MEETING THE COOL NEIGHBORS. I. NEARBY STARS IN THE NLTT CATALOGUE: DEFINING THE SAMPLE

I. Neill Reid
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; and Department of Physics and Astronomy, University of Pennsylvania, 209 South 33d Street, Philadelphia, PA 19104; inr@stsci.edu

K. L. Cruz
Department of Physics and Astronomy, University of Pennsylvania, 209 South 33d Street, Philadelphia, PA 19104; kelle@hep.upenn.edu

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ABSTRACT

We are currently undertaking a program aimed at identifying previously unrecognized late-type dwarfs within 20 pc of the Sun. As a first step, we have cross-referenced Luyten's NLTT proper-motion catalog against the second incremental release of the Two Micron All Sky Survey (2MASS) Point Source Catalog and use optical/infrared colors, derived by combining Luyten's $m_i$ estimates with 2MASS data, to identify candidate nearby stars. This paper describes the definition of a reference sample of 1245 stars and presents a compilation of literature data for more than one-third of the sample. Only 274 stars have trigonometric parallax measurements, but we have used data for nearby stars with well-determined trigonometric parallaxes to compute color-magnitude relations in the $(M_V, V-K)$, $(M_J, V-I)$, and $(M_J, I-J)$ planes and use those relations to determine photometric parallaxes for NLTT stars with optical photometry. Based on the 2MASS $JHK_s$ data alone, we have identified a further 42 ultracool dwarfs $(J-K_s > 0.99)$ and use $J-K_s$ colors to estimate photometric parallaxes. Combining these various techniques, we identify 308 stars with formal distances of less than 20 pc, while a further 46 have distance estimates within $1\sigma$ of our survey limit. Of these 354 stars, 75, including 39 of the ultracool dwarfs, are new to nearby-star catalogs. Two stars with both optical and near-infrared photometry are potential additions to the immediate solar neighborhood, with formal distance estimates of less than 10 pc.

Key words: Galaxy: stellar content — stars: late-type

On-line material: color figures, machine-readable tables

1. INTRODUCTION

The scientific bases for completing a thorough survey of the constituents of the immediate solar neighborhood can be grouped under two main categories: (1) the identification of individual representatives of particular stellar types for detailed follow-up observation and (2) the compilation and analysis of statistical parameters. As individuals, the nearest stars provide the brightest examples of a particular class, and they therefore permit the most exhaustive scrutiny of physical characteristics and of how those characteristics vary from star to star. Indeed, it is worth noting that the fact that there are differences in the properties of individual stars became apparent with the completion of the first successful determinations of stellar parallax: Henderson’s (1839) analysis of Cape measurements found both components of α Centauri to be similar in brightness to the Sun, but Bessel’s (1836) earlier results showed that the fainter star in 61 Cygni is ~35 times fainter than the Sun, while Struve’s 1840 observations indicated that Vega is brighter than the Sun by a similar factor.

From a statistical point of view, the scientific justification for compiling a catalog of the nearest stars is summarized succinctly by Kuiper (1942). Besides probing the details of stellar evolution through their distribution in the Hertzsprung-Russell diagram, the nearest stars provide the basis for the determination of the stellar luminosity function, the mass-luminosity relation, the stellar contribution to the local mass density, the velocity distribution, and the stellar multiplicity statistics (including the frequency of occurrence of planetary systems). Supplementing the photometric and astrometric data with chemical abundance determinations, the nearby stars can be used to map the metallicity distribution of the (local) Galactic disk. Finally, with the addition of age estimates, these stars can probe the local star formation history and the variation of stellar kinematics (and other parameters) as a function of time.

Success in pursuing Kuiper’s research agenda rests on the availability of a well-defined, representative sample of the local stellar populations. At the time, no such data set existed—the most complete sample of nearby stars was van de Kamp’s (1940) catalog of 34 systems within 5 pc of the Sun. Considerable advances have been made in the succeeding three score years, notably through the efforts of Gliese (1957, 1969), later in collaboration with Jahreiss (Gliese & Jahreiss 1979, 1991, hereafter pCNS3), in compiling results from follow-up observations of nearby-star candidates identified from a variety of sources. The most recent catalog, the preliminary version of the Third Catalogue of Nearby Stars (pCNS3), lists over 3800 stars with nominal distances of less than 25 pc, although quantitative spectroscopy (Reid, Hawley, & Gizis 1995, hereafter PMSU1; Hawley, Gizis, & Reid 1996, hereafter PMSU2) and astrometry show that many stars lie beyond that distance limit.1

1 Updated measurements for the pCNS3 stars, together with observations of additional, post-Hipparcos nearby-star candidates, are included in the CNS Web site at http://www.ari.uni-heidelberg.de/aricns. The PMSU data are available at http://dept.physics.upenn.edu/~inr/pmsu.html.
**Hipparcos** mission (ESA 1997) has solidified the local sample of solar-type stars but provides data for only a limited subset of stars fainter than 9th magnitude ($M_V = 7.5$, or spectral type M0, at 20 pc). Thus, while the number of known nearby systems has increased by 2 orders of magnitude, the current M dwarf census becomes significantly incomplete at distances beyond 10 pc. Estimates of the level of incompleteness vary, ranging from 30% to 50% for early- and mid-type M dwarfs to over 75% at the latest spectral types (PMSU1; Henry 1998).

The NASA/NSF “NStars” initiative was designed, at least partly, with the aim of remedying this notable deficit in our knowledge. Working under these auspices, we are undertaking a wide-ranging project that aims to use data from the Two Micron All Sky Survey (2MASS), in combination with other large-scale surveys and databases, to identify previously unrecognized late-type dwarfs within the immediate solar neighborhood. The near-infrared coverage offered by 2MASS is ideally suited to detecting and classifying nearby cool dwarfs; indeed, 2MASS (Skrutskie et al. 1997) and the companion Deep Near Infrared Survey (DENIS; Epchtein et al. 1994) are responsible for discovering the overwhelming majority of the ultracool low-mass stars and brown dwarfs that have been used to define the new spectral classes L (Kirkpatrick et al. 1999; Martín et al. 1999) and T (Burgasser et al. 2002; Geballe et al. 2002).

The prime goal of our project is the identification of all M and L dwarfs within 20 pc of the Sun. The near-infrared colors provided by 2MASS are sufficient to identify late-type M and L dwarfs, but are essentially degenerate for mid-K to M7 dwarfs. Thus, achieving our goal demands that we employ a variety of techniques, combining a range of observational strategies. Future papers in this series will discuss the application of purely photometric selection effects (Cruz et al. 2002), but first we concentrate on a variation on a more traditional theme: 2MASS photometry of stars in the New Luyten Two-Tenths (NLTT) catalog (Luyten 1980). Section 2 outlines the relevant characteristics of the NLTT survey. Section 3 describes the selection criteria we have used to identify nearby-star candidates, combining the NLTT data with the photometry from the second incremental release of the 2MASS Point Source Catalog. Section 4 describes the calibration of photometric parallaxes; § 5 summarizes the data available in the literature for a subset of those sources and identifies stars likely to lie within our distance limit of 20 pc; § 6 summarizes the results.

### 2. THE NLTT CATALOGUE AND NEARBY STARS

Proper motion has a well-proven track record as a means of identifying nearby stars. As members of a rotationally supported, low velocity dispersion system, most disk dwarfs have heliocentric space motions of less than 50 km s$^{-1}$. Thus, the majority of high proper motion stars are members of the immediate solar neighborhood—the remainder are high-velocity members of the Galactic halo. Proper-motion determination is also straightforward; measurements can be made for all stars in a particular region of the sky using wide-field images taken at only two epochs.

