M dwarfs in the b201 tile of the VVV survey

Colour-based Selection, Spectral Types and Light Curves

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ABSTRACT

Context. The intrinsically faint M dwarfs are the most numerous stars in the Galaxy, and have main-sequence lifetimes longer than the Hubble time, and host some of the most interesting planetary systems known to date. Their identification and classification throughout the Galaxy is crucial to unravel the processes involved in the formation of planets, stars and the Milky Way. The ESO Public Survey VVV is a deep near-IR survey mapping the Galactic bulge and southern plane. The VVV b201 tile, located in the border of the bulge, was specifically selected for the characterisation of M dwarfs.

Aims. We used VISTA photometry to identify M dwarfs in the VVV b201 tile, to estimate their subtypes, and to search for transit-like light curves from the first 26 epochs of the survey.

Methods. UKIDSS photometry from SDSS spectroscopically identified M dwarfs was used to calculate their expected colours in the Y, J, H, K\(_s\) bandpasses. VISTA photometry from SDSS spectroscopically identified M dwarfs was used to calculate their expected colours in the V, J, H, K\(_s\) bandpassed. A colour-based spectral subtype calibration was computed. Possible giants were identified by a \((J - K\_s, H)\) reduced proper motion diagram. The light curves of 12.8\(< K\_s< 15.8\) colour-selected M dwarfs were inspected for signals consistent with transiting objects.

Results. We identified 23,345 objects in VVV b201 with colours consistent with M dwarfs. We provided their spectral types and photometric distances, up to ~300 pc for M9s and ~1.2 kpc for M4s, from photometry. In the range 12\(< K\_s< 16\), we identified 753 stars as possible giants out of 9,232 M dwarf candidates. While only the first 26 epochs of VVV were available, and 1 epoch was excluded, we were already able to identify transit-like signals in the light curves of 95 M dwarfs and 12 possible giants.

Conclusions. Thanks to its deeper photometry (~4 magnitudes deeper than 2MASS), the VVV survey will be a major contributor to the discovery and study of M dwarfs and possible companions towards the center of the Milky Way.

1 Introduction

Stars with masses less than 0.6 \(M_\odot\) span the peak of the stellar initial mass function and dominate the galactic stellar populations by number (Bastian et al. 2010). These objects are the M dwarfs: cool and faint stars, with complex spectra characterised by molecular absorption of TiO, CaH and VO in the optical, and FeH and H\(_2\) in the near infrared (Morgan et al. 1943; Mould 1976). Their main sequence lifetimes are longer than the age of the universe, with the least massive (\(M_\odot<0.25 M_\odot\)) remaining fully convective during their evolution (Laughlin et al. 1997). Some of them exhibit strong magnetic fields that can produce more magnetic activity than the sun (Johns-Krull & Valenti 1996). They are the hosts of the closest rocky planets to the Earth, and overall, they should be the most likely hosts of terrestrial planets in the Galaxy (Bonfils et al. 2013; Dressing & Charbonneau 2013; Koppvarapu 2013; Tuomi et al. 2014).

In the past decade, the study of M dwarfs has greatly benefited from photometric optical and near-infrared wide field deep surveys, such as the Sloan Digital Sky Survey (SDSS, York et al. 2000), the Two Micron All Sky Survey (2MASS, Skrutskie et al. 2006) and the UKIRT Infrared Deep Sky Survey (UKIDSS, Lawrence et al. 2007). Such surveys have found nearby low-mass and ultra cool dwarfs by colour-selection and proper motion searches (e.g. Kirkpatrick et al. 1997; Deacon et al. 2009; Lodieu et al. 2012c), have provided fundamental properties of a large number of low-mass stars from colour-based relations (e.g. parallaxes and spectral types. Hawley et al. 2002, have enlightened their magnetic activity (e.g. West et al. 2004; Morgan et al. 2012) and flaring properties (e.g. Liebert et al. 1999; Hilton et al. 2010; Davenport et al. 2012), and have allowed the measurements of mass and luminosity functions of low-mass dwarfs in the Galactic disk (Covey et al. 2008; Bochanski et al. 2010), as well as the photometric initial mass function from Galactic clusters (e.g. Lodieu et al. 2012a,b; Boudreaux et al. 2012; Lodieu 2013).

Of the mentioned surveys, only 2MASS mapped the bulge the Milky Way down to magnitude ~14, in two epochs. VISTA Variables in the Via Láctea (VVV) is a public ESO near-infrared (near-IR) variability survey aimed at scanning the Milky Way Bulge and an adjacent section of the mid-plane (Minniti et al. 2010). VVV complements previous near-IR surveys, providing better spatial resolution and deeper photometry (~4 magnitudes.
deeper than 2MASS) and multi-epoch $K_s$-band images which allows the identification of nearby faint/late M dwarfs as well as faraway unknown early M dwarfs with variable photometry consistent with transiting companions (Saito et al. 2011).

We present a colour-based selection of M dwarfs in the b201 tile of the VVV survey. In section 2, we give the description of the survey and of the tile b201. In section 3, we present our M dwarf selection method based on 6 colour-selection cuts obtained from SDSS spectroscopically observed M dwarfs with UKIDSS photometry. A spectral subtype calibration based on $(Y−J)$, $(Y−K_s)$, and $(H−K_s)$ is given in section 4. In section 5, we identify possible giants contaminants from a reduced proper motion criterion. In section 6, we identify M dwarf candidates with transit-like light curves. We discuss our results and conclusions in section 7.

