SUBSYSTEMS IN NEARBY SOLAR-TYPE WIDE BINARIES

ANDREI TOKOVININ1, MARKUS HARTUNG2, AND THOMAS L. HAYWARD2

1 Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile; atokovinin@ctio.noao.edu
2 Gemini Observatory, Southern Operations Center, c/o AURA, Casilla 603, La Serena, Chile; mhartung@gemini.edu, thayward@gemini.edu

ABSTRACT

We conducted a deep survey of resolved subsystems among wide binaries with solar-type components within 67 pc of the Sun. Images of 61 stars in the K and H bands were obtained with the Near-Infrared Coronagraphic Imager adaptive-optics instrument on the 8 m Gemini-South telescope. Our maximum detectable magnitude difference is about 5 mag and 7.8 mag at 0.15 and 0.09 separations, respectively. This enables a complete census of subsystems with stellar companions in the projected separation range from 5 to 100 AU. Out of seven such companions found in our sample, only one was previously known. We determine that the fraction of subsystems with projected separations above 5 AU is 0.12 ± 0.04 and that the distribution of their mass ratio is flat, with a power-law index of 0.2 ± 0.5. Comparing this with the properties of closer spectroscopic subsystems (separations below 1 AU), it appears that the mass-ratio distribution does not depend on the separation. The frequency of subsystems in the separation ranges below 1 AU and between 5 and 100 AU is similar, about 0.15. Unbiased statistics of multiplicity higher than 2, advanced by this work, provide constraints on star formation theory.

Key words: binaries: general

1. INTRODUCTION

The quest for exoplanets has attracted attention to stars in the solar neighborhood. A complete understanding of their formation requires a quantitative and predictive description of stellar multiplicity. Empirical data on stellar multiplicity serve as a benchmark for star formation theories, for example, to compare with recent large-scale hydrodynamical simulations (Bate 2009). Although multiplicity statistics of solar-type dwarfs have been assumed to be known since the survey of Duquennoy & Mayor (1991), in fact, that survey did not constrain multiplicities higher than 2 because (1) the sample of 164 stars was too small and (2) the discovery of wide binaries relied on traditional visual techniques. Raghavan (2009) showed that Duquennoy & Mayor (1991) missed half of the higher-order multiples within 25 pc from the Sun.

Several studies of large samples of nearby stars are now in progress. Radial velocity (RV) techniques ensure a secure detection of all short-period stellar companions (see summary in Grether & Lineweaver 2006). However, for wider separations (>10 AU) RV variations are too slow or too small, and such companions are better discovered by direct imaging. Several recent deep imaging surveys, summarized by Metchev & Hillenbrand (2009), aimed to detect sub-stellar or planetary-mass companions to nearby stars, and obtained statistics of stellar companions as a by-product. The typical sample size of imaging surveys is still small, on the order of 100 targets.

Most imaging and RV surveys for low-mass companions explicitly avoid known visual binaries (e.g., Chauvin et al. 2010), so important star formation effects may not be represented in their samples. For example, cataloged triples show that the mass-ratio distributions in close inner subsystems discovered spectroscopically and in wider “visual” subsystems are radically different (see Section 5). One of our goals is to investigate if this is a selection effect or a genuine feature of the star formation process.

In order to improve the multiplicity statistics of a well-defined and sufficiently large distance-limited sample, we focus on ∼5000 dwarfs with 0.5 < V − I < 0.8 within 67 pc from the Sun. According to preliminary estimates, there should be some 400 triples and 100 quadruples in this sample. Surveying such a large sample to detect those multiples with a reasonably deep and known completeness limit is a large task; here we address only a small part of it. Instead of avoiding known binaries, we purposefully selected wide visual binaries from this sample. Some of these targets are also monitored in RV, giving complementary constraints on subsystems with short periods (Desidera et al. 2006).

We imaged the chosen wide binaries with adaptive optics (AO) to study the properties of inner subsystems. AO imaging on 8 m class telescopes provides nearly diffraction-limited resolution of 0.06 in the near-infrared, which corresponds to a projected orbital radius of 4 AU for the farthest target stars in our sample, filling an important gap between RV and seeing-limited imaging surveys.

Our sample is detailed in Section 2. Observations, data reduction, and detection limits are described in Section 3, and the results are presented in Section 4. Sections 5 and 6 present the discussion and conclusions, respectively.

2. THE SAMPLE OF WIDE BINARIES

The wide binaries chosen for our survey belong to a large sample of nearby solar-type dwarfs (Nsample) selected from the latest version of the Hipparcos catalog (van Leeuwen 2007) by the following criteria: (1) trigonometric parallax πHIP < 15 mas (within 67 pc from the Sun, distance modulus <4.12 mag); (2) color 0.5 < V − I < 0.8 (this corresponds approximately to spectral types from F5V to K0V); and (3) unevolved, satisfying...
the condition $M_{V} > 9(V - I) - 3.5$, where $M_{V}$ is the absolute magnitude in the *Hipparcos* band calculated with $\pi_{\text{Hip}}$.

