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NEW ULTRACOOL DWARFS IN GAIA DR2

C. Reylé[1]

Abstract. Detailed population studies of ultracool dwarfs are persistently plagued by incompleteness. While hundreds of ultracool dwarfs have been uncovered in red and infrared sky surveys, this population remains incomplete, even in the solar neighborhood, due to their faint magnitudes. The Gaia mission has provided the means to uncover nearby VLM dwarfs through astrometric, rather than purely photometric, selection. This holds the promise of a truly volume-complete sample.

In this paper, we present the content of *Gaia* DR2 at the low-mass end. We first investigate the known sample of ultracool stars and brown dwarfs retrieved in *Gaia* DR2 and compare it with the up-to-date BT-Settl atmosphere models. We next show that thousands of new candidates are revealed by *Gaia* DR2, covering the whole sky. Over 200 candidates have measured distances of less than 30 parsec, showing that even the nearby census is not complete.

Keywords: Stars: low-mass – Brown dwarfs – Solar neighbourhood – Galaxy: stellar content – Surveys: *Gaia* – Catalogs: *Gaia* DR2

1 Introduction

The *Gaia* mission (Gaia Collaboration et al. 2016b) provides full sky coverage down to the *Gaia* magnitude G = 20 (V≃20-22), at the spatial resolution of the HST, with about 70 observations per source over 5 years. Trigonometric parallaxes – with the amazing precision of 1% up to 2.5 kpc at the end of the mission– and proper motions are now measured for 1.3 billions stars.

As highlighted in the scientific demonstration paper from Gaia Collaboration et al. (2018a), *Gaia* astrometry and photometry are powerful tools for studying fine structures within the Hertzsprung-Russell (HR) diagram. It is now possible to distinguish the locus of different type of objects, as model-predicted, including at the low-mass end of the HR diagram.

Ultra-cool dwarfs have been defined by Kirkpatrick et al. (1997) as M7 and later main sequence stars. This corresponds to an effective temperature of $\lesssim$ 2700 K (Rajpurohit et al. 2013). These objects serve as a link between known stars and brown dwarfs. Indeed, they span the stellar/sub-stellar mass transition: such an effective temperature in expected in a 0.03 $M_\odot$ object of 8 Myr or in a 0.095 $M_\odot$ object of 10 Gyr (Baraffe et al. 2015), both at solar metallicity.

Smart et al. (2017) compiled an input catalogue of known L and T dwarfs, with estimated *Gaia* magnitude G<20.3, within the reach of Gaia. They identified part of them in *Gaia* DR1 (Gaia Collaboration et al. 2016a). They found 321 L and T dwarfs, with 10 >=L7, which corresponds to 45% of the brown dwarfs bright enough to be seen by *Gaia*. As they pointed out, this incompleteness is mainly due to the cuts made in the catalogue to insure the quality of the data. With eight more months of observations, *Gaia* DR2 (Gaia Collaboration et al. 2018b) should provide more complete and precise data, and help to fill that gap. Recent discoveries show that even the local census is not complete as illustrated by the discovery of a L7 at 11 pc, close to the galactic plane (Scholz & Bell 2018; Faherty et al. 2018).

In a first step, we search for known ultra-cool and brown dwarfs in *Gaia* DR2 and investigate their properties using their *Gaia* observations (section 2). In a second step, we use the properties from the known sample to show the potential of *Gaia* DR2 to reveal new candidates (section 3). The conclusions and perspectives are given in section 4.

