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Panel discussion on the brown dwarf – exoplanet connection

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Abstract. We present a summary of the panel discussion session on the brown dwarf exoplanet connection, at the Brown Dwarfs Come of Age conference in Fuerteventura. The discussion included an audience vote on the status (planet or brown dwarf) of a selection of interesting objects, as well as a vote on the current components of the IAU definition separating planets and brown dwarfs, and we report the results. In between these two opinion tests we discussed a set of key questions that helped us explore a variety of important areas, and we summarise the resulting discussion both from the panel and the conference audience.

Key words. Stars: brown dwarfs, planetary systems

1. Introduction

Eighteen years on from the discovery of the first brown dwarfs and exoplanet, the Brown Dwarfs Come of Age conference provides an opportunity to re-examine and discuss the connection between these two exotic populations, and consider how we might better understand their nature now that the field has matured. The very first discovered brown dwarfs and exoplanets showed some clear disconnection, but also ambiguity from the very start. The relatively unambiguous brown dwarf Teide 1 has a mass of 40-70 $M_{\rm Jup}$ (just below the Hydrogen burning limit) and is a free-floating M8 dwarf in the Pleiades cluster (Rebolo et al. 1995). In contrast the first exoplanet, 51 Peg b, has a likely sub-Jupiter mass ($\sim$0.5 $M_{\rm Jup}$) and orbits at a tight (hot) 0.05 AU separation (Mayor & Queloz 1995). Early ambiguity appeared in the form of Gl229B (Nakajima et al. 1995), with a mass (20-50 $M_{\rm Jup}$) much closer to the giant planet regime, a 40 AU orbit, and a spectrum

Send offprint requests to: D. Pinfield showing strong similarities with that of Jupiter. So the distinction between brown dwarfs and exoplanets has been blurred since the earliest discoveries, and we would like to explore developed/growing opportunities for clarity.

1.1. Where do things stand? - the IAU definition

As part of the re-classification exercise that made Pluto a "dwarf planet" following new Kuiper-Belt discoveries, the IAU Working Group on Extrasolar Planets (WGESP) agreed on a "Planet" definition in a position statement first issued on 28 Feb 2001 (and last modified 28 Feb 2003; see Boss et al. 2003). The statement consists of the following points:

- Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are "planets" (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System.
- Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs", no matter how they formed nor where they are located.
- Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "planets", but are "sub-brown dwarfs" (or whatever name is most appropriate).

The WGESP noted that these statements are a compromise between definitions based purely on the deuterium-burning mass or on the formation mechanism, and as such did not fully satisfy anyone on the working group.

Very young free-floating objects are not just found in young clusters of course, and have been identified in the field e.g. as members of kinematic moving groups. As such the final point is naturally extended to include all free-floating objects, so we assume this modification hereafter.

1.2. Structure of the panel discussion

Our discussion session took the following structure, which we describe in the rest of this write-up.

- To canvass opinion from the community, and more generally encourage clarity over ambiguity we began with a vote on a series of interesting objects - brown dwarf or planet?
- We then presented five key questions to foster discussion, with panel and audience member participation.
- And at the end we took a vote on the main elements of the existing IAU definition, to elicit an overview of how current opinion maps onto existing definition.

2. Community view - individual objects

To stimulate discussion on what properties might best distinguish brown dwarfs from exoplanets, we asked the audience to vote on the planethood of a sample of 11 systems which span the brown dwarf/exoplanet "regimes", covering a variety of masses, primary types (including no primary), ages and separations. This was a binary selection - either an object is or is not a planet. There were 55–60 votes per system, implying a sampling error of 4–6%.

