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Conference summary

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Abstract. "Brown dwarfs come of age" was a stimulating conference attended by a large number of very active researchers, including many young students and post-docs who were largely responsible for the lively atmosphere that we enjoyed during the full meeting. Major theoretical and observational challenges currently faced in the study of brown dwarfs were reviewed. Key spectroscopic work is being conducted to determine atmospheric temperatures, surface gravities and metallicities, essential to understand the evolution of substellar objects. Research on ultracool atmospheres is extended down to temperatures typical of the atmosphere of the Earth. Characterisation of brown dwarfs at all wavelengths from X-ray to radio is ongoing and investigation of time domain phenomena reveal interesting new processes in cool atmospheres. In addition to talks on these topics, a large number of presentations addressed the formation and evolution of brown dwarfs, the lower end of the Initial Mass Function, the properties of substellar binaries, the angular momentum and disk evolution in very low-mass systems, results of large scale surveys aimed to find the lowest luminosity and coolest brown dwarfs, searches in star clusters delineating the evolution with age of the properties of brown dwarfs, binary searches and subsequent follow-up work enabling dynamical mass determinations. The excellent level of the review talks, oral and poster presentations and the work of the enthusiastic researchers that attended the meeting ensure a brilliant future for substellar research 18 years after the discovery of the first brown dwarfs.

1. Introduction

As a result of searches in star clusters and nearby stars, the first directly imaged brown dwarfs were reported in 1995. After years of very active research, the knowledge about these – once elusive – objects has increased dramatically as made evident by the contributions presented during this meeting. Observational efforts have led to detection of hundreds of brown dwarfs in star clusters and in the field, providing a very valuable collection of objects spanning a range of ages, temperatures and luminosities. Fundamental spectroscopic follow-up work helped to constrain evolutionary models and achieve a better understanding of the evolution of these objects. Major theoretical efforts during these years also contributed to explore many aspects of the physics of brown dwarfs from the interiors to the atmospheres. The large number of substellar topics, both theoretical and observational, addressed during this conference, showed the maturity of the field. I summarise below, in a rather incomplete way, those topics which I personally found more interesting.

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2. Formation and evolution of brown dwarfs

Brown dwarfs can form in relative isolation, in binaries and also in multiple systems. In star forming regions, the properties of very low mass stars extend smoothly into the brown dwarf regime, suggesting that the same formation mechanism could be responsible for the smallest stars and for the most massive brown dwarfs. On the other hand, the frequency of low mass brown dwarfs ($\sim 15\,M_{\rm Jup}$) orbiting stars and the frequency of massive giant planets (few times the mass of Jupiter) are also found very similar and suggests that the same formation mechanism may be responsible for objects above and below the deuterium burning mass limit. Current data do not provide evidence for a frontier in nature between low mass brown dwarfs and massive giant planets.

The mass distribution of free-floating planetary-mass objects in the range 5-15 $M_{\rm Jup}$ has been explored in several star forming regions, and there is not yet evidence for the theoretically expected cut-off in the mass function associated to the fragmentation of clouds. If it exists, it will occur at a mass below 5 $M_{\rm Jup}$. The existence of a population of objects with such low mass in the solar neighbourhood is starting to be explored thanks to the detection by WISE of nearby extremely cool dwarfs, the Y dwarfs. The first results of WISE suggest a smooth behaviour of the mass function and possibly a single mechanism for the production of free-floating objects at both sides of the deuterium burning limit. As stated by F. Palla, the underlaying mechanism of brown dwarf formation remains to be confirmed, in particular the role of dynamical interactions and disk fragmentation has to be better understood, as well as turbulence and its interplay with gravity.

We expect that brown dwarfs can form as a scale down process for stars but also via disk gravitational fragmentation processes as giant planets may do. There are hybrid scenarios (as discussed by Vorobyov and Zakhozhay) where ejection of fragments from protostellar disks followed by cooling and contraction to stellar densities result feasible. The ejected low-velocity fragments would be surrounded by an envelope or mini-disk. ALMA may offer empirical evidence on this and other potential mechanisms. L. Ricci reported that brown dwarfs have disks when they form (see the 0.89 and 3.2 mm ALMA images of 2M0444+2512) and V. Joergens showed results on cold dust and disk properties for a statistically significant sample of young brown dwarfs using Herschel/PACS. There is evidence for substantial disks with material to form from Earth mass to Neptune mass planets. The investigated systems also display active accretion with rates in the range 10^{-9} - $10^{-12}\,M_\odot\,{\rm yr}^{-1}$. Interestingly, accretion and outflows have been reported since 2005 for at least 10 brown dwarfs. As discussed by R. García López and B. Riaz in the meeting, in spite of the amazing progress in the study of forbidden emission lines and spectral-astrometry, the mass outflow to mass accretion rates (with values in the range 0.05 - 0.5) are still rather uncertain to establish a clear pattern with mass and set constrains on formation models. Angular momentum and disk evolution are also particularly relevant in the early stages of brown dwarf formation. Evidence for disk braking in brown dwarfs was reported while no observational support is found for wind braking (A. Scholz).