The most extensive proper-motion catalogs currently available are due to Willem Luyten, based primarily on his work with the 48 inch (1.2 m) Palomar Oschin Schmidt. Attention has mainly centred on the Luyten Half-Second (LHS) catalog (Luyten 1979), which includes 3601 stars with $\mu > 0.5$ yr$^{-1}$ (and data for a further 869 stars with lower proper motions). This partly reflects the substantial annual motions of those stars, indicative of either close proximity or high space motion, sometimes both, but also partly reflects the fact that those stars are relatively easy to identify. Luyten & Albers (1979) produced the LHS Atlas, which includes finding charts for all of the fainter LHS stars. The NLTT Catalogue, including 58,845 stars with $\mu > 0.018$ yr$^{-1}$, lacks a comparable identification aid. While the majority of NLTT stars have positions accurate to a few arcseconds, errors exceeding 15$''$ are not uncommon. In searching for the latter targets, astronomers have been known to resort to techniques such as using blue and red filters on telescope acquisition systems as blink comparators, picking out the reddest (or, for white dwarf candidates, bluest) star in the field. Such methods are far from efficient and tend to discourage detailed follow-up observations of extensive target lists at larger telescopes.

Luyten’s proper-motion surveys also offer the disadvantage of low-accuracy photometry (sometime based on by-eye estimates), ill-defined completeness limits, and nonuniform sky coverage. The regions of the celestial sphere accessible from the Northern Hemisphere were surveyed in the early 1960s using the Palomar Schmidt, with the original Palomar Sky Survey (POSS I; Minkowski & Abell 1963) providing first-epoch data. The plates provide both red ($m_r$) and blue ($m_B$) magnitude estimates, accurate to $\pm 0.5$ mag and with $m_B \sim B$ and $m_r \sim R + 0.8$ (Gliese & Jahreiss 1980; Dawson 1986). The faintest stars cataloged have $m_r \sim 19$ and $m_B \sim 20.5$.

South of $\delta = -33^\circ$, both the LHS and NLTT Catalogues are derived primarily from the Bruce Proper Motion Survey, which is based on photographic plates taken with the Harvard 24 inch (0.65 m) Bruce refractor. The first-epoch Southern Hemisphere plates were taken between 1896 and 1910, when the telescope was located in Arequipa, Peru; Luyten obtained second-epoch plates between 1927 and 1929, when both he and the telescope were stationed at Harvard’s Bloemfontein Observatory in South Africa. Although the Bruce survey extends to a proper-motion limit of 0.07 yr$^{-1}$, it provides only blue-band photographic photometry and includes few stars fainter than $m_B \sim 15.5$.

The absence of deep photographic material at southern declinations is an obvious limitation in searching for low-luminosity dwarfs. However, even the Palomar data provide far from uniform coverage. The high proper motion stars in the NLTT are drawn from a relatively small volume, centered on the Sun, so we expect a uniform distribution over the celestial sphere. Figure 1 plots the $(\alpha, \delta)$ distribution of NLTT dwarfs for three magnitude ranges: $11 < m_B < 14$, $14 < m_B < 15.5$, and $15.5 < m_B < 16$. Two features are evident: first, the transition from Palomar Schmidt data to the Bruce survey, obvious at the faintest magnitudes but also discernible at intermediate magnitudes; and, second, the Milky Way. The high star density close to the plane leads to confusion (overlapping images) at magnitudes well above the POSS I plate limits, and to difficulties in correctly associating first- and second-epoch images of moving objects. It is clear from Figure 1 that at low latitudes, with the exception of a few regions (such as the Perseus-Auriga region, $\alpha \sim 5^h$, $40^\circ < \delta < 50^\circ$), the

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2 But not all; see Reid, Sahu, & Hawley (2001).
NLTT Catalogue has effectively the same limiting magnitude as the Bruce survey.

The number-magnitude distribution of NLTT stars at higher Galactic latitudes is illustrated in Figure 2, where we also show the distribution of LHS stars in the same regions. As discussed by Flynn et al. (2001), if the kinematics of a stellar population is invariant over the sampling volume, then the number of stars in a proper-motion–limited survey varies with \( l_{\lim}^{-3} \) (since the distance limit \( d_{\lim} \) is inversely proportional to \( l_{\lim} \)). The characteristic distance of a proper-motion star also scales inversely with \( l_{\lim} \), so the typical distance modulus for the catalog scales as \( l_{\lim}^{-2} \). Thus, if we compare the number-magnitude distributions of two unbiased proper-motion surveys, \( S_1 \) and \( S_2 \), with proper-motion limits of \( \mu_1 \) and \( \mu_2 \), the sampling volumes scale as

\[
\frac{\text{Vol}_2}{\text{Vol}_1} = f_v = \left( \frac{\mu_1}{\mu_2} \right)^3,
\]

and the relative distance modulus is

\[
(m - M)_2 - (m - M)_1 = \delta(m - M) = 5 \log \left( \frac{\mu_1}{\mu_2} \right).
\]

We need to allow for the change in average distance modulus to ensure we are matching stars of similar absolute magnitude. Thus, in comparing the number counts, we expect

\[
N_2(m) = f_v N_1(m - \delta(m - M)).
\]

In the specific case of the LHS and NLTT surveys, \( \mu_1 = 0".5 \text{ yr}^{-1} \) and \( \mu_2 = 0".18 \text{ yr}^{-1} \), so if there are no other selection biases, we expect

\[
N_{NLTT}(m) \approx 21 N_{LHS}(m - 2.2).
\]

Dawson (1986) estimates that the LHS survey is complete at the 90% level for \( m_r < 18 \) and \( |b| > 10^\circ \). The LHS therefore provides a reference to \( \sim 20^\circ \) magnitude for the NLTT Catalogue. As Figure 2c shows, scaling the number counts from the two surveys gives a ratio close to the predicted value for \( m_r \) (NLTT) brighter than \( \sim 16^\circ \) magnitude, with the ratio dropping by \( \sim 20\% \) between 16th and 18th magnitude. This suggests that the NLTT may be complete only at the 75% level at the latter magnitudes.

Despite these limitations, the NLTT Catalogue remains a powerful resource for searching for new candidate stars within 20 pc. A proper-motion limit of 0".18 yr\(^{-1}\) corre-
The 2MASS catalog includes sources that have a signal-to-noise ratio exceeding 7, corresponding to typical limiting magnitudes of $J \sim 16.1$, $H \sim 15.2$, and $K_s \sim 14.9$ in uncrowded fields. M dwarfs within 20 pc have near-infrared magnitudes significantly brighter than these limits—for example, even an M9.5 dwarf, comparable to BRI 0021 or LP 944-20, has $M_K \sim 11.1$, or $K_s \sim 12.6$ at a distance of 20 pc. At those magnitudes, the typical photometric uncertainties are 0.02 to 0.04 mag.

The 2MASS survey observations were completed in early 2001, but at the time of writing, data are available publicly for only 46.5% of the sky via the second incremental release. The results described in this paper, and in subsequent papers in the series, rest on the latter data set. In addition to photometry, the catalog provides astrometry for each source, accurate to less than 1"; morphological information, allowing segregation of extended and point sources; and a number of data-quality flags, identifying artifacts and potentially confused (in the crowding sense) objects.

