Gaspard Duchêne – Program 2015A_U083N2

Assessing the fundamental limits of (multiple) star formation and the origin of the brown dwarf desert

1. Scientific Justification

1.1. Context

Stellar multiplicity is ubiquitous throughout the Galaxy and is generally believed to be the outcome of turbulent fragmentation of a prestellar core during the early phases of core collapse (Tohline 2002). Very low mass "seeds" (5–10 M_{Jup}) form and subsequently accrete from their parent core. The final component masses are thus stochastically determined and difficult to interpret individually. Instead, this process is best probed by the ensemble population of multiple systems, i.e., the overall distribution of mass ratios ($q = M_2/M_1 \leq 1$). The observed, shallow distribution for visual binaries is remarkably uniform for all stellar masses over $\sim 0.3\,M_\odot$ (Reggiani & Meyer 2013; Duchêne & Kraus 2013). This suggests that fragmentation and accretion on the seed binary proceeds in a scale-free manner and can be studied focusing on any population within this range.

One intriguing aspect of the mass ratio distribution for solar-type stars is the so-called brown dwarf (BD) desert, namely the remarkable dearth of companions in the approximate 20–50 M_{Jup} range. This feature was initially identified by radial velocity monitoring (e.g., Marcy et al. 2000; Grether & Lineweaver 2006) but later studies revealed that it extends to much wider separations, out to at least 300 au (e.g., Chauvin et al. 2010; Leconte et al. 2010). While "extreme" binary systems ($q < 0.1$) may be somewhat more common at even wider separations (Metchev & Hillenbrand 2009), these system may form through different processes, so we focus here on separations ≤ 300 au. This is also the primary search space for new planet-imaging capabilities (GPI, SPHERE) and the upcoming discovery of a slew of new planetary (and other substellar) companions in this regime is a new motivation to re-open the question of the physical origin of the BD desert.

Besides confirming that planetary mass companions form through a different channel than stellar binaries, the BD desert raises the question of the physical mechanism that sets a lower limit to stellar mass companions, and whether the conjunction of this limit and the stellar/substellar boundary is a mere coincidence or a profoundly revealing fact. Specifically, is the lower limit for stellar companions effectively set at around the substellar limit ("fixed mass" limit), or is it instead an indication that binaries simply cannot form with more extreme mass ratios ($q \lesssim 0.1$, "fixed q" limit)? Hydrodynamical simulations of the formation of stellar clusters form remarkably few extreme mass ratio systems (e.g., Bate 2012). Either way, this phenomenon points to a fundamental limit in the physics of (multiple) star formation, probably stemming from the accretion history of the initial seeds, but the absolute-vs-relative nature of the limit remains to be determined. Addressing this question is the key objective of the present program.

1.2. This program

Whereas the properties of the BD desert (separation extent, "aridity") have been well studied for solar-type stars over the years, we need to approach to this issue from another angle to disentangle the two main explanations outlined above. **The key idea behind this project consists in searching extreme mass ratio companions to stars of different masses, for which the substellar boundary corresponds to a different mass ratio**. Low-mass stars seem to have a dearth of BD companion (Dieterich et al. 2012), hinting at a "fixed mass" limit, but detecting substellar objects around (on average very old) low-mass stars remains a steep observational challenge. **Here we propose to take the opposite route and to consider stars that are significantly more massive than the Sun, as a scaled-up proxy for BD-desert-like systems**.

Extensive searches for substellar companions have been conducted for A- to F-type (1.5–2 $M_\odot$) stars, revealing a relative paucity of substellar companions (e.g., Kouwenhoven et al. 2007; Janson et al. 2013), but the distinction between the "fixed mass" and "fixed q" scenarios remains too narrow to reach a decisive conclusion. Furthermore, most surveys only achieved the required high contrast to probe down to the substellar limit at large angular separations due to contrast limitations inherent to the technique used (coronagraphy, angular differential imaging and/or heavily saturated exposures). In this range, confusion with background stars is a prominent issue that requires time-consuming follow-up (De Rosa et al. 2014).