3. Mass function

The mass function ($dN/dM = kM^{-\alpha}$) is one of the most powerful tools to discriminate among formation models. As shown by C. Alves de Oliveira, at low masses there is a discrepancy between the field mass function ($\alpha \leq 0$) and the mass function determined in star clusters ($\alpha \sim 0.6$). For low-mass stars the agreement between the mass functions determined in star clusters (σ Orionis, Upper Scorpius, NGC 6611, Pleiades, etc.) and in the general field is good, however for low-mass brown dwarfs (i.e. below $\sim 20\,M_{\rm Jup}$) there is an apparent lack of objects in the field with respect to young clusters. This is likely due to the difficult identification of the old field counterparts of the young low-mass brown dwarfs seen in clusters. These old counterparts become very faint and extremely cool with atmospheric temperatures that may reach 300 K and below. In spite of major efforts to find the coolest brown dwarfs, the Y dwarfs in the solar neighbourhood, their census remain quite incomplete. Note that the recent discovery of the nearby brown dwarf Luhman 16 also points out the incompleteness of the census of the nearest L and T dwarfs. If the brown dwarf mass function from clusters applies to the solar neighbourhood, deeper near and mid-IR large scale-surveys have the potential to reveal a large population of nearby extremely cool brown dwarfs.

4. Binaries and multiple systems

Identification and characterisation of binaries at various ages is of extraordinary importance as recognized by the large number of contributions on this subject: M. Bonnefoy, A. Burgasser, S. Casewell, S. Catalan, P. Delorme, C. Ginski, J. González-Hernández, C. del Burgo, Q. Konopacky, N. Lodieu (and more than 20 poster presentations on binaries and multiple systems in this meeting) reported the latest results in this field. The recent (surprising) discovery of Luhman 16, the nearest known brown dwarf, and its binary nature (it consists of a a late L and an early T-type brown dwarfs) has attracted large interest and generated a lot of follow-up work, as reported by A. Burgasser in the conference. A full dynamical characterization of the system is underway. It will be very interesting to know the strength of the lithium resonance line in both components and how it relates to the individual masses and effective temperatures.

In general, the orbital follow-up of substellar companions provide accurate dynamical masses which are essential for the study and characterisation of brown dwarfs. Amazing results were presented in the meeting, the advent of laser guide stars and sophisticated adaptive optics instruments in very large diameter telescopes have led to detection of many subarcsecond substellar binaries and substellar companions at such small physical separations, which make possible the determination of orbital motion and after a few years a complete dynamical characterisation. As a consequence, there are a number of brown dwarfs for which very accurate mass determinations are available and many more where the data flow is continuing and masses will be determined in a near future. These observations are mainly obtained for field binaries, and therefore the ages are not well known, except for some very interesting cases where space motions may relate the binary to other components of stellar associations. In the coming years, these studies will be extended to the nearest star clusters.

The measurement of orbital parameters, binary frequency, semi-major axes, component mass ratios and other dynamical parameters of binary systems provide very valuable insight on numerical simulations that predict the distribution of these parameters and set valuable constraints on the mechanisms of formation of brown dwarfs. The number of brown dwarfs relative to stars or the possible deficit of close-orbit brown dwarf companions hint on the relative weight of disk fragmentation versus direct gravitational collapse. As Vorobyov and Basu conclude, disk fragmentation can explain formation of brown dwarfs in a wide range of masses and separations around sufficiently massive stars ($> 0.7\,M_{\odot}$), but the many known brown dwarfs around very low mass stars appear to require a different mechanism based on core fragmentation or gravitational capture.

