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# Outlier benchmark systems with Gaia primaries

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## Abstract

Benchmark systems are critical to assisting sub-stellar physics. While the known population of benchmarks has increased significantly in recent years, large portions of the age-metallicity parameter space remain unexplored. Gaia will expand enormously the pool of well characterized primary stars, and our simulations show that we could potentially have access to more than 6000 benchmark systems out to ∼300 pc, allowing us to whittle down these systems into a large sample with outlier properties that will reveal the nature of ultra-cool dwarfs in rare parameter space. In this contribution we present the preliminary results from our effort to identify and characterize ultra-cool companions to Gaia-imaged stars with unusual values of metallicity. Since these systems are intrinsically rare, we expand the volume probed by targeting faint, low-proper motion systems.

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## 1 Introduction

The interpretation of spectra of ultra-cool dwarfs (hereafter UCDs) is complicated by a number of factors: the degeneracy between age and mass for sub-stellar objects; non-equilibrium chemistry; the formation of dust grains in their photosphere, their growth, the dynamics of the clouds, and finally their settling. In particular, deriving the atmospheric parameters from the spectra is a challenging task, since one have to rely on empirical relations. A number of UCDs spectral features have been shown to be sensitive to metallicity and surface gravity (both proxies for age), but the majority of studies have been so far purely qualitative (e.g. Lucas et al., 2001; Kirkpatrick et al., 2010), and the quantitative attempts to calibrate these age indicators suffer from large scatter and limited sample size (e.g. Cruz et al., 2009; Allers & Liu, 2013) or simply do not extend all the way down through the full UCDs regime (e.g. Lépine et al., 2007).

The way forward to achieve more robust calibrations is to study large samples of benchmark systems, i.e. multiple systems formed by stellar objects hosting sub-stellar companions (Pinfield et al., 2006). Age and chemical composition inferred from the primary constrain the atmospheric properties of the sub-stellar companion, and allow for the calibration of the spectroscopic atmospheric parameter indicators. While several benchmark systems have already been found and characterized (e.g. Gomes et al., 2013; Deacon et al., 2014) their number remains limited, and the parameter space is therefore largely under-sampled.

Gaia will greatly increase the size of the UCD population for which atmospheric parameters can be obtained, by providing measurements for a large number of primary stars. Having such a large pool of potential primaries is fundamental, since the fraction of stars with L dwarfs as wide companions could be as low as 0.33% (Gomes et al., 2013). Gaia will allow us to whittle down these systems into a large sample with outlier properties that will reveal the nature of UCDs in rare parameter space (e.g. high and low metallicity).

## 2 Simulations

We simulated the yield of new benchmark systems expected from Gaia by combining the Gaia Universe Model Snapshot (GUMS, Robin et al., 2012) with our own simulations of the field and companion populations of UCDs. Details on the UCDs simulations will be presented in Marocco et al. (in prep). After simulating a realistic observational follow-up, we distinguish between "Confirmable Gaia Benchmarks" (CGBs), i.e. systems that we can hope to confirm with ground-based follow-up, and "non-Confirmable Gaia Benchmarks" (non-CGBs), i.e. systems that we would not be able to confirm. The two populations can be seen in Figure 1 where we plot non-CGBs in gray and CGBs in red, blue and green depending on the type of follow-up required: red points indicate systems that are confirmable requiring common spectrophotometric distance only, blue points are systems that require common spectrophotometric distance and proper motion, green points are systems that require common spectrophotometric distance, proper motion, and radial velocity. Even with minimal follow-up (i.e. requiring common spectrophotometric distance and

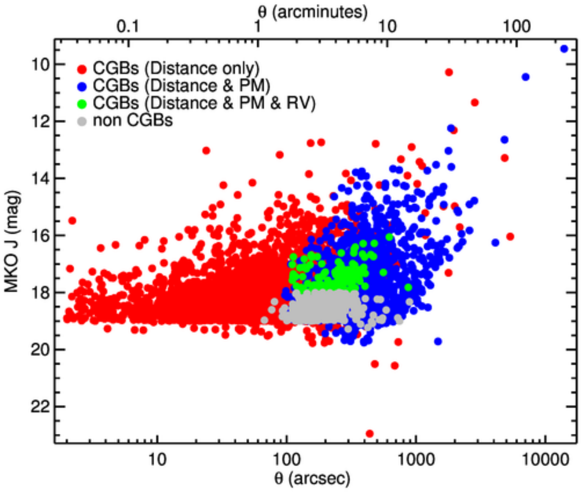

Figure 1: Confirmable and non-Confirmable Gaia Benchmarks. Even with minimal follow-up (i.e. requiring common spectrophotometric distance and proper motion) we can access $\sim$5000 systems, probing out to angular separations $\theta \sim 100$ arcminutes.

proper motion) we can already access a large population ($\sim$5000 systems) extending out to very large angular separation ($\theta \sim 100$ arcminutes).

It is particularly interesting to compare the predicted yield from our simulations to the current population of benchmark systems in terms of distribution in the age−mass parameter space, as we show in Figure 2. The results of our simulations are in the top panel, while in the bottom panel we reproduce Figure 1 from Day-Jones et al. (2011) showing the current population of benchmarks (colour-coded and symbol-coded to highlight the different types of systems). It is clear to see that Gaia will allow us to populate a much larger area of the parameter space, and in particular regions that are so far completely unexplored. These systems are fundamental if we wish to understand the physics of ultra-cool atmospheres.

