Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

An Insider's View of Brown Dwarfs

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Abstract. This review seeks to provide the background material necessary to understand the newest developments in the study of brown dwarfs. I describe the physical and observational properties of low mass stars and brown dwarfs, and discuss our ability to distinguish between them. Other topics include atmospheric variability in the form of magnetic activity and weather, and the mass function and local density of brown dwarfs in the solar neighborhood. The connection between brown dwarfs and planets will be covered in the companion review paper on extrasolar planets.

1. Introduction

In the six years since the first bona fide brown dwarf was identified (Gliese 229B; Nakajima et al. 1995), an enormous wealth of information has been gathered on these objects. The history of brown dwarf searches, the early discoveries, and much of the background data underlying our current knowledge is described in our book "New Light on Dark Stars" (Reid & Hawley 2000), as well as in recent review articles (e.g. Burrows, Hubbard & Lunine 2001; Chabrier & Baraffe 2000; Reid 2000). I will not attempt to provide a complete description here, nor will I cover topics that will be discussed by the contributed speakers (the T dwarf spectral sequence, L and T dwarf infrared colors, models including clouds and weather – see papers by Burgasser; Geballe; Leggett; Marley; this volume). Instead I will give an overview suitable for the typical cool-star astronomer who does not work on brown dwarfs, but would nevertheless appreciate a brief description of the salient features – at least enough to understand the talks that will follow! Here is an outline of the issues surrounding brown dwarfs that I will discuss:

- What are they? – physical properties
- What do they look like? – colors, spectra
- Variability? – magnetic activity, weather
- How many are there? – mass function, local density

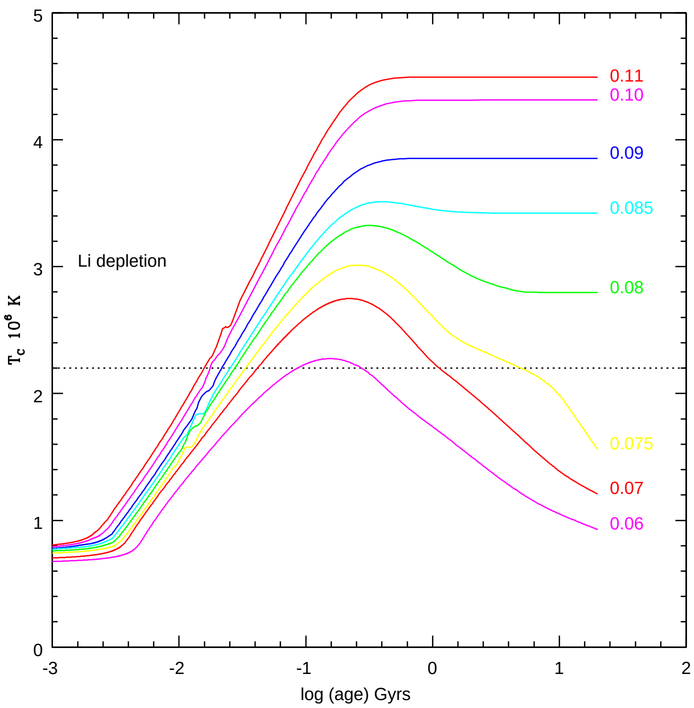

Figure 1. The run of central temperature with age for a sequence of models from Burrows et al. (1997). Models with masses $M \gtrsim 0.075 M_\odot$ have Hydrogen fusion; those between $\sim 0.06 - 0.075$ $M_\odot$ will burn Lithium (Reid 2000).

2. What Are They?

2.1. Interiors

The central temperature of an object is set by its mass (see Figure 1), with some important regimes for brown dwarfs:

1. $M \gtrsim 0.075 M_\odot$, T_c high enough to sustain H fusion, object is a star;
2. $M \lesssim 0.075 M_\odot$, T_c too low for sustained H fusion, object is a brown dwarf, but does burn Lithium;
3. $M \lesssim 0.06 M_\odot$, T_c too low for Lithium burning, object shows Lithium in its spectrum and can be unequivocally identified as a brown dwarf (the "Lithium test"; Rebolo, Martin & Magazzu 1992);
4. $M \lesssim 0.013 M_\odot \sim 13 M_{Jupiter}$ is the Deuterium burning limit. Objects less massive than this will not deplete Deuterium. Some have argued that this represents a "physical" dividing line between planets and brown dwarfs, regardless of their origin. We return to this question in the extrasolar planet review to follow (see paper by Hawley & Reid, this volume).

