The \textit{Gaia} ultracool dwarf sample – I. Known L and T dwarfs and the first \textit{Gaia} data release

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ABSTRACT

We identify and investigate known ultracool stars and brown dwarfs that are being observed or indirectly constrained by the \textit{Gaia} mission. These objects will be the core of the \textit{Gaia} ultracool dwarf sample composed of all dwarfs later than M7 that \textit{Gaia} will provide direct or indirect information on. We match known L and T dwarfs to the \textit{Gaia} first data release, the Two Micron All Sky Survey and the \textit{Wide-field Infrared Survey Explorer} AllWISE survey and examine the \textit{Gaia} and infrared colours, along with proper motions, to improve spectral typing, identify outliers and find mismatches. There are 321 L and T dwarfs observed directly in the \textit{Gaia} first data release, of which 10 are later than L7. This represents 45 per cent of all the known LT dwarfs with estimated \textit{Gaia} $G$ magnitudes brighter than 20.3 mag. We determine proper motions for the 321 objects from \textit{Gaia} and the Two Micron All Sky Survey positions. Combining the \textit{Gaia} and infrared magnitudes provides useful diagnostic diagrams for the determination of L and T dwarf physical parameters. We then search the Tycho-\textit{Gaia} astrometric solution, \textit{Gaia} first data release subset, to find any objects with common proper motions to known L and T dwarfs and a high probability of being related. We find 15 new candidate common proper motion systems.

Key words: binaries: visual – brown dwarfs – Hertzsprung–Russell and colour–magnitude diagrams – stars: late-type – solar neighbourhood.

1 INTRODUCTION

\textit{Gaia} is observing over a billion objects in our Galaxy and is revolutionizing astronomy in many areas (Gaia Collaboration et al. 2016a). One of these areas is the study of the bottom of the main sequence and beyond. L and T (hereafter LT) dwarfs are very cool faint objects that are either substellar or at the stellar–substellar boundary (Delfosse et al. 1997; Kirkpatrick et al. 1999; Martín, Basri & Zapatero Osorio 1999; Burgasser et al. 2006a; Dieterich et al. 2014). In the billion-object catalogue of \textit{Gaia}, there will be direct observations of about a thousand LT dwarfs with estimated \textit{Gaia} $G$ magnitudes brighter than 20.3 mag. We determine proper motions for the 321 objects from \textit{Gaia} and the Two Micron All Sky Survey positions. Combining the \textit{Gaia} and infrared magnitudes provides useful diagnostic diagrams for the determination of L and T dwarf physical parameters. We then search the Tycho-\textit{Gaia} astrometric solution, \textit{Gaia} first data release subset, to find any objects with common proper motions to known L and T dwarfs and a high probability of being related. We find 15 new candidate common proper motion systems.

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http://gaia.esac.esa.int/documentation/GDR1/
Table 1. Distance limits for L0 to T7 spectral types using equation (2). $D_{G<20.3}$ =distance limit assuming $G<20.3$ mag and $D_{G<20.7}$ for $G<20.7$ mag.

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>$D_{G&lt;20.3}$ (pc)</th>
<th>$D_{G&lt;20.7}$ (pc)</th>
<th>T ) Spectral Type</th>
<th>$D_{G&lt;20.3}$ (pc)</th>
<th>$D_{G&lt;20.7}$ (pc)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>82</td>
<td>T0</td>
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<td>55</td>
<td>67</td>
<td>T1</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
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<td>45</td>
<td>54</td>
<td>T2</td>
<td>12</td>
<td>14</td>
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<tr>
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<td>36</td>
<td>44</td>
<td>T3</td>
<td>12</td>
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</tr>
<tr>
<td>L4</td>
<td>29</td>
<td>35</td>
<td>T4</td>
<td>11</td>
<td>14</td>
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<td>19</td>
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<td>T6</td>
<td>8</td>
<td>10</td>
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<td>10</td>
<td>12</td>
<td>T9</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

developed in Section 3.1. In addition to solar-metallicity LT dwarfs, Gaia will also provide a volume limited sample of old thick disc or halo L-type subdwarfs, and young LT objects in the solar neighbourhood.

Other LT and even cooler Y dwarfs (Cushing et al. 2011) will be indirectly detected in Gaia observations, for example, as low-mass companions in unresolved binary systems (Pope, Martinache & Tuthill 2013; Littlefair et al. 2014; Sozzetti et al. 2014; Burgasser et al. 2015; Ma et al. 2016) and as gravitational microlenses (Belokurov & Evans 2002; Proft, Demleitner & Wambsganss 2011; Ranc & Cassan 2014; Sahu et al. 2014). Gaia will constrain other LT and Y dwarfs in common proper motion (CPM) systems of wide binaries or moving groups where distances and kinematics of the brighter members, visible to Gaia, can be matched to the fainter objects with kinematics found from other surveys.

Ultracool dwarfs (UCDs) are defined as objects later than M7 (see Jones & Steele 2001). We have begun a systematic project to catalogue and characterize the cooler part of the Gaia Ultracool Dwarf sample (hereafter GUCDS), being all L, T and Y dwarfs that Gaia will directly observe or indirectly constrain. The GUCDS will be the primary sample in the near future to test atmospheric models and evolution scenarios, and to derive fundamental properties of objects at the end of the main sequence.

Here, we find the LT dwarfs directly observed by Gaia as isolated objects with an identifiable entry in the Gaia DR1 and we find those LT dwarfs in CPM systems with the Gaia DR1 subset with astrometric solutions. In Section 2 we describe the L, T and Y dwarf input catalogue used to search the Gaia DR1; in Section 3 we describe the production of the GUCDS catalogue of known matched LT dwarfs; in Section 4 we describe the discovery of new CPM candidates; in Section 5 we discuss the two catalogues in various magnitude, colour and proper motion parameter spaces and in the last section we summarize the results.

