

WIDE COMPANIONS TO HIPPARCOS STARS WITHIN 67 PC OF THE SUN

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ABSTRACT

A catalog of common-proper-motion (CPM) companions to stars within 67 pc of the Sun is constructed based on the SUPERBLINK proper-motion survey. It contains 1392 CPM pairs with angular separations $30'' < \rho < 1800''$, relative proper motion between the two components less than 25 mas yr^{-1} , magnitudes and colors of the secondaries consistent with those of dwarfs in the $(M_V, V - J)$ diagram. In addition, we list 21 candidate white-dwarf CPM companions with separations under $300''$, about half of which should be physical. We estimate a 0.31 fraction of pairs with red-dwarf companions to be physical systems (about 425 objects), while the rest (mostly wide pairs) are chance alignments. For each candidate companion, the probability of a physical association is evaluated. The distribution of projected separations s of the physical pairs between 2 kAU and 64 kAU follows $f(s) \propto s^{-1.5}$, which decreases faster than Öpik's law. We find that Solar-mass dwarfs have no less than $4.4 \pm 0.3\%$ companions with separations larger than 2 kAU, or $3.8 \pm 0.3\%$ per decade of orbital separation in the 2 to 16 kAU range. The distribution of mass ratio of those wide companions is approximately uniform in the $0.1 < q < 1.0$ range, although we observe a dip at $q \simeq 0.5$ which, if confirmed, could be evidence of bimodal distribution of companion masses. New physical CPM companions to two exoplanet host stars are discovered.

Subject headings: stars: binaries

1. INTRODUCTION

Very wide binaries play a special role in astrophysics. Low binding energies make them sensitive probes of Galactic dynamical environment. The very existence of wide binaries can constrain properties of the dark matter (e.g. Weinberg, Shapiro & Wassermann 1987; Yoo, Chanamé, & Gould 2004). The typical size of proto-stellar cores ($\sim 0.1 \text{ pc}$) is comparable to the separation of the widest binaries that survive against gravitational perturbations in the Galaxy. Most stars form in clusters, in which wide (and even relatively closer) binaries are susceptible to disruption; the surviving wide pairs provide constraints on the dynamical environments and processes at the epoch of star formation (Parker et al. 2009). At larger scales of $\sim 1 \text{ pc}$ we also encounter co-moving remnants of nearby clusters and associations (e.g. Zuckerman et al. 2001, 2004). These groups of stars, related by common origin, cannot be classified as physical systems (binaries) because as far as we know, they do not move on stable orbits around each other. The transition between *binaries* and *co-moving stars* is still an unsettled issue. Shaya & Olling (2011) found pairs with projected separations of few pc in the *Hipparcos* catalog, many of which belong to known moving groups. Caballero (2010) argues that one multiple system with 1-pc separation (member of the Castor moving group) could be “hard” enough to remain bound.

Yet another use of wide binaries is in the calibration of luminosities and abundances in the low-mass regime, referencing to their hotter well-studied primary compo-

nents. Parallaxes of the bright primaries from, e.g., the *Hipparcos* catalog can be assigned to the secondaries and provide accurate luminosity measurements (Gould & Chanamé 2004). A well-characterized primary is particularly useful to calibrate the fundamental parameters of M dwarfs, whose complicated spectra dominated by molecular absorption bands still resist detailed atmospheric modeling. The metallicity scale of M dwarfs remains largely dependent on metallicity measurements of FGK primaries in common proper motion (CPM) pairs (Rojas-Ayala et al. 2012). It is thus important to assemble catalogs of common proper motion pairs where the primaries are well-characterised *Hipparcos* FGK dwarfs, and the secondaries are M dwarfs spanning a broad range of colors and luminosities.

The main motivation of this study is to provide a reasonably complete census of very wide companions to nearby Solar-type stars. Combined with information on closer pairs also available for this sample, it will lead to the un-biased multiplicity statistics much needed as a benchmark for star-formation theories (Bate 2009). The recent study by Raghavan et al. (2010) furnished such statistics for 454 stars within 25 pc from the Sun, but a much larger sample is needed to study triple and higher-order hierarchies because they comprise only $\sim 10\%$ of all objects. Most solar-type exo-planet hosts are also beyond the 25 pc horizon of previous multiplicity surveys. It is important to search for and identify wide companions to known exoplanet hosts, and companions to other nearby stars which are still being observed in search of exo-planets, in order to characterize planet populations in binary systems (Roell et al. 2012).

Primary targets for our search for CPM companions are all stars with parallax $\pi_{\text{HIP}} > 15 \text{ mas}$ selected from the *Hipparcos-2* catalog (van Leeuwen 2007, hereafter HIP2). The *Hipparcos* catalog is complete to 67 pc for dwarfs of mid-G spectral type or brighter, thus providing

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a clean distance-limited sample for multiplicity statistics. At the same time, these nearby stars move fast enough to discriminate CPM companions against background stars and are close enough to detect intrinsically faint companions. Little is to be gained by extending the distance limit further.

Existing data on CPM binaries is in large part based on the Luyten visual searches for CPM binaries with $\mu > 0.1'' \text{ yr}^{-1}$ (LDS, Luyten 1987). A recent study has repeated the visual search, by blinking the Digitized Sky Survey fields around exo-planet host stars (Raghavan et al. 2006) and stars within 25 pc (Raghavan et al. 2010). A more systematic search for companions to *Hipparcos* stars was conducted by Lépine & Bongiorno (2007, hereafter LB2007), who used the LSPM-north catalog of stars with proper motions $\mu > 0.15'' \text{ yr}^{-1}$ (Lépine & Shara 2005); the paper also gives a good overview of prior work. Detecting CPM binaries in large databases was also demonstrated by Chanamé & Gould (2005), Makarov, Zacharias, & Hennessy (2008), and Dhital et al. (2010), for systems with fainter primaries.

In this paper, we expand on the search performed by LB2007, and use the full SUPERBLINK all-sky proper motion catalog, which is an extension of the published LSPM-north catalog. The method for selecting CPM companion candidates is presented in Section 2. Statistics of all companions are discussed in Section 4. Then we concentrate in Section 5 on the statistics of wide physical binaries, namely the distributions of projected separations and mass ratios. Our conclusions and discussion of results are presented in Section 6.

2. IDENTIFICATION OF COMMON PROPER MOTION COMPANIONS

2.1. *SUPERBLINK* selection

The SUPERBLINK survey is based on an automated search for moving sources from multi-epoch images of the Digitized Sky Survey (DSS), notably scans from the first and second epoch Palomar Sky Surveys (POSS-I, POSS-II). Compared to LSPM-north, the detection threshold in the full SUPERBLINK catalog is significantly lower, $\mu > 40 \text{ mas yr}^{-1}$ for stars north of declination -20° , and extends the survey to a proper motion limit $\mu > 150 \text{ mas yr}^{-1}$ for all declinations south of -20° . The survey is still in progress; more information can be found in the recent paper by Lépine & Gaidos (2011). SUPERBLINK is at least 90% complete down to visual magnitude $V = 19$, and has a very low level of false detections ($< 0.1\%$) thanks to stringent quality controls including visual confirmation of all targets. The V magnitudes of faint stars are estimated from the DSS photographic photometry reported in Monet et al. (2003), using the procedure described in Lépine & Shara (2005).

We select as possible primaries of CPM pairs all stars from HIP2 with parallax greater than 15 mas and proper motion larger than the SUPERBLINK limit ($\mu > 40 \text{ mas yr}^{-1}$ for stars north of declination -20° and $\mu > 150 \text{ mas yr}^{-1}$ otherwise). Potential CPM companions to these stars were selected from SUPERBLINK by the following three criteria.

1. Separation of the companion ρ should be in the interval $30'' \leq \rho \leq 1800''$. Closer companions are affected by the oreols of primary stars in DSS photo-