Tables 1 and 2 summarize the results (system parametres and polling respectively) in order of decreasing "planetness". The benchmark companions to HR 8799 and that of Gliese 229 were extremities on the planet-brown dwarf spectrum; these systems have similar separations and possibly ages, but the clear distinguishing factors were companion mass and mass ratio, the latter differing by an order of magnitude. The presence of more than one substellar object and a debris disk in HR 8799 but not Gliese 229 may also have a significant impact on the outcome of the planetness vote. The most split vote came for the companion to WD 0806-661, which is even within the margin of error; the companion to Corot-3 and the "free-floating" planetary mass objects CFBDS 2149−04 and those in σ Orionis were all within 2.5 σ of the margin of error. The last of these reflects the even split on whether such unbound objects should be considered planets in a later poll (below).

We examined the correlation between fraction of planet votes to the systems' various physical parameters. The most significant factors were object mass and separation from primary star, both of which had marginally significant ($1.6\,\sigma$ and $1.2\,\sigma$) negative correlations (larger values decreased "planethood"). Primary mass, system mass ratio and presence of a primary were insignificantly correlated. A linear regression of these data provides a simple but probably unreliable prediction of this audience's planethood for a given object based on these parameters:

$$\begin{aligned}\%\text{Planethood} \;=\; & 54.8 + 9.78\text{M}_A - 2.22\text{M}_B \\ & +57.5q - 11.9\log_{10} a \\ & +36.8C \qquad (1)\end{aligned}$$

where M_A is primary mass in solar masses, M_B is companion mass in Jupiter masses, q is the mass ratio M_B/M_A, a is the separation in AU and $C = 1$ if a primary is present or 0 if not. This is accurate to within 9% for the most significant factors

$$\begin{aligned}\%\text{Planethood} \;=\; & 105 - 2.30\text{M}_B \\ & -12.1\log_{10} a \qquad (2)\end{aligned}$$

is accurate to within 16%.

3. Discussion questions

3.1. How might we define the fundamental differences (e.g. properties, formation) between brown dwarfs and giant planets?

The voting brought out that even at this specialized conference there is a wide range of views on definitions, or rather what differences are fundamental. The IAU definition, which is largely influenced by the Solar System, worked well in the radial velocity and transiting planet regimes, where the brown dwarf desert separates the stellar and planetary populations. Brown dwarf researchers, however, are now working in regimes where these definitions are not very helpful. Direct imaging searches are detecting objects above and below the deuterium-burning limit at wide separations from the primary. These may or may not have anything to do with formation in a disk.

The panel discussion emphasizes the problems of formation-based and mass-based definitions. The HR 8799 system had wide support as a planetary system, as it consists of multiple low mass objects that seem to have formed in a disk, though not necessarily through core accretion. If disk formation is not important, then 2M1207b seems to meet most planet definitions. Current work suggests that formation scenarios are not a simple binary choice. Theorists at this conference predicted a new population of objects that form through disk instabilities. These may lie in the range 3 to "42" jupiter masses. Many of these are predicted to be ejected and become isolated, "free-floating" objects. Some observers of star forming regions reported evidence that the mass function increases below the deuterium-burning limit, which if confirmed, also suggests a new formation mechanism. There was a discussion of the latest microlensing evidence of a new population of free-floating or wide companion objects below the deuterium-burning limit. Ultimately, the panel wondered if the disk instability should be considered a planetary or a stellar formation mechanism.

There was spirited challenge from some audience members on whether there are truly fundamental differences between planets and brown dwarfs. Perhaps these limits are arbitrary and astronomers should be more open-minded. For example, if we lived on an earth-like planet orbiting Gliese 229A, would we consider Gliese 229B a planet? Perhaps the desire to define planets to be like those in our own system is just an emotional attachment, a psychological bias that astronomers should strive to overcome. Panelists warned that this psychological bias is also a sociological effect. An object called a "planet" might attract funding that the same object called a "brown dwarf"

Table 1. Parametres of the systems being polled for planet/brown dwarf status.

