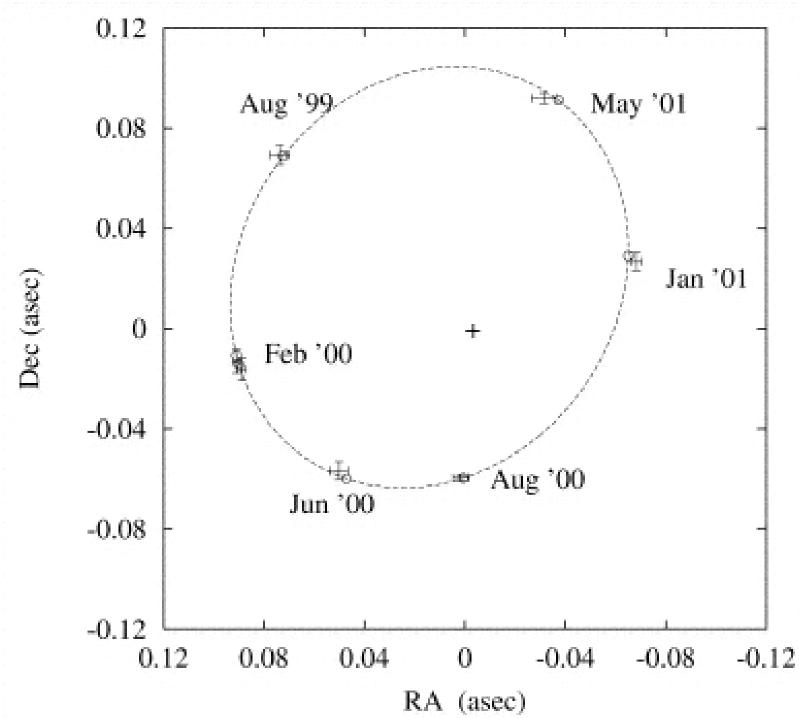
Orbital motion of Gl 569 B and C



- Gl 569 B and C have been monitored with Keck AO since its discovery in August 1999.
- The separation varies from 0.1" to 0.07"

Dynamical Substellar Masses of Gl 569 B and C

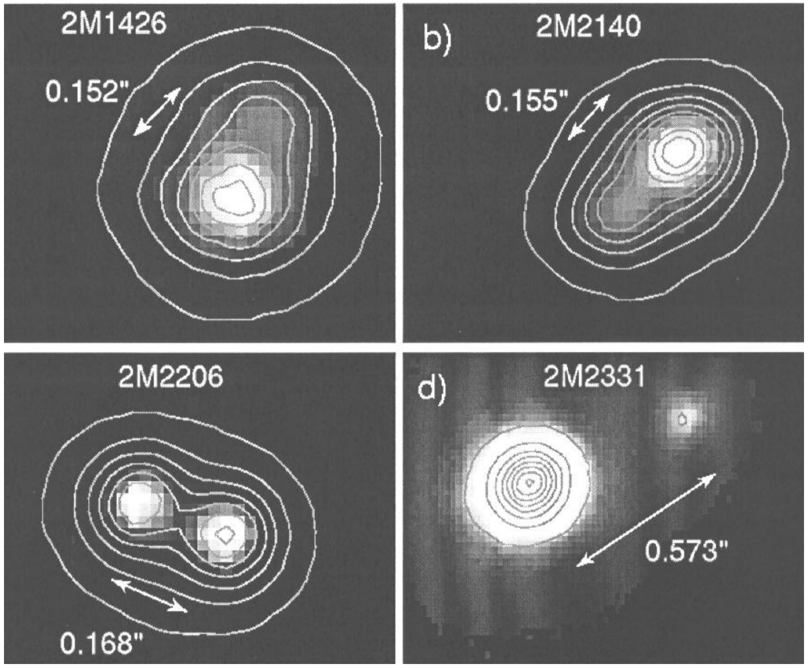
- The orbital parameters are: Period=892days, eccentricity=0.3, semi-major axis=0.9AU.
- The masses are substellar, with an allowed range between 0.078 -0.055 M_{Sun} for Gl569B and 0.070-0.048M_{Sun} for Gl569C.
- The age is ~300 Myr from evolutionary models of brown dwarfs.