There are 5040 stars (i.e., *Hipparcos* catalog entries) satisfying these conditions. Some of these stars with erroneous parallaxes or colors will be eventually removed from the sample, but this contamination is expected to be minor. The $N_{\text{sample}}$ defined above is reasonably complete because the cumulative object count versus distance $d$ follows the $d^3$ law, deviating from it by only 10% at $d = 67$ pc.

Visual binaries with separations $5'' < \rho < 20''$ and one or both components belonging to the $N_{\text{sample}}$ were selected for AO observations from the Washington Double-Star Catalog (WDS; Mason et al. 20013). Additionally, we require each pair to have at least three observations and magnitudes of both components listed in the WDS, and that apparent motion of the wide pair be compatible with $\pi_{\text{Hip}}$. As most targets have large proper motions, relative stability of the binary position over time permits rejection of optical pairs. An additional check was made by placing the components on the $(M_V, V - K)$ color–magnitude diagram (CMD). There are ~200 wide binaries in this list, 101 with negative declinations.

In Table 1, we list basic data on the components of the 33 wide pairs observed in this run. Column 1 gives the *Hipparcos* numbers of the primary and, in some cases, secondary components. The next three columns contain $\pi_{\text{Hip}}$, binary separation $\rho$, and projected separation $r = \rho/\pi_{\text{Hip}}$. Then follow the magnitudes of the primary (A) and secondary (B) components in the $V, H$, and $K_s$ bands as listed in the WDS and Two Micron All Sky Survey (2MASS; Cutri et al. 2003). The last two columns contain the date of observations and remarks where we indicate five cases when only one component was observed and three cases when the coronagraphic mask was used.

3. OBSERVATIONS AND DATA REDUCTION

3.1. Observing Procedure

The Near-Infrared Coronagraphic Imager (NICI) on the Gemini-South telescope is an 85-element curvature AO instrument based on natural guide stars (Toomey & Ftaclas 2003; Chun et al. 2008). We used NICI in normal (non-coronagraphic) mode as a classical AO system. However, simultaneous imaging in the two infrared bands $H$ and $K$ offered by NICI helps to distinguish faint companions from static speckles (the radial distance of a static speckle scales with wavelength, while the position of a real detection does not change). The two detectors have 1024$^2$ pixels of 18 mas size, covering a square field of 18$''$.

To avoid saturation, we used narrow-band filters with central wavelengths 2.272 $\mu$m and 1.587 $\mu$m in the red and blue channels, respectively. The minimum possible exposure time is 0.38 s, still causing saturation for bright targets. We observed three of the brightest stars with the coronagraphic mask of 0.32 radius, using in this instance broadband $K$ and $H$ filters. For the remaining bright targets we allowed moderate saturation. As the tradeoff between slower observations with more complex data reduction in coronagraphic mode and slightly saturated point-spread functions (PSFs) is not obvious, we tried both.

Typically, each target was observed at five to six dithered positions for a total accumulation time of about 5 minutes. The dither offsets were designed to take images of both wide-binary components in one frame whenever possible ($\rho < 10''$) while closing the AO loop on the primary. Components of wider pairs were observed separately, except secondaries with $V > 12$ mag, too faint to serve as AO guide stars.

Of the two nights allocated to this program, one was lost due to a technical problem. Three targets were observed on 2009 December 10 in service mode. The remaining objects were observed on the night of 2010 January 31 to February 1 in classical mode. The seeing during that night was good. As measured from the NICI AO loop data, it ranged between 0.34 and 0.94, with a median of 0.50 (at 500 nm, not corrected to the zenith). High AO performance was achieved (see the following section). The transparency was variable (light cirrus). Out of 202 binary components accessible to NICI, we were able to observe 61, or 30%. The efficiency was high with an average of 12 minutes per target including telescope slew, tuning of the primary mirror, acquisition of the object on the science camera, closing the AO loop, and data taking.

3.2. Data Processing

The data were processed in a standard way using custom IDL programs. Individual images written to separate FITS files were combined into data cubes, separately in red and blue channels. The sky image was obtained for each target as a median of the cube, then subtracted from each plane of the cube. After correcting for bad pixels and dividing by the flat field, the images were re-centered by cross-correlation and median-combined.

Most frames contain just one or two bright point sources corresponding to the components of the wide binary. The position of each point source was recorded by “clicking” on its image, then refined by fitting a two-dimensional Gaussian to the central part of the PSF within a 5 pixel radius. The ratio of the central intensity of this Gaussian to the total flux in a 0.9 diameter circle gives an estimate of the Strehl ratio. The typical Strehls are 43% and 22% in the red and blue channels, respectively, with maximum values reaching 54% and 38%. The median FWHMs of the PSF core were 65 mas and 57 mas in the red and blue channels, respectively. The diffraction limits $\lambda/D$ are 63 mas and 44 mas for the effective aperture diameter $D = 7.5$ m set by the coronagraphic mask.

