1. INTRODUCTION

Interest in low-mass stars in the solar neighborhood is mostly inspired by searches for exoplanets. Looking for stellar companions is less popular nowadays, although solid empirical data on the distribution of periods, mass ratios, and hierarchies are still required for understanding the origin of stars, multiple systems, and planets (Bate 2008). Even within a distance of 25 pc the multiplicity statistics of G-dwarfs is still being updated and revised (Raghavan et al. 2010). An order-of-magnitude larger sample is required, however, to study detailed distributions of orbital parameters and higher-order hierarchies (triples, quadruples, etc.).

Periods of binary systems range from a half-day to millions of years. The discovery of all companions over the entire parameter space requires a combination of complementary techniques. Precise radial velocities cover periods of up to a few years, but information at longer periods is still dominated by visual discoveries made over the last two centuries. These data, collected in the Washington Double Star (WDS) catalog (Mason et al. 2001), are notoriously incomplete, especially for low-mass companions.

The Two Micron All Sky Survey (2MASS; Cutri et al. 2003) covers the whole sky in the \( JHK_s \) near-IR bands. Its sensitivity is sufficient for detecting even a 0.08 \( M_\odot \) companion to a G-dwarf star at 60 pc. The problem is in separating true (physical) companions from the background stars (optical companions). At large separations, physical companions can be identified by their common proper motion (PM; Lépine & Boniorno 2007; Makarov et al. 2008). However, the PM data are mostly based on archival photographic images where the vicinity of bright primary stars is contaminated by their halo, preventing detection of very faint companions (the magnitude difference in the visible is larger than in the IR). Meanwhile, physical companions should dominate over background interlopers at small separations. IR imaging has been used to find visual companions to exoplanet host stars by, e.g., Mugrauer & Neuhaüser (2009). Kirkpatrick et al. (2010) took second-epoch images of 10% of the sky and found many new common proper motion (CPM) companions by comparison with 2MASS.

The purpose of this work is to explore the potential of 2MASS for reaching a complete census of stellar companions to nearby dwarfs with separations from a few arcseconds to 20”–30”.

At smaller separations, adaptive-optics imaging (Shatsky & Tokovinin 2002; Kraus et al. 2008; Metchev & Hillenbrand 2009; Chauvin et al. 2010) can be used; at larger separations the existing PM data may be sufficient. I take second-epoch images of carefully selected companion candidates from the 2MASS Point-Source Catalog (hereafter PSC; Cutri et al. 2003) to determine their status (physical or optical). The detection limit of the PSC is modeled. The data set on visual companions in the selected range of separations is complemented by the new discoveries from 2MASS and used to study the distribution of the companion mass ratio, \( f(q) \). I show that \( f(q) \) is approximately uniform. This refers to the wide binaries studied here; a typical 10” binary at 60 pc distance has a semimajor axis of 600 AU and an orbital period on the order of 15,000 years.

New companions to G-dwarfs found here extend their number by 55%, complementing the census in the low-mass regime. About a third of the new binaries are higher-order multiples. More companion candidates from the PSC remain to be confirmed by contemporary imaging. This study thus contributes to the larger task of obtaining unbiased multiplicity statistics of nearby G-dwarfs.

The sample of nearby G-dwarfs and criteria for selecting candidate companions are presented in Section 2. Section 3 describes the observations and their processing. The results are presented in Section 4, followed by a statistical analysis in Section 5. The paper closes with a discussion in Section 6.

2. THE SAMPLE

The targets chosen for this survey belong to a large sample of nearby solar-type dwarfs (\( N_{\text{sample}} \)) selected from the \( \text{Hipparcos} \) catalog (ESA 1997) in its latest version (van Leeuwen 2007) by the following criteria.
1. Trigonometric parallax $\pi_{\text{HIP}} < 15$ mas (within 67 pc from the Sun, distance modulus $<4^{m}12$).
2. Color $0.5 < V - I < 0.8$ (this corresponds approximately to spectral types from F5V to K0V).
3. Unevolved, satisfying the condition $M_{\text{HIP}} > 9(V - I) - 3.5$, where $M_{\text{HIP}}$ is the absolute magnitude in the Hipparcos band calculated with $\pi_{\text{HIP}}$.

There are 5040 catalog entries satisfying these conditions. The selection criteria may introduce some bias with respect to unresolved binaries, to be addressed in the final statistics, but irrelevant for the present study. Systems containing white dwarfs should be removed from the statistics, as the present-day G-dwarfs are not original primaries. Removal of the secondary components of binaries with separate HIP numbers and six stars with parallax errors larger than 7.5 mas leaves 4915 primary targets. This sample includes many stars monitored for exoplanets and young stars in the solar neighborhood (X-ray sources, members of T-associations).

All point sources within a 2.5′ radius from each target are extracted from the PSC. The number of companions around each target, $N^*$, varies strongly and is a good measure of crowding. The total number of stars around primaries is 114,404, or $N^*$ = 23.3 on average. Most of these companions are faint.

