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Outstanding brown dwarf questions

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Abstract. Gaia is set to revolutionize our understanding of the Milky Way. Although the visible-light wavelengths at which it works might at first seem to preclude any possibility of brown dwarf research, Gaia will nonetheless observe, either directly or indirectly, a sufficient substellar population to make this possibility a reality. In this paper I discuss some of the broad questions of brown dwarf research that Gaia is likely to help answer.

Key words. stars: low-mass, brown dwarfs – stars: subdwarfs – stars: fundamental parameters – Galaxy: solar neighborhood – catalogs

1. Introduction

Twenty years ago, the only question in the field of brown dwarf research was "Do brown dwarfs exist?" At the 1994 conference "The Bottom of the Main Sequence – and Beyond" no incontrovertible brown dwarfs had yet been found, and only one object – GD 165B (Becklin & Zuckerman 1988) – had been uncovered with a post-M spectral type. The situation changed in dramatic fashion a year later at the Ninth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun in Florence, Italy, when a group from Caltech announced the discovery of the T dwarf Gl 229B (Nakajima et al. 1995).

Now, many hundreds of cold objects with post-M spectral types are recognized (Figure 1, left). Over 1500 objects are known with types of L, T, or Y, most of which are substellar and all of which have effective temperatures less than ~2200K (Kirkpatrick 2005). Gaia, because it observes shortward of 1 μm, is not especially sensitive to these cold objects, whose peak emission falls at longer wavelengths. Nevertheless, Gaia will detect some of the nearest L and T dwarfs and provide unprecedented astrometric accuracy. Figure 1 (right) shows a cartoon diagram of the approximate distances out to which Gaia can detect post-M dwarfs. For more specifics on the Gaia L and T dwarf sample, see Smart (2014).

In the following sections, I address four broad questions in brown dwarf astrophysics that observations by Gaia might be able to answer.

2. How do brown dwarfs form?

The question of how brown dwarfs form cannot be addressed until brown dwarfs themselves are defined. Back in 1994, the only definition of a brown dwarf was one that linked stars and brown dwarfs together – that is, a brown dwarf was a hypothesized by-product of star formation, one too low in mass to sustain thermonuclear burning in its core. After brown dwarfs and extrasolar giant planets began to be discovered in large numbers, an alternative definition was sometimes used. This

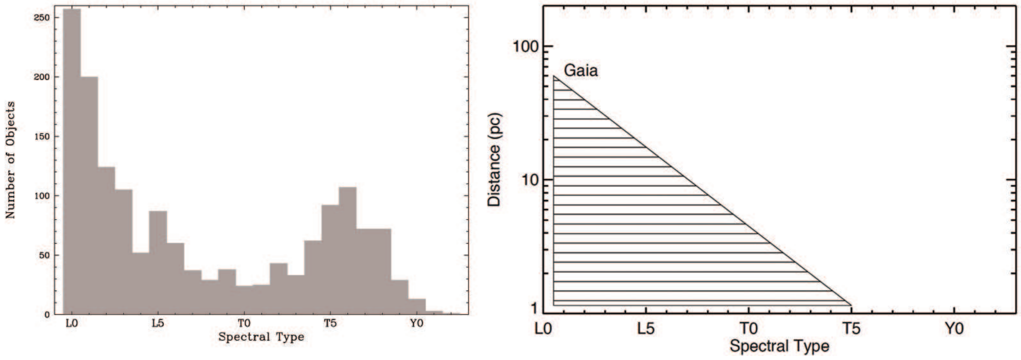

Fig. 1. Left – The number of L, T, and Y dwarfs known in early 2014 as a function of spectral type. Right – A cartoon diagram showing the approximate distance limit probed at each of these types by Gaia.

definition is based on mass, and specifies that a brown dwarf is an object that burns deuterium for a short time but never burns normal hydrogen, regardless of formation method. For solar metallicity, the mass range would be ~13 to ~75 Jupiter masses, according to Burrows et al. (1997). For the rest of this section, we will use the second definition.