2 CATALOGUE OF KNOWN L, T AND Y DWARFS

2.1 Input catalogue

LT dwarfs seen by Gaia will all be nearby ($d < 82$ pc; Table 1) and, therefore, have significant proper motions. With this in mind, we used as the starting point for our input catalogue of known late M, L, T and Y dwarfs the online census being kept by J. Gagné. This included objects from the Dwarf archives, the work of Dupuy & Liu (2012), and the PhD thesis catalogue of Mace (2014). To this compilation, we added the objects in Marocco et al. (2015) and Faherty et al. (2016). We did not include the significant number of UCD candidates with photometry-based spectral types (e.g. Folkes et al. 2012; Smith et al. 2014; Skrzypek, Warren & Faherty 2016), since they are mostly too faint for Gaia and do not yet have proper motion estimates.

We confine our sample to all objects that have an optical or infrared spectral type equal to or later than L0 or are young late type M dwarfs that are probable brown dwarfs (e.g. TWA 27 A; Gizis 2002). These objects cover a large age range and include objects in the stellar, brown dwarf and giant-planet regimes. While Gaia is only observing directly a few objects later than L7, we included all published L, T and Y dwarfs, as the same list is used to search for CPM objects in the Gaia DR1. Most UCDs (in particular late-M and early-L dwarfs) have been classified using both their optical and near-infrared spectra, leading to two different and sometimes discordant spectral types. When we had to choose a spectral type, for example to calculate spectroscopic distances, we adopted optical spectral types for late-M and L dwarfs when available, since they are mostly too faint for Gaia.

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catalogue the faintest object had a match within 3 arcsec, and eight had a non-zero proper motion objects. Of these, six objects had more than one DR1 compromise between too many false matches and missing true high-resolution (2 arcsec) and larger (5 arcsec), and found 3 arcsec to be the best matching radius. We also considered other matching radii both smaller and larger than 3 arcsec. Of the original 1317 UCDs, 328 of the objects had a DR1 entry within a matching radius of 3 arcsec and a zero DR1 epoch using the proper motions in our input list. We found that each object, we matched the published position moved to the DR1 of the LT dwarfs in the DR1 required a careful cross match. For different epochs and with varying completeness, the identification both the ground-based GUCDS input catalogue and the DR1 are of Since our input objects generally have high proper motions, and

3 IDENTIFICATION OF DR1 MATCHES

3.1 Initial matching

Since our input objects generally have high proper motions, and both the ground-based GUCDS input catalogue and the DR1 are of different epochs and with varying completeness, the identification of the LT dwarfs in the DR1 required a careful cross match. For each object, we matched the published position moved to the DR1 epoch using the proper motions in our input list. We found that 328 of the 1317 UCDs had a DR1 entry within a matching radius of 3 arcsec. We also considered other matching radii both smaller (2 arcsec) and larger (5 arcsec), and found 3 arcsec to be the best compromise between too many false matches and missing true high proper motion objects. Of these, six objects had more than one DR1 match within 3 arcsec, and eight had a non-zero duplicated_source flag in the DR1, which indicates that during the Gaia processing the source at some point was duplicated.

We then determined a new relationship for estimating G magnitudes from 2MASS J magnitudes and tabulated spectral types. We selected the 304 cross-matched L dwarfs that (i) had only one DR1 match within 3 arcsec, (ii) had a zero Gaia duplicated_source flag, and (iii) were earlier than L7. For this subsample, using least squared absolute deviation we found the first-order polynomial relationship between the colour $G - J$ and spectral type as:

$$G_{\text{est}} = J - 1.098 + 0.080 \, \text{SpT}$$

valid for SpT = 70 to 77, i.e. L0 to L7.

The colour–spectral type diagram in Fig. 2 illustrates the measured $G$ minus $J$ magnitudes with lines that represent $G_{\text{est}}$ (equation 1), and this new robust fit, $G_{\text{col}}$ (equation 2). The new relation in equation (2) is much flatter than equation (1). We found seven objects with a measured and estimated $G$ difference, $\Delta G = |G - G_{\text{col}}|$, larger than 1 mag. While the underestimation of the $G - J$ for the T6 object indicates extrapolating the fit beyond L7 provides

![Figure 2](image-url)

Note: The full table of 1886 entries is available online, references for each variable are in the online version. Superscripts 1 and 2 indicate that the adopted spectral type were measured in the optical and near-infrared, respectively.

2.2 Predicted G magnitude

To first estimate a Gaia $G$ magnitude for the input catalogue, we used the procedure developed in Smart (2014). Briefly, we combined the Two Micron All Sky Survey (hereafter 2MASS; Skrutskie et al. 2006) J magnitudes, Sloan Digital Sky Survey (hereafter SDSS; York et al. 2000) colours as a function of spectral type from table 3 in Hawley et al. (2002), and colour transformations between Gaia photometry and the SDSS system from Jordi (2012) to find a predicted $G$ magnitude. To this table we fitted a simple linear polynomial of predicted $G$ magnitudes as a function of spectral type and $J$ magnitude to obtain:

$$G_{\text{pred}} = J - 12.63 + 0.244 \, \text{SpT},$$  

where SpT is the numerical representation of the LT types from 70 to 89 equivalent to L0 to T9.

The Jordi (2012) Gaia-to-SDSS transformations were based on main-sequence stars in the colour range $g - r = (-0.5, 7.0)$ mag. There will be a systematic error in equation (1) due to the difference between M and LT dwarf spectral energy distributions, but we estimated this to be less than 0.2 mag by extrapolating the difference between M giants and dwarfs in the transformation construction.

The transformation is imprecise because of the multiple steps, the use of 2MASS magnitudes and this systematic error. However, equation (1) was only used to constrain the objects that we search for, so we considered it sufficient. From the input list we searched the Gaia DR1 for all objects with a predicted magnitude $G_{\text{pred}} < 23$ mag. Since the nominal DR1 limit is $G = 20.7$ mag, this allowed for significant random or systematic errors in our relationship and its parameters ($J$, SpT). Of the original 1885 objects, 1317 were brighter than this conservative $G_{\text{pred}} < 23$ mag cut. In the final matched catalogue the faintest object had a $G_{\text{pred}} = 22.6$ mag.
uncertain results, we only used this \( \Delta G \) flag as an indicator of possible problems.