The internal structure of a brown dwarf is rather simple. It is fully convective, and a degenerate core provides pressure support in a manner similar to white dwarfs. As the mass decreases, the radius increases, but the degeneracy also lessens slightly, resulting in all brown dwarfs having similar radii $\sim 0.1 R_{\odot} \sim R_{Jupiter}$ (see Basri 2000 for a nice color picture illustrating the radii of brown dwarfs compared to Jupiter).

2.2. Atmospheres

In contrast, the atmospheres of brown dwarfs are exceedingly complex, and much work has already been done (Jones et al. 1996; Jones & Tsuji 1997; Burrows & Sharp 1999; Allard 2000; Allard et al. 2001) with much more left to do. As the temperature in the atmosphere decreases, most of the metals condense onto dust grains. For example, Titanium (Ti), which is primarily present in the form of molecular TiO in stars above 2000K, condenses onto perovskite ($CaTiO_3$) at lower temperatures (Burrows & Sharp 1999). Atmospheres of L dwarfs thus become "clear" in comparison to M dwarfs. Models that account for metal depletion by dust, but do not include dust opacity, provide good fits to the spectral data (Basri et al. 2000) though newer "dusty" models fit well in the infrared (Schweitzer et al. 2001). The lack of dust opacity is usually explained by having the dust gravitationally "settle" (i.e. diffuse) below the photosphere, but is difficult to justify in detail.

The remaining atmospheric opacity is primarily from the alkali metals (Na, K, Rb, Cs, Li) which condense into chlorides only at very low temperatures $\lesssim$ 1400K. Because L dwarf atmospheres are relatively transparent, one sees in to very high pressure, resulting in the formation of enormously strong Lorentz damping wings in the resonance lines of particularly the high abundance species Na I and K I (several hundred Å!). Eventually, at temperatures below about 1200K, Carbon preferentially forms methane rather than CO, and the resulting methane opacity produces very distinctive infrared spectral features which define the T dwarfs (Burgasser et al. 2001; Geballe et al. 2001; Leggett et al. 2001). T dwarf colors, spectra and classification schemes are a hot topic these days, and we have several contributed talks and a splinter session devoted to them.

2.3. Evolution

The evolution of brown dwarfs proceeds very rapidly, as the internal energy provided by gravitational contraction and a brief bout of Deuterium, and in the higher mass objects Lithium, burning is quickly radiated away. The atmospheric temperature, and hence the spectral type, is a strong function of the age of the object, as shown in Figure 2 for two different sets of models (Burrows et al. 1997; Baraffe et al. 1998). The dotted lines in the figure show the evolutionary paths for various mass brown dwarfs (those fading to the lower right corner) and low-mass stars (those with temperatures asymptotically approaching $T_{eff} \sim 2000$K at late times). The blue solid line depicts the Lithium depletion boundary at approximately $0.06 M_{\odot}$. It is instructive to consider the position of brown dwarfs in the Pleiades, with an age of ~ 100 Myrs (log age$= -1$ in Gyrs on the scale of the figure). Objects with masses as low as 0.04 $M_{\odot}$ still have M dwarf spectral types at this age. Conversely, objects with mass between 0.08 and 0.075 $M_{\odot}$ will sustain hydrogen fusion and end up on the main sequence with L dwarf spectral

