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Ultra-cool dwarfs in wide binaries from Gaia

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Abstract

Ultra-cool dwarfs (UCDs) serve as a link between the lowest mass stars and the brown dwarfs. *Gaia* DR2 revealed thousands of ultra-cool dwarfs not identified as such before. In this work, we searched for companions to those in the *Gaia* catalogue, from their common proper motions and parallaxes. We found about 2,300 stars in multiple systems, about 1,300 of them being UCDs out of the original 16,500 sample. Among the companions, there are several tens of young stellar objects and white dwarfs, but also new M7-L2 candidates. Such a sample can be used to better understand the binary properties of UCDs and to better characterize the physics of UCDs thanks to the characterization of higher mass companions.

1 Introduction

Ultra-Cool dwarfs (UCDs) are the lowest-mass, coldest, and faintest products of star formation, making them difficult to study. They were defined by Kirkpatrick *et al.* (1997) as objects with spectral types M7 and later, through L, T, and Y types, have masses $\lesssim 0.1$ $M_\odot$, and effective temperatures $\lesssim 2700$ K. UCDs are of particular interest since they include both very low-mass stars that slowly fuse hydrogen, and brown dwarfs, which have insufficient mass (below about 0.075 $M_\odot$) to sustain hydrogen fusion in their cores, and cool down with time. These objects are nevertheless abundant (> 20% of all stars) and are key probes in Galactic studies. Moreover, they are known to host exoplanets, and are ideal targets for searches for potentially habitable terrestrial planets (such as the recent discoveries around TRAPPIST-1, Gillon *et al.* 2017).

The *Gaia* mission Gaia Collaboration *et al.* (2016) offers the means to uncover nearby UCDs through astrometric, rather than purely photometric, selection. On its completion, *Gaia* should provide high precision astrometry and multi-epoch photometry for over 1000 L- and T-type dwarfs, and potentially tens of thousands of late M dwarfs (Sarro *et al.* 2013). Reylé (2018); Smart *et al.* (2019); Scholz (2020); Gaia Collaboration *et al.* (2020b); and others have undertaken the systematic searches of UCDs in *Gaia* second (*Gaia* DR2, Gaia Collaboration *et al.* 2018) and Early Third (*Gaia* EDR3, Gaia Collaboration *et al.* 2020a) data releases. Nearly 14,000 previously non characterized UCDs candidates have been identified. These are evenly distributed across the sky, filling in “missing” populations in the Southern hemisphere and Galactic plane.

Yet they remain elusive due to their low brightness, and the modeling of their cold and complex atmosphere, and in particular the onset of dust formation, remains challenging. Binaries with UCDs are expected to be relatively common, with binary systems containing M dwarfs accounting for 26.8% of the M dwarf population in the solar neighbourhood according to (e.g. Winters *et al.* 2019). Systems with a higher mass and well characterized primary are benchmarks to constrain the atmospheric parameters and ages of the UCDs (e.g. Marocco *et al.* 2020). Improving our knowledge of binary systems including UCDs can bring constraints on their physics and formation mechanisms.

In this work we use the sample of UCDs revealed by *Gaia* and search for companions from their common parallax and proper motion to investigate their binarity. The sample and the method are described in Sect. 2. The results are given in Sect. 3. Sect. 4 gives the conclusions and perspectives.

2 Sample and method

We started from a sample of 16,526 UCDs selected from the precise *Gaia* DR2 colour absolute magnitude diagram (see Fig. 1), using the data filtering and selection described by Reylé (2018).

We query the *Gaia* DR2 archive[1] (Salgado *et al.* 2018) for companion stars matching the following criteria:

$$\rho < 100\varpi; \Delta\varpi < \max[1.0, 3\sigma_\varpi]; \Delta\mu < 0.1\mu; \Delta\theta < 15^\circ \quad (1)$$

Where ρ is the query radius, equivalent to a maximum projected separation of 100,000 AU from the source star (a conservative upper limit according to Caballero (2009)), $\Delta\varpi$ is the parallax range in the LOS direction, $\Delta\mu$ is the difference in proper motion and $\Delta\theta$ is the angular difference between proper motion vectors. These criteria are discussed in Smart *et al.* (2019).