Fig. 3 is the distribution of the input catalogue in \( G_{\text{cat}} \) magnitudes using equation (2) for the input catalogue and the 328 matched objects with measured \( G \) magnitudes. The degree of completeness varies greatly from 0 per cent in the bright bins below \( G = 16.5 \) mag and the faint bins beyond \( G = 21 \) mag to over 50 per cent at \( G = 19 \) mag. The brightest bins have the objects with the highest proper motions and so are systematically affected by \textit{Gaia} observation matching problems (Fabricius et al. 2016). In general, the incompleteness can be attributed to objects that were excluded from DR1, matching problems due to imprecise positions and/or proper motions or mis-classifications in the GUCDS input catalogue leading to overestimated \( G_{\text{cat}} \) magnitudes.

In total, there are 1010 L and 58 T dwarfs brighter than \( G_{\text{cat}} = 21.5 \) mag, and 543 L and 10 T dwarfs brighter than \( G = 20.3 \) mag. In contrast, Smart (2014) predicted only two T dwarfs to \( G = 20.3 \) mag. The higher number estimated in this work is due to the systematic underestimation of the \( G_{\text{pred}} \) (equation 1) used in Smart (2014) with respect to the \( G_{\text{cat}} \) (equation 2). Using a more theoretical approach, Sarro et al. (2013) predicted of the order of 10 T dwarfs brighter than \( G = 20.0 \) mag.

In Fig. 4, we plot the sky distribution of all the input catalogue with \( G_{\text{cat}} < 21.5 \) mag using equation (2). The region of overdensity in the Northern hemisphere is from the SDSS footprint, and is probably representative of a complete sky (Schmidt et al. 2010). However, the Galactic plane is incomplete, as most of the LT dwarfs discovered to date have been via photometric selection, and the crowding in the plane makes this difficult.

Of the six objects that had more than one DR1 entry within 3 arcsec some may be due to binarity or a background object near to the catalogue dwarf, but most are due to multiple entries in the DR1 (see section 4 in Gaia Collaboration et al. 2016b). It is estimated that the multiple entries in the DR1 catalogue are a few per cent (Fabricius et al. 2016), consistent with this finding.

In the GUCDS input catalogue, objects either have published proper motions or we estimated them from the 2MASS and Wide-field Infrared Survey Explorer (WISE) AllWISE\(^4\) positions (Wright et al. 2010). We compared these input values with a derived proper motion from the difference of the \textit{Gaia} DR1 and the 2MASS position. When the magnitude of the proper motions differed by more than 20 per cent, we flagged the object. This resulted in 145 objects being flagged, i.e. \( \sim 50 \) per cent. This high percentage is not unexpected given that both proper motions are of low precision and the parallactic motion of the object is unknown.

### 3.2 Identifying mismatches

Since \textit{Gaia} does not produce images (in general), we cannot perform the usual visual confirmation to look for mismatches. We confined our examination for mismatches to the catalogue maps and various flags. For each target we constructed a quality assurance output including: the flags for proper motion and \( \mid G - G_{\text{cat}} \mid \) magnitude differences; number of DR1 observations; the 2MASS images; positions and magnitudes from the 2MASS, AllWISE and DR1 catalogues; the input spectral types; parallaxes when published; input comments (e.g. known binarity or subdwarf); literature and calculated proper motions; and plots of the fitted proper motions and sky maps for the field in 2MASS, AllWISE and DR1 catalogues.

In Fig. 5 we show an example of the sky distribution plots for the field around the T6 J0817–6155 (Artigau et al. 2010). The slight misalignment between the cross and the square in the DR1 panel is due to imprecise starting proper motions from the input catalogue. When needed, we also examined online ground-based images of the fields.

We examined all 328 targets to see if any of the candidates were obvious mismatches. In particular, we paid special attention to the objects with large magnitude differences, multiple DR1 entries within 3 arcsec and the 10 objects later than L7. Of the 328 targets, we identified three objects that we believe are mismatches and are listed in Table 3. Most of these had \( \Delta G > 1.0 \) mag, proper motion differences larger than 20 per cent, and/or visual inspection of the field did not allow an unambiguous identification. The \textit{Gaia} second data release is expected to resolve these ambiguities.

### 3.3 DR1 multiple matches

There are six LT dwarfs with multiple matches within 3 arcsec. Three, J0257–3105 (Kirkpatrick et al. 2008), J0543+6422 (Reid

\(^4\) http://irsa.ipac.caltech.edu/data/download/wise-allwise/
Known LT dwarfs and the Gaia DR1

3.4 Completeness

If we consider input catalogue objects with $G_{\text{est}} < 20.3$ mag we find only 45 per cent in the Gaia DR1. This incompleteness is primarily due to the quality assurance cuts of Gaia which are $N > 5$, $\epsilon_i < 20$ mas and $\sigma_{\text{pos, max}} < 100$ mas, where $N$ is the number of field-of-view transits used in the solution, $\epsilon_i$ is the excess source noise and $\sigma_{\text{pos, max}}$ is the semimajor axis of the error ellipse in position at the reference epoch (from section 5 in Lindegren et al. 2016). In addition, we required all included objects to have valid photometry. The number of field-of-view transits led to a systematic incompleteness that follows the scanning law and can be seen in the sky plots of Gaia DR1.5 Importantly for these objects, the cyclic processing does not yet use internal proper motions to update the position of objects during the matching, so the correct matching of high proper motion objects is deficient (Fabricius et al. 2016). Given the documented incompleteness of 50 per cent at $G = 20.3^6$ mag, and the very high proper motion of most bright LT dwarfs, we consider the success rate of 45 per cent to be reasonable. The matching for DR2 will include internal proper motions, so it will not have this deficiency.

