Part 11
Summary

https://doi.org/10.1017/S0074180900211315 Published online by Cambridge University Press

Brown Dwarfs
IAU Symposium, Vol. 211, 2003
E. L. Martín, ed.

Conference Summary

R. F. Jameson

Department of Physics and Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, England

Abstract. The subject of brown dwarfs has grown enormously since the announcement of the first brown dwarfs in 1995. Thus this conference is the largest conference ever devoted solely to brown dwarfs, with 150 delegates, 82 talks and 52 posters. This summary will struggle, therefore, to give a complete picture and, of course, it is only the impression of one individual.

1. Introduction and History

The conference started and finished on an historical note. The first talk was by Shiv Kumar, entitled 'The Bottom of the Main Sequence and Beyond'. He described how he first calculated the minimum hydrogen burning mass (MHBM) and the problems he had getting his paper, Kumar (1963), published. On the last day of the conference in a late scheduled talk, Dr. Tamura showed a paper by Hayashi and Nakano who had also calculated the MHBM and published in 1963. This latter paper was in Progress of Theoretical Physics, which perhaps explains why it escaped the attention of astronomers[1].

The title of Shiv's talk was coincidentally also the title of a conference hosted by ESO and organised by Chris Tinney in Garching in 1994. Although a very rewarding conference, it could have been summarised by '*there is nothing beyond*'. That is, no confirmed brown dwarfs were known. 1995 changed all that, with the discovery of the brown dwarfs Teide 1 (Rebolo, Zapatero-Osorio and Martín 1995) and GL 229B (Nakajima et al. 1995) and the first extrasolar planet around 51 Peg by Mayor and Queloz (1995). Since 1994, in just eight years, progress has been explosive. There are now so many brown dwarfs that no-one keeps a tally and about 90 extrasolar planets are known. Not surprisingly, the number of researchers working on brown dwarfs has also grown. Thus this is the largest every conference devoted solely to brown dwarfs with 150 delegates, 82 talks and 52 posters.

2. Forming Brown Dwarfs. Theory and Observation

Brown dwarfs (BDs) can be thought of as failed stars, i.e. by definition they form by the same process that forms stars. In contrast, massive planets should form as

[1] Editor's note: see the historical paper by Nakano in this volume

planets do, and are believed to form by the aggregation of dust particles to form planetesimals that in turn clump together to form 'solid' bodies, approximately Earth size, that may then, if there is sufficient gas around, go on to accrete this gas to form Jupiter mass, or even greater mass, planets. So what does current theory predict ?

Guenther Wuchterl outlined his ideas on brown dwarf properties at very early ages. Bo Reipurth predicts that BD/BD binaries should not be widely separated. Matthew Bate predicted that there should be very few BD/BD binaries, about 5% of all BD systems. Alan Boss believes including magnetic fields in the star formation process aids the formation of very low mass bodies. Finally, Phil Armitage explained how the 'BD desert' (the known shortage of BDs close to approximately solar mass stars), could be explained by disc/BD interaction. This either pushes the BD inwards to merge with the star or outwards to about 100 AU.

On the observational side there were many talks on searching for BDs in star forming regions and very young clusters, i.e. in Orion, Rho Ophiuchi, R Coronae, Australis, Chaemeleon, Lupus, Serpens and Taurus. Mark McCaughrean reminded us that it is not sufficient just to find very cool objects in these regions, but that we must also find evidence for cluster membership and youth, i.e. Hα emission or evidence of discs. The two most promising clusters are the Trapezium in Orion, discussed by both Mark McCaughrean and Philip Lucas, and Sigma Orionis, discussed by Maria Rosa Zapatero Osorio. All these speakers claimed to have found BDs with masses down to $5\,M_J$. IC 348, described by Kevin Luhman, is also a promising cluster with which to study very young (~ 2 Myr) brown dwarfs.

Charles Lada, Leonardo Testi and Michael Liu gave talks on the ways to recognise T-Tauri type discs around very young BDs, by looking for infra-red excesses in the L band, or even longer wavelengths, e.g.,. with ISOCAM. It is worth remembering that if BDs have discs they must also have additional luminosity due to accretion. Therefore using standard models without accretion will make a cluster appear younger than it really is, and this in turn will lead to under estimating the BD masses.

3. Open Cluster Brown Dwarfs

In the early days, open clusters, particularly the Pleiades, were leading places to search for BDs. Open clusters are still very important test beds for BD theory, since they have well-measured distances and ages and are not troubled by serious reddening due to interstellar dust. Also the cluster mass function should not be greatly changed from the IMF by dynamical losses if the age is below 100 Myr.

