Meeting the neighbours:
A 2MASS-based survey of stars and brown dwarfs within 20 parsecs of the Sun

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Summary of Personnel, Commitment and Costs

This project brings together personnel who each have a substantial track record of research on cool stars, and whose combined range of expertise spans almost all sub-disciplines in that field of research. The PI has made significant contributions to the analysis of low-mass stars, particularly the study of the stellar/substellar luminosity function and mass function, for two decades. Reid also has extensive expertise in undertaking large-scale surveys, and analysing survey data, both through participation in the second Palomar Sky Survey, and in prior research using UK Schmidt plate material. Liebert's contributions cover a similar period, and he brings to the project wide-ranging knowledge of the atmospheric and chromospheric characteristics of low-mass stars and brown dwarfs.

Reid, Monet, Liebert, Kirkpatrick, Gizis and Burgasser (with C.Dahn, USNO) constitute the Brown Dwarf Consortium of the 2MASS Rare Objects Core Project, and have together been responsible for the identification of over three-quarters of currently-known isolated brown dwarfs. Monet's contribution to the present project is particularly crucial, since he is primarily responsible for astrometric calibration of the 2MASS database, and has compiled the extensive astrometric and photometric database based on photographic survey material currently available. Tinney is well versed in trigonometric parallax determination, and, finally, Henry and Golimowski have extensive experience in M dwarf astronomy, particularly in searching for low-mass companions.

Scientific and technical description

1. Introduction

Our nearest stellar and substellar neighbours play a vital role in astrophysics as representatives of their respective classes. Not only does proximity allow detailed study of both the objects themselves and their immediate environs, including planet detection, but properties of individual systems can be combined to derive fundamental parameters such the kinematics, binary frequency, the range of magnetic activity, the luminosity function and the mass function. Statistical analysis, however, demands completeness, and the catalogue of nearby stars is known to become incomplete at relatively small distances from the Sun. The primary purpose of the NStars project is finding the missing stars; this proposal aims to meet that goal.

Incompleteness is particularly pronounced for stars of low intrinsic luminosity, a circumstance emphasised with the discovery of isolated dwarfs with temperatures cooler than spectral class M: L dwarfs and T dwarfs (Kirkpatrick et al, 1999; Strauss et al, 1999; Burgasser et al, 1999). Late-type M dwarfs account for $\sim 25\%$ of stellar systems; substellar-mass brown dwarfs likely outnumber stars; thus, the combined population of low luminosity, ultracool dwarfs is an extremely significant constituent of the Galactic disk.

Near-infrared sky surveys have been crucial in identifying ultracool dwarfs. The 2MASS database will provide the first all-sky near-infrared photometric catalogue, including a total of a 4×10^8 point source detections. We have demonstrated that those data provide an extremely effective method of identifying late-type dwarfs. We have also demonstrated our ability to analyse such an extensive database in an efficient manner. This proposal outlines techniques for reducing that catalogue of ~ 400 million sources to $\sim 7,000$ late-type, nearby star candidates.

Survey goals: We propose to combine 2MASS photometry with other photometric and astrometric data to construct a comprehensive, all-sky catalogue of late-type dwarfs within the immediate Solar Neighbourhood. We expect to identify at least 600 M-dwarf systems, ~ 150 L dwarfs and ~ 120 T dwarfs at distances of less than 20 parsecs from the Sun. At present, ~ 250 such systems are known, with all save 15 being M dwarfs. If practical, we will extend our survey to earlier-type M dwarfs. Data for those nearby dwarfs, together with ancillary catalogues providing accurate positions and near-infrared photometry for high proper-motion stars, will be made available at the earliest opportunity to the general astronomical community.

2. A nearby star census

2.1. The status quo

How complete is our current knowledge of the Solar Neighbourhood? Since the mid-1950s, a catalogue of stars believed to be within 25 pc of the Sun has been maintained at Heidelberg, initially by W. Gliese and presently by H. Jahreiss. The most recent published version (the CNS3, 1991) includes 3800 stars in 3260 systems. However, this catalogue is a compilation of data from many sources of widely varying accuracy and reliability, and many of those stars are now known to lie at greater distances.

Data for the ESA astrometric satellite, Hipparcos (ESA, 1997), have proven invaluable in refining this sample. Hipparcos obtained astrometry for almost every star known to have a magnitude $V < 7.9 + 1.1 sin|b|$, where b is Galactic latitude, providing a complete sample to 20 pc for intrinsically luminous AFG dwarfs, $M_V < 6.5$. At fainter magnitudes, Hipparcos observations include only a pre-selected subset of stars, few targets with $V > 11$ and none fainter than V=13 mag. However, all systems in the CNS3 classified as main-sequence dwarfs with $M_V > 7.5$ have been observed spectroscopically by Reid et al (1995) and Hawley et al (1996) [the PMSU survey], and those spectroscopic parallaxes provide homogeneous distance estimates for late K and M dwarfs.