3.5 Gaia observed L and T dwarf catalogue

We produced a catalogue of the parameters for the 321 L and T dwarfs with a reliable entry in Gaia DR1, which are distributed as shown in Fig. 6. This will be actively updated online along with the input catalogue. In Table 4 we report new parameters for the first five objects from this catalogue table with: DR1 positions; calculated proper motions with errors; $G$ magnitudes and errors; number of observations in DR1; Gaia Source ID; $\Delta G = G - G_{\text{est}}$; number of DR1 entries within 3 arcsec and a flag that indicates if the calculated proper motion was within 20 per cent of the published or estimated value. The published catalogue also has other literature information such as 2MASS and WISE magnitudes for each entry.

4 COMMON PROPER MOTION LT DWARFS AND DR1 STARS

4.1 The Tycho-Gaia astrometric subset

The Gaia DR1 included a subset of more than 2 million objects that incorporated earlier positional information to find parallaxes...

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Figure 5. Sky plots of a 2.5 x 2.5 arcmin field around J0817−6155 in 2MASS J (top panel, epoch 2000.0), AllWISE W2 (middle, epoch 2010.6) and DR1 G (bottom, epoch 2015.0). Brighter objects are plotted as larger symbols. The 'X' matches the predicted position based on the literature position and proper motions, the 20 arcsec2 is centred on the respective catalogue source.
The starting CPM candidate list was generated from finding all bad quality flag (Qflag) 2MASS relations presented in Dupuy & Liu (2012), with the measured spectrophotometric distance we used the polynomial adopted UCD spectral types and near-infrared magnitudes. To complemented with spectrophotometric distances estimated using the LT dwarfs we used measured parallaxes from the literature, compiled a list of known binary and CPM systems by combining the objects and list from the following publications: Mason et al. (2001), Deacon et al. (2014, 2017), De Rosa et al. (2014), Dhital et al. (2015), Gauza et al. (2015), Smith et al. (2015), Scholz (2016).

where $\mu$ is the total proper motion, $\Delta \mu_\alpha \cos \delta, \Delta \mu_\delta$ are the difference between the proper motion components of the UCD and the TGAS star. All selected TGAS objects are close so we do not need to invoke inference techniques to find distances (e.g. Bailer-Jones 2015), but use the simple inverse of the parallax as the estimated distance and as its error, a proportion equal to the relative error of the parallax.

The selection criteria require the objects to have relatively high proper motions and the probability of having two objects with such high proper motions in a limited area is already small. For each candidate pair we used the sample of all TGAS field stars in a radius of 2 of the UCD to determine the distance and proper motion distribution of the field population. The distance and proper motion distribution were treated as a probability density function, which we reconstructed using a kernel density estimation. We then drew 10 000 samples of stars from the reconstructed probability density function and determined how many ‘mimics’ of our system were generated. We considered any star within 3 of the distance and proper motion of our selected primaries as a mimic of our CPM system. The chance alignment probability was assumed to be the number of mimics divided by 10 000. If this probability was below $6 \times 10^{-5}$, equivalent to a 4σ level, we consider the pair to be a ‘robust’ CPM system. Systems with larger chance alignment probability were ruled out.

4.2 Selection criteria

The starting CPM candidate list was generated from finding all TGAS stars within 2 of our input LT dwarfs and applying the following criteria:

(i) $\mu > 100 \text{ mas yr}^{-1}$

(ii) $\Delta \mu_\alpha \cos \delta < 20 \text{ mas yr}^{-1}$ and $\Delta \mu_\delta < 20 \text{ mas yr}^{-1}$.

Table 4. New parameters for the GUCDS-DR1 catalogue.

<table>
<thead>
<tr>
<th>Short name</th>
<th>$\alpha, \delta$</th>
<th>$\mu_\alpha \cos \delta, \mu_\delta$ (mas yr$^{-1}$)</th>
<th>$G$ (mag)</th>
<th>$\Delta G$ (mag)</th>
<th>$N_{\text{obs}}, N_3, F_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0006−1720</td>
<td>2414607592787544320</td>
<td>$-1.582553567, -17.343451311$</td>
<td>$-41 \pm 11, 0 \pm 12$</td>
<td>$20.525 \pm 0.043$</td>
<td>$0.163$ 970,0</td>
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<td>$-61 \pm 12, -324 \pm 12$</td>
<td>$18.485 \pm 0.008$</td>
<td>$0.078$ 219,0</td>
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<tr>
<td>J0006−6436</td>
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<td>$0.103$ 145,0</td>
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<td>$0.073$ 185,0</td>
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<td>$324 \pm 6, -381 \pm 13$</td>
<td>$19.774 \pm 0.025$</td>
<td>$0.110$ 108,0</td>
</tr>
</tbody>
</table>

Notes. Equatorial coordinates and apparent magnitudes are from Gaia DR1 at epoch J2015.0, while proper motions were computed by us after using 2MASS and Gaia astrometry. $\Delta G = G - G_{\text{G5}}$, $N_{\text{obs}} = \text{number of Gaia observations}$; $N_3 = \text{number of DR1 entries within 3 of the input value}$. The full table of 321 LT dwarfs with other supporting magnitudes is references are available online.
Kirkpatrick et al. (2016) and Gálvez-Ortiz et al. (2017). Of the 32 CPM pair candidates 17 were previously known and the remaining 15, listed in Table 5, are presented here for the first time. The majority of new wide systems presented here are not physically bound pairs, but the low chance alignment probabilities we interpret as an indication of common origin. Intrinsically wide binaries and multiple systems can in fact become unbound due to Galactic tides and close encounters (e.g. Veras 2016; Elliott & Bayo 2016), and their ejecta would represent a new, as yet unexplored pool of benchmark dwarfs and the DR1 TGAS subset is probably many hundreds. The UCD class bin.