2. Data

The VVV survey gives near-IR multi-colour information in five passbands: $Z$ (0.87 $\mu$m), $Y$ (1.02 $\mu$m), $J$ (1.25 $\mu$m), $H$ (1.64 $\mu$m), and $K_s$ (2.14 $\mu$m) which complements surveys such as 2MASS (Skrutskie et al. 2006), DENIS (Epchtein et al. 1997), GLIMPSE II (Churchwell et al. 2005), VPHAS+ (Drew et al. 2013), MACHO (Alcock et al. 1993), OGLE (Udalski et al. 1992), EROS (Aubourg et al. 1993), MOA (Muraki et al. 1999), and GAIA (Perryman et al. 2001). The survey covers a 562 square degree portion of the Galactic bulge where star density is lower and extinction is small called “b201”. The galactic coordinates of this tile’s center are (unfilled) pointings (or “pawprints”) and covers a 1.64 deg2 field of view. To fill up the VVV area, a total of 348 tiles are used, one specific tile from the bulge to characterise M dwarf stars of the Galactic plane (a 4 × 14 grid) and 152 for the Galactic plane (a 4 × 38 grid) (Saito et al. 2012b). We selected one specific tile from the bulge to characterise M dwarf stars called “b201”. The galactic coordinates of this tile’s center are $l=350.74816$ and $b=-9.68974$. This tile is located in the border of the bulge where star density is lower and extinction is small allowing good photometry, as shown in Figure 1. Photometric catalogues for the VVV images are provided by the Cambridge Astronomical Survey Unit (CASU)1. The catalogues contain the positions, and some shape measurements obtained from different apertures, with a flag indicating the most probable morphological classification. In particular, we note that “-1” is used to denote the best-quality photometry of stellar objects (Saito et al. 2012b). Some other flags are “-2” (borderline stellar), “0” (noise), “-7” (sources containing bad pixels), and “-9” (saturated sources).

3. Colour-Selection Cuts from SDSS-UKIDSS M dwarfs

To identify potential M dwarfs in the VVV b201 tile, we performed several colour-selection cuts using the VVV passbands as described in the subsections below. Before performing those cuts, we did a pre-selection of the objects in the tile b201 to ensure that the objects have the best-quality photometry. In this pre-selection, we included only objects that had photometry in all five passbands ($ZYJHK_s$), and that were classified as “stellar” in each passband. A total of 142,321 objects in the tile b201 satisfied these conditions.

![Fig. 1. Extinction map of the VVV field b201. The values are based on the maps of González et al. (2012), using the Cardelli et al. (1989) extinction law, for a resolution of 6’ × 6’. This field is located in the bottom-right corner of the VVV bulge area, within coordinates $-10^\circ \leq l \leq -8.5^\circ$ and $-10^\circ \leq b \leq -9^\circ$. For a large portion of the area the total extinction $A_K$ is less than the lower limit computed by the González et al. (2012) map, of $A_K \leq 0.0001$ mag. While the maximum value found is $A_K = 0.0890$ mag, the mean extinction over the entire field is $A_K = 0.0083$ mag. The total extinction is expected to be mostly in the background of the M dwarfs, and therefore overestimated. However, the values are small and the effect should be negligible, at least in this particular region (the effect would be significant in other more reddened regions of the bulge as shown by the reddening maps of González et al. (2012)). This degree of extinction produces no or negligible effects in the photometric limits used in our target selection.

The colour selection cuts were defined from spectroscopically identified M dwarfs with UKIRT Infrared Deep Sky Survey (UKIDSS) photometry.

We selected the Sloan Digital Sky Survey DR7 Spectroscopic M dwarf catalogue by West et al. (2011) as the comparative M dwarf sample. The 70,841 M dwarf stars in this catalogue had their optical spectra visually inspected and the spectral type of each object was assigned by comparing them to spectral templates. Their spectral types range from M0 to M9, with no half subtypes. This catalogue also provides values for the CaH2, CaH3 and TiO5 indices, which measure the strength of CaH and TiO molecular features present in the optical spectra of M dwarfs.

We performed a cone search with a radius of 5” of these SDSS M dwarf stars in the UKIDSS-DR8 survey (Lawrence et al. 2012). The UKIDSS survey is carried out using the Wide Field Camera (WFCAM), with a $Y$ (1.0um), $J$ (1.2um), $H$ (1.6um) and $K$ (2.2um) filter set. The cone search provided UKIDSS-DR8 matches for almost half of the SDSS M dwarf sample (34,416 matches). Next, we only kept the UKIDSS counterparts consistent with being a stellar objects (pStar > 0.9), with measured magnitudes in all WFCAM $YJHK$ filters, and with CaH and TiO indices compatible with average M dwarf stars. The final SDSS-UKIDSS comparative M dwarf sample consists of 17,774 objects.

To convert the WFCAM $YJHK$ magnitudes of the SDSS-UKIDSS M dwarf sample to VISTA $YJHK_s$ magnitudes, we used the conversions provided by CASE2 derived from regions observed with both VISTA and WFCAM.

The mean and standard deviation for all of the colours from VISTA $YJHK_s$ photometry per M spectral subtype, as well as

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1 http://aprm49.ast.cam.ac.uk/
2 http://aprm49.ast.cam.ac.uk/surveys-projects/vista/technical/photometric-properties
the number of stars considered for their computation, are shown in Table 1.

We have defined the colour-based selection of M dwarf by inspecting the colours of all the stars within 1-sigma from the mean colour. The resulting limits are:

0.336 < (Y − J) VISTA < 0.929
0.952 < (Y − H) VISTA < 1.544
1.100 < (Y − Ks) VISTA < 1.969
0.432 < (J − H) VISTA < 0.727
0.642 < (J − Ks) VISTA < 1.051
0.045 < (H − Ks) VISTA < 0.438.

From our pre-selection of 142,321 objects, only 23,345 objects have colours that are consistent with M dwarf stars, according to the colour-cuts shown above. Forty-percent of these objects have magnitudes 12 < Ks < 16, and therefore have reliable magnitudes for variability and are the best M dwarf candidates to detect any possible transits (9,232 objects).

4. Spectral Types and Photometric Distances for VVV M dwarfs

The mean colours per spectral type in Table 1 show that spectral type is a monotonically increasing function for the following colours: Y − J, Y − Ks and H − Ks. We conducted multivariate regressions on the Y − J, Y − Ks, and H − Ks colours for the 17,774 stars in the SDSS-UKIDSS comparative M dwarf sample to identify the best-fit relationship to predict each star’s spectral type. The resulting subtype calibration is

\[
\text{Msubtype} = 5.394(Y-J) + 4.370(Y-J)^2 + 24.325(Y-Ks) - 7.614(Y-Ks)^2 + 7.063(H-Ks) - 20.779, \tag{1}
\]

with \( RMS E_V \) being the root-mean-square error of validation, a sensible estimate of average prediction error (see appendix in Rojas-Ayala et al 2012). Spectral types for all the M dwarf candidates are given in Table 3.