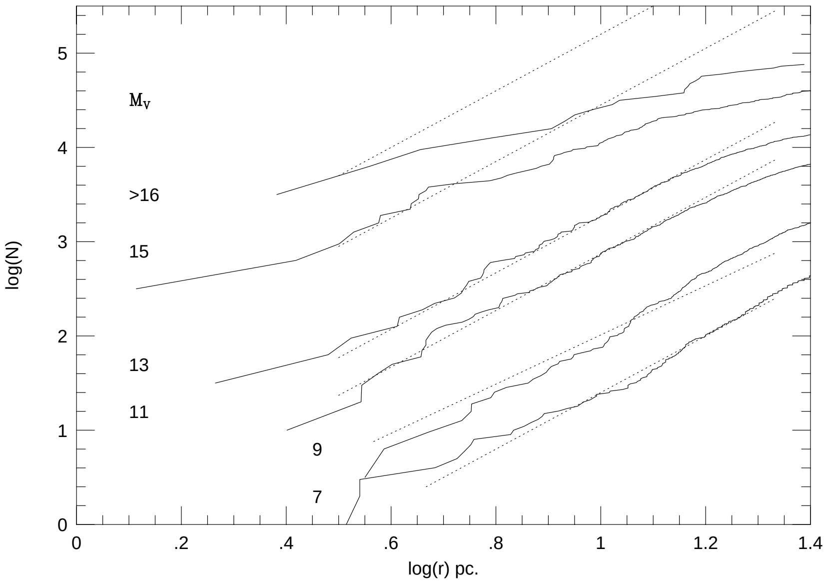

Figure 1. Cumulative distance distributions, (log(N), log(r)) for the current CNS3 catalogue. From bottom to top, the observed distributions are for $M_V = 7 \pm 1$, $M_V = 9 \pm 1$, $M_V = 11 \pm 1$, $M_V = 13 \pm 1$, $M_V = 15 \pm 1$ and $M_V > 16$. The dotted lines indicate the expected distribution for a uniform density distribution ($N \propto r^3$) at each absolute magnitude interval. The latter are normalised to the density within ~ 5 parsecs.

Both the Hipparcos astrometry and ground-based spectroscopy are efficient at eliminating misclassified stars; neither provides an effective means of adding previously uncatalogued systems at faint magnitudes. This is particularly important, given the flood of cool, low-luminosity dwarfs discovered recently by wide-angle near-infrared and optical surveys. Setting aside the latter sources for the moment, the revised CNS3 includes 1633 systems with $r < 20$ pc; the predicted number of main-sequence systems, based on stars known to be within 8 parsecs of the Sun, is $\sim 2125 \pm 210$. This suggests that the current sample of nearby stars is incomplete by a factor of $\approx 30\%$. Figure 1 further quantifies this result, and demonstrates that incompleteness becomes significant at distances of <8 parsecs for $M_V > 14$.

At lower luminosities, the local sample is even less complete. Near-infrared sky surveys, notably 2MASS, have resulted in the identification of objects which are cooler than spectral class M: TiO and VO absorption disappear as those elements solidify as dust, and the spectra are dominated by metal hydrides and alkali lines. Designated L dwarfs (Kirkpatrick et al, 1999), a handful are known within 20 parsecs of the Sun (Kirkpatrick et al, 2000). Of the ~ 100 sources known, 85 were identified from our 2MASS follow-up observations. At even cooler temperatures, methane forms in the atmosphere, leading to the characteristic blue near-infrared colours, first seen in the cool companion, Gl 229B (Nakajima et al, 1995). We designate the latter objects T dwarfs; a total of ten spectroscopically-confirmed isolated dwarfs and two binary companions (Gl 229B, Gl 570D) are known at present.

2.2. Completing the census

Our strategy in the proposed project is to use photometric criteria, outlined in the following section, to identify a preliminary list of candidate nearby stars. The initial colour-magnitude cut eliminates 99.9% of the 2MASS catalogue; further selection in colour-colour planes reduces the target list by a further 98%, to only a few thousand candidate nearby dwarfs. We will use supplementary astrometric, photometric and spectroscopic observations to further refine the sample. Our prime goal is the identification of low-mass systems within 20 parsecs of the Sun. As described below, photometric selection is most effective in identifying dwarfs with spectral types between M4 and L9. Nearby M0 to M4 dwarfs, warmer Gl 229B-like T dwarfs and L/T transition objects (none of the latter are currently known) represent secondary targets of our survey.

How many nearby dwarfs do we expect to identify? Extrapolating from the 8-parsec sample, we predict ≈1600 M dwarf systems to $r < 20$ pc, at least 600 of which have an M dwarf with $M_V > 13$ (spectral type > M4) as the brightest component. Spectral type M9 corresponds to a main-sequence mass of 0.07 to 0.09 $M_\odot$; extrapolating predictions to lower luminosities, and lower masses, demands that we model the mass function for the Galactic disk, $\Psi(M) = \frac{dN}{dM}$. We have completed such calculations, deriving the first reliable estimate of $\Psi(M)$ at substellar masses in the field (Reid et al, 1999). Given the constraints set by the observed surface density of L dwarfs and T dwarfs, and modelling $\Psi(M)$ as a power law, $\propto M^{-\alpha}$, the best match is obtained with $\alpha \sim 1$: figure 2 shows the luminosity function predicted based on a constant star formation rate.

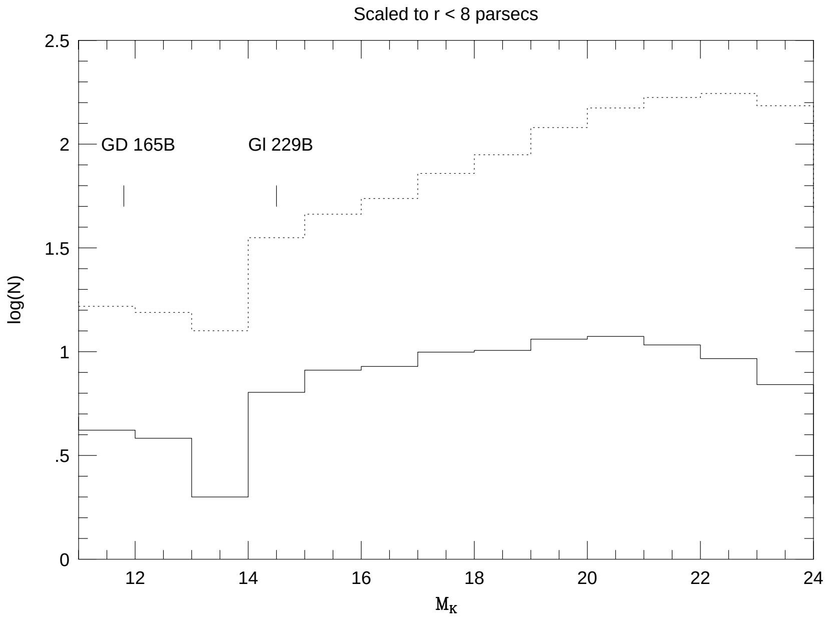

Figure 2. The K-band luminosity function predicted for a mass function $\Psi(M) \propto M^{-1}$ (solid line) and $\Psi(M) \propto M^{-2}$ (dotted line). In both cases, the models assume a constant star formation rate and the numbers are scaled to a spherical volume, radius 8 parsecs, centred on the Sun (from Reid et al, 1999).