Companion(s) to	Primary ($M_\odot$/SpT)	Companion ($M_{\rm Jup}$/SpT)	Mass Ratio (M_B/M_A)	Separation (AU)	Age
HR 8799	1.5 (A)	5–7 (late-L)	0.4%	15–70	30 Myr
MOA-2010-BLG-073L	0.16 (M)	9–13 (...)	6.5%	1.2	few Gyr
2MASS 1207−39	0.03 (M)	3–10 (late-L)	20%	41	8-12 Myr
κ And	2.5 (B)	12–15 (...)	0.5%	55	≈30 Myr
Corot-3	1.4 (F)	22 (...)	1.6%	0.06	few Gyr
WD 0806-661	1.5 (DQ)	5–9 (Y)	0.4%	2500	1.5 Gyr
σ Orionis members	...	3+ (L & T)	...	...	2–4 Myr
CFBDS 2149−04	...	7–9 (T7)	...	...	≈100 Myr?
2MASS 0103-55AB	0.36 (MM)	12–14 (L0)	4%	84	≈30 Myr
Ross 458AB	0.6 (MM)	6–11 (T8)	1–2%	1100	0.2–0.8 Gyr
Gliese 229	0.6 (M)	20–50 (T7)	5–8%	44	<1 Gyr?

might not. It was also pointed out that two talks at the conference suggested that the current scientific literature is biased by researchers prioritizing publishing planets over brown dwarfs.

3.2. How should we differentiate between brown dwarfs and planets observationally?

During the discussion, a number of observational signatures or characteristics were posed that could potentially be used to distinguish between brown dwarfs and planets. First, spectroscopic signatures were brought up as a possible probe of formation scenario. It has been suggested that objects forming in a circumstellar disk via core accretion would have measurably enhanced metallicity (e.g. Fortney et al. 2008). Further, it has been proposed that the condensation of various species from gas phase into solid phase at different locations in a disk could lead to observational signatures such as an elevated carbon-to-oxygen ratio (e.g. Öberg et al. 2011). Indeed, such enhanced ratios have already had tentative detections (e.g., Madhusudhan et al. 2011; Konopacky et al. 2013). However, there was some concern about the fidelity of atmospheric models that would be used to measure the abundances and ratios of species. These models have not been tested against the copious brown dwarf spectra that are available to determine whether systematics exist. Furthermore, there was discussion of the difficulty of measuring such signatures even within the planets in our own Solar System, casting doubt on our ability to do so for much more distant objects. However, these signatures may represent one way of distinguishing between brown dwarfs and planets if a formation scenario definition is adopted.

It was proposed that an observational signature could be simply whether the object orbited another star or was free floating. The suggestion was made that perhaps four categories were necessary, with brown dwarfs orbiting another star being called something slightly different than single brown dwarfs. This would then be somewhat analogous to the planet vs. planetary mass object nomenclature that is often used. However, there was discussion that such a scheme might be too confusing given that many of the "first" brown dwarfs were discovered orbiting other stars (e.g. Nakajima et al. 1995), and had become in some sense prototypes for entire spectral sub-classes.

Somewhat along those lines, another observational signature suggested for distinguishing brown dwarfs and planets was mass ratio rather than mass. If the mass of the object is already considered via the deuterium burning limit to be the demarking line between planets and brown dwarfs, then it is fairly straightforward to apply instead the mass ratio between the substellar object and its host star. It was sug-

Table 2. Polling results for planet/brown dwarf sample.

Companion(s) to	Planet (%/#)	Not Planet (%/#)
HR 8799	**91% (50)**	9% (5)
MOA-2010-BLG-073L	**83% (50)**	17% (5)
2MASS 1207−39	**67% (40)**	33% (20)
κ And	**66% (41)**	34% (21)
Corot-3	58% (36)	42% (26)
WD 0806-661	47% (29)	53% (33)
σ Orionis members	42% (25)	58% (35)
CFBDS 2149−04	41% (25)	**59% (36)**
2MASS 0103-55AB	40% (25)	**60% (37)**
Ross 458AB	33% (20)	**67% (40)**
Gliese 229	11% (6)	**89% (50)**

gested that 13 $M_{\rm Jup}$ was, though fairly straightforward in terms of a workable definition, a very arbitrary limit because objects straddling this border have very similar interior physics. This is in contrast to the hydrogen burning limit definition for a brown dwarf, where the interior physics is quite different. A mass ratio definition could therefore account for objects like 2M1207b (Chauvin et al. 2004), which likely formed more like a star but certainly has a planetary mass. Hence, mass ratio perhaps also traces formation.

