A homogeneous sample of 34 000 M7–M9.5 dwarfs brighter than $J = 17.5$ with accurate spectral types\textsuperscript{*}

S. Ahmed and S. J. Warren

Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK

e-mail: s.j.warren@imperial.ac.uk

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ABSTRACT

The space density of late M dwarfs, subtypes M7–M9.5, is not well determined. We applied the photo-type method to $iz$ photometry from the Sloan Digital Sky Survey and $JHK$ photometry from the UKIRT Infrared Deep Sky Survey, over an effective area of 3070 deg$^2$, to produce a new, bright $J$(Vega) < 17.5, homogeneous sample of 33 665 M7−M9.5 dwarfs. The typical $S/N$ of each source summed over the six bands is >100. Classifications are provided to the nearest half spectral subtype. Through a comparison with the classifications in the BOSS Ultracool Dwarfs (BUD) spectroscopic sample, the typing is shown to be accurately calibrated to the BUD classifications and the precision is better than 0.5 subtypes rms; i.e. the photo-type classifications are as precise as good spectroscopic classifications. Sources with large $\chi^2 > 20$ include several catalogued late-type subdwarfs. The new sample of late M dwarfs is highly complete, but there is a bias in the classification of rare peculiar blue or red objects. For example, L subdwarfs are misclassified towards earlier types by approximately two spectral subtypes. We estimate that this bias affects only ~1% of the sources. Therefore the sample is well suited to measure the luminosity function and investigate the softening towards the Galactic plane of the exponential variation of density with height.

Key words. stars: low-mass – catalogs – surveys

1. Introduction

A detailed census and study of the coolest stellar objects, i.e. late M dwarfs and cooler, first became possible with the implementation of wide-field surveys at wavelengths 0.8–2.4 $\mu$m, especially the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). The highlight in this area was the discovery and characterisation of the L and T dwarf populations (Kirkpatrick et al. 1999; Martín et al. 1999; Strauss et al. 1999; Geballe et al. 2002; Burgasser et al. 2002, 2006; Hawley et al. 2002; Schmidt et al. 2010). At the same time new insights into the properties of M dwarfs have been obtained, including the quantification of their activity as a function of spectral type and age (West et al. 2008, 2011; Schmidt et al. 2015), as well as measurement of the luminosity function (LF; Cruz et al. 2007; Covey et al. 2008; Bochanski et al. 2010). From the LF, using a relation between luminosity and mass (e.g. Delfosse et al. 2000), the stellar initial mass function (IMF) may be derived. The LF of M dwarfs is important because the characteristic mass of a log-normal mass function (IMF) may be derived. The LF of M dwarfs has been obtained, including the quantification of their activity as a function of spectral type and age (West et al. 2008, 2011; Schmidt et al. 2015), as well as measurement of the luminosity function (LF; Cruz et al. 2007; Covey et al. 2008; Bochanski et al. 2010). From the LF, using a relation between luminosity and mass (e.g. Delfosse et al. 2000), the stellar initial mass function (IMF) may be derived. The LF of M dwarfs is important because the characteristic mass of a log-normal fit to the IMF lies within this spectral range (Chabrier 2003; Bochanski et al. 2010).

The study by Bochanski et al. (2010) is the most complete analysis of the M dwarf LF. They determined new photometric parallax relations (absolute magnitude as a function of colour) and applied these values to a sample of ~15 $\times$ 10$^5$ M dwarfs from 8400 deg$^{-2}$ of SDSS Data Release 7 to derive the LF over the absolute magnitude interval $7 < M_{r}^{AB} < 16$. Their LF varies smoothly over the interval $7 < M_{r}^{AB} < 14$, corresponding to spectral types M0–M5, but displays significant fluctuations between bins for absolute magnitudes $M_{r}^{AB} > 14$. This is partly owing to the relatively small numbers at these absolute magnitudes, which is a consequence of their use of the $r$ band for the sample magnitude limit, $r(AB) = 22$. Because late M dwarfs, $>M5$, are so red, imposing a cut in $r$ leads to a rapid reduction in limiting distance, and thus sample size, towards later spectral types. The space densities for the latest M dwarfs are additionally uncertain because the photometric parallax relation is less well calibrated in this region. The measured IMF is further impacted because the colour correction from the $r$ band to the $J$ band, which is the passband of the Delfosse et al. (2000) mass-luminosity relation, is large for late M dwarfs and not precisely determined (Hawley et al. 2002).