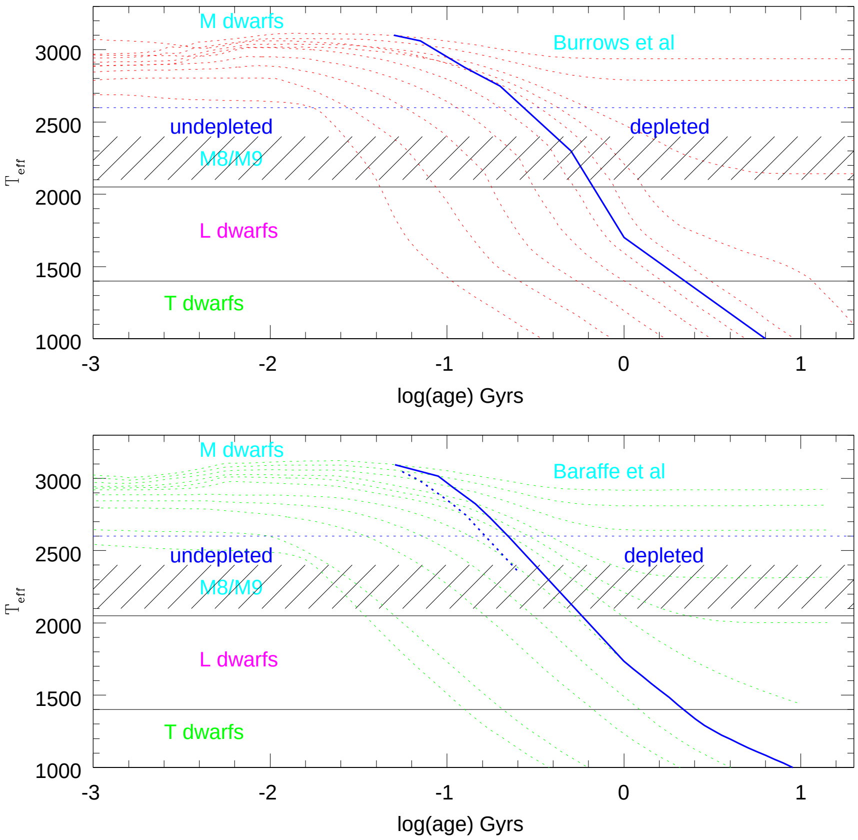

Figure 2. The effective temperature evolution of brown dwarfs for models with masses above and below the Lithium depletion limit ($M \sim 0.06 M_\odot$). Young brown dwarfs have mostly M spectral types, while old brown dwarfs have T spectral types (Reid, priv. comm.)

types. Finally if one follows the evolution of the object with $M \sim 0.06 M_\odot$ (the solid blue line), it is clear that it is an M dwarf until $\tau \sim 1$ Gyr, an L dwarf between 1-2.5 Gyr, and a T dwarf thereafter. An old L dwarf (e.g. the age of the disk) must then be either a very high mass brown dwarf or a very low mass star. I emphasize the following maxims:

Some M dwarfs are brown dwarfs

Not all L dwarfs are brown dwarfs

One must know the age of the object, or detect Lithium, to be sure of its brown dwarf status. Thus, for higher mass brown dwarfs, $0.06 M_\odot < M < 0.075 M_\odot$, one **MUST** know the age to establish whether the object is a brown dwarf.

3. What Do They Look Like?

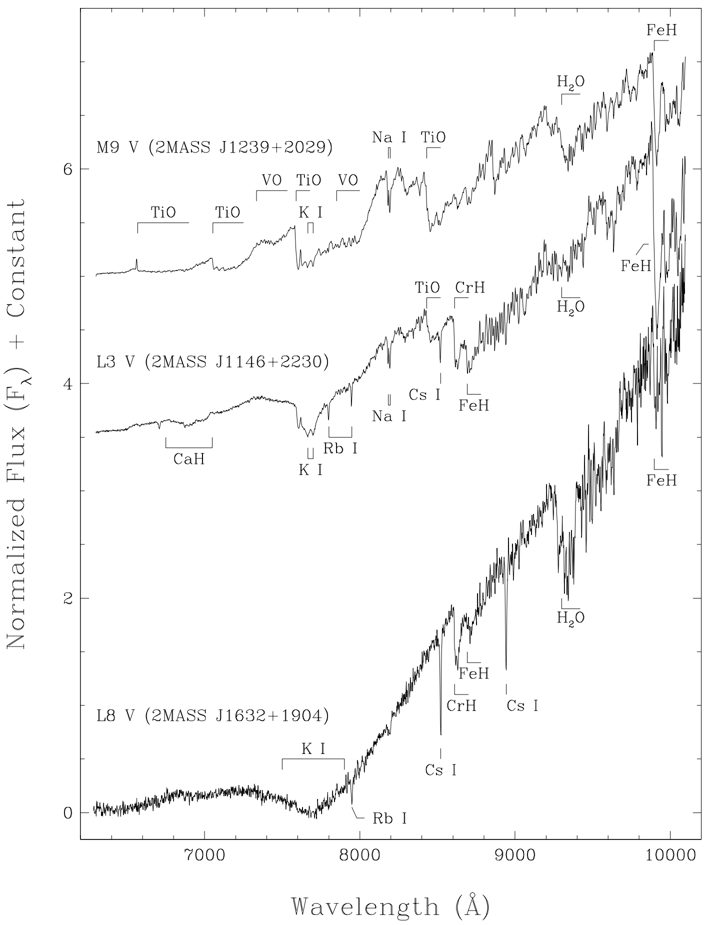

Figure 3. M and L dwarf spectra with features marked (Kirkpatrick et al. 1999).