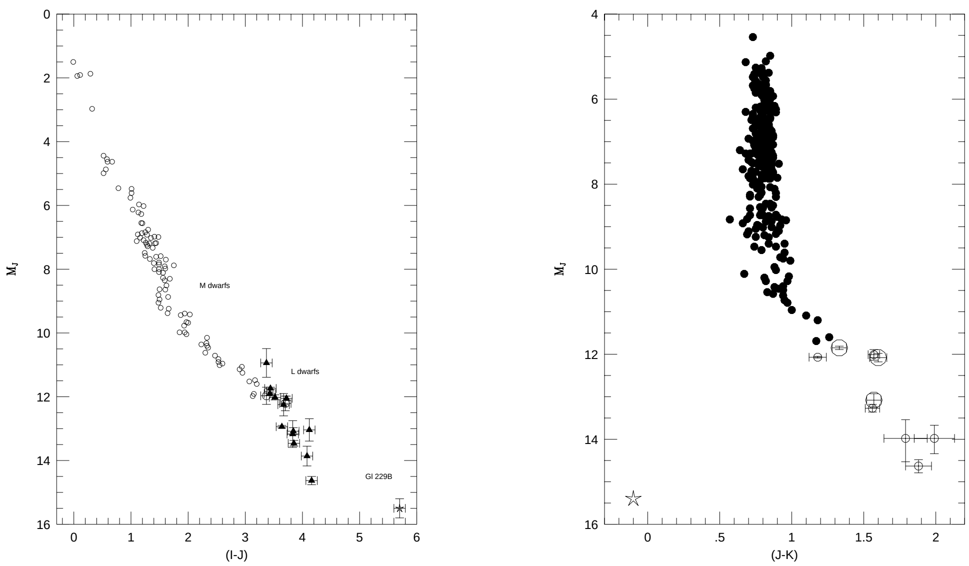

Figure 3. The (M_J, (I-J)) and (M_J, (J-K_S)) colour-magnitude diagrams defined by late-type dwarfs with accurate photometry and well-defined trigonometric parallax measurements.

The $\Psi(M) \propto M^{-1}$ model predicts a total of $\sim$ 150 L dwarfs within that volume, as well as 110 T dwarfs brighter than J< 16 magnitude. A steeper mass function will result in a higher local density (figure 3). Together, these two components include between 10 and 15% of the brown dwarfs within 20 parsecs of the Sun: the remainder are cool T dwarfs, with magnitudes below our detection limit. Combining M, L and T dwarfs, we expect to identify $\sim$ 850 late-type dwarfs within 20 parsecs of the Sun; the current census includes only $\sim$ 240 systems.

3. Stage 1: Photometric selection of nearby late-type dwarfs

The results obtained in the last three years demonstrate conclusively that wide-field photometric surveys, particularly at near-infrared wavelengths, provide the most effective means of identifying cool stars and brown dwarfs: M dwarfs, L dwarfs and T dwarfs. Based on our current understanding we identify M dwarfs ($\sim 5.5 < M_J < 12$) as predominantly hydrogen-burning stars, L dwarfs ($12 < M_J < 15$) as a mixture of very low mass (VLM) stars and brown dwarfs, and T dwarfs ($M_J > 15$) as cool brown dwarfs. Figure 3 illustrates the sequences defined by those objects in optical/near-infrared and near-infrared colour-magnitude diagrams (CMD). Three characteristics should be highlighted: First, in the (M_J, (I-J)) CMD, dwarfs become increasingly red with decreasing luminosity *except* at $8 < M_J < 9.5$ (spectral type $\sim$M4), where the main-sequence is nearly vertical. This feature is also evident in other colour-magnitude diagrams (such as (M_V, (V-I)), and may mark the onset of full convection. Note also the increased dispersion, $\sigma_{M(J)}$ on the upper main sequence. Second, the (J-K_S) colour provides no luminosity information for $M_J < 11$, but can be used to determine photometric parallaxes for L dwarfs and M dwarfs later than spectral type M8. Finally, the brown dwarf sequence evolves from (J-K_S) ~ 2 to (J-K_S) ~ 0 as the atmospheric temperature cools sufficiently for methane formation.

The range of photometric characteristics displayed by these objects demands a variety of search techniques. In the course of the 2MASS Rare Objects Core Science project, we have devoted extensive effort to searching for low-luminosity dwarfs, combining the 2MASS JHK_S photometry with R, I optical data from the USNO Photographic Measuring Machine (PMM) scans of Palomar and UK Schmidt plate material. We have gained considerable experience in analysing these datasets, and have devised well-proven techniques for finding late-type dwarfs. The following subsection outlines the main properties of the 2MASS and PMM database, and succeeding subsections describe how we will use those data, together with other resources, to identify the Sun's nearest neighbours.