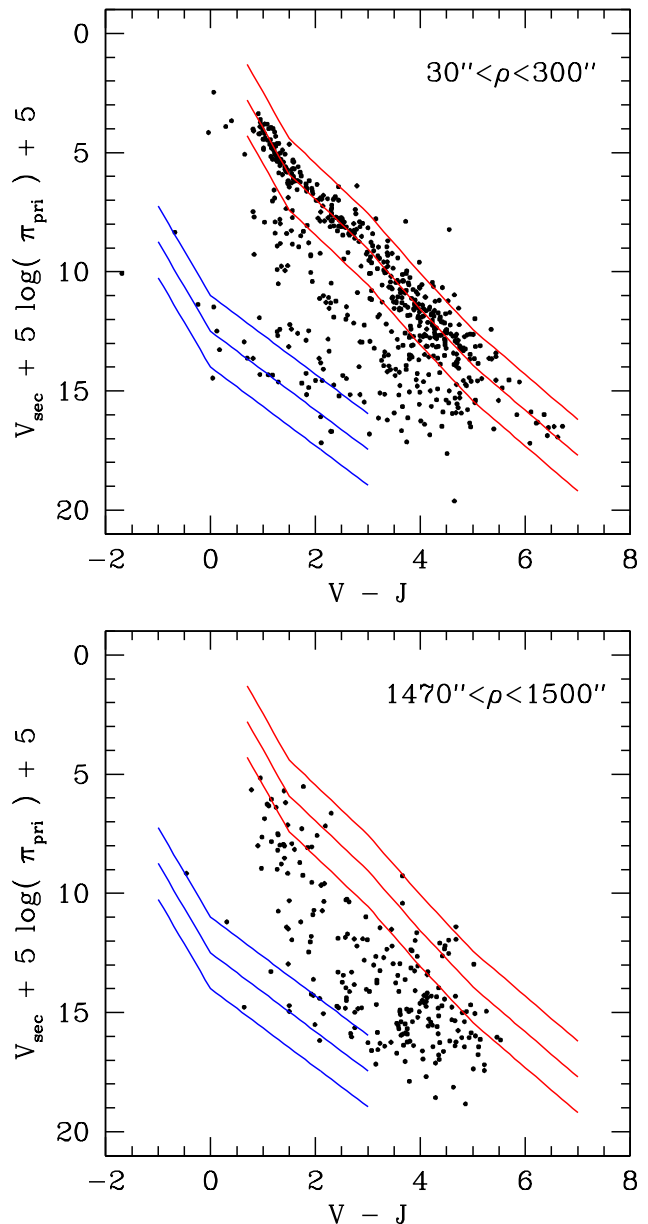


FIG. 1.— Color magnitude diagram of the common proper motion secondaries, assuming they have the same parallax as the (*Hipparcos*) primaries. Physical companions are expected to fall either close to the main sequence (red) or the white dwarf sequence (blue); a scatter of $\pm 1.5 \text{ mag}$ is adopted for the selection (shown). Stars falling outside the bounds are assumed to be chance alignments of unrelated stars. Top: diagram for the 608 pairs with separations $30'' < \rho < 300''$. Bottom: diagram for the 240 pairs with separations $1470'' < \rho < 1500''$, which cover a similar search area. Pairs in the first sample are more numerous and tend to concentrate within the expected main sequence and white dwarf sequence, suggesting that the ≈ 400 extra pairs in the first distribution are physically related.

graphic images, introducing selection against faint companions. Most pairs wider than $300''$ (projected separation 20 kAU at 67 pc) are chance alignments (optical), but including them in the catalog helps us to evaluate the proportion of true (physical) wide binaries.

2. Proper motion difference with the primary compo-

ment $\Delta\mu$ should be less than 25 mas yr^{-1} . Typical proper motion errors in SUPERBLINK are 8 mas yr^{-1} , so this cutoff allows for larger errors or some additional proper motion difference caused by motion in hierarchical sub-systems.

3. Color and magnitude of the secondary should be consistent with a main sequence star or a white dwarf at the same distance as the primary. This criterion effectively requires that the photometric distance of the secondary as estimated from $(V, V-J)$ be consistent with the parallax distance of the alleged *Hipparcos* primary.

The first two criteria identify 130 882 possible pairings, the vast majority of which are simple chance alignments. For the third criterion, we first calculate the absolute magnitudes of the CPM companions ($[M_V]_{\text{SEC}}$) assuming that the secondary is at the same distance as the *Hipparcos* primary:

$$[M_V]_{\text{SEC}} = V_{\text{SEC}} + 5 \log(\pi_{\text{PRI}}) + 5, \quad (1)$$

where π_{PRI} is the *Hipparcos* parallax of the primary. We then use the $(M_V, V-J)$ color magnitude relationship as calibrated in (Lépine 2005) for main sequence (MS) stars in the SUPERBLINK survey. These define photometric absolute magnitudes $[M_V]_{\text{MS}}$ estimated from $V-J$:

$$\begin{aligned} [M_V]_{\text{MS}} &= 0.08 + 3.89(V-J) & [V-J < 1.5] \\ [M_V]_{\text{MS}} &= 2.78 + 2.09(V-J) & [1.5 < V-J < 3.0] \\ [M_V]_{\text{MS}} &= 1.49 + 2.52(V-J) & [3.0 < V-J < 4.0] \\ [M_V]_{\text{MS}} &= 2.17 + 2.35(V-J) & [4.0 < V-J < 5.0] \\ [M_V]_{\text{MS}} &= 4.47 + 1.89(V-J) & [5.0 < V-J < 9.0]. \end{aligned} \quad (2)$$

In addition, we introduce the following simple color-magnitude relationship which we use to define absolute magnitudes for white dwarfs (WD) based on $V-J$:

$$\begin{aligned} [M_V]_{\text{WD}} &= 12.5 + 3.75(V-J) & [-1 < V-J < 0] \\ [M_V]_{\text{WD}} &= 12.5 + 1.89(V-J) & [0 < V-J < 3]. \end{aligned} \quad (3)$$

We then select only pairs whose $[M_V]_{\text{SEC}}$ agree to within 1.5 magnitudes of either photometrically estimated absolute magnitudes $[M_V]_{\text{MS}}$ or $[M_V]_{\text{WD}}$. For 124 companions without 2MASS photometry the $V-J$ color is estimated from the (b, r, i) photographic magnitudes as described by Lépine & Shara (2005).

The color-magnitude selection is illustrated in Figure 1. The top panel shows $[M_V]_{\text{SEC}}$ as a function of $V-J$ for all 608 pairs with angular separations $30'' < \rho < 300''$, with the selection range for MS stars in red, and the selection range for WDs shown in blue. The bottom panel in Figure 1 shows the same distribution but for 240 pairs with angular separations in the $1470'' < \rho < 1500''$ range. Note that the two ranges cover the same area on the sky, so if all CPM pairs were the result of chance alignments, one would expect the two samples to have similar numbers. Instead we find an excess of 368 pairs at closer separations. In addition, the color-magnitude distribution is very different in the two samples. Most pairs with $1470'' < \rho < 1500''$ fall outside of the MS or WD bands, while the majority of the close pairs have colors consistent with true companions. This demonstrates

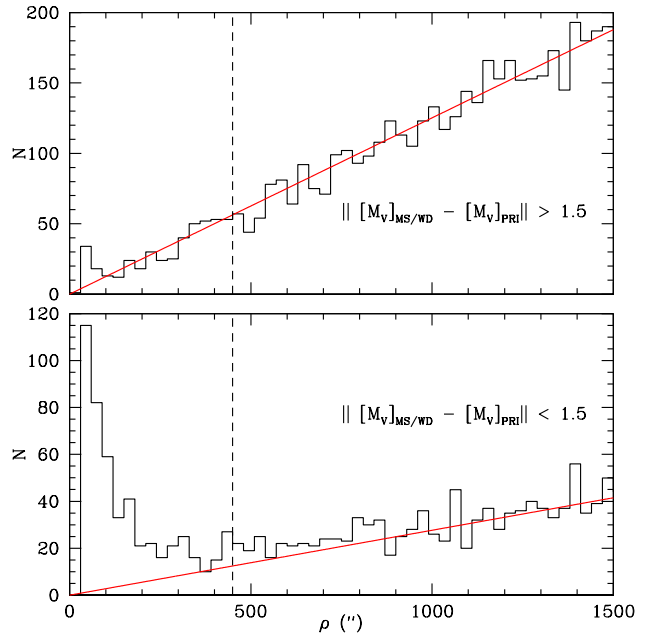


FIG. 2.— Histogram of the number of pairs found as a function of angular separation ρ . Top: distribution for pairs assumed to be chance alignments, based on the inconsistency in the parallax of the primary and photometry of the secondary, i.e. stars falling outside of the MS or WD sequences (see Fig. 1). Bottom: distribution for pairs in which the secondary would have $(V, V-J)$ consistent with a main sequence star or white dwarf. In either case, the red line shows the distribution expected from chance alignments (linear increase with ρ). Pairs in which the color/magnitude of the secondary is consistent with a physical companion show a net excess at $\rho < 200''$.

that ~ 400 CPM pairs in our catalog are physical, binary/multiple systems.

The color-magnitude selection reduces the catalog to only 2078 pairs with consistent colors. A histogram of the number of pairs as a function of their angular separation ρ is shown in Figure 2. The distribution for pairs with consistent parallax/photometric distances (bottom panel) is compared to the distribution of pairs where the primary and secondary do not have colors consistent with physical association (top panel). The latter distribution shows the trend expected from chance alignments, i.e. a linear increase with ρ proportional to the increase in the area of sky; this is modeled by the red line. The distribution of stars with consistent MS or WD color-magnitude, however, shows a marked excess of pairs with $\rho < 200''$, which again points to the existence of physical pairs. At larger angular separations $\rho > 450''$, the distribution shows the linear increase expected from chance alignments; the red line shows the predicted trend based on the number of pairs with $\rho > 1000''$. One notices that while a significant number of physical pairs are undoubtedly detected at $\rho < 450''$, this sub-sample still suffers from contamination from chance alignments.

We note that some companions share common proper motion with more than one *Hipparcos* star. Likewise some *Hipparcos* stars have several CPM companions. Some are genuine multiple systems (triples), but in most cases they are more likely to be the result of chance alignments, e.g. the alignment of a foreground/background proper motion star with a true physical pair. In any case, all possible pairings are retained in our list.

2.2. Treatment of the White Dwarf CPM Companions

Magnitudes and colors of 386 companions place them in the WD band in Figure 1. They are found in smaller numbers than MS candidates, and are significantly more affected by contamination. Indeed, only 21 pairs have $\rho < 300''$, and some of those are expected to be chance alignments. We evaluated the number of physical WD companions within some separation ρ by their excess over the linear distribution, as in Figure 2, and found that the number of likely physical pairs with WD companions does not increase beyond $\rho > 200''$, reaching an excess of around 10 pairs.