An independent estimate of the M dwarf LF for spectral types M7–M9 was made by Cruz et al. (2007), using a sample of 53 stars within 20 pc of the Sun. The objects were identified using 2MASS $JHK_s$ photometry by application of a colour cut $J - K_s > 1.0$, Cruz et al. (2007) estimated that 79% of M7 dwarfs are redder than this colour limit and all M8 and M9 dwarfs. Unfortunately this sample is also problematic. Recent analysis of the 2MASS colours of M dwarfs by Schmidt et al. (2015) provided median colours $J - K_s = 0.96, 1.03$ for M7, M8. These results suggest that only ~50% of M7 and M8 dwarfs satisfy the above colour cut, meaning their space densities have been substantially underestimated.

These questions motivate the compilation of a new sample of late M dwarfs, hereafter M7–M9.5, in order to obtain an improved measurement of the LF. We now briefly consider the issues involved in making an accurate measurement of the LF. Various studies of the LF may be distinguished by whether distances are measured by trigonometric, spectroscopic (absolute...
Skryzpek et al. (2016) developed the method using photo-type classifications in precision of spectroscopic parallax relations. In this paper we present a new large homogeneous sample of 34,000 M7–M9.5 dwarfs. We use “homogeneous” to mean that the sample has high completeness for which the incompleteness is accurately quantified. The new sample exploits the deeper UKIRT Infrared Deep Sky Survey (UKIDSS) photometry (Lawrence et al. 2007), compared to 2MASS, and combines some of the respective advantages of the two previous studies, in that it is not only large but also benefits from precise distances. The sample approximates a complete spectroscopic sample: we use the phototype method of Skrzyzpek et al. (2015, 2016), combining SDSS i, z and UKIDSS YJHK photometry, to measure accurate spectral types. The spectroscopic parallax relation of Dupuy & Liu (2012) then provides distances precise to 15%.

2. Selection

2.1. Photo-type method

The phototype method (Skrzyzpek et al. 2015) uses multiband photometry to measure spectral types. The wide wavelength coverage can compensate for the very low wavelength resolution of broadband photometry, and with high signal-to-noise ratio data phototype classifications of late-type dwarfs are competitive with spectroscopic classifications in precision of spectral typing. Skrzyzpek et al. (2015) developed the method using SDSS+UKIDSS+ALLWISE i, zYJHKW1W2 8-band photometry for the discovery of L and T dwarfs in wide-field survey data. Using a set of stars and brown dwarfs classified by standard spectroscopic methods, polynomial relations between colour and spectral type were determined for the seven colours. A source is classified accurately for identifying sources with spurious photometry and interesting peculiar objects.

In Skrzyzpek et al. (2016) the method was applied to the classification of point sources in the magnitude range 13.0 < J < 17.5, with colours Y − J > 0.8, resulting in a sample of 1281 L and 80 T dwarfs, from an effective area of 3070 deg². The matching radius criteria (within UKIDSS, and in matching to SDSS and WISE) ensures that incompleteness due to proper motion is negligible. The effective area calculation accounts for sources lost due to unreliable photometry in any of the bands from a variety of causes. The relative depths in the different bands, the matching criteria, and the J magnitude range mean that incompleteness due to the requirement that a source is detected in all of the YJHK bands is negligible. The result is that the sample is essentially complete for all spectral types L0−T8, other than a small incompleteness that is estimated at 3% because peculiar blue L dwarfs are classified M and a related overcompleteness because peculiar red M dwarfs are classified L.