[1] Institut UTINAM, CNRS UMR6213, Univ. Bourgogne Franche-Comté, OSU THETA Franche-Comté-Bourgogne, Observatoire de Besançon, BP 1615, 25010 Besançon Cedex, France

2 Already known ultra-cool and brown dwarfs found in Gaia DR2

We focus on the well-characterized sample of ultra-cool and brown dwarfs, having a spectroscopic spectral type. A compilation of all L, T and Y dwarfs that *Gaia*should directly observe, or indirectly constrain (e.g. in a common proper motion systems with brighter members), the so-called *Gaia*Ultracool Dwarf Sample (GUCDS), has been published in Smart et al. (2017). GUCDS is based on the on-line census compiled by J. Gagné[*] which contains all objects from the Dwarfarchives[†] database, complemented by the Dupuy & Liu (2012) and Mace (2014) catalogs. Some of these objects have an information on their age or metallicity, and are listed in the census as young candidates or subdwarfs. Smart et al. (2017) added the recent discoveries from Marocco et al. (2015); Faherty et al. (2016). This catalog has 1886 entries, with 1010 L and 58 T dwarfs having a predicted G magnitude brighter than 21.5, within the reach of *Gaia*.

To this census, we add the ultra-cool (M7-M9.5) dwarfs listed by J. Gagné[‡], and the new spectroscopically confirmed objects from Rajpurohit et al. (2014); Robert et al. (2016); Faherty et al. (2018); Zhang et al. (2018). Because we want to study the location in the fine *Gaia* DR2 HR diagram of a well-characterized sample, the numerous candidates found in photometric surveys without spectroscopic confirmation are not included.

We retrieve these entries in *Gaia* DR2 and found 3671 ultra-cool ($\geq$M7), 647 L, and 16 T dwarfs. Twenty six are noted in the census as subdwarfs, and 75 as young candidates. The spectral type distribution of the input catalog (black line), the sample with an entry in *Gaia* DR2 (gray line), and the sub-sample with $\sigma_\varpi \leq 10\%$ (filled-gray) is shown in Fig. 1, left panel.

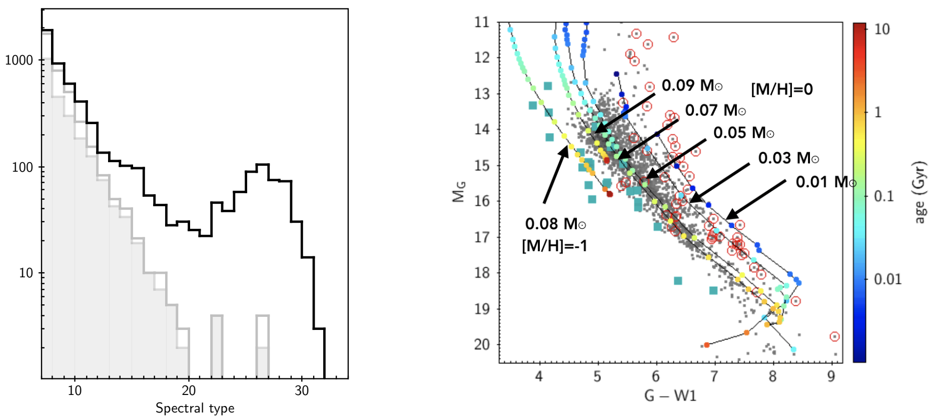

Fig. 1. Left : Spectral type distribution of the known ultracool ($\geq$M7) and brown dwarfs. 10 stands for L0 and 20 for T0, 30 for Y0 on the spectral type axis. **Right :** BT-Settl evolution tracks superimosed with the known sample. Mass and metallicity of the tracks are indicated. The color-bar gives the logarithm of the age in Gyr.

We built the HR diagram by computing the absolute *Gaia* magnitude in the G band for individual stars using $M_G = G - 5\log_{10}(1000/\varpi) + 5$, where ϖ is the parallax in milli arcsec. The simple distance determination from ϖ is valid when $\sigma_\varpi \lesssim 20\%$ (Luri et al. 2018).

Fig. 2 shows the HR diagram of the known sample. We use G-G_{RP} as the color index (upper left panel), as these faint and red objects have lower flux in the BP bandpass. In the other panels, we show the HR diagram with color indices using 2MASS and WISE bandpasses, using the cross-match of *Gaia* DR2 with 2MASS and WISE provided in the *Gaia* archive (Marrese et al. 2017).The red circles and cyan squares show the objects found to have low gravity (young objects) and low metallicity (subdwarfs) from there spectrum. Thanks to the high accuracy of these diagrams, the locus of young objects and subdwarfs can be separated from other objects, in particular when using the WISE bands, where the end of the sequence splits into two parts.