Since the vast majority of the stars falling in the WD region are thus chance alignments, we removed from the catalog all companions in the WD band with $\rho > 300''$, keeping only the 21 most likely pairs.

2.3. Exclusion of nearby cluster stars

The selection of CPM pairs is sensitive to faint members of the Hyades and Pleiades clusters, whose members have proper motions within the $\mu > 40 \text{ mas yr}^{-1}$ limit of the SUPERBLINK catalog, and are thus generally detected. Some nearby young associations and moving groups also have members detected in SUPERBLINK (Schlieder et al. 2012). Faint cluster stars share a proper motion with the brighter members, which are also *Hipparcos* sources. Cluster stars have photometric distances consistent with the parallax of the brighter members, so they will generally meet our selection criteria for CPM pairs with colors and magnitudes consistent with physical companions.

We wish, however, to exclude those pairings because they are not physical binaries. We thus eliminate 311 pairs where the primary stars are known members of clusters and associations according to the XHIP catalog (Anderson & Francis 2012). Of those, 230 belong to the Hyades. This leaves 1392 CPM companions with MS colors and 21 companions with WD colors in the catalog.

2.4. Multiple stars

In the catalog compilation and analysis presented below we assume implicitly that both the primary and wide secondary companion are themselves single stars, i.e. there are no unresolved companions. In reality a substantial but still poorly known fraction of the components in wide systems are themselves close binaries (e.g. Makarov, Zacharias, & Hennessy 2008). Internal orbital motion can contribute additional components to the proper motions and increase $\Delta\mu$ with the primary. Analysis of astrometric binaries among FG dwarfs within 67 pc listed by Makarov & Kaplan (2005) shows that for 86% of them the difference between long-term and *Hipparcos* proper motion is less than 25 mas yr^{-1} . Therefore, our catalog may be slightly biased against triple systems.

To verify this, we simulated a realistic population of sub-systems around primary targets with periods from 1 yr to 1000 yr susceptible to create $\Delta\mu$ by photo-center motion during the 3.2-yr long *Hipparcos* mission. Maximum effect is produced at periods from 4 yr to 40 yr, but the mean and median $\Delta\mu$ do not exceed 6 mas yr^{-1} at 50 pc distance; in 90% of cases $\Delta\mu < 12 \text{ mas yr}^{-1}$ for all periods. According to these simulations, the fraction of multiple systems rejected by the $\Delta\mu < 25 \text{ mas yr}^{-1}$

threshold should be significantly smaller than the 14% implied by the paper of Makarov & Kaplan (2005). The discrepancy is alleviated by including in the simulation some massive companions that are close binaries and cause larger $\Delta\mu$ (Tokovinin et al. 2012).

Multiple systems can also be missed because of inaccurate or distorted photometry. Visual magnitudes in the SUPERBLINK catalog are largely based on photographic measurements, and sometimes have large errors, especially if the star is blended with another source, such as in the vicinity of a very bright primary or in a dense field. The composite magnitudes of unresolved sub-systems also bias photometric distance estimates which might yield to rejection based on color and magnitude – although the 1.5 magnitude selection range (see Section 2.1) mitigates this effect. In any case, this may be another non-negligible, but poorly quantified, incompleteness factor for hierarchical systems with CPM companions.

3. CATALOG DESCRIPTION

The complete catalog of 1413 CPM pairs is listed in Table 1, the full version of which is available electronically. The presentation has some similarity with LB2007. The first columns contain information on the primary target: (1) *Hipparcos* number HIP_{PRI} , (2) SUPERBLINK identification, (3,4) equatorial ICRS coordinates at the 2000.0 epoch in degrees, (5,6) proper motions in RA and Dec in arcsec yr^{-1} , (7) V magnitudes derived from the DSS for faint stars or taken from *Tycho-2* for bright ones, (8-11) $V - J$ color and J, H, K magnitudes from the 2MASS All-Sky Point Source Catalog (Cutri et al. 2003). Then follow the parallax (12), its error (13), and the parallax code (14), namely PLX1 for trigonometric parallax from HIP2. The following columns list (15) separation ρ in arcseconds, (16) proper motion difference with the primary target $\Delta\mu$ in mas yr^{-1} , and (17) estimated probability of physical association P_{phys} (Section 4.4). Companions in the WD band (see Section 2.2) are distinguished by $P_{\text{phys}} = -1$ and listed at the end.

The remaining columns of Table 1 contain data on the CPM companions. Columns (18) to (31) give same information for companion as columns (1) to (14) for the primary. The HIP_{SEC} number in (15) is 999999 if not available. Similarly, missing magnitudes are listed as 99. Photometric parallaxes in column (29) estimated from the $M_V, V - J$ relation have code PHOT in column (31), their errors are set to zero. Parallax of some companions is taken from the literature and marked by the following codes: PLX2 (van Altena et al. 1995)⁴, PLX3 from the NSTARS database⁵, and PLX4 (Myers et al. 2002)⁶. Trigonometric parallaxes of two WDs (McCook & Sion 1999) have code PLX5, the photometric parallaxes of WDs are calculated from (3).

We emphasize again that this catalog contains all CPM pairs identified using the selection method described in §2, and includes not only physical binaries but also a significant number of chance alignments. One should therefore *not* assume that the catalog lists true companions of the *Hipparcos* stars, and the user should keep an eye

⁴ <http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=I/238A>

⁵ http://nstars.nau.edu/nau_nstars/index.htm

⁶ <http://cdsarc.u-strasbg.fr/viz-bin/Cat?V/109>

on column 17, which provides a probability for the pair to be physical. We describe below our statistical method to assign probabilities of physical association for all the CPM pairs.

The 21 candidate WD companions are highlighted in Table 2, extracted from the main catalog. The *Hipparcos* number of the primary component HIP_{PRI} is listed in column (1), followed by the equatorial coordinates of the companion for 2000.0 in hexadecimal format in columns (2) and (3). Subsequent columns contain separation (4), $\Delta\mu$ (5), proper motion of the primary component (6), its parallax (7), V_{SEC} magnitude of the companion (8), and its $V - J$ color or its estimate (9). The last column (10) gives the identifications of 5 previously known WDs found in SIMBAD. Another 6 promising WD candidates are marked as wd? in this column on the basis of their large proper motion or small separation. The companion to HIP 118010 is also listed in LB2007. HIP 60081 hosts a planet with 48 d period (Schneider 2011).

4. STATISTICAL PROPERTIES OF THE CATALOG

Half of our targets have $\mu < 87 \text{ mas yr}^{-1}$ and 3/4 have $\mu < 150 \text{ mas yr}^{-1}$. Therefore the extension of the SUPERBLINK proper motion limit to 40 mas yr^{-1} is critical for this work. On the other hand, the catalog is still incomplete at $\delta < -20^\circ$. The distribution of companions on the sky is uniform, but with fewer stars south of $\delta = -20^\circ$ due to the larger proper motion cutoff. Interestingly, there is no obvious concentration towards the Galactic plane. Although the density of background stars strongly depends on the Galactic latitude, they mostly have small μ and thus are not included as companion candidates (see Lépine & Gaidos 2011).

Selection of primary targets with relatively large proper motion naturally favors nearby stars. Median parallax of the catalog entries is 18.1 mas . The number of FG dwarfs within distance d is proportional to $d^{2.1}$ in our catalog, whereas it is close to d^3 in *Hipparcos*; the difference is caused by the proper motion selection. In this Section we do not consider the 21 WD candidate companions and analyze only the 1392 MS companions.

The parallax distributions for close and wide companions in our catalog are slightly different; the median parallax is 22.1 mas and 17.1 mas for $\rho < 300''$ and $\rho > 1200''$, respectively. Distant stars have, on average, a smaller proper motion and a larger number of optical companions, producing this correlation between π_{HIP} and ρ .

4.1. Proper motion difference

Figure 3 plots proper motion difference $\Delta\mu$ for the pairs with main sequence secondaries against their angular separation ρ . The distribution reveals statistical differences between physical (close) and optical (wide) companions. Companions with $\rho < 200''$ have uniform distribution of $\log \rho$ and mostly $\Delta\mu < 15 \text{ mas yr}^{-1}$. In contrast, wide companions with $\rho > 1200''$ tend to have larger $\Delta\mu$. The difference of the $\Delta\mu$ statistics between these two groups is illustrated in Figure 4: while 56% of close companions have $\Delta\mu < 10 \text{ mas yr}^{-1}$, this cutoff contains only 19% of wide companions. Cumulative distribution for wide companions can be fitted by a power law:

$$F_{\text{opt}}(\Delta\mu) \approx (\Delta\mu/25)^{1.78}. \quad (4)$$

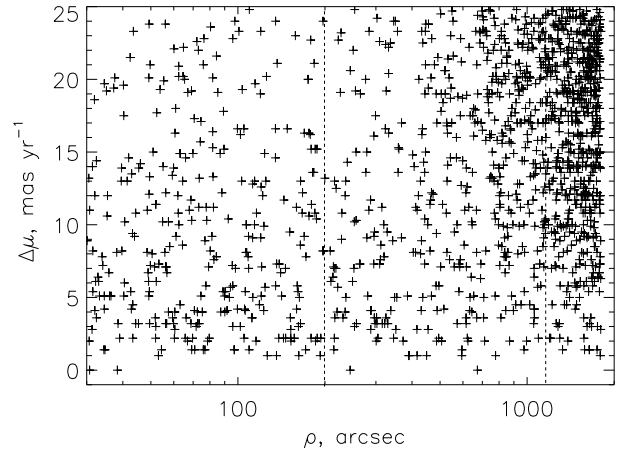


FIG. 3.— Proper motion difference $\Delta\mu$ vs. angular separation ρ for the 1392 common proper motion pairs with MS secondaries in our catalog. Pairs with short separations are dominated by physical systems, whereas pairs with large separations are mainly chance alignments. Vertical dashed lines mark separations of $200''$ and $1200''$.