Figure 1 shows the mosaic of seven close subsystems found around some primary components of wide binaries. Most companions are rather obvious, well above the detection threshold. The PSFs also contain a faint secondary reflex at 13 pixels (0.24) with a magnitude difference in the red channel of about 4.3 mag. This ghost (illustrated in Figure 1 in the case of HIP 37332) is detected in all targets, and can be taken advantage of as a fiducial (see Section 3.4). Its position is the same in both channels, whereas the static speckle pattern scales in proportion to the wavelength.

3.3. Measurement of Binaries

To measure the relative position and flux ratio of wide binaries more precisely, we fit the scaled and shifted image of the primary component (A) to the secondary (B). Such fits work very well, leaving only small residuals, and produce mutually consistent measurements in the two channels. The rms scatter between the wide-binary positions measured in two NICI channels is 5.5 mas in both the radial and tangential directions.

---

3 The current version of WDS is available online:
http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/WDS.

4 The oversized spider mask has been taken into account and yields a correction factor of 1.079.
east to the right. The intensity scaling is negative logarithmic. The first seven frames show all binary components where we detected a close companion. The last frame shows the PSF of the unresolved target HIP 37332, with the ghost marked. The faint companions to HIP 24711A and HIP 49520B are marked by arrows. Note that at good AO correction the typical features of the NICI PSF become visible. These are particularly the double diffraction spikes and the four spots on the first Airy ring, giving it a “boxy” look. These features are caused by the oversized vanes of a spider mask placed in the pupil plane to control scatter.

Table 1
Data on Observed Targets

| HIP(A/B) | \( \pi_{\text{HIP}} \) (mas) | \( \rho \) (\(^\circ\)) | \( r \) (AU) | Component A | Component B | Date (2000+) | Rem |
|----------|-----------------------------|----------------|-------------|-------------|-------------|--------------|-----|
| 2028/29  | 24.0                        | 16.5           | 687         | 8.39        | 7.46        | 7.41         | 9.56 | B          |
| 10579    | 17.2                        | 6.7            | 390         | 9.43        | 8.06        | 7.97         | 9.97 | 09.9400    |
| 20552    | 36.1                        | 5.6            | 155         | 6.87        | 5.37        | 5.32         | 7.23 | 10.0851    |
| 20610/12 | 16.7                        | 10.5           | 629         | 8.06        | 6.89        | 6.84         | 8.27 | 10.0851    |
| 21963    | 18.2                        | 8.2            | 450         | 8.13        | 6.69        | 6.62         | 13.30 | B          |
| 22531/34 | 26.0                        | 12.9           | 496         | 5.61        | 4.88        | 4.80         | 6.24 | 10.0852    |
| 23926/23 | 18.7                        | 10.1           | 540         | 6.83        | 5.20        | 5.10         | 10.29 | CRN        |
| 24711/12 | 15.3                        | 13.3           | 867         | 8.46        | 7.00        | 6.95         | 10.57 | 10.0852    |
| 27922    | 42.4                        | 10.4           | 246         | 7.60        | 5.84        | 5.76         | 10.57 | 10.0852    |
| 28790    | 37.2                        | 5.6            | 150         | 6.02        | 4.92        | 4.75         | 8.98  | 10.0853    |
| 30158    | 17.8                        | 7.0            | 390         | 8.57        | 7.02        | 6.91         | 10.58 | 10.0853    |
| 32644    | 21.2                        | 4.9            | 230         | 7.37        | 6.05        | 5.97         | 8.66  | 10.0852    |
| 36165/60 | 31.2                        | 17.7           | 566         | 7.08        | 5.92        | 5.80         | 8.06  | 10.0854    |
| 37332/33 | 15.1                        | 15.7           | 1043        | 7.89        | 6.47        | 6.41         | 10.01 | 10.0855    |
| 37335    | 21.8                        | 6.1            | 282         | 8.93        | 7.05        | 6.99         | 12.38 | 10.0855    |
| 39409    | 15.7                        | 5.1            | 328         | 9.26        | 7.57        | 7.44         | 9.36  | 10.0855    |
| 43947    | 26.6                        | 10.2           | 383         | 8.44        | 7.28        | 7.19         | 9.95  | 10.0857    |
| 44584/85 | 17.0                        | 10.5           | 617         | 8.09        | 6.99        | 6.90         | 9.19  | 10.0857    |
| 44804    | 15.5                        | 7.4            | 478         | 8.80        | 7.20        | 7.15         | 10.70 | 10.0857    |
| 45734    | 17.6                        | 9.0            | 513         | 8.41        | 6.85        | 6.78         | 9.66  | 10.0856    |
| 45940    | 28.6                        | 6.8            | 237         | 8.17        | 6.55        | 6.43         | 11.86 | 10.0856    |
| 46236    | 21.4                        | 19.3           | 900         | 7.03        | 5.77        | 5.69         | 10.18 | 10.0856    |
| 47839/36 | 40.2                        | 18.8           | 468         | 8.08        | 6.79        | 6.70         | 8.23  | 10.0858    |
| 49520    | 16.9                        | 9.6            | 565         | 8.82        | 7.35        | 7.24         | 8.99  | 10.0858    |
| 50638/36 | 83.3                        | 17.1           | 205         | 7.67        | 5.18        | 4.98         | 9.67  | 10.0858    |
| 50883    | 16.2                        | 6.7            | 413         | 7.90        | 6.71        | 6.62         | 13.00 | 10.0858    |
| 55288    | 20.8                        | 9.5            | 456         | 7.10        | 5.91        | 5.82         | 7.91  | 10.0859    |
| 58240/41 | 21.1                        | 18.9           | 895         | 7.67        | 6.24        | 6.13         | 7.83  | 10.0859    |
| 59021    | 19.4                        | 6.0            | 308         | 6.69        | 5.24        | 5.10         | 8.84  | 10.0859    |
| 61595    | 17.8                        | 8.4            | 472         | 8.28        | 6.80        | 6.68         | 10.48 | 10.0860    |
| 64498    | 18.0                        | 9.3            | 516         | 7.74        | 6.40        | 6.25         | 10.10 | 10.0861    |
| 65176    | 17.8                        | 5.0            | 282         | 7.85        | 6.47        | 6.40         | 8.59  | 10.0861    |
| 67408    | 33.9                        | 11.6           | 342         | 6.62        | 5.29        | 5.22         | 10.21 | 10.0860    |

