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Gaia limits for brown dwarf studies

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Abstract. In this work we present a study of the expected properties of the *Gaia* sample of ultracool dwarfs (UCDs). This is defined preliminary (at a stage where we do not have real *Gaia* data yet) by analysing the detectability by *Gaia* of known UCDs in the Dwarf Archive. We complement the observations listed in the Dwarf Archive (J-, H-, and K- band magnitudes) with SDSS magnitudes and compare them with the BT-Settl model library in order to assess detectability. We also discuss the fraction of UCDs that will have accompanying RVS spectra in the Calcium triplet wavelength region.

Key words. Methods: data analysis – Stars: brown dwarfs – Stars: fundamental parameters

1. Introduction

Gaia was successfully launched on 14 Dec. 2013 and, at the time of this writing, the commissioning phase is coming to an end with the final set of EPSL (Ecliptic Pole Scanning Law) orbits. From this period we have learned that condensations in the mirrors and stray light will slightly degrade the instrument performances, especially in the RVS (Radial Velocity Spectrometer) data. Despite these uncertainties, this is a good time to review the expected characteristics of the *Gaia* data base with respect to its brown dwarf content.

To that end, we review the nominal instrument performances at the time of launch in Sect. 2, and apply the resulting limits to the Dwarf Archives[1] set of brown dwarfs to determine the detectability of each source therein, and assess the expected properties of *Gaia* brown dwarf data set (Sect. 3).

[1] `http:dwarfarchives.org`

2. *Gaia* instrument performances

The nominal instrument performances can be found in the official *Gaia* mission web site[2]. These performances come from the *Gaia* Mission Critical Design Review in 2011 and thus do not incorporate the performance degradation mentioned in the previous section and still under quantification. Frequent updates on the status of the commissioning phase can be found at `http://blogs.esa.int/gaia/`, and a more complete and technical report is expected at the end of the phase.

Sarro et al. (2013) detailed the technical aspects of the software module dedicated to the detection and characterization of brown dwarfs in the Apsis (Bailer-Jones et al., 2013) chain of the *Gaia* data processing and analysis pipeline. The aspects of instrument performance most directly linked to the proper-

[2] `http://www.cosmos.esa.int/web/gaia/science-performance`

ties of the *Gaia* ultracool dwarf sample (hereafter GUCDS) are (*i*) the dependence of the detectability of brown dwarfs with distance and spectral type, (*ii*) the expected astrometric uncertainties for very red objects in the faint detection limit, and (*iii*) the expected signal-to-noise ratio for Red Photometer spectra at that limit.

The first aspect in the list was addressed in Sarro et al. (2013) and depends on the assumed relationship between spectral type, age/gravity, and absolute G magnitude. In that work we used BT-Settl models Allard et al. (2012) and the nominal G band transmission to infer a maximum distance at which a given ultracool dwarf (UCD) could be detected. In terms of the absolute I band magnitude, we can summarise it with a few values. The maximum distance for a M6–7 dwarf is of the order of 190 pc; for spectral type M8–9, 120 pc; for spectral type L3–4, 35 pc. We refer the reader to that work and Caballero et al. (2008) for details on the derivation. The expected astrometric uncertainty for an M6 dwarf at the detection limit G = 20 mag is 100 μas and is not expected to change significantly for later spectral types.

The nominal RVS magnitude limit was $G_{\rm RVS} \approx 16$ mag. Ultracool dwarfs have typical $V-I$ colour indices in the range between 4 and 7.5 mag, which translate into $G-G_{\rm RVS}$ between 1.75 and 2.1 mag according to the parametrization in Jordi et al. (2010) and the set of BT-Settl models used in this work. Assuming the local spatial densities of Caballero et al. (2008), it implies that RVS spectra would be available for a few hundred UCDs (mostly of the earliest spectral types) down to G = 18.1 mag, as shown in Fig. 4 of Sarro et al. (2013). Unfortunately, the RVS spectrometer measurements are the ones most affected by the stray light detected during the commissioning phase, and a one magnitude shift in instrument performance is a reasonable estimate at the time of writing, therefore severely reducing the number of potentially available RVS spectra of ultracool dwarfs. Figure 1 shows the BT-Settl spectra in the RVS range for five temperatures between 500 and 2500 K. At present there is little hope for the utility of RVS spectra of UCDs for the estimation of physical parameters.

3. Properties of the (expected) *Gaia* brown dwarf sample

In this Section we aim at predicting what known UCDs will be detected by *Gaia* and what would be the distribution of the GUCDS if the sample of known UCDs were complete down to the nominal *Gaia* detection limit. In order to do so, we focus our study in the Dwarf Archives catalogue of 1281 L, T and Y dwarfs.