One key element in our selection process is the requirement of common distance between the main sequence TGAS star and its potential companion. We show in Fig. 9 a comparison between the measured astrometric distance to the primaries in our CPM pairs, against the distance (astrometric or spectrophotometric) to their potential companions. Common-distance systems are highlighted in black. Uncertainties on the spectrophotometric distance dominate, and at a larger distance this results in a much larger scatter around the one-to-one correspondence line. Pairs that passed our angular separation constraint, but were rejected by the common-distance cut, consist of a foreground UCD matched to a background star. In Fig. 10 we plot only those systems that we select as having common distance, with those UCDs with measured parallaxes highlighted in green. As expected, systems with astrometric measurements are much closer to the one-to-one correspondence line than those with spectrophotometric distance estimates only. The UCD spectroscopic distances tend to be underestimated compared to the TGAS parallactic distances, e.g. the UCD is brighter than the spectral type indicates. This is as expected from unresolved binarity or a Malmquist bias-like effect as our input sample is probably biased to the brighter examples of a given spectral class bin.

### 4.4 Selected CPM systems

Extrapolating the simulations in Marocco et al. (2017) we predicted that the number of confirmable LT binary systems for the TGAS subset of Gaia DR1 is more than 100, while the number of unbound, but still CPM systems, is significantly higher. The procedures modelled in Marocco et al. (2017) did not include moving groups and disintegrating clusters as our knowledge of these systems is still in its infancy, hence the total number of CPM systems between LT dwarfs and the DR1 TGAS subset is probably many hundreds. The ongoing large-scale infrared surveys will provide a complete list of nearby LTs and at that point a comparison to Gaia results will also allow us to constrain many of the uncertain factors used in the Marocco et al. (2017) work.

For the illustration of the diverse characteristics and possible uses of the CPM systems presented here it is useful to consider a few of the systems individually:

(i) J0230–0225 is an L8 with a peculiar spectrum (Thompson et al. 2013) that we have associated with HIP 12158 (FT Cet), a
Figure 7. A probable wide CPM: TGAS objects within 2° of the L8.0 J0230−0225. In the left panel we show the TGAS on-sky positions with proper motions indicated by the vectors and the size of the symbols indicating the magnitude. The large diamond encloses the TGAS candidate CPM HIP 12158 and the plus sign indicates the position of J0230−0225. In the right panel we show a vector point diagram for all objects again with the cross indicating J0230−0225, the small symbols are the proper motions of the TGAS objects and the large diamond encloses HIP 12158.

Figure 8. A probable binary: TGAS objects within 2° of the L0.5 J1632+3505. The meaning of the symbols is as in Fig. 7; however, the TGAS object, TYC 2587-1547-1, overlaps the L dwarf position in this example.

K1V star that has been indicated as a member of the Hyades Moving Group (Tabernero, Montes & González Hernández 2012). If coeval with the Hyades it will have an age between 0.4 and 1.0 Gyr and any interpretation of the spectral peculiarities will have to take that into consideration.

(ii) J0915+0531 is a T7 associated with TYC 230−109−1 (HD 80462), the primary of a visual binary system of two mid-G-type stars separated by 10 arcsec and discovered by F. G. W. Struve in the early 19th century (Mason et al. 2001). For such a binary system Gaia will produce precise astrometry and high-resolution RVS spectra that will provide a significant improvement on their astrophysical parameters which in turn can be used to constrain the UCD if the companionship is confirmed.

(iii) J1154−3400 (West et al. 2008) is an L0 and was proposed as a candidate member of the Argus Association (Gagné et al. 2015), which is a young 30-50 Myr system, so if this UCD is a member it is in an age regime where the radius is rapidly changing (Baraffe et al. 2002). Further work in Faherty et al. (2016) evidence that it is a very difficult case with moderate to high probabilities of being in various kinematic groups. We associate this dwarf to the primary HIP 58240 (HD 103742), in a G4V+G3V binary system with HIP 58241 (HD 103743). Adopting the precise TGAS astrometry of the binary system, it did not register as a candidate member of any moving group in either the BANYAN II (Gagné et al. 2014) or LACEwING (Riedel et al. 2017) tools to estimate probabilities of candidate objects to nearby kinematic groups. BANYAN II did
Faherty et al. (2009) in BANYAN II we find there is an indication that it may be a member of Argus (probability 53 per cent) or the TW Hydrae Association (probability 10 per cent) while LACEwING gives zero probabilities for all moving groups. We await future releases of the Gaia results to resolve these conflicting indications.

(iv) J1632+3505 (L0.5) and TYC 2587–1547–1 (HD 149361, K0 V) are separated by ρ = 57 arcsec at position angle θ = 49°. At a heliocentric distance of 34.6 ± 0.3 pc this translates into a projected physical separation of only 1960 au and a gravitational potential energy of the order of ~ 10^{-5} J, between 40 and 300 times larger in absolute value than the most fragile bound systems known (Caballero 2009). The relatively short projected physical separation, large absolute potential energy and similarity of recalculated proper motions of both primary and secondary with Gaia led us to classify this pair as the only bound system in our sample. The primary star is at the brighter end of the Gaia magnitude range (G = 7.97 mag) while J1632+3505 is at the faint end (G = 19.18 mag), so the consistency of the two Gaia distances will be testing both noise- and photon-limited astrometric results. The Gaia spectroscopic observations of the primary will lead to astrophysical parameters that can be used to constrain those of the secondary.

(v) J0943+0942 is a T4.5 that is found to be a CPM companion candidate of two TGAS stars (HIP 47704 and TYC 824-423-1). However, from the more precise proper motions of the two stars they would not be considered CPM companions. This highlights a weakness of our procedure; we calculate a probability but there will be false positives. This is one of the faintest objects that we found CPM pairs for and like most UCDs in these systems Gaia will not detect them; however, we expect future infrared and deep optical surveys to allow us to improve the proper motion of all UCDs.