We checked the pixel scale and detector orientation by comparing the measured positions of 16 wide pairs (the widest in Table 2 after the exclusion of HIP 21963, 43947, and 50883, which were not used) with the positions listed in the Hipparcos Double and Multiple Star Catalog (ESA 1997). We did not find any systematic effect above noise and therefore used the nominal pixel scale of 18.0 mas for both channels. We found that the detector orientation of the channels differs by 1°01 ± 0°01, so 1°0 was added to measured angles in the blue channel.

For close pairs where the PSFs overlap, we use a variant of iterative blind deconvolution. Good preliminary estimates of the relative component’s position and intensity are already
available from the Gaussian fits of the PSF cores. The image Fourier transform (FT) is divided by the FT of the binary with preliminary parameters to get an estimate of the PSF. Negative parts of this PSF are set to zero and it is replaced by its azimuthal average at radial distances over 5 pixels from the center. The binary parameters are refined by fitting the image with this synthetic PSF again. Then the process is repeated, obtaining a second approximation to the PSF and using it (without azimuthal averaging) to obtain the final binary parameters again. The success of this procedure is verified by inspecting the resulting PSF, which should be “clean,” with the least possible trace of the companion.

3.4. Detection Limits

To determine detection limits, we mostly use the data from the red NICI channel where the detection of low-mass components is deeper because of the smaller magnitude difference and larger Strehl ratios. The maximum magnitude difference of detectable companions ($\Delta m_{\text{lim}}$) is estimated by calculating the rms flux variations ($\sigma(\rho)$) in circular zones of increasing radii ($\rho$) centered on the main component. It is assumed that a detectable companion will have a maximum intensity exceeding $5\sigma$, therefore,

$$\Delta m_{\text{lim}}(\rho) = -2.5 \log_{10}[5\sigma(\rho)/I_{\text{max}}].$$

This assumption is, of course, simplistic. We do not account for the existence of two simultaneous images in red and blue channels and for good knowledge of the PSF from other companions of the same target or from other targets observed shortly before or after. Nevertheless, this simple strategy of estimating detection limits is sufficient for our purpose and has been tried before with good results (e.g., Tokovinin et al. 2006).

The limits computed for HIP 37322 are shown in Figure 2. A bump is produced in the curves at $\rho \approx 13$ pixels by the ghost and the fixed speckle pattern (see the PSF in Figure 1). To confirm the validity of Equation (1), we performed Monte Carlo simulations adding artificial companions within $\pm 1.5$ mag from the estimated $\Delta m_{\text{lim}}$. Secure detection of the ghost ($\Delta m = 4.3, \rho = 0^\prime.24$) in all images gives confidence in our estimation of $\Delta m_{\text{lim}}$.

