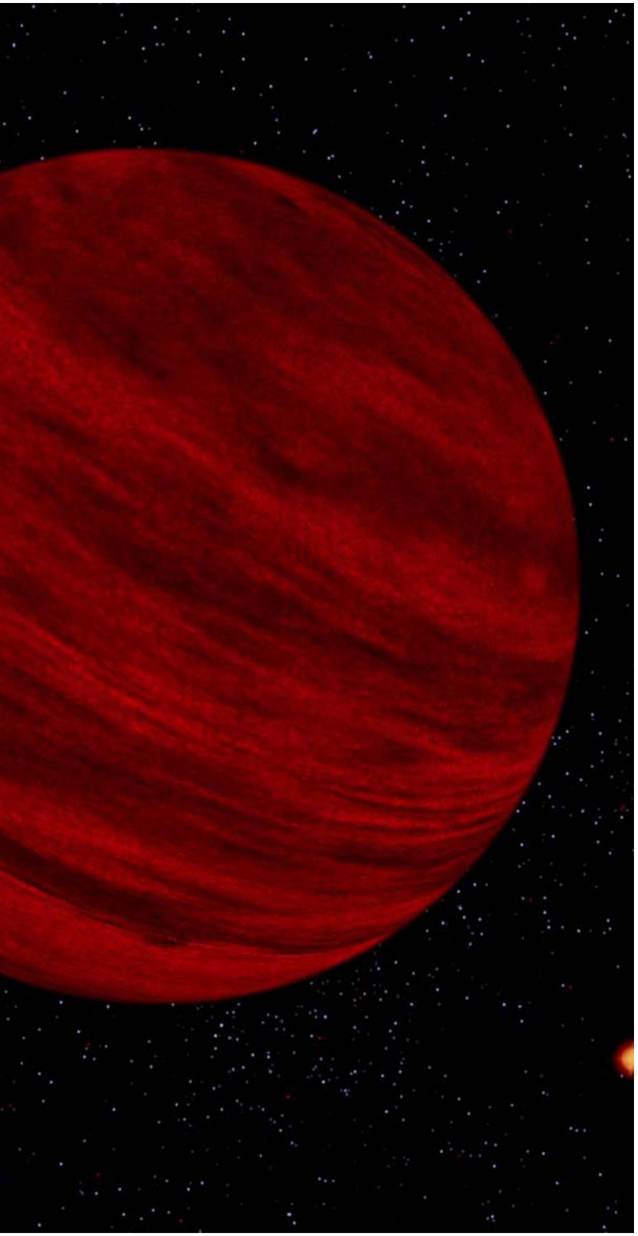
Impression of Gl229B by Pat Rawlings, Scientific American



UKIRT and the Brown Dwarfs: From Speculation to Classification

Sandy Leggett, Gemini Observatory

With gratitude to the UKIRT staff, the SDSS and UKIDSS teams, & all my collaborators, especially:

Tom Geballe (Gemini),

Dave Golimowski and Keith Noll (STScI),

Jill Knapp (Princeton),

Mark Marley (NASA Ames),

David Pinfield and Ben Burningham (Herts),

Didier Saumon (LANL), and

Steve Warren (Imperial College London).

Brown Dwarfs Postulated in 1963

Electron degeneracy prevents core from collapsing further and heating to point of H fusion. Described independently in two 1963 papers:

THE STRUCTURE OF STARS OF VERY LOW MASS

SHIV S. KUMAR*

NASA Goddard Space Flight Center, Institute for Space Studies, New York 27, N.Y.

Received October 20, 1962; revised November 27, 1962

ABSTRACT

Completely convective models have been constructed for stars of masses 0 09, 0 08, 0 07, 0 06, 0 05, and 0 04 (solar units), taking into account the non-relativistic degeneracy of the stellar material. It is shown that there is a lower limit to the mass of a main-sequence star. The stars with mass less than this limit become completely degenerate stars or "black" dwarfs as a consequence of gravitational contraction, and, therefore, they never go through the normal stellar evolution.

Progress of Theoretical Physics, Vol. 30, No. 4, October 1963

Evolution of Stars of Small Masses in the Pre-Main-Sequence Stages

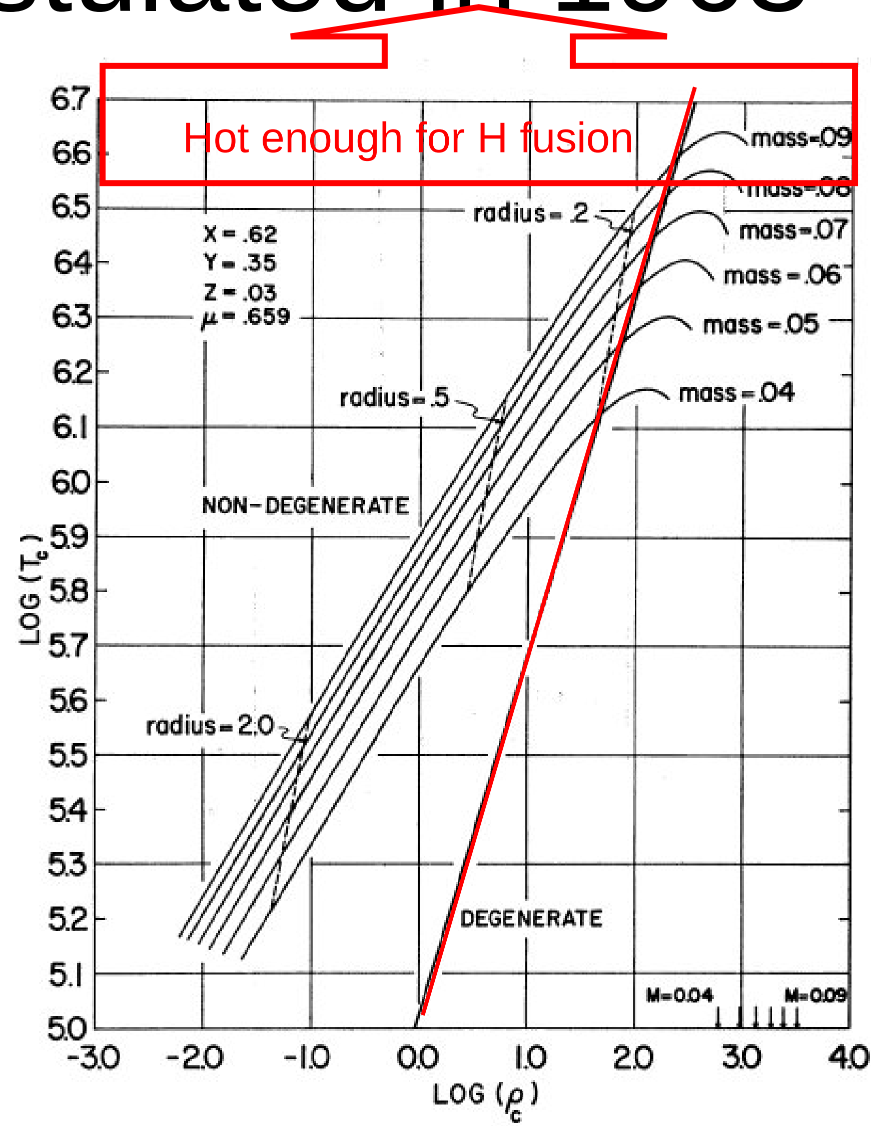
Chushiro HAYASHI and Takenori NAKANO

Department of Nuclear Science, Kyoto University, Kyoto

(Received June 12, 1963)

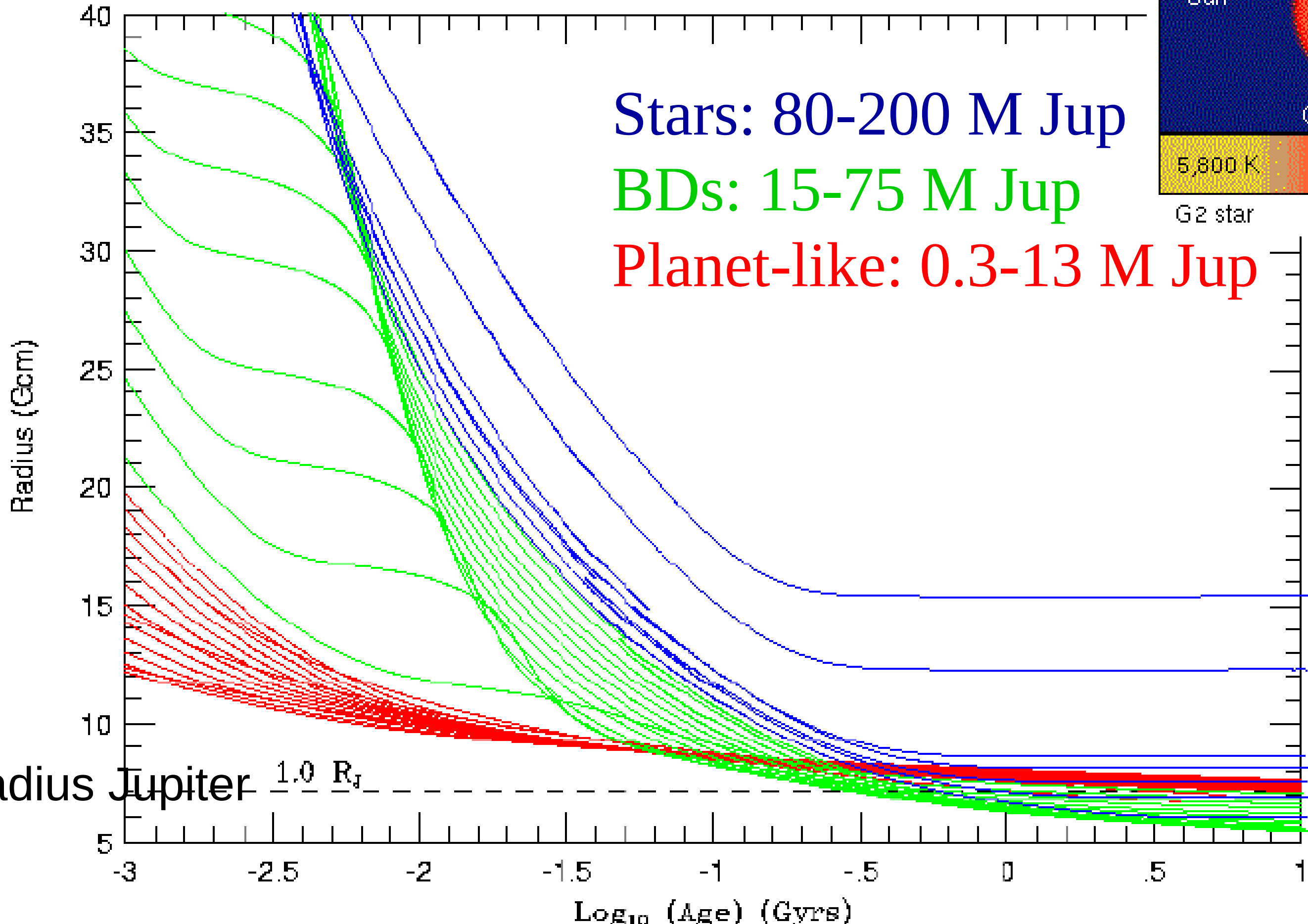
The structure of the outer envelope with an H-ionization zone and an H_2-dissociation zone is investigated for Population I stars of small masses ($2M_\odot \gtrsim M \gtrsim 0.05M_\odot$), which have low luminosities ($L_\odot \gtrsim L \gtrsim 10^{-3}L_\odot$) and low effective temperatures (6000 °K $\gtrsim T_e \gtrsim$ 2500 °K), in order to find the surface condition for the internal structure of these stars. The effective temperature of a star which is wholly convective and which has an H_2-dissociation zone is found to be nearly constant in the wide range of its luminosity.