There are two main mechanisms believed to produce low-mass objects. The first is the direct collapse of an interstellar cloud of gas and dust. The second is the evolution of a protoplanetary disk around an object formed via the first mechanism. Both mechanisms have multiple branches.

In the first mechanism, turbulent fragmentation of the gas may produce very low-mass objects directly (Padoan et al. 2005; Boyd & Whitworth 2005), or they may form from proto-stellar embryos whose further development is retarded either by dynamical ejection of those embryos from the cloud, which removes the embryo from its supply of accreting material (Reipurth & Clarke 2001; Bate & Bonnell 2005), or by photo-evaporation of the embryos, thereby ablating material from what would otherwise have been a full-fledged star (Kroupa et al. 2001; Whitworth & Zinnecker 2004). In the second mechanism, fragmentation within the disk can form low-mass objects (Mayer et al. 2007; Basu & Vorobyov 2012), but so can gas accretion onto a nucleated core (Mizuno 1980; Inaba et al. 2003; Fortier et al. 2007).

Which of these effects are the dominant ones? The incidence of brown dwarf binaries and the distribution of their orbital separations provide important clues about whether ejection mechanisms play a major role. The dominant effect may also depend upon the environment in which a brown dwarf is born. High-density star formation sites will have more dynamical interactions, so ejection mechanisms may be expected to play a larger role there. Regions with many high-mass stars would be expected to have higher rates of photo-evaporation. What do current observations suggest? An examination of the results of two recent papers reveals that the answer is still far from clear:

First, Kroupa et al. (2013) argue that if brown dwarfs form primarily from gas fragmentation, they ought to follow the same binary pairing rules that stars do. However, they state that their simulations produce far too many wide brown dwarf + brown dwarf binaries, whereas the observed distribution shows that most brown dwarf + brown dwarf binaries are closely separated. Also, the observed incidence of star + brown dwarf pairs (the brown dwarf desert) disagrees with simulations that assume stars and brown dwarfs form via the same mechanism. Kroupa et al. (2013) conclude from these facts that brown dwarfs, like planets, are formed from gravitationally pre-processed material.[1]

Second Chabrier et al. (2014) argue that the brown dwarf mass function can be fit as an extension of the stellar power law + log-normal functional form, that brown dwarfs and stars share the same velocity and spatial distributions, that there is little evidence for differences in the binary distributions between stars and brown dwarfs[2], that the observed mass function of planets differs greatly from that of brown dwarfs, and that isolated brown dwarfs are known along with at least one pre-brown-dwarf core. Chabrier et al. (2014) thus conclude that brown dwarfs form the same way that stars do.

Using the same observational data, then, two different groups have reached two vastly different conclusions. Further complicating the picture are the microlensing results of Sumi et al. (2011), who find that there is a vast population of sources with masses below $\sim$10 Jupiter masses that do not follow the standard power law + log-normal functional form. Although Quanz et al. (2012) argue that some of these objects are widely separated planets around M dwarf hosts, the Sumi et al. (2011) results still suggest that many solivagant planetary-mass objects exist. Which of the two main formation mechanisms produced these objects?

Gaia will be able to study the kinematic distribution of young, high-mass brown dwarfs in some of the nearest open clusters, star formation sites, and moving groups in a homogeneous fashion and in bulk (Sarro et al. 2014). It will also be able to study the binary distribution of old brown dwarfs within the immediate confines of the Solar Neighborhood. Although these observations are unlikely to answer the formation question definitively, they should add important new insights into the processes that create the brown dwarf populations we see.

3. What are brown dwarfs' fundamental parameters?

Gaia will enable us to study the fundamental physical parameters of a large population of brown dwarfs in ways not possible before. Below are some examples –

Luminosity: Gaia will provide 0.1-0.3 milliarcsecond parallax precision for L dwarfs (see Marocco contribution in these proceedings). Combined with Gaia G-band magnitudes, 2MASS J, H, and K_s, and WISE $W1$, $W2$, $W3$, and $W4$, these results will give exquisitely determined bolometric luminosities.