The first step in our analysis consists in estimating the apparent G magnitude of the UCDs in the Dwarf Archives sample. The *Gaia* detection limit is determined by the apparent G magnitude, with a threshold nominally set at G = 20 mag although on-going studies may lower the magnitude limit to G = 21 mag. Given the predominantly red spectral energy distribution of UCDs, and the relative availability of photometric measurements in the SDSS system of bandpasses with respect to other systems, we attempt to parameterise the apparent G magnitude in terms of the i and z bands. We use the BT-Settl models to define a parametrization defined by:

$$G - i = 0.13 + 1.43(i - z) - 1.20(i - z)^2 + 0.35(i - z)^3 - 0.06(i - z)^4 \quad (1)$$

We subsequently search the SDSS[3] catalogue to complement the Dwarf Archives data base with i and z photometric measurements. Dwarf Archives include infrared photometry in the J, H and K bands, but these do not produce narrow, monotonous correlations with the optical broad band filter that defines the G magnitude. We find potential counterparts to 948 sources in the Dwarf Archives catalogue, 587 below 2 arcsec.

Figures 2 show the distribution of the sample of UCDs in the Dwarf Archives catalogue with cross-match candidates within 2 arcsec, in several colour-colour diagrams. In each plot we show the photometric measurements

[3] http://www.sdss.org/

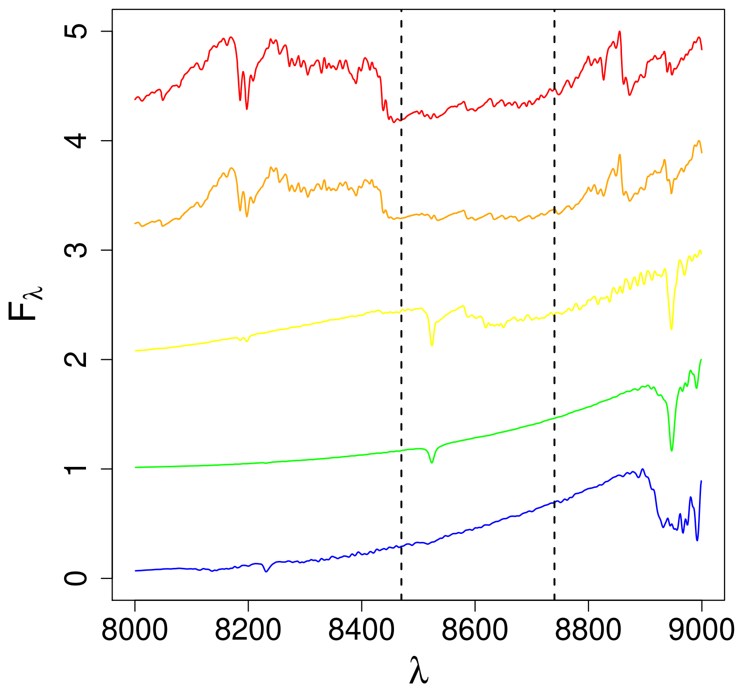

Fig. 1. BT-Settl spectra of UCDs of effective temperatures equal to 500 K (blue), 1000 K (green), 1500 K (yellow), 2000 K (orange), and 2500 K (red). The vertical dashed lines represent the blue and red limits of the *Gaia* RVS spectrograph. All five spectra have been degraded to the nominal RVS spectral resolution.

with corresponding error bars in a gray scale, and the collection of BT-Settl models with colours. The colour code for the error bars goes from black for small cross-match separations to white at the largest allowed separation of 2 arcsec. The BT-Settl models on the other hand are coded according to the corresponding effective temperature as shown in the color scale to the right of the plots.

These figures should be compared to the preliminary results with SDSS data by Hawley et al. (2002). Their sample extends to spectral types significantly earlier than ours, but there is a region of overlap between both samples in the sense that their cooler sources correspond to our hotter ones. Thus, we have extended the dataset of UCDs with complete photometric measurements in *riz* and *JHK* bands to fainter, cooler spectral types. Our results coincide with those of Hawley et al. (2002) in the region of overlap, but show significant discrepancies with the BT-Settl models in all diagrams involving the *r*-band magnitude.