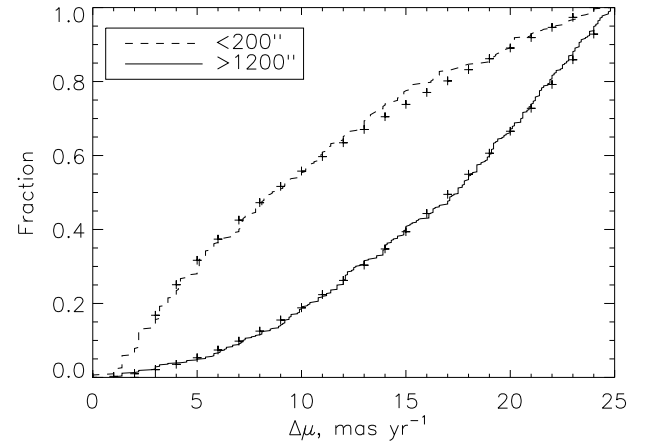


FIG. 4.— Cumulative distributions of $\Delta\mu$ for close ($\rho < 200''$, $N = 315$, dashed line) and wide ($\rho > 1200''$, $N = 552$, full line) CPM pairs. The crosses show analytical fits. Close pairs show a distribution which decreases in $\Delta\mu$, consistent with physical systems, while wider pairs show one that is increasing in $\Delta\mu$, consistent with chance alignments.

If the proper motion vectors of background stars were distributed uniformly, one would expect a quadratic law (LB2007), but the actual power index is slightly less than two; this is because nearby stars have systemic motions relative to the Sun and their proper motions thus show local correlations on the sky. The analytical model for close (physical) companions is:

$$F_{\text{phys}}(\Delta\mu) \approx [(\Delta\mu - 2)/22]^{0.57}. \quad (5)$$

These two distributions overlap substantially, preventing us from using a smaller cutoff in $\Delta\mu$. Both distributions extend beyond the 25 mas yr^{-1} cutoff (the cumulative curves have non-zero slope near the cutoff), suggesting that the catalog misses some physical companions with $\Delta\mu > 25 \text{ mas yr}^{-1}$, e.g. wide triples with motion in inner sub-systems. Physical companions with $\Delta\mu > 25 \text{ mas yr}^{-1}$ are indeed identified in LB2007. However, the large number of chance alignments with $\Delta\mu > 25 \text{ mas yr}^{-1}$ places very low probabilities on any pair being physi-

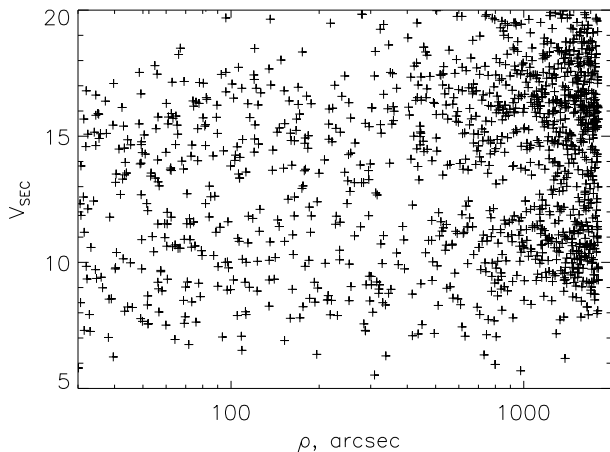


FIG. 5.— Visual magnitude of the secondaries V_{SEC} as a function of the angular separation ρ of the CPM pair. The secondaries in close ($\rho < 100''$) pairs, which are largely physical systems, have a relatively uniform magnitude distribution. Secondaries in wider (and mostly chance alignment) pairs show a magnitude gap at $V_{\text{SEC}} \approx 13$ which can be explained by a combination of selection effects.

cal and would require significant follow-up resources for triage and confirmation. For now, we prefer to adhere to this (somewhat arbitrary) upper limit in $\Delta\mu$.

4.2. Magnitudes and colors

In our catalog of CPM binaries, secondaries in wide pairs tend to be fainter than those in closer pairs (Figure 5). Detection of faint close companions is affected by the oreols around bright primary targets (LB2007), but at $\rho > 30''$ it seems to be complete at least down to $V_{\text{SEC}} = 17^m$.

There appears to be a deficiency of companions with V_{SEC} from 12^m to 14^m . Bright candidates with $V_{\text{SEC}} < 12$ were selected from the *Tycho-2*, while fainter candidates are identified directly from the DSS with SUPERBLINK. There is, however, an overlap of a couple magnitudes between the *Tycho-2* catalog and SUPERBLINK identifications. Lépine & Shara (2005) argued that the merged *Tycho-2* + SUPERBLINK catalog should be 98% complete in this overlapping range of magnitudes, based on the high rate of recovery by SUPERBLINK of the faintest of the *Tycho-2* stars. However, the V_{SEC} magnitudes of faint companions are still derived from the DSS scans of photographic plates, with estimated errors of $\pm 0.5^m$ or larger. At the bright end, saturation of the stars on the plates may lead to systematic errors, and a slight over-estimation of V could create the discontinuity of the V_{SEC} distribution seen in Figure 5.

There is, however, an alternative explanation. One can see from Figure 5 that the gap is most apparent in the very wide secondaries, which are largely dominated with chance alignments, and much less obvious in the close ($\rho < 100''$) pairs. While any field star could potentially be selected as CPM secondary based on proper motion alone, our color-magnitude requirement eliminates most of the foreground and background contaminants, because their colors and magnitude would not fit the expected MS at the distance of the star. Exceptions to this rule are background giant and subgiant stars, which generally cannot be distinguished from foreground MS stars based on color and magnitude. Effectively, this causes

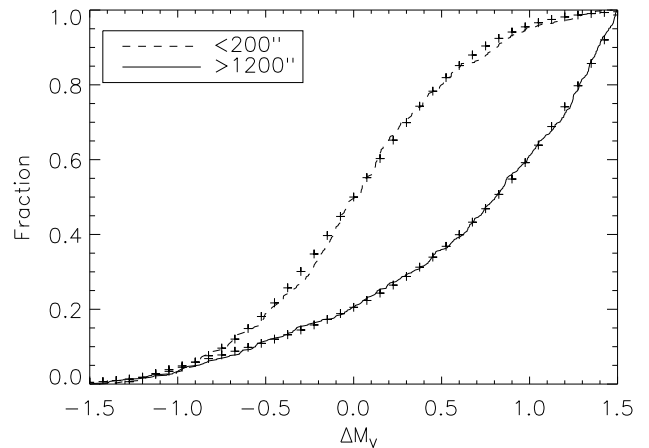


FIG. 6.— Cumulative distributions of ΔM_V for close ($\rho < 200''$, $N = 315$, dashed line) and wide ($\rho > 1200''$, $N = 552$, full line) companions. Analytical models are plotted as crosses.

an excess of (chance alignment) wide CPM secondaries in the $7 < V_{\text{SEC}} < 12$ magnitude range; fainter subgiants are not found in the SUPERBLINK catalog because of the distance bias introduced by the high proper motion cut. This over-selection of bright giants/subgiants conspires with the rising luminosity function of field stars to create the magnitude gap for wide companions.

A color-magnitude diagram (CMD) of the companion candidates is plotted in Figure 1. There is no clear separation between optical and physical companions in this CMD, but the statistics of the deviation from the nominal MS $\Delta M_V = [M_V]_{\text{SEC}} - [M_V]_{\text{MS}}$ (see Section 2.1) is different between those two groups. Most close (physical) companions have $\Delta M_V \sim 0$, while wide companions tend to be fainter and mostly have positive ΔM_V . Cumulative distributions of ΔM_V are compared in Figure 6. The cumulative distribution of ΔM_V for wide companions is approximated by a cubic polynomial in ΔM_V with coefficients (0.2052, 0.2342, 0.1210, 0.0468). The ΔM_V distribution of close companions is however normal with a dispersion of 0.575^m and zero average. Our cutoff of $\pm 1.5^m$ (2.6σ) rejects only 1% of this normal distribution. This indicates that our color-magnitude selection misses very few MS companions. A reduction of the cutoff would likely reduce the contamination by optical pairs, but would result in a lower completeness for physical systems.