Using stellar models composed of a radiative core and a convective envelope together with the above surface condition, the evolution of contracting stars is calculated up to the onset of hydrogen burning and the results are compared with the observed red dwarf stars. It is found that the stars on the zero-age main-sequence have radiative cores for $M > 0.26M_\odot$ but they are wholly convective for $0.26M_\odot \gtrsim M \gtrsim 0.08M_\odot$. The stars less massive than $0.08M_\odot$ are found to contract toward the configurations of high electron-degeneracy without hydrogen burning.



All brown dwarfs older than ~200Myr have a radius R within ~20% of Jupiter's. The small dependency on mass and age means a tight relationship between luminosity L and effective temperature T_{eff} ($L=\sigma\pi R^2 T_{eff}^4$).

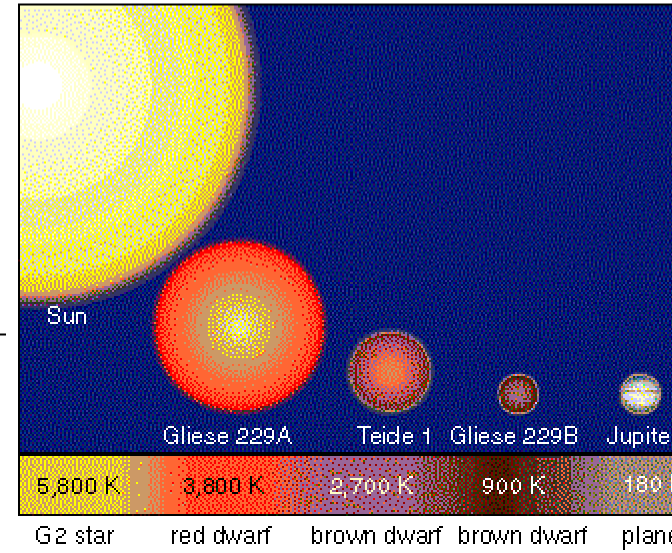
Radius



Radius Jupiter

0.3 1 10 Age Gyr

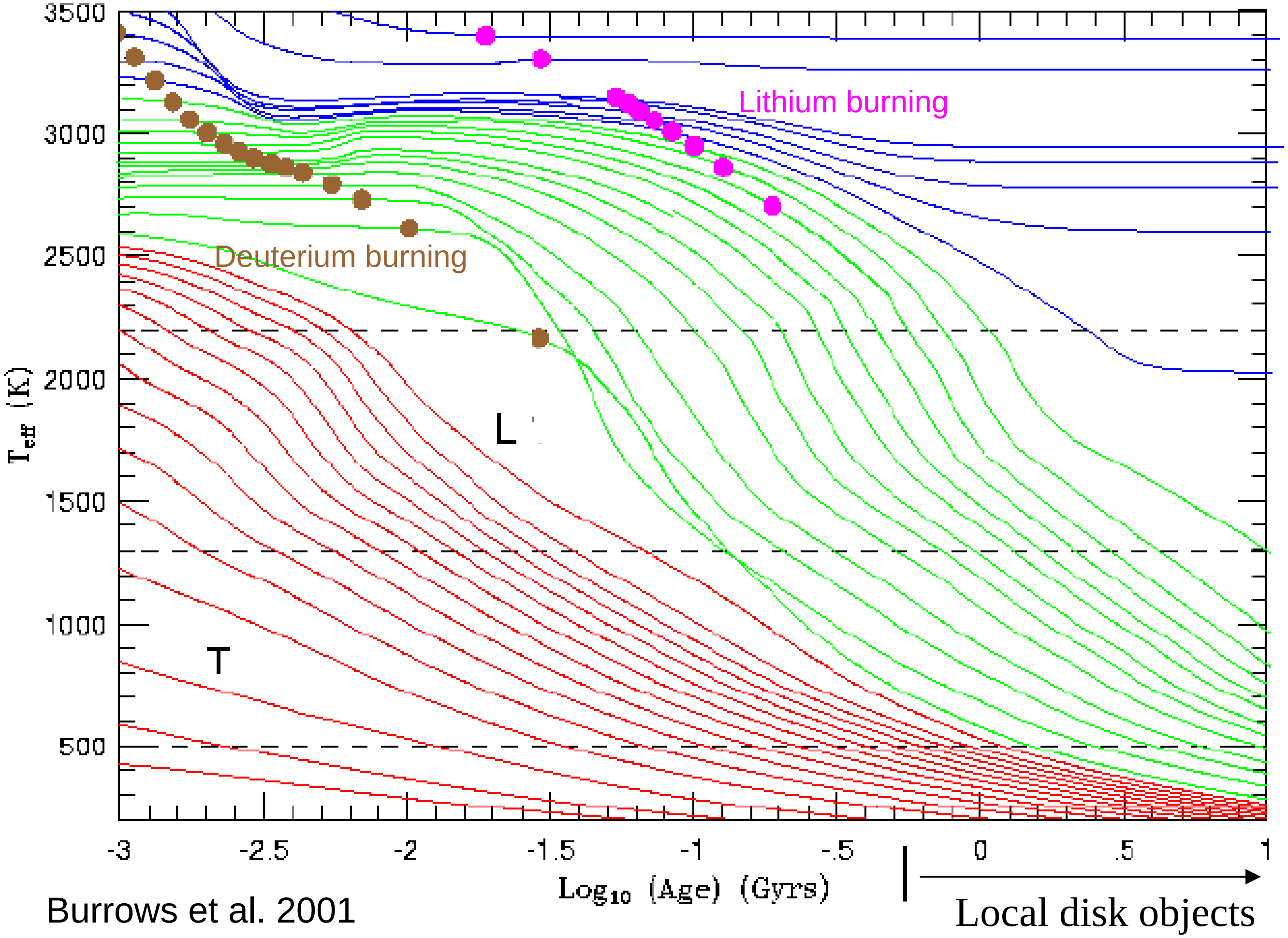
Burrows et al. 2001 Rev.Mod.Phys. 73



Size diagram from E. Martin 1997 American Scientist

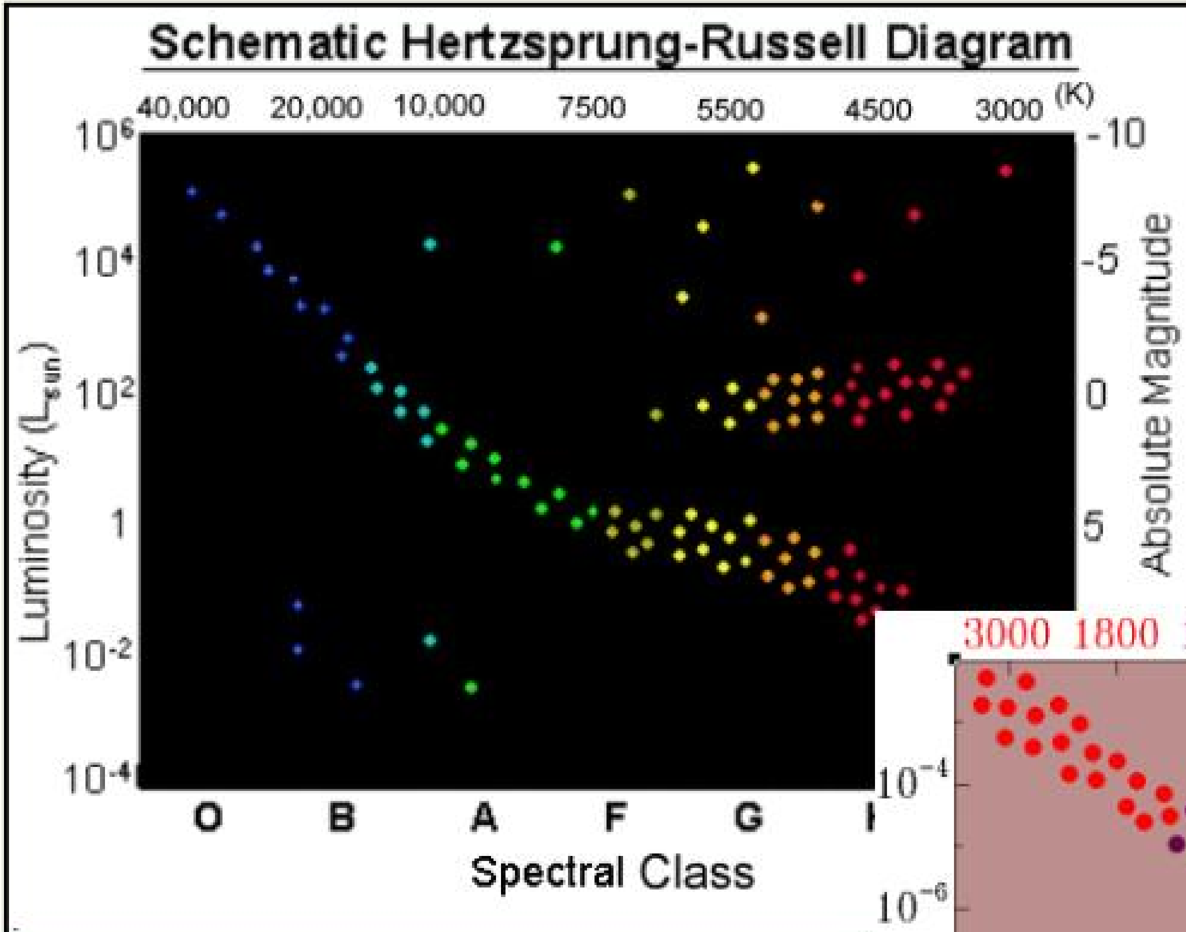
This Review - Low Temperature Field Brown Dwarfs