Despite the reservations concerning the NLTT astrometry noted in the previous section, positional coincidence is the most effective method of cross-referencing the proper-motion catalog against the 2MASS database. We have applied proper-motion and precession corrections to the NLTT data to transform the coordinates to epoch 1998.0 (approximating the mean epoch of the data in the 2MASS second incremental release) and equinox J2000.0. We have cross-referenced this search list against the 2MASS database using the GATOR tool provided by the Infrared Science Archive (IRSA),3 setting a search radius of 10" and including only nonextended sources. Given the discussion in the previous section, we have also excluded all NLTT dwarfs within 10" of the Galactic plane. Of the 58,845 source in the NLTT catalog, 23,795 (40.4%) have at least one 2MASS source within the 10" search radius; approximately 1400 have two or more matches, giving a total of 25,305 potential near-infrared counterparts to the proper-motion stars.

This data set provides the basis for constructing our primary NLTT sample of nearby-star candidates. However, it does not include all of the NLTT stars within the area covered by the currently available 2MASS data. We identified those objects by removing the matched NLTT stars from the search list and rerunning the database query, but with a search radius of 60". A total of 4875 additional NLTT stars (8% of the catalog) have potential 2MASS counterparts at those larger separations.4 Figure 3 plots the $(\alpha, \delta)$ distribution of the two data sets. It is clear that the wide-paired NLTT stars (the 4875 stars) are not randomly distributed: there are obvious concentrations, notably near the north celestial pole and near the south Galactic pole ($\alpha \sim 1^h$, $\delta \sim -30^\circ$). It is likely that these features stem from systematic errors in the NLTT positions in those regions.

Figure 3 highlights two issues: first, as already discussed, a sizable subset (20%) of the stars in the NLTT catalog have astrometry of only modest accuracy; second, even though 23,795 NLTT stars have 2MASS sources within 10", there is no guarantee that those sources include the NLTT star itself. Thus, just as the NLTT catalog includes only an incomplete subset of late-type dwarfs with 20 pc, our cross-

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3 At http://irsa.ipac.caltech.edu.
4 A further 853 NLTT stars with $-10^\circ < \delta < 10^\circ$ have 2MASS counterparts.
referencing against the 2MASS database succeeds in identifying only a subset of the nearby late-type dwarfs in the NLTT. We will discuss the 4875 sources in the NLTT wide-matched sample in a later paper in this series; for the present, we concentrate on the sample of 23,795 NLTT dwarfs with 2MASS counterparts within 10° of the predicted J2000.0 positions.

3.2. Color Selection of Candidate Nearby Stars

Clearly it is unreasonable to attempt detailed follow-up observations of all 25,000-plus potential NLTT-2MASS pairings. However, we can use Luyten’s *mr* photometry to pare the sample to a manageable size. Dawson’s (1986) analysis of data for over 2000 LHS stars confirmed Gliese & Jahreiss’s (1980) calibration of *mr* against standard Kron *R* photometry, deriving

\[ m_r = R_K + 0.80. \]

The *R* − *K* color spans a long baseline in wavelength and ranges from ~3.0 at spectral type M0 to ~6.6 at spectral type M8. Thus, even with uncertainties of ±0.5 mag in *m*, the location of a star in the (*m*, *m* − *K*)-plane can discriminate between a relatively distant early-type M dwarf and an M6 dwarf in the immediate solar neighborhood.

Figure 4 illustrates how we have defined our selection criteria. Since *m* is a poorly defined photometric system, with a passband limited to the blue half of more conventional *R* passbands, we have not attempted to transform data from standard photometric systems to define a calibration sequence. Instead, we define the sequence directly, using photometry listed in the NLTT Catalogue for nearby stars with accurate trigonometric parallax measurements. The near-infrared data for those stars are taken either from Leggett’s (1992) compilation or from 2MASS itself. Figure 4 plots these data, where the magnitudes are adjusted to match a distance of 20 pc. As expected, there is considerable scatter, so rather than fit a mean relation, we have defined a series of linear relations that underlie the overall distribution. These provide a set of conservative criteria, erring toward including stars lying beyond the 20 pc limit rather than excluding nearby stars with particularly erratic positions.
The nearby stars at 20 pc.

Fig. 4.—Nearby-star selection in the \((m_r, m_r-K_s)\) plane. The solid points plot data for known nearby stars with accurate trigonometric parallax measurements, adjusting the magnitudes to a distance of 20 pc. The solid line underlying the main sequence outlines the selection criteria described in the test.

photometry. The relations are as follows:

\[
m_r(\text{lim}) = \begin{cases} 
2.17(m_r-K_s) + 3.65, & \text{if } m_r-K_s \leq 4.3, \\
5.25(m_r-K_s) - 9.58, & \text{if } 4.3 < m_r-K_s \leq 4.7, \\
1.48(m_r-K_s) + 8.15, & \text{if } 4.7 < m_r-K_s \leq 7.
\end{cases}
\]

We set a lower limit of \(m_r-K_s = 3.5\), corresponding to \(R-K_s \leq 2.7\), or spectral type \(\sim \text{K5}\), and include all matches with \(m_r-K_s > 7\). NLTT-2MASS pairings are eliminated from our candidate list if \(m_r > m_r(\text{lim})\). Applying these selection criteria reduces the NLTT sample by almost 95%, from 25,305 pairings to only 1434 candidates.

3.3. NLTT Binaries and Extreme Colors

Over 2300 stars in the NLTT Catalogue are identified in the notes as probable common proper motion (CPM) companions of brighter stars. A substantial fraction of those systems have separations of less than 200\('\). Our cross-referencing against the 2MASS database is based only on positional coincidence, so it is possible for an NLTT binary to produce four pairings, including two correct matches, NLTT(A) + 2MASS(A) and NLTT(B) + 2MASS(B), and two mismatches, NLTT(A) + 2MASS(B) and NLTT(B) + 2MASS(A). Of the two mismatches, the latter is more important for present purposes, since it pairs the fainter optical source against the brighter infrared source, giving the reddest possible \(m_r-K_s\) color. Those sources are most likely to be included in our list of nearby-star candidates.

We dealt with this possible source of contamination through visual inspection (via IRSA) of the 2MASS images of the CPM companions included in our candidate list. Since Luyten’s notes give the position angle for each system, it is straightforward to determine whether the 2MASS position corresponds to the correct component. Based on that comparison, we have eliminated a further 161 pairings, reducing our primary NLTT sample to 1273 candidates and eliminating many of the apparently reddest stars in the sample (Fig. 5).

3.4. Near-Infrared Colors

Finally, we have examined the photometric properties of 2MASS sources to check their consistency with both the \(m_r-K_s\) colors and known properties of late-type dwarfs. Figure 6 plots the \((m_r-K_s, J-K_s)\) and \((J-H, H-K_s)\) two-color diagrams for the 1273 NLTT-2MASS pairings that survive as nearby-star candidates. The overwhelming majority have colors consistent with those expected for M dwarf stars, but there are a small number of outliers. In particular, 20 sources have near-infrared colors more consistent with either earlier-type (G, K) main-sequence stars or red giants, while a further eight have nonstellar \(JHK\) colors. Figure 6 shows that most of the outliers in the \(JHK\) plane (where we have more accurate photometry) are also discrepant in the optical/near-infrared two-color diagram; in particular, the 2MASS sources with early-type near-infrared colors have faint NLTT counterparts and correspondingly red \(m_r-K_s\) colors. Visual inspection confirms that both these objects and the candidates with red giant \(JHK\) colors are mismatches, and we have eliminated them from the sample.

The unusual colors of the remaining outliers can be attributed to an error in one band of the 2MASS photometry, in some cases probably due to confusion. For completeness, Table 1 lists relevant data for these objects. All are known nearby stars, and at least four lie within 20 pc of the Sun.

3.5. Summary: NLTT Sample 1

With the elimination of mismatches and stars with unreliable photometry, our primary sample of NLTT nearby-star
cusses low-resolution spectroscopy of 70 of the fainter NLTT stars.