The $5\sigma$ detection limits ($\Delta m_{\text{lim}}(\rho)$) were fitted by two straight lines intersecting at $\rho = 8$ pixels ($0^\prime.144$). The second segment extends from 8 to 50 pixels ($0^\prime.9$), but the region between the 8 and 16 pixel radii affected by the ghost and strong speckle is avoided in the fit. At $\rho > 50$ pixels, $\Delta m_{\text{lim}}$ is assumed to be constant. Only two numbers, $\Delta m(8)$ and $\Delta m(50)$, adequately describe the actual $\Delta m_{\text{lim}}(\rho)$ curves, with a typical rms error of only 0.3 mag (excluding the zone between 8 and 16 pixel radii where the $5\sigma$ method does not properly account for the static speckle).

Detection limits were determined by the above procedure for all targets, although the Monte Carlo simulation checks were only performed for a subset. The two detection parameters,
4. RESULTS

4.1. Companion Data

We have found six new close companions, one previously known companion, and several faint optical companions (Figure 1). Table 2 lists the relative positions and magnitude differences in known and new pairs. Each pair is identified by the HIP number and component designations. The measured position angles (in degrees), separations (in arcseconds), and magnitude differences are listed separately for the two NICI channels.

The large rms difference between Hipparcos and our measurements of the wide pairs (130 mas in $\rho$ and 1:05 in $\theta$) is mostly caused by their motion between the two epochs. Comparison with the relative positions of the same binaries deduced from the 2MASS Point-Source Catalog (Cutri et al. 2003) has confirmed that no systematic corrections are needed and has shown a scatter of similar magnitude.

Remarks in the last column of Table 2 indicate cases when the image was saturated (the relative photometry may be compromised), newly detected close companions, and likely optical companions. These faint companions with separations of a few arcseconds would be dynamically unstable within wide binaries, should they be physical.5

4.2. Notes on Individual Systems

HIP 28790. This has a common-proper-motion companion C at 196$''$.

HIP 36165 A. This is suspected to be a spectroscopic binary (SB).

HIP 43947. This is unexpectedly discovered to be a resolved quadruple system. Both components are located $\sim$2 mag below the main sequence (MS) in the $(M_V, V-K)$ CMD, possibly because the Hipparcos parallax measurement was biased by the motions in the subsystems. The position and $\Delta m$ of the wide pair Aa,Ba are derived from the Gaussian fits, therefore they may be less accurate.

HIP 45734. This is a young pre-MS system and X-ray source RX J0919.4–7738. It projects on the Chamaeleon star-forming region, but is located much closer than the corresponding association. Covino et al. (1997) found from a single spectrum that component B (southern) is a double-lined SB, with a large RV difference from A (see also Desidera et al. 2006). A itself is a close visual binary KOH83 resolved in 1996 March by Köhler (2001). He measured the position (173$''$9, 0$''$109) and $\Delta K = 0.45$. This is the only previously known resolved subsystem among the observed stars. Follow-up observations will soon lead to the visual orbit and mass measurement, adding another empirical point to the evolutionary tracks of young stars.

HIP 49520. The faint companion Bb is close to the detection limit (see Figure 1). Yet, it is securely detected in both channels and stands up clearly in residuals when fitting the image of B with the image of A.

HIP 50638/36. The wide pair has been observed since 1835; it is definitely physical. Component B is variable. It is probably for this reason that it is located on the CMD some 6 mag below the MS, while A is on the MS with the parallax $\pi_{\text{HIP}} = 83$ mas listed in Table 1. According to van Leeuwen (2007), the parallaxes and proper motions of the two components are discordant, but have large errors. Future RV measurements can settle the controversy.

HIP 59021. Component A is a suspected SB and also an astrometric binary (acceleration solution in Hipparcos). Non-detection of the subsystem with NICI means that its period is likely less than 10 yr, or it is a white dwarf.

4.3. Estimation of the Mass Ratios

K-band absolute magnitudes ($M_K$) of all companions were computed based on the photometry from 2MASS (see Table 1) and trigonometric parallaxes $\pi_{\text{HIP}}$ from Hipparcos. For resolved pairs, we assume that $\Delta m$ in the red NICI channel corresponds to magnitude differences in the $K$ band. The masses were estimated from $M_K$ using the empirical relations of Henry & McCarthy (1993). We also tried a quadratic approximation of relation between mass and $M_K$ from Girardi et al. (2000). The relative difference with Henry & McCarthy (1993) is less than 10% for masses above 0.1 $M_\odot$. We checked that the influence of using either of these relations on the final result is not critical. Table 3 lists the estimated masses of the companions in the resolved subsystems, their projected separations $r = \rho/\pi_{\text{HIP}}$, and order-of-magnitude period estimates $P^* = r^{3/2} (M_1 + M_2)^{-1/2}$.}

Figure 2. Estimated 5σ companion detection limit (solid line) in the red channel for HIP 37332. The simulated companions are overplotted as asterisks (detected) or empty squares (missed). The dotted line shows the two-segment model.