To identify the location of M dwarfs at different distances in the Colour-Magnitude Diagram (CMD), we used the near-by M dwarfs with \( M_K \) and spectral type estimates in Rojas-Ayala et al. (2012). Using the colour transformations from WFCAM to the VISTA system, we estimated the apparent \( K_s \) magnitudes at different distances per spectral type (Table 2). The locations of the M dwarf sequence at 60 pc, 300 pc and 1000 pc coincide with the location of the colour-based selection of M dwarfs described above, as well as the \( K + M \) dwarf sequence identified by Sato et al. (2012b), as shown in the CMD of Figure 2. Based on the estimated subtypes derived by Equation 1, we provide estimated distances for the colour-based selected M dwarfs in Table 3. We emphasise that these distances are provided to have an approximate location of the objects with respect to the bulge, and they are not expected to be accurate.

Considering the spectral types in Table 3, the deeper photometry of VVV has a higher impact in the number of late type M dwarfs that can be found in the b201 tile. By performing a 5" search of the 23,345 objects in 2MASS Point Source catalogue (Cutri et al. 2003), we can estimate that the number of M9 stars found by VVV in the b201 tile is ~30 times larger than the one that can be found with only 2MASS photometry (1 versus 30 M9 stars at distances up to ~ 300 pc). The number of M8 and M7 stars is 18 and 13 times larger that the ones by only 2MASS photometry (at distances up to ~ 500 pc), while the number of M4 is about 4 times more (at distances up to ~ 1000 pc).

5. Possible Giant Contaminants

Giant stars are the most common contaminants of colour-based selections of M dwarfs. Bessell & Brett (1988) derived intrinsic colours in the Johnson–Glass system for several V and III class stars, and schematically showed the position of dwarfs, giants, supergiants, carbon stars and long-period variables in the (H − K, J − H) diagram. By using (V − K) as proxy for spectral type, Bessell & Brett (1988) showed that giants and dwarf stars share similar (J − H) and (H − K) colours for (V − K) < 3.5, but their (H − K) colours make them almost indistinguishable up to (V − K) ~ 6. Colour cuts based on (J − Ks) and (J − H) colours have been used to identify giants in different parts of the Galaxy (e.g. Sharma et al. 2010; Bochanski et al. 2014), however they only

### Table 1. VISTA mean colours and standard deviations per spectral subtype.

| Sp.T  | Y − J    | Y − H    | Y − Ks   | J − H    | J − Ks   | H − Ks   | # stars |
|-------|----------|----------|----------|----------|----------|----------|--------|
| M0    | 0.428 ± 0.092 | 1.039 ± 0.087 | 1.163 ± 0.063 | 0.611 ± 0.116 | 0.734 ± 0.092 | 0.124 ± 0.079 | 1946   |
| M1    | 0.449 ± 0.077 | 1.047 ± 0.061 | 1.200 ± 0.064 | 0.598 ± 0.086 | 0.751 ± 0.081 | 0.153 ± 0.046 | 2520   |
| M2    | 0.467 ± 0.061 | 1.042 ± 0.073 | 1.219 ± 0.058 | 0.575 ± 0.088 | 0.752 ± 0.071 | 0.177 ± 0.058 | 3043   |
| M3    | 0.487 ± 0.081 | 1.043 ± 0.062 | 1.241 ± 0.064 | 0.556 ± 0.089 | 0.754 ± 0.083 | 0.198 ± 0.038 | 3293   |
| M4    | 0.515 ± 0.083 | 1.057 ± 0.090 | 1.278 ± 0.086 | 0.542 ± 0.110 | 0.762 ± 0.085 | 0.220 ± 0.075 | 2872   |
| M5    | 0.555 ± 0.096 | 1.092 ± 0.069 | 1.340 ± 0.082 | 0.538 ± 0.103 | 0.786 ± 0.099 | 0.248 ± 0.044 | 1264   |
| M6    | 0.619 ± 0.082 | 1.150 ± 0.067 | 1.442 ± 0.076 | 0.531 ± 0.087 | 0.823 ± 0.084 | 0.292 ± 0.033 | 1224   |
| M7    | 0.664 ± 0.117 | 1.198 ± 0.126 | 1.513 ± 0.136 | 0.533 ± 0.064 | 0.849 ± 0.068 | 0.315 ± 0.037 | 1141   |
| M8    | 0.758 ± 0.070 | 1.304 ± 0.102 | 1.662 ± 0.122 | 0.546 ± 0.052 | 0.904 ± 0.067 | 0.358 ± 0.033 | 320    |
| M9    | 0.850 ± 0.079 | 1.429 ± 0.114 | 1.830 ± 0.139 | 0.579 ± 0.054 | 0.980 ± 0.071 | 0.401 ± 0.038 | 151    |

### Table 2. Average \( M_K \) and \( K_s \) at different distances per M subtype.

| Sp.T  | \( M_K \) | \( J − K_s \) | \( K_s^{20pc} \) | \( K_s^{300pc} \) | \( K_s^{1000pc} \) |
|-------|-----------|----------------|----------------|----------------|----------------|
| M0    | 5.240     | 0.753          | 9.131          | 12.626         | 15.240         |
| M1    | 5.656     | 0.773          | 9.547          | 13.042         | 15.656         |
| M2    | 6.126     | 0.748          | 10.017         | 13.512         | 16.126         |
| M3    | 6.681     | 0.775          | 10.572         | 14.067         | 16.681         |
| M4    | 7.790     | 0.788          | 11.680         | 15.175         | 17.790         |
| M5    | 7.976     | 0.788          | 11.866         | 15.361         | 17.976         |
| M6    | 8.980     | 0.842          | 12.871         | 16.366         | 18.980         |
| M7    | 9.609     | 0.901          | 13.499         | 16.994         | 19.609         |
| M8    | 10.113    | 0.980          | 14.003         | 17.498         | 20.113         |
| M9    | 10.589    | 1.153          | 14.480         | 17.975         | 20.589         |
serve to isolate the cooler giants from M dwarfs \((J-K_s) > 0.85\). The giant sequence passes through the M dwarf region in the \((J-K_s, J-H)\) diagram, with K and early M giants contaminating the sample of colour identified M dwarfs (see Figure 2). The colour selection criteria described in Sharma et al. (2010) identifies 299 objects as giants stars in our whole M dwarf sample, 60 of them within the magnitude range 12<\(K_s<16\).