4. PHOTOMETRIC PARALLAX CALIBRATION

The prime goal of our NStars project is identifying stars within 20 pc of the Sun. Given the accuracy possible in current astrometric work (better than 1 mas), trigonometric parallax measurements offer the most reliable distance estimates. However, acquiring the necessary astrometric observations remains a time-consuming process. Photometric parallaxes, derived by estimating the absolute magnitude based on measurement of appropriate colors, are much simpler to obtain. The main disadvantage is that, since absolute magnitude is calibrated based on a mean relation, the photometric method takes no account of intrinsic scatter in the Hertzsprung-Russell diagram, due, for example, to abundance variations or unrecognized binarity. Moreover, a mean relation can smooth over abrupt changes in slope in the main sequence, leading to systematic under- or overestimates of absolute magnitude in a particular color range. Nonetheless, if one bears those caveats in mind, photometric parallax estimates can be used to further refine the list of nearby-star candidates.

4.1. Calibrating the Main Sequence for Nearby Stars

We have chosen three color indexes for calibration purposes: \( V - K \) is the longest-baseline color index available for most stars in the sample; \( V - I \), where \( I \) is on the Cousins system, is widely used as an optical distance indicator; and \( I - J \) was identified as the cleanest optical/near-infrared color index by Leggett et al. (1996). We have calibrated the mean relations using data from three main sources: Leggett’s (1992) compilation of \( UBVRIJHK \) photometry of nearby K and M dwarfs; a combination of Bessell’s (1990) \( BVRI \) data and 2MASS \( JHK \), photometry for stars from the second Catalogue of Nearby Stars (Gliese 1969, hereafter CNS2; Gliese & Jahreiss 1979); and Dahn et al.’s (2000) optical and near-infrared photometry of ultracool M and L dwarfs. All of the stars have trigonometric parallax measurements, derived from either \( Hipparcos \) (ESA 1997) or US Naval Observatory observations (Monet et al. 1992 and references therein), accurate to better than 10%; in most cases, the accuracy exceeds 5%, rendering statistical Lutz-Kelker corrections of negligible proportion. Finally, all known

### TABLE 1

| NLTT   | \( \alpha \) (J2000.0) | \( \delta \) (J2000.0) | \( m_I \) | \( m_I - K_J \) | \( J - H \) | \( H - K_J \) | \( \pi \) | \( M_K \)        |
|--------|------------------------|------------------------|----------|-----------------|-------------|----------------|--------|--------------|
| G74-34 | ...02 36 47.8           | ...32 04 20            | 12.6     | 4.33            | 0.72        | 0.03           | 65.2   | 1.5          | 7.35         |
| GJ 1194B | ...15 40 03.7           | ...43 29 35            | 13.0     | 4.75            | -0.37       | 1.02           | 74.2   | 4.8          | 7.60         |
| LP 229-17 | ...18 34 36.6           | ...40 07 26            | 11.5     | 4.42            | 0.67        | -0.55          | 138    | ...40        | ...          |
| +46:2654 | ...19 16 11.7           | ...47 05 13            | 11.2     | 3.54            | 0.68        | -0.32          | 36.2   | 1.4          | 5.45         |
| +48:3952B | ...23 10 21.4           | ...49 01 02            | 10.0     | 3.67            | 0.31        | -0.02          | 21.6   | 0.9          | 3.00         |
| G273-93 | ...23 38 08.1           | ...16 14 09            | 12.3     | ...            | 0.60        | ...            | 62.0   | 18           | ...          |

Notes. — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. G74-34: binary, \( \delta V = 0.3 \) mag (pCNS3), parallax from van Altena et al. 1995. GJ 1194B: parallax from van Altena et al. 1995. LP 229-17: parallax from \( M_K \) relation, spectral type M3.5, and \( M_K = 12.1 \) (PMSU1). BD +46:2654: HIP 94701; \( M_K \) is consistent with spectral type listed in SIMBAD. BD +48:3952B: HD 218790B or HIP 11442B, \( V \sim 10.4 \); 2MASS photometry possibly affected by primary, \( V = 7.4 \), \( \Delta \sim 4\rightangle, \theta = 157^\circ \). G273-93: parallax from \( M_K \) relation, spectral type M2, and \( M_K = 10.3 \) (PMSU1).
binaries and halo subdwarfs (e.g., Gl 191, Kapteyn’s star) have been excluded from the sample, together with a few additional stars that lie significantly above or below the main body of the data. These calibrators should therefore provide a reliable estimate of the mean location of the main sequence in the local Galactic disk.

Figure 9 plots the color-magnitude distribution of main-sequence stars in the \((M_V, V-K)\)-plane. We have derived a mean relation by fitting a sixth-order polynomial,

\[
M_V = -30.36 + 44.34(V-K) - 21.84(V-K)^2 \\
+ 5.600(V-K)^3 - 0.7543(V-K)^4 \\
+ 0.05105(V-K)^5 - 0.001370(V-K)^6 \\
10(V-K) > 2.5, \sigma = 0.412 \text{ mag, 198 stars}
\]

Note the preponderance of data points below the mean relation in the color range \(5 < V-K < 6\).

Our adopted \((M_V, V-I)\) calibration is shown in Figure 10. We match the observations using a composite relation, combining the following three polynomials:

\[
M_V = -4.415 + 27.62(V-I) - 28.45(V-I)^2 \\
+ 14.63(V-I)^3 - 2.967(V-I)^4 \\
- 0.02758(V-I)^5 + 0.05848(V-I)^6, \\
1.0 \leq V-I < 2.8, \sigma = 0.40 \text{ mag, 175 stars};
\]

\[
M_V = 12.20(V-I) - 21.96, \quad 2.8 \leq V-I < 2.9; \\
M_V = 5.923 + 2.249(V-I) + 0.171(V-I)^2 \\
- 0.01886(V-I)^3, \\
2.9 \leq V-I < 4.5, \sigma = 0.22 \text{ mag, 29 stars}.
\]

As discussed in previous papers (PMSU2; Reid & Gizis 1997), this tripartite approach is required by the noticeable steepening of the main sequence at \(V-I > 2.85\).

Finally, Figure 11 plots the \((M_J, I-J)\) relation. There is clearly an abrupt change in slope at \(I-J \sim 1.5\), and we have derived separate mean relations for the brighter and fainter stars.
stars,
\[ M_I = 2.879 + 1.635(I-J) + 5.258(I-J)^2 \]
\[-4.516(I-J)^3 + 1.632(I-J)^4 - 0.107(I-J)^5, \]
\[ 0.4 \leq I-J < 1.45, \sigma = 0.42 \text{ mag}, 194 \text{ stars}; \]
\[ M_I = 16.491 - 16.499(I-J) + 14.003(I-J)^2 \]
\[-4.717(I-J)^3 + 0.697(I-J)^4 - 0.0330(I-J)^5, \]
\[ 1.65 \leq I-J < 4.0, \sigma = 0.31 \text{ mag}, 37 \text{ stars}. \]

The main sequence is essentially vertical in the region of overlap, with an almost even distribution of data points over the range \( 1.45 < I-J < 1.65, 9.2 < M_I < 11.2 \). Rather than attempt to fit a mean relation, we assign an absolute magnitude estimate of \( M_I = 10.2 \pm 0.7 \) for NLTT stars falling in this color range.

4.2. Structure in the Main Sequence

The disk main sequence does not, unfortunately, present a simple linear relation in color-magnitude diagrams—hence the necessity for the polynomial relations computed in the previous section. Before applying those calibrations to derive photometric parallaxes for the NLTT stars, we briefly consider both the interpretation of the changing slope of the main sequence evident in Figures 9, 10, and 11 and the implications for our analysis.