Close et al. 2002

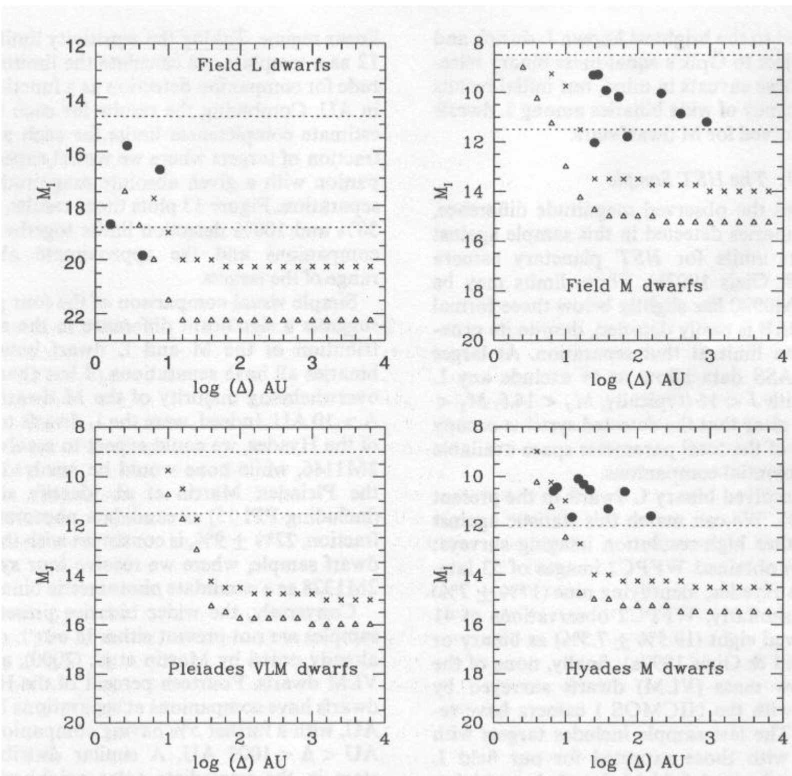
AO Survey of M7-M9 Dwarfs

- The Hokupa'a AO system on the Gemini telescope allowed for first time to guide on ultracool M dwarfs with Vmag~20.
- Four binaries discovered with separations in the range 0.15" to 0.57" (4-14 AU) out of a sample of 20 M8-M9 dwarfs.



Martin et al. 1999, 2000; Reid et al. 2001

HST surveys of BD primaries

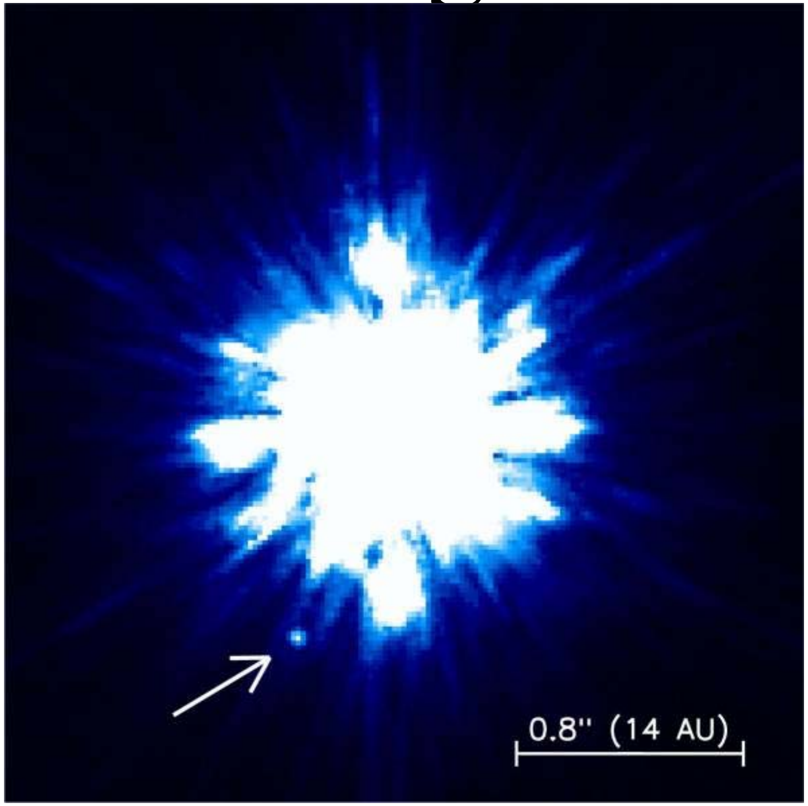


- ~22 L dwarfs in the solar neighborhood, and ~40 VLM members of the αPer and Pleiades clusters have been imaged with HST.
- 7 binaries have been identified with semi-major axis ranging from 2.7 to 12 AU.
- Absence of binaries wider than ~ 15 AU.