4.3. Distribution of angular separations

We expect that the number of *optical* (i.e. chance alignment) companions closer than ρ should be proportional to ρ^2 . Physical companions, on the other hand, are expected to be distributed almost uniformly in $\log \rho$ (Öpik's law, Öpik 1924). This allows us to model the cumulative distribution of separations as a sum of physical and optical populations,

$$F(\rho) = ax + bx^2 + c(\rho/\rho_2)^2, \quad (6)$$

where:

$$x = \log(\rho/\rho_1)/\log(\rho_2/\rho_1).$$

Here $\rho_1 = 30''$ and $\rho_2 = 1800''$ are the separation limits of the catalog. The variable x maps this interval logarithmically into (0, 1), and the parameters a and b describe the distribution of physical companions linear in x

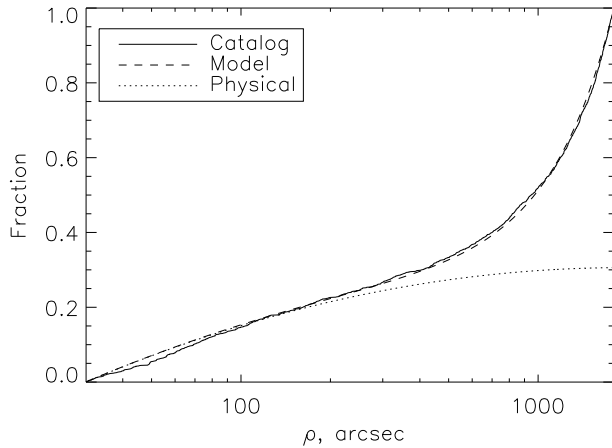


FIG. 7.— Cumulative distribution of separations (full line) and its model (dashed line). The dotted line corresponds to physical companions.

(instead of uniform distribution we allow some slope b), while $c = 1 - a - b$ is the fraction of optical companions. This simple model with only two free parameters fits well the observed distribution of separations in Figure 7 with $a = 0.600$ and $b = -0.294$. The estimated fraction of optical companions in our catalog is therefore $c = 0.69$, so it appears to contain about 425 physical wide pairs. The same model predicts that 92.7% of companions with $\rho < 300''$ are physical.

4.4. Probability of physical association

We have modeled the distributions of two astrometric parameters, angular separation ρ and proper motion difference $\Delta\mu$, by fitting analytical formulae to the cumulative histograms (eqs. 4-6). We also modeled the distribution of the deviation from the main sequence ΔM_V . Probability density functions for physical (close) and optical (wide) companions are readily obtained by differentiating these formulae. We assume here statistical independence of variables ρ , $\Delta\mu$, and ΔM_V , which is not quite true owing to correlations between these parameters, but still a reasonable approximation. Neglecting the correlations, the three-dimensional probability density functions for physical and optical companions are products of their one-dimensional distributions, $f(\rho, \Delta\mu, \Delta M_V) = f_\rho(\rho)f_{\Delta\mu}(\Delta\mu)f_{\Delta M_V}(\Delta M_V)$.

Each companion can be either physical or optical. So the probability of physical association can be estimated as

$$P_{\text{phys}}(\rho, \Delta\mu, \Delta M_V) = f_{\text{phys}} / (f_{\text{phys}} + f_{\text{opt}}) \quad (7)$$

provided that the distributions f_{phys} and f_{opt} are normalized in the same way. We list estimates of P_{phys} in the catalog, but do not use them in the statistical analysis presented below. The values of P_{phys} cluster near zero and one, discriminating well most candidates. Only 133 companions have intermediate P_{phys} between 0.2 and 0.8, most of them with separations of few hundred arcseconds. We checked the estimates of P_{phys} on 175 companions with trigonometric parallaxes of ± 5 mas or better precision and found that for all pairs with $P_{\text{phys}} > 0.5$ the parallaxes of primary and secondary companions match within errors, thus confirming the physical nature of those pairs. However, 39 wide pairs with $P_{\text{phys}} < 0.5$ (out of 70) also have parallaxes that match within 5 mas

and are probably physical. Our estimates of P_{phys} based on empirical data modeling are therefore useful as a guidance but should not be taken too literally.

Lépine & Bongiorno (2007) also included the mean proper motion of the pair μ in their statistical model and showed that the probability of optical companions is proportional to $\mu^{-3.8}$, i.e. that CPM pairs with larger proper motions are more likely to be physical. This analysis, however, neglected the role of color-magnitude selection in eliminating background contaminants, here represented by $f_{\Delta M_V}$. In addition, LB2007 used $\Delta\mu \propto \rho^{-1}$ as a cutoff, which introduced incompleteness at large separations by restricting the range of $\Delta\mu$ values. For these reasons we decided not to include μ in the statistical criteria used to separate physical and optical companions, instead relying on $f_{\Delta M_V}$ to eliminate most optical pairs at large angular separations.

To summarize, the current catalog of CPM companions to *Hipparcos* stars contains a mixture of physical and optical companions with different statistical properties such as distributions of separations, $\Delta\mu$, magnitudes, and colors. We develop a model for these distributions which we use to evaluate the probability of membership in either of the two groups. Additional parameters, such as total proper motion μ , could be used to refine those probability estimates, but are not applied here for simplicity and uniformity.

5. STATISTICS OF WIDE BINARIES

5.1. Masses and mass ratios

The masses of the primary and secondary components are evaluated here from their absolute magnitudes M_K using the relation from Henry & McCarthy (1993) for dwarfs and assuming that both companions are single (although binarity has little effect on estimated mass). The mass-magnitude relation in the K band is less sensitive to age and metallicity, compared to optical magnitudes. Evolved stars do not obey the relation for dwarfs, and as a result are assigned masses above $1.5 M_\odot$ owing to their high luminosity. In any case, 87% of primary components have estimated masses between 0.6 and $1.5 M_\odot$, i.e. are nearby solar-type dwarfs. The narrow range of masses for the primaries is of course achieved by design, from a combination of the 67 pc distance limit and the magnitude limit of the *Hipparcos* catalog itself. Massive stars are rare in the vicinity of the Sun, and most $< 0.6 M_\odot$ dwarfs in the 67 pc volume are below the *Hipparcos* magnitude limit. The secondary components, in contrast, span a range of masses from $0.1 M_\odot$ up to the mass of the primary component, consistent with our broad detection of secondary stars down to the $V = 20$ magnitude limit of the SUPERBLINK survey.

A comparison of the estimated masses of the primary and secondary components is shown in Figure 8 for the 403 pairs with $P_{\text{phys}} > 0.5$. The majority of mass ratios $q = M_{\text{SEC}}/M_{\text{PRI}}$ are comprised between 0.1 and 1; we set $q = 1$ in a few cases where $M_{\text{SEC}} > M_{\text{PRI}}$ (which happens because the V magnitudes are used to define which star is the primary/secondary whereas the K magnitudes are used to estimate their masses).

The scarcity of very low-mass companions is obvious in the CMD (Figure 1) by the scarcity of points with $V - J > 5.5$ or spectral types later than M6V. At 67 pc (distance modulus 4.12) a $V = 19$ star near the SU-

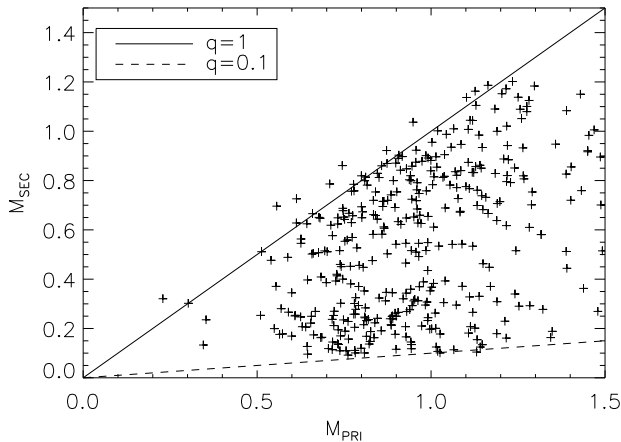


FIG. 8.— Masses of primary M_{PRI} and secondary M_{SEC} components of 403 systems with $P_{\text{phys}} > 0.5$. The full and dashed lines indicate mass ratios of 1 and 0.1, respectively.

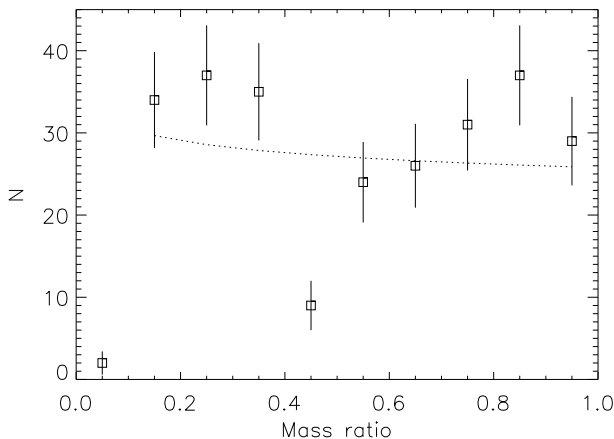


FIG. 9.— Distribution of the mass ratio $q = M_{\text{SEC}}/M_{\text{PRI}}$ for 275 pairs with $0.7 < M_{\text{PRI}} < 1.2 M_{\odot}$ and $P_{\text{phys}} > 0.5$. The dotted line shows a power-law fit $f(q) \propto q^{-0.07}$.

PERBLINK magnitude limit corresponds to a $0.12 M_{\odot}$ dwarf with $V - J = 5.2$, according to the standard relations of Henry & McCarthy (1993). Therefore, the catalog is incomplete below $M_{\text{SEC}} \sim 0.12 M_{\odot}$, although CPM companions of lower mass are found around some of the nearest primaries in the catalog.