This data set of sources with complete measurements in SDSS and 2MASS bands can be used to estimate the corresponding apparent G magnitudes using the parametrization in Eq. 1 and predict which of these Dwarf Archives UCDs will be brighter than the *Gaia* detection threshold. We find a total number of 124 Dwarf Archive sources brighter than $G = 20$ mag, and 320 brighter than $G = 21$ mag. If we apply a simplistic correction to account for the fraction of Dwarf Archive sources without counterpart available in the SDSS passbands (43% of the Dwarf Archive data set),

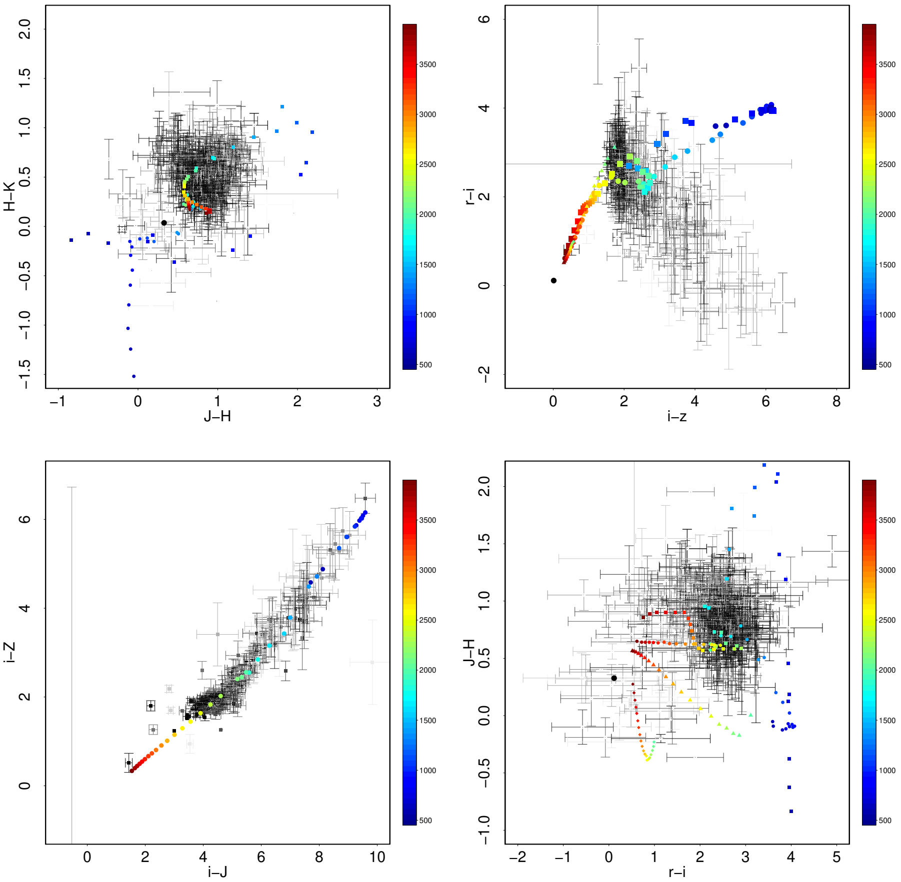

Fig. 2. Colour-colour diagrams for the Dwarf Archives UCDs with *riz* magnitudes obtained from the SDSS database. BT-Settl models are superimposed with a colour code that represents effective temperatures according to the scales to the right of each plot.

these numbers transform to 288 sources down to G = 20 mag and 744 sources down to G = 21 mag. The first figure is similar to the estimate by Smart (2014) while the second is significantly larger than his, but still less than expected given the volume factor expansion in going from G = 20 to 21 mag. We believe that the difference between Smart's estimates and ours arises because he is using the calibration between *Gaia* and SDSS by Jordi (2010) which is based on the spectral library of O- to M-type dwarf and giant stars by Pickles (1998). Therefore, it is of limited applicability for the coolest spectral types L and T, which would explain the discrepancy when going to the fainter G = 21 mag limit.

Figure 3 shows the number of sources in apparent G bins estimated from the local densities by Caballero et al. (2008) (gray), and from the Dwarf Archives catalogue (corrected for the fraction of sources without available cross matches in the SDSS bands; violet). It seems to indicate that either the local densities result in a 0.3–0.5 dex overestimate of the counts per bin, or the Dwarf Archives catalogue is incomplete by that same factor, or a mix of both effects may be present at the same time. According to the work presented by Smart (2014), there is

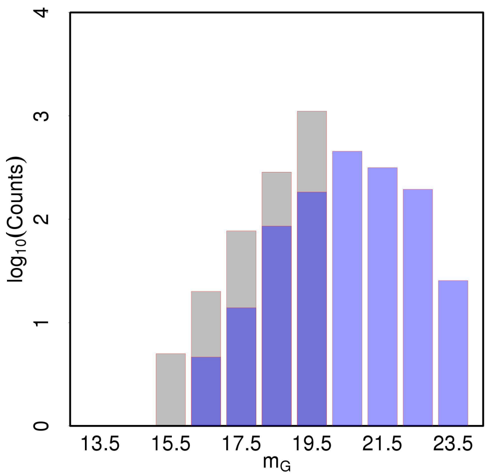

Fig. 3. Predicted UCD counts per magnitude bin in the GUCDS according to the BT-Settl models and (*i*) the local spatial densities from Caballero et al. (2008) (gray) and (*ii*) the Dwarfs Archive sample corrected for the fraction of entries measurements in the SDSS photometric system.