2.2. Selection of M7–M9.5 dwarfs

The goal of the current paper is to extend the survey of Skrzyzpek et al. (2016) to earlier spectral types M7–M9.5. The methods used are almost identical to those previously used. Small modifications to this approach mostly result from the difficulty to scrutinise all the images of all the objects in the much larger sample of over 30,000 late M dwarfs compared to 1361 L and T dwarfs. In this work we provide only a brief outline of the methods, referring to the earlier papers for details, but we explain any differences in depth. Because we used almost identical procedures for the sample of late M dwarfs, we assume that the effective area calculated for the LT sample, 3070 deg², also applies to the M dwarfs. We also assume that contamination of the sample by giants is negligibly small based on the arguments presented by Ferguson et al. (2017).

The photometric bands used in this study are the i and z bands in SDSS and the YJHK bands in UKIDSS. All the magnitudes and colours quoted in this paper are Vega based, unless explicitly labelled as AB, by for example r(AB). The YJHK survey data are calibrated to Vega, while SDSS is calibrated on the AB system. We applied the offsets tabulated in Hewett et al. (2006) to convert the SDSS i, z AB magnitudes to Vega.

Starting with a set of point sources in the UKIDSS Large Area Survey data release 10, detected in all four bands, YJHK, and in the range 13.0 < J < 17.5, we matched to SDSS DR9 using a 10′′ match radius and selected the point spread function (psf) photometric measurements. We note that a M7 dwarf has colours i − z = 1.36, Y − J = 0.68 (Skrzyzpek et al. 2016), and so we apply colour cuts i − z > 1.0, Y − J > 0.4 to reduce the total number of sources, while ensuring all sources M7 and later are retained (this assumption is checked later). To allow for sources with significant proper motion, we match to the nearest SDSS source that does not have a closer match to a different UKIDSS source. Considering the i, z, YJHK colours of M7–M9.5 dwarfs (Skrzyzpek et al. 2016), and the limiting depths in the different bands, sources with 13.0 < J < 17.5 are easily detected in all the other bands. A small number of the faintest M7–M9.5 dwarfs do not have photometry in the ALLWISE W1 and W2 bands because the sources are undetected in both bands; a source only needs to be above 5σ in one band to be measured in both bands. In any case the colours K − W1 and W1 − W2 vary very little over this spectral range and therefore add essentially no useful information to the classification of late M dwarfs. Recalling that some 7% of sources are blended in the WISE images (Skrzyzpek et al. 2016), which would all have to be identified by eye, we decided not to match to ALLWISE and limited our analysis to the i, zYJHK photometry.
This initial sample contained 404,496 sources. We used template colours for L0–T8 from Skrzypek et al. (2015) and for M7–M9 from Skrzypek et al. (2016). We used newly determined colours for M0–M6 from Barnett et al. (in prep.). We classified all sources to the nearest half spectral subtype by interpolating the colours. The final sample of M7–M9 dwarfs, after quality control, contains 33,665 sources.

A distinct difficulty with starting with a near-infrared catalogue and matching to an optical catalogue to identify genuinely cool stellar objects is that hotter objects with erroneously faint photometry in the SDSS $i$ bands will be selected as candidates. With the L and T sample of Skrzypek et al. (2015) it was possible to identify these by scrutinising every candidate, but this is not possible with the much larger late M dwarf sample. This leads to a detailed consideration of the use of the data quality flags provided for all SDSS sources in each band. We first eliminated sources if either of the flags PSF_FLUX_INTERP or BAD_COUNTS_ERROR were set in either $i$ or $z$. We also removed any candidates that were close to a bright star $J < 11$ in the 2MASS catalogue, using the criterion $\theta'' < 108 - 8J$. This relation was derived by first selecting sources in the catalogue with large $\chi^2$, and plotting the angular separation to 2MASS sources brighter than $J = 11$, against $J$ of the 2MASS source. A clearly defined locus presented itself, demonstrating that the photometry is incorrect. Therefore the classifications should be reliable. We wish to retain these objects, because in some cases they are binary companions to the bright star from which they were deblended, and therefore could be valuable as benchmark systems.