Thus this well characterized sample provides an unprecedent dataset - with distance estimate - to define absolute magnitude versus color, and versus spectral type relations (Reylé 2018; Smart et al. 2019). Furthermore the parallaxe is a strong added-value to test and refine evolution and atmosphere models. As an illustration,

[*] https://jgagneastro.wordpress.com/list-of-ultracool-dwarfs/
[†] http://dwarfarchives.org
[‡] https://jgagneastro.wordpress.com/list-of-m6-m9-dwarfs/

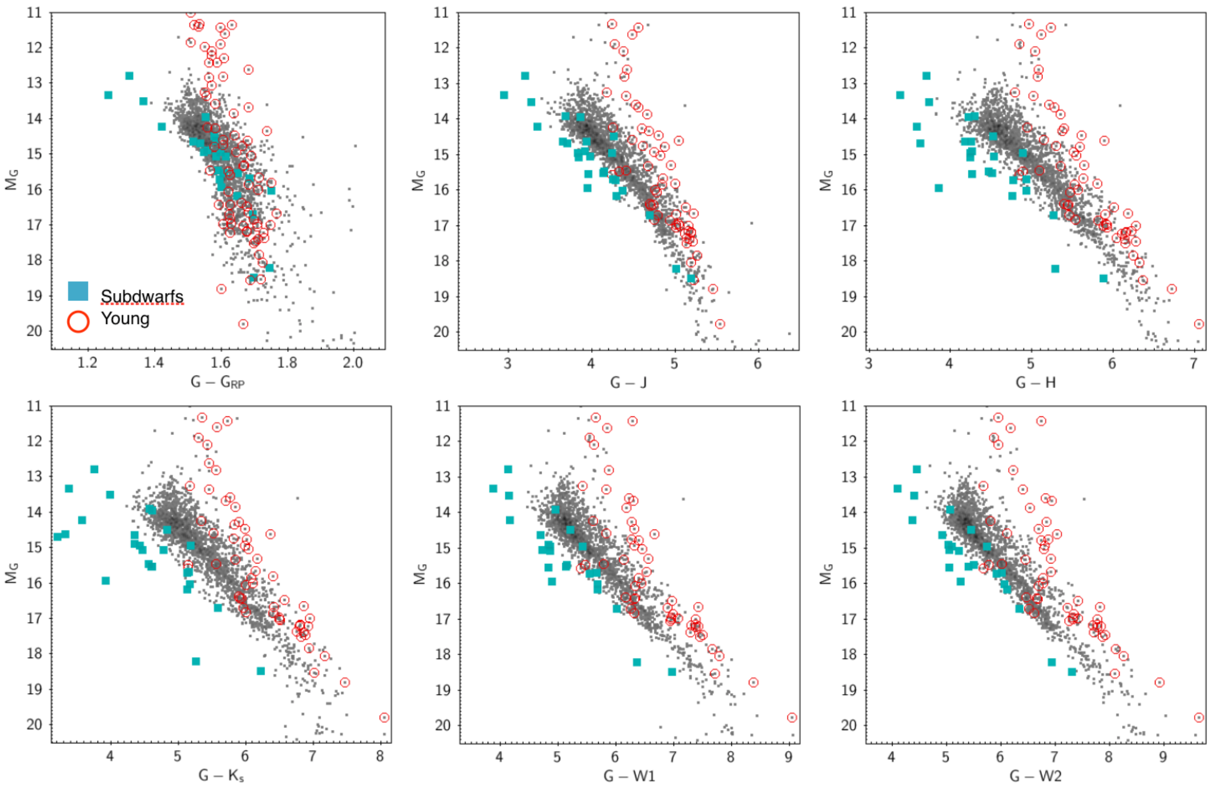

Fig. 2. HR diagram of the known ultra-cool dwarfs found in *Gaia* DR2.

Fig. 1, right panel, shows a comparison with the evolutionary models from Baraffe et al. (2015) that consistently couple interior structure calculations with the BT-Settl atmosphere models (Allard et al. 2013). The comparison tends to confirm the locus of the objects as a function of their peculiarities (age, metallicity).