5 Dynamical stability of a triple system is possible when the ratio of the inner semimajor axis to the outer periastron distance is larger than $\sim 3$ (e.g., Harrington 1972). As only projected separations are known for our triples, assessment of their dynamical stability is approximate.
Figure 3. Mass ratios $q = M_2/M_1$ of the seven resolved subsystems vs. their projected separations. The shaded region indicates incomplete detections (light gray corresponds to detection probabilities from 0.5 to 0.9, while dark gray from 0.1 to 0.5).

Table 3

| HIP   | Comp | $M_1$ (M$_\odot$) | $M_2$ (M$_\odot$) | $r$ (AU) | $P^*$ (yr) |
|-------|------|------------------|------------------|----------|------------|
| 24711 | Aa,Ab| 1.04             | 0.15             | 43.6     | 260        |
| 43947 | Aa,Ab| 0.64             | 0.59             | 15.9     | 60         |
| 43947 | Ba,Bb| 0.55             | 0.24             | 10.9     | 40         |
| 44804 | Aa,Ab| 0.95             | 0.61             | 29.3     | 130        |
| 45734 | Aa,Ab| 0.88             | 0.81             | 6.8      | 14         |
| 49520 | Ba,Bb| 0.92             | 0.26             | 12.6     | 40         |
| 64498 | Aa,Ab| 1.09             | 0.71             | 20.6     | 70         |

Figure 3 shows the mass ratios $q = M_2/M_1$ in the resolved inner subsystems as a function of projected separation. The median parallax of observed targets is 19 mas, so the upper limit of the separation range, 100 AU, corresponds to $\rho \approx 1.9$. Maximum separations of dynamically stable subsystems should not exceed 100 AU in most cases because the projected separations of the wide binaries range from 150 to 1000 AU (Table 1). Indeed, all detected subsystems have $r < 44$ AU. The lower limit of 5 AU corresponds to $\rho \approx 0.1$, well above the NICI resolution limit.

The detection limits in the red channel were converted into mass ratios and averaged over the 61 observed components, producing a smooth detection probability $p_{\text{det}}(r, q)$. Contours of this function at 0.1, 0.5, and 0.9 levels are overplotted in Figure 3. We see that the chosen region of the $(r, q)$ parameter space is well covered with NICI.

4.4. Statistical Analysis

The purpose of this study is to reach statistical conclusions about the frequency and the properties of subsystems in solar-type wide binaries. Considering the small number of components, we keep this analysis at a basic level, and assume that the mass ratios in secondary subsystems have a power-law distribution independent of separation:

$$f(q) = \epsilon (\beta + 1) q^\beta. \quad (2)$$

This model has only two free parameters: the total companion frequency $\epsilon$ and the power-law index $\beta$. Neglecting incomplete detection, the companion count gives $\epsilon = 7/61 = 0.12 \pm 0.04$.

The distribution of the companion projected separations in the considered range from 5 to 100 AU matters only because the detection limits depend on $r$. We assume that $f(\log r) = \text{const}$.

The input data are the $(r, q)$ values for $K = 7$ subsystems, the total number of surveyed targets $N = 61$, and the array of detection probabilities $p_{\text{det}}(r, q)$. We find the estimates of parameters $(\epsilon, \beta)$ by the maximum likelihood (ML) method (see, e.g., Tokovinin et al. 2006, their Appendix B). The likelihood function $L$ is a product of the probabilities to obtain observations for each component (non-detections for $N-K$ systems or detections of $K$ subsystems with mass ratios $q_k$).

The minimum of $S = -2 \ln L$ is sought. This function depends on the input data and the model parameters as

$$S = 2nf_0 - 2 \sum_{k=1}^{K} \ln[f(q_k)p_{\text{det}}(r_k, q_k)]. \quad (3)$$

The summation over $k$ is done for the seven detected companions. The companion probability $f_0$ equals the product $f(r, q)p_{\text{det}}(r, q)$ averaged over the considered part of the parameter space $(r, q)$. If the detection probability $p_{\text{det}}$ equals 1 everywhere, the result is $f_0 = \epsilon$, otherwise $f_0 < \epsilon$.

The contours of $S$ in the parameter space define confidence limits: $\Delta S = 1$ corresponds to the 68% interval (1σ), $\Delta S = 2.71$ corresponds to the 90% interval, and $\Delta S = 4$ corresponds to the 95% interval, in direct analogy with the Gaussian probability distribution. We verified the ML method on a simulated data set. The input parameters were recovered and the confidence intervals were as expected.