Another way to identify giants, when their distances are unknown, is by their location in a reduced proper motion diagram (e.g. Lépine & Gaidos 2011). To get estimates of the proper motions of the whole M dwarf colour-based selection, we performed a cone search with a 5° radius of their coordinates in the PPMXL catalogue (Roeser et al. 2010) and the SPM4 catalogue (Girard et al. 2011). The PPMXL catalogue covers both hemispheres, while the SPM4 catalogue covers objects between the south celestial pole and -20° declination, with higher proper motion precision than PPMXL. Both of these catalogues provide the crossmatched 2MASS photometry for their objects, and we only considered the objects with \(|K_s^{\text{VISTA}}-K_s^{\text{2MASS}}| \leq 0.5\) mag. We obtained total proper motions, \(\mu\) in \("/\text{yr}\), for 6,464 and 2,940 objects from PPMXL and SPM4, respectively. The number of stars in the 12<\(K_s<16\) M dwarf selection with PPMXL and SPM4 total proper motions is 6,216 and 2,760, respectively. We calculated their \(J\) magnitude reduced proper motion \(H_J\) using the definition

\[
H_J = J + 5 \log_{10} \mu.
\]

Lépine & Gaidos (2011) defined a criterion to separate M dwarfs from giants based on \(V\) magnitude, reduced proper motion \(H_V\), and \((V-J)\) colour. This criterion cannot be used for our stars since \(V\) magnitudes are hard to find in the literature for the 12<\(K_s<16\) M dwarfs. For that reason, we computed an equivalent criterion based on \(J\) and \(K_s\) magnitudes. We grouped the stars of the Lépine & Gaidos (2011) study by their estimated spectral types, obtained their mean \((V-J)\) and \((J-K_s)\) colours, and calculated the dwarf/giant discriminator \(H_J\) as function of mean \((V-J)\) per spectral type, using our definition of \(H_J\), by rewriting Equation 8 of Lépine & Gaidos (2011) as follows:

\[
H_J = 1.5(V-J) - 3.0.
\]

Then, using the mean \((J-K_s)\) colour corresponding to each mean \((V-J)\) per spectral type, we performed a linear fit to obtain \(H_J^{\text{dwarf}}\) as function of \((J-K_s)\), and, therefore, an equivalent criterion to Equation 5 based on \((J-K_s)\), instead of \((V-J)\)

\[
H_J^{\text{dwarf}} > H_J > 68.5(J-K_s) - 50.7.
\]

In the 12<\(K_s<16\) M dwarf sample, using the criterion above, we identified 555 likely giant stars from PPMXL proper motions, with 24 of them exhibiting \((J-K_s)\) and \((J-H)\) colours compatible with giants. From SPM4 proper motions, we identified 328 likely giants, with 18 of them exhibiting cool giant colours. Almost all of the 12<\(K_s<16\) objects in SPM4 have also PPMXL proper motions (2,595 stars). For about 40% of them, the PPMXL and SPM4 total proper motions agree within \(\pm 0.01"/\text{yr}\), with the PPMXL catalogue providing higher values of total proper motions than SPM4 (by more than 0.01"/yr) for the majority of the rest. Considering the reduced proper motion criterion, only 164 objects are likely giants with both PPMXL and SPM4 proper motions (16 of them have giants colours, too).

Their locations in the CMD and \((H-K_s, J-H)\) diagram are shown in Figure 3.

The names, VISTA photometry, spectral type, and estimated distances of the 23,345 colour-selected M dwarf candidates are listed in Table 3. The total proper motion, \(\mu_{\text{RPM}}\) and likely giant flag are given for the stars with PPMXL and SPM4 proper motions, as well as the 299 colour selected giants.

6. VVV Light Curves for M dwarfs

We constructed the light curves of the 9,232 M dwarf candidates with 12<\(K_s<16\) in the tile b201, considering only the first 26 epochs of VVV observations. These epochs cover observations taken from December 2010 to September 2012. Considering the unevenly sampled data and the low number of epochs, we searched for objects with light-curves with "transit-like" signals by identifying "outliers", i.e. epochs with magnitudes considerably fainter than the median magnitude of all epochs, in each light-curve. We used the median and median absolute deviation (MAD) statistics to identify outliers, given that they are very insensitive to the presence of outliers in the data, contrary to the mean and the standard deviation. An epoch is classified as an outlier if its magnitude is 3-MAD away from the median magnitude of the light-curve.

By inspecting the outliers in each light-curve, we found that certain epochs were consistently flagged as outliers. These epochs correspond to the observation dates with sightings smaller than 0.8", where several stars with \(K_s < 12.8-13\) mag appear to be consistently fainter. We also found that epoch 14 exhibits the higher dispersion in all magnitudes. Considering the above, and the fact that at all epochs the dispersion increases at \(K_s > 15.8\) mag, we restricted our study of the light-curves to the M dwarf candidates with 12.8<\(K_s<15.8\) mag, without considering epoch 14. Due to the small number of epochs, we also only considered objects with "1" flag (stellar) in all epochs and with mean magnitude errors of all the epochs smaller or equal to 1.5 MAD.

We found 95 M dwarf candidates and 12 likely giants that exhibit at least 3 epochs with 3-MAD fainter \(K_s\) magnitudes than the median of the 25 epochs (removing epoch 14) out of the 3,843 objects that satisfied all of the conditions mentioned above. Examples of the type of light curves found can be seen in Figure 4.