In attempting to isolate potential physical companions, I consider only point sources within 20′ from primary targets which do not belong to crowded fields, $N^* < 100$. Primary components not found in 2MASS (within 6′) are omitted. This leaves 5347 stars, of which 4281 are primaries and 1066 are candidate secondaries. Among the secondaries, 238 are known companions listed in the WDS (Mason et al. 2001).

Observations are conducted to determine which of the companions are physical. New imaging covers the right ascension zone from 2° to 18° and declinations south of +20°, covering 0.447 of the whole sky. As the majority of the candidate companions are too faint to be on the main sequence (MS), an additional selection criterion is imposed:

$$J_{\text{abs}} < 6 + 7(J - K) \quad \text{and} \quad J_{\text{abs}} < 11. \quad (1)$$

Thus, 366 potential companions are above the solid line on the $(J_{\text{abs}}, J - K)$ color–magnitude diagram (CMD) in Figure 1, constructed by assigning the parallaxes of primary targets to their companion candidates. The selection criterion is intentionally “soft” because some physical companions are known to deviate from the MS (see the discussion of Hipparcos dwarfs with deviant colors in Koen et al. 2010). The nature of companions already listed in the WDS can be established with existing data, so most of them are dropped from the observing program, leaving 136 targets in the list. However, known companions are included in the statistical analysis.

3. OBSERVATIONS AND DATA REDUCTION

3.1. Imaging Data

Simultaneous images in the visible and IR were taken at the CTIO 1.3 m telescope (the telescope used in 2MASS) with the ANDICAM instrument\(^1\) (DePoy et al. 2003). The visual channel has a CCD with 1024\(^2\) binned pixels of 0″.369 size, and the IR channel has 512\(^2\) binned pixels of 0″.274.

Observations were carried out in 2010 February–March (2010.09 to 2010.19), in service mode. Five 4 s images of each target were taken in the $K_s$ band with dithers of 40 pixels ($\sim$11″6), followed by five 30 s dithered images. Simultaneously, several $V$-band images with 2 s and 30 s exposures were recorded. Most results reported here were obtained from the short-exposure images.

There are several problems in the data. HIP 10710 was not aligned correctly; HIP 59250, 60155, 60251, 60337, 61298, 61608, 73764 were not observed at all. For seven other targets (HIP 41620, 44579, 44777, 47312, 52676, 54285, 75839) the short-exposure sequence was not executed, leaving only 30 s exposures. The median image quality (FWHM from Gaussian fits) was 0″9 in the $K_s$ band and 1″1 in the $V$ band, and 50% of the data were within ±10% from the median image size. Some images were elongated, especially in the $K$ band (25% had ellipticity larger than 0.27).

Reduced images were retrieved from the SMARTS (Small and Moderate Aperture Research Telescope System) data center at Yale University (the CCD images were bias-subtracted and corrected for flat field). Dithered IR images were combined in the standard way. The sky image was calculated as a median over the dithered frames. Then each sky-subtracted frame was shifted to match the first frame (the shift was determined by cross-correlation). The re-centered frames were then median-combined. Figure 2 contains an example of the combined $K_s$ image with three companions around HIP 25662, one of which is physical. This star has a known CPM companion LDS 6186 at 99″4 and is a spectroscopic binary with a 3.9 year period (Vogt et al. 2002). The newly found companion makes this system at least quadruple.

3.2. Relative Astrometry and Photometry

Accurate relative positions and intensity ratios were determined by fitting the secondary companion image with the point-spread function (PSF) of the primary. Additional freedom to treat difficult cases (blended or slightly saturated images) was provided by the choice of the inner and outer radii for the fits. Usually the inner radius is zero, the outer one is 6 pixels. Even for saturated images, the fits recover relative coordinates quite well and give underestimated, but still useful, magnitude differences. The results are stable against changes in the fit radius. For close companions, the PSFs overlap, leading to overestimation of the magnitude difference $\Delta m$ and overestimation of the separation $\rho$.

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\(^1\) http://www.astronomy.ohio-state.edu/ANDICAM/detectors.html
Astrometric calibration of two CCD frames (crowded fields around HIP 76572 and 36414) was done by J. Subasavage by referencing them to the PSC. He found a pixel scale of 0.′3715 and angular offset of 1.′5 (to be added to the measured angles). The Ks frames were calibrated by comparing the relative companion positions with the V-band measurements. The nominal pixel scale of 0.′274 was confirmed and −2:3 had to be added to the position angles measured in the IR images. Using these calibration parameters, I found for 22 pairs with ΔV < 4 the average difference (θV − θKs) = 0.02 ± 0.3. The rms scatter between V and Ks positions was 0.′26 in separation and 1.′2 in position angle. These numbers estimate the measurement errors, dominated by systematic effects rather than by random noise.