The optical (red) spectra are characterized by decreasing TiO bands, which are the strongest opacity source in M dwarfs, and increasing alkali metal lines, particularly the resonance doublets of Na I (5890/5896) and K I (7665/7699). The alkali metals are the strongest opacity source in the optical spectra of L dwarfs, due to the disappearance of all the other metals (by condensation onto dust grains) in these cool atmospheres, as described above. Figure 3 shows spectra of M9, L3 and L8 dwarfs with the prominent spectral features marked (Kirkpatrick et al. 1999). Hydride bands are also present in the mid-late L dwarfs, and the K I feature has grown to be several hundred Å wide by type L8. The L dwarf spectral sequence most commonly used is defined by spectral indices (including measurements of TiO, CrH, VO, Rb I and Cs I, among others) as described in Kirkpatrick et al. (1999). Martin et al. (1999) offer an alternate definition based primarily on a color index; their sequence differs from Kirkpatrick's mainly at late L spectral types (L5-L8). Basri et al. (2000) have applied a model temperature scale to the Martin L dwarf sequence using fits to the Cs I and Rb I lines, while the Kirkpatrick scale has temperatures defined by the disappearance of features from the spectra. Additional L dwarf classification schemes in the infrared are given by Testi et al. (2001) and Reid et al. (2001).

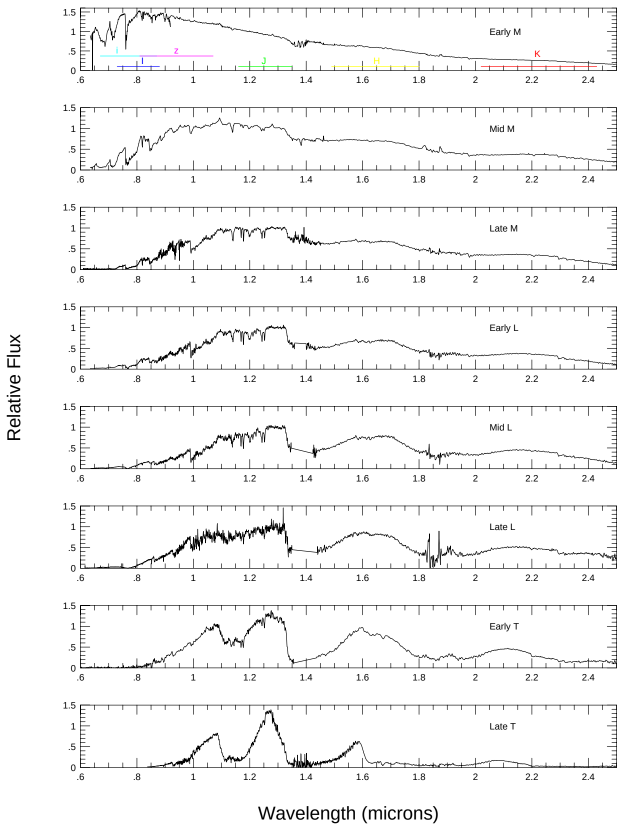

Figure 4. Spectra of M,L and T dwarfs with filter bandpasses marked.

The optical and infrared colors of M, L and T dwarfs are strongly affected by the opacity sources described above (disappearance of TiO, domination of alkali metals) as well as, in the T dwarfs, the appearance of methane. Figure 4 shows spectra ranging from early M to late T through the optical and near-infrared wavelength regions. Commonly used filter bandpasses are marked on the top panel, including the Sloan i and z filters.

It is clear that the optical colors used for characterizing M dwarfs (e.g. V-I) become worthless for dwarfs later than mid-M types, as there is virtually no flux being emitted at those wavelengths. As shown by Figure 5, J-K is problematic