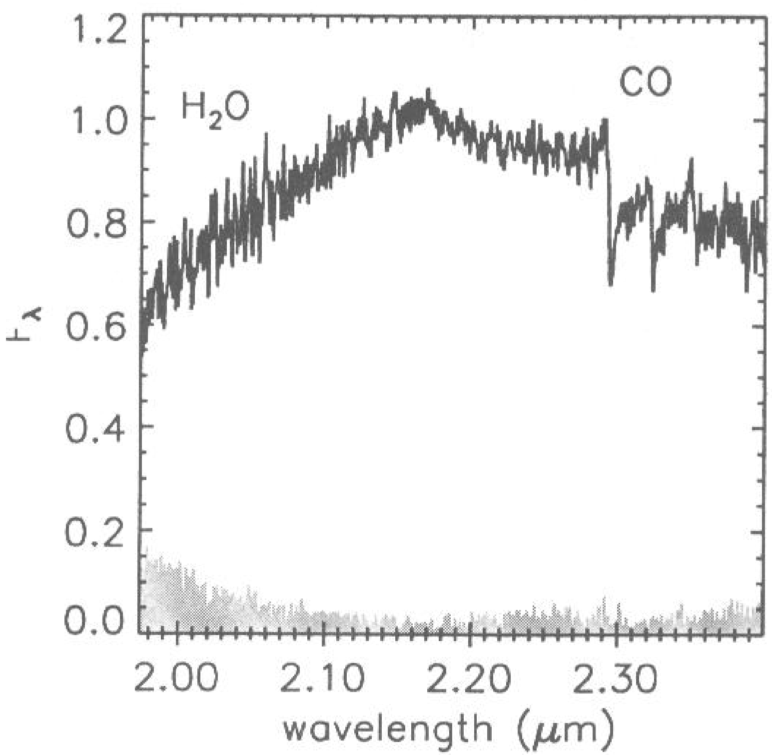
Liu et al. 2002

A Close VLM Companion to a Nearby Solar Analog

- Primary: HR7672, G1V, V=5.8, d=17.7pc
- Companion discovered with Hokupa'a AO/Gemini, separation=0.8", 8.6 magnitudes fainter than the star in K'-band (2.2 microns).



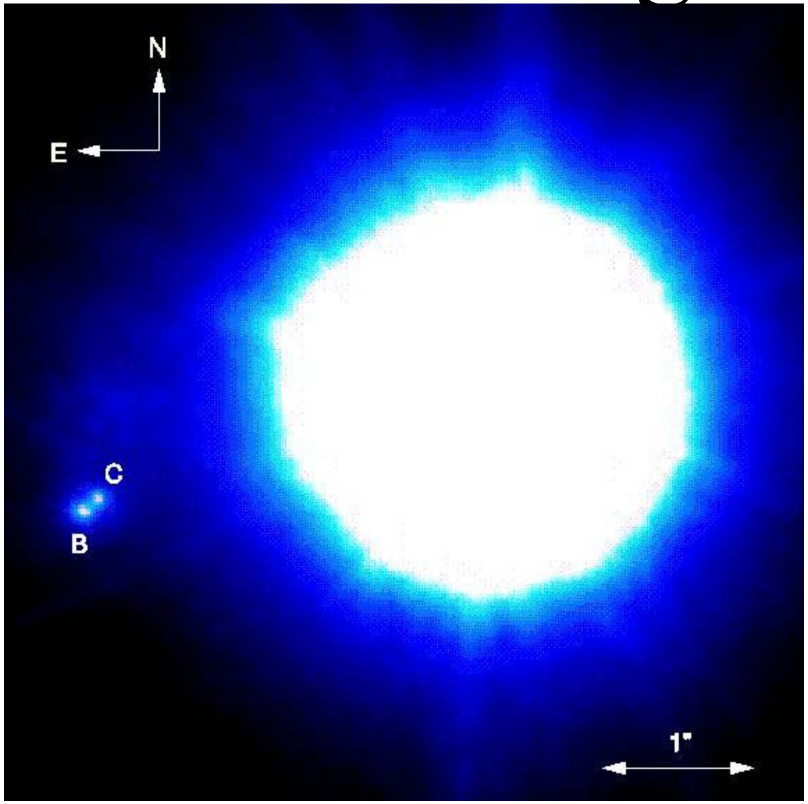
AO Proper Motion and Spectroscopy of HR7672B



- AO imaging six months after discovery confirms that HR7672B has the same proper motion as the nearby star
- AO-fed spectroscopy with Keck/NIRSPEC gives a spectral type ~L4
- Cumming et al. 1999 had found Msini=66 Mjup.