## 3 Target selection

We selected candidate ultra-cool dwarfs using photometry from ULAS and SDSS, applying simple colour cuts based on the colours of known L and T dwarfs (see e.g. Schmidt et al., 2010; Day-Jones et al., 2013). We then cross-matched UCD candidates with potential FGK primaries which have estimated atmospheric parameters taken from various databases (e.g. the LAMOST DR2, Yuan et al. 2015; the RAVE DR4, Kordopatis et al. 2013; the compendium of photometric metallicities for 100,000 FGK stars in the Tycho-2 catalogue, Ammons et al. 2006; the catalogue of photometrically selected M dwarfs by Cook et al. 2016). We imposed a maximum separation of 3 arcminutes as a compromise between maximizing the number of candidates and minimizing the number of spurious matches. For each candidate system we used either the spectrophotometric or astrometric distance to the primary to calculate the absolute mag-

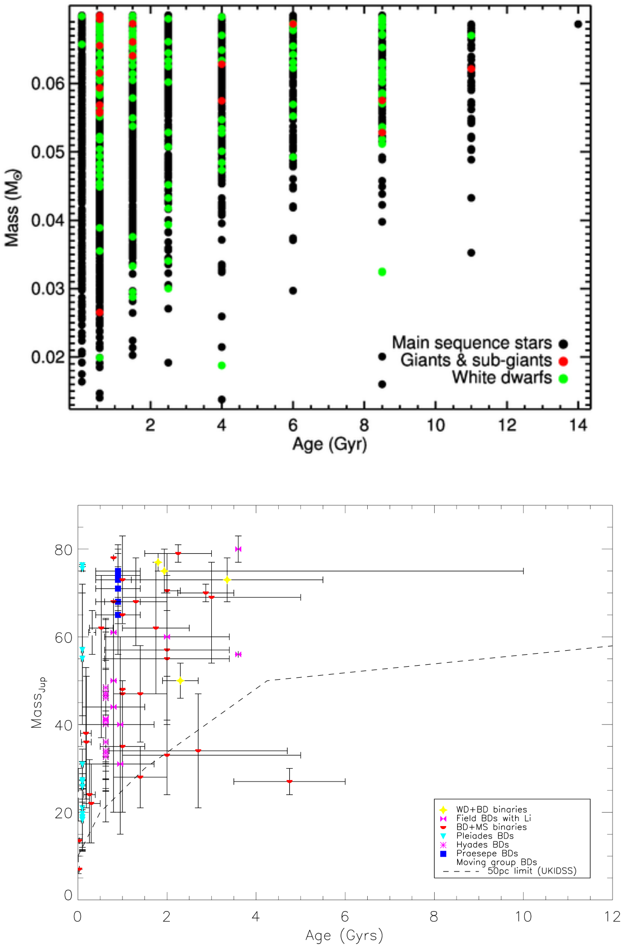

Figure 2: The distribution in the age−mass parameter space of the simulated population of CGBs (top panel) compared to the distribution of known benchmark systems (bottom panel, reproduced from Day-Jones et al., 2011). Gaia will allow us to populate regions of the parameter space that have so far remained unexplored.

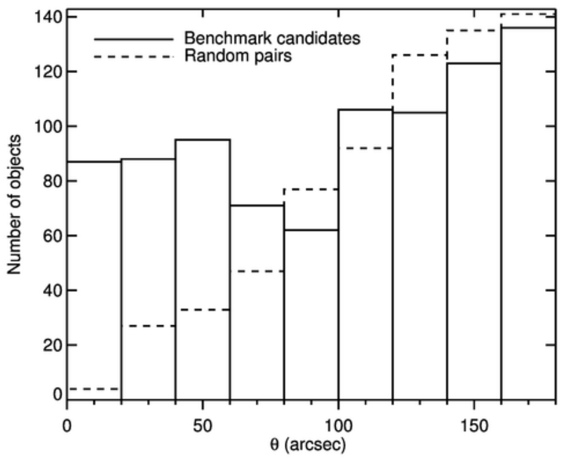

Figure 3: The separation distribution of our candidates, compared with the separation distribution for random pairs. It is clear to see that we retrieve a population of real binaries for $\theta < 90$ arcsec, while at larger separations we are dominated by contamination.

nitude of the companion and then impose more stringent colour−magnitude cuts, based again on the colours and magnitudes of known L dwarfs (see e.g. Dupuy & Liu, 2012) to remove contamination from reddened stars, background galaxies, and quasars.

In Figure 3 we compare the separation distribution for our benchmark candidates with the separation distribution of random pairs of objects in the sky (selected using the same criteria). It is clear to see that while the number of random pairs increases with separation, the benchmark candidates show an excess of systems out to $a \sim 1.5$ arcminutes. At larger separations, spurious matches dominate.

## 4 Conclusions & future work

Although our selection method rules out much contamination, producing a candidate list that is rich with genuine systems, observational confirmation is still an important requirement in order to reject spurious associations. Observations are ongoing to obtain high-resolution spectra with Mercator/HERMES, to characterize the FGK primaries, and low-resolution spectra with WHT/LIRIS and GTC/OSIRIS, to confirm and characterize the UCDs.

Our initial sample targets crucial parameter space using currently available survey and catalogue data, and we are in the process of expanding our sample further by including photometrically selected primaries, and as the LAMOST spectroscopic catalogue grows in size. Moreover, the first data release from Gaia will include the Tycho – Gaia AStrometric Solution (TGASS, Michalik et al., 2015),allowing us to further expand our selection. The search for brown dwarf benchmark systems will be completely revamped. TGASS will provide astrometry for all nearby primaries where the brown dwarf companions are sufficiently bright for characterization. In this way our sample is fully exploiting Gaia to establish a benchmark population that will reveal UCD atmosphere physics across the full sub-stellar parameter space. The correlations derived from our benchmark systems would then be applied to the entire population of L dwarfs, to study the properties of the solar neighbourhood population at the stellar – sub-stellar boundary.

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