5 AN EXAMINATION OF UCDs MAGNITUDE, COLOUR AND PROPER MOTION RELATIONS

The Gaia G is a new passband from 330 to 1050 nm with transmission peaking around 600 nm and dropping to 10 per cent at 970 nm.\(^7\) The G magnitude represents a new resource in terms of both homogeneity and wavelength coverage, albeit with possibly limited diagnostic ability for short baseline colours due to its very wide spectral passband. It will help to constrain the spectral energy distribution of LT dwarfs across the whole of the sky in the optical. As well as this G magnitude, the second Gaia data release will provide both a blue and a red magnitude (G\(_{BP}\) and G\(_{RP}\); see Fig. 1), the application of which to UCDs has been discussed at length in Sarro et al. (2013). In this section we examine the locus of UCD objects in relations among magnitude, colour and proper motion with a focus on those related to the Gaia G band.

5.1 Colour–colour relations

In the optical wavebands, LT dwarfs only have homogeneous magnitude estimates for parts of the sky (e.g. see Epchtein et al. 1999; Ahn et al. 2014), while in the infrared most have homogeneous magnitudes from the 2MASS and AllWISE surveys. This is also where these objects are the brightest, and combined with G produce a very long colour baseline, so here we examine the Gaia and 2MASS/WISE infrared relations. The 2MASS is 99 per cent complete to \(J = 15.8\) mag\(^8\) and, from Fig. 2, the nominal \(G – J\) offset of an L0 is 4.5 mag; we therefore expect 2MASS to be complete for all Gaia objects with spectral types L0 and later (as they are redder) to \(G = 20.3\) mag. The magnitude limit of AllWISE is \(W2 = 15.7\) mag

\(^7\) http://www.cosmos.esa.int/web/gaia/science-performance
\(^8\) http://www.ipac.caltech.edu/2mass/overview/about2mass.html
and the colour offset is greater, so all Gaia LT dwarfs are expected to have an ALLWISE W2 detection.

In Fig. 11 we plot $J - W_2$ as a function of $G - J$ and zoomed in on the LT portion of the $W_2 - W_3$ versus $G - W_2$ graph. In Appendix A we plot the LT region in a series of combinations of $G$ with 2MASS and ALLWISE magnitudes. The $G$-related blue colour is always on the $X$-axis and the redder magnitude combination on the $Y$-axis. We did not include $W_4$ as it is generally not sensitive enough to detect these objects. To highlight particular populations, we have plotted different symbols for the young or subdwarfs from the comments of Table 1, and the 10 objects with spectral types later than L7.

We find that the seven objects listed in Table 6, which are not indicated as young or subdwarf objects, are outliers in most colour–colour plots, and we have labelled them as 1 through 7, respectively, in the figures. If these seven objects are classed as M/L boundary dwarfs they would no longer be considered outliers as their position is with the majority of M dwarfs that dominate the background objects.

From Fig. 11 and the colour–colour plots in Appendix A we note the Gaia–2MASS colours differentiate the full sample better than the background sources, while the subdwarf, young objects and late LT objects are differentiated better when the AllWISE bands are used. This variation in properties makes it possible to photometrically isolate both the general LT dwarfs and also the differing subpopulations.

### 5.2 Spectral type and colour relations

Using the 321 candidates with DR1 photometry, we can recalibrate the $G - J$ as a function of SpT relation, which was used earlier to provide an estimated $G$ value from spectral type and $J$ magnitude. In Table 7 we report the mean colours, standard deviation and number of entries for all spectral bins with more than three objects.

In Fig. 12 we plot the $G - J$ and $G - W_2$ with spectral type graphs, and in Appendix A we plot all of the $G$-based colours with spectral types. In addition to estimating magnitudes, these relations are useful for the identification of outlier objects, as they are reasonably monotonic for the early-L dwarfs. The onset of $Ks$-band suppression due to the atomic and molecular absorption, methane in particular (Oppenheimer et al. 1998; Noll et al. 2000; Cushing, Rayner & Vacca 2005), and collision induced absorption (Burrows et al. 2001; Kirkpatrick 2005), can be seen by the position of the two T6 objects compared to the main bulk of the targets in the $G - J$ and $G - K$ graphs. Young objects tend also to be redder in the AllWISE colours, perhaps due to circum(sub)stellar discs or enhanced dust formation due to low gravity (e.g. Zapatero Osorio et al. 2010).

### 5.3 Reduced proper motion diagrams

The reduced proper motion in the $G$ magnitude is defined as

$$H_G = G + 5 + 5 \log \mu,$$

where $\mu$ is the total proper motion (Jones 1972). The $H_G$ is correlated with the absolute magnitude in $G$ via the tangential velocity. Since objects in the solar neighbourhood tend to share the same rotational velocity around the Galactic Centre as the Sun, their kinematics are restricted to velocity ellipsoids. Also since spectral types are also correlated to absolute magnitudes, a plot of $H_G$ versus a surrogate of spectral type provides a reduced proper motion diagram, which is a powerful tool for isolating different stellar populations.

**Figure 11.** Colour–colour diagrams for $J - W_2$ versus $G - J$ and a zoom on the LT region of the $W_2 - W_3$ versus $G - W_2$. Filled circles are subdwarfs, squares are young dwarfs, triangles are objects later than L7, stars are other L0–6 dwarfs, and yellow points are anonymous sources within 2 arcmin of each LT dwarf. Typical error bars are shown. The seven outliers J0109+4954, J0133+6314, J1116+6037, J1245+4902, J1250+4418, J1251+6243 and J1333+1509 are labelled 1 through 7, respectively. Additional colour–colour diagrams are found in Appendix A.
Table 6. Probable late M dwarfs identified in the colour–colour and colour–spectral type diagrams.