A final suggestion was that system architecture could help distinguish whether an object formed like a "planet" or more like a star. The question was raised whether someone looking at our Solar System would be able to determine whether Jupiter was a brown dwarf or a planet. It was noted by the panel that the architecture of our Solar System, with multiple planets orbiting in the same direction with very low eccentricity, was an extremely compelling case for formation in a common disk. It was also mentioned that this was why the objects orbiting HR 8799 (Marois et al. 2008) were overwhelming considered to be planets rather than brown dwarfs in the vote (92%). Though such a criteria would be difficult for cases where there are not multiple objects orbiting a given star, it is at least a fairly obvious signature of formation when available.

A final brief suggestion of an observable signature was density. It was mentioned that COROT-3b, detected via the transit method, has a density that necessitates it having a dense core (Deleuil et al. 2008). Such measurements are often possible in the case of transiting objects. This is another line of evidence for formation via a process like core accretion, and perhaps planetary definition.

In summary, the general consensus seemed to favor a formation rather than a mass definition, and the discussion focused on whether formation was observationally distinguishable.

3.3. What are the priorities for improving theory to differentiate brown dwarfs and planets?

It was felt that this topic could be usefully separated into two main areas; what would observers like in the way of a shopping list from the theorists, and how can the community use benchmark systems (ultra-cool dwarfs whose physical properties are constrained at some level in a relatively model-independent way) to foster our ability to measure the properties of brown dwarfs and giant exoplanets in general.

The measurement and study of individual element abundances was felt to be of fundamental importance, in particular the possibility of measuring atmospheric deuterium. A deuterium test could provide a physically robust means of separating brown dwarfs and exoplanets (akin in some sense to the lithium test at the other end of the brown dwarf mass regime; Nelson et al. 1993). This would require some individual element abundances as input to the models, and will be challenging to implement due to the relative under-abundance of deuterium. However, feedback from the modelling community was upbeat. They felt that the observational challenge of measuring deuterium rather out-weighed the theoretical challenge. It was also commented that wide binary systems containing a star and an ultra-cool companion could provide an excellent means of making individual abundance studies. This has also been noted in connection with the discovery of BD+012920 (Pinfield et al. 2012).

This brought the discussion naturally onto benchmark wide binary systems, and it was noted that young systems containing low gravity ultra-cool companions would provide the best giant planet analogues. Targeted and database searches for ultra-cool companions around young stars, particularly the (numerous) young M dwarfs, were advocated. And it was commented on that in general what is required is a large number of benchmark objects, populating a grid of parameter-space ($T_{\rm eff}$/log g/[M/H]). The panel also noted that rotation could play an important role in the formation and nature of atmospheric dust, and there was some concern expressed that L dwarfs seen in young clusters seem to show a range of properties (very red spectra, triangular H-band) even at the same age and composition. However, possible contamination amongst the cluster sequence was suggested as a source of confusion, and clearly more detailed studies of the young cluster populations are important.

Another issue raised was that planet atmospheres are generally believed to be enriched compared to those of brown dwarfs, leading to a desire for metal-rich benchmark systems as well as low gravity. One avenue towards this goal was considered in the form of an expanded study of young open clusters. Figure 2 from Pinfield et al. (2006) was considered to illustrate the potential scope for such studies, though many potentially suitable clusters do not have metallicity constraints at this time. However, there could be a strong science case for deep searches of many more young clusters for substellar members, though a note of caution was added that even an expanded set of young clusters may not actually span the required metallicity range.