Figure 3 compares our differential photometry in the Ks band with the PSC photometry for separations ρ > 8′. There are only 12 cases where the two ΔK measures differ by more than 0.′′5; the robust estimate of the rms difference is 0.′′095.

Relative astrometry and photometry of candidate binaries is listed in Table 1. It contains the Hipparcos number and pair identification. Then follow the separation ρ, position angle θ, and magnitude difference ΔKs derived from the PSC, with the PSC quality flag Q for the Ks-band photometry (Cutri et al. 2003). The remaining columns give (ρ, θ, Δm) measured in 2010.14 with ANDICAM in the Ks and V bands. Cases where primary components were saturated are marked by the flag S. For the most part, I use measurements from the short-exposure images.

3.3. New Sub-systems?

Some objects in the ANDICAM images are resolved close pairs. I do not discuss such pairs for optical companions and show in Figure 4 only the three most obvious cases of resolved physical companions. Measurements of the relative positions and magnitude differences in these close pairs are only approximate because the PSFs overlap.

HIP 13544BC is a known pair A 2341, making a triple system together with the main target. ANDICAM resolves BC into nearly equal stars at 1′3, 4′, ΔK ~ 0.6.

HIP 26030A has a faint satellite at 1′6, 91°, ΔK = 2.7. The new companion could be optical because this field is crowded, N* = 57; there are four other stars in the K-band ANDICAM images and many more in the CCD frames. HIP 58240B is in fact a pair Ba,Bb with parameters 3′6, 116°, ΔK = 5.8. Further observations will help to determine the status of this pair in a moderately crowded field with N* = 34.

4. RESULTS

The sample of binary stars is assembled by merging companions found in the PSC with existing data from the WDS in the same part of the sky (R.A. from 2h to 18h, decl. < +20°). The separation of WDS companions considered here is from 5′ to 20′, although closer companions found in the PSC are included in the sample as well. The WDS binaries in crowded fields (N* > 100) are excluded to avoid statistical bias. These selection criteria are satisfied for 1913 primary stars in the Nsample. I ignore 18 WDS companions not detected by the PSC for various reasons (e.g., primary component too bright or partially resolved) and exclude 15 PSC companions which are likely artifacts (not detected in all bands by 2MASS or not confirmed here). There are 221 binary companions or candidates remaining.

All companions are classified into three groups: true (physical), background stars (optical), and uncertain. Three criteria are used.
1. Astrometry, i.e., constancy of the relative companion position over time. For the known pairs, the first-epoch positions are taken from the WDS, the last-epoch from the PSC. The new candidate binaries are checked by comparing the PSC positions with the second-epoch 2010 data. The change of the relative position is compared to the reflected PM of the primary component (Figure 2).

2. Companion location in the \((J_{\text{abs}}, J - K)\) CMD with respect to the MS line (Lang 1992), using the distance modulus based on \(\pi_\text{HIP}\). The photometry comes from the PSC.

3. Companion location in the \((K_{\text{abs}}, V - K)\) CMD. The \(V\) magnitudes are taken from the WDS for known pairs or determined from the \(\Delta V\) measured here for candidate companions detected in the \(V\) band.

If the random and systematic errors of the data used in these criteria were known, the formal probability of passing the tests could be computed. However, such a formal approach makes little sense for various reasons. The astrometric criterion (1) is affected by the orbital motion in the wide binaries, by motions of the components caused by undetected inner sub-systems, and, mostly, by the unknown PMs of the background stars. In many instances, the available astrometry allows a clear distinction between optical and physical companions (Figure 2), but there remain marginal cases, especially for targets with small PM and 10 year time coverage. Similarly, the application of the criteria (2) and (3) is affected by errors in the photometry and by the possibility of physical companions being located off the MS.

I evaluated each of the three criteria subjectively on a continuous scale, assigning negative values for optical companions and positive values for physical ones. Larger absolute numbers mean stronger evidence; zero stands for a complete lack of information. The combination of all three criteria is resumed in the opticity flag \(O\), with \(-2\) and \(-1\) for certain or almost certain optical companions, \(+1\) and \(+2\) for very likely and certain physical companions.

Figure 5 presents the distribution of companions over the three categories (optical, uncertain, physical) and over the data sources (WDS, ANDICAM), indicating partial overlaps between these groups. The sample contains 136 physical companions, 47 of which are new (discovered in the PSC and confirmed with ANDICAM). This work thus increases the number of known physical companions in the \((5^\circ, 20^\circ)\) separation range around nearby G-dwarfs by 55%.