7. Conclusions

We identified 23,345 M dwarf candidates in the VVV b201 tile from colour-cuts based on 17,774 M dwarfs with SDSS spectra and UKIDSS photometry. Their positions in VISTA-colour diagrams match the stellar locus derived from stars with 2MASS photometry by Covey et al. (2007), as well as the dwarf sequences from synthetic colours calculated from IRTF Library spectra (Appendix A). From that sample, we selected 9,232 stars with 12<\(K_s<16\) magnitudes for further characterisation of their light curves. From their position on a reduced proper motion diagram and their \(J-K_s\) and \(J-H\) colours, we identified 753 objects with a higher chance of being giants instead of M dwarfs. From the sample of likely M dwarfs, we searched for transit-like light curves based on 25 epochs of the VVV survey. We found 95 objects with light curves with 3 or more epochs with significant decrease of their luminosity. Assuming that the light curves correspond to non-grazing objects fully transiting the M dwarf, the sizes of these possible companions range from the ones of ultracool dwarfs (~0.12) to sizes of a couple of earth radii. However,
Table 3. M dwarfs in the VVV b201 tile. Only a portion of this table is shown here to demonstrate its form and content.

| Name                  | Z mag | Y mag | J mag | H mag | K_s mag | Sp.T. | d pc | PM(pm,ma) mas/yr | H'F145 mag | PM(Pm,pxl) | H'F145 mag | Obs. |
|-----------------------|-------|-------|-------|-------|---------|-------|-----|------------------|------------|-------------|------------|------|
| VVVJ17594599-4205194  | 18.242| 17.667| 17.105| 16.316| 16.396 | 3     | 877 |                  |            |             |            |      |
| VVVJ17594605-4206345  | 19.523| 19.004| 18.040| 17.467| 17.413 | 3     | 288 |                  |            |             |            |      |
| VVVJ17594628-4206516  | 18.166| 17.964| 17.432| 16.786| 16.638 | 3     | 980 |                  |            |             |            |      |
| VVVJ17594899-4206457  | 17.463| 17.103| 16.599| 15.976| 15.812 | 3     | 670 |                  |            |             |            |      |
| VVVJ17595098-4205074  | 16.729| 16.466| 16.024| 15.399| 15.27  | 3     | 674 |                  |            |             |            |      |
| VVVJ17594944-4207152  | 14.435| 14.135| 13.744| 13.12  | 12.949 | 3     | 287 |                  |            |             |            |      |
| VVVJ17594955-4205529  | 13.493| 13.210| 12.871| 12.512| 12.27  | 3     | 110 |                  |            |             |            |      |

Notes. In Obs. columns, likely giants are flagged as “G” followed by numbers 1 and/or 2, and/or 3, where 1-proper motion from SPM4, 2-proper motion from PPMXL, and 3-colour selected. Stars with transit-like curves are flagged as “T”.

this is assuming the conditions mentioned above and assuming that the light curves are due to transiting objects. More VVV epochs and further spectroscopic follow-up are needed to confirm the properties of the stars and the real nature of their light curves. The deeper photometry of VVV has a higher impact in the number of nearby, late type M dwarfs that can be found towards the bulge of the Galaxy, missed by previous NIR surveys. VVV will be a major contributor to the discovery and study of very low-mass stars and and possible companions towards the center of the Milky Way.

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This work is based in part on data obtained as part of the UKIRT Infrared Deep Sky Survey. This publication makes use of data products from the Two Micron Sky Survey. This publication makes use of data products from the Two Micron Sky Survey. This publication makes use of data products from the Two Micron Sky Survey.

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Appendix A: Giant and Dwarf Sequences for VISTA Colours

We estimated VISTA colours of the FGKM dwarf and giant sequences by computing VISTA ZYJHK$_s$ magnitudes for 52 FGKM dwarf and 54 FGKM giant stars from the Infrared Telescope Facility (IRTF) Spectral Library. The IRTF Spectral Library has a collection of R $\sim$ 2000-2500 FGKM stellar spectra observed with the SpeX spectrograph, with a spectral range of 0.8 to at least 2.5 $\mu$m (Cushing et al. 2005; Rayner et al. 2009). The stars in the library were absolutely flux calibrated using 2MASS photometry, with their spectral continuum shape preserved.

The VISTA synthetic magnitude in each filter was estimated using the following equation:

$$m_\lambda = -2.5 \log_{10} \left( \int F_\lambda S_\lambda \, d\lambda \right) + 2.5 \log_{10} \left( \int F_\lambda^0 S_\lambda \, d\lambda \right).$$ (A.1)

The second term of the Equation [A.1] corresponds to the zero point of the magnitude scale. For calculation of the VISTA synthetic magnitudes presented here, the $F_\lambda^0$ flux corresponds to that of the Vega spectrum in the CALSPEC library (Bohlin 2014). The response function of the VISTA filter set, $S_\lambda$, was calculated from the quantum efficiency curve of the detector and transmission curves for each filter. The VISTA synthetic colours calculated for dwarf and giant stars in the IRTF library are given in Tables A.1 and A.2 respectively.

Using the stars in Tables A.1 and A.2, we fitted the colours of the giant and dwarf sequences using a fifth-order polynomial in $H - K_s$ with the form:

$$\text{colour}_X = \sum_{i=0}^{5} A_i (H - K_s)^i.$$ (A.2)

We tabulated the fitted colours of the giant and dwarf sequences as function of $H - K_s$ colour in Table A.3. The positions of the stellar sequences are shown as orange lines in Figure 2.