3.4. *Does the field population contain free-floating planets, and what can we learn from them?*

The existence of free-floating planets in the field is backed by several independent lines of evidence. Firstly, their young counterparts in young clusters and stellar formation regions have been identified by several imaging surveys, down to a few Jupiter masses (see for instance Zapatero Osorio et al. 2002; Burgess et al. 2009; Marsh et al. 2010; Haisch et al. 2010; Ramírez et al. 2011; Scholz et al. 2012). If free-floating planets are currently forming in stellar formation regions, it is reasonable to assume they have been forming during the previous Gyrs and that a corresponding population of field free-floating planets does exist.

Secondly, their is some direct evidence for the existence of field objects in the planetary mass range, backed by a few observations, notably of cool field brown dwarfs which would be of planetary mass for a significant fraction of their estimated age range (see for instance Burningham et al. 2009; Liu et al. 2011; Kirkpatrick et al. 2012). The case of CFBDSIR2149 (Delorme et al. 2012) is particularly interesting because its probable membership to a young moving group provides a much tighter constraint on its age and therefore on its mass, robustly anchoring it in the planetary mass range. Wide field surveys for brown dwarfs consequently provide strong evidence that at least a few free-floating planets do exist in the field.

Thirdly, microlensing surveys have uncovered what could be a huge population of field free-floating planets, up to 1.8 giant free-floating planets per star in the Milky way (Sumi et al. 2011). It is to be noted this is not compatible with the relative scarcity of young free floating planets uncovered in the wide field surveys of the field and of stellar formation regions. Microlensing observations also back the existence of an old population of free-floating planets, but with a different frequency compared to the young ones. However a fraction of the microlensing detections could be caused by bound planets that are distant enough from their host star so that the signal of the host star does not appear in the microlensing event. On-going high angular resolution observations are underway to check whether or not these free floating candidates indeed do not have a companion star.

In the case that most of the microlensing detections are caused by such distant planets, results from microlensing and imaging surveys could be reconciliated toward the existence of a small population of free floating planets. Conversely, the observed scarcity of planetary mass objects in imaging surveys could be compatible with a huge population of free-floating planets, if the atmosphere and evolutionary models (that constrain the mass of imaged objects) would significantly overestimate the luminosity of planetary mass objects.

3.5. *How can future surveys help address these questions?*

The panel and audience had a variety of discussion about future surveys. In the following we give a summary of the surveys considered, and key points.

- Pan-STARRS and LSST: These large-scale surveys will identify brown dwarfs through parallax, and explore the time domain for the local substellar population. Many variable objects will be identified, and it is likely that field brown dwarf eclipsing binaries will be discovered. These will yield mass-radius data providing superbly quantified benchmark systems to test atmosphere and evolutionary models. Indeed, there is some chance that the first Pan-STARRS telescope (PS1) may reveal the first such eclipsing system.
- GAIA: The very large number of ultra-cool dwarfs now contained within large-scale near- and mid-infrared surveys can link up with the GAIA population in a very important. This link-up will produce a vast collection of benchmark brown dwarfs in wide binary systems whose properties can be known with unprecedented accuracy. Ultra-cool dwarf distances will be inferred from the primary stars, with accuracies of ~0.1% limited only by the unknown separation of the companions. The comprehensive SED-fit properties of the GAIA primaries can be used to constrain the benchmark companions, yielding metallicity and age data for many thousand systems Indeed, this sample will be so large that it will be important to be selective, studying only the systems with the best constraints on their properties (including e.g. those with subgiants or high-mass white dwarfs as primaries, where the age and/or metallicity measurements are best).
- Euclid: Although Euclid has primarily cosmological and extragalactic science drivers, it will yield very important ultra-cool dwarf results as well. It will survey the sky to unprecedented depth (24.5 in 1 optical and 3 NIR bands) over a very large area (¿15000 sq degs), and provide diffraction limited spatial resolution. Results-wise this will increase the number of resolved ultra-cool binaries by more than an order of magnitude, providing stringent constraints on models. It is also expected to find significant numbers of rare free-floating objects (free-floating planets, and pop III ultra-cool dwarfs; Martín et al. 2013a).
- JWST: The mid-infrared (~5 micron) capabilities of Nirspec will provide the means to spectroscopically characterise a high fraction of the emitted flux from a wide range of ultra-cool dwarfs. And its multi-object spectroscopic mode (with a 3x3 arcminute of field of view) will be particularly amenable to cluster populations.
- EChO: The Exoplanet Characterisation Observatory (Tinetti et al. 2012) is a proposed ESA mission to measure extremely accurate and stable 0.5-16 micron spec-