The results are summarized in Table 2, one line per pair. The systems are identified by the HIP numbers of their primary components (the cases where secondaries have distinct HIP numbers are indicated in the notes, Table 3). The \(V\) magnitudes of the primary components are taken from the \(Tycho\) catalog (ESA 1997) and the \(J\) and \(K\) magnitudes from the PSC. For each primary target I list \(\pi_\text{HIP}\) and \(N^*\). For the secondary and tertiary components, the separation \(\rho\) and position angle \(\theta\) based on the PSC are given. The \(V\)-band photometry of the known secondaries comes from the WDS, for some new candidates—from our measurements of \(\Delta V\). The flag \(W = 1\) is set if the companion is known (e.g., found in the WDS), flag \(A = 1\) means that the companion was observed with ANDICAM. The last column contains the opticity flag \(O\). Table 2 also lists masses of the stars estimated from their absolute \(K\) magnitudes by relations of Henry & McCarthy (1993); obviously, for optical companions such estimates are meaningless.

More information (nature of the sub-systems, etc.) is given in the notes (Table 3). In the following, I ignore the sub-systems, considering each component of a wide binary as a single star even when it is known to be a pair. This survey has produced 15 new multiple systems (HIP 11417, 11537, 12764, 25148, 25662, 34212, 36832, 39999, 41871, 47312, 52145, 54366, 56282, 68507, 84866). Spectroscopic companions to primary targets discovered by Nordström et al. (2004) are marked as \(N^*\) in the notes together with the range of radial velocity variation \(\Delta RV\) in \(\text{km s}^{-1}\). Astrometric binaries discovered by Makarov & Kaplan (2005) are reported. About a third of the new wide binaries are actually higher-order multiples; Makarov et al. (2008) encounter a similarly high fraction of multiples, 25%, in their sample of CPM pairs. I give in the notes the PMs (in mas year\(^{-1}\)) and \(V\)-band photometry from the NOMAD catalog (Zacharias et al. 2004a) for companions which are found there. However, the sources and errors of the PMs in NOMAD are not known, and in many instances they contradict my findings (discrepant PMs for physical companions or matching PMs for

Table 1

| HIP | Sys | 2MASS | ANDICAM (K) | ANDICAM (V) |
|-----|-----|-------|-------------|-------------|
|     |     | \(\rho\) | \(\theta\) | \(\Delta K\) | \(Q\) | \(\rho\) | \(\theta\) | \(\Delta K\) | \(S\) | \(\rho\) | \(\theta\) | \(\Delta V\) | \(S\) |
| 9499 | AB | 12.20 | 225.2 | 6.83 | A | 12.59 | 224.9 | 6.77 | 12.63 | 225.7 | 7.48 |
| 10621 | AB | 18.84 | 202.6 | 5.93 | A | 18.39 | 202.2 | 6.09 | 18.43 | 203.0 | 7.64 |
| 11024 | AB | 10.29 | 81.1 | 1.24 | A | 10.34 | 82.2 | 1.21 | 10.05 | 79.6 | 2.52 |
| 11417 | AB | 19.41 | 297.7 | 3.85 | A | 19.82 | 297.6 | 3.80 | 19.48 | 297.2 | 6.81 |
| 11909 | AB | 3.70 | 346.5 | 0.39 | D | 4.14 | 343.3 | 3.15 | 4.15 | 345.2 | 5.36 |
| 12764 | AB | 5.12 | 271.6 | 1.83 | D | 5.77 | 273.4 | 3.85 | 5.15 | 271.6 | 3.85 |
| 13544 | AB | 18.45 | 23.8 | 0.10 | A | 18.05 | 22.3 | 0.35 | 18.29 | 23.6 | 0.83 |

The last column contains the opticity flag \(O\).
Zacharias et al. (2004b) does not extend deep enough (is ignored in deciding the companion status. The UCAC2 catalog
reach the faintest secondaries.

photometry. Most physical companions concentrate around the
standard MS according to Lang (1992) shown.

Figure 6. The V-photometry is affected by small separation, $4''$ here for guidance regarding its form and content.)

There is a CPM companion HIP 10754 at $836$
Astrometric binary in HIPPARCOS (Makarov & Kaplan 2005), possibly a new triple?
SIMBAD: PMS star and X-ray source 1RXS J022843.6

Notes on Individual Targets

HIP 10303 is physical
HIP 10754 at $836$
Astrometric binary in HIPPARCOS (Makarov & Kaplan 2005), possibly a new triple?
SIMBAD: PMS star and X-ray source 1RXS J022843.6–311332

(A table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 2
Photometry and Companion Status