3.1. 2MASS and the PMM database

The Two-Micron All-Sky Survey is being undertaken by the University of Massachusetts and the Infrared Processing and Analysis Center (IPAC, Caltech). Two 1.3-metre telescopes, sited at Mt. Hopkins, Arizona and Cerro Tololo, Chile, are surveying the entire sky in the J (1.25 μm), H (1.6 μm) and K_S (2.15 μm) passbands. The observations achieve a S/N=10 for point sources at J=15.8, H=15.1 and K_S=14.3 mag, and the data are released to the general community as calibrated catalogues, including all point sources detected with S/N$>$ 7 (J $\sim$ 16.2). The typical photometric uncertainties decrease to $\sigma < 0.03$ mag at J$<$ 14, $K_S < 13$, with saturation at J, K$\sim$ 5. We will confine our analysis to those publicly-released data, which will include all M dwarfs and almost all L dwarfs within 20 parsecs of the Sun. With the Fall, 1999 data release, over 20,000 square degrees will be available, and the remainder of the sky will become available during the first year of the NStars project. Members of the 2MASS Science Team (Liebert, Monet) will continue to have access to the full database for quality assessment and source verification.

The PMM database includes scans of all of the original Palomar Sky Survey (POSS I) plates, both O (blue) and E (red) emulsions; the Whiteoak extension (E plates, $-36 > \delta > -45$); the Palomar Infrared Milky Way survey (PIMWA: 098 and IVN emulsion, R and I band); the second Palomar Sky Survey (POSS II) IIIaJ (blue), IIIaF (R) and IVN (I: currently incomplete); the UK Schmidt IIIaJ survey ($\delta < -30$); the UK Schmidt equatorial IIIaJ and IIIaF surveys ($-30 < \delta \leq 0$); and the ESO IIIaF survey of the southern skies ($\delta \leq -30$). Scans of the remaining POSS II IVN plates (to be taken) and of the UK Schmidt I/short-R southern Milky Way survey are planned for the near future.

Combined, these scans provide B-band and R-band data over 4π steradians, and I-band data for over 50% of the sky. *With a limiting magnitude of R$\sim$ 21, all $r < 20$ pc dwarfs with spectral types earlier than L4 should be detected on the R-band IIIaF plates.* The R- and I-band plates covering the Milky Way are crucial in providing coverage near the Galactic Plane, reducing image crowding, due to the short exposures, but preserving cool dwarf detection through the red sensitivity. In addition, the large-scale surveys span a baseline of almost 50 years for the northern three-quarters of the sky and $\sim$ 20 years for the southernmost quarter, allowing accurate proper motion measurements. Brighter targets, $V < 18$, will also be detected on the Lick Northern Proper Motion Survey and the Yale Southern Proper Motion Survey plates, which have also been scanned by Monet. We will use those measurements, together with a comparison of photographic and 2MASS positions, to supplement our photometric search for nearby stars.

The photometric accuracy for point sources in the current PMM database is ± 0.3 magnitudes. The main uncertainty rests with establishing the zeropoint in individual fields. STScI has compiled CCD photometric sequences for every POSS II/UK Schmidt survey field, and those data will be published within the next 2-3 years. As part of this project, we will integrate those calibrations into the PMM database with the aim of improving photometric accuracy. However, combined with 2MASS JHK_S data, the current

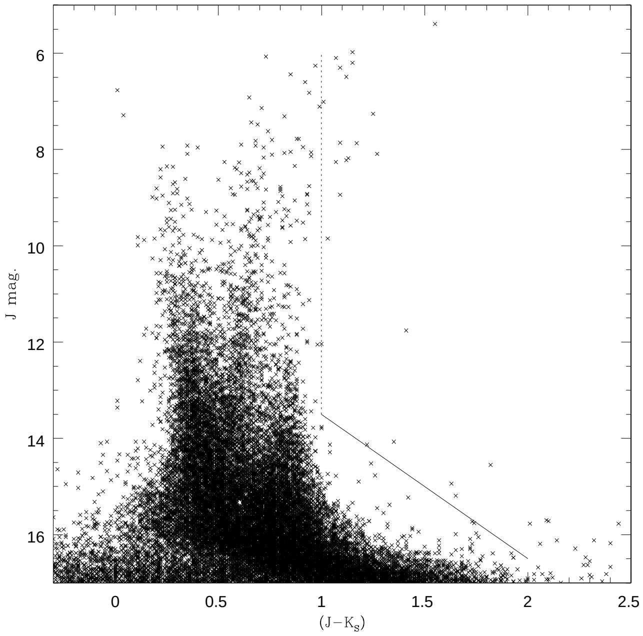

Figure 4. The (J, (J-K$_S$)) colour-magnitude diagram for all 2MASS sources within a 5 sq. deg. area. Sources with spectral type later than M8 and distances of less than 20 parsecs should lie above the solid line.

accuracy is sufficient to identify candidate nearby M and L dwarfs. As demonstrated below, the final candidate lists are sufficiently short that supplementary observations can permit reliable identification of the genuine nearby stars.

3.2. Finding isolated L dwarfs and late-type M dwarfs

Experience has shown that these ultracool dwarfs can be identified in a straightforward manner using photometric criteria: (J-K$_S$) $>$ 1.0, together with corroborating optical/infrared colours (such as (I-J)>2.5). We have used this method to identify not only almost 100 L dwarfs (Kirkpatrick et al, 1999; 2000), but also over 60 M7 to M9 dwarfs (Gizis et al, 2000). In the absence of significant interstellar reddening, near-infrared colours alone provide a robust identification criterion, as illustrated in figure 4, where we plot 2MASS data for all sources within a randomly chosen field covering 5 sq. deg. The solid line marks the approximate location of the M8-L8 sequence for a distance of 20 parsecs - nearby dwarfs must lie above that line. Only 33 of the $\sim 40,000$ sources ($< 0.1\%$) meet this criterion. Most of the bright sources (J<8) are likely to be giants, and can be eliminated using the JHK two-colour diagram (section 4.1). Even in the presence of background reddened sources, these low luminosity dwarfs can be identified in a straightforward manner: we have achieved a detection efficiency of $\sim$ 85% in recent observing runs (i.e. 85% of the candidates have proven to be dwarfs with spectral types later than M7).