5. Surveys

As reviewed by B. Burningham, an impressive amount of survey work conducted in these 18 years with a large number of telescopes (DENIS; 2MASS, SDSS, UKIDSS, CFHT, WISE, VISTA) has led to significant samples of L-dwarfs (more than 1000), T dwarfs (more than 500) and more recently led to the discovery of the first Y dwarfs (about 15 so far). Finding brown dwarfs of various masses, ages and metallicities is still a major activity driven by the need to understand how the properties of brown dwarfs change as a function of these fundamental parameters. The number of brown dwarfs has increased drastically along the last decade, however we are still far to establish empirically the dependence of luminosity and effective temperature with mass, age and metallicity. These empirical relations are key to constrain evolutionary models and ultimately achieve a much better understanding of the physics of substellar objects. The upcoming surveys promise many more substellar objects, the various surveys being currently conducted by VISTA (VHS, VIKING, etc.) will likely identify several thousand additional L and T dwarfs. The Dark Energy Survey (DES), PanStarrs in the near future, and LSST later in this decade may rise the number of brown dwarfs by a factor at least 100! This major surveys will allow us to fully explore the mass-age degeneracy in the substellar domain.

Results from many ongoing small scale surveys were reported during the meeting as oral or poster contributions covering a very wide range of objects from metal poor halo subdwarfs (e.g. Smith, Espinoza), to companions of field white dwarfs (Day-Jones), new members of star clusters like for example the Hyades (Goldman) or σ Orionis (Zapatero Osorio), low-gravity young field brown dwarfs (Faherty, Gagné) and extremely cool brown dwarfs (Dupuy, Gomes). In the limited space of this summary, it is not possible to describe the many contributions in this area. The proceedings give justice to the long list of results presented at the meeting.

6. Spectroscopy

Finding new objects in photometric surveys is an important first step which usually produces a large number of candidates. Follow-up spectroscopy (effective temperature, gravity) and astrometry (parallax determination, proper motions) provide key information to disentangle the nature and evolutionary stage of any substellar object. This follow-up work is particularly relevant for isolated objects in the field for which little additional information may be available. The role of spectroscopy for our understanding of brown dwarfs was addressed in the talks by V. Béjar, K. Allers and M. R. Zapatero Osorio, who provided a comprehensive overview of the state of the art. Significant progress was reported on the characterisation of low-gravity very low mass brown dwarfs and planetary mass objects in young star clusters. The distance and faint magnitudes of these objects limit systematic spectroscopic work in clusters mainly to spectral types earlier than T-type, but the information so far obtained is very helpful to understand the large amount of high quality spectroscopic data for field objects. It is now clear the existence of a large population of young L-type dwarfs in the catalogues. This is the result of the higher luminosity of these objects at early stages of evolution and the obvious limitations and biases of the surveys. Similarly, young field T-dwarfs are being characterised in the field, unfortunately their counterparts in clusters are much more difficult to observe given their intrinsic faintness. One caveat, may objects of the same age have different spectral signatures of youth? Hopefully not, but atmospheric conditions (for instance dust concentration) may change in short time scales and it is worth to explore the variability of spectroscopic indicators with respect those changes.

The lines of alkalis are among the most studied spectroscopic indicators, as extremely broad Na and K absorption lines dominate the optical spectrum of cool dwarf atmospheres (see Pavlenko). Li is particularly relevant to constrain the maximum temperatures reached in the interiors of these fully convective objects. The presence of Li in very cool objects is an indication of substellarity which combined with effective temperature and luminosity provide constraints on age. A large fraction of L-dwarfs show the Li resonance doublet at 670.8 nm in their spectra. Early type T-dwarfs are expected to show this line although no detections are reported yet due to the strongly depressed continuum and the difficult observation of the resonance line. The nearest early T-dwarf (Luhman 16B) offers a good opportunity to explore the formation of the Li line in such cool objects. Rb and Cs are also easily detected in L and T-dwarfs, offering further insight on the chemical equilibrium of the atmospheres. As we move to cooler temperatures we may expect that hydrides will progressively capture the free alkali atoms and the atomic lines become increasingly difficult to be detected. This progressive depletion of free atoms into molecules will be traced by future spectroscopic observations.

Spectroscopy of the Y-dwarfs, objects with atmospheric temperatures around 400 K and below, of course attracted large interest in the meeting. Near IR spectra are available for several of these objects and have set the basis for spectral classification and differentiation with the very late T-dwarfs. Spectroscopy in the optical very far red is available for only a few objects and at a very modest signal to noise, given the very faint magnitudes in the z-band. Obtaining near IR spectra for objects of $J > 21$ is feasible as shown in the meeting, but a very demanding task even at the largest diameter telescopes. Significant progress in the spectroscopic characterisation of the Y-dwarfs will require the new generation of extremely large telescopes which may start operation at the end of this decade. In the meantime, searches for very nearby Y-dwarfs keep very active and may hopefully provide some brighter examples which will become key reference objects to understand extremely cool atmospheres.