| HIP | $\pi_{HIP}$ (mas) | $N^*$ | $V$ | $J$ | $K_S$ | $M_1$ ($M_\odot$) | $\rho$ ($\arcsec$) | $\theta$ ($\arcsec$) | $V$ | $J$ | $K_S$ | $M_2$ ($M_\odot$) | WA | O |
|-----|------------------|------|-----|----|------|----------------|--------------|--------------|----|----|------|----------------|-----|---|
| 9499 | 15.3             | 11   | 8.07 | 6.94 | 6.58 | 1.15            | B             | 12.20        | 225 | 15.55 | 14.05 | 13.41 | 0.10 | 01 | −2.0 |
| 10175 | 24.4             | 13   | 8.66 | 6.91 | 6.58 | 0.90            | B             | 12.04        | 243 | 9.13  | 7.21  | 6.85  | 0.84 | 10 | 2.0  |
| 10305 | 25.2             | 14   | 5.65 | 5.05 | 4.33 | 1.52            | B             | 16.79        | 233 | 6.69  | 6.54  | 6.17  | 0.97 | 10 | 2.0  |
| 10579 | 17.2             | 6    | 9.24 | 8.31 | 7.97 | 0.77            | B             | 6.70         | 288 | 9.66  | 8.65  | 8.24  | 0.72 | 10 | 2.0  |
| 10621 | 16.9             | 13   | 7.78 | 6.85 | 6.56 | 1.09            | B             | 18.84        | 202 | 15.42 | 13.08 | 12.49 | 0.13 | 01 | −1.0 |
| 10710 | 15.9             | 13   | 8.93 | 7.72 | 7.33 | 0.94            | B             | 14.39        | 312 | 10.47 | 10.22 | 10.22 | 0.00 | 00 | 0.0  |
| 11024 | 24.4             | 10   | 7.87 | 6.72 | 6.36 | 0.95            | B             | 10.29        | 81  | 10.39 | 8.31  | 7.61  | 0.70 | 11 | 2.0  |
| 11324 | 19.0             | 6    | 9.26 | 8.15 | 7.88 | 0.75            | B             | 15.33        | 165 | 9.37  | 8.39  | 8.12  | 0.71 | 10 | 2.0  |
| 11417 | 17.9             | 7    | 8.43 | 7.10 | 6.66 | 1.04            | B             | 19.41        | 297 | 15.24 | 11.35 | 10.51 | 0.31 | 01 | 2.0  |
| 11537 | 16.7             | 8    | 9.25 | 7.71 | 7.15 | 0.95            | B             | 3.70         | 346 | 14.61 | 8.07  | 7.54  | 0.87 | 01 | 1.0  |

(A table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 3
Notes on Individual Targets

| HIP | Text |
|-----|------|
| 9499 | A is SB, no orbit. N04: $\Delta RV = 70.7$. The B-companion is optical |
| 10305 | A is SB2, period 94.786d. resolved by speckle (TOK 39). A is evolved. B = HIP 10303 is physical |
| 10621 | NOMAD: PM(B) = (0, −30), PM(A) = (18, 60). AB is optical. BC is a binary at $25', 180, 0, \Delta K = 0.47, \Delta V = 0.89$ |
| 10710 | There is a CPM companion HIP 10754 at $836''$ |
| 11024 | No data. The PSC companion at $14''$ is likely physical based on the CMD and $N^* = 13$ |
| 11324 | B = HIP 11323, physical. Both components are below the MS, the true parallax should be 12.6 mas (as for the B-component in Hipparcos) |
| 11417 | SB, no orbit (N04). NOMAD: PM(B) = (−12, −68), V = 14.73. B is physical. PM(A) = (−22, −76). A new triple system |
| 11537 | The V-photometry is affected by small separation, $4''$. B is a new physical companion. Red in the $V − K$ color, variable? Astrometric binary in HIPPARCOS (Makarov & Kaplan 2005), possibly a new triple? SIMBAD: PMS star and X-ray source 1RXS J022843.6–311332 |

(A table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 6. ($J_{abs}, J − K$) CMD of the secondary companions with $\rho > 5''$. The standard MS according to Lang (1992) is shown.

The spread of the points is large and there are several true companions below the MS, some of those quite bright. These outliers mostly have large photometric errors in the PSC. However, there is a real $\sim 0.2''$ spread in the $J − K$ colors of physical companions, as follows, e.g., from the work of Henry & McCarthy (1993). Most optical and uncertain companions are located below the MS. The companion selection criterion (I) leaves a convenient margin, admitting many optical candidates but not rejecting physical companions with deviant colors.

The ($K_{abs}, V − K$) CMD is plotted in Figure 7. The $V − K$ color has a larger sensitivity to effective temperature, compared to $J − K$, and therefore discriminates better between physical and optical companions. The number of physical outliers is correspondingly less. However, faint and red low-mass companion candidates were not detected in the $V$ band with ANDICAM, leaving the lower right corner of the CMD empty. A few physical companions below the MS are explained by largely underestimated $\Delta V$ in ANDICAM images with saturated primary stars (the companions then appear bluer).

5. STATISTICAL ANALYSIS

5.1. Detection Limit in the PSC

Detection of faint sources in the PSC is complicated by the presence of nearby bright stars (primary targets). It is important to estimate this bias. Some sources are detected only in the
bands bias, I select companions with valid PSC photometry in all three genuine physical companions. To evaluate the PSC detection removed from the candidate list, and some turn out to be $K$ band; most of them are artifacts. They are, however, not pessimistic detection thresholds, respectively.

Figure 8. Magnitude difference $\Delta K$ vs. separation for 982 PSC companions with valid photometry. The dashed and solid lines indicate the realistic and pessimistic detection thresholds, respectively.