This search results in 3,445 stars in multiple systems. However the method used is likely to find a non-negligible amount of by chance aligned stars. Since no radial velocity measurements are available for most of the stars nor can we calculate the mass of the system in an accurate enough manner to ensure it is gravitationally bound, we must find an alternative way of assessing the probability of a star being a binary. We thus follow a similar method for Bayesian analysis as described by Hartman & Lépine (2020). In order to compute the bayesian probabilities, we perform a "real" and a "spurious" search. The first one is done within a radius of 1 from the original UCD positions at a parallax of $\varpi \pm \max[1, 3\sigma_\varpi]$. The

[1] https://gea.esac.esa.int/archive/

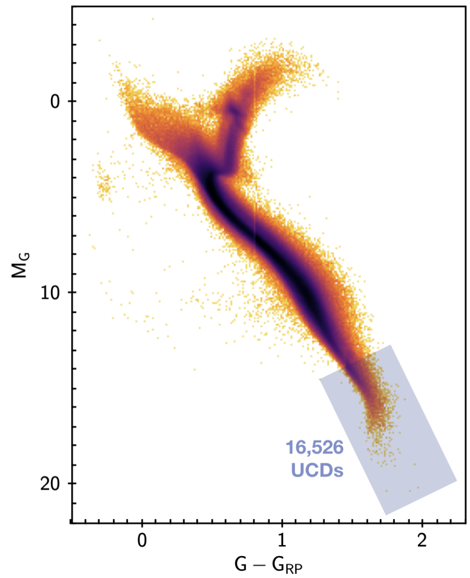

Figure 1: Colour absolute magnitude diagram from *Gaia* DR2 of 3,716,407 stars with reliable astrometric and photometric solutions, avoiding Galactic regions with high extinction, and after removing stars showing color excess using G-J (Reylé 2018). The locus of the UCDs is indicated by the blue rectangle. It is defined from the expected position based on a sample of spectroscopically characterized UCDs.

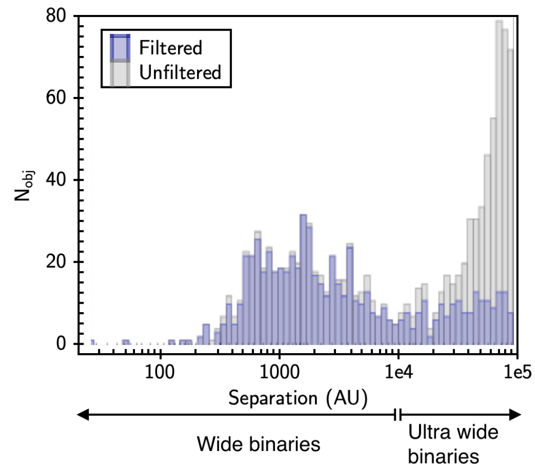

Figure 2: Distribution of logarithmic projected separation before (grey) and after (blue) filtering binaries with Bayes probability less than 0.8. The ultra wide binaries are dominated by chance aligned pairs.

second one is done the same way but shifting the search by 4200 arcsec in declination. Proper motion difference and separation distributions are then computed in both cases and used to defined the difference Bayes probability of being a true or false binary with proper motion difference and separation as priors.

The selection of stars with probability > 0.8 of being binary returns 1,534 stars in systems. Adding all stars in higher order systems, we finally get 2,332 stars.

3 Results

3.1 Multiplicity frequency

Our sample contains 2,332 stars in systems out of which 1,286 are UCDs distributed in 926:182:178 binary, tertiary and higher order systems, respectively. This yields to a multiplicity rate of 7.8% for the UCDs. In comparison, Winters *et al.* (2019) searches for companions to M0 to M9.5 dwarfs including close pairs and finds a multiplicity rate of 26.8%. Since our sample is devoid of close binaries and we do not search for companions to the brighter M0 to M6 dwarfs, it is reasonable to expect our sample to exhibit a lower multiplicity rate.

We also compared this result with the expected UCD binarity from the Gaia Universe Model Snapshot (Robin *et al.* 2012, GUMS), a simulator developped for *Gaia*, and based on a stellar population synthesis model of the Galaxy. We retrieved stars within 100 pc with similar positions in the colour absolute magnitude diagram as our initial UCD sample. 6.2% are in wide binary systems (orbital radius larger than 500 AU. In comparison, our sample shows 5.5% of UCDs being wide binaries, which is consistent with the GUMS result since our initial sample is probably not complete due to the strict filters applied by Reylé (2018) in order to get robust candidates.

3.2 Projected separations

Fig. 2 shows the projected separation distribution, in astronomical unit, of the binary systems, before (in grey) and after (in blue) the filtering from the bayesian analysis.

It can be divided in two groups: wide binaries (< 10^4 AU, herafter WB), and ultra-wide binaries (> 10^4 AU, hereafter UWB). The distribution for WB follows a similar trend as the one shown by Hartman & Lépine (2020) or Arenou *et al.* (2018), with increasing binary number as separation decreases, up to some limit likely due to limiting resolution. In terms of angular separation distribution our sample shows a sharp drop at separation < 6 arcsec. This is higher than the 0.4 arcsec limiting resolution found by Arenou *et al.* (2018), because our sample is dominated by rather faint stars. The change of distribution in the WB and UWB regimes might indicate a different formation mechanism for WB and UWB (see e.g. Tokovinin 2017).