A change in slope of the main sequence in a color-magnitude diagram generally reflects either a significant change in the opacity distribution within the individual spectral bands sampled (a local effect) or a significant change in the underlying physical structure (a global effect). The most striking example of the former is the abrupt change in near-infrared \((H, K)\) colors at the transition between spectral types L and T due to the onset of CH, absorption at 1.6 and 2.2 \( \mu m \). In contrast, most of the changes in slope evident in Figures 9–11 likely stem from global effects.

Several notable points of inflection are evident in Figures 9 and 10: at \( M_V \sim 8.5 \) (spectral type M1), where the main-sequence steepens; at \( M_V > 14 \) (spectral type M4.5/M5), where the gradient becomes shallower, almost matching the slope at \( M_V < 8 \); and, less pronounced in \( V-K \) but nonetheless present, at \( M_V \sim 12.5 \) (spectral type M3.5/M4), where the main sequence steepens sharply. The “break” in the main sequence produced by the latter two points of inflection is evident at near-infrared wavelengths at \( I-J \sim 1.5 \), while PMSU2 and Reid & Gizis (1997) have shown that this feature is also present if one uses TiO band strength as a surrogate for color (effective temperature). We emphasize that the same stars outline the configuration at all wavelengths; thus, Gl 15B (\( M_V = 13.33, V-I = 2.82, M_I = 10.51, I-J = 1.48, M3.5) \) is one of the bluest and faintest contributors, while Gl 555 (\( M_V = 12.36, V-I = 2.86, M_I = 9.50, I-J = 1.59, M4) \) lies at the opposite extreme. The fact that this feature occurs over such a wide range in wavelength, coupled with the lack of any obvious rapidly varying spectral features, suggests strongly that this is a global effect, indicative of a significant change in luminosity over a small range in color (effective temperature). In contrast, the steepening in the \((M_V, V-I)\) distribution at \( M_V > 18 \), behavior that is not reflected in \( V-K \), is probably a local effect, marking the presence of substantial TiO and metal hydride absorption in the \( I \) band.

Several theoretical mechanisms are known to modify the shape of the lower main sequence. At masses below \( \sim 0.1 M_\odot \), degeneracy becomes increasingly important, leading to
the shallower slope at $M_V > 13$ (D’Antona & Mazzitelli 1985). On the higher luminosity side of the break, Copeland, Jensen, & Jørgensen (1970) originally demonstrated that H$_2$ formation affects the atmospheric temperature structure in late K and early M dwarfs. At those temperatures the formation region lies in the convection zone, leading to a shallower adiabatic gradient, a higher luminosity, and a higher surface temperature for stars below the threshold mass. Copeland et al. place the onset of this effect at $M_{bol} \sim 7$, broadly consistent with the observed change of slope at $M_V = 8.5$. More recent theoretical calculations by Kroupa, Tout, & Gilmore (1990), on the other hand, find a lower threshold luminosity, $M_{bol} \sim 9$, or $M_V \sim 11$.

As yet, there is no widely accepted theoretical explanation for the break in the main sequence at $V - I = 2.8$. Clemens et al. (1998) suggest that the feature may be a result of a relatively abrupt decrease in radius, possibly correlated either with the onset of full convection or with an internal change in the structure of the core. In any event, none of the available theoretical models reproduce the observed main sequence at these luminosities. As an illustration, Figures 9, 10 and 11 plot the 5 Gyr isochrone from the solar-abundance models calculated by Baraffe et al. (1998, hereafter BCAH), together with 5 Gyr isochrones form the more recent DUSTY models (Chabrier et al. 2000). The latter include both grain opacities and an improved TiO line list, although incompleteness in the H$_2$O line list leads to inaccuracies at near-infrared wavelengths (G. Chabrier 2001, private communication; see also Reid & Cruz 2002 for comparison against infrared data for late-type dwarfs).

The BCAH models are closest to the empirical main sequence in the $(M_V, I - J)$-plane, albeit to some extent smoothing over the break at $M_V \sim 10.5$. The extremely red colors at low luminosities reflect the absence of grain opacities in those models; the DUSTY models are clearly a better match to the data. At optical wavelengths, the BCAH models show poorer agreement, falling below the main sequence at $M_V \sim 10$ and remaining 0.5 to 1 mag fainter than the observations at lower luminosities. Again, the DUSTY models better match the data, reflecting the more extensive TiO line lists, but these models still miss the M3/M4 break in $(M_V, V - I)$, while the mismatch at near-infrared wavelengths reflects the H$_2$O opacity deficiencies. Bedin et al. (2001) point out similar discrepancies between theory and observation at lower abundances. As the latter authors emphasize, resolving those discrepancies is important both in interpreting color-magnitude diagrams and in establishing reliable theoretical mass-luminosity transformations.

In terms of the present survey, structure in the main sequence has two consequences: first, systematic miscalibration, if the color-magnitude relation we adopt fails to follow the empirical distribution; second, higher Malmquist bias, and a consequent increased contamination from more distant stars, at colors where the main sequence is steepest. Both of these biases are likely to be most significant near the break at $M_V = 12-14$ ($5 < V - K < 5.6, 1.45 < I - J < 1.65$). These effects will be taken fully into account in statistical analysis of the nearby-star sample. For present purposes, we simply note the increased uncertainty in photometric parallax for stars of the appropriate colors.

5. LITERATURE DATA FOR NLTT SAMPLE 1

We have used the SIMBAD database to cross-reference the NLTT sample against the published literature, checking all potential named counterparts within 1' of the 2MASS position. The latter step is essential, since SIMBAD does not include cross-references to all of the LP names cited in the NLTT, while some stars appear twice (or more) with different names and slightly different positions. Moreover, a significant number of stars in the NLTT Catalogue have no associated name—a deliberate choice on Luyten’s part. The overwhelming majority of these stars are actually from the Lowell Observatory proper-motion survey (Giclas, Burnham, & Thomas 1971). Over 400 stars prove to have either photometric or astrometric observations available in the literature.

5.1. Photometry and Astrometry

Among the 1245 stars in our primary NLTT sample, 649 have at least $V$-band photometry, of which 469 are considered here (the remaining 180 stars will be discussed in Paper II). Three hundred forty-two of the 469 are listed in the pCNS3, including a number of known spectroscopic or small angular separation binary systems. While the latter are not photometric outliers, unlike the stars listed in Table 1, photometric parallaxes will lead to underestimated distances, so we have culled those stars from the sample. Data for those systems are listed in Table 2. Table 3 collects published photometry and parallax measurements for the remaining stars. We list the NLTT designation for each, adding the Giclas numbers ignored by Luyten, and give Gl or GJ numbers (as appropriate) as a secondary identification. We have also cross-referenced the sample against the LHS catalog.

All of the optical photometry included in Table 3 is on the Johnson/Cousins $BVR$ system. The original $R_I$ photometry is taken from sources that use either the Kron or the Kron-Cousins system, since experience has shown that transforming data for M dwarfs from other systems can give unreliable results. We have used the relations given by Bessell & Weis (1987) to transform between the Kron and Cousins systems. The main contributor is E. Weis, who has obtained optical data for nearly 3000 NLTT stars, including all m-class stars with $\delta > 0^\circ$ and $m_r < 13.5$ (Weis 1988 and references therein), together with almost 25% of the LHS catalog (Weis 1996). Two hundred sixty of those stars are included in Table 3. Other sizable contributions are from Bessell (1990; BVR, 46 stars), the $Hipparcos$ Catalogue (ESA 1997; $BV$, 43 stars), the pCNS3 ($BV$, 28 stars), and Sandage & Kowal (1986; $BV$, 27 stars). We also include photometry by Ryan (1989), Fleming (1998), Patterson, Ianna, & Begam (1998), and Eggen (1987).