3 New ultra-cool and brown dwarf candidates in Gaia DR2

Our aim is to find candidates robust candidates, so we applied trong filter on *Gaia* DR2. These filters are fully described in (Gaia Collaboration et al. 2018a, , and references therein). Here we only give a brief description of their effects. They retain objects with $\sigma_{M_G} < 0.22$ mag, $\sigma_G < 0.022$ mag, $\sigma_{G_{RP}} < 0.054$ mag, reliable five parameters solution (astrometric and photometric), and remove most artifacts. The corresponding *Gaia* archive[§] query is given in the annexe B of Gaia Collaboration et al. (2018a). Following Gaia Collaboration et al. (2018a), we also restrict the sample to low extinction regions in the Milky Way, and keep the objects with $E(B-V) < 0.015$ according to the 3D extinction map of Capitanio et al. (2017). The resulting fine HR diagram can be seen in Fig. 3 (left panel).

The HR diagram has a fuzzy appearance between the white dwarfs and the main sequence, and redward of the main sequence. This can be explained by a background contamination in the blue (BP) and red (RP) photometers. These objects with color excess can be rejected using an empirical filter, as defined by Evans et al. (2018); Arenou et al. (2018). The resulting HR diagram when applying this filter is shown in the middle panel of Fig. 3. Because ultra-cool and brown dwarfs have low flux in the BP bandpass, they are very sensitive to any background over-estimation yielding to a high color excess. As a consequence, most of these objects are rejected, as can be clearly seen at the low-mass end of the main sequence. As an illustration, applying this filter on the known sample dramatically removes 47% of the objects (68% of the L and T dwarfs) found in *Gaia* DR2.

In Reylé (2018) we define a more suitable criterion to retain these faint and red objects, which does not rest upon the BP flux, but on the 2MASS J magnitude. Note that the use of the J magnitude is rejecting ∼20% of

[§]https://gea.esac.esa.int/archive/

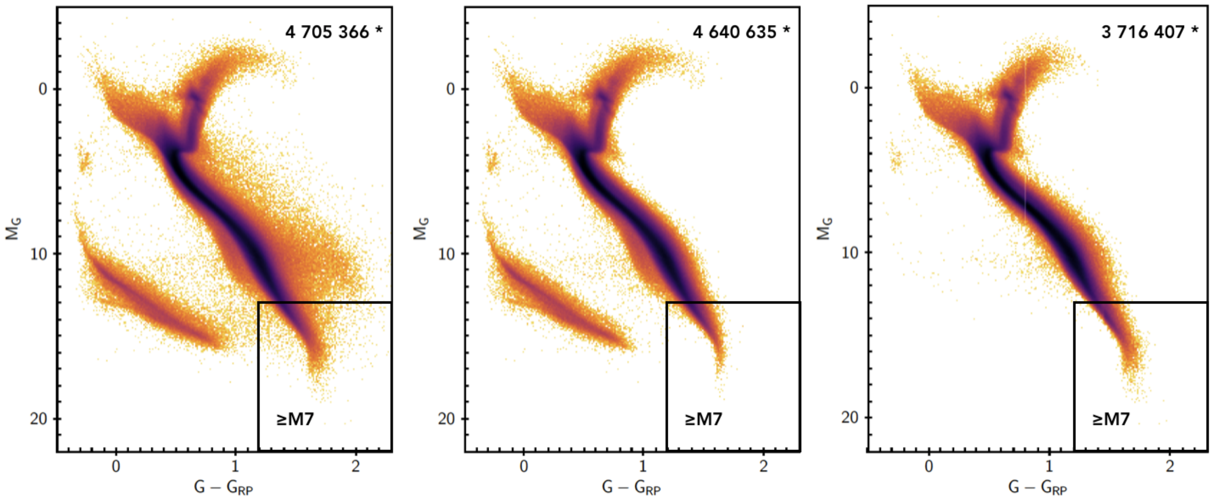

Fig. 3. The HR diagram of *Gaia* DR2. See text for the description of the different selections. The squares show the expected locus of M7 and later dwarfs.

the candidates with no 2MASS counterpart or a 2MASS photometric quality flag $Q_{fl} \neq$ AAA. The removing of objects below this limit allows to get rid of objects with spurious colors but still to retain the low-mass objects, as well as most of the already known sample. The resulting HR diagram is shown in the right panel of Fig. 3.