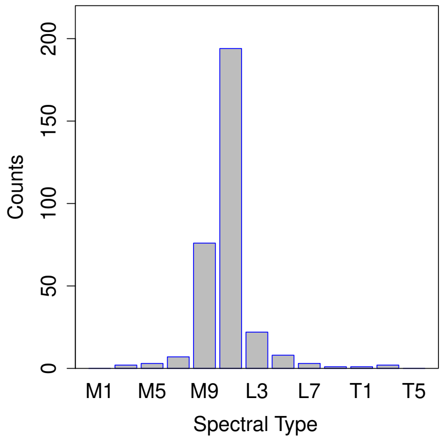

Fig. 4. Distribution of spectral types of sources in the Dwarf Archive that can be detected by *Gaia* (with estimated *G* magnitudes brighter that 20 mag).

evidence supporting an incompleteness factor of at least two in the Dwarf Archive under the assumption of isotropy and local homogeneity in the local distribution of UCDs, which would explain part of the discrepancy.

If we convert the $i - J$ colour index into a spectral type using the calibration by Hawley et al. (2002), we obtain the distribution of types shown in Fig. 4.

If we apply a similar analysis to a set of nearby star forming regions and clusters, assuming the corresponding set of distances and ages, and the BT-Settl family of synthetic spectra, we can estimate the I-band magnitude that corresponds to the Gaia detection limit of $G = 20$ mag, and the corresponding values of mass, effective temperature, and spectral type. The results are summarised in Table 1. *Gaia* will detect a significant number of UCDs with spectral types from mid-M to late M, and few L0. Note that in the case of very young, nearby associations, the masses will be close or even below the deuterium burning mass limit. Thus, some "isolated planetary-mass objects" might be detected.

4. Conclusions

We have used the *Gaia* pre-launch performances as assessed during the Critical Design Review carried in 2011 to infer what can be expected of the GUCDS, in particular, the distribution of spectral types and the detectability of known UCDs in the Dwarfs Archive data base. In the process of inferring apparent G magnitudes for these Dwarf Archives UCDs, we have extended the set objects with observations in both *riz* and *JHK* bands well beyond the coolest examples in the previous work by Hawley et al. (2002). We obtained SDSS photometry for 587 UCDs in the Dwarfs Archive database, reaching spectral types in the T sequence.

As in Sarro et al. (2013), these conclusions rely on many uncertain assumptions. They depend on the final performance of the satellite instruments in the first place, but also critically on the calibration of the relationship between magnitudes in different passbands obtained from the BT-Settl models, or the calibration of spectral types with the $i-J$ colour index. In particular, we show that the predictions from the Dwarfs Archive and from local spatial densities disagree by a factor at least two. We recommend caution when using these estimates

Table 1. An estimate of the coolest spectral type detectable with *Gaia* in several young nearby star forming regions and clusters.

Region	d [pc]	Age [Myr]	Dimmest M_I [mag]	Mass [M_{Jup}]	T_{eff} [K]	Sp. type
ρ Ophiuchi	120–145	1	13.05	10	2200	L0
Taurus	140	1–2	12.70	16	2400	M9
Serpens	260	2	11.38	27	2600	M8
Chamaeleon I / II	140	1–3	12.70	18	2400	M9
Lupus I / II / III	140	1–3	12.70	18	2400	M9
IC 348	385	2–4	10.54	37	2700	M7
Trumpler 37	800	4	7.83	201	3200	M4
σ Orionis	400	2–4	10.45	42	2800	M6
Collinder 69	400	5–10	10.45	49	2800	M6
Upper Scorpius	145	5	12.62	21	2400	M8
NGC 7160	800	10	7.83	317	3400	M3
IC 2391	175	30–55	12.21	45	2600	M7
IC 2602	160	30–50	12.41	42	2600	M7
IC 4665	350	45	10.77	91	3000	M5
α Persei	185	80	12.09	60	2700	M7
Blanco 1	270	100	11.31	83	2900	M6
Pleiades	150	125	12.55	58	2600	M7
Hyades	50	600	14.99	37	2200	L0
Praesepe	187	800	12.07	72	2800	M6

since at the time of writing this manuscript the impact of condensations and stray light on the final performances of the *Gaia* instruments is still uncertain. On the other hand, the on-going study about a potential extension of the *Gaia* limiting magnitude down to $G = 21$ mag would have an important and positive effect on the completeness of the GUCDS.

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