To address this issue more effectively, we are now initiating a project aimed at **assessing the mass ratio distribution, and especially its low-q end, for 3–8 $M_\odot$ stars** (spectral types ranging from B3 to A0), at separations closer than 300 au. With a median mass of 5 $M_\odot$, the gap between the "fixed mass" and "fixed q" limit is much broader than for A- and F-type stars, allowing for statistically significant results. If we do find a substantial populations of companions in the 0.075–0.5 $M_\odot$ range (well above the 1–2% characterizing the BD desert for solar-type stars), then the "fixed q" limit scenario can be excluded. On the other hand, a rarity of companions to 3–8 $M_\odot$ with $q \leq 0.1$ would indicate that the accretion phase that follows the formation of "seeds" functions as an efficient regulator, precluding the formation of extremely unequal systems.

One key advantage of studying 3–8 $M_\odot$ stars is that even extreme mass ratio systems have companions in the stellar regime, which translates into much less stringent requirements on the achieved contrast compared to previous searches for substellar companions. As shown in Fig 1, a contrast of $\Delta K = 8$ mag is sufficient to detect essentially all stellar companions to stars with $M \leq 7\,M_\odot$. Nonetheless, previous efforts to probe the mass ratio distribution of visual binaries with B-type primaries have been hindered by similar contrast and confusion issues as for intermediate-mass stars. The best dedicated survey hinted at a significant population of extreme mass ratio systems (Shatsky & Tokovinin 2002, , using the ESO 3.6m ADONIS AO system), but only identified one candidate companion with $q < 0.1$ within 300 au, leaving considerable uncertainties. Owing to the quality of the Keck telescope AO system and its 10 m aperture, we can revisit this topic and probe low-mass stellar companions much closer to the central stars than previous surveys.

To draw a statistically robust conclusion, our ultimate goal is to survey over 200 B-type stars. If the binary population extends down to about the substellar limit, this will yield more than 20 companions below the $q = 0.1$ limit, allowing for an unambiguous distinction with the 1–2% "aridity" of the BD desert for solar-type stars. To ensure sample homogeneity and to maximize linear resolution, we will draw our sample from nearby, young open clusters (10–100 Myr, ≤ 500 pc; see Technical Justification). The well-determined ages of these clusters will further allow us to derive accurate masses for the companions, which will be close to or already on the ZAMS. **In the first installment of this project, we propose to survey all 30 B3–A0 members of the IC 4665 cluster** (30 Myr, 350 pc Lodieu et al. 2011).

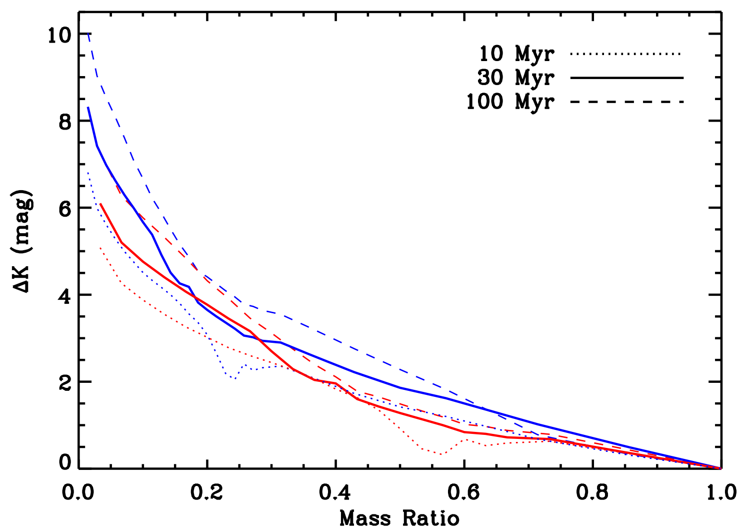

Fig. 1.— K-band flux- to mass-ratio relationship for $3\,M_\odot$ and $7\,M_\odot$ primary stars (red and blue curves, respectively) based on the evolutionary models of Siess et al. (2000). The 10 and 100 Myr curve illustrate the span of cluster ages studied in this project, while the thicker solid line represent the 30 Myr mass-luminosity relationship at the age of the IC 4665 cluster, focus of the present proposal. The wiggles in the 10 Myr curves indicate that the lowest mass stars have not yet reached the Main Sequence at that early age; we will not consider younger populations in this project.