David Barrado y Navascués discussed his data on IC 2391 and found a *Li* age of 53 Myr and a mass function index alpha = 0.96. Similarly John Stauffer finds a *Li* age of 90 Myr and alpha = 0.74 for the Alpha Perseus cluster. However, he pointed out that the star Alpha Perseus itself is an F supergiant whose age is thought to be 50 Myr. Jerome Bouvier reviewed the mass functions of the Pleiades, Blanco 1, NGC 2516 and M35 and concluded all had an index of alpha = 0.51 $\pm$ 0.1.

Richard Jameson pointed out that many clusters, probably all clusters, had a luminosity function dip at spectral types M7/8. This implies a steepening of the luminosity mass relation slope which is not apparent in current theoretical models and hence that theoretical BD masses will be somewhat over estimated.

4. Field Brown Dwarfs

Three field surveys, DENIS, 2MASS and SDSS have vastly increased the numbers of known brown dwarfs over the last few years. Of course, the age of low luminosity cool field objects is very uncertain, it being only possible to estimate ages from kinematics. Thus these dwarfs are described by their spectral type M, L or T dwarfs. T dwarfs, $T_e < 1300\,K$, show evidence for methane absorption and it is generally agreed must all be BDs. L dwarfs, $1300\,K < T_e < 2300\,K$, may be either low luminosity stars or BDs, but are probably BDs for spectral type later than $\sim$ L5. Only very young M dwarfs, probably very rare in the field, will be BDs.

Thierry Forveille gave the results of the Deep Near Infrared Survey (DENIS) which is essentially complete, having covered much of the southern sky. It has found some 300 M8 to late L dwarfs. The 2 Micron All Sky Survey (2MASS) is also complete and results for the entire sky will be published in the summer (2002). Davy Kirkpatrick described the On-line Archive Science Information Service (OASIS) that will correlate the 2MASS dwarf photometry, positions, finder charts and spectra. This will be a huge benefit to the BD community. Kevin Covey described the Sloan Digital Sky Survey (SDSS) that is still in progress. SDSS is responsible for most of the T dwarf discoveries since T dwarfs have blue near infrared colours and are thus not readily distinguished from hot stars by J, H, K photometry alone. The SDSS is not complete, of course, and publication is on-going.

Jim Liebert reported on a sample of 2MASS M and L dwarfs. Their kinematics were similar to the early middle dMe dwarfs and showed strong Hα emission. This suggests they are younger than 2-3 Gyr.

Gilles Chabrier reviewed the mass function of the field stars and BDs, which are model dependent, of course, since their exact ages are not known. He also considered the mass functions of young clusters and globular clusters. He claimed all these mass functions could be fitted with a log normal distribution. Guido De Marchi also came to the same conclusion for globular clusters.

5. Companion Brown Dwarfs

This session was, by number of papers, the largest session of the conference, with some 16 oral presentations and many posters. It was devoted to searches for both BD companions to stars and BD/BD binaries. Many of the papers used adaptive optics and coronagraphs to aid the search for companions. There were too many papers to review individually so I will only try to convey a broad summary.

Didier Queloz reviewed the radial velocity searches for planets and brown dwarfs around solar type stars. He concluded the BD desert (lack of BDs as close companions to solar type stars) is still very dry. However, a number of other speakers have found BDs as visual binaries (i.e. widely separated) to both solar type and cooler stars. Thus the 'BD desert' seems to be confined only to very close stellar/BD binaries.

My two personal favourite multiple systems from among the sixteen papers were HD 130948 described by Dan Potter and GL 577 described by Patrick Lowrance. HD 130948 is taken from a sample of young ($< 1\,Gyr$) solar analogue stars and is found to have two L2 dwarf companions which are close to one another but well separated from the primary. Age considerations suggest these L dwarfs will be BDs with masses $< 75\,\mathrm{M_J}$. Since they form a 'visual binary' it should eventually be possible to measure their masses from first principles. GL 577 is a young active G star with, again, two BDs forming a very close visual binary separated from the primary by 5.7 arcsec. So again, eventually, the masses of the BDs should be directly measurable. Unfortunately, although both these systems are young there is no obvious way of getting an accurate measurement of their age.

What is really needed to check theoretical BD models is some star/BD or BD/BD binaries in a cluster of known age, so that the masses of BD of known age can be directly determined from Kepler's laws. Since clusters are rather distant, this is most likely to be achieved by finding something like PPL 15 in the Pleiades, but in an eclipsing binary system.