We did not use ALLWISE photometry for the new sample, but it was used for the LT sample of Skrzypek et al. (2016). Therefore there is a slight ambiguity in membership between the two samples for a handful of sources at the M9.5/L0 boundary at the level of 0.5 subtypes. For example we might classify some of their L0 sources as M9.5 (these would then appear in both samples) and we might classify some sources as L0 that they classified as M9.5 (these would then be absent from both samples). For those few sources that cross the M9.5/L0 boundary with/without ALLWISE, we resolved in favour of the classification that used ALLWISE, ensuring that there is no inconsistency between the sample in this paper and the sample in Skrzypek et al. (2016).

### 3. Sample

The new sample is presented in Table 1, sorted by right ascension, listing in successive columns as follows: (1) the UKIDSS ICRS coordinates, (2) the angular separation in arcsec to the SDSS match, (3–14) the six-band $izYJHK$ photometry, (15) the photo-type classification PhT (to the nearest half subtype), and (16) the $\chi^2$ of the fit. Column (17) lists the quantity $E_B$, which is the Bayestar17 (Green et al. 2018) reddening computed for a distance modulus of 8.0 (a distance of 400 pc). This quantity is the Bayestar17 (Green et al. 2018) reddening computed for a distance modulus of 8.0 (a distance of 400 pc). This quantity is the Bayestar17 (Green et al. 2018) reddening computed for a distance modulus of 8.0 (a distance of 400 pc). This quantity is the Bayestar17 (Green et al. 2018) reddening computed for a distance modulus of 8.0 (a distance of 400 pc).

### Table 1. Sample of 33,665 M7–M9.5 dwarfs.

| Name           | sep. | $i$ | $\sigma_i$ | $z$ | $\sigma_z$ | $Y$ | $\sigma_Y$ | $J$ | $\sigma_J$ | $H$ | $\sigma_H$ | $K$ | $\sigma_K$ | PhT | $\chi^2$ | $E_B$ | dist. | $l$ | $b$ |
|----------------|------|----|------------|----|------------|----|------------|----|------------|----|------------|----|------------|-----|---------|------|-------|-----|-----|
| ULAS J000000.0+151212.9 | 0.18 | 19.86 | 0.03 | 18.29 | 0.05 | 17.66 | 0.02 | 16.88 | 0.02 | 16.33 | 0.02 | 15.93 | 0.03 | M7.5 | 2.36 | 0.04 | 99  | 158.3 | 104.97 | -45.87 |
| ULAS J000001.2+104504.8 | 0.02 | 19.45 | 0.03 | 18.07 | 0.03 | 17.46 | 0.02 | 16.71 | 0.01 | 16.15 | 0.02 | 15.76 | 0.02 | M7.5 | 5.20 | 0.08 | 94  | 146.6 | 103.00 | -50.12 |
| ULAS J000002.8+081047.8 | 0.26 | 19.96 | 0.04 | 18.68 | 0.05 | 17.96 | 0.03 | 17.36 | 0.03 | 16.79 | 0.04 | 16.35 | 0.05 | M7   | 4.72 | 0.06 | 99  | 220.1 | 101.71 | -52.56 |

Notes. Only the first three lines of the table are provided. The full table is available at the CDS.
SpT if the object is present in the BOSS Ultracool Dwarfs (BUD) sample of Schmidt et al. (2015) (listed as 99 otherwise); (19) the distance in pc estimated from PhT, using the relation between spectral type and absolute magnitude provided by Dupuy & Liu (2012) for the J band; and (20, 21) the Galactic coordinates l, b. The total number of sources in the sample is 33 665.