$K$ band; most of them are artifacts. They are, however, not removed from the candidate list, and some turn out to be genuine physical companions. To evaluate the PSC detection bias, I select companions with valid PSC photometry in all three bands $JHK$, within 20″ from the targets and plot the magnitude difference with primary components $\Delta K$ versus separation $\rho$ in Figure 8. The dashed line approximates the upper envelope by two segments.

A primary target of 1 $M_\odot$ has $K_{\text{abs}} \approx 3.1$, so the restriction on the absolute magnitude $J_{\text{abs}} < 11$ imposed on the candidates translates into $\Delta K < 7$. The actual physical companions obey this restriction and delineate a more pessimistic threshold

$$\Delta K_{\text{lim}} = A \log_{10}(\rho/3'')$$

with $A = 10$ (solid line in Figure 8). Statistical interpretation of the data depends on the adopted detection limit.

5.2. Distribution of the Mass Ratio

The statistical analysis is performed on 120 physical binaries with $\rho \geq 5''$ selected by the criterion $O \geq 1$ (Table 2). Masses of the primary and secondary components, $M_1$ and $M_2$, are estimated from their absolute magnitudes $K_{\text{abs}}$ using the relation from Henry & McCarthy (1993). For 3893 targets of $N_{\text{sample}}$ common with the survey of Nordström et al. (2004) I find a good agreement with their mass estimates, to better than ±10%. For the binaries studied here, $M_1$ ranges from 0.68 to 1.52 $M_\odot$, and the median $M_1$ is 1.03 $M_\odot$.

Figure 9 plots the mass ratio $q = M_2/M_1$ versus separation $\rho$. The estimated PSC detection limit in $\Delta K$ is translated into $q$ assuming $M_1 = 1 M_\odot$. At first sight, the points are distributed uniformly in $q$ in the space above the detection limit. There appears to be a slight preference for small $q$ at $\rho > 12''$ and a tendency to large $q$ at smaller separations. The actual detection limit of the PSC remains somewhat uncertain, affecting the statistical analysis. I tried several assumptions. The results reported below correspond to the hard detection limit $A = 10$, supposing that all fainter companions are missed in the PSC; all brighter ones are detected.

Considering that the companion detection “depth” is a strong function of $\rho$, I study the mass ratio distribution $f(q)$ for pairs with $\rho \geq \rho_{\text{min}}$, for different cutoffs $\rho_{\text{min}}$. The assumption is made that separations are distributed according to Opik’s law (constant in log $\rho$), well established for separations around $10^3$ AU (Poveda & Allen 2004). The companion frequency $\epsilon$ is normalized per decade of separation, i.e., divided by $\log(20''/\rho_{\text{min}})$, and referred to the total number of $N_{\text{sample}}$ targets in the surveyed portion of the sky, $N = 1913$.

A power-law model of mass-ratio distribution

$$f(q) = \epsilon(\beta + 1)q^\beta$$

is frequently used in the literature (e.g., Metchev & Hillenbrand 2009). Here $\epsilon$ is the total companion fraction and $\beta$ is the power index (slope). These two parameters are related because correction for the missed low-mass companions depends on $\beta$.

A histogram of the mass ratios is shown in Figure 10. The number of companions in each bin is increased to account for incomplete detections (divided by the average detection probability in each $q$-bin in the separation interval $\rho_{\text{min}}, 20''$) and normalized per decade of separation. The first bin with large incompleteness is avoided; the remaining data are fitted by a line in the log–log coordinates (a power law) with $\beta = -0.15$ and $\epsilon = 0.13$. The power-law distribution describes the observed histogram adequately.
Alternatively, the model (3) can be fitted to the data directly by the maximum likelihood (ML) method, as done, e.g., in Tokovinin et al. (2010). The detection limit is included in the analysis. The likelihood function is usually interpreted as a probability distribution in the parameter space, enabling the definition of the confidence area and a better visualization of the mutual dependence between parameters (Press et al. 1992). On the other hand, the ML method requires a parameterization, in this case (3).

The results of the ML analysis depend on the assumed companion detection limit and on the separation cutoff $\rho_{\text{min}}$. By adopting a more strict (pessimistic) detection limit, I obtain smaller values of $\beta$ and less dependence of $f(q)$ on $\rho_{\text{min}}$. The derived companion fraction $\epsilon$ remains nearly constant. It is expected that $f(q)$ should not depend on $\rho$ in the relatively small interval considered here (e.g., Raghavan et al. 2010). After trying several detection limit models, I finally use a sharp threshold with $\rho_{\text{min}} = 8''$ and $A = 10$. Note that the ML results will be somewhat different for other detection models.