Figure 12 superposes photometry for the NLTT stars on the Johnson/Cousins $BVRI$ system. The original $R_I$ photometry is taken from sources that use either the Kron or the Kron-Cousins system, since experience has shown that transforming data for M dwarfs from other systems can give unreliable results. We have used the relations given by Bessell & Weis (1987) to transform between the Kron and Cousins systems. The main contributor is E. Weis, who has obtained optical data for nearly 3000 NLTT stars, including all m-class stars with $\delta > 0^\circ$ and $m_r < 13.5$ (Weis 1988 and references therein), together with almost 25% of the LHS catalog (Weis 1996). Two hundred sixty of those stars are included in Table 3. Other sizable contributions are from Bessell (1990; BVR, 46 stars), the $Hipparcos$ Catalogue (ESA 1997; $BV$, 43 stars), the pCNS3 ($BV$, 28 stars), and Sandage & Kowal (1986; $BV$, 27 stars). We also include photometry by Ryan (1989), Fleming (1998), Patterson, Ianna, & Begam (1998), and Eggen (1987).

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Figure 12 superposes photometry for the NLTT stars on the two-color ($B-V, V-K$) and ($V-I, V-K$) diagrams outlined by nearby main-sequence stars. In most cases, the data are broadly consistent with the expected distributions, albeit with significantly more scatter in the ($B-V, V-K$)-plane. A few stars prove special comment:

1. LP 335-13 (HIP 91489): The $B-V$ color listed in the $Hipparcos$ Catalogue ($B-V = 0.68$) is clearly incompatible

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5 This mismatch accounts for the remarkably young age of $\sim 30$ Myr deduced for Gl 229A by Leggett et al. (2002). Since the BCAH models fall below the empirical main sequence, the only means of matching the observed luminosity is by reducing the age.
with both the observed spectral type (M2) and the absolute magnitude inferred from the apparent magnitude and parallax ($M_V = 8.71$). Since the $V$ magnitude (10.85) is consistent with the NLTT photometry ($m_i = 11.0$), we adopt that value in computing $V-K_s$.

2. LP 984-91 (HIP 112312): The $V$ magnitude listed in Table 3 is derived from the Hipparcos $H_p$ measurement, adopting the color correction appropriate to a mid-type M dwarf. We note that the Hipparcos measurements indicate variability of $\sim 0.35$ mag.

3. LP 653-15 (LHS 176): The optical colors listed in Table 3 (from Dawson & Forbes 1989) are inconsistent with the both the inferred $V-K_s$ and the $JHK_s$ colors, perhaps as a result of misidentification. Further observations are required, and the $V-K_s$ photometric parallax computed here must be regarded as tentative.

4. LP 469-50 is clearly identical with G3-34. Inspection of POSS I and II images, however, shows that the position listed in SIMBAD for the latter star is coincident with a nearby, nonmoving star of similar magnitude, lying $\sim 2.5$ northwest of the proper-motion star. It is not clear which star was observed by Sandage & Kowal, so the $V-K_s$ photometric parallax requires confirmation.

5. BD +19°5093B: The $B-V$ color derived by Eggen may be affected by the presence of the nearby 6th magnitude primary star.

### TABLE 3

| Name | LHS | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $m_i$ | $V$ | $B-V$ | $V-J$ | $K_s$ | $\pi$ (mas) | Ref. |
|------|-----|-----------------|-----------------|-------|-----|-------|-------|-----|------------|------|
| +44:4548... |  GI2 | 00 05 10.7 | 45 47 11 | 9.8 | 9.95 | 1.51 | 0.97 | 2.08 | 1 | 6.695 | 6.093 | 5.848 | 87.0 ± 1.4 | 1 |
| G158-27... |  GI2002 | 00 06 43.2 | -07 32 14 | 13.0 | 13.83 | ... | 1.59 | 3.59 | 11 | 8.351 | 7.786 | 7.448 | 213.0 ± 3.6 | 2 |
| G17... |  GI7 | 00 09 04.2 | -27 07 19 | 11.5 | 11.68 | 1.47 | 0.95 | 1.90 | 11 | 8.642 | 8.142 | 7.851 | 42.8 ± 2.6 | 1 |
| 464-42... |  GI12 | 00 15 49.1 | 13 33 21 | 12.2 | 12.60 | 1.65 | 1.15 | 2.56 | 11 | 8.615 | 8.059 | 7.789 | 86.6 ± 13.4 | 2 |
| 404-61... |  GI006A | 00 16 14.5 | 19 51 38 | 10.9 | 12.26 | 1.54 | 1.21 | 2.79 | 1 | 7.900 | 7.311 | 7.100 | 66.1 ± 1.6 | 2 |

Notes.—Table 3 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Col. (1) lists the designation from the NLTT Catalogue: R = Ross, W = Wolf, Ox = Oxford catalog. We have added Lowell Proper Motion Survey identifications (Giclas et al. 1971) where appropriate. Col. (2) lists the alternative name, usually from the pCNS3; col. (3) gives the LHS number; cols. (4) and (5) list the position of the 2MASS source; col. (6) lists the $V$ magnitude from the NLTT Catalogue; cols. (7)–(10) list the optical photometry, and col. (11) gives the source: (1) Weis 1984, 1986, 1987, 1988, 1991, 1993, 1996, 1999; (3) ESA 1997; (4) pCNS3; (5) Sandage & Kowal 1986; (6) Ryan 1989, 1992; (7) Fleming 1998; (8) Patterson et al. 1998; (9) Eggen 1966, 1975, 1980, 1987; (10) Andruk et al. 1995; (11) Bessell 1990; (12) Leggett 1992; (13) Dawe & Forbes 1989, 1992; (14) Humphreys et al. 1991; (15) Gullixson et al. 1995; (16) USNO (Harrington et al. 1993 and references therein; $B^V$ only); (17) Hartwick, Cowley, & Mould 1984; (18) Dahn et al. 2000; (19) Stauffer & Hartmann 1986; (20) Uppgren & Lu 1986; (21) Reid 1990; (22) Kron, Gascoigne, & White 1957; (23) van Altena et al. 1995; (24) Liao 1989. Cols. (12)–(14) list the 2MASS photometry; col. (15) lists the trigonometric parallax, if available, and col. (16) gives the source of the astrometry: 1 = ESA 1997; 2 = Yale catalog (van Altena et al. 1995); 3 = Tinney 1996.
measured to a formal accuracy better than 9%. Figure 13 plots the residuals in distance modulus for that, in the sense
\[ \delta(\pi - \text{phot.}) = (m - M)_\pi - (m - M)_{\text{phot}}, \]
as a function of absolute visual magnitude. Table 5 lists the mean residuals and the dispersion in residuals for the individual photometric estimates and for the averaged photometric parallax. The rms dispersion is typically 0.3 to 0.4 mag, rising sharply in the \( M_V = 13 \) bin, centered on the main-sequence break discussed in § 4.2, but there is no evidence of a systematic offset.

Table 4 also lists the trigonometric distance estimates. Since the measured uncertainties \( \sigma_\pi \) are symmetric in parallax, the uncertainties in distance modulus are asymmetric. For present purposes, we adopt
\[ \epsilon_\pi = 5 \log \frac{\pi}{\pi - \sigma_\pi} \]
and use those values as weights in averaging \( (m - M)_\pi \) and \( (m - M)_{\text{phot}} \). Based on the above discussion and the comparison shown in Table 5, we set a lower limit of \( \pm 0.3 \) mag on the weight associated with \( (m - M)_{\text{phot}} \) to take into account the intrinsic dispersion of the main sequence. This ensures that high-accuracy trigonometric measurements are given due weight, while preserving a self-consistent distance estimation process. Our final adopted estimates of the distance to each star, \( d_f \), and the associated uncertainty, \( \epsilon_d \), are listed in Table 4.