Jupiter masses: 80-200 15-73 0.3-13



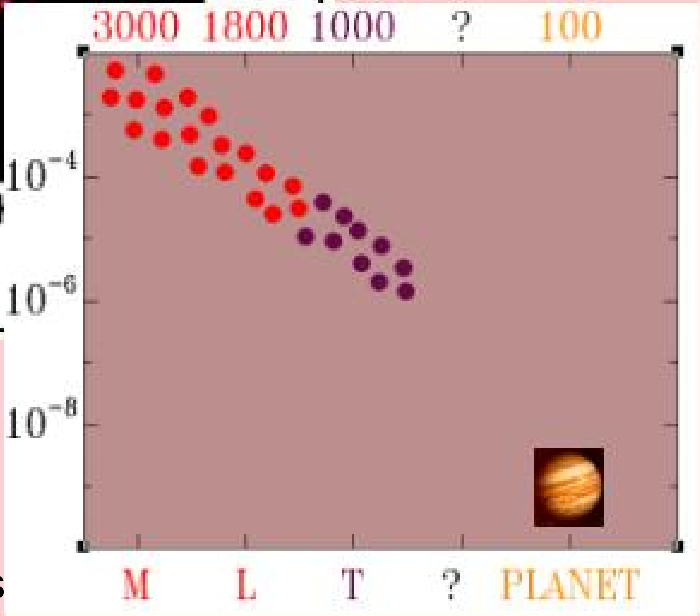
Burrows et al. 2001
Rev.Mod.Phys.73

Because brown dwarfs cool with age, T_{eff} alone cannot constrain mass, so age (or surface gravity) also needs to be known. This review deals with low luminosity, low temperature, field brown dwarfs which are typically older than 0.5 Gyr. *UKIRT has also made large contributions to studies of warmer but very low mass young brown dwarfs in open clusters (e.g. work by Hambly, Jameson, Lodieu) and in star forming regions (e.g. work by Lucas).*



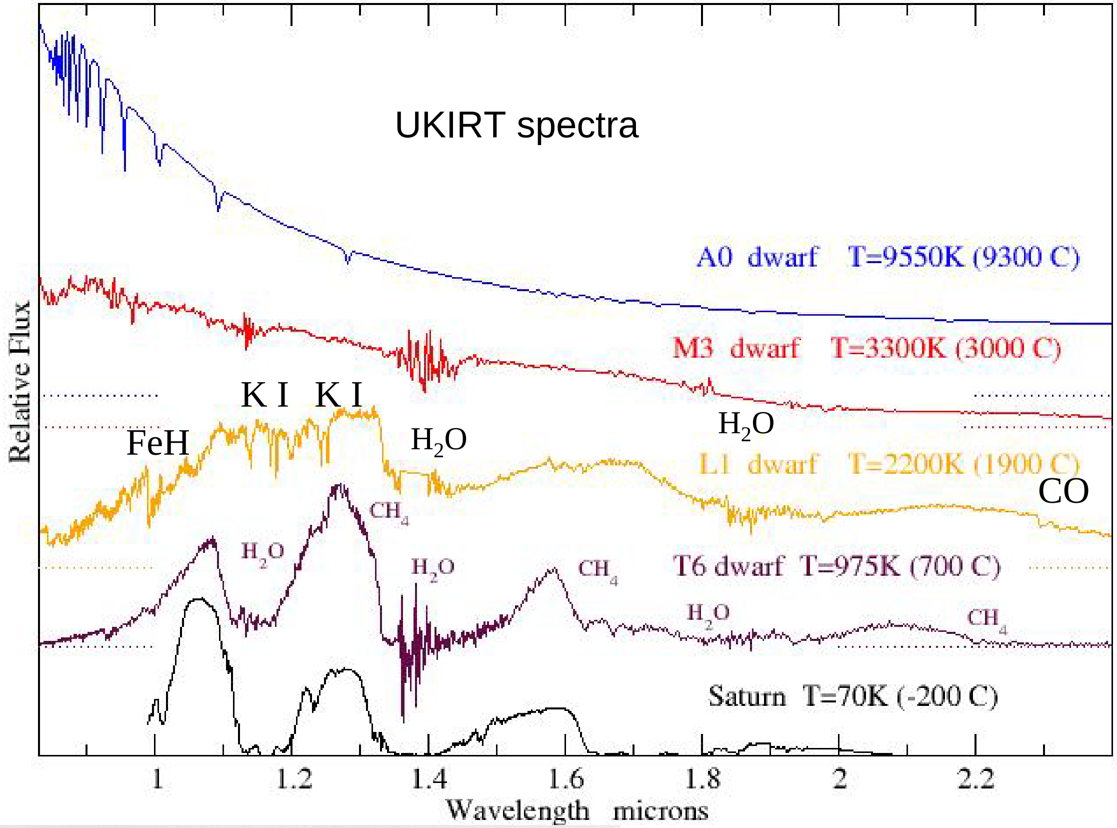
Extending the Main Sequence to Faint Limits

The faintest M dwarfs have $L=10^{-3.5}L_\odot$. In 1988 a $10^{-4}L_\odot$ object was found, and in 1995 a $10^{-5}L_\odot$ object. Starting in 1997 populations were found with $L\sim10^{-5.7}$-$10^{-3.6}\ L_\odot$.



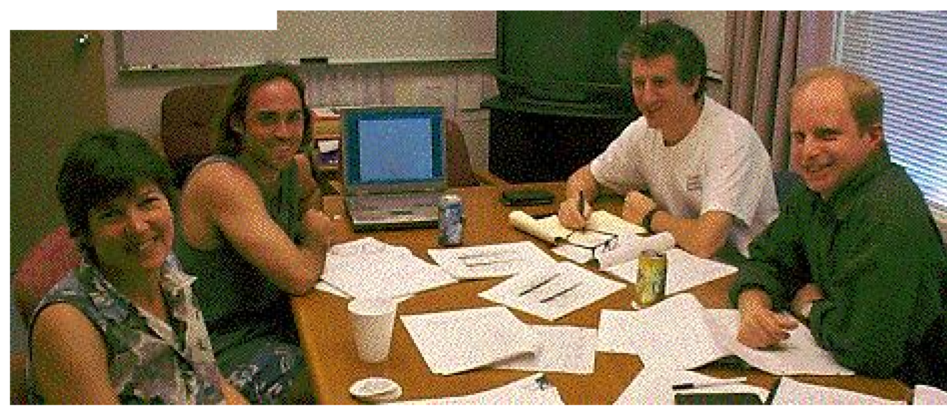
UKIDSS, starting in 2007, found the faintest dwarfs known with $L\sim10^{-6}\ L_\odot$ and $T_{eff}\sim600K$. UKIRT has discovered or confirmed half the objects with $L<10^{-5}L_\odot$. This fraction will increase rapidly with more, imminent, UKIDSS discoveries (see talk by Warren/Burningham later.)

Classifying Stars and Brown Dwarfs



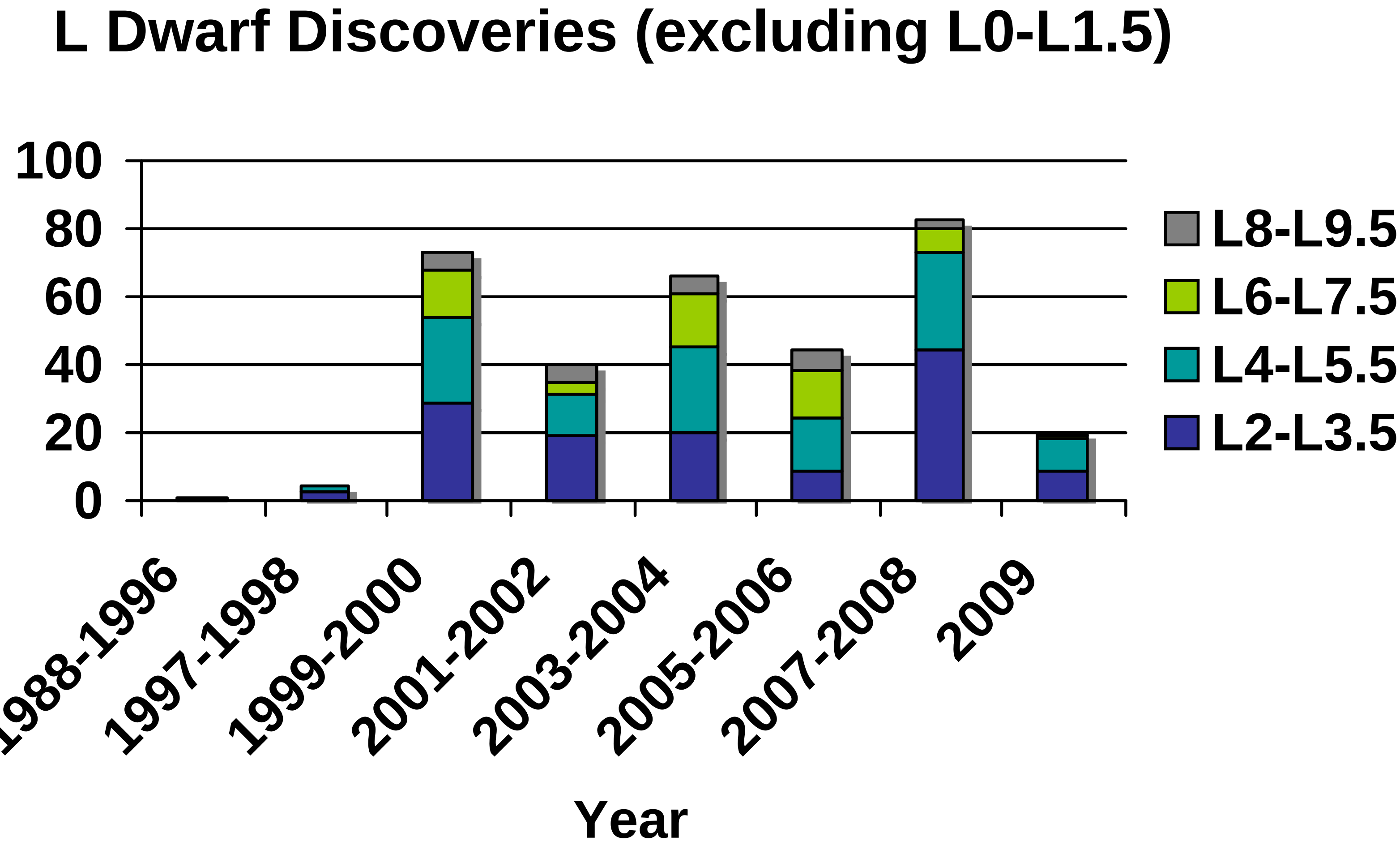
Type	Effective Temperature K
O	> 30000
B	10000 - 30000
A	7500 - 10000
F	6000 - 7500
G	4800 - 6000
K	3800 - 4800
M	2200 - 3800
L	1350 - 2200
T	400? - 1350
Y	? - 400?