Figure 11 shows a representative result of the ML procedure for $\rho_{\text{min}} = 8''$ (83 companions). The best-fit parameters are $\epsilon = 0.13$ and $\beta = -0.10$; the lines show the confidence areas in the parameter space corresponding to 68% (“one sigma”) and 90%. The confidence area is skewed, therefore I obtained the standard errors of parameter estimates by integrating the probability distribution over other coordinate. Figure 12 shows the dependence of the best-fit parameters and their formal $\pm \sigma$ errors on $\rho_{\text{min}}$. The companion fraction $\epsilon$ is rather stable against $\rho_{\text{min}}$, ranging between 0.15 and 0.13, but the power-law index $\beta$ becomes more negative at larger separations, in agreement with the trend noticeable in Figure 9.

### 5.3. Alternative Analysis

Considering the uncertainty of the PSC detection limit for faint and close companions, I carry out an alternative analysis on wider companions between 10'' and 30''. This time, the PSC data over the whole sky are used. Only candidates with $J_{\text{abs}} < 11$ (bright enough to be stellar companions) and reliable PSC photometry (quality flags A–D or E in JHK$_s$ bands) are retained. Scaling the total number of such candidates within 2.5 radius to the 10''–30'' annulus, I expect to find 2502 and actually find 2115. There is still a small deficiency of candidates indicative of a potential detection bias. If all companions without constraints on $J_{\text{abs}}$ are selected, the expected number is twice the actual number (10177 and 5299, respectively). Therefore, the PSC magnitude limit in the vicinity of bright stars is indeed not as deep as in the field, even at 10'' separation.

Physical companions can be distinguished from the optical ones statistically, if not individually. To ease this task, I restrict the study to 4473 primaries where the number of stars with $J_{\text{abs}} < 11$ within 2.5 radius is less than 100. The CMD of the 1470 companions in the (10'', 30'') separation range is shown in Figure 13. Bright companions clearly concentrate toward the MS, merging progressively with background stars at fainter magnitudes. The separation distributions of bright and faint companions are different, the former following Opik’s law $f(\rho) \propto 1/\rho$ and the latter being proportional to $\rho^2$.

Cumulative distributions of the $J-K$ color in four intervals of $J_{\text{abs}}$ are plotted in Figure 14. The vertical lines show the color range for the physical companions $0.75 < J-K < 0.9$ (P) and the comparison range $0.45 < J-K < 0.75$ (O) where only optical companions are expected. These intervals correspond to the boxes in Figure 13. Obviously, most companions with $6 < J_{\text{abs}} < 7$ are physical, but the companion density in the ranges P and O becomes more similar and eventually equal with increasing $J_{\text{abs}}$. This gives a way to estimate the number of
physical companions \( n_e \) in each interval of \( J_{abs} \) as

\[
n_e = n_p - 0.5n_o = \alpha n_p, \quad \alpha = 1 - n_o/(2n_p).
\]

This formula assumes that optical companions are uniformly distributed in \( J - K \), that physical companions are concentrated in the \( P \)-interval, and that the \( O \)-interval is twice as large. The contamination factor \( \alpha \) decreases from one to nearly zero with increasing \( J_{abs} \). The rms error of \( n_e \) estimate is, obviously, \( (n_p + n_o/4)^{1/2} \). Table 4 lists the companion counts.

The fraction \( \alpha \) of companions in the \( P \)-interval and above the tilted line in Figure 13 are physical. Masses of the primary stars and companion candidates are estimated from their \( K_{abs} \) magnitudes using the relation from Henry & McCarthy (1993), the mass ratios \( q \) are calculated, and the distribution of \( q \) in 0.1 wide bins is constructed, applying the factors \( \alpha \) to correct for contamination. These factors are modeled after data in Table 4 as \( \alpha(q) \approx 1 - 1.5(1 - q)^2 \); they become significant for \( q < 0.5 \); otherwise they are close to 1. The last column of Table 4 gives approximate mass ratios \( q_0 \) corresponding to the centers of the \( J_{abs} \) intervals for \( M_1 = 1 M_\odot \).

Figure 15 shows the resulting histogram. The first bin is avoided because it has a large error and a large \( \alpha \)-correction. The values of \( f(q) \) are normalized per decade of separation, assuming Opik’s law. The dotted line shows a linear fit in the log–log coordinates, i.e., a power law. The exponent is \( \beta = 0.19 \). The sum of \( f(q) dq \) over all bins except the first one leads to \( \epsilon = 0.10 \).

In comparison with the histogram in Figure 10, Figure 15 shows a smaller fraction of low-mass companions, presumably because I do not correct here for incomplete detection. This also explains why the estimated companion fraction \( \epsilon \) is slightly less than in Section 5.2. However, the companions considered here are wider, hence less affected by the bright glow of the primary targets. The \( f(q) \) distributions obtained by two different approaches on different (although overlapping) samples of companions are close to each other, except for the first bins at \( q < 0.3 \). Therefore, the previously adopted detection threshold seems to be a reasonable choice. Despite the remaining uncertainties, it is clear that \( f(q) \) is nearly uniform and does not rise dramatically at \( q < 0.3 \).