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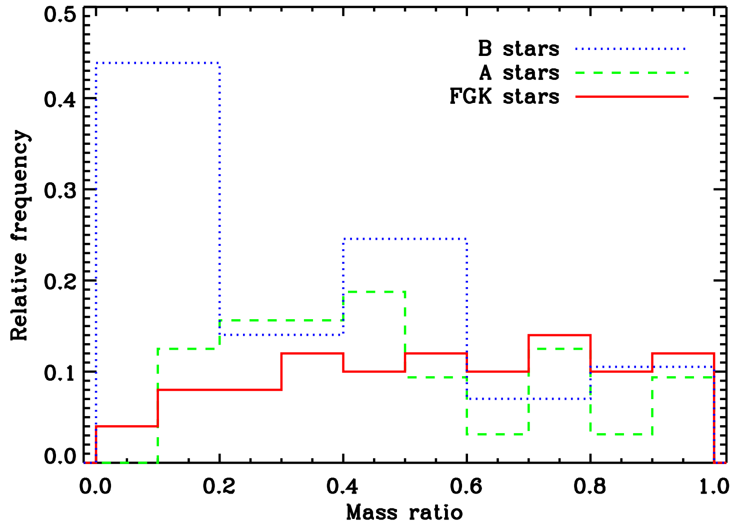

Fig. 2.— Mass ratio distribution for B-type, A-type and solar-type stars for visual binaries, renormalized over the whole [0,1] range for comparison purposes. The solar-type distribution (solid red curve; measured from 20 to 300 au; Raghavan et al. 2010) is the only one that is robustly estimated below q=0.1; the actual frequency of companions in this range is about 1–2% (McCarthy & Zuckerman 2004; Metchev & Hillenbrand 2009; Raghavan et al. 2010). The intermediate-mass stars distribution (dashed green curve; measured from 20 to 125 au; De Rosa et al. 2014) is cut at the $q = 0.15$ completeness limit; including companions located further out results in an increase of low-q systems, although confusion becomes a concern. Finally, the peak at low-q for B-type stars (dotted blue curve; Shatsky & Tokovinin 2002) is overwhelmingly dominated by companions outside of 300 au. Such low-mass companions could not be detected at shorter separations, which is precisely the gap that this project aims at filling. In any event, that distribution is too severely limited by small number statistics (hence the wider bin size) to be a useful probe of extreme mass ratio systems.

Siess, L., Dufour, E., et al. A&A, 358, 2000, 593
Tohline, J. E. ARA&A, 40, 2002, 349

2. Technical Justification

2.1. Program implementation

2.1.1. Sample selection

Owing to the IMF in the Galaxy, B-type stars are relatively rare and must be searched at larger distances than lower-mass stars. To draw significant samples while maintaining sample homogeneity (particularly in terms of distance), we thus focus our attention on rich open clusters located within 500 pc. In this situation, focusing on sub-arcsecond companions reduces drastically

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the risk of contamination from background sources. We further select clusters whose age are in the 10–100 Myr range. For older ages, the 5–8 $M_\odot$ stars no longer are on the Main Sequence and it becomes challenging to estimate their mass as they move rapidly across the H-R diagram. At younger ages, the Pre-Main Sequence nature of the companion and the possibility that they host infrared-emitting circumstellar disks would seriously hinder our ability to characterize them. Finally, we exclude heavily extincted clouds so that our targets are bright ($7 \lesssim V \lesssim 10.5$, excellent for Keck AO observations; see Table 1), and to avoid situations where the spectral characterization of the primaries is poorer. Using the WEBDA open cluster database[1], we identified 19 clusters containing at least 20 stars in the B3–A0 spectral type range, 11 of which are accessible from Mauna Kea ($-25^\circ \leq \delta \leq 65^\circ$). As a first step in this project, we have selected the rich IC 4665 cluster (30 targets), ideally located for observations with Keck ($\delta \approx +06^\circ$). The cluster is about 30 Myr old, ensuring that its 3–8 $M_\odot$ members and virtually all low mass stellar companions have reached the Main Sequence. Also, with $E(B-V) = 0.17$, line-of-sight extinction will not be a significant problem in analyzing the stellar properties of our targets and their candidate companions.