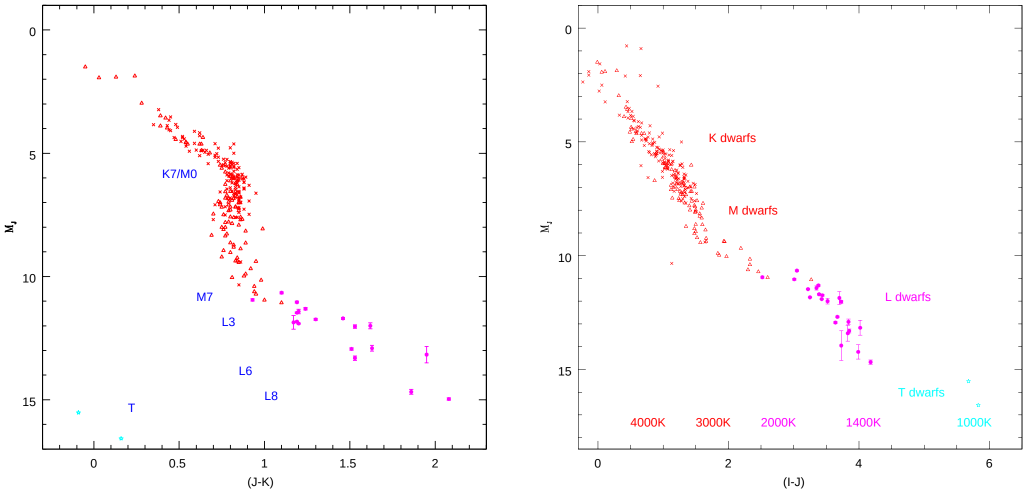

Figure 5. Calibrated M_J HR diagrams showing that the optical-infrared (I-J) color is preferred over the infrared (J-K) color for separating M, L and T dwarfs (see http://www.physics.upenn.edu/∼inr/cmd.html for these and a host of other useful color-magnitude and color-color diagrams of late type dwarfs).

for both M dwarfs (which all have J-K $\sim$ 0.8) and for T dwarfs, because of the methane absorption in the K band (which makes K as faint as J, hence J-K becomes blue!). In fact, the first isolated T dwarf was identified as being very red in the optical Sloan filters (Strauss et al. 1999). The best colors to characterize dwarfs from M through T appear to be a combination of optical and infrared colors, as shown in the M_J vs. I-J HR diagram in Figure 5 (Reid 2000). Papers by Covey; Leggett; and Stephens in this volume contain further discussion of the optical and infrared colors, while the whole subject of L/T dwarf spectral types and colors will be the topic of a splinter session at this meeting.

4. Variability

The incidence of magnetic activity in M dwarfs reaches a peak at nearly 100% near spectral type M7 (cf. the PMSU survey: Hawley, Gizis & Reid 1996; http://www.physics.upenn.edu/∼inr/pmsu.html) and declines among the later M's and early L's (Gizis et al. 2000). There are no firm detections of Hα in L dwarfs later than spectral type L4. The strength of the activity as measured by the ratio $L_{H\alpha}/L_{bol}$ also declines precipitously past spectral type M7, as shown in Figure 6 (Burgasser et al. 2002). The decline in both the frequency and strength of activity may be connected to the very cool atmospheric temperatures, and hence low ionization fraction in the atmosphere. Papers by Mohanty; Gelino (this volume) discuss this in more detail. Coronal activity (Xrays) and flares are commonly observed in late M dwarfs: some examples are the Xray flare on

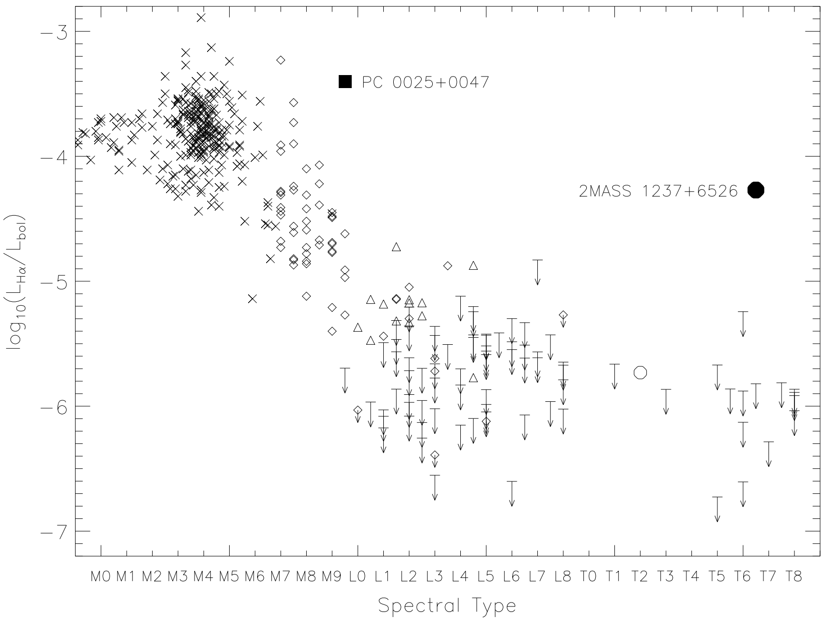

Figure 6. Activity strength as a function of spectral type (Burgasser et al. 2002). Note the decline in activity strength past spectral type M7, with the exception of two major outliers, PC0025 and 2M1237.