PLATE 8. The Harvard College Observatory was known in the 1890s for the many women it employed to classify stellar spectra. Among those shown here in 1892 are Henrietta S. Leavitt (third from left), Williamina P. Fleming (standing), and Annie Jump Cannon (far right). (*New England Magazine*, n.s. 6 [1892]:166.)



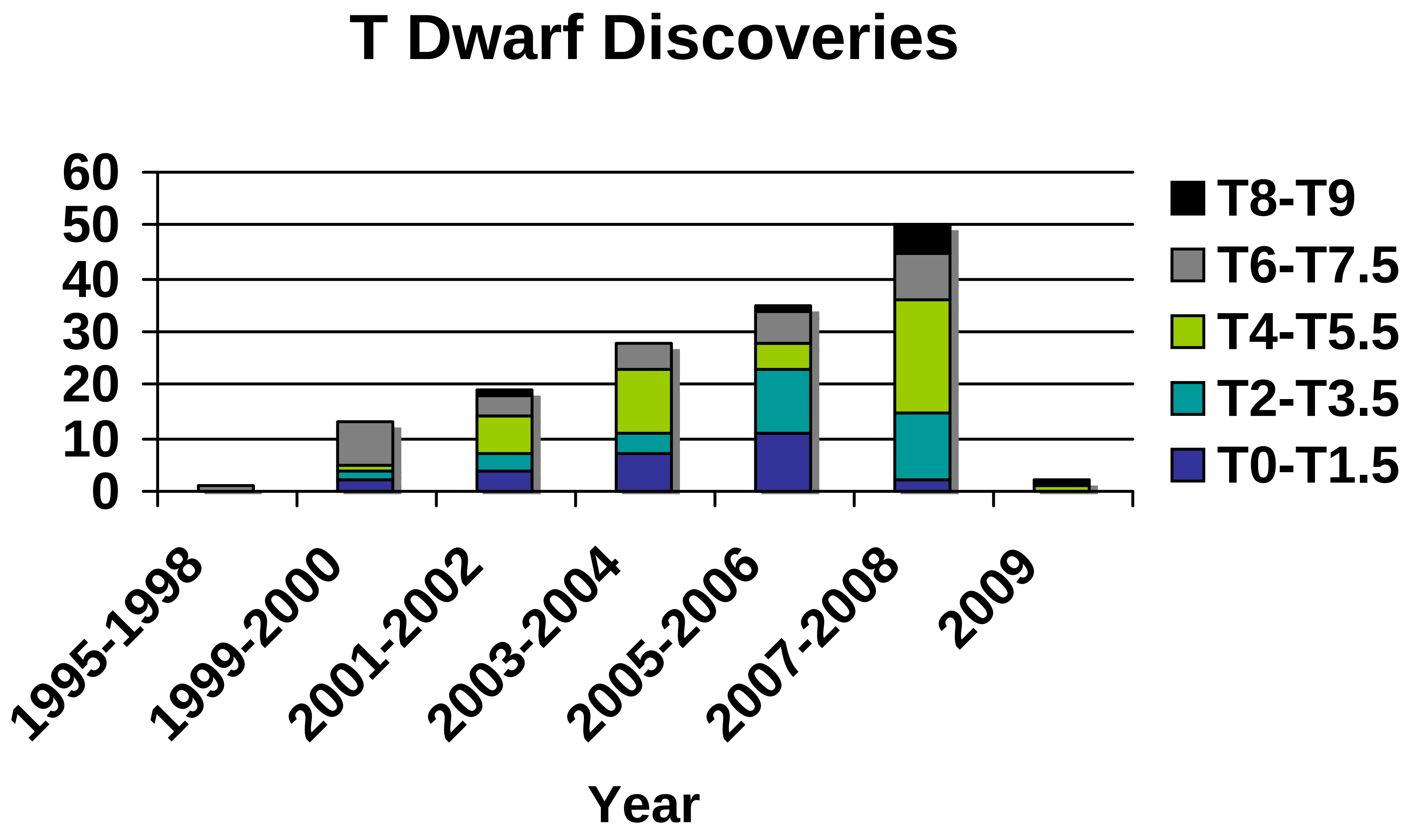
The 2MASS and SDSS groups merge T dwarf classification schemes (left to right: Leggett, Burgasser, Geballe, Golimowski, 2001).

L and T Dwarf Discoveries



As of August 25 2009, based on *DwarfArchives.org.*

L and T Dwarf Discoveries

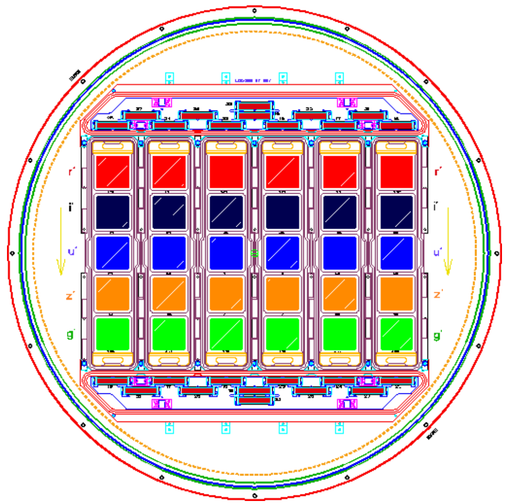


As of August 25 2009, based on *DwarfArchives.org.*

L and T Dwarfs Found Predominantly by Surveys

Near-infrared **Two Micron All Sky Survey, 2MASS: 1997-2003**, 2-m telescopes in Arizona & Chile surveyed the entire sky (41000 deg.^{2}) at *JHK* (Skrutskie et al. 2006 AJ 131).

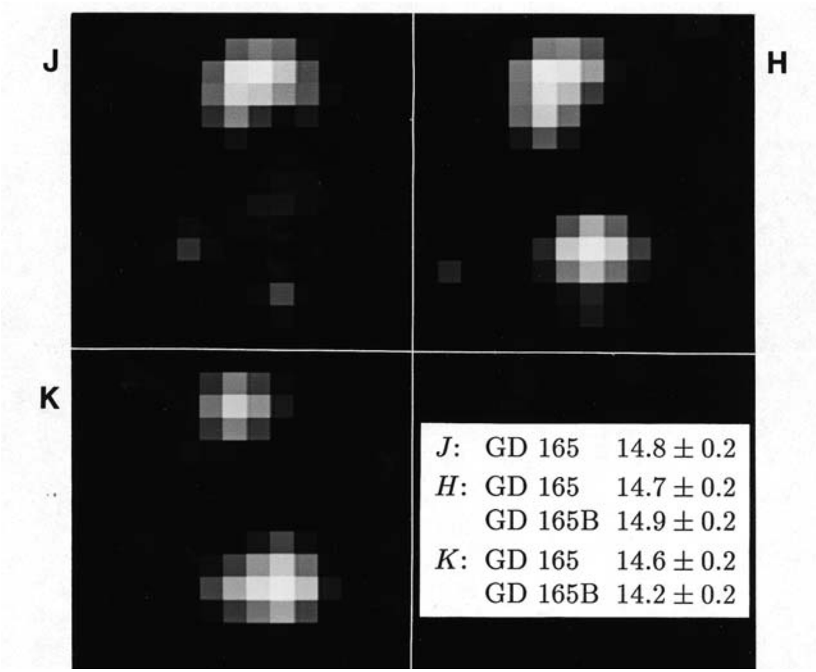
Red/Optical **Sloan Digital Sky Survey, SDSS: 1999-2006**, 2-m telescope in New Mexico mapped 8000 deg.^{2} of the Northern sky with *ugriz* filters (York et al. 2000 AJ 120).



Near-infrared **UKIRT Infrared Deep Sky Survey, UKIDSS: started May 2005**, will cover several thousands of degrees of sky in *YJHK* and goes 3-4 magnitudes fainter than 2MASS (Lawrence et al. 2007 MNRAS 379).

As of August 25 2009, 30% of the published T dwarfs come from 2MASS, 30% from SDSS, and 25% from UKIDSS.