3.3 Spectral type distribution

We used 190,000 objects with spectral type from a SIMBAD[2] (Wenger *et al.* 2000) query to define a spectral type calibration from the median absolute magnitude M_G, and used it to estimate the spectral types of the companions. The distribution of primaries and secondaries (and higher order multiplicity objects) is shown in Fig. 3. The secondaries distribution peaks at M7 due to the selection of our starting UCDs sample. The primaries distribution peak around M3 since there are the most numerous stars in the Galaxy.

Fig. 4 shows the systems in the colour absolute magnitude diagram. The lowest spectral type found is a L3 dwarf which might be a wide companion to the already known binary system LP 395-8 A-B at a projected separation of 42,000AU. The total sample contains 57 L type dwarfs (30 L0, 20 L1, 5

[2] `http://simbad.u-strasbg.fr`

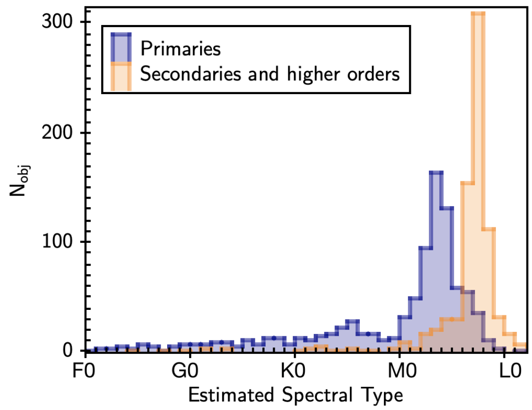

Figure 3: Spectral type distribution of the system components.

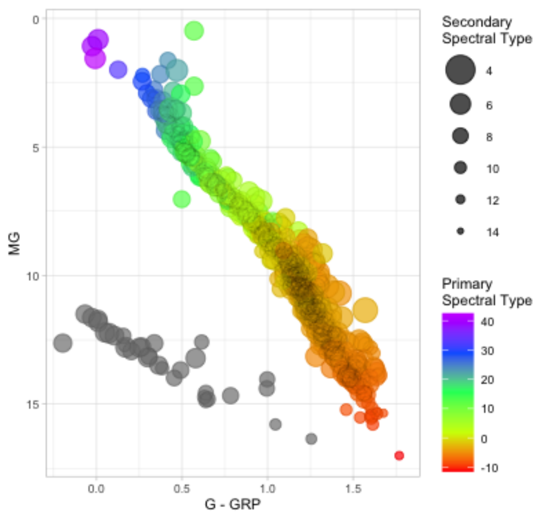

Figure 4: Colour absolute magnitude diagram of the stars in systems. The colour indicates the primary spectral type (white dwarfs are in grey) and the size indicates the secondary spectral type.

L2, 2 L3), 13 of which were not in the initial UCDs sample, meaning they are companions of M7 and later UCDs. There are seven systems with more than one L dwarf. Interestingly enough, only two of them are binary, the others having multiple M-L stars. However, only three of the L dwarfs among the 13 in these systems have 2MASS (Two Micron All Sky Survey; Skrutskie *et al.* 2006) counterpart and the others need confirmation.

We also found 48 white dwarf companions to UCDs. 65% of these systems has a separation lower than 10^4AU, compared to 48% for the full sample. This is reasonable since wide and ultra-wide binaries are relatively instable and easily disrupted, old systems are less likely to have survived. White dwarf and UCD binaries are unlikely to have formed as binaries (from processes that may result in wide binaries such as core fragmentation), a likely mechanism of formation for these systems is through cluster dissolution (see for instance Kouwenhoven *et al.* 2010).

Out of all the multiple systems, four were found to belong to star forming regions, with at least one Young Stellar Object (hereafter YSO) candidate in each group. They lie on the right part of the main sequence. A group of twelve stars are found in the Barnard 59 cloud in the Pipe Nebula. Large parts of this region are obscured by dust so it is likely that more sources are missing. The next most populated group with YSOs is located in the Lupus I cloud and has eight members in our sample.

4 Conclusion

UCDs represent a high percentage of the stars in our neighbourhood, yet they are largely undiscovered because of their typically faint magnitudes. Multiple systems with UCDs offer additional constraints which make it possible to calculate physical properties of each star from orbital dynamical parameters. Since wide systems with UCDs are expected to origin from different formation mechanisms than systems with smaller separations, studying wide and ultra-wide systems can give additional hints on the formation mechanisms of such stars.

Starting from a sample of 16,526 UCDs, we found 1,286 belonging to a multiple system. Most of them were unknown prior to *Gaia* DR2, and 85 UCDs, not included in our original UCD sample, are found to be companions.

These systems are divided into wide and ultra-wide systems according to their projected separations and follow different distributions with projected separation which are consistent with expectations from literature.

We will confront our findings with recent similar searches (Gaia Collaboration *et al.* 2020b; El-Badry *et al.* 2021) using Gaia EDR3. We started spectroscopic follow-up of these pairs (see Low *et al.* 2021) to learn UCDs physical properties from the higher mass primary.

Acknowledgments

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