Minimization of Equation (3) leads to $(\epsilon, \beta) = (0.12, 0.18)$. If we ignore the detection limits and set $p_{\text{det}} = 1$, the result changes little: $(\epsilon, \beta) = (0.11, 0.40)$. The companion fraction 0.12 is not different from its naive estimate. As to the power index $\beta$, the ML points to a uniform distribution in $q$ as being most likely, although the uncertainty is large. The confidence areas of the parameters are shown in Figure 4. Considering that the contours are not very elongated, we can determine the 68% and 90% confidence intervals for each parameter by a simple cross section through the minimum (Table 4). The data are marginally compatible with $\beta \sim -0.5$, in which case the fraction of subsystems may exceed 0.2 (see the lower right extension of the 90% contour in Figure 4).
5. DISCUSSION

5.1. Completeness of the Existing Catalog

The fact that, in a sample of only 33 systems, six of the seven observed companions are new shows that current knowledge of multiplicity among nearby solar-type systems is very incomplete and that near-IR AO imaging is a powerful technique for detecting new companions.

In Figure 5, we plot the mass-ratio distribution in the inner subsystems of known triple stars. The data are extracted from the updated version of the Multiple-Star Catalog (MSC; Tokovinin 1997), where component masses are estimated by a variety of methods. We selected 220 systems within 200 pc of the Sun with masses of primary components from 0.5 to 1.5 \( M_\odot \). They were subdivided by the separation in the inner subsystems in two groups: 123 close (semimajor axis <1 AU) and 61 wide (between 5 and 100 AU). The remaining 36 pairs have even wider separations. The mass-ratio distributions in these two groups are markedly different, but our unbiased survey results in a flat mass-ratio distribution, within errors. Therefore, the difference seen in Figure 5 is caused by observational selection. Given an approximately equal number of close and wide subsystems with large mass ratios (two last bins in Figure 5) and assuming that the mass-ratio distributions in these two groups are indeed similar, we expect that the number of close and wide subsystems (with separations below 1 AU and between 5 and 100 AU, respectively) are similar, too. The completeness of the MSC for wide subsystems is thus about 1/2.

5.2. Companion Fraction

Is the presence of a wide binary companion influencing the frequency of inner subsystems? To answer this question, we compare our results on triples with surveys of solar-type binaries. Unfortunately, binary-star statistics are usually derived regardless of higher-order multiplicity, so a cleaner comparison must await a new study of a large unbiased sample.

The separation range from 5 to 100 AU explored here corresponds to orbital periods between 10 yr and 1000 yr. According to Duquennoy & Mayor (1991), about 20% of solar-type dwarfs have companions with such periods. In the actual, narrower range of projected separations from 6.8 AU to 44 AU, 12% of solar-type dwarfs have companions. Therefore, the frequency of subsystems around components of wide binaries is similar to the frequency of binary companions to single stars in the same separation range.

The frequency of subsystems with periods below 3 yr in visual multiples has been determined by Tokovinin & Smekhov (2002) to be between 11% and 18%. Again, it turned out to equal within observational errors the companion frequency among single dwarfs of similar masses in the solar neighborhood and in some open clusters. Desidera et al. (2006) surveyed RVs of

56 wide visual pairs and found that 0.135 ± 0.05 fraction of companions have spectroscopic subsystems.

Therefore, one might surmise that the presence of a wide companion does not affect the formation of inner, closer subsystems in a wide range of separations. This question is, however, far from having been settled for both stellar and planetary subsystems (see the discussion in Eggenberger et al. 2007). We know that almost all close binaries with periods below 3 days do have additional outer companions, although the mass ratios of close binaries with and without tertiary companions have similar distributions (Tokovinin et al. 2006).

5.3. Is the Mass-Ratio Distribution Universal?

Metchev & Hillenbrand (2009) advocate the idea of a companion mass function with a universal power law over a wide range of separations and masses. They fit the mass-ratio distribution in solar-mass visual binaries to a power law with \( \beta = -0.39 \pm 0.36 \). Visual companions to stars more massive than the Sun follow a power law \( f(q) \propto q^\beta \) with \( \beta \) from −0.3 to −0.5, as established in AO imaging surveys by Shatsky & Tokovinin (2002) and Kouwenhoven et al. (2005). Certainly, these distributions do not correspond to the most simplistic case of random companion pairing, as described in detail by Kouwenhoven et al. (2009).

Our survey of triples points to a flat mass-ratio distribution with \( \beta \sim 0 \). The errors are large, so the difference with visual binaries is not yet significant. The mass-ratio distribution in closer SBs is approximately flat (Mazeh et al. 2003; Hallwachs et al. 2003), similar to the mass-ratio distribution in close subsystems of triple stars (Figure 5). If we confirn on a larger sample that subsystems in triples do differ from pure binaries in their mass-ratio distribution, its universality will be seriously challenged.

5.4. Brown Dwarf Desert

The mass function of companions to binary and multiple stars is radically different from the initial mass function. Therefore, the fraction of low-mass companions is much smaller than the fraction of low-mass stars in the field. This fact, known as the brown dwarf (BD) desert, is well established (Grether & Lineweaver 2006). Adopting a flat mass-ratio distribution for
our sample, also typical for SBs, we estimate that only 7% of companions to a solar-mass star will be in the BD regime. Considering the companion frequency of 0.12 in the studied separation range, one BD companion per \( \sim 100 \) primaries is expected. Our result thus suggests that the BD desert in multiple systems extends to separations of 100 AU.