3.3. Finding isolated M4 to M8 dwarfs

M dwarfs earlier than spectral type M8 have nearly identical (J-K$_S$) colours, and the relatively short baseline provided by (J-H) and (H-K$_S$) affords only limited luminosity calibration. However, optical/infrared colours, such as (R-J) and (I-J), continue to provide a reliable method of identifying dwarfs later than spectral type M4. Photometric parallaxes can be derived with moderate accuracy: the main-sequence has a slope of $\frac{\partial M_J}{\partial(I-J)} \sim 1.8$, implying $\sigma_{M(J)} \sim \pm 0.6$ mag for $\sigma_{I-J} \sim \pm 0.3$ mag. The intrinsic dispersion on the lower main sequence is only $\sigma_{M(J)} \pm 0.15$ mag, so higher precision photometry can provide more accurate photometryc parallaxes. The photometric uncertainties of the PMM photometry must be taken into account in defining a colour-selected sample, but, as illustrated in figure 5, only a small fraction of 2MASS sources satisfy these selection criteria; that is, the overwhelming majority can be rejected outright as candidate nearby dwarfs.

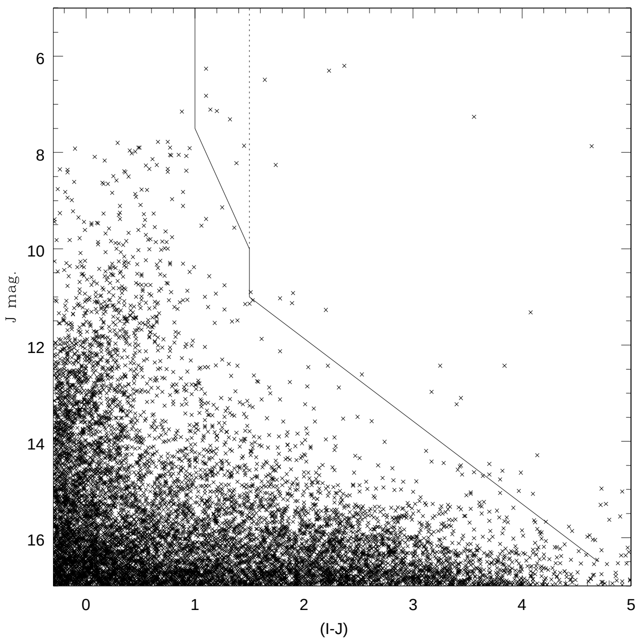

Figure 5. The (J, (I-J)) colour-magnitude diagram for all 2MASS/PMM sources within a 4.1 sq. deg. area. The solid line outlines the (M_J, (I-J)) main sequence for a distance modulus of 1.5 magnitudes, allowing for $\sigma_{I-J} = \pm 0.3$ mag. Candidate nearby stars lie above this relation. The dotted line marks the division between candidates with spectral type >M4 and <M4.

3.4. Finding isolated early-type M dwarfs

These intrinsically luminous objects present the most difficulties for defining a volume-complete sample. The main-sequence steepens sharply at (I-J)$\sim$ 1.8, with the slope of $\frac{\partial M_J}{\partial(I-J)} \sim 4$ at $M_J < 8$. The uncertainties in the photometric parallax estimates increase in corresponding fashion: $\sigma_{I-J} \sim \pm 0.3$ mag implies $\sigma \sim 1.2$ mag. in M_J. Moreover, intrinsic dispersion in the main sequence produces significant Malmquist bias which affects every photometric survey, regardless of its intrinsic precision. M dwarfs within 20 parsecs will have bright magnitudes, J< 11, and a colour-selected sample will include significant numbers of red giants, which have similar colours and a higher surface density at these magnitudes. The latter can be identified through their position in the JHK diagram, however. Malmquist effects and contamination by earlier type stars, scattered into the sample due to photometric uncertainties, are more significant limiting factors. More detailed analysis is required before we can assess our potential success in this régime.

3.5. Finding field T dwarfs

The lowest-luminosity isolated constituents of the Galactic disk population currently known are analogues of the $\sim$ 1000K methane brown dwarf Gl 229B. As originally pointed out by Tsuji (1964), at those low temperatures methane absorption removes $\sim 70\%$ of the flux in the H and K passbands, leading to blue near-infrared colours. The optical/near-IR colours remain extremely red (figure 3), and the first isolated T dwarf was identified by the Sloan Digital Sky Survey based on its then-unique (i-z) colour (Strauss et al, 1999). A second SDSS dwarf is known (Tsetvanov et al, subm.), and subsequent examples have been discovered through analysis of 2MASS/PMM data, identifying sources with blue JHK$_S$ colours and no optical counterpart (Burgasser et al, 1999). To date, 5000 square degrees have been searched to a limiting magnitude of J$\sim$ 16, yielding nine T dwarfs in addition to the SDSS dwarf, SDSS1624. All, including the two SDSS dwarfs have J$\sim$ 16th magnitude. The lowest luminosity source, Gl 570 D, has $M_J \sim 16$, one magnitude fainter than Gl 229B.