the M9 brown dwarf (brown dwarf status secure by virtue of lithium detection, Tinney 1998) LP 944-20 (Rutledge et al. 2001), the Hα flare on the M9.5 dwarf (no lithium) 2M0149 (Liebert et al. 1999) and numerous Xray detections of brown dwarf candidates (with M dwarf spectral types) in young clusters (e.g. Comeron, Neuhauser & Kaas 2000). Note that all of these objects have **M dwarf spectral types**. The occurrence of magnetic activity apparently depends more on the surface temperature and structure than on conditions in the core (whether or not hydrogen fusion is occurring). This is perhaps not a surprise, since we've known for many years that M dwarfs are well able to generate and sustain strong magnetic activity in their atmospheres (though we still aren't sure how the fields are produced, cf. Hawley, Reid & Gizis 2000).

What is a huge surprise is the appearance of relatively strong Hα emission in a T dwarf! Figure 7 shows the initial detection (Burgasser et al. 2000) which has since been confirmed by numerous additional observations (Burgasser et al. 2002). The emission is steady, with no indication of a flaring origin. This object, 2M1237, is shown in Figure 6 as the solid circle at spectral type $\sim$ T6, and is as remarkably active in this plot as the very odd object PC 0025+0047 (solid square). Speculation is that the emission in these objects could be due to some kind of accretion, but the case is very much open as to their true nature.

Leaving the T dwarf aside, the paucity of magnetic activity in the L dwarfs has led several groups to infer that photometric variability which is observed in these objects is not due to starspots but rather to rotational modulation by dust

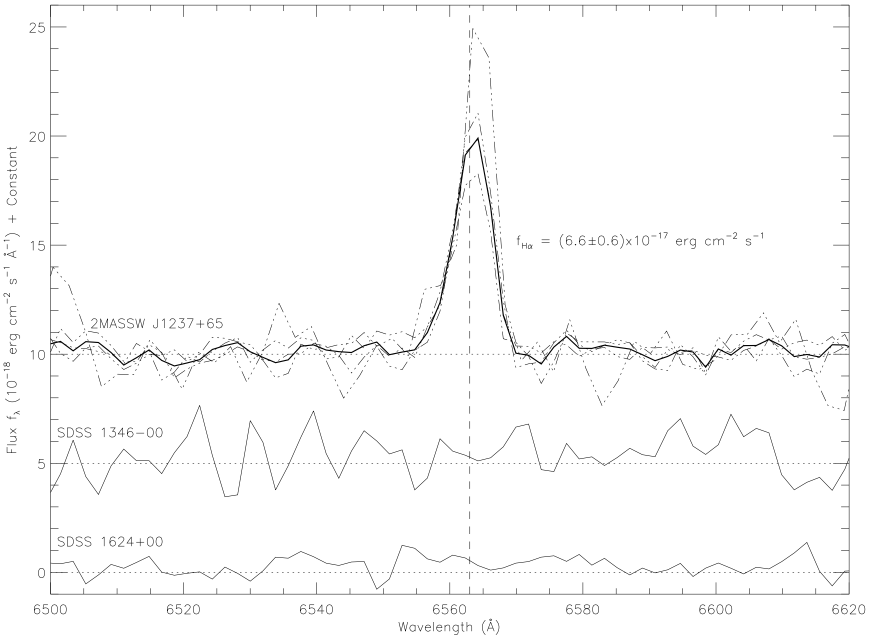

Figure 7. The observation of Hα in the T dwarf 2M1237 stunned the scientific community at the turn of the century (Burgasser et al. 2000)

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clouds – a form of "weather" (Tinney & Tolley 1999). Recent work includes that of Bailer-Jones et al. (2001) and Gelino (this volume). Both magnetic activity and clouds/weather will be discussed more extensively in a splinter session at this meeting.

5. How Many Are There?

Before discussing the mass function of brown dwarfs, I will first review what we know about the mass function of low-mass stars, since we expect that this will be a smoothly varying quantity with no *a priori* reason to care whether an object burns hydrogen or not. The field mass function for stars with $1M_\odot < M < 0.1M_\odot$ has been investigated by Reid et al. (1999) for the nearby stars using an empirical mass-luminosity relation from Henry & McCarthy (1993) and model relations from Baraffe et al. (1998) as illustrated in Figure 8 (left panel). More recently, Chabrier (2001) redetermined the mass function using a newer mass-luminosity calibration from Delfosse et al. (2000). Both groups find $\Psi(M) = dN/dM \sim M^{-\alpha}$ with $\alpha \sim 1 - 1.5$. The steeper values for α are heavily influenced by the surprisingly poor high mass constraints, as shown in Figure 8 (right panel). There is an urgent need for a redetermination of the G and K star mass function using Hipparcos data to tie down the high mass end.