Table 1: List of B3–A0 members of IC 4665 targeted in semester 2015A.

Target	Sp.T.	V	K	Target	Sp.T.	V	K
HD 161573	B3	6.843	6.817	HD 161426	A0	9.07	8.557
V2320 Oph	B5	7.36	7.293	HD 161445	A0	10.16	9.750
HD 161677	B5	7.137	7.063	BD +06 3521	A0	10.49	9.466
HD 161480	B6	7.70	7.576	HD 161481	A0	9.09	8.372
HD 161572	B6	7.59	7.587	HD 161542	A0	7.51	7.118
HD 161733	B6	7.995	7.866	IC4665 V 93	A0	10.53	9.592
V2327 Oph	B6	7.508	7.519	BD +05 3487	A0	8.80	8.349
V2323 Oph	B7	7.76	7.789	BD +05 3494	A0	10.06	9.480
BD +05 3466	B8	8.04	7.865	BD +05 3495	A0	10.69	9.787
HD 161261	B8	8.26	8.042	HD 161786	A0	9.95	9.175
HD 161734	B8	8.87	8.464	HD 161940	A0	9.26	8.822
HD 161165	B8.5	8.73	8.469	HD 162162	A0	9.32	8.043
V2324 Oph	B8.5	8.26	7.862	IC4665 ALC 22	A0	10.30	9.279
HD 161055	A0	10.06	9.440	HD 162177	A0	8.67	7.696
HD 161370	A0	9.42	8.582	HD 162282	A0	9.66	9.134

2.1.2. Data acquisition strategy

We will conduct the survey in the K band, giving up the highest possible angular resolution in exchange for optimum quality and stability of the AO correction. Companions detected in real time will be followed-up with J and H observations to obtain color information. The extreme mass ratio systems we are interested in, however, will most likely not be detected before post-processing and we will request dedicated follow-up time in another semester.

[1] http://www.univie.ac.at/webda/

At a distance of 350 pc, the 300 au search limit corresponds to 0\.″85. To be sensitive to all stellar companions, we need to achieve a contrast of 8 mag given the age of the cluster (see Figure 1). While this is not in the realm of extreme contrast ratios discussed in the context of planet searching surveys, past AO surveys have reached such contrasts outside of 1″, generally relying on coronagraphy (or saturated exposure) to achieve this, often combined with angular differential imaging (whose power is most effective at large distances from the star). The challenge posed here is to achieve this contrast within the central arcsecond, which requires obtaining unsaturated short exposures. For bright stars, a series of 15–20 dithered, unsaturated exposures can provide a contrast of up to 6 mag outside of 0\.″2 and 8 mag at 1″ (e.g., Duchêne et al. 2013). To achieve the goals of this project, we will accumulate a much larger number in order to suppress efficiently the AO point spread function (PSF). Individual exposures will be coadded by small groups (resulting in "individual" exposure times of a few seconds) to reduce the influence of random speckles, and we will obtain a total of 15 min integration on source. We will thus achieve similar contrasts as reported by Daemgen et al. (2007) but the choice of unsaturated exposures will further improve on this at short separations.

Our observing strategy will use the fixed pupil orientation (and its associated pattern of quasi-static speckles) to improve the quality of PSF subtraction. With observations of 30 targets and 5 PSF stars (see below) of similar brightness, our observations will enable a LOCI-like PSF subtraction (Lafrenière et al. 2007) which will substantially improve the achievable contrast even in the central arcsecond. In addition to our targets, we will also observe 5 bona fide single stars (selected from deep substellar search samples) to serve as additional PSF stars. This way we will achieve the required contrast for this project. We emphasize that the performance requirements for this project are much less stringent than those of recent surveys for substellar and planetary-mass companions. These searches are now best conducted on "extreme AO" systems (GPI, SPHERE). Instead, the performance required here is best matched to the capabilities of the Keck AO system.