In searching for T dwarfs with 2MASS, the main contaminants in candidate lists are asteroids (neutral colours + motion between 2MASS and PMM) and faint M dwarfs with inaccurate JHK photometry. The deep optical photometry obtained by SDSS offers more direct identification, particularly of L/T transition objects, although only the closest dwarfs will be detected at i: SDSS1624 is ~ 1 magnitude fainter than the formal survey limiting magnitude, and was detected only because that area was re-scanned during commissioning. Moreover, Sloan will cover only π steradians at high latitude, and the low surface density of these objects makes it imperative to obtain full sky coverage, particularly to identify the coolest, lowest-luminosity dwarfs. We will therefore continue our survey, aiming to identify all T dwarfs with J$<$ 16.2 magnitudes ($r < 15$ pc for Gl 229B).

4. Stage 2: Supplementary criteria

The simple colour/magnitude criteria outlined in the previous section eliminate the vast majority of 2MASS sources as candidate nearby stars. However, substantial numbers still remain: in a preliminary analysis of 4.5×10^7 sources drawn from 6000 square degrees spanning the full range of Galactic latitude, some 51,000 (0.1%) are selected; this implies $\approx 350,000$ sources will survive the initial cut in an all-sky survey. Only $\sim 1\%$ of those sources are genuine nearby stars or brown dwarfs. Individual follow-up observation, or even visual inspection, of all these sources is clearly impractical, but other statistical techniques can be used to reduce the sample to manageable proportions.

4.1. Colour-colour plots: giants and reddened main-sequence stars

The main contaminants in our colour-selected sample are expected to be red giants, reddened main-sequence stars, photometric artefacts ('glints' and persistence defects) and young T Tauri stars. All of these species fall in different locations in the JHK and IJK/RJK two-colour diagrams (as noted above, nearby dwarfs earlier than spectral type L4 should be detected on both IIIaF and IVN plates). 2MASS artefacts tend to have very unusual colours, allowing their immediate rejection. Since the majority of celestial interlopers are bright, with correspondingly accurate photometry, most can be eliminated from the initial sample.

Figure 6 outlines the distinct sequences followed by dwarfs and giants in the JHK and IJK two-colour diagrams. These diagrams also show that, while reddened M dwarfs can have near-infrared colours similar to late M or L dwarfs, these objects occupy different locations in the IJK two-colour plane. Since there is little reddening material within 100 parsecs of the Sun, most reddened sources are more distant, earlier-type stars (AFGK dwarfs), whose post-reddening optical-to-infrared colours are significantly bluer than genuine late-type stars. Indeed, experience has shown that most reddened early-type sources are detected easily on IIIaF, and sometimes IIIaJ, sky survey plates. T Tauri stars are

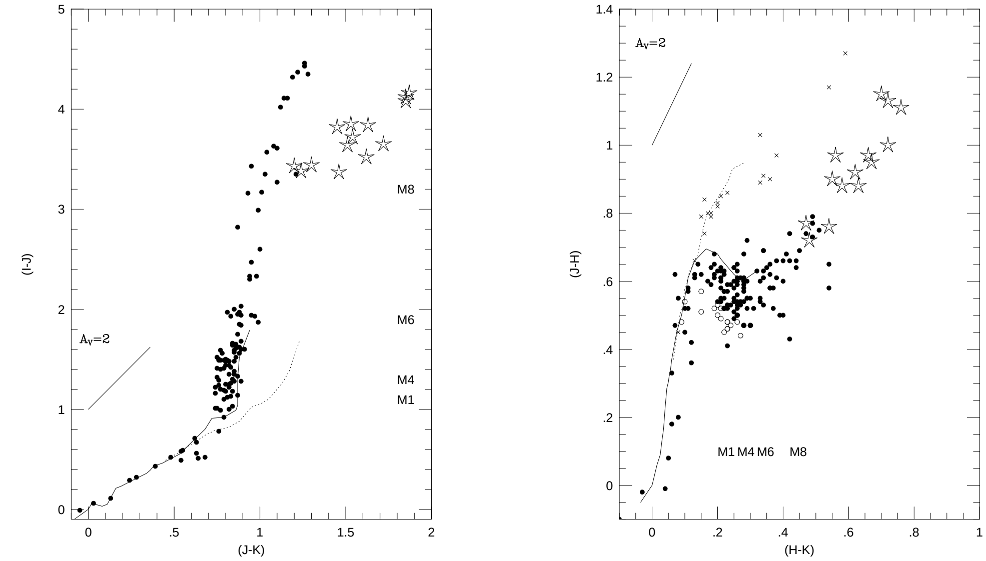

Figure 6. The near-infrared JHK and IJK two-colour diagrams for late-type stars. Solid points are main-sequence dwarfs; open circle (JHK only) are halo subdwarfs; crosses (JHK only) are giants; 5-point stars are L dwarfs. The dotted line marks the giant sequence defined by Bessell & Brett (1988). The reddening line, for A_V=2 mag, is indicated in both diagrams.

less easily distinguished, but have a significantly lower surface density, being concentrated near star-forming regions. These objects are of interest in their own right.

Our preliminary analysis confirms that the two-colour JHK diagram is extremely effective at eliminating interlopers. Figure 7 plots data for 1244 sources selected from the 2MASS database using the colour selection criteria outlined in figures 4 and 5; only ~ 25 of those sources, 2% of the sample, have colours consistent with their being late-type dwarfs. Thus, this simple technique is capable of reducing the initial all-sky sample of $\sim 350,000$ candidates to a total of $\sim 7,000$ targets; 10-20% of that sample will prove to be nearby dwarfs at $r < 20$ parsecs; the majority of the remainder are genuine late-type dwarfs at distances beyond 20 parsecs. This reduced sample is sufficiently small to permit visual inspection of the 2MASS pixel data for each source, and rejection of any remaining artefacts. We cannot determine trigonometric parallax observations for every target. However, Reid, Gizis and Hawley succeeded in obtaining spectroscopy of the ~ 2000 CNS3 M dwarfs in a period of only 2 years; the resources available to the current consortium will permit similar follow-up observations for this somewhat larger sample.