The sample is of high S/N and low reddening. To characterise the S/N of the data we list in Table 2 the median uncertainty in each band and the 90% quantile. The typical S/N is 30 in the optical bands and 50 in the near-infrared bands, providing a combined S/N over the six bands of over 100. Green et al. (2018) have published three-dimensional maps of reddening E, therefore it is not possible to provide an accurate reddening for each source. Instead we list the estimated reddening E for a distance modulus of 8.0, providing an upper limit to the actual reddening to highlight the few sources for which the reddening could affect the classification. The quantiles of E are also provided in Table 2. In fact 95% of sources have E < 0.117. In considering the effect of extinction on colours it should be appreciated that the template colours themselves are not dereddened. Rather they are the median observed colours of stars in the BUD sample along a line of sight with extinction of E = 0.20. For a small proportion of sources the SDSS uncertainties are larger than expected in comparison with other sources of similar brightness. These are objects for which the SDSS deblending algorithm has boosted the uncertainties relative to the Poisson values. We identified 582 sources, or 1.7% of the total, where either the i band uncertainty was >0.20 or the z band uncertainty was >0.15 (or both). For these sources the classification is denoted as uncertain. The majority of cases are stars with a nearby brighter companion, causing difficulty in deblending. Many of the objects could be members of close binary systems. Because of the large uncertainties the bands with bad photometry effectively do not contribute to the classification, which should otherwise be reliable. Because the photometry in the affected band is not useful, we removed these sources from the plots presented in Figs. 1–4.

In this spectral range M7–M9.5, for each colour i – z, z – Y, Y – J, J – H, H – K, there is an approximately linear relation as a function of Galactic latitude b in Table 3, for the reduced effective area of 3031 deg$^2$.
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Fig. 1. Two-colour diagram $i - Y$ vs. $Y - K$ for the new sample. The large points are the known subdwarfs in the sample, listed in Table 5: blue circles show types sdM and sdL, and green squares show type esdL. The red open circles indicate sources with $\chi^2 > 15$ and $E_b < 0.2$.

Fig. 2. Colour-magnitude diagram $i - K$ vs. $J$ for the new sample.

Fig. 3. Histograms of the distribution of $i - K$ colours for each subtype, in half subtype bins, from M7 (left, violet) to M9.5 (right, red).

Fig. 4. Comparison of the colours of M7 dwarfs in the sample against the selection colour cuts.

between colour and spectral type; the later types are redder. For this reason the stellar sequence presents a linear relation in a two-colour diagram. This is illustrated in Fig. 1, which plots $i - Y$ versus $Y - K$. Therefore the $i - K$ colour is the single colour most closely correlated with spectral type. In Fig. 2 we plot $i - K$ versus $J$ for the new sample. This figure illustrates the steep increase in number towards fainter magnitudes and the steep decrease in number counts towards redder colours. The colour $i - K$ on its own provides a good measure of spectral type, as illustrated in Fig. 3, where the histograms of the $i - K$ colour range of each spectral type are presented, showing little overlap between spectral types.

In the sample selection (Sect. 2), colour cuts $i - z > 1.0$, $Y - J > 0.4$ were applied before classifying. In Fig. 4 we plot histograms of these two colours for the earliest spectral classification in the sample, M7, i.e. plotting the bluest objects in the new sample. It is clear from both histograms that the number of sources lost from applying these colour cuts is negligible.

The numbers of sources broken down into half subtype bins are listed in Table 4. The numbers of sources per full spectral bin (e.g. M7 and M7.5 are combined as M7) are plotted against spectral type and compared against the counts of L dwarfs from Skrzypek et al. (2016), which are for the same area and magnitude cuts. The numbers decline towards later spectral types. The decline is steeper for the late M dwarfs and less steep for the L dwarfs. There is a break in the slope that occurs at L0. We assume a functional form $N = 10^{a - bs}$, i.e. the counts are linear in $\log_{10}$. In this case $s$ is spectral type, numbering M7 as 7 to L9 as 19, and $a$ and $b$ are constants. We fit to the counts separately for M7–L0 and for L0–L9, finding $b_M = 0.57$ for the range M7–L0, and $b_L = 0.25$ for the range L0–L9. These fits are plotted in Fig. 5.