Radius: Gaia will identify transiting star + brown dwarf and binary brown dwarf systems. Continued ground-based follow-up of such systems will provide directly measured radii.

Temperature: For transiting systems in which the individual component magnitudes and spectra can be measured, the bolometric luminosity and radius will provide model-independent measures of effective temperature.

Space motions: Gaia will provide measurements of tangential velocities for L dwarfs to precisions of 10-30 m s^{-1} (see Marocco contribution in these proceedings). Full U, V, W space motions are possible once these are combined with ground-based measurements of radial velocities.

Mass: There are two ways of directly measuring mass. The first method involves monitoring the gravitational interactions of the objects in a binary system (e.g., Lane et al. 2001; Zapatero Osorio et al. 2004; Konopacky et al. 2010). Through astrometric monitoring, Gaia will be able to identify new brown dwarf binaries and find hidden brown dwarf secondaries around objects of higher mass that can then be monitored in more detail to provide dynamical mass measurements. The second method involves the astrometric displacement of background objects by a microlensing brown dwarf

[1] These authors nonetheless note that other indications, such as the presence of disks around some brown dwarfs and similar velocity distributions for stars and brown dwarfs in the Taurus Molecular Cloud, point toward a star-like birth process for brown dwarfs.

[2] This is the case only once it is considered that most weakly bound systems will not survive later gravitational encounters with other objects; after all, wide brown dwarf + brown dwarf binaries, though rare, *are* known to occur.

in the foreground (Cushing et al. 2014). Gaia will likely uncover previously hidden brown dwarfs against the Galactic Plane, measure their parallaxes and proper motions very accurately, and allow us to predict which ones will induce future microlensing events that can be monitored by other facilities. Gaia may also be able to directly aid in the observation of microlensing events already predicted for known objects (e.g., Sahu et al. 2014) or alert to unexpected events in progress (Wyrzykowski et al. 2012).

Age: Many brown dwarfs have now been cataloged as companions to main sequence stars whose ages are known, and these objects provide important checks of evolutionary models (e.g. Burningham et al. 2013). Others, like the original L dwarf GD 165, which itself may be a very low-mass star, have an age provided by a sibling that has now evolved off the main sequence (e.g. Kirkpatrick et al. 1999). At present, an association with a higher mass star is the only way to establish accurate ages for brown dwarfs of intermediate age. However, the ages of single brown dwarfs can be obtained if the object is either very young or very old, as discussed below.

3.1. Extreme youth

Our ability to distinguish age directly from the low-resolution spectra of solivagant L, T, and Y dwarfs goes back to the discovery of the early-L dwarf 2MASS J01415823−4633574 (Kirkpatrick et al. 2006). It was recognized as having much lower gravity than normal, which is indicative of a young brown dwarf still contracting to its final radius. We now know (Gagné et al. 2014) that this object has a high probability of belonging to the Tucana-Horologium Association, which has an age of 20-40 Myr.

Since this initial discovery, other teams have identified many more young objects in the field, and a classification scheme has been created to include these. This scheme appends a Greek letter suffix onto the core spectral type, where α refers to objects of normal gravity, β refers to the presence of mildly low-gravity features, γ refers to more pronounced low-gravity features, and δ refers to even more extreme features implying even lower gravity (Cruz et al. 2009; Kirkpatrick et al. 2010). The expectation was that the Greek letter sequence would be indicative of age, where α would correspond to objects of age $>>$100 Myr, β would be $\sim$100 Myr, γ would be $\sim$10 Myr, and δ would be $\sim$1 Myr.