<table>
<thead>
<tr>
<th>Short name</th>
<th>Long name</th>
<th>Opt SpT</th>
<th>NIR SpT</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0109–4954</td>
<td>SSSPM J0109–4955</td>
<td>M8$^1$</td>
<td>L1$^2$</td>
<td>This object is bluer in all diagrams than we would expect for an M8 but further spectral observations are needed to clarify its spectral type.</td>
</tr>
<tr>
<td>J0109–4954</td>
<td>...</td>
<td>L0$^2$</td>
<td>-0.45</td>
<td></td>
</tr>
<tr>
<td>J0133–6314</td>
<td>...</td>
<td>...</td>
<td>-0.33</td>
<td></td>
</tr>
<tr>
<td>J1116+6037</td>
<td>2MASS 11164800+6037309</td>
<td>L0$^3$</td>
<td></td>
<td>This is at the border of the majority of L0 colour loci. Using the best-fitting template procedure from Marocco et al. (2015) on its published SDSS spectra we find it is a late M dwarf.</td>
</tr>
<tr>
<td>J1245+4902</td>
<td>2MASS 12455566+4902105</td>
<td>L1$^3$</td>
<td>-0.90</td>
<td></td>
</tr>
<tr>
<td>J1250+4418</td>
<td>2MASS 12504567+4418551</td>
<td>L0$^5$</td>
<td>-0.66</td>
<td>Very blue in many colour–colour plots and comparisons of the SDSS spectra using the procedure from Marocco et al. (2015), the same spectra as used by West et al. (2008) to find L0, we find the object to be a late M dwarf. The W3 magnitude is an upper limit and its extreme position in the W3 colour combinations indicates that it is significantly fainter than the published value.</td>
</tr>
<tr>
<td>J1250+4418</td>
<td>2MASS 12512841+6243108</td>
<td>M8V$^3$</td>
<td></td>
<td>This object was listed as an L4 but erroneously cited as coming from Zhang et al. (2009); West et al. (2008) classified it as an M8V. Our G magnitude would be more consistent with the earlier type and we think this is a case of object mis-identification and the actual object is an M8V.</td>
</tr>
<tr>
<td>J1333+1509</td>
<td>2MASS 13331284+1509569</td>
<td>L0$^3$</td>
<td>-0.26</td>
<td>This object has been classified as M8$^4$ in the infrared and both L0$^3$ and M9$^4$ – (West et al. 2011) in the optical – both from SDSS spectra. It is a borderline M/L object.</td>
</tr>
<tr>
<td>J1333+1509</td>
<td>2MASS 13331284+1509569</td>
<td>M8$^4$</td>
<td>0.65</td>
<td></td>
</tr>
</tbody>
</table>

Spectral type references: $^1$Reid et al. (2008), $^2$Lodieu et al. (2005b), $^3$Schmidt et al. (2010), $^4$Bardalez Gagliuffi et al. (2014), $^5$West et al. (2008)

Table 7. Mean colours and standard deviation for all spectral type bins from L0 to L5 where there were at least three entries.

<table>
<thead>
<tr>
<th>Optical SpT</th>
<th>$&lt;G - J&gt;$ (mag)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>4.52 ± 0.19</td>
<td>126</td>
</tr>
<tr>
<td>L0.5</td>
<td>4.53 ± 0.07</td>
<td>7</td>
</tr>
<tr>
<td>L1</td>
<td>4.58 ± 0.13</td>
<td>55</td>
</tr>
<tr>
<td>L1.5</td>
<td>4.63 ± 0.10</td>
<td>14</td>
</tr>
<tr>
<td>L2</td>
<td>4.70 ± 0.15</td>
<td>29</td>
</tr>
<tr>
<td>L2.5</td>
<td>4.65 ± 0.14</td>
<td>8</td>
</tr>
<tr>
<td>L3</td>
<td>4.72 ± 0.17</td>
<td>17</td>
</tr>
<tr>
<td>L3.5</td>
<td>4.95 ± 0.09</td>
<td>5</td>
</tr>
<tr>
<td>L4</td>
<td>4.92 ± 0.14</td>
<td>11</td>
</tr>
<tr>
<td>L4.5</td>
<td>5.01 ± 0.13</td>
<td>3</td>
</tr>
<tr>
<td>L5</td>
<td>5.02 ± 0.17</td>
<td>8</td>
</tr>
</tbody>
</table>

(e.g. Faherty et al. 2009; Lépine & Gaidos 2011; Jiménez-Esteban et al. 2012)

In Fig. 13, we plot the reduced proper motion $H_0$ versus $G - J$ and $G - W3$ for the LT dwarfs identified in the DR1, and include anonymous objects within 2 arcmin of each LT dwarf with proper motions calculated in the same way (i.e. Gaia DR1–2MASS). The plots with other $G$ and 2MASS and AllWISE colours are included in Appendix A. The anonymous objects trace out the locus of the combined thin and thick discs, while the majority of LT dwarfs clump in a relatively unoccupied region. The subdwarfs tend to occupy the lower part of the LT cloud while the young objects are on the right-hand edge.

There are 12 high proper motion objects with $H_0 > 24.0$ mag listed in Table 8; these include subdwarfs and objects later than L6. For the early-L normal dwarfs, a high $H_0$ would be an indication of a subdwarf nature; however, as $H_0$ is a compound variable including both intrinsic magnitude and kinematical properties, it may be that it has a high velocity because of encounters that have led to an unusually high value for $H_0$. The distance and other parameters from Gaia DR2 will clarify the nature of these objects.

5.4 Hertzsprung–Russell diagrams

For the 49 targets that have published parallaxes, we can determine absolute magnitudes and tangential velocities. In Figs 14 and 15 we plot the HR diagrams with absolute $G$ magnitudes and both the $G - J$ colour and the spectral type as surrogates for temperature. We have colour coded the symbols to indicate the tangential velocities. There is a spread of 0.7 mag in absolute magnitude that, based on the propagation of the formal errors, appears to be largely intrinsic. On each HR diagram we have included the most recent PHOENIX isochrones9 (Allard, Homeier & Freytag 2013, and references therein) for a 0.005, 1 and 10 Gyr, as shown in the legends.