There are a number of sources with large values of $\chi^2$, because the colours are a poor match to the templates. These sources are potentially interesting. The $\chi^2$ distribution for the sample is plotted in Fig. 6. Each SED has six data points and

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there are two parameters to fit: the brightness (i.e. overall normalisation) and the spectral type, leaving four degrees of freedom. Overplotted on the $\chi^2$ histogram is the theoretical $\chi^2$ distribution for four degrees of freedom. The curve is a reasonable fit, but the data are skewed to slightly smaller values, indicating that the uncertainties are slightly overestimated. The reason for the poor fit probably lies in the way the spread in the properties of the population has been modelled. In fitting templates to each SED, an additional uncertainty of 0.05 mag is added in quadrature to the photometric error in each band, to model the spread in each colour of the population, at each spectral type. This is a simplification, since it treats each band as independent, whereas the actual spread in colours is characterised by correlations between bands. The theoretical $\chi^2$ curve is nevertheless useful for comparison. If the errors were modelled perfectly, and the source list contained no peculiar objects, we would expect 158 (17) sources with $\chi^2 > 15$, whereas the actual numbers are 298 (108) or 260 (87) if we exclude sources with $E_8 > 0.2$, which are presumably peculiar because of the large reddening. With this in mind we selected $\chi^2 > 20$ as indicating that a source is peculiar, and the classifications are marked e.g. M7p. We scrutinised the images of these 108 sources in all bands, and it appears that all the sources are genuinely peculiar. Nevertheless it is in the nature of the selection to pick out sources with incorrect photometry, so there could be some remaining errors.

Table 4. Number counts by spectral type.

| SpT | Count |
|-----|-------|
| M7  | 16202 |
| M7.5| 9436  |
| M8  | 3680  |
| M8.5| 1877  |
| M9  | 1369  |
| M9.5| 1101  |

Fig. 5. Number counts of M7–9 dwarfs (solid symbols) compared to number counts for L dwarfs (open symbols) over the same area and depths. The dashed lines indicate the log-linear fits referred to in the text.

Fig. 6. Distribution of $\chi^2$ for the full sample compared to the theoretical distribution for 4 degrees of freedom.

Several of the 87 peculiar (and not reddened) sources are known subdwarfs, including the two sources with the largest values of $\chi^2 = 111$ and 62. To investigate this further we matched the large sample of L subdwarfs in Table 1 of Zhang et al. (2018), as well as additional M subdwarfs in their Table 6, to our full sample. The 19 matched L subdwarfs and 2 matched M subdwarfs are listed in Table 5. Six of these are classified esdL, which are of lower metallicity than the sdL class (for details of the classification scheme, see Zhang et al. 2017). On average the photo-type classifications are two subtypes earlier than the correct spectral classification because of their unusual blue colours. Their colours are plotted in Fig. 1. The $\chi^2$ values for this sample range from 9 to 111 and have an average value of 32. Of the 21 matched subdwarfs, 15 have $\chi^2 > 20$, or 17% of the 87 peculiar sources that are not highly reddened. It would therefore be interesting to investigate further the remaining 72 sources. They might include subdwarfs missed by proper motion selection.

We can use the subdwarfs as a guide to estimate how many objects are significantly misclassified because of their peculiar colours. Of the 21 known subdwarfs, 19, that is nearly all, have $\chi^2 > 15$. The other two subdwarfs, with lower $\chi^2$, are misclassified by only 0.5 and 1 subtypes. There are only 260 sources in total with $\chi^2 > 15$, $E_8 < 0.2$. These are plotted as red circles in Fig. 1. The majority, like the subdwarfs, lie to the left of the sequence visible in Fig. 1, but have on average less extreme colours. The selection $\chi^2 > 15$ therefore probably identifies nearly all sources misclassified by two subtypes or more, as well as intermediate objects. This suggests that the proportion of blue objects misclassified by two subtypes or more is safely less than 1%. The proportion of red circles lying to the right of the sequence in Fig. 1 is considerably smaller. These may represent dwarfs of spectral type earlier than M7 that are selected as M7 or later because they are peculiar and red.