The last column of Table 4 identifies which stars are likely to lie within 20 pc of the Sun. Stars with formal distances \( d_f \leq 20 \) pc are identified as probable inhabitants of the immediate solar neighborhood ("Y" = 266 stars), while candidates with \( d_f - \epsilon_d \leq 20 \) pc are possible members ("?" = 46 stars). One hundred fifty-seven stars have formal distances \( d_f - \epsilon_d > 20 \) pc and are therefore excluded from our census. Among the solar neighborhood members, 43 have formal distances of less than 10 pc (identified as "Y*" in Table 4). While most are well-known, much-studied nearby stars with accurate trigonometric parallax measurements, two stars are potential additions:

1. G39-29, with a formal distance of 9.6 ± 1.3 pc and \( M_K = 7.4 \); no trigonometric data.
2. G180-11, \( d_f = 9.3 ± 1.2 \) pc and \( M_K = 8.1 \); no trigonometric data.

### Table 4

Distance Modulus Estimates for NLTT Stars

| NLTT     | \( m - M_K \) | \( m - M_I \) | \( m - M_J \) | \( m - M_J \) | \( m - M \)_{\text{phot}} | \( m - M \)_{\text{phot}} | \( d_f \) (pc) | \( M_K \) | \( M_V \) | 20 pc? |
|----------|---------------|---------------|---------------|---------------|----------------|----------------|--------------|----------|--------|--------|
| +44:4548* | 0.24 ± 0.41   | 0.20 ± 0.40   | 0.26 ± 0.42   | 0.23 ± 0.24   | 0.30 ± 0.04    | 11.5 ± 0.2     | 5.55         | 9.65     | Y      |
| +45:4408A* | 0.17 ± 0.41   | 0.27 ± 0.40   | 0.25 ± 0.42   | 0.23 ± 0.24   | 0.26 ± 0.06    | 11.3 ± 0.3     | 5.03         | 8.71     | Y      |
| +45:4408B* | 0.05 ± 0.41   | 0.33 ± 0.40   | -0.15 ± 0.42  | 0.08 ± 0.24   | 0.26 ± 0.06    | 11.1 ± 0.3     | 5.03         | 8.79     | Y      |
| G158-27    | -1.36 ± 0.41  | -1.49 ± 0.22  | -1.35 ± 0.31  | -1.42 ± 0.16  | -1.64 ± 0.04   | 4.7 ± 0.1      | 9.07         | 15.45    | Y*     |
| -27:16*    | 2.57 ± 0.41   | 2.53 ± 0.40   | 2.37 ± 0.42   | 2.49 ± 0.24   | 1.84 ± 0.14    | 25.6 ± 1.4     | 5.81         | 9.64     | N      |

Notes.—Table 4 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Col. (1) lists the designation from the NLTT Catalogue, adding Lowell Observatory identifications; col. (2) gives the distance modulus derived from the \( V - K \) photometric parallax; cols. (3) and (4) list distance moduli based on \( V - I \) and \( I - J \), respectively, for stars with I-band photometry; col. (5) gives the weighted average of the photometric parallax measurements; col. (6) lists the distance modulus indicated by the trigonometric parallax; col. (7) gives our final estimate of the distance, based on a weighted average of the photometric average and the trigonometric result; cols. (8) and (9) list the resultant absolute magnitudes at \( K \) and \( V \) respectively; col. (10) indicates whether the star lies within our distance limit of 20 pc ("Y"), within 1 \( \sigma \) of the boundary ("?"), or beyond the limit ("N"). A plus sign indicates that the star is not included in the pCNS3.

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Fig. 12.—The \((B - V) - (V - K)\) and \((V - J) - (V - K)\) two-color diagrams. Stars listed in Table 2 are plotted as open squares; crosses mark the two-color relation defined by nearby main-sequence stars. The outliers are discussed in the text.
Fig. 13.—Comparison between distance moduli derived from photometric parallaxes and astrometric distance measurements for stars with trigonometric parallaxes measured to an accuracy better than 9%. The mean residuals as a function of absolute magnitude (derived from $\Delta m_{\text{phot}}$) are given in Table 4.

| $\langle M_V \rangle$ | $\Delta m_{1}$ | $\sigma$ | $n_1$ | $\Delta m_{2}$ | $\sigma$ | $n_2$ | $\Delta m_{3}$ | $\sigma$ | $n_3$ | $\Delta m_{4}$ | $\sigma$ | $n_4$ |
|----------------------|----------------|---------|-------|----------------|---------|-------|----------------|---------|-------|----------------|---------|-------|
| 7.0 ......            | 0.239          | 0.289   | 19    | 0.065          | 0.279   | 9     | 0.286          | 0.465   | 9     | 0.225          | 0.302   | 19    |
| 9.0 ......            | 0.178          | 0.431   | 87    | 0.179          | 0.423   | 70    | 0.172          | 0.499   | 70    | 0.174          | 0.415   | 87    |
| 11.0 ......           | 0.075          | 0.542   | 83    | 0.075          | 0.417   | 75    | 0.089          | 0.758   | 74    | 0.082          | 0.518   | 83    |
| 13.0 ......           | −0.211         | 0.608   | 36    | 0.032          | 0.667   | 34    | 0.318          | 0.524   | 33    | −0.013         | 0.636   | 36    |
| 15.0 ......           | 0.046          | 0.413   | 15    | 0.135          | 0.335   | 13    | 0.159          | 0.407   | 13    | 0.092          | 0.350   | 15    |
| 17.0 ......           | −0.128         | 0.150   | 6     | 0.016          | 0.082   | 5     | −0.090         | 0.220   | 5     | −0.083         | 0.120   | 6     |

Notes.—Mean residuals, as a function of absolute magnitude, between photometric and trigonometric parallax estimates for stars with trigonometric parallaxes accurate to better than 10%. The residuals are listed as differences in distance modulus in the sense $\Delta = \frac{\sum (m - M)_{\text{phot}} - (m - M)_{\text{phot}}}{n}$, where $(m - M)_{\text{phot}}$ is derived from the photometric parallax, $\sigma$ is the dispersion about the mean, and $n$ is the number of stars contributing to each bin. The table lists comparisons against the individual photometric parallaxes $\Delta m_1$ against $(m - M)_{\text{V-K}}$, $\Delta m_2$ against $(m - M)_{\text{V-J}}$, and $\Delta m_3$ against $(m - M)_{\text{J}}$ and against the weighted average of the photometric estimates $(\Delta m_4)$. 
Both are listed in the pCNS3, but with higher distance estimates. Accurate trigonometric parallax data are required to confirm the photometric distance estimates.

5.3. Late-Type Dwarfs

The solar neighborhood census is complete for stars of low luminosity. Early- and mid-type M dwarfs have near-infrared colors spanning a very small range in magnitude; in particular, $J - K$ is essentially constant, at $J - K_0 = 0.9 \pm 0.1$ for spectral types K7 to M6. The coolest main-sequence stars, ultracool dwarfs with spectral types later than M6, have sufficiently strong energy distributions that $J - K_0$ changes significantly with decreasing temperature. We can therefore identify the ultracool dwarfs in our NLTT sample and use the near-infrared colors to estimate photometric parallax. Gizis et al. (2000b) have calibrated this relation, deriving

$$M_K = 7.593 + 2.25(J - K_0), \quad \sigma = 0.36 \text{ mag},$$

which is valid for spectral types later than M6.5. We have used this relation to estimate distances to NLTT dwarfs in the current sample with $J - K_0 > 0.99$. Tables 6 and 7 present the results. Table 6 lists nine dwarfs with previous spectroscopic observations, including LHS 2090, an M6.5 dwarf recently identified as lying within the 8 pc sample (Scholz, Meusinger, & Jahrreiss 2001); LP 944-20, the nearest isolated brown dwarf (Tinney 1998); four dwarfs from the ultracool 2MASS sample selected by Gizis et al. (2000a); and an earlier type dwarf, LP 860-46, which appears coincident with one of the brighter stars in Ardila, Martín, & Basri’s (2001) U Sco photometric survey.