The mass ratio of wide binaries has approximately uniform distribution (Figure 9). Excluding the first bin affected by incompleteness, we fit the distribution by a power law $f(q) \propto q^{-\beta}$ with $\beta = 0.07$. This matches the result of Raghavan et al. (2010) who found uniformly distributed mass ratio for all binaries independently of their period, and the result of Tokovinin (2011) who studied the mass-ratio distribution of companions within $20''$ and also found it to be uniform. Hierarchical multiples are neglected by this analysis.

However, we observe a prominent local minimum around $q \sim 0.5$, which is apparent in Figure 9 and corresponds to companions of $\sim 0.5 M_{\odot}$ mass with $[M_V]_{\text{SEC}} \sim 10$ and $V - J \sim 3.4$. At a typical distance of 50 pc such companions have $V_{\text{SEC}} \sim 13.5$. As noted above, SUPERBLINK is expected to be complete in this magnitude range. However, systematic errors in the V_{SEC} magnitudes may affect the position in the CMD (Figure 1), leading to a rejection of some physical compan-

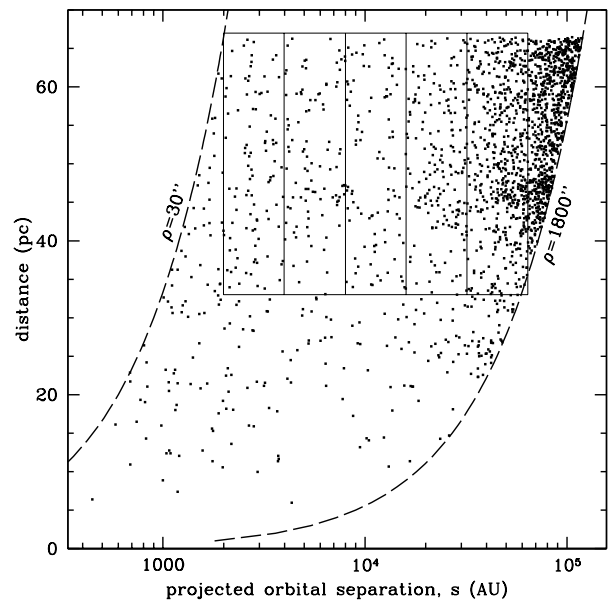


FIG. 10.— Distribution of projected orbital separations plotted against distance from the Sun. The projected separations are calculated assuming the secondary is at the same distance from the Sun as the Hipparcos primary. Angular separation limits of the survey are indicated by the dashed line. Our census is complete for physical pairs with $s > 2000$ AU, but contamination from optical pairs becomes significant at $s > 20000$ AU. The boxes show the range of the five bins in separation and distance used in our estimate of the distribution of orbital separations.

ions. Recently Rica (2012) found CPM companions to exo-planet hosts with high proper motion; one of those, HIP 112414 ($\rho = 51''$, $V_{\text{SEC}} = 14.1$, $\mu = 214 \text{ mas yr}^{-1}$) is overlooked in our catalog. Yet, we see only few such potentially rejected companions on the right side of the MS band in Figure 1, which suggests that such rejections should be relatively unfrequent, and cannot explain the observed deficit at $q \sim 0.5$.

Companion masses estimated from the K_{SEC} magnitudes are not affected by any systematic errors of V_{SEC} . However, the standard relation of Henry & McCarthy (1993) used here changes slope at $M_K = 5.9$, contributing to the deficit of estimated masses around $\sim 0.5 M_{\odot}$. Use of an alternative smooth relation between mass and M_K decreases the depth of the minimum around $q \approx 0.5$, without however getting rid of it entirely.

Should the minimum be real, it might indicate a bimodal distribution in the masses of the wide secondaries. A population of roughly equal-mass systems, combined with another where the secondaries have a mass distribution similar to field stars, could produce a bimodal distribution of mass ratios such as the one suggested here. Because of the relatively small number of systems in the present study, this apparent deficit at $q \approx 0.5$ should be confirmed before it can be accepted as real.

5.2. Projected separations

Projected orbital separations s for our wide systems can be calculated from $s = \rho/\pi_{\text{HIP}}$. The separations are statistically related to the orbital semi-major axis a . Simulations show that in most cases the ratio s/a is comprised between 0.5 and 2 and the median of s/a is close to 1.0 (it depends slightly on the eccentricity distribution). We plot the distribution of orbital separations against the

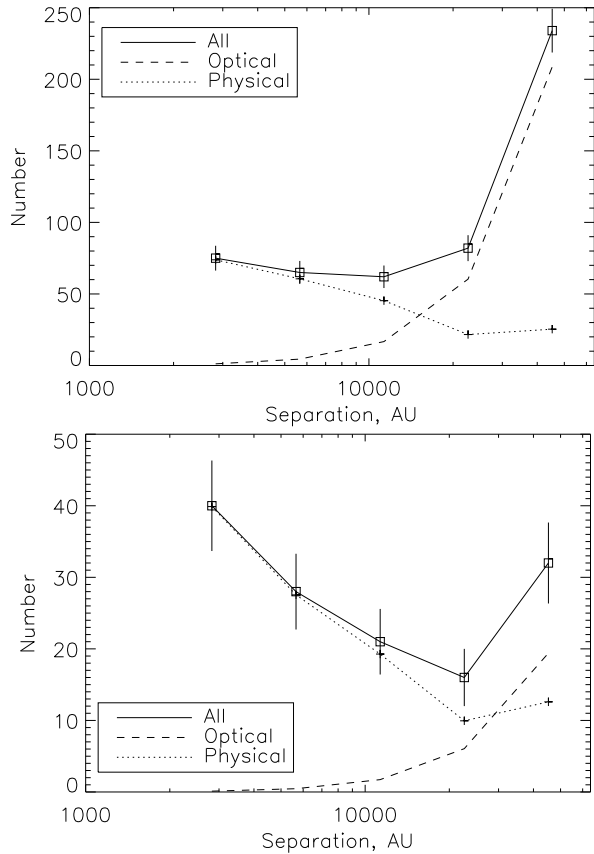


FIG. 11.— Distribution of projected separations for catalog subset with primary masses from 0.7 to $1.4 M_{\odot}$ and parallax between 15 mas and 30 mas. Top panel: without restriction on proper motion ($N = 518$), bottom panel: $\mu > 150 \text{ mas yr}^{-1}$, $N = 137$, $N_{\text{ref}} = 3277$. Full line and squares – observed histogram, dashed line – estimated optical companions, dotted line and pluses – estimated physical companions.

distance of the pair from the Sun in Figure 10. The range of projected orbital separations over which our survey is sensitive is defined by the lower and upper limits of angular separations, which are noted by the dashed lines. The majority of the pairs have $33 \text{ pc} < d < 67 \text{ pc}$; over that range our census is complete for systems with projected orbital separations $2 \text{ kAU} < s < 64 \text{ kAU}$. In that regime, the distribution of projected angular separations appears to be uniform over $\log(s)$ up to a projected separation of 10 kAU , beyond which the density increases significantly. This increase in density marks the increasing contamination from optical pairs (i.e. chance alignments).

For evaluating the companion frequency, we define the *reference sample* of *Hipparcos* stars that fulfill the selection criteria of our catalog on distance ($\pi_{\text{HIP}} > 15 \text{ mas}$) and proper motion ($\mu > 40 \text{ mas yr}^{-1}$ north of -20° and $\mu > 150 \text{ mas yr}^{-1}$ otherwise). We evaluate their masses by the same method as for the catalog targets using K -band magnitudes from XHIP (Anderson & Francis 2012); for a small subset without 2MASS photometry, V magnitudes were used instead. The reference sample is not complete within its distance limit. It only serves to relate the number of CPM companions in our catalog to the total number of primary stars with similar characteristics.

In the following, we apply additional selection criteria on π_{HIP} , μ , and mass of primary components to both our

catalog and reference sample. We also limit the analysis to primary stars in the mass range $0.7 M_{\odot} < M < 1.4 M_{\odot}$, which includes 77% of the pairs in our catalog.

To derive the distribution of projected separations, we need to account for the optical companions which contaminate the sample. We cannot use here the estimates of P_{phys} because they depend on ρ and hence bias the result. Considering a restricted range of parallax values, we estimate the number of optical companions in five bins of projected orbital separations (see Figure 10), by translating their limits (s_1, s_2) into angular separation limits (ρ_1, ρ_2) using the average parallax of the selected stars. Then $N_{\text{opt}} = A_{\text{opt}}(\rho_2^2 - \rho_1^2)$, where the parameter A_{opt} is evaluated from the number of companions between $1200''$ and $1800''$, assuming they are all optical in that range (a slight over-estimate). The estimate of A_{opt} relies mostly on companions with $s > 64 \text{ kAU}$, outside the range of separations studied here.

The procedure to derive the separation distribution is thus as follows. A subset of the catalog satisfying some additional criteria is chosen and the number of reference targets N_{ref} satisfying the same criteria is found. The histogram of projected separations N_i is constructed and the estimated number of optical pair contaminants is subtracted from each bin i to get $N_{i,\text{phys}} = N_i - N_{i,\text{opt}}$. The companion frequency is $N_{i,\text{phys}}/N_{\text{ref}}$. We ignore the tiny incompleteness of the fifth ($32\text{--}64$) kAU bin.