4.2. Proper motions

Our selection of candidate nearby, ultracool dwarfs is based solely on photometric criteria, avoiding potential kinematic bias. However, the extensive photographic astrometry available in the PMM database allows proper motions to be derived to an accuracy of better than 10 milliarcseconds/year over most of the sky. This accuracy corresponds to a transverse velocity of 1 kms^{-1} at a distance of 20 parsecs, and should permit motions to be determined for all nearby dwarfs. Sources with negligible motion will be flagged as potential background interlopers, and rejected if other observations confirm that status. In addition, the positional comparison between the 2MASS data and the recent

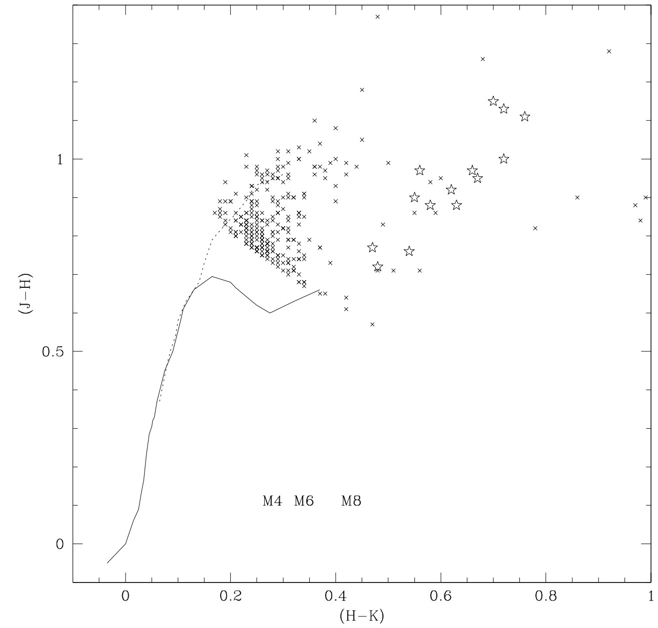

Figure 7. The JHK two-colour diagram for 1244 sources satisfying the colour-magnitude criteria defined in figures 4 and 5. The solid line marks the M-dwarf sequence, the dotted line the M giant sequence, and the 5-point stars plot data for L dwarfs. No more than 25 of the 2MASS field sources (2%) have JHK colours consistent with unreddened late-M or L dwarfs.

photographic surveys (POSS II; UKST R-band) may permit the detection of high motion sources, $\mu > 2$arcsec yr^{-1}, beyond the limits of Luyten's surveys.

The PMM database, combined with 2MASS astrometry, will permit us to extend astrometric observations to within the Galactic Plane, a region generally neglected by currently-available, large-scale proper-motion surveys (Luyten's Palomar compendium, the Lick NPM survey). As described above, the short-exposure R-band plates reduce the degree of image crowding, providing first-epoch astrometry and, combined with 2MASS, a 10-20 year baseline for cool dwarfs. Improved proper-motion data for nearby stars in the Plane are of importance for several proposed Space Interferometry Mission programs, notably in providing potential targets for a microlensing project (to be proposed by a team headed by A. Gould, OSU; Reid is a member of that team). A foreground star passing within 1 arcsecond of a background source will produce several-microarcsecond positional displacements which, if measured by SIM, will permit mass determination of the proper motion star. The high star density in the Galactic Plane renders it the most likely region for identifying potential targets.

We will also cross-reference existing proper motion catalogues, notably Luyten's Half-second (LHS) and Two-Tenths (NLTT), against the combined 2MASS/PMM database, and provide both accurate positions and reliable near-infrared photometry for those sources. The resulting datasets will be invaluable for extending statistical analysis beyond the immediate Solar Neighbourhood. Similar photometric catalogues will be compiled for other useful datasets, such as the current nearby star catalogue (CNS3) and nearby stars in the Hipparcos catalogue.

4.3. Follow-up observations

Once the list of targets has been reduced to manageable proportions, we will undertake a range of follow-up observations. Note that Reid, Gizis and Hawley succeeded in obtaining spectra for the almost 2000 candidates M dwarfs in the CNS3 in a period of only 2 years.

- Low-resolution objective prism data are available for much of the southern hemisphere, and part of the northern equatorial regions, from the UK Schmidt telescope. Those photographic plates are available to the general astronomical community at the UK Schmidt facility at the Royal Observatory.
- The majority of candidate M dwarfs will be relatively bright, and we will obtain spectroscopic follow-up observations of those sources using the 2.3 metre telescope at Steward Observatory and the ARC 3.5-metre telescope. Kirkpatrick and Burgasser also have access to the Palomar 60-inch telescope, which can provide optical and near-infrared spectroscopic data. Follow-up observations of southern candidates will be undertaken in collaboration with C. Tinney (AAO). Low luminosity northern sources will be targeted using the MMT, the Hale 200-inch telescope and national facilities, such as KPNO and Gemini.
- Optical photometry of selected sources will be obtained using the smaller telescopes at USNO, Palomar and Steward/KPNO, and by Henry, in conjunction with his parallax programme. Liebert & Gizis are currently pursuing such observations for 2MASS late-M and L-type dwarfs, using the 60-inch at Cerro Tololo, and we aim to continue that programme, concentrating on brighter targets, through observations on the YALO telescope.
- As a key member of the Palomar sky survey team, Reid has access to the STScI scans of all POSS II plate material, and over 20 years experience in analysing such data. Since the STSCI were made using a PDS microdensitometer, the data provide more accurate $B_J R_F I$ photometry for northern targets, with the potential of reducing the photometric uncertainties to ± 0.15magnitudes.
- Trigonometric parallax observations are time intensive. A sub-set of high priority candidates will be targeted for observations by USNO, at both optical and near-infrared wavelengths; as part of Henry's CTIO project; and, in collaboration with C. Tinney, at Siding Spring, using the AAT. We are also investigating the possibilities of using the infrared detectors on the YALO telescope at Cerro Tololo for parallax astrometry.