UKIRT and the faintest objects outside the Solar System - the years 1988 to 1995

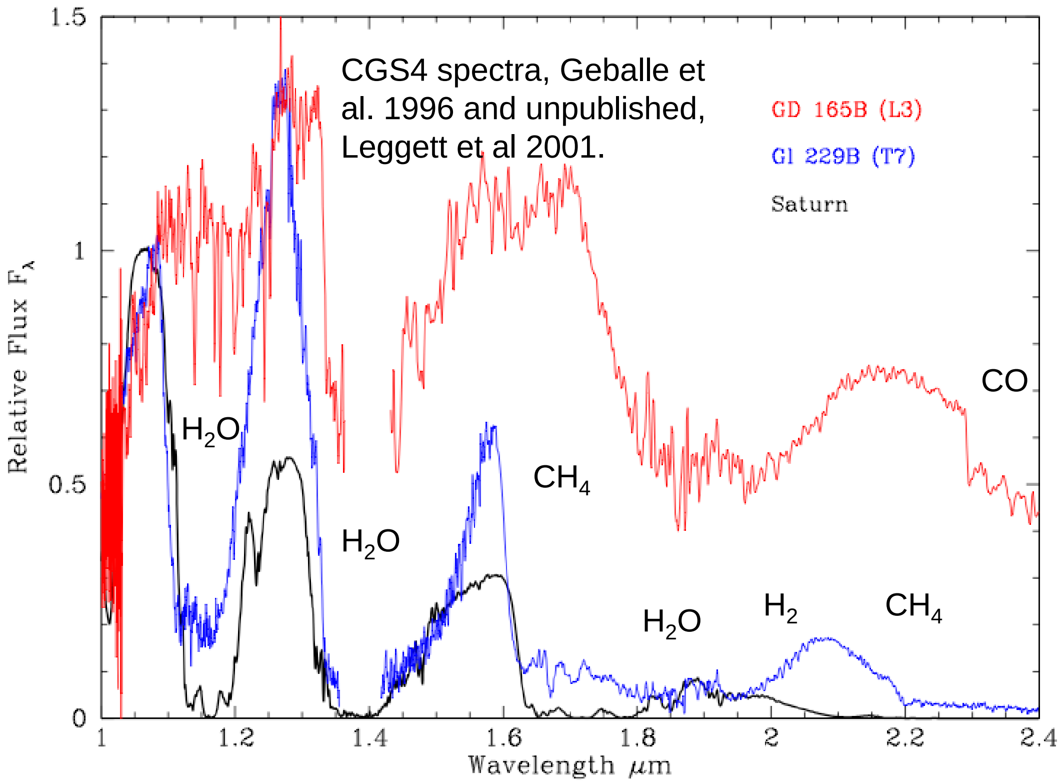


GD165B Becklin & Zuckerman 1988 *Nature* 336

GD 165B is now classified as an L3, with $L=10^{-4.1}\ L_\odot$ and T_{eff}=1850 K. It was the first L-type dwarf, and the only one known from 1988 to 1997 (although only classified as such when more were found, in 1999).

Becklin & Zuckerman surveyed white dwarfs looking for red companions, using UKT9 and IRCAM, with other Mauna Kea cameras. In 1988 they announced a possible companion to GD 165 seen in UH 88" images. The object was confirmed as a proper motion companion, and thus the coolest dwarf known, in their 1992 paper (ApJ 386) which included the UKIRT data. CGS4 data were used by Tinney et al. (1993 AJ 105) to determine a bolometric luminosity and confirm the object as the lowest luminosity dwarf known. CGS4 was also used by Jones et al. (1994 MNRAS 267) in their investigation of the correlation between near-IR spectral features with $T_{eff,}$ (in particular H_2O) which showed GD165B to be the coolest dwarf known.

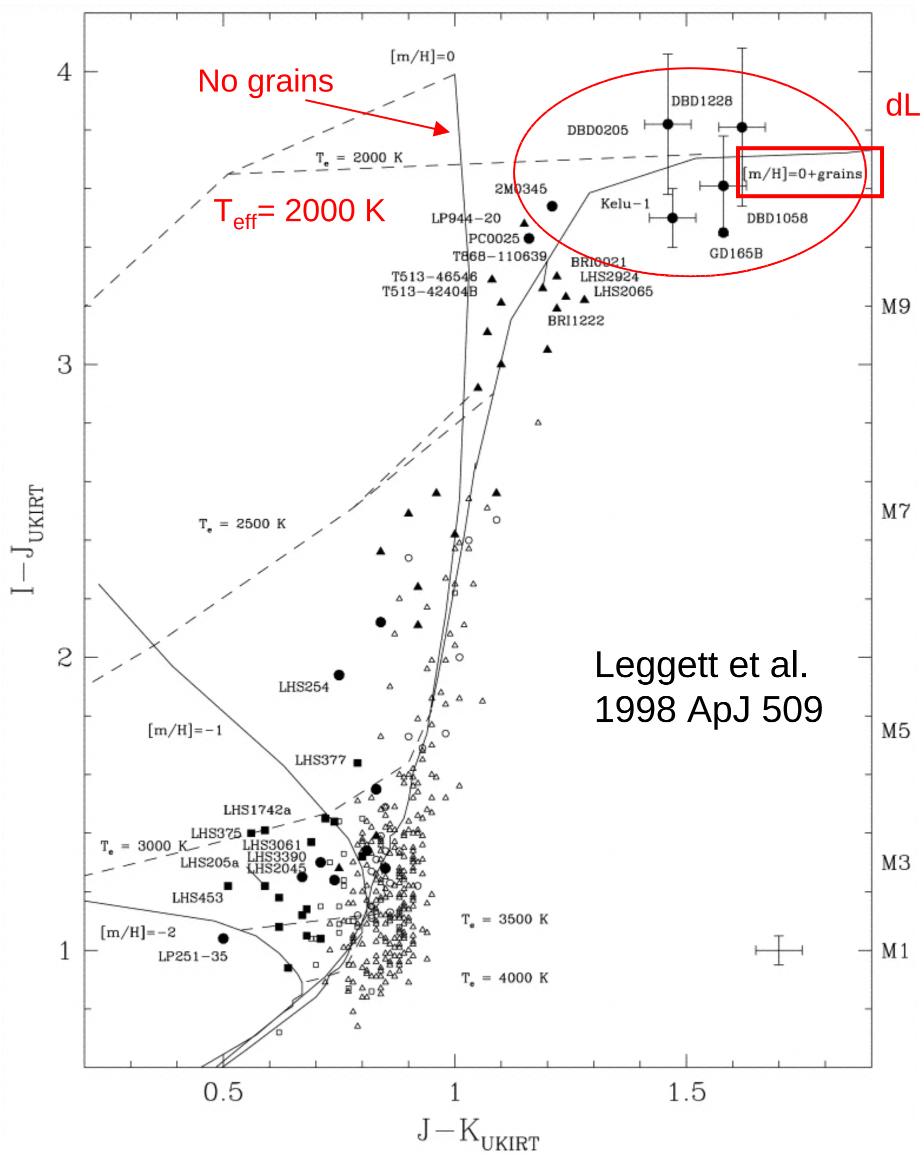
UKIRT and the faintest objects outside the Solar System - the years 1995 to 1997



GL 229B is now classified as a T7p, with L= $10^{-5.2}$ $L_\odot$ and T_{eff}=950 K. It was the first T-type dwarf, and the only one known from 1995 to 1999 (although only classified as such in 2000).

Nakajima et al. (1995 Nature 378) discovered GL 229B by imaging M dwarfs for companions. An early spectrum indicated it was extremely cool; the CGS4 spectrum in Geballe et al. (1996 ApJ 467) became the definitive measurement, and showed strong H_2O and CH_4 absorption bands, and similarity to spectra of Saturn and Titan. Later Noll et al. (1997 ApJ 489) used CGS4 at 5μm to demonstrate that CO is enhanced over chemical equilibrium models by >10^3. They suggested that mixing occurs in the atmosphere, and that, as in Jupiter, CO is dredged up from deeper layers.

UKIRT and the L dwarfs - the years 1997 to 2000

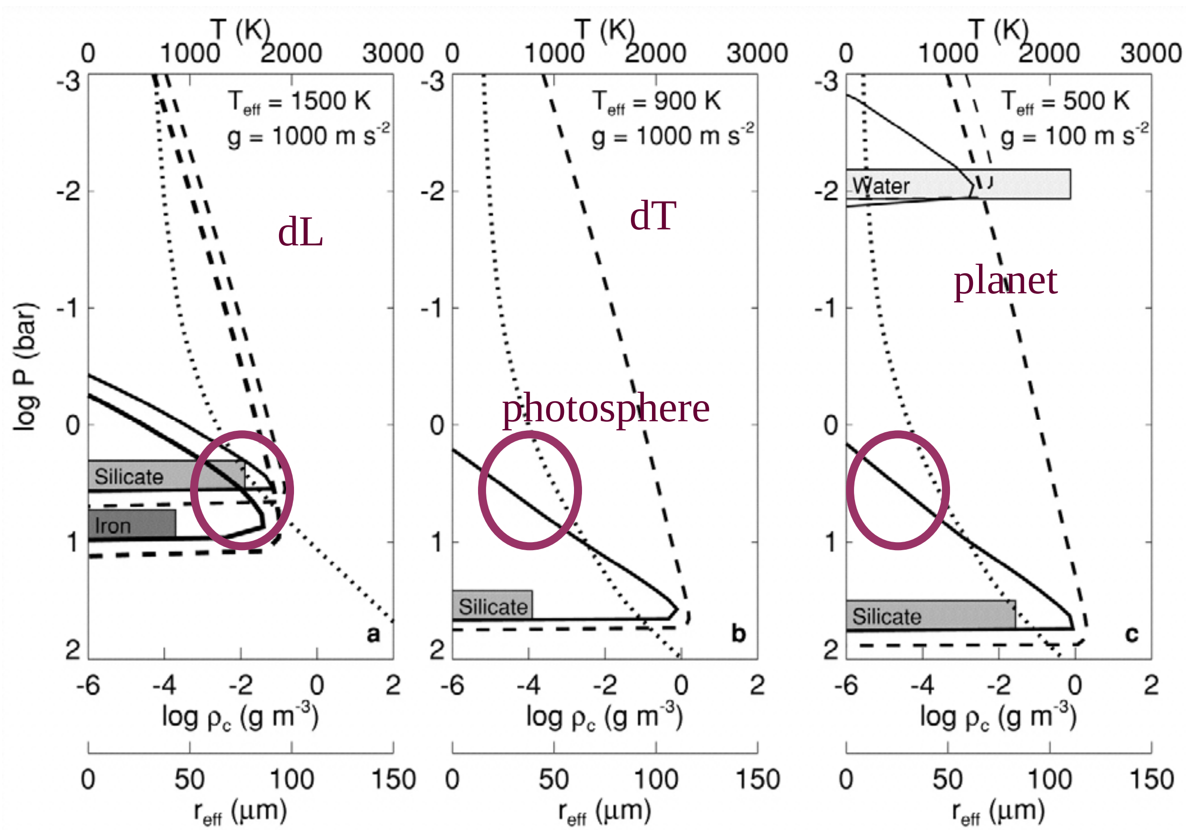


More GD165B-like objects were finally discovered in 1997. IRCAM and CGS4 data were used by Ruiz et al. (1997) to classify the high proper motion object Kelu-1 as one of these new beyond-M class of objects. The other four objects were found as red objects in early 2MASS and DENIS infrared survey results. Leggett et al. (1998 ApJ 509) used IRCAM data to demonstrate that grains must redden the atmospheres of the L dwarfs, and that these dwarfs have T_{eff}~2000K. In 1999 2MASS found many more Ls; Kirkpatrick et al. (1999 ApJ 519) defined an optical classification scheme for L dwarfs, and used CGS4 to demonstrate that no CH_4 is seen in their near-IR spectra. Noll et al. (2000) used CGS4 to show that the 3μm CH_4 feature is seen however in L5 and later type dwarfs.