The sample is limited to objects classified as point sources in UKIDSS. Point sources include unresolved binaries. A significant proportion of the sources appear in the Gaia DR2 catalogue and the parallaxes, combined with the apparent magnitudes in our catalogue, are useful to identify which sources are unresolved binaries. Any such objects in our sample with small values of $\chi^2$ are likely to be pairs of dwarfs of similar spectral type. Unresolved binaries with large $\chi^2$ may comprise a M dwarf primary and a secondary of later spectral type so that the colours are dominated by the primary. Another possibility is a M dwarf with a cool white dwarf (WD) companion. A large sample of M+WD binaries has been compiled by Rebassa-Mansergas et al. (2013) also using SDSS+UKIDSS. The majority of the M stars in their sample are M2 and M3. Therefore any white dwarfs in
M+WD binaries found in our new sample might have different characteristics to the white dwarfs in their sample. The source ULAS J115908.00+103944.0, which is the object with the fifth largest value of $\chi^2$ in our sample, could be one example. The source was selected by SDSS for spectroscopic observation as a quasi-stellar object candidate, but the spectrum is classified M7 and displays excess blue continuum light. The colours of the source are such that it does not satisfy the selection criteria of Rebassa-Mansergas et al. (2013).

4. Precision of spectral types

We can establish the precision of the photo-type classifications by comparing them against classifications in the BUD sample (Schmidt et al. 2015) that was used to establish the relations between colour and spectral type in this range (Skrzypek et al. 2016). The precision of the classification impacts the number of the best automated spectral classifiers (e.g. Christlieb et al. 2002). For a power-law slope of the number counts of 0.57 (Fig. 5), and a precision of 0.5 subtypes, the Eddington bias is at the level of 20%, i.e. the number counts are too large by a factor 1.2. Nevertheless it is debatable whether this calculation of Eddington bias has much meaning. If the sample had been obtained by a spectroscopic campaign with classifications to this precision it is unlikely any correction to the number counts would be deemed necessary, and therefore we ignore this correction in computing the LF.

5. Summary

In this paper we have presented a homogeneous sample of 33665 bright $J < 17.5$ M7–M9.5 dwarfs, which have accurate spectral types obtained by applying the photo-type method to $iz\ YJHK$ SDSS and UKIDSS photometry. The effective area of the survey is $3070 \text{deg}^2$. The sample is of high S/N and low reddening. We took care to include, where possible, dwarfs that are located at small angular separations from bright stars. These may be binary companions to the bright stars, and are sometimes excluded in working with SDSS data. The sample is a companion to the sample of 1361 L and T dwarfs provided by Skrzypek et al. (2016), selected from the same multicolour dataset, and to the same depth. The number counts as a function of spectral type fall since, of course, the BUD sample itself was used to measure the template colours. The scatter in the differences establishes the precision (random error). The standard deviation of the differences in classification is just 0.6 subtypes. The same value is obtained whether the scatter is measured about the mean, or about zero, and whether the handful of sources with large differences in classification (greater than 2 subtypes) is clipped, or not.

This scatter is remarkably small considering that it is made up of three contributions added in quadrature: (1) the precision of photo-type; (2) the precision of the spectroscopic classifications; and (3) a contribution of $0.5/\sqrt{3} = 0.3$ solely from the quantisation of the spectroscopic classifications into whole subtypes, rather than half subtypes. This means that both the photo-type and the spectroscopic classifications have a precision of better than 0.5 subtypes rms. This precision is as good as the precision of the best automated spectral classifiers (e.g. Christlieb et al. 2002). For a power-law slope of the number counts of 0.57 (Fig. 5), and a precision of 0.5 subtypes, the Eddington bias is at the level of 20%, i.e. the number counts are too large by a factor 1.2. Nevertheless it is debatable whether this calculation of Eddington bias has much meaning. If the sample had been obtained by a spectroscopic campaign with classifications to this precision it is unlikely any correction to the number counts would be deemed necessary, and therefore we ignore this correction in computing the LF.