The objects labelled 1, 2, 3 are 2MASS 12563716–0224522, TWA 27 A and Kelu-1 A. 2MASS 12563716–0224522 is a

Figure 12. Colour–spectral type diagrams for $G - J$ and $G - W_2$. Symbols have the same meaning as Fig. 11. The four outliers J0133−6314, J1245+4902, J1250+4418 and J1251+6243 are labelled 1–4, respectively. Additional colour–spectral type diagrams are found in Appendix A.

subdwarf (Scholz et al. 2009) and TWA 27 A is a member of the young TW Hya association (Gizis 2002) hence the outlier positions. Kelu-1 is a triple system, with Kelu-1 A, a spectroscopically identified L0.5+T7.5 (Stumpf et al. 2009) and Kelu-1 B, a L3pec dwarf 300 mas towards the southeast (Liu & Leggett 2005) of the primary double. Gaia should resolve and detect both the double primary system and the secondary so we assume that the object matched is the brighter Kelu-1 A. Indeed if we use the $J$ magnitude of the combined system the object takes an outlier position in the absolute magnitude as a function of $G - J$ but not in absolute magnitude as a function of spectral type.

Figure 13. Colour–reduced proper motion $H_G$ diagrams for $G - J$ and $G - W_3$. Symbols have the same meaning as in Fig. 11. The top panel includes a significant part of the background objects, and the bottom panel is a zoom on the region with LT dwarfs. Additional colour–spectral type diagrams are found in Appendix A.
Known LT dwarfs and the Gaia DR1

We have produced a catalogue of all known LT dwarfs with estimates of their $G$ magnitude and proper motions. We investigated 321 known LT dwarfs identified in the Gaia DR1. The number of LT dwarfs identified is in line with the expectation that Gaia will directly observe around 1000 LT dwarfs. The addition of new homogeneous optical magnitudes opens new possibilities for interpretation, and the addition of distances and proper motions directly from Gaia will allow hypothesis testing on a statistically significant sample size. In particular as we will be able to construct, for the first time, volume limited complete samples.

6 CONCLUSIONS

We have added the 28 CPM objects found in Section 4 to Fig. 15 with $J$-band magnitudes and adopting the parallax of the TGAS CPM companion. In some cases using the TGAS parallax is inappropriate, e.g. in systems that are unbound, but the consistency in the HR diagram indicates this is not a bad assumption. The fact that we can see differences, even in this small sample with heterogeneous parallaxes, is a taste of what to expect with the full GUCDS. The Gaia DR2 is expected to furnish precise parallaxes for most of the GUCDS and we will use the small differences in colour and absolute magnitude trends to find more direct indicators of age, metallicity and other physical properties.
The energy of LT dwarfs is primarily emitted in the near-infrared bands, and the energy being emitted in the G band is from the very red edge of the filter or is non-thermal. An example of non-thermal emission can be seen in the 1997 flare of 2MASSW J1411175+393663 which appears to have been for a short period brighter in the optical than it is in the infrared in its quiescent state (Liebert et al. 1999). Gaia in its normal operation will make an average of more than 80 observations per target with nine precise measures of $G$ during each observation. This will be a well-defined, well-sampled data set that will be able to constrain and characterize the occurrences of flares in LT dwarfs in the optical regime.

Even though many of these objects will be close to the detection limit of Gaia their relative closeness and nominal Gaia precision will allow us to calculate tangential velocities with high precision of metres-per-second. This precision will in turn allow us to colocate them with local moving groups, streams and CPM systems that will provide a wealth of constraints on the physical properties of LT dwarfs. This is evidenced by the diverse locations of young and subdwarf LT objects.

We have found 15 candidate CPM systems by a comparison of our input catalogue to the Gaia TGAS subset. The ability to identify CPM pairs will allow us to push down towards the coolest brown dwarfs and the Gaia results will be crucial to fully characterize the systems and constrain objects that will be too faint for Gaia. Eventually, these benchmark GUCDS objects with age, metallicity and distance constraints provided by thebrighter companion or by the parent association will be the sample to constrain our global picture of UCDs. Ultimately, we hope the GUCDS will allow us to identify observational spectral and colour indicators for the direct determination of physical properties like age and mass.

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10 http://www.cosmos.esa.int/gaia
11 http://www.cosmos.esa.int/web/gaia/dpac/consortium
12 http://pno.ucsd.edu/~adam/browndwarfs/spexprism

Table 8. Objects with $H_G > 24.0$.

<table>
<thead>
<tr>
<th>Long name</th>
<th>OptSpT</th>
<th>NIRSpT</th>
<th>$H_G$ [mag]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULAS J033350.84-001406.1</td>
<td>L0 sd1</td>
<td>L0 sd2</td>
<td>24.2</td>
</tr>
<tr>
<td>DENIS J081730.0-615520</td>
<td>T6 sd1</td>
<td></td>
<td>24.9</td>
</tr>
<tr>
<td>2MASS 11555389+0559577</td>
<td>L7 sd1</td>
<td></td>
<td>24.0</td>
</tr>
<tr>
<td>2MASS 11582077+0435014</td>
<td>L7 sd1</td>
<td></td>
<td>25.6</td>
</tr>
<tr>
<td>SDSSp J120358.19-001550.3</td>
<td>L3 sd1</td>
<td></td>
<td>24.4</td>
</tr>
<tr>
<td>2MASS 12074717+0244249</td>
<td>L8 sd1</td>
<td>T0 sd1</td>
<td>24.5</td>
</tr>
<tr>
<td>2MASS 12304562+2827583</td>
<td>L1 sd1</td>
<td></td>
<td>24.3</td>
</tr>
<tr>
<td>ULAS J124425.90+102441.9</td>
<td>L0.5 sd1</td>
<td></td>
<td>24.2</td>
</tr>
<tr>
<td>2MASSW J1411175+393663</td>
<td>L1.5</td>
<td>L1.5</td>
<td>24.1</td>
</tr>
<tr>
<td>2MASSW J1515008+484742</td>
<td>L6</td>
<td>L6.13</td>
<td>25.2</td>
</tr>
<tr>
<td>2MASS 21124470+685626</td>
<td>L2</td>
<td></td>
<td>24.0</td>
</tr>
<tr>
<td>2MASS 22490917+3205489</td>
<td>L5</td>
<td></td>
<td>25.0</td>
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