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3 http://irtfweb.ifa.hawaii.edu/spex/IRTF_Spectral_Library/
4 http://www.stsci.edu/hst/observatory/crds/calspec.html
5 http://www.eso.org/sci/facilities/paranal/instruments/vircam/inst.html
Table A.1. VISTA synthetic magnitudes for dwarfs in the IRTF library

| Name       | Sp. T. | Z   | Y   | J   | H   | Ks  |
|------------|--------|-----|-----|-----|-----|-----|
| HD 108519  | F0     | 7.265 | 7.231 | 7.113 | 6.973 | 6.935 |
| HD 213135  | F1     | 5.462 | 5.427 | 5.263 | 5.092 | 5.076 |
| HD 113139  | F2     | 4.444 | 4.372 | 4.176 | 3.998 | 3.976 |
| HD 26015   | F3     | 5.355 | 5.305 | 5.156 | 5.043 | 5.057 |
| HD 16232   | F4     | 6.298 | 6.262 | 6.081 | 5.876 | 5.848 |
| HD 87822   | F4     | 5.611 | 5.559 | 5.372 | 5.194 | 5.164 |
| HD 27524   | F5     | 6.166 | 6.144 | 5.966 | 5.788 | 5.767 |
| HD 218804  | F5     | 5.266 | 5.197 | 4.983 | 4.745 | 4.694 |
| HD 215648  | F6     | 3.577 | 3.519 | 3.299 | 3.075 | 3.042 |
| HD 126660  | F7     | 3.389 | 3.349 | 3.148 | 2.936 | 2.883 |
| HD 27383   | F8     | 6.075 | 5.999 | 5.799 | 5.589 | 5.573 |
| HD 219623  | F8     | 4.963 | 4.873 | 4.642 | 4.386 | 4.342 |
| HD 176051  | F9     | 4.376 | 4.303 | 4.039 | 3.718 | 3.667 |
| HD 114710  | F9.5   | 3.427 | 3.382 | 3.181 | 2.988 | 2.996 |
| HD 109358  | G0     | 3.504 | 3.438 | 3.195 | 2.905 | 2.876 |
| HD 10307   | G1     | 4.284 | 4.205 | 3.964 | 3.685 | 3.657 |
| HD 20619   | G1.5   | 6.274 | 6.168 | 5.878 | 5.537 | 5.475 |
| HD 76151   | G2     | 5.203 | 5.115 | 4.855 | 4.555 | 4.481 |
| HD 10697   | G3     | 5.442 | 5.315 | 5.024 | 4.695 | 4.616 |
| HD 214850  | G4     | 4.835 | 4.747 | 4.464 | 4.069 | 3.972 |
| HD 165185  | G5     | 5.097 | 5.055 | 4.831 | 4.575 | 4.525 |
| HD 115617  | G6.5   | 3.591 | 3.522 | 3.281 | 2.998 | 2.985 |
| HD 75732   | G8     | 4.938 | 4.807 | 4.504 | 4.139 | 4.047 |
| HD 101501  | G8     | 4.397 | 4.276 | 3.995 | 3.665 | 3.612 |
| HD 145675  | K0     | 5.562 | 5.438 | 5.135 | 4.796 | 4.743 |
| HD 10476   | K1     | 4.269 | 4.139 | 3.809 | 3.405 | 3.318 |
| HD 3765    | K2     | 6.173 | 6.025 | 5.678 | 5.262 | 5.183 |
| HD 219134  | K3     | 4.586 | 4.358 | 3.955 | 3.444 | 3.333 |
| HD 45977   | K4     | 7.578 | 7.403 | 7.033 | 6.555 | 6.455 |
| HD 36003   | K5     | 6.199 | 5.996 | 5.588 | 5.031 | 4.915 |
| HD 201092  | K7     | 4.014 | 3.824 | 3.427 | 2.875 | 2.736 |
| HD 237903  | K7     | 6.813 | 6.562 | 6.108 | 5.499 | 5.376 |
| HD 19305   | M0     | 7.199 | 6.932 | 6.471 | 5.837 | 5.671 |
| HD 209290  | M0.5   | 6.992 | 6.676 | 6.174 | 5.544 | 5.348 |
| HD 42581   | M1     | 5.866 | 5.555 | 5.073 | 4.465 | 4.277 |
| HD 36395   | M1.5   | 5.746 | 5.407 | 4.893 | 4.215 | 4.032 |
| Gl 806     | M2     | 8.107 | 7.786 | 7.304 | 6.741 | 6.581 |
| HD 95735   | M2     | 4.928 | 4.611 | 4.125 | 3.611 | 3.435 |
| Gi 381     | M2.5   | 7.895 | 7.522 | 6.993 | 6.438 | 6.236 |
| Gi 581     | M2.5   | 7.545 | 7.163 | 6.649 | 6.123 | 5.887 |
| Gi 273     | M3.5   | 6.679 | 6.225 | 5.668 | 5.149 | 4.915 |
| Gi 388     | M3     | 6.334 | 5.936 | 5.403 | 4.841 | 4.645 |
| Gi 213     | M4     | 8.141 | 7.665 | 7.112 | 6.641 | 6.415 |
| Gi 299     | M4     | 9.392 | 8.933 | 8.377 | 7.958 | 7.711 |
| Gi 51      | M5     | 9.799 | 9.225 | 8.575 | 8.029 | 7.758 |
| Gi 406     | M6     | 8.613 | 8.119 | 7.504 | 6.483 | 6.131 |
| GJ 1111    | M6.5   | 9.761 | 8.954 | 8.181 | 7.648 | 7.295 |
| Gi 644C    | M7     | 11.357 | 10.533 | 9.741 | 9.224 | 8.862 |
| LP 412-31  | M8     | 13.672 | 12.681 | 11.732 | 11.089 | 10.675 |
| DENIS-P J1048-3956 | M9 | 11.456 | 10.389 | 9.459 | 8.933 | 8.537 |
| LP 944-20  | M9     | 12.933 | 11.718 | 10.664 | 10.052 | 9.605 |
| BRIB 0021-0214 | M9.5 | 14.195 | 12.995 | 11.843 | 11.132 | 10.625 |
Fig. 2. Colour-Magnitude diagram and colour-colour diagrams for objects classified as "stellar" in the tile b201. The colour-based selection of M dwarfs is shown in pink in all diagrams. Black open circles are giant stars located at similar $(l, b)$ as b201 by the BRaVA Project [Rich et al. 2007; Kunder et al. 2012]. a) The colour identified M dwarfs fill the region that agrees with the K+M dwarf sequence in the $(J - K_s, K_s)$ CMD of the outermost region in the VVV bulge area, identified by Saito et al. (2012b). The estimated M dwarf spectral sequences at 60 pc, 300 pc and 1000 pc are shown. b), c), and d) $(H - K_s, J - H)$, $(J - K_s, Y - J)$, and $(Y - J, Z - Y)$ diagrams for all "stellar" objects with $12 < K_s < 16$ only. The blue lines represent the dwarf (filled circles) and giant (open circles) sequences, based on UKIDSS synthetic colours by [Hewett et al. 2006]. The orange lines represent the dwarf (filled circles) and giant (open circles) sequences, based on VISTA synthetic colours derived from stars in the IRTF Spectral Library (see APPENDIX A). In the $(H - K_s, J - H)$ diagram, the black line corresponds to the $JHK_s$ stellar locus by Covey et al. (2007), derived from SDSS and 2MASS photometry, and it is in agreement with the one derived in this work from VISTA synthetic colours. The disagreement between the UKIDSS and VISTA sequences may be due to the differences between the $Z$ and $Y$ synthetic filters of each survey.
Fig. 3. Reduced proper motion (RPM), colour-magnitude, and \((H - K_s, J - H)\) diagrams for the 12<\(K_s\)<16 M dwarfs selected by colour-based relations (pink contours). Bulge giant stars from the BRaVA Project are shown as black open circles.  