The BD desert and the tendency to equal companion masses are explained in the current star formation scenario by continuing accretion onto a binary. Whenever a low-mass companion forms by fragmentation of a massive disk, continuing accretion usually brings its mass into the stellar regime (e.g., Kratter et al. 2010). Companions of sub-stellar masses should be intrinsically rare. At the same time, the orbital drag (inward migration) reduces the separation, producing close subsystems. It appears that about half of the companions settle in close orbits with separation < 1 AU; the rest of them remain in wider orbits.

6. CONCLUSIONS

We surveyed 33 nearby wide binaries with solar-type primaries and found seven resolved subsystems, most of them previously unknown. We derive the fraction of subsystems with projected separations from 5 to 100 AU to be 0.12 ± 0.04. The mass-ratio distribution in these subsystems appears to be flat, to within a large statistical error.

The sample can be increased six times if we continue observations with NICI and extend them to the northern sky using some other AO facility. Such an investment of five nights on 8 m telescopes will enable us to reduce the size of the confidence intervals in Figure 4 by 2.5 times. Then, it will become possible to distinguish between the negative power index \( \beta \sim -0.3 \) typical for resolved binaries and flat mass-ratio distribution \( \beta \sim 0 \) characteristic of close binaries.

The joint fraction of both visual and spectroscopic subsystems in wide solar-type binaries is about 0.25. In consequence, the majority of the components are single and provide an accommodating environment for hosting planetary systems.

We thank M. Chun and F. Rigaut for helping us diagnose an NICI AO misbehavior, and F. Rantakyro for his assistance in the preparation and execution of the observations. We are thankful to W. Brandner and N. Huelamo for discussions about the manuscript. This work used NASA’s Astrophysics Data System, data products from the 2MASS funded by the NASA and the NSF, and the SIMBAD database maintained by the University of Strasbourg, France. The comments of the anonymous referee helped us to improve the presentation.

Facility: Gemini-South (NICI)

REFERENCES

Artigau, E., et al. 2008, Proc. SPIE, 7014, 66
Bate, M. R. 2009, MNRAS, 392, 590
Biller, B., et al. 2008, Proc. SPIE, 7015, 184
Chauvin, G., et al. 2010, A&A, 509, A52
Chun, M., et al. 2008, Proc. SPIE, 7015, 49
Covino, E., et al. 1997, A&A, 328, 187
Cutri, R. M., et al. 2003, The IRSA 2MASS All-Sky Point Source Catalog, NASA/IPAC Infrared Science Archive (Pasadena, CA: CalTech)
Desidera, S., Gratton, R. G., Lucatello, S., Claudi, R. U., & Dall, T. H. 2006, A&A, 454, 553
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Eggenberger, A., Udry, S., Chauvin, G., Beuzit, J.-L., Lagrange, A.-M., Ségransan, D., & Mayor, M. 2007, A&A, 474, 273
ESA 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200; Noordwijk: ESA)
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Grether, D., & Lineweaver, C. H. 2006, ApJ, 640, 1051
Hallwachs, J. L., Mayor, M., Udry, S., & Arenou, F. 2003, A&A, 397, 159
Harrington, R. S. 1972, Celest. Mech., 6, 322
Henry, T. J., & McCarthy, D. W. 2001, AJ, 106, 773
Köhler, R. 2001, AJ, 122, 3325
Kouwenhoven, M. B. N., Brown, A. G. A., Goodwin, S. P., Portegies Zwart, S. F., & Kaper, L. 2009, A&A, 493, 979
Kouwenhoven, M. B. N., Brown, A. G. A., Zinnecker, H., Kaper, L., & Portegies Zwart, S. F. 2005, A&A, 430, 137
Kratter, K. M., Murray-Clay, R. A., & Youdin, A. N. 2010, ApJ, 710, 1375
Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2001, AJ, 122, 3466
Mazeh, T., Simon, M., Prato, L., Markus, B., & Zucker, S. 2003, ApJ, 599, 1344
Metchev, S. A., & Hillenbrand, L. A. 2009, ApJS, 181, 62
Raghavan, D. 2009, PhD thesis, Georgia State Univ.
Shatsky, N., & Tokovinin, A. 2002, A&A, 382, 92
Tokovinin, A. 1997, A&A, 124, 75
Tokovinin, A. A., & Smechkov, M. G. 2002, A&A, 382, 118
Tokovinin, A., Thomas, S., Sterzik, M., & Udry, S. 2006, A&A, 450, 681
Toomey, D. W., & Ftaclas, Ch. 2003, Proc. SPIE, 4841, 889
van Leeuwen, F. 2007, A&A, 474, 653