Cloud models by Ackerman & Marley (2001 ApJ 556)

At T ~1500K iron and silicate grains condense, forming liquid or solid iron and silicates like olivine ($(Mg,Fe)_2SiO_4$) or enstatite ($MgSiO_3$). Marley models horizontal decks of condensates, with the vertical extent determined by the balance between upward turbulent mixing and downward sedimentation. A parameter f_{sed} is used, which is the ratio of sedimentation to convection velocities.

Smaller values of f_{sed} imply more extensive cloud decks. For L dwarfs $1<f_{sed}<3$, for T dwarfs f_{sed}=4 to infinity (cloud free).

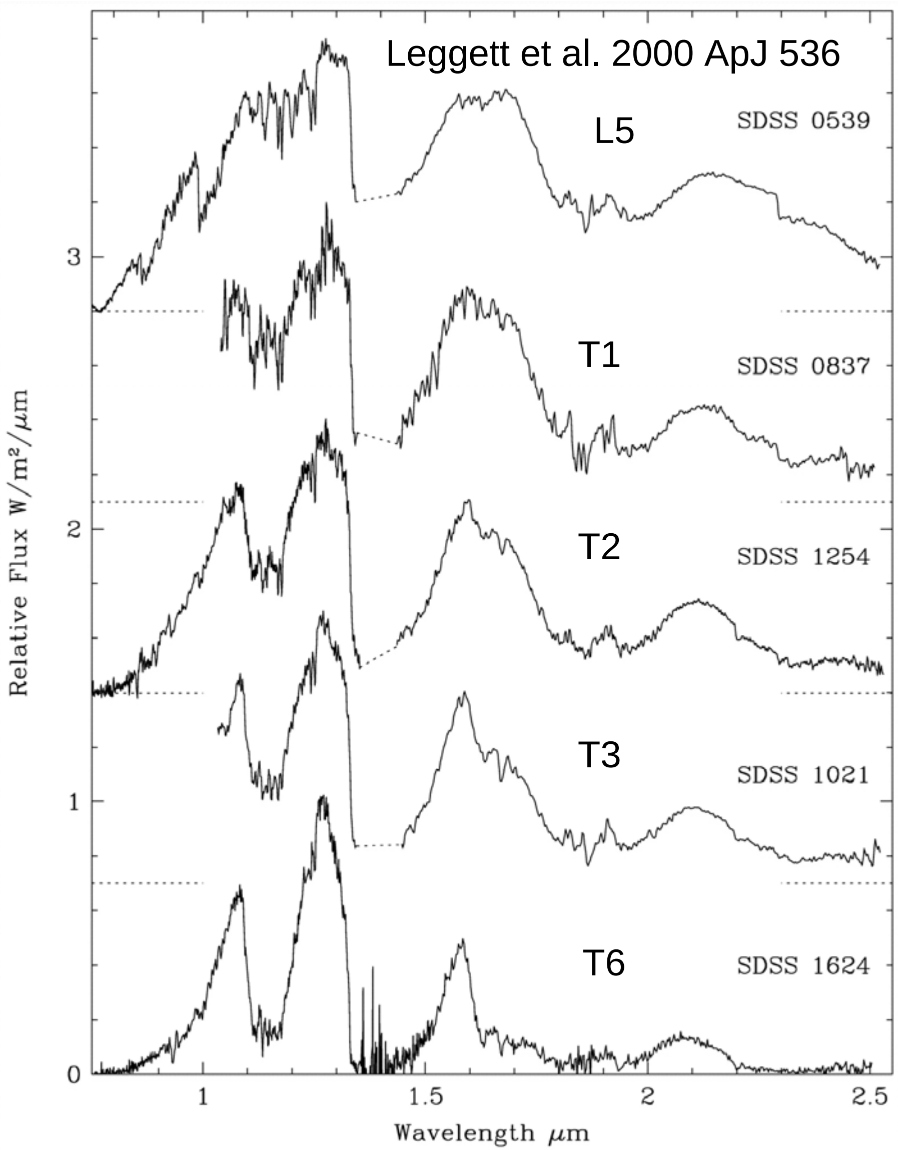


UKIRT and the second 1000K methane dwarf - 1999

```
Envelope-to: s.leggett@jach.hawaii.edu
Delivery-date: Tue, 20 Apr 1999 15:38:37 -1000
From: Xiaohui Fan <fan@astro.Princeton.EDU>
Subject: position and finding chart for SDSS object
To: t.geballe@jach.hawaii.edu, s.leggett@jach.hawaii.edu
Date: Tue, 20 Apr 1999 21:38:27 -0400 (EDT)
Cc: strauss@astro.Princeton.EDU (Michael Strauss), gk@astro.Princeton.EDU (Jill Knapp)
MIME-Version: 1.0
Content-Transfer-Encoding: 7bit

Dear Tom and Sandy,

 Here is the information regarding the red SDSS object (methane dwarf?):

 SDSSJ162414.37+002915.6                  rise 1540pm   w/blind 1000

 RA: 16:24:14.37                               trans 230   Set 630
 DEC: +00:29:15.6 (2000)

 i=22.85 +/- 0.23                       if ~Kelu  I-K = 5    K ~ 18  J ~ 19.5
 z=19.02 +/- 0.03                       if ~229B     "       K ~ 18  J ~ 18

 therefore JHK should be quite bright.

 You can find the finding chart at:                K, H, J: 2x9 jit   for ~5%
                                                        "
ftp astro.princeton.edu
login as anonymous
cd fan/sdss/red

 the file is red.ps

 Please tell me if there is any problem, you can give me a call
if you can trouble identifying object (home: 609-683-0125).

 Thanks very much!

 Best,
--
Xiaohui Fan
Princeton University Observatory
Peyton Hall
Princeton, NJ 08544

email : fan@astro.princeton.edu
tel   : (609) 258-5153 (O)
        (609) 683-0125 (H)

             CGS4   DBS   BS 6093
               40s  1x2  ?
             50s   ~.5x5  ?

        Gals  G40
             target. check
```

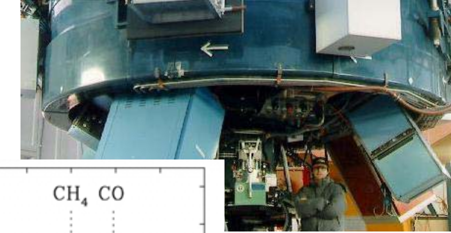
In April 1999 the Princeton group of the Sloan Survey contacted Tom Geballe and I to obtain IR follow up observations of a uniquely (optically) red object they had found in survey commissioning data. We were able to quickly get IRCAM and CGS4 data which confirmed this to be the second example of a GL 229B-like object (Strauss et al. 1999 ApJ 522). The spectrum was almost identical to that of GL 299B. Finally, after more than 30 years, we were on our way to discovering and studying the local population of cold brown dwarfs, objects that spectrally appeared much more similar to planets than stars.

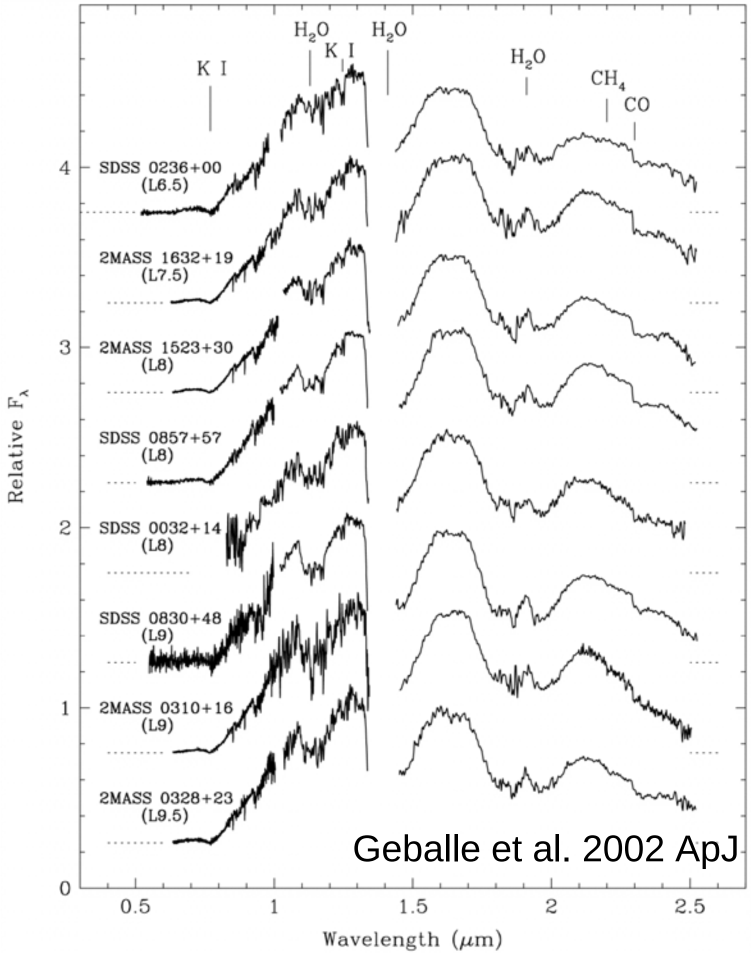
UKIRT identifies the T spectral sequence - 2000