Fig. 4 focuses on the *Gaia* DR2 HR diagram at the low-mass end, superimposed with the sample of spectroscopically confirmed ultracool dwarfs retrieved in *Gaia* DR2.

We use the information on the spectral type to define separations in the HR diagram. They are shown by the lines on the left panel. We also use the peculiarities of the known sample to tentatively define regions where subdwarfs and young candidates are expected to be dominant (dashed lines on the right panel). These selections suggest that *Gaia* DR2 contains a large number of new candidates : 14 176 $\geq$ M7 and 488 L (all earlier than L5). Among them 233 $\geq$ M7 and 70 L are young candidates, and 466 $\geq$ M7 and 17 L are subdwarfs candidates. These are, of course, indicative numbers. They are published on a table available on-line ¶.

Fig. 5 shows the sky distribution of known (left) and new candidates (right). The new candidates are evenly distributed across the sky, filling in "missing" populations in the Southern hemisphere and Galactic plane. The imprint of the *Gaia*scanning law is visible on the plot, where no candidates are found in some Galactic regions, which are rejected as they do not fulfill our conditions. Thus new candidates are expected to be found in the forthcoming *Gaia*data releases.

Fig. 6 shows the distance distribution of known (pink) and *Gaia* DR2 new candidates (blue) L (left) and >M7 (right) dwarfs. Whereas several recent efforts (see Best et al. 2018) were made to complete the volume-limited sample of brown dwarfs up to 25 pc, *Gaia* shows that the census is not complete beyond 30 pc. The situation is even worst for >M6 dwarfs, which is not surprising since we only consider here the objects with spectroscopic confirmation. The ongoing and future spectroscopic large survey such as APOGEE (Majewski et al. 2017), LAMOST (Cui et al. 2012), WEAVE (Dalton et al. 2014), 4MOST (de Jong et al. 2016) will soon complete the census further away.

4 Conclusion

Gaia DR2 reveals numerous new ultracool candidates. The given numbers are indicative only but they also prove that the census is not complete yet, even locally. *Gaia* DR2 contains 65% of all bright enough objects estimated to be within the reach of *Gaia*. Moreover *Gaia* DR2 is an intermediate release, on which we applied strong filters. Thus further releases may provide even more candidates.

The high precision of the HR diagram allows us to give an indication of some of the characteristics of these