Table 7 collects data for a further 42 ultracool dwarfs selected from our current sample based on the 2MASS photometry. We have estimated distances to these dwarfs using the $(M_K, J - K_0)$ relation given above. While the majority of these stars have no prior observations, nine dwarfs have optical photometry. Photometric parallaxes derived from the latter data (usually $V - K_0$) indicate larger distances than those from the $J - K_0$ calibration. Indeed, the optical-based distances for the three brightest Gicas stars are a factor of 4 higher than the near-infrared calibration. These stars probably have spectral types earlier than M6.5, but they have near-infrared colors on the red extreme of the $J - K_0$ distribution. The agreement between $d_J$ and $d_{J - K}$ is better among the fainter (apparent magnitude) stars in Table 7 (which are also likely to have fainter absolute magnitudes), although the near-infrared color index still tends to give lower distances by $\sim 30\%$. Nonetheless, all of the dwarfs listed in Tables 6 and 7 have formal distances either less than 20 pc or within 1 $\sigma$ of our distance limit. Of the 51 ultracool dwarfs in Tables 6 and 7, only LP 944-20 has a trigonometric parallax measurement.

6. SUMMARY

Our NStars survey aims to identify late-type stars and brown dwarfs lying within 20 pc of the Sun. In this first paper, we have concentrated on defining an initial sample of

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**TABLE 6**

**Spectroscopically Confirmed Ultracool Dwarfs**

| NLTT   | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $m_\text{Sp}$ | J   | H   | $K_0$ | $d$ (pc) | Ref. | $M_K$ |
|--------|-------------------|-------------------|---------------|-----|-----|-------|---------|------|-------|
| 368-128... | 09 00 23.5 | 21 50 05 | 15.5 | M6.5 | 9.423 | 8.856 | 8.429 | 5.2 $\pm$ 1 | 1 | 9.85 |
| 860-46..... | 15 53 57.1 | $-23 11 52$ | 16.3 | 13.56 | 11.570 | 10.957 | 10.636 | 22.2 $\pm$ 4 | 2 | 8.90 |
| 213-67..... | 10 47 12.6 | 40 26 43 | 16.3 | ... | 11.417 | 10.777 | 10.400 | 12.7 $\pm$ 2.5 | 3 | 9.88 |
| 349-25..... | 00 27 55.9 | 21 19 32 | 17.0 | M8 | 10.608 | 9.970 | 9.561 | 8.4 $\pm$ 1.7 | 4 | 9.93 |
| 315-53..... | 10 16 34.7 | 27 51 49 | 17.4 | M7.5 | 11.951 | 11.294 | 10.946 | 16.5 $\pm$ 3 | 4 | 9.86 |
| 944-20..... | 03 39 35.2 | $-35 25 44$ | 17.5 | M9.5 | 10.748 | 10.017 | 9.525 | 5.0 $\pm$ 0.1 | 5 | 8.02 |
| 356-770.... | 03 30 05.0 | 24 05 28 | 18.1 | M7 | 12.357 | 11.745 | 11.361 | 20.2 $\pm$ 4 | 4 | 9.83 |
| 213-68..... | 10 47 13.8 | 40 26 49 | 18.7 | ... | 12.445 | 11.705 | 11.277 | 16.3 $\pm$ 3 | 3 | 10.22 |
| 413-53..... | 03 50 37.3 | 18 18 06 | 19.2 | M9 | 12.951 | 12.222 | 11.763 | 19.4 $\pm$ 4 | 4 | 10.27 |

**Note.**—Col. (5) lists either Cousins $I$-band photometry or the spectral type.

**References.**—(1) Scholz et al. 2001, LHS 2090: distance from $J - K_0$; (2) Ardila et al. 2001, UScoCTIO: distance from $I - J$; (3) Gizis et al. 2000a: distance from $J - K_0$; (4) Gizis et al. 2000b: distance from $J - K_0$; LP 315-53 = LHS 2243. (5) Tinney 1996, 1998: distance from trigonometric parallax.

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**TABLE 7**

**Photometrically Selected Ultracool Dwarfs**

| NLTT   | LHS   | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $m_\text{Sp}$ | J   | H   | $K_0$ | $d_J-K$ (pc) | $d_J$ (pc) |
|--------|-------|-------------------|-------------------|---------------|-----|-----|-------|-------------|------------|
| G118-43... | ... | 10 15 06.9 | 31 25 11 | 12.9 | 9.410 | 8.780 | 8.410 | 9.84 | 5.2 $\pm$ 1.0 | 17.7 |
| G180-11.... | ... | 15 55 31.8 | 35 12 02 | 12.9 | 8.999 | 8.290 | 7.986 | 9.87 | 4.2 $\pm$ 0.8 | 13.3 |
| G139-3..... | ... | 16 58 25.3 | 13 58 10 | 13.5 | 8.859 | 8.284 | 7.737 | 10.12 | 3.3 $\pm$ 0.7 | 13.6 |
| G199-16..... | 6234 | 12 29 09.5 | 62 39 38 | 14.2 | 10.337 | 9.775 | 9.315 | 9.89 | 7.7 $\pm$ 1.5 | ... |
| 245-10..... | 1378 | 02 17 09.9 | 35 26 33 | 14.7 | 9.965 | 9.355 | 8.974 | 9.82 | 6.8 $\pm$ 1.4 | 10.2 |

**Notes.**—Table 7 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Col. (10) lists the distance based on the $(M_K, J - K_0)$ calibration given in the text; col. (11) lists $d_J$ from Table 2 for stars with optical photometry.
nearby-star candidates from the NLTT Catalogue by combining Luyten’s red magnitude estimates with near-infrared photometry from the 2MASS database. We also describe a number of techniques that will be used in subsequent papers, both to identify other nearby-star candidates and to estimate their distances.

Cross-referencing our initial sample against the literature, we have located optical photometry for 469 of the 1245 stars. We have also used the near-infrared data provided by 2MASS to identify a further 41 ultracool dwarfs. Most of the stars in the former sample were already known to lie within the immediate solar neighborhood and are included in the preliminary version of the Third Catalogue of Nearby Stars. Our reanalysis provides improved distance estimates to many of these objects. Three hundred fifty-six stars listed in Table 3 have formal distances of less than 25 pc, the distance limit of the CNS2 and pCNS3; 45 of those stars have no pCNS3 designation. Our analysis also indicates that all 51 dwarfs listed in Tables 6 and 7 (10 stars are included in Table 3) also meet the pCNS3 distance limit. Two hundred ninety stars from Table 2 and all of the stars in Tables 6 and 7 meet the formal criteria of our own survey, with a more modest distance limit of 20 pc. Thirty-seven of the former sample, and 40 of the latter, are additions to the 20 pc nearby-star census.

Future papers in this series will present more detailed observations of the less well studied stars discussed in this paper, notably the ultracool dwarfs, and of the remaining 735 stars in our initial NLTT sample. In addition, we will apply the techniques outlined here in analysis of the 4875 NLTT dwarfs that were not included in the parent sample discussed here but have potential 2MASS matches within 60°.

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