Continued follow-up of these low-gravity objects had enabled researchers to assign many of them to specific associations and moving groups near the Sun. Table 1, which is based on data compiled from Gagné et al. (2014), shows that objects with subtypes of β are found only at the high end of the age range (20-120 Myr), whereas objects with subtypes of γ typically fall at the low end (8-40 Myr) as expected, although curiously some objects of subtype γ are also seen near 100 Myr. Gaia will allow us to refine and improve the membership probabilities of many more known low-gravity objects, to identify new brown dwarfs members of these same associations, and perhaps to identify new moving groups all together.

3.2. Extreme old age

During a search for field T dwarfs, (Burgasser et al. 2003) uncovered the first metal-poor L dwarf, 2MASS J05325346+8246465. This object is believed to be a member of the halo population and to fall below the hydrogen-burning mass limit (Burgasser et al. 2008). Very few of these L subdwarfs are currently known, but all-sky motion surveys are capable of finding additional examples. Both Pinfield et al. (2014) and Kirkpatrick et al. (2014) have noted a dearth in the number of subdwarfs between early-L and late-L/mid-T types, There is expected to be a temperature gap between very old, low-mass stars and very old, high-mass brown dwarfs because the latter continue to cool whereas the former settle stably onto the main sequence. Gaia should be able to derive improved statistics for early- to mid-L subdwarfs and to show whether a drop in numbers for the later types can be taken as evidence of the bottom edge of the low-metallicity main sequence.

Table 1. The Number of β and γ Youth Sub-types as a Function of Age

Group	Age (Myr)	# of β's	# of γ's
AB Dor	70-120	1	1
Argus	30-50	2	1
Tuc-Hor	20-40	1	9
Columba	20-40	0	3
β Pic	12-22	0	2
TW Hya	8-12	0	1

4. What else shapes the spectra of brown dwarfs?

The optical spectral type for L and T dwarfs exhibits a linear trend with effective temperature except around the L/T transition. For the near-infrared type, on the other hand, all objects classified from mid-L to mid-T have essentially the same temperature of 1350±150K. (See Figure 7 of Kirkpatrick 2005.) Clouds are thought to cause the anomalous behavior at the L/T transition and to be the primary shaper of the near-infrared spectral morphology of mid-L to mid-T dwarfs. Six brown dwarf binaries are now known (Gelino et al. 2014) in which the brighter component at z or J band becomes the fainter component at H or K band. It is assumed that the brighter component at z or J is the one later in spectral type, and the increased flux at these bands is believed to be due to patchy clouds that allow lines of sight into warmer layers below.

How do we probe specifics regarding clouds? Does cloud coverage fraction vary with time? Are clouds banded or spotty? Are there differences in observational effects depending on orientation of the spin axis? Doppler imaging work by Crossfield et al. (2014) shows global spottiness and a near-polar bright spot on the T0.5 component of the binary WISE J104915.57−531906.1AB (Luhman 16AB), one of the few objects near the L/T transition bright enough for this technique to be applied. Gaia will have photometric time series data on this system, the T1 dwarf ϵ Ind Ba, and many L dwarfs. These visible-light studies can be paired with ground-based and/or *Spitzer Space Telescope* photometric monitoring along with ground-based and/or *Hubble Space Telescope* spectral monitoring to provide important new data with which to investigate atmospheric properties in more detail.

5. What aspects of brown dwarf science have we not foreseen?

The all-sky nature of Gaia along with its many revisits at each position guarantees that there will be unexpected discoveries. It is almost a certainty, for example, that Gaia will uncover previously missed, very nearby brown dwarfs in the Galactic Plane since a dearth in the number counts of known objects is seen there. (See Figure 1 of Smart 2014.) It is also quite likely that Gaia will uncover rare examples of L dwarfs missed previously, since most previous all-sky searches for L dwarfs have used color, not kinematics, for selection. In finding new brown dwarfs near the Sun and in improving the astrometric data on those that are already known, it is also possible that new moving groups, perhaps having only low-mass members, will be identified, which could signal a low-mass-only mode of star formation.

6. Conclusions

For more specifics about the ideas presented above, as well as other brown dwarf questions not addressed here, readers should consult the many other contributions from this workshop.

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