An interesting conclusion from this study is that the PSC companions within 30" from the targets with \( J_{abs} < 7 \) and suitable \( J - K \) colors are physical with a probability of \( \geq 84\% \). Many of those companions not listed in the WDS are strong candidates for having their status checked with second-epoch imagery. This will lead to the census of visual companions around \( N_{sample} \) G-dwarfs being complete down to \( q \sim 0.2 \).

\section{6. DISCUSSION}

The sample of low-mass visual companions assembled in Section 4 can still be biased. On the one hand, some known pairs with large \( q \) are excluded because they do not appear in the PSC. On the other hand, some low-mass companions are missed because their physical status could not yet be confirmed. The total number of missed companions in each of these two groups is \( \sim 10\% \) of the total number of binaries. Their inclusion would slightly increase the estimated companion fraction \( \epsilon \) and would affect \( f(q) \), although not dramatically. The largest

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\( J_{abs} \) & \( n_p \) & \( n_o \) & \( n_e \) & \( \alpha \) & \( q_0 \) & \\
\hline
6–7 & 61 & 20 & 51 & 0.84 & 0.51 & \\
7–8 & 45 & 27 & 31 & 0.70 & 0.34 & \\
8–9 & 41 & 51 & 15 & 0.38 & 0.19 & \\
9–10 & 39 & 107 & 5 & 0.99 & 0.12 & \\
\hline
\end{tabular}
\caption{Companion Count}
\end{table}
uncertainty of the derived \( f(q) \) is related to the adopted model of the companion detection limit in the PSC.

I intentionally ignored inner sub-systems. The masses are estimated from the total light in the \( K \) band. For unresolved sub-systems, these estimates are closer to the mass of their primary components than to the total mass. As the knowledge of sub-systems is currently very incomplete (especially for the secondary companions), correction for them could only be partial. The \( f(q) \) derived here remains a preliminary estimate until a multiplicity survey of the sample is carried out to enable a reasonably comprehensive account of the inner sub-systems.

The distribution of the mass ratio \( q \) of wide companions to solar-type dwarfs is found here to be nearly uniform. These binaries have typical projected separations of \( 10^3 \) AU and orbital periods on the order of \( 10^7 \) days. Metchev & Hillenbrand (2009) find a similar mass-ratio distribution with \( \beta = -0.39 \pm 0.36 \) in a sample of 30 closer companions to solar-type stars surveyed with adaptive optics. A mass-ratio distribution with \( \beta \sim -0.5 \) was derived by Shatsky & Tokovinin (2002) for visual companions to B-type stars in the Sco OB2 association, while Kraus et al. (2008) found a nearly flat \( f(q) \) for low-mass visual binaries in this association. In any case, the conclusion of Duquennoy & Mayor (1991), that masses of wide companions to G-dwarfs match random selection from the initial mass function, is now firmly refuted.

The possible dependence of \( f(q) \) on the orbital period remains a debatable subject. Duquennoy & Mayor (1991) found no convincing evidence of any such dependence in their 22 pc sample of 164 G-dwarfs. However, a modern study by Raghavan et al. (2010) of the 25 pc sample containing 454 dwarf stars does show a clear trend to smaller \( q \) in wide binaries, while short-period pairs prefer equal-mass components (see their Figure 17). They find that the mass-ratio distribution integrated over all periods is remarkably flat and declines at \( q < 0.1 \). It seems well established that for spectroscopic binaries with orbital periods below \( 10^7 \) d the \( f(q) \) is nearly flat (Mazeh et al. 2003; Halbwachs et al. 2003). The mass-ratio distribution in the inner sub-systems of multiple stars with solar-type primaries also appears to be flat, to the best of our knowledge (Tokovinin et al. 2010).

The frequency of companions to solar-type stars with orbital periods on the order of \( 10^7 \) days is around 0.08 per decade of period, or 0.12 per decade of separation according to both Duquennoy & Mayor (1991) and Raghavan et al. (2010). The companion frequency estimate obtained here, 0.13 \( \pm 0.015 \), is essentially the same, but more accurate statistically, owing to the larger number of binaries.

This work shows the great potential of the 2MASS PSC for discovering new low-mass companions. Further observations are needed to confirm candidate companions at larger separations and in other, as yet unsurveyed, parts of the sky in order to reach a complete census of wide binaries in the \( N_{\text{sample}} \).

The combination of this information with spectroscopic and adaptive-optics surveys of the same sample will provide a unique possibility to obtain comprehensive statistics of binary and multiple systems with unprecedented accuracy and detail. This, in turn, will advance our understanding of star formation and our origins.

I thank SMARTS observers J. Vasquez, A. Miranda, and J. Espinosa for making observations and SMARTS data archive at Yale managed by S. W. Toutelotte for pre-processing and delivering the images. The help of J. Subasavage with astrometric calibration is much appreciated. This work used the 2MASS data products, WDS catalog, ADS services, and SIMBAD.

**Facility:** SMARTS

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