6. Atmospheres, Weather and Magnetic Activity

We know that dust, or dust clouds, are vital ingredients in the atmospheres of the L dwarfs. We believe also that in the T dwarfs the dust has sunk below the photosphere, thus also removing from the upper atmosphere those heavy elements that form dust such as Fe, Si, Ca, Mg, etc. From a theoretical point of view, the L to T transition is thus also the transition from DUSTY model atmospheres to CONDENSED model atmospheres (i.e. atmospheres free of dust and free of heavy elements). Takashi Tsuji explained this and showed that dust will exist in a narrow temperature range $\mathrm{T_{crit}} < \mathrm{T} < \mathrm{T_{cond}}$ where $\mathrm{T_{cond}}$ is the temperature at which dust starts to condense and $\mathrm{T_{crit}}$ is the temperature at which the grains become large and start to fall.

Sandy Leggett has calculated bolometric luminosities for those M, L and T dwarfs that have parallaxes and I, Z, J, H, K, L and M photometry. Most of these dwarfs are expected to be old and thus all have the same radius ($\sim 0.1\mathrm{R_\odot}$). Using this radius she can then calculate effective temperatures. A plot of $\mathrm{T_e}$ against spectral type shows that $\mathrm{T_e}$ only changes slightly from L8 to T2, reinforcing the above idea that spectral type of the L, T boundary is dependent on dust rather than temperature. Sandy also found that detailed observations of GL 299A compared with the Baraffe models give GL 299A an age of 30 Myr. If this is correct, then GL 299B is a planet which becomes the first directly observed extrasolar planet. Chris Tinney reported new parallaxes for T dwarfs and Hugh Harris for some 17 L dwarfs and 3 T dwarfs.

France Allard described theoretical model atmospheres that include grain condensation (increasing the grain size), coalesence (two or more grains merging) and sedimentation (grains falling or raining down through the atmosphere). The models also include, of course, convection which can push grains higher in the

https://doi.org/10.1017/S0074180900211315 Published online by Cambridge University Press

atmosphere. These models appear to be a promising start, but as yet imperfect, in modelling the dramatic colour changes that occur across the L-T boundary.

France Allard's models might be described as atmospheres with a grain fog, i.e. grains distributed evenly in any horizontal plane and a density changing with height. Mark Marley described atmosphere models that not only included the progressive sinking of grains but also horizontal break-up into discrete clouds with, of course, gaps between the clouds. He showed this is rather successful in modelling the L, T transition. In particular, it explains the brightening in the J band and the resurgence of FeH absorption found in the early T dwarfs. He drew the analogy with the Jovian $5\,\mu$m hot spots.

Jupiter's spectrum shows a dramatic spike at about $5\,\mu$m. This is known to be caused by very small gaps in the clouds which release radiation from much hotter regions below the clouds. The effect is most prominent at $5\,\mu$m since there is a window in the gaseous absorption of methane and ammonia. The idea of discrete clouds effectively leads to 'weather' in BD atmospheres. No doubt eventually we will have to try and model the cloud distribution, again one can think of Jupiter to picture what may be needed.

Didier Saumon discussed the effects of non equilibrium chemistry. It is known that GL 229B has stronger CO lines than would be expected for its effective temperature. CO is made/destroyed by the following reaction:

$$3\,H_2 + CO \underset{fast}{\overset{slow}{\rightleftharpoons}} CH_4 + H_2O.$$

Thus CH_4 falling due to convection and thus getting hotter converts rapidly to CO. But CO rising and getting cooler converts rather slowly to CH_4. Thus CO is expected to be 'over abundant'. In even cooler BDs we can eventually expect to see NH_3 'under abundant' for similar reasons, since

$$N_2 + 3\,H_2 \underset{fast}{\overset{slow}{\rightleftharpoons}} 2\,NH_3.$$

Of course, discrete clouds (weather) may be distributed asymmetrically around the BD spin axis. Thus one may 'hope to see' the weather to some extent by searching for BD dwarf variability. Etienne Artigau and several poster papers presented results of BD variability. Amplitudes of variations up to 0.1 mag and possibly as much as 0.2 mag have been observed.

Variations can also be caused by magnetic activity and its associated flares, Hα and radio emission. Gibor Basri reviewed this subject and concluded that, in general, this kind of activity drops steadily with increasing spectral type, probably because the amount of ionised material is reducing rapidly. However, very cool BDs can have rapid rotation and flaring in Hα, X-rays and radio does not disappear completely. New X-ray observations were discussed by Beate Stelzer and Scott Wolk, who both found a few X-ray bright BDs in the youngest clusters.