### Table 5. Catalogued subdwarfs in the M dwarf sample.

| name            | $\chi^2$ | PhT  | SpT        |
|-----------------|----------|------|------------|
| ULAS J002009.36+160451.2 | 19.78    | M7.5 | sdM9       |
| ULAS J021258.08+064115.9 | 25.16    | M8p  | sdL1       |
| ULAS J023803.12+054526.2 | 27.73    | M8p  | sdL0       |
| ULAS J033351.11+001405.9 | 30.74    | M7p  | esdL0      |
| ULAS J082206.61+044101.9 | 36.28    | M8.5p| sdL0       |
| ULAS J124425.76+102439.3 | 60.84    | M7p  | esdL0.5    |
| ULAS J124947.05+095019.9 | 26.71    | M7.5p| sdL1       |
| ULAS J125226.63+092920.1 | 18.68    | M8.5 | sdL0       |
| ULAS J133348.27+273505.6 | 37.25    | M8p  | sdL1       |
| ULAS J134206.87+053725.0 | 20.21    | M9p  | sdL0.5     |
| ULAS J134749.80+333601.7 | 62.42    | M8.5p| sdL0       |
| ULAS J134852.93+101611.9 | 23.86    | M9p  | sdL0       |
| ULAS J135359.58+011586.6 | 13.87    | M9   | sdL0       |
| ULAS J141405.67−014204.1 | 24.18    | M7p  | esdL0      |
| ULAS J141832.36+025323.1 | 25.24    | M9p  | sdL0       |
| ULAS J143517.19−014713.2 | 8.96     | M7.5 | sdM8       |
| ULAS J145234.66+043738.5 | 16.24    | M8   | esdL0.5    |
| ULAS J151913.04−000030.1 | 111.97   | M8p  | esdL4      |
| ULAS J225902.15+115602.1 | 19.75    | M9p  | sdL0       |
| ULAS J230256.54+121310.3 | 26.74    | M8p  | sdL0       |
| ULAS J231924.36+052524.6 | 38.25    | M7p  | esdL1      |

**Fig. 7.** Histogram of the difference in the classification between spectroscopy and using photo-type for the 3239 M7–M9 dwarfs from Schmidt et al. (2015) that matched the classified parent sample.
steeply over the range M7–M9.5 towards later types and there is a break at L0 to a flatter relation in the L dwarfs. For each source we list coordinates, $izYHK$ photometry, Galactic reddening, and the $\chi^2$ of the six-band photometric fit, in addition to the photo-type classification. The classifications are provided to the nearest half subtype and are precise to better than 0.5 subtypes rms. We argued that the precision is so good that Eddington bias in the number counts as a function of spectral type may be disregarded. The sources with large $\chi^2$ include subdwarfs, probably dwarfs of intermediate metallicity, and other peculiar types.

All the sources lie within a distance of 235 pc, so the sample will be useful for measuring the structure of the Milky Way disc close to the Galactic plane, and it will provide a new, more accurate, measurement of the space density of M7–M9.5 dwarfs. To measure the local space density we must measure the variation of the space density with height $|z|$ from the Galactic plane and extrapolate to $z = 0$. The variation of the density of stars with height from the plane is often characterised using a $\text{sech}^2(\frac{|z|}{z_0})$ function (Spitzer 1942). The function is exponential $e^{-|z|/z_0}$ at large heights but softens such that the central-plane density is reduced by a factor of four compared to the extrapolation to the central plane of the exponential distribution. While the $\text{sech}^2$ function has been widely used, there is very little observational evidence of the actual softening near the Galactic plane. The new sample will be very useful to examine the form of the density distribution at small heights from the Galactic plane.

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