a) In the RPM diagram, likely giants contaminants lie above the black line which represents the \(H'\) as function of \((J - K_s)\) colour. b) In the CMD, likely giant stars from SPM4 (blue dots) exhibit brighter magnitudes due to the magnitude cut of the survey, while PPMXL provides parallaxes for fainter likely giants (red dots). Crosses depict likely giants identified by colour-cuts from Sharma et al. (2010). c) Likely giants selected by colour-cuts (crosses) follow the trend of the BRaVa giants (open circles) in the \((H - K_s, J - H)\) diagram. Likely giants identified by proper motions are mostly located in the upper part of the M dwarf region (redder \(J - H\) colours), and exhibit \(H - K_s\) colours redder than \(\sim 0.13\) mag.

Fig. 4. Light curves of 6 M dwarf candidates. The dotted black lines indicate the \(\pm 3\)-MAD cuts to find the outliers. The red dotted line indicates the mean magnitude of the outliers. Considering the mean magnitude of the outliers and assuming a non-grazing transit, the possible companions have sizes consistent with ultra-cool dwarfs down to terrestrial bodies.
Table A.2. VISTA synthetic magnitudes for giants in the IRTF library

| Name   | Sp. T. | Z    | Y    | J    | H    | Ks  |
|--------|--------|------|------|------|------|-----|
| HD 89025 | F0     | 2.956 | 2.914 | 2.763 | 2.606 | 2.578 |
| HD 21770 | F4     | 4.683 | 4.645 | 4.473 | 4.295 | 4.275 |
| HD 17918 | F5     | 5.671 | 5.599 | 5.412 | 5.224 | 5.215 |
| HD 124850 | F7     | 3.431 | 3.352 | 3.121 | 2.883 | 2.862 |
| HD 220657 | F8     | 3.913 | 3.809 | 3.521 | 3.196 | 3.093 |
| HD 6903  | F9     | 4.925 | 4.813 | 4.535 | 4.216 | 4.155 |
| HD 21018 | G1     | 5.305 | 5.146 | 4.827 | 4.475 | 4.391 |
| HD 86839 | G3     | 4.988 | 4.837 | 4.504 | 4.111 | 4.049 |
| HD 108477 | G4    | 5.299 | 5.135 | 4.799 | 4.402 | 4.312 |
| HD 193896 | G5    | 5.305 | 5.095 | 4.712 | 4.265 | 4.151 |
| HD 27277 | G6     | 6.808 | 6.587 | 6.215 | 5.795 | 5.715 |
| HD 182694 | G7    | 4.865 | 4.729 | 4.395 | 3.988 | 3.888 |
| HD 16139 | G7.5   | 6.755 | 6.549 | 6.173 | 5.715 | 5.595 |
| HD 135722 | G8    | 2.174 | 2.006 | 1.645 | 1.153 | 1.034 |
| HD 104979 | G8    | 3.108 | 2.944 | 2.589 | 2.105 | 2.013 |
| HD 122563 | G8    | 4.969 | 4.785 | 4.392 | 3.862 | 3.765 |
| HD 222093 | G9    | 4.692 | 4.508 | 4.123 | 3.619 | 3.517 |
| HD 100006 | K0    | 4.511 | 4.295 | 3.893 | 3.363 | 3.261 |
| HD 9852  | K0.5   | 6.183 | 5.859 | 5.356 | 4.755 | 4.605 |
| HD 25975 | K1     | 4.979 | 4.849 | 4.522 | 4.098 | 4.028 |
| HD 91810 | K1     | 5.497 | 5.256 | 4.831 | 4.303 | 4.169 |
| HD 36134 | K1     | 4.415 | 4.209 | 3.797 | 3.359 | 3.165 |
| HD 124897 | K1.5  | -1.535 | -1.759 | -2.203 | -2.853 | -2.987 |
| HD 137759 | K2    | 1.998 | 1.756 | 1.314 | 0.747 | 0.611 |
| HD 132935 | K2    | 5.206 | 4.931 | 4.441 | 3.779 | 3.614 |
| HD 2901  | K2     | 5.653 | 5.391 | 4.931 | 4.325 | 4.225 |
| HD 99998 | K3     | 3.037 | 2.717 | 2.159 | 1.414 | 1.215 |
| HD 35620 | K3     | 3.637 | 3.336 | 2.845 | 2.227 | 2.048 |
| HD 17208 | K3     | 5.185 | 4.892 | 4.411 | 3.821 | 3.674 |
| HD 221246 | K3    | 4.675 | 4.364 | 3.863 | 3.203 | 3.055 |
| HD 114960 | K3.5  | 4.852 | 4.558 | 4.088 | 3.471 | 3.316 |
| HD 207991 | K4    | 4.909 | 4.548 | 3.983 | 3.209 | 3.005 |
| HD 181596 | K5    | 5.721 | 5.357 | 4.799 | 4.073 | 3.867 |
| HD 120477 | K5.5  | 2.172 | 1.823 | 1.268 | 0.532 | 0.316 |
| HD 3346  | K6     | 3.126 | 2.786 | 2.225 | 1.452 | 1.213 |
| HD 194193 | K7    | 4.025 | 3.646 | 3.064 | 2.252 | 2.022 |
| HD 213893 | M0    | 4.812 | 4.444 | 3.885 | 3.125 | 2.916 |
| HD 204724 | M1    | 2.488 | 2.116 | 1.593 | 0.875 | 0.618 |
| HD 120052 | M2    | 2.894 | 2.488 | 1.864 | 1.022 | 0.747 |
| HD 219734 | M2.5  | 2.519 | 2.098 | 1.493 | 0.681 | 0.428 |
| HD 39045 | M3     | 3.621 | 3.181 | 2.551 | 1.719 | 1.446 |
| HD 28487 | M3.5   | 3.851 | 3.324 | 2.659 | 1.781 | 1.485 |
| HD 27598 | M4     | 4.038 | 3.562 | 2.953 | 2.128 | 1.856 |
| HD 214665 | M4    | 2.556 | 1.886 | 1.114 | 0.156 | -0.182 |
| HD 4408  | M4     | 2.539 | 2.043 | 1.405 | 0.546 | 0.239 |
| HD 204585 | M4.5  | 2.294 | 1.691 | 1.062 | 0.278 | 0.026 |
| HD 175865 | M5    | 0.496 | -0.128 | -0.769 | -1.570 | -1.811 |
| HD 94705 | M5.5   | 1.822 | 1.089 | 0.401 | -0.429 | -0.763 |
| HD 18191 | M6     | 1.739 | 0.966 | 0.252 | -0.622 | -0.938 |
| HD 196610 | M6    | 1.653 | 0.816 | 0.144 | -0.649 | -0.945 |
| HD 108849 | M7    | 2.488 | 1.362 | 0.495 | -0.332 | -0.722 |
| HD 207076 | M7    | 1.186 | 0.195 | -0.500 | -1.206 | -1.477 |
| IRAS 21284-0747 | M8 | 8.752 | 7.262 | 6.107 | 5.373 | 4.819 |
| BRIB 1219-1336 | M9 | 10.689 | 9.446 | 8.556 | 7.919 | 7.447 |
Table A.3. VISTA colours as function of \((H - K_s)\) for dwarfs and giants