The top panel of Figure 11 shows the result for all stars with solar-type primaries (masses from $0.7 M_{\odot}$ to $1.4 M_{\odot}$). This selects 518 companions, 227 of which should be physical, while $N_{\text{ref}} = 5196$. The total frequency of companions between 2 kAU and 64 kAU is therefore $4.4 \pm 0.3\%$. We do not find any strong dependence of companion fraction on the mass of the primary. The total binary fraction, however, critically depends on the subtraction of optical pairs, especially in the last two bins which are significantly affected by the contamination. The first three bins contain 180 physical companions, or $3.8 \pm 0.3\%$ per decade of separation, and are not much affected by the contamination.

Our catalog is incomplete for companions of very low masses ($q < 0.15$). The magnitude of this incompleteness depends on the actual distribution of q : if the distribution is uniform all the way down to $q = 0$, then the catalog misses only 15% of low-mass companions. However, the number of sub-stellar companions is probably small (the so-called brown-dwarf desert) and the incompleteness at low q is correspondingly less. Wide triples may also be under-represented due to our color-magnitude selection (see §2.4), though the losses are probably modest. Assuming that our census of wide companions is 80% complete, their true frequency would be 5.5%. This value corroborates the result from Raghavan et al. (2010), who estimated that 5.9% of nearby dwarfs have companions with $s > 2 \text{ kAU}$.

More critical to the analysis is whether the distribution of orbital separations is flat with $\log s$ or undergoes a significant decline. By limiting our analysis to subsets of pairs with larger proper motions, we can substantially reduce the optical contamination, although at the expense of sample size. Both the distributions of orbital separations s and the total companion fraction derived from this restricted sample (bottom panel of Fig-

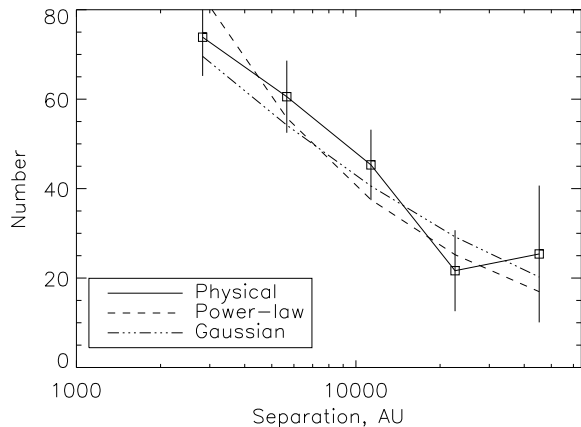


FIG. 12.— Distribution of projected separations for FGK dwarfs derived in this paper (line and squares) compared to two models consistent with the data – Gaussian (Raghavan et al. 2010) and a power law with $l = 1.57$ (dashed line).

ure 11) are very similar to the results for the full sample, and strongly support a decline with $\log s$. We see only a slight reduction of the companion fraction with increasing μ cutoff: $3.6 \pm 0.3\%$ for $\mu > 100 \text{ mas yr}^{-1}$ and $3.3 \pm 0.3\%$ for $\mu > 150 \text{ mas yr}^{-1}$. The slight reduction for stars with higher proper motions could be consistent with those stars being statistically older, and thus more susceptible to disruption. In addition, the distribution in $\log \rho$ is also declining, as evidenced by $b = -0.29$ in the model (6). The slope is $-0.29 \times 1.78 = -0.52$ per decade (the range of ρ is 1.78 dex), in excellent agreement with $l = 1.5$ found here by a different method.

The distribution of physical companions for Solar-mass stars in the vicinity of the Sun in $\log s$ is thus declining faster than Öpik's law: $f(s) \propto s^{-l}$ with $l \sim 1.5$ (where $l = 1$ would correspond to Öpik's law). This conclusion is valid at least over the $2 \text{ kAU} < s < 20 \text{ kAU}$ range. A deficit of wide binaries at large separations (or periods) relative to the Öpik's law was also documented by Chanamé & Gould (2005), and suggested by Lépine & Bongiorno (2007) using a subset of our current data. This decline is supported by the current, extended sample. Lépine & Bongiorno (2007) found a declining distribution with $l \approx 1.6$ at $s > 3 \text{ kAU}$; the slightly faster decline could however be the result of an additional selection criterion ($\Delta\mu \propto \rho^{-1}$) which favors closer binaries.

Figure 12 compares the empirical distribution of separations with two possible analytical models: a simple power law, and the log-normal period distribution of Raghavan et al. (2010). For the latter, the median period 10^5 d , logarithmic dispersion 2.28, and binary frequency 0.5 was converted to the distribution of semi-major axis by assuming total mass of $1.5 M_{\odot}$ and total sample size $N_{\text{ref}} = 5196$. The agreement with the log-normal distribution is better than one might expect, given the fact that their sample does not overlap with the stars studied here and that the analysis methods are different.

The frequency of 500-AU companions to FG dwarfs is higher, 13% per decade of separation (Tokovinin 2011). This agrees with the distribution declining at long orbital periods. Indeed, extrapolation from the first three

bins (geometric mean $s = 5.65 \text{ kAU}$, frequency 3.8% per decade) to $s \sim 500 \text{ AU}$ with the $s^{-1.5}$ power law predicts 3.4 times more companions, 13% per decade. In other words, the $s^{-1.5}$ law seems to hold at separations less than 1 kAU.

6. SUMMARY AND DISCUSSION

We have searched for wide companions to *Hipparcos* stars in the SUPERBLINK proper motion catalog based on common proper motion. The main results are:

- The mass ratio of wide companions to nearby solar-mass dwarfs is found to be distributed uniformly to first order, with a possible deficit of companions with mass ratios $q \simeq 0.5$.
- The distribution of projected separation s declines as $f(s) \propto s^{-1.5}$, faster than the Öpik's law.
- Total frequency of wide companions to solar-type dwarfs with $2 < s < 64 \text{ kAU}$ is $4.4 \pm 0.3\%$. The frequency in the range from 2 to 16 kAU is $3.8 \pm 0.3\%$ per decade of separation. Both numbers are lower limits because a fraction of wide companions is missed.

In addition, our search has produced a catalog of 1413 CPM companions to *Hipparcos* stars. The present catalog gives the most complete census of wide CPM companions to nearby stars available to date. A decline in companion frequency at large s found here can be used to constrain gravitational perturbations in the Galactic field.

We found 21 potential WD companions to nearby stars (Table 2). Half of those should be true WDs, the rest are faint background stars. Indeed, 5 WD companions are already known in the literature, 6 look promising based on their separation and PM.

Our catalog contains new wide companions to exoplanet host stars (Schneider 2011), in addition to previously known CPM companions. Relevant data on two high-probability physical companions to HIP 17747 and HIP 90593 are listed in Table 3, the potential WD companion to HIP 60081 is listed in Table 2. More information on these candidates (spectral types, radial velocities) are necessary for their definitive attribution.

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REFERENCES

- Anderson, E., Francis, C. 2012, *AstL*, 38, 331 (CDS 2011yCat.5137)
- Bate, M. R. 2009, *MNRAS*, 392, 590

- Caballero, J. A. 2010, *A&A*, 514, A98
- Chanamé, J. & Gould, A. 2005, *ApJ*, 601, 289
- Cutri, R. M., Skrutskie, M. F., van Dyk, S., Beichman, C. A., Carpenter, J. M., Chester, T., Cambresy, L., Evans, T., Fowler, J., Gizis, J. et al. 2003, The IRSA 2MASS All-Sky Point Source Catalog. NASA/IPAC Infrared Science Archive.
- Dhital, S., West, A. A., Stassun, K. G., Bochanski, G. G. 2010, *AJ* 139, 2566
- Gould, A., & Chanamé, J. 2004, *ApJS*, 150, 455
- Henry, T. J. & McCarthy, D. W. 1993, *AJ*, 106, 773
- Lépine, S. 2005, *AJ*, 130, 1680
- Lépine, S., & Shara, M. M. 2005, *AJ*, 129, 1483
- Lépine, S., Bongiorno, B. 2007, *AJ*, 133, 889 (LB2007)
- Lépine, S. & Gaidos, E. 2011, *AJ*, 142, 138
- Luyten, W. J. 1987. The LDS Catalogue: Double Stars with Common Proper Motion (Minneapolis: Astron. Obs. Univ. Minnesota)
- Makarov, V. V. & Kaplan, G. H. 2005, *AJ*, 129, 2420
- Makarov, V. V., Zacharias, N., & Hennessy, G. S. 2008, *ApJ*, 687, 566
- Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G. & Worley, C. E. 2001, *AJ* 122, 3466 (see the current version at <http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/wds.html>)
- McCook, G. P. & Sion, E. M. 1999, *ApJS*, 121, 1
- Monet, D. G., et al. 2003, *AJ*, 125, 984
- Myers, J. R., Sande, C. B., Miller, A. C. et al. 2002, SKY2000 Master Catalog, Version 4. Goddard Space Flight Center, Flight Dynamics Division (on-line catalog V/109 at CDS)
- Öpik, E. J. 1924, *Tartu Obs. Publ.*, 25
- Parker, R. J., Goodwin, S. P., Kroupa, P., Kouwenhoven, M. B. N. 2009, *MNRAS*, 397, 1577
- Raghavan, D., Henry, T., Mason, B. D., Subasavage, J., Wei-Chun Jao, Beaulieu, T. D., & Hambly, N. C. 2006, *AJ*, 646, 523
- Raghavan, D., et al. 2010, *ApJS*, 190, 1
- Rica, F. 2012, *IAUDS*, 176
- Roell, T., Neuhauser, R., Seifahrt, A., & Mugrauer, M. 2012, *A&A*, 542, 92
- Rojas-Ayala, B., Covey, K. R., Muirhead, P. S., & Lloyd, J. P. 2012, *ApJ*, 748, 93
- Schlieder, J. E., Lépine, S., & Simon, M. 2012, *AJ*, 143, 80
- Schneider, E. 2011, *A&A*, 532, A79 (see <http://exoplanet.eu>)
- Shaya, E. J. & Olling, R. P. 2011, *ApJS*, 192, 2
- Tokovinin, A. 2011, *AJ*, 141, 52
- Tokovinin, A. Hartung, M., Hayward, Th. L., & Makarov, V. V. 2013 *AJ*, 144, 7
- van Altena, W. F., Lee, J. T., & Hoffleit, E. D. 1995, The general catalogue of trigonometric [stellar] parallaxes (on-line catalog I/238A at CDS)
- van Leeuwen, F. 2007, *A&A*, 474, 653 (HIP2)
- Weinberg, M. D., Shapiro, S. L., Wassermann, I. 1987, *ApJ*, 312, 36
- Yoo, J., Chanamé, J., & Gould, A. 2004, *ApJ*, 601, 311
- Zuckerman, B., Song, I., Bessell, M. S., & Webb, R. A. 2001, *ApJ*, 562, 87
- Zuckerman, B., Song, I., & Bessell, M. S. 2004, *ApJ*, 613, 65