7. Atmospheres

The talks by F. Allard, Y. Pavlenko, B. Freytag, C. Morley showed the amazing progress in the understanding of brown dwarf atmospheres that has been achieved during these years. Models have evolved from the analytical approach of the transfer equation to line-by-line opacity sampling and now include 3D radiative transfer treatments. A major challenge is to incorporate cloud formation and describe properly the distribution of condensates with depth in the atmosphere for a large range of atmospheric parameters. As shown by Allard, the BT-Settl models describe reasonably well brown dwarfs of all types, except possibly the M-L transition and the unified cloud models of Tsuji, published a decade ago, continue to satisfy many observational constraints. The physics of dust clouds and the interplay between convection, overshoot, gravity waves, rotation convective motions and cloud properties is far of being understood but current efforts to explore the micro and macrophysics of dust will certainly lead to more accurate descriptions of brown dwarf atmospheres in the near future.

As cooler objects are discovered, and atmospheric temperatures approach the surface temperature of the Earth, water clouds become more and more important in modelling the atmospheres, as shown by C. Morley. The implications of time domain activity and weather in cool atmospheres result more intuitive to us, just have a look at our skies. To gain further insight on the properties of clouds it is important to conduct monitoring campaigns in the optical and infrared and explore time variability in a wide range of atmospheres (P. A. Wilson, J. Radigan) including polarization measurements (P. Miles). In addition to cloud activity, magnetic activity (magnetic reconnection events and flares) may take place in brown dwarf atmospheres (J. Gizis). Rotation/Activity, magnetism, radio emission and ionization mechanisms were discussed by P. Williams, O. Kuzmychov and C. Stark, who sent the clear message that a lot remain to be learnt on these topics.

8. Final remarks

In addition to the standard contributions in the form of oral presentations and posters, during the meeting we had a special very successful round of one-minute poster presentations organised by A. Burgasser. This worked amazingly well, and the synthetic effort associated to these presentations was highly appreciated by the audience, who had in this way a much closer approach to the scientific content of the poster sessions. D. Pinfield also organised an interesting round-table on the Planet/Brown dwarf connection. This addressed, among other topics, a particularly difficult one, the frontier between brown dwarfs and planets. I think no obvious conclusion could be reached beyond the need to find more examples of very low-mass brown dwarfs and massive planets both orbiting stars and free-floating and then conduct an extensive set of observations to establish their properties in as much detail as possible. As stated by P. Delorme, "some direct imaging detections blur the border" and indeed the border between giant planets and low-mass brown dwarfs is not well defined. The opinion of the audience on the classification as planet or brown dwarf for selected objects was put to the vote. Interestingly, except for a few cases which are clearly very difficult to classify, there was frequently a preferred option supported by a majority.

Do frontiers help to make progress? The only demonstrated relevant frontier in the substellar domain is the hydrogen burning mass limit ($\sim 75\,M_{\rm Jup}$) which determines a drastic difference in the evolution of objects with mass above and below. However, we have not found yet evidence that this burning limit affects the mechanism of formation of objects. Similarly, the deuterium burning mass limit ($\sim 13\,M_{\rm Jup}$) does not seem to be significant from the point of view of formation, neither for evolution. The burning of this isotope takes place on a limited period of time for brown dwarfs, it is a phase in the evolution but not a major determining factor of the evolution itself. For the moment, neither formation or evolution require a different classification for substellar objects with masses above and below the deuterium limit.

Since the formation mechanisms are far to be established, in particular objects about this mass found in orbit around stars could be classified as massive giant planets. Up to which mass this could be a valid classification? We do not really know, it will depend on further insight that we may gain on the mass distribution of substellar objects both around stars and free-floating and on progress in our understanding of the physics of formation. At lower masses, approaching the mass of Jupiter there may be other relevant frontiers associated with formation, if so, we will need to explore them and subsequently adapt the terminologies used in the classification of substellar objects. In any case, the bridge between stars and planets provided by brown dwarfs is currently transited at very high speed and will certainly drive us to the discovery of new scientific landscapes.

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