7. Spectral Classification

Denise Stephens pointed out that the present L dwarf classification is rather unsatisfactory. For a given spectral type, particularly around mid L, the J-K colour can vary by up to 1 mag. She suggests that, ultimately, we will need to have two classifications, one representing T_e and one representing the cloud classification, i.e. rather analogous to the temperature and luminosity (dwarfs to giants) classes currently used for stellar spectra.

Tom Geballe and Adam Burgasser both discussed the spectral classification of T dwarfs. It was very pleasing to hear that they are both, together with several others, sharing their ideas and have agreed a list of about 10 T dwarf spectral standards. It is, of course, highly desirable that whatever classification scheme is finally devised, it is accepted as a universal standard. Both the M and L dwarfs have had competing classification schemes which can cause muddle and confusion in the literature. Also, hopefully, T dwarf classification should prove simpler than the L dwarfs since the clouds are below the photosphere.

Finally, although no-one has yet discovered a dwarf that clearly belongs beyond the T class, we can talk about such objects. The suggested name for the next class beyond T is Y.

8. Evolutionary Models

Isabelle Baraffe described the progress with the Lyon group models. The models are continuously improving with better TiO and H_20 line lists but, of course, we also need yet to fully understand the atmospheric dust behaviour since the atmosphere is the outer boundary condition of any model. She also emphasised that the models are uncertain for ages below 10 Myr and very uncertain below 1 Myr. This is because the initial conditions and early accretion from discs are themselves very uncertain. Adam Burrows described various phenomena that are important to evolutionary models, e.g. rain out or the precipitation of heavy elements. He emphasised the importance of the huge wings of Na and K to the 'optical' spectra of dwarfs and, of course, when these two elements rain out the spectrum will be greatly altered. He also described how extra solar planets that are close to their parent stars, i.e. the ones most likely to show transits, are swollen. This swelling being due to a slowing down of their heat loss rather than direct heating by their parent star.

9. The Future

As is customary, the final session of the conference was devoted to future prospects, in particular those instruments and surveys most likely to drive the subject forward. Eric Becklin described SOFIA, a 2.5 m telescope on a Boeing 747 that will make accessible spectral regions impossible from the ground. The region most suitable to brown dwarfs being $5 - 8\,\mu$m and possibly longer than $15\,\mu m$. The first science flights begin in 2004. Didier Queloz described HARPS, a spectrograph that will achieve a precision better than 1 m/sec and thus should be able to find extrasolar planets down to about 0.1 M_J. Nigel Hambly now wishes to be known as Aaron A. Ardvark so that his name will be first on the many multi-author papers from UKIDSS. The UKIRT Infrared Deep Sky Survey will go about 4 magnitudes deeper than 2MASS and DENIS, reaching J = 20, H = 19.2 and K = 18.4. At these sensitivities it will do a large area of some 4000 sq. deg. (within the area covered by SDSS), target a number of galactic clusters and survey parts of the galactic plane. All these sub-surveys should make a major contribution to brown dwarf research, finding hopefully, for example, some Y dwarfs. Proper motions will also eventually be measured, which might lead to the discovery of Pop II BDs. It will also survey about 100 square degrees to greater depth and 1 square degrees to K = 23. These latter two surveys being targetted mainly towards galaxies and cosmology. UKIDSS is scheduled to start in late 2003. The CFHT also plan a deep IR survey with MEGACAM, starting in March 2003, over smaller areas to a depth of J = 22.8, H = 21.7 and K = 21.5. Deborah Padgett outlined the potential of SIRTF (The Space IR Telescope Facility) for finding brown dwarfs. SIRTF is an 85 cm telescope, cooled to 4 K with wavelength coverage from $3.6 - 160\,\mu$m, due for launch in late 2002. It will carry out 2 surveys, 20 square degrees on nearby star forming regions, which should find many young brown dwarfs. Also a 70 square degree survey at high galactic latitudes which has a good chance of finding dwarfs with $T_e < 600$ K (the Y dwarfs). Davy Kirkpatrick is seeking funding for the Next Generation Sky Survey. This MIDEX mission is to map the entire sky from $3.7 - 23\,\mu$m with a cooled 50 cm telescope. This should also find Y dwarfs and has the great advantage over SIRTF of doing the entire sky.