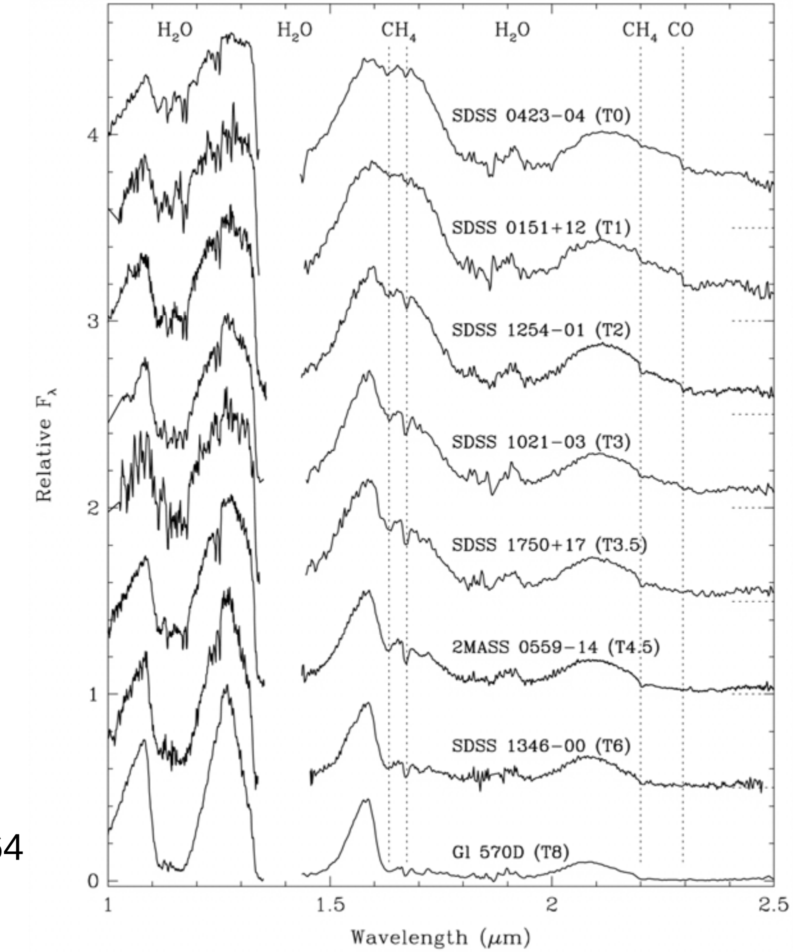
After the 1999 SDSS 1624+00 discovery, several more Ts were found by 2MASS and SDSS. All looked very much like GL 229B, with strong CH_4 features. In an SDSS brown dwarf candidate follow up observing run in March 2000, in one night with CGS4, we finally found examples of early-type T dwarfs. Three objects were found with weak *H*-band CH_4 features, and so these provided the spectral link between the late-type L dwarfs and the 229B-like mid-type Ts (Leggett et al. 2000, ApJ 536). These objects were easier to find in SDSS than 2MASS as their optical colors are distinctive while their *JHK* colors are similar to early type stars, and so SDSS+UKIRT had the monopoly on early T dwarfs for some time.

UKIRT and classification schemes for M, L and T dwarfs - the years 2001 to 2006



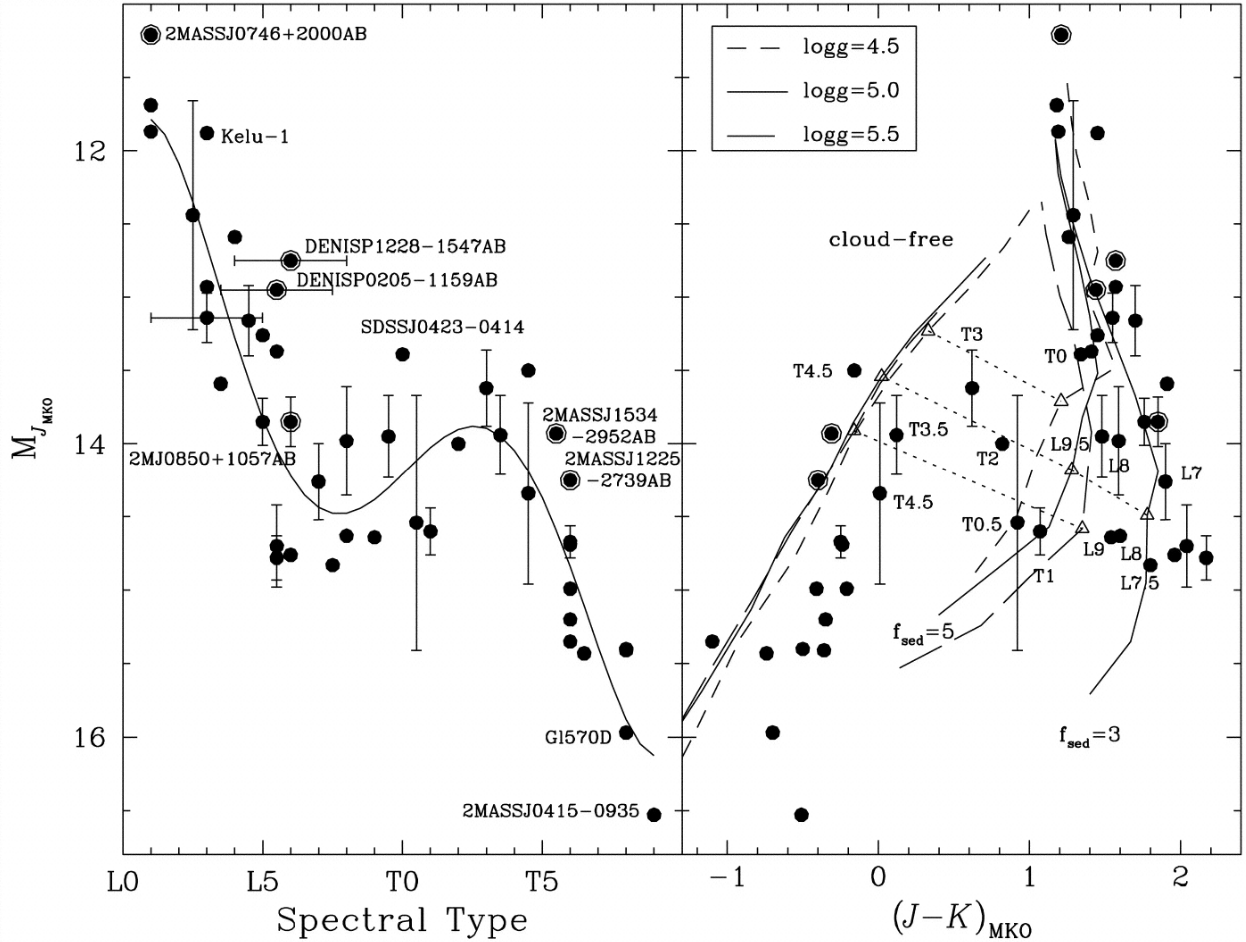


Geballe et al. 2002 ApJ 564



High quality CGS4 spectra have defined the infrared spectral classification of the lower main sequence and beyond. Reid et al. (2001 AJ 121) presented a scheme to classify M and L dwarfs, which was superceded by the Geballe et al. (2002 ApJ 564) scheme for L and T types. The universally adopted scheme for T dwarfs (Burgasser et al. 2006 ApJ 637) incorporates and builds on the Geballe et al. results.

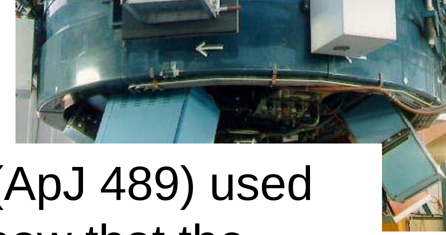
UKIRT and the fast L to T transition - 1999 to 2006

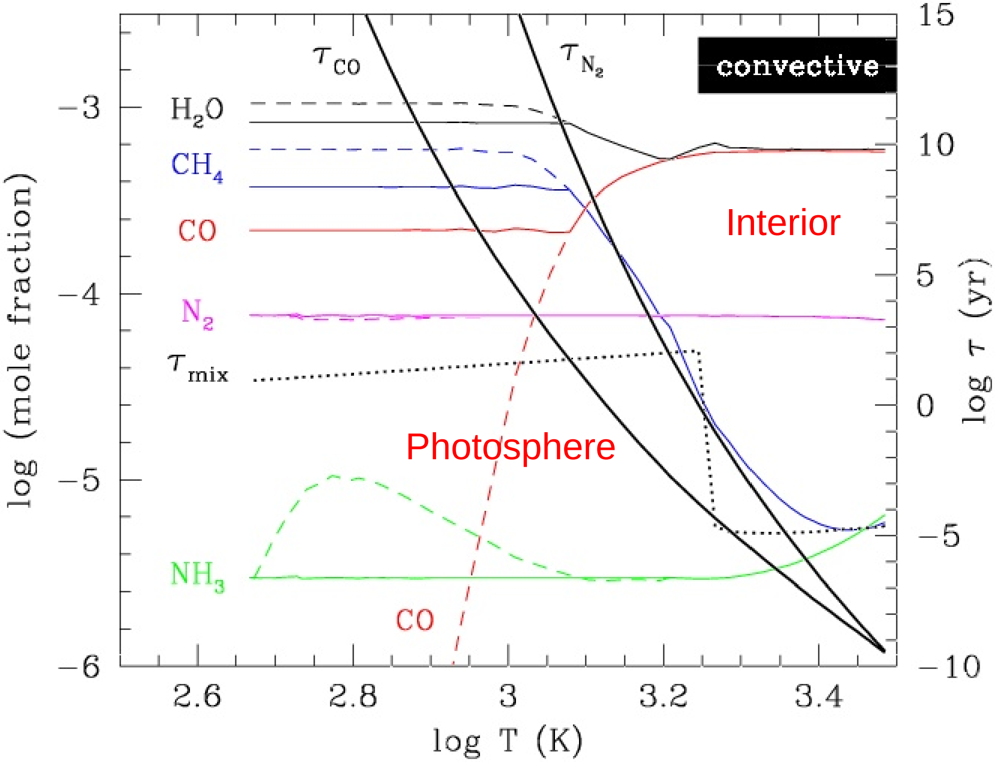


M_J as a function of type and color (Knapp et al. 2004 AJ 127)

IRCAM, UFTI, CGS4 and UIST data for ~120 SDSS L and T dwarfs produced a well quantified sample in several publications between 1999 and 2006. One still puzzling aspect of this population is the rapid clearing of condensates from the photosphere of late-L dwarfs. Knapp et al. (2004 AJ 127) showed that this could be explained by an increase in sedimentation at T_{eff}~1300K, dubbed the “Hilo rain” scenario. Another possibility is holes between the clouds, as seen in Jupiter’s atmosphere.