TABLE 1
CATALOG OF WIDE CPM COMPANIONS. I. PRIMARIES

HIP _{PRI}	PM Id	R.A. (deg)	Dec. (deg)	μ_α (as yr ⁻¹)	μ_δ (as yr ⁻¹)	V (mag)	$V - J$ (mag)	J (mag)	H (mag)	K (mag)	π (mas)	σ_π (mas)	code	Sep (arcsec)	$\Delta\mu$ (mas yr ⁻¹)	P_{phys}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
159	I00020-0245	0.510909	-2.766169	0.040	-0.003	6.96	0.63	6.33	6.27	6.21	16.0	0.5	PLX1	1715.8	11.2	0.003
238	I00029-2002	0.739543	-20.045879	0.103	0.081	6.30	1.02	5.28	5.07	4.96	16.3	0.5	PLX1	1207.2	20.2	0.025
277	I00034-3615	0.859494	-36.251194	0.071	0.005	7.00	0.67	6.33	6.23	6.15	15.2	0.5	PLX1	1470.3	17.0	0.006
473	I00056+4548	1.420712	45.812103	0.879	-0.154	8.20	2.06	6.14	4.71	5.28	88.4	1.6	PLX1	328.2	9.5	0.723
493	I00059+1814	1.478141	18.235023	-0.151	-0.150	7.45	1.12	6.33	6.08	6.03	26.9	0.6	PLX1	573.0	3.2	0.741
577	I00070+3252	1.752726	32.870110	0.177	-0.077	9.61	1.39	8.22	7.86	7.72	16.1	1.3	PLX1	1401.7	5.0	0.024
599	I00072-4153	1.814071	-41.889565	-0.063	0.018	8.29	1.21	7.08	6.82	6.72	16.9	0.8	PLX1	653.1	16.1	0.021
682	I00084+0637	2.107265	6.616799	0.085	-0.003	7.66	1.24	6.42	6.15	6.12	25.6	0.7	PLX1	1776.1	11.7	0.000
731	I00090+2739	2.262037	27.651575	0.223	0.147	11.65	2.23	9.42	8.78	8.66	23.5	2.9	PLX1	68.8	11.7	0.927
840	I00103-0514	2.578626	-5.248588	0.037	-0.029	5.95	1.94	4.01	3.38	3.37	17.1	0.5	PLX1	1561.7	12.1	0.017

TABLE 1
CATALOG OF WIDE CPM COMPANIONS. II. SECONDARIES

HIP _{PRI}	HIP _{SEC}	PM Id	RA(2000) (deg)	DEC(2000) (deg)	μ_α (as yr ⁻¹)	μ_δ (as yr ⁻¹)	V (mag)	$V - J$ (mag)	J (mag)	H (mag)	K (mag)	π (mas)	σ_π (mas)	code
(1)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)
159	999999	I00002-0256	0.069661	-2.947790	0.045	-0.013	10.00	1.36	8.64	8.37	8.23	11.9	0.0	PHOT
238	999999	I00032-1943	0.808330	-19.716831	0.086	0.070	15.46	4.09	11.37	10.79	10.52	18.4	0.0	PHOT
277	999999	I00034-3550	0.868067	-35.842834	0.079	0.020	9.61	1.77	7.84	7.37	7.22	23.7	0.0	PHOT
473	428	I00051+4547	1.295195	45.786587	0.870	-0.151	9.95	3.25	6.70	6.10	5.85	88.9	1.4	PLX1
493	495	I00059+1804	1.481153	18.075890	-0.150	-0.147	8.58	1.46	7.12	6.72	6.46	26.9	1.2	PLX1
577	999999	I00061+3312	1.534962	33.214226	0.173	-0.074	16.16	3.99	12.17	11.63	11.37	11.9	0.0	PHOT
599	999999	I00082-4154	2.055929	-41.911892	-0.049	0.010	11.76	2.00	9.76	9.18	9.06	11.0	0.0	PHOT
682	999999	I00065+0645	1.630693	6.756144	0.096	-0.007	12.38	2.56	9.82	9.22	9.06	14.1	0.0	PHOT
731	999999	I00089+2739	2.248174	27.666235	0.212	0.151	13.70	3.27	10.43	9.81	9.60	16.1	0.0	PHOT
840	999999	I00120-0513	3.013638	-5.225371	0.048	-0.024	14.82	3.82	11.00	10.41	10.16	18.2	0.0	PHOT

TABLE 2
CANDIDATE WHITE DWARF CPM COMPANIONS

HIP _{PRI}	R.A. <i>h m s</i>	Dec. <i>° ' "</i>	Sep (as)	$\Delta\mu$ (mas yr ⁻¹)	μ (mas yr ⁻¹)	$[\pi_{\text{HIP}}]_{\text{PRI}}$ (mas)	V_{SEC} (mag)	$(V - J)_{\text{SEC}}$ (mag)	Comment
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
8588	01 50 52.1	+11 05 34.1	178.0	16	74	23.8	20.29	2.11	
11028	02 21 57.9	+04 45 17.9	53.1	17	82	24.7	16.67	0.81	wd?
42783	08 42 57.6	+24 09 30.8	104.6	23	113	27.1	17.17	1.18	
50760	10 21 43.4	+59 34 35.1	126.5	6	57	19.0	19.69	2.10	
54530	11 09 30.1	-26 01 06.9	100.3	5	238	24.9	17.33	0.94	WD1107-257
56004	11 28 34.9	-45 05 13.8	195.3	21	43	15.6	18.60	2.13	
60081	12 19 13.7	-03 19 46.1	35.0	19	72	19.5	16.82	0.17	wd?
63181	12 56 33.7	+36 50 05.6	129.8	16	62	24.7	19.73	2.29	
69178	14 09 43.0	+15 39 39.8	164.8	14	73	17.8	20.45	2.31	
70446	14 24 23.6	+47 51 02.6	177.5	15	65	30.9	17.76	2.45	
80182	16 22 03.9	+12 13 33.6	62.4	10	94	19.3	15.05	0.06	WD1619+123
85799	17 31 46.7	+16 51 45.7	174.9	21	41	21.2	18.04	1.74	
90593	18 28 59.9	+11 41 07.5	167.0	24	50	15.9	18.55	2.00	
99956	20 16 55.6	-03 27 51.0	127.3	8	108	15.4	16.55	0.12	wd?
101268	20 31 36.4	+34 21 14.9	85.6	18	53	21.8	17.57	1.82	
102488	20 46 05.3	+33 58 12.2	92.0	2	485	44.9	14.68	0.64	GJ 9707C
103735	21 01 26.7	-35 09 33.4	186.0	6	188	21.5	16.96	0.70	wd?
106335	21 32 16.2	+00 15 14.4	133.1	10	415	22.1	14.65	-0.24	WD2129+004
110218	22 19 28.5	+21 22 19.5	83.1	13	422	20.3	18.32	1.87	WD2217+211
117011	23 43 00.8	-64 47 37.8	41.6	16	241	27.2	17.15	1.10	wd?
118010	23 56 09.2	+59 47 43.6	101.8	9	342	19.7	18.68	1.83	wd?

TABLE 3
NEW WIDE COMPANIONS TO EXO-PLANET HOSTS

HIP _{PRI}	HD _{PRI}	P_{pl} (d)	ρ (as)	s (kAU)	$\Delta\mu$ (mas yr ⁻¹)	μ (mas yr ⁻¹)	P_{phys}	ΔM_V (mag)
17747	23596	1656	70.7	3.6	4	58	0.996	-0.8
90593	170469	1145	43.2	2.7	9	51	0.989	-1.1