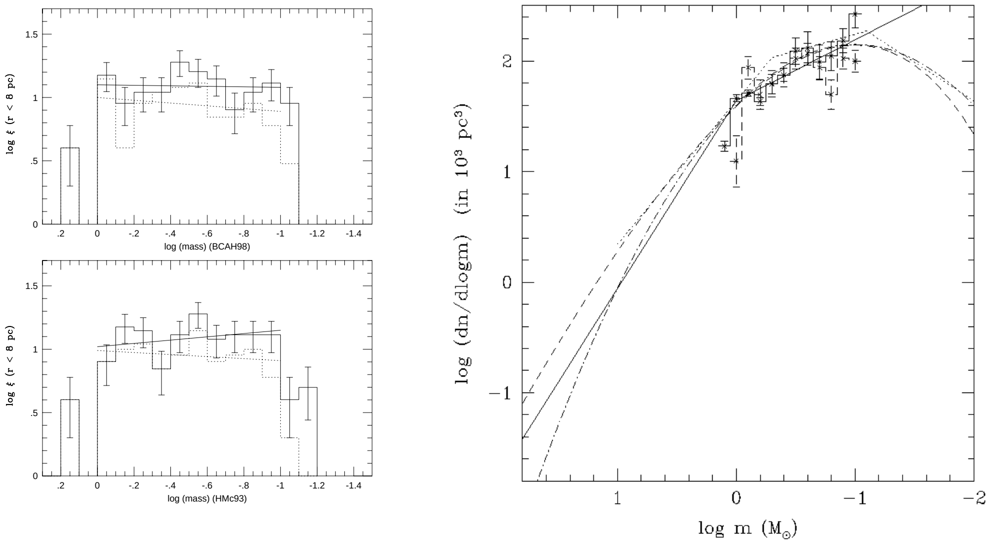

Figure 8. Field star mass function determinations from left: Reid et al. (1999), $\alpha \sim 1$; right: Chabrier (2001) $\alpha \sim 1.5$.

A preliminary determination of the field mass function for the mass decade 0.01-0.1 $M_\odot$ using 2MASS data is described in Reid et al. (1999) who find $\alpha \sim 1-2$, probably closer to 1 – a very similar result as for the low mass stars.

In young clusters, the brown dwarfs are still M dwarfs so they are much easier to see (e.g. paper by Liu, this volume). Several groups are working on IMF determinations, with most finding $\alpha \sim 0.5-1$ (Luhman et al. 2000; Bejar et al. 2001; see also paper by Bejar in this volume). Figure 9, from Bejar et al. (2001), illustrates representative IMFs for the cluster σ Ori, using models with three different ages.

If we assume for the moment that $\alpha \sim 1$, we find (to J=16; Reid et al. 1999)

L dwarfs – 1 per 20 sq deg, 2000 total

T dwarfs – 1 per 400 sq deg, 100 total

Thus, L and T dwarfs make up only a small fraction of the local mass density, not enough to account for a substantial amount of the missing mass/dark matter. To quote from a recent paper by Neill Reid: (Reid 1999)

"... the results are not inconsistent with a smooth extrapolation of the stellar mass function into the brown dwarf regime. Under those circumstances, brown dwarfs outnumber stars by almost a factor of 2 to 1, but contribute less than 10% of the stellar mass density. The median temperature of the local brown dwarf population is $\sim$ 400K, and the few L and T dwarfs discovered to date represent the tip of a very large iceberg."

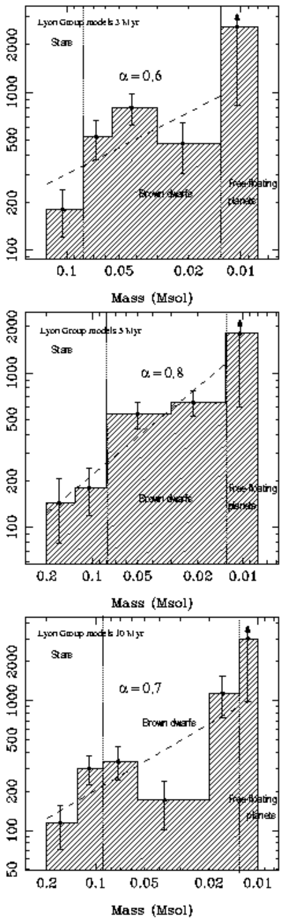

Figure 9. IMF determinations for σ Ori using models with age 3, 5 and 10 Myr (Bejar et al. 2001). All of these models give similar $\alpha \sim 0.6 - 0.8$.