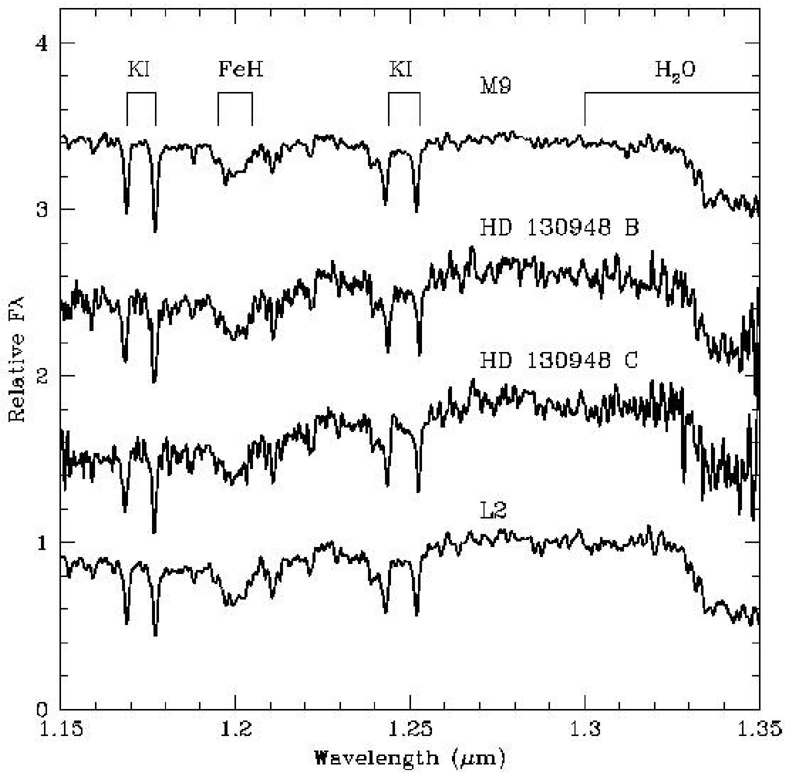
Potter et al. 2002

A Brown Dwarf Binary Close to a Young Solar Analog



- Primary:HR5534,G2V,V= 5.9, Rotation P=7.8 days, active chromosphere, likely member of Ursa Major stream, age~300 Myr
- Companion discovered with Hokupa'a AO/Gemini, separation 2.6", 8 magnitudes fainter than star in H-band (1.6 microns).

AO Proper Motion and Spectroscopy of HR5534B and C

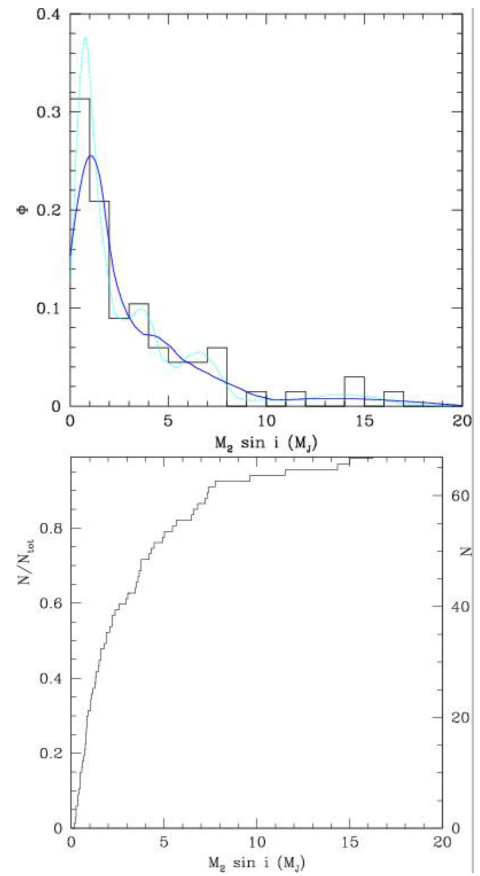


- AO observations 204 days after discovery confirm common proper motion.
- Keck/AO NIRSPEC spectroscopy of each one of the two brown dwarfs (separation 0.13" or 2.3 AU) allow to derive spectral type ~L3.

Marcy et al. 2000; Jorissen et al. 2001; Zucker & Mazeh 2001

The MF of Extrasolar Planets

- The M2sini distribution of extrasolar planets confine the vast majority of planetary companions to masses below 10 $M_{jupiter}$
- BDs are rare (<0.1%) within 5 AU of low-mass main-sequence stars (the Brown Dwarf desert).



Final Remarks

- The stellar/substellar boundary is defined by the HBMM. The BD/planet boundary is controversial, but might be defined by the DBMM.
- BDs may form isolated, in unstable multiple systems or around single stars.
- The number density of stars and BDs are similar.
- The lowest mass objects found in SFRs appear to have masses below the DBMM.
- BD binaries appear to be common, but confined to separations < 15 AU.
- BDs are rare within 5 AU of stars, but could be common for separations > 10 AU.