UKIRT and non-equilibrium chemistry - 1997 to 2004



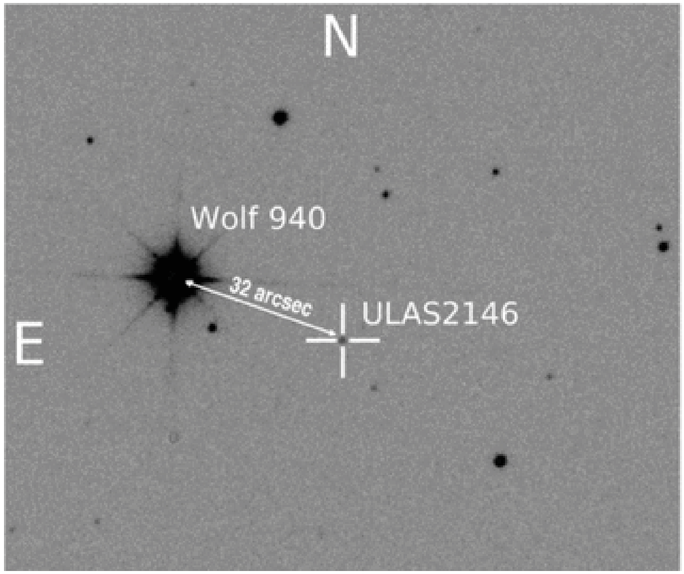


Solid and dashed lines show the changes in abundance that occur when mixing occurs; Saumon et al. 2006 ApJ 647.

In 1997 Noll et al. (ApJ 489) used CGS4 at 5μm to show that the photosphere of GL 229B had an unexpectedly large amount of CO. Leggett et al. (2002 ApJ 564) and Golimowski et al. (2004 AJ 127) used IRCAM and UIST M-band photometry to show that this is a universal feature of T dwarfs. Enhanced CO and N_2, and diminished CH_4 and NH_3, can be explained by vertical mixing in the atmosphere. The very stable CO and N_2 can be dredged up, leading to changes in abundance of one to several orders of magnitude.

The mixing can be modelled as turbulence with timescales H^2/K where H is the pressure scale height and K is the coefficient of diffusion. The data shows that $K \sim 10^2$-$10^6 cm^2/s$, implying fast mixing timescales of 10 yrs to 1 hr respectively. The factor ~2 loss in flux at 5μm is critical for mid-IR space missions like Spitzer and WISE.

UKIRT and fundamental benchmarks - 2001 to 2008



The T8.5 companion to the M4V star Wolf 940; Burningham et al. 2009 MNRAS 395.

Burningham et al. (2009 MNRAS 395) has found the coolest companion to a MS star to date, in UKIDSS data: the T8.5 at 400 AU from the M4V star has T_{eff}= 575+/-25K, and mass 20-30 M_{jup}. (see talk by Warren/Burningham).

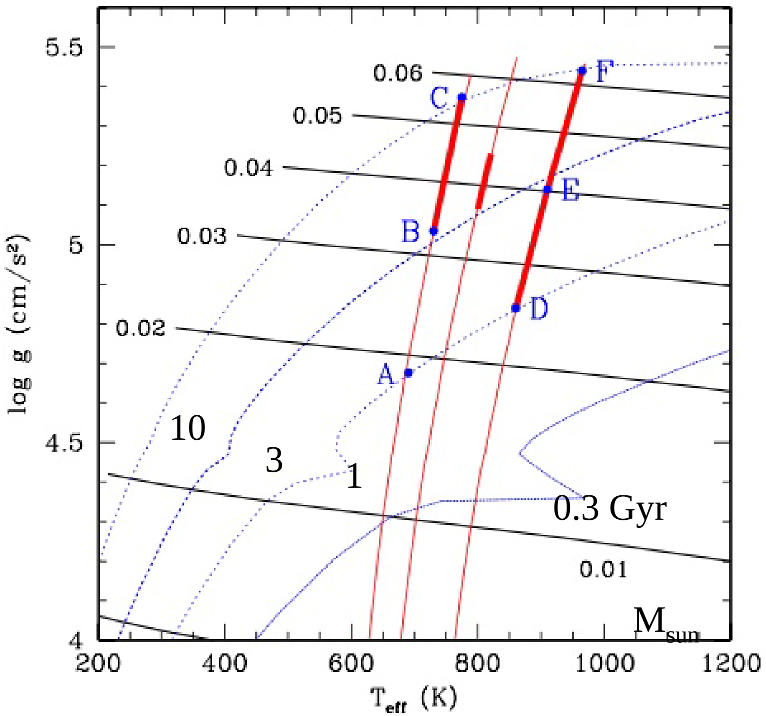
Following the pioneering work on GL 229B, UKIRT continued to make large contributions to the study of brown dwarf (BD) companions to main sequence (MS) stars. Such objects are very important, as the MS star constrains metallicity and age, and hence mass, for the BD, which otherwise is difficult or impossible to do.

Geballe et al. (2001 ApJ 556) used UFTI, IRCAM and CGS4 to study GL 570D, a T7.5 dwarf in a K and M dwarf system. They found T_{eff}=800 +/-20K, and mass 40-70 M_{jup}, showing this to be the coolest object known in these early days of T dwarf discoveries.

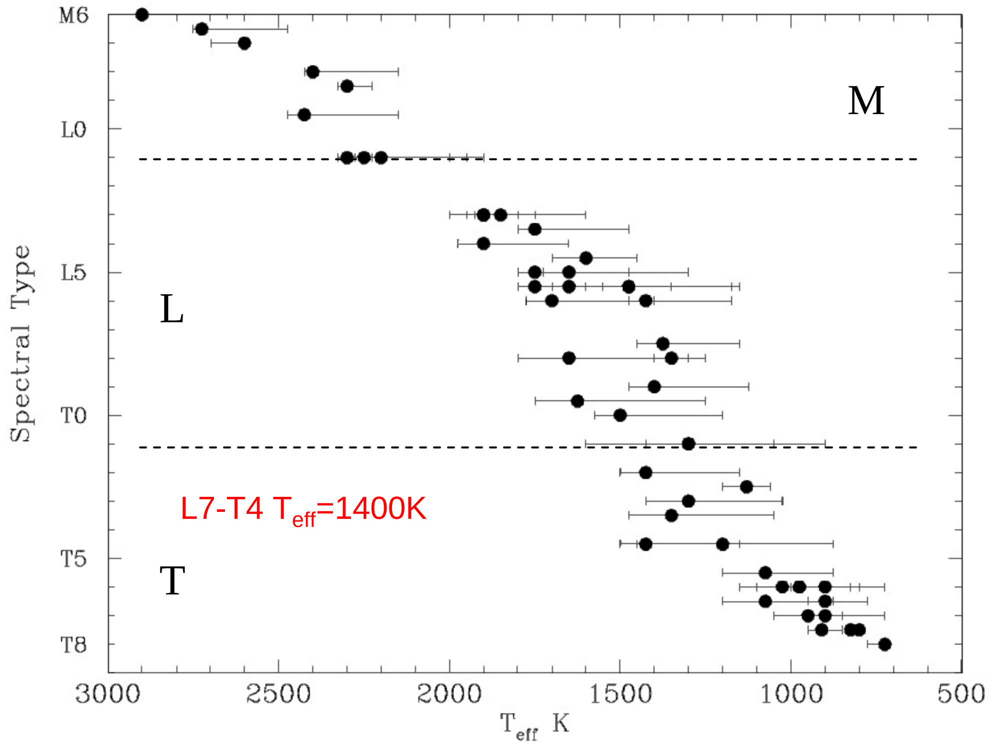
Mugrauer et al. (2006 MNRAS 273) used UFTI to confirm a proper motion companion to the K0V star, HD 3651, the first BD companion to a planet-hosting star. The 40-70 M_{jup} T7.5 dwarf is ~ 500 AU from the star, with T_{eff}=810 +/-30K.

Effective Temperatures of L and T Dwarfs

The most robust determinations of T_{eff} use luminosity, L which is proportional to $R^2T_{eff}^4$. As radius ~constant for field dwarfs, L determines T_{eff} and if age or gravity can be constrained, so can mass. Programs to measure infrared trigonometric parallaxes are very important!



Saumon et al. 2007 ApJ 656, luminosity-derived parameters for the T7.5 - T8 dwarfs 2M 0415-09, Gl 570D, 2M 1217-03 (red vertical lines left to right). Dark red regions are best fits.



T_{eff} and (infrared) spectral type, from observed L_{bol} (Golimowski et al. 2004 ApJ 127, and Stephens et al. 2009 ApJ 702). Error bars reflect unknown ages.

Summary

Ten years ago evidence of a local population of cold brown dwarfs was found, 36 years after their existence was hypothesized. The population has been classified into L dwarfs with T_{eff} ~ 1350 - 2200K (log $L \sim 10^{-5}$-$10^{-4} L_{\odot}$) and T dwarfs with T_{eff} ~ 500 - 1350K (log $L \sim 10^{-6}$-$10^{-5} L_{\odot}$) . UKIRT provided fast response, high quality, easily reduced, well understood and quickly published data that provided, and continues to provide, the core dataset for this rapidly advancing field. Highlights include:

• Spectroscopy which defined the classification schemes for L and T dwarfs.

• 3-5μm data (for which Mauna Kea is ideal) which demonstrated turbulent atmospheres and unexpected chemical abundances.

• Near-IR imaging data enabling many discoveries, including the first examples of isolated field L and T dwarfs: Kelu-1 in 1997 and SDSS 1624+00 in 1999. UKIDSS has found 500-600K objects at the brink of the next spectral class and soon will have found more T dwarfs than 2MASS and SDSS combined (talk by Warren/Burningham).

Star trails over Gemini, UH 88 and UKIRT by John Davies, ATC.