6. Final Comments

I have attempted to provide an overview of the current state of brown dwarf research, but as always must end with the caveat that this is a very active field that changes quickly. The discerning reader will note that I did not discuss the formation of brown dwarfs. For one possible scenario, see the paper by Reipurth in this volume. More extensive discussion of formation in binary systems, and comparison to extrasolar planet formation, is contained in the companion review paper on extrasolar planets by Hawley & Reid (this volume).

Acknowledgments. My thanks to Neill Reid for his help in preparing this talk, and to Kevin Covey and Rachel Osten for their forbearance in producing last minute figures. I would also like to thank CASA and the University of

Colorado for hosting Cool Stars 12, which proved to be an interesting, innovative and informative meeting.

References

Allard, F. et al. 2001, ApJ, 556, 357

Allard, F. 2000, in "Very Low-mass Stars and Brown Dwarfs", ed. R. Rebolo & M.R. Zapatero-Osorio, Cambridge University Press, pg. 144

Baraffe, I. et al. 1998, A&A, 337, 403

Basri, G. et al. 2000, ApJ, 538, 363

Basri, G. 2000, Scientific American, 282, no. 4, 57

Bejar, V.J.S. et al. 2001, ApJ, 556, 830

Burgasser, A.J. et al. 2000, AJ, 120, 473

Burgasser, A.J. et al. 2002, AJ, submitted

Burgasser, A.J. et al. 2001, ApJ, 563, in press

Burrows, A., Hubbard, W.B., Lunine, J.I. 2001, Rev. Mod. Physics, in press

Burrows, A. & Sharp, C.M. 1999, ApJ, 512, 843

Burrows, A. et al. 1997, ApJ, 491, 856

Chabrier, G. 2001, ApJ, 554, 1274

Chabrier, G. & Baraffe, I. 2000, ARA&A, 38, 337

Comeron, F., Neuhauser, R., Kaas, A.A. 2000, A&A, 359, 269

Delfosse, X. et al. 2000, A&A, 364, 217

Geballe, T. et al. 2001, ApJ, 563, in press

Gizis, J.E. et al. 2000, AJ, 120, 1085

Hawley, S.L., Gizis, J.E. & Reid, I.N. 1996, AJ, 112, 2799

Hawley, S.L., Reid, I.N. & Gizis, J.E. 2000, in "Giant Planets and Cool Stars", ed. C. Griffiths & M. Marley, ASP Conf. Ser. 212, 252

Henry, T.J. & McCarthy, D.W. 1993, AJ, 106, 773

Jones, H.R.A., Longmore, A.J., Allard, F., Hauschildt, P.H. 1996, MNRAS, 280, 77

Jones, H.R.A. & Tsuji, T. 1997, ApJ, 408, 39

Kirkpatrick, J.D. et al. 1999, ApJ, 519, 802

Liebert, J. et al. 1999, ApJ, 519, 345

Luhman, K.L. et al. 2000, ApJ, 540, 1016

Martin, E.L. et al. 1999, AJ, 118, 2466

Nakajima, T. et al. 1995, Nature, 378, 463

Rebolo, R., Martin, E.L. & Magazzu, A. 1992, ApJ, 389, L83

Reid, I.N. et al. 2001, AJ, 121, 1710

Reid, I.N. 2000, in "Galactic Structure, Stars and the ISM", ed. C. Woodward, M. Bicay, J.M. Shull, ASP Conf Ser. 231, 468

Reid, I.N. 1999, in "Star Formation 99", ed. T. Nakamoto, Nobeyama Radio Observatory Reports

Reid, I.N. et al. 1999, ApJ, 521, 613
Rutledge, R.E. et al. 2000, ApJ, 538, L141
Schweitzer, A. et al. 2001, ApJ, 555, 368
Strauss, M.A. et al. 1999, ApJ, 522, L61
Testi, L. et al. 2001, ApJ, 522, L147
Tinney, C.G. & Tolley, A.J. 1999, MNRAS, 304, 119
Tinney, C.G. 1998, MNRAS, 296, L42