¶`http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=J/A+A/619/L8`

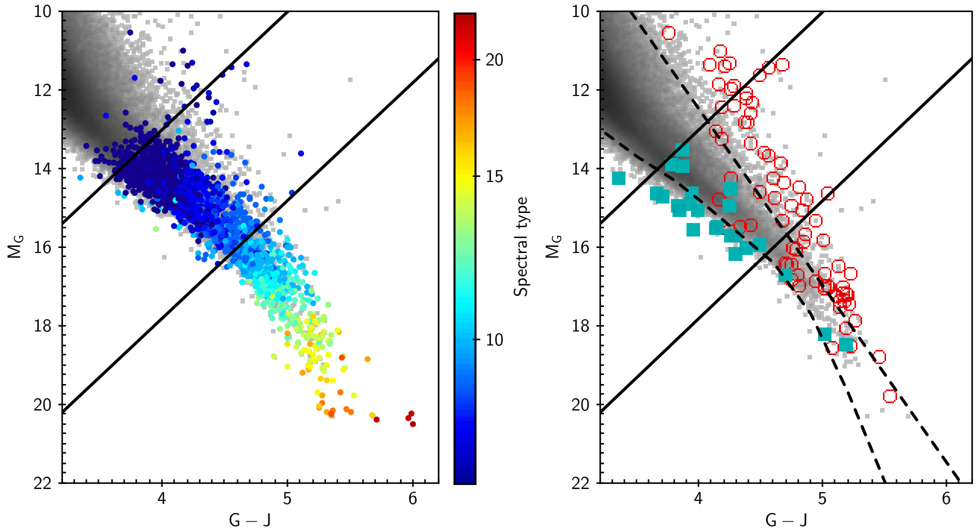

Fig. 4. HR diagram of the filtered *Gaia* DR2 at the low-mass end, superimposed with the already known, spectroscopic sample. Left: $M_G$vs G-G_{RP}. The color-code is function of spectral type and allows to define three regions, shown by the the lines: >M7, L, and T dwarfs. Right: $M_G$vs G-J. Squares are the known subdwarfs, open circles are the young candidates. The dashed lines aim to separate these different types.

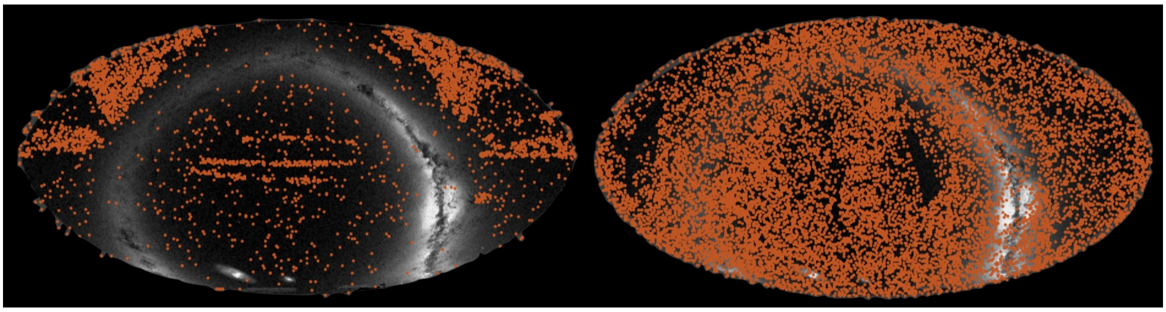

Fig. 5. Sky distribution in galactic coordinates of known ultracool dwarfs having a counterpart in *Gaia* DR2 (left), and of all candidates found in *Gaia* DR2 (right).

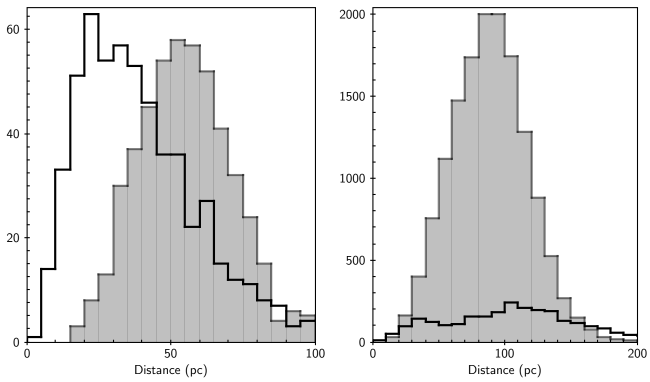

Fig. 6. Distance distribution of the L (left) and >M6 (right) dwarfs, for the already known sample (pink) and the candidates found in the filtered *Gaia* DR2 data (blue).

objects (spectral type, young, or subdwarf). This rough classification is done to guide the target selection for follow up, depending on the scientific case one may want to study. These numerous candidates are most valuable for follow-up since they benefit from the reliable *Gaia* observations, including precise parallax and proper motion.

Further exploitation of this dataset will be useful for making a complete census of late-M and at least early-type brown dwarfs, refining their luminosity function, testing stellar and substellar models, and probing the old population in the Galaxy through the subdwarf candidates.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France. The original description of the VizieR service was published in A&AS 143, 23. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. The author made queries at CDS using Virtual Observatory with python (Paletou & Zolotukhin 2014). All figures have been generated using the TOPCAT[‖] tool (Taylor 2005).

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