tra of exoplanet hosts (with mainly transiting planets) from L2. EChO will measure emission and transmission spectra, during secondary and primary eclipse respectively. Optimal interpretation of these observations will only be fully facilitated by the kind of empirical studies and calibration offered by current and near-future ultra-cool dwarf populations.
– New opportunities: Warm Spitzer is offering major opportunities for very large-scale programmes, that could be survey-based or targeted. Also there is an opportunity to search for wide eclipsing brown dwarf companions in Kepler. Such long period systems await discovery, and could produce invaluable mass-radius-metallicity. Also very low-mass dwarfs have already been identified in the Kepler field of view (e.g. Gizis et al. 2011; Martín et al. 2013b).

4. Community view - IAU definition

After discussion of the main questions, the panel posed four additional questions to the conference to gauge opinion on the existing IAU definition (separating planets from brown dwarfs). We asked;

1. Is the Deuterium burning mass limit useful for separating brown dwarfs and planets?
2. Should another mass limit be involved in the definition (e.g. ~40 $M_{\rm Jup}$)?
3. Should planets be required to orbit stars or stellar remnants?
4. Should free-floating planetary mass objects in clusters (or in the field) be given a separate label (e.g. sub-brown dwarfs)?

The votes cast were as follows:

1. **Yes=46**, No=16
2. Yes=6, **No=55**
3. Yes=32, No=30
4. Yes=7, **No=55**

The clearest decision was to reject the idea of using an additional or alternative mass limit to separate brown dwarfs from planets. Feeling was also strong that there should not be a separate label for free-floating planetary mass objects. The conference was fairly evenly split regarding the requirement for planets to orbit stars or stellar remnants. And in the final analysis there was fairly strong support for the continued use of the Deuterium burning mass limit as a separator between brown dwarfs and planets.

5. Closing

It seems a crucial point that disk instability can lead to a range of substellar mass objects, including masses reasonably close to that of Jupiter, with some of these objects being ejected into the field. It thus seems impractical to imagine a planet-brown dwarf definition that is linked to formation in a disk but is based on measurements of mass, mass-ratio, separation and/or orbital properties.

Using a mass-based definition does allow one to place a fence around certain types of objects, such as those that are not undergoing fusion. However, indications are that such badging, while good at identifying objects that are currently close to the detectability limits of the latest instruments, does not reflect an improved understanding of substellar populations. The existing "planet" label has implications for telescope time awards, grant funding, and press coverage, though we are still in search of more meaning in the name.

If a means was available to determine/constrain interior structure observationally, then this might offer a far more meaningful way to differentiate between sub-stellar objects. Formation in a disk in itself would not then be the requirement for planet-hood, but rather we could chose to separate objects with cores and layered structure, from those that are simply balls of gas (more akin to low-mass stars). In this type of definition disk instability would lead to brown dwarfs whatever their mass and location, while core accretion would lead to planets. Such a definition would be rooted in formation and interior structure, and the challenge would be to find the observational means to make this separation.

Developing rigorous methods to constrain the physical properties of ultra-cool dwarfs will be crucial in the coming years if such goals are to be achieved, and benchmark systems will be vital in this respect. Also the study of detailed atmospheric chemistry should shed light on the provenance of substellar objects and give many clues to their internal structure.

Having said this, we note that at this time the vote on existing IAU criteria shows that astronomers at this conference quite like a simple separation based on mass. So perhaps this has its place for the time being.

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