These observations will allow continuous update of the nearby dwarf catalogue, both in its constituents and in their characteristics. While making these data generally available, we will also undertake our own analysis, both of the mass function in the Galactic disk, building on the techniques outlined in Reid et al (1999), and of the statistical properties (kinematics, chromospheric activity, abundances) of the nearest stars and brown dwarfs.

4.4. Organisation

A large scale project of this type demands expertise and significant investment of effort. All of the investigators and collaborators on this project have made significant contributions to the study of late-type main-sequence stars and brown dwarfs, and most are currently involved in the 2MASS Rare Objects key project, aimed at the identification of these low-luminosity dwarfs.

The present project will be co-ordinated from Space Telescope Science Institute by Reid, working closely with K. Cruz (U. Penn. graduate student). They will construct and maintain nearby-star and proper motion star databases. Those will include cross-referencing both to observations obtained by this consortium and to data in the literature. We anticipate employing up to two undergraduates each year, funded by summer work-study programmes, to help reduce and catalogue these data.

Monet will correlate the PMM and 2MASS databases, and providing a catalogue of point sources. That correlated list includes sources with 2MASS-only detections. A graduate student based at University of Arizona will work closely with Monet in this area, particularly on providing improved photometric calibration for the photographic data. Gizis, with extensive experience gained in working on the 2MASS project, will play a key role in preliminary analysis of the candidate nearby-star lists, and in the subsequent elimination of background sources.

All of the investigators in this project will contribute to the necessarily extensive follow-up observations. Kirkpatrick will continue to work with Burgasser on searching the 2MASS database for T dwarfs, and will collaborate with Lowrance in surveying the environs of known nearby stars for previously-undetected low-mass companions; Liebert's access to Steward Observatory and to the MMT are crucial to the follow-up observations; Golimowski provides expertise on identifying low-luminosity binaries, and has access to the ARC telescope for follow-up observations; besides being an expert on mass determination and the mass-luminosity relation, Henry is leading a southern trigonometric parallax program, and will contribute both photometric and astrometric data to the project. Both Golimowski and Henry are members of the SDSS brown dwarf consortium.

4.5. Data Dissemination

Our goal is to produce a catalogue including all dwarfs later than spectral type M4 which are within 20 parsecs of the Sun. The catalogue will provide accurate positions, proper motions, parallax measurements (either photometric or, where possible, trigonometric), and near-infrared and optical photometry for each source. Where possible, we will provide basic spectroscopic information: spectral type, bandstrengths and equivalent width for Hα emission, if detected.

Our results for dwarfs confirmed to be within 20 parsecs will be transmitted to the NStars project. In addition, we will establish our own web-site as a central location for collecting information on candidate nearby dwarfs. That site will be linked to subsidiary on-line catalogues, including 2MASS data for sources from relevant datasets, such as the Luyten Half-Second (LHS) and Two-Tenths (NLTT) proper motion catalogues. Finally, many of the nearby dwarfs identified in this programme, both within and without the 20 parsec volume, will be suitable targets for the recently-funded FAME astrometric mission.

References

Bessell, M.S., Brett, J.M. 1988, A&AS, 100, 1134; JHKLM photometry - Standard systems, passbands and intrinsic colors

Burgasser, A.J., Kirkpatrick, J.D., Brown, M.E., Reid, I.N *et al.*, 1999, ApJ, 522, L65; Discovery of four methane (T-type) dwarfs with the Two Micron All-Sky Survey

ESA 1997, The Hipparcos catalogue, ESA SP-1200

Gizis, J.E., Monet, D.G., Williams, R., Reid, I.N., 2000. AJ, subm; Late-type M dwarfs in the 2MASS survey

Hawley, S.L., Gizis, J.E., Reid, I.N. 1996, AJ, 112, 2799; The Palomar/MSU Nearby-Star Spectroscopic Survey - II: The southern M-dwarfs and investigations of magnetic activity

Kirkpatrick, J.D., Reid, I.N., Liebert, J., Cutri, R., Nelson, B., Beichman, C.A., Dahn, C.C., Monet, D.G., Skrutskie, M.F., Gizis, J.E. 1999, ApJ, 519, 802; Dwarfs cooler than "M": The definition of spectral type "L" using discoveries from the 2-Micron All-Sky Survey (2MASS)

Kirkpatrick, J.D., Reid, I.N., Gizis, J.E., Burgasser, A.J., Liebert, J., Monet, D.G., Dahn, C.C., Nelson, B. 2000, in prep; The next 67 L dwarfs

Nakajima, T., Oppenheimer, B.R., Kulkarni, S.R., Golimowski, D.A., Matthews, K., Durrance, S.T. 1995, Nature, 378, 463; Discovery of a cool brown dwarf

Reid, I.N., Hawley, S.L., Gizis, J.E. 1995, AJ, 110, 1838; The Palomar/MSU Nearby-Star Spectroscopic Survey - I: The Northern M-dwarfs - Bandstrengths and Kinematics

Reid, I.N., Kirkpatrick, J.D., Liebert, J., Burrows, A., Gizis, J.E., Burgasser, A., Dahn, C.C., Monet, D., Cutri, R., Beichman, C.A., Skrutskie, M. 1999, ApJ, 521, 613; L dwarfs and the substellar mass function

Strauss, M. *et al.*, 1999, ApJ, 522, L61; The discovery of a field methane dwarf from Sloan Digital Sky Survey Commissioning Data

Tsuji, T. 1964, Ann. Tokyo Obs. ser. II, 9, 1; Molecular abundance in stellar atmospheres