While our observing strategy will result in field rotation, we are not designing the program to use the angular differential imaging technique, since most stars will not be osberved with enough field rotation (as we follow the cluster through transit, only a few sources will have significant rotation in 20 min clock-time). The field rotation requirement is further enhanced by our focus on the central arcsecond. We do thus not expect to gain significantly from this approach overall. Considering the large-scale survey nature of the project, a full angular differential imaging approach would be prohibitive.

Since our targets are bright and observations will be conducted on-axis (with dithers of a few arcsecond), we do not anticipate any complication beyond nominal overheads. Including acquisition, dithering and file writing overheads, we plan on spending about 20 min clock-time per target. With 35 targets, **we thus request about 12h of telescope time, or two half-nights** (first half in July or second half in May) to track the targets at the highest possible elevation.

2.1.3. Analysis plan

For each candidate companion, we will first determine the likelihood of confusion from background sources by using the source counts in the overall 10″ NIRC2 field-of-view and/or the 2MASS source counts in the vicinity of the target, depending on the brightness of companions and specific individual fields. It is plausible that a significant source of confusion will be low-mass members of the cluster, which we will estimate based on the known structure and stellar content of the cluster provided by IMF studies of the cluster (Lodieu et al. 2011).

We will then estimate the mass of the companions by using near-infrared mass-luminosity relationship for late-type stars (Delfosse et al. 2000) as well as evolutionary models (Siess et al. 2000; Baraffe et al. 1998; Chabrier et al. 2000; Allard 2009), taking advantage of the well known age of the cluster. When observations at multiple wavelengths are available, comparison of the different mass estimates will be used to confirm the bound nature of the companion.

2.2. Why AO at Keck?

As explained above, we are interesting in companions within ≈300 au, since wider companions may form through a separate mechanism. Given the distance to the cluster, this implies a search within the central arcsecond, which can only be conducted with ground-based AO or HST observations. To achieve the required resolution, an HST program would need to be conducted at visible wavelengths, where the contrast needed to detected the faintest stellar companions reaches 14 mag, i.e., the "extreme AO" regime. Our targets are bright ($V \leq 10.5$) and thus perfect sources for the NGS mode of the Keck AO system, which will consistently provide Strehl ratios in excess of 50% at K band. Observing our targets in consecutive mode will take advantage of the stability of the AO correction.

2.3. Backup Programs

Since our targets are bright, no back-up plan is needed for the project.

3. Experience & Relevant Publications

3.1. Experience and Resources

Gaspard Duchêne is an Assistant Researcher at the University of California, Berkeley who has a long record of studying stellar multiplicity, particularly through AO imaging. He has been awarded a 3 yr NSF grant this Summer (2014) to conduct this project on extreme mass ratio stellar systems. Funds are thus readily available to fully support this activity and prepare resulting publications.

3.2. Relevant publications

Selection of relevant first-author publications by the PI (where ⋆ symbols denote papers in which Keck data are presented):

Duchêne (1999), *A&A*, 341, 547

Duchêne et al. (1999), *A&A*, 343, 831

Duchêne et al. (2001), *A&A*, 379, 147

⋆ Duchêne et al. (2002), *ApJ*, 568, 771

⋆ Duchêne et al. (2004), *ApJ*, 606, 969

Duchêne et al. (2004), *A&A*, 427, 651

⋆ Duchêne et al. (2005), *A&A*, 628, 832

Duchêne et al. (2007a), *A&A*, 476, 229

Duchêne et al. (2007b), in *Protostars & Planets V*, 379

⋆ Duchêne et al. (2010), *ApJ*, 712, 112

Duchêne & Kraus (2013), *ARA&A*, 51, 269

* Duchêne et al. (2013), *A&A*, 555A, 137

3.3. Status of previously approved Keck programs

The last Keck program led by the PI was conducted during semesters 2008B and 2009B using NIRC2 and the Keck AO system in LGS mode. The goal was to conduct a multiplicity survey of the lowest mass members of the nearby Hyades clusters (including L and T-type brown dwarfs). Results were published in Duchêne et al. (2013).