Coming back to ground-based instruments, many adaptive optics systems and interferometers are underway or planned. These have great potential for finding many more companion brown dwarfs. Gael Chauvin and Masa Hayashi described the AO systems on the VLT and Subaru respectively, both have potential resolutions of about 0.06 arcsec. Christopher Ftaclas described a Near IR Coronagraphic Imager NICI for Gemini South and Ben Oppenheimer (poster) another even higher order AO Coronagraph for the US Air force telescope on Haleakala. Damien Ségransan described the VLT Interferometer, which is almost operating, and Vincent Coudé du Foresto 'OHANA', an even larger system planned for the Mauna Kea telescopes. These can both, in principle, measure the diameters of dwarf stars and, of course, find companions. Finally, Hans Bernstein looked forward to the discovery of astrometric binaries by DIVA and GAIA. It is very exciting to see that the technology is moving ahead so rapidly. The discovery of the next class of brown dwarfs, the Y dwarfs, should be with us in one or two years and in the related field of extrasolar planets it cannot be long before we directly detect the first extrasolar planet.

10. Conclusions and Acknowledgements

As I said at the beginning of this summary, it is very exciting how the subject of brown dwarfs has grown from almost nothing to its present state in just eight years. This explosive growth looks set to continue, driven by the increased number of researchers in the field and the ever improving technology. This conference will undoubtedly contribute further to this growth by bringing researchers together, which in itself generates fresh ideas. We are therefore very grateful to the Institute for Astronomy of the University of Hawaii, the Subaru telescope, the

https://doi.org/10.1017/S0074180900211315 Published online by Cambridge University Press

Joint Astronomy Center, NASA IRTF, the Canada-France-Hawaii telescope corporation, the Hawai'i Island Economic Development Board, the Hawai'i tourism authority, and the International Astronomical Union for hosting this conference in such a beautiful setting. We are also indebted to both the Local Organising Committee and the Scientific Organising Committee for putting together an excellent programme of both science and entertainments, sporting, cultural and gastronomic. We would particularly like to thank Sandrine Bottinelli, Jana Pittichova and Karen Teramura for much of the "behind the scenes" organisation, for example the volley ball competition and the photo sessions, and Josh Hoblit for a brilliant job of assisting the presentations, particularly with the power point system, which ran extremely smoothly. Finally, and most importantly, our thanks must go to Eduardo Martín, the principal organiser of this excellent conference.

References

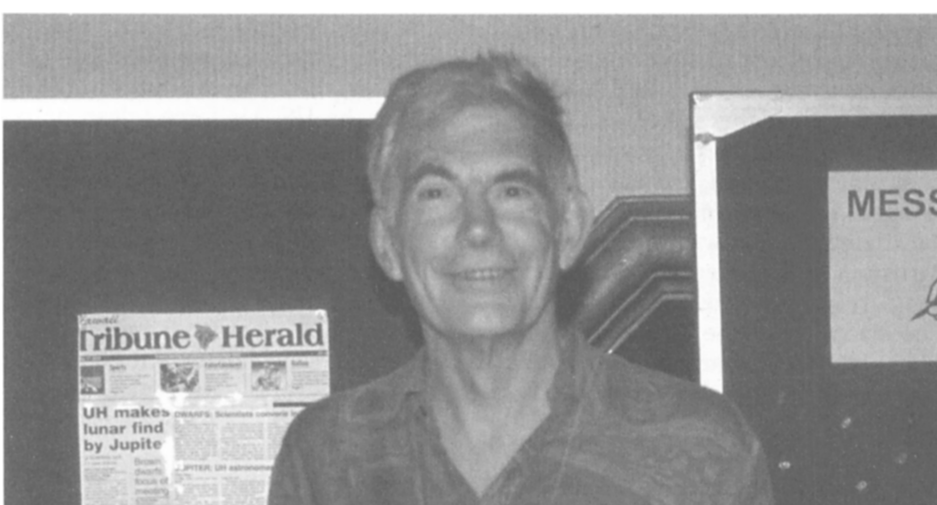
Hayashi, C., & Nakano, T. 1963, Prog. Theor. Phys, 30, 460

Kumar, S. 1963, ApJ, 187, 1123

Mayor, M., & Queloz, D. A. 1995, Nature, 378, 355

Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golomowski, D. A., Matthews, K., & Durrance, S. T. 1995, Nature, 378, 463

Rebolo, R., Zapatero Osorio, M. R., & Martín, E. L. 1995, Nature, 377, 129



Richard Jameson

https://doi.org/10.1017/S0074180900211315 Published online by Cambridge University Press