| Dwarfs | Giants |
|--------|--------|
| \((Z - Y)\) | \((Y - J)\) | \((J - H)\) | \((Z - Y)\) | \((Y - J)\) | \((J - H)\) | \((H - K_s)\) |
| 0.065  | 0.181  | 0.169  | -0.015 | 0.074  | 0.187  | 0.172  | 0.035 |
| 0.052  | 0.176  | 0.162  | 0.005  | 0.051  | 0.177  | 0.164  | 0.015  |
| 0.046  | 0.178  | 0.168  | 0.072  | 0.051  | 0.178  | 0.164  | 0.225  |
| 0.059  | 0.214  | 0.234  | 0.094  | 0.070  | 0.232  | 0.266  | 0.263  |
| 0.070  | 0.232  | 0.266  | 0.109  | 0.084  | 0.253  | 0.300  | 0.301  |
| 0.100  | 0.274  | 0.335  | 0.140  | 0.117  | 0.296  | 0.370  | 0.370  |
| 0.136  | 0.318  | 0.405  | 0.168  | 0.155  | 0.340  | 0.437  | 0.460  |
| 0.174  | 0.362  | 0.467  | 0.195  | 0.194  | 0.383  | 0.494  | 0.487  |
| 0.214  | 0.403  | 0.517  | 0.223  | 0.233  | 0.422  | 0.537  | 0.540  |
| 0.253  | 0.439  | 0.553  | 0.253  | 0.273  | 0.456  | 0.565  | 0.589  |
| 0.293  | 0.472  | 0.573  | 0.286  | 0.313  | 0.486  | 0.578  | 0.659  |
| 0.333  | 0.500  | 0.580  | 0.324  | 0.354  | 0.513  | 0.578  | 0.703  |
| 0.374  | 0.525  | 0.574  | 0.366  | 0.396  | 0.537  | 0.567  | 0.742  |
| 0.418  | 0.549  | 0.559  | 0.414  | 0.441  | 0.560  | 0.549  | 0.778  |
| 0.465  | 0.572  | 0.539  | 0.467  | 0.490  | 0.585  | 0.528  | 0.808  |
| 0.516  | 0.598  | 0.517  | 0.525  | 0.544  | 0.612  | 0.507  | 0.820  |
| 0.574  | 0.628  | 0.498  | 0.589  | 0.605  | 0.644  | 0.491  | 0.840  |
| 0.637  | 0.662  | 0.485  | 0.658  | 0.672  | 0.682  | 0.482  | 0.852  |
| 0.707  | 0.703  | 0.482  | 0.730  | 0.745  | 0.726  | 0.484  | 0.853  |
| 0.783  | 0.751  | 0.490  | 0.807  | 0.823  | 0.778  | 0.498  | 0.849  |
| 0.864  | 0.806  | 0.510  | 0.885  | 0.906  | 0.836  | 0.525  | 0.872  |
| 0.947  | 0.867  | 0.543  | 0.965  | 0.989  | 0.899  | 0.563  | 0.982  |
| 1.030  | 0.932  | 0.585  | 1.045  | 1.069  | 0.964  | 0.609  | 1.045  |
| 1.106  | 0.997  | 0.633  | 1.124  | 1.141  | 1.028  | 0.657  | 0.819  |
| 1.171  | 1.058  | 0.679  | 1.199  | 1.197  | 1.086  | 0.699  | 0.680  |
| 1.217  | 1.110  | 0.714  | 1.270  | 1.230  | 1.129  | 0.724  | 0.666  |
| 1.234  | 1.144  | 0.726  | 1.335  | 1.229  | 1.151  | 0.718  | 0.515  |
| 1.212  | 1.150  | 0.698  | 1.391  | 1.437  | 1.054  | 0.654  | 0.525  |
| 1.182  | 1.140  | 0.663  | 1.416  | 1.456  | 1.084  | 0.670  | 0.535  |
|        |        |        |        | 1.471  | 1.116  | 0.695  | 0.545  |
|        |        |        |        | 1.482  | 1.151  | 0.731  | 0.555  |