COOL SUBDWARF INVESTIGATIONS. II. MULTIPLICITY

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ABSTRACT

Cool subdwarfs of types K and M are the fainter counterparts of cool main-sequence dwarfs that dominate the Galactic population. In this paper, we present the results of an optical speckle survey of 62 confirmed cool subdwarf systems within 60 pc. We have resolved two new companions and confirmed two previously known companions with separations 0.13–3.29″. After including previously known wide companions and all known spectroscopic binaries, we determine the multiplicity rate of cool subdwarfs to be 26% ± 6%, which is somewhat lower than comparable main-sequence stars that have a multiplicity rate of 37% ± 5%. We find that only 3% of the cool subdwarfs surveyed have companions within 10 AU, 3% have companions between 10 and 100 AU, and 14% have companions beyond 100 AU. The other 6% of cool subdwarfs are spectroscopic binaries. This is very different from K/M dwarfs that have most companions (13%) at separations closer than 10 AU. However, because a search for close binaries among a large sample of nearby cool subdwarfs remains elusive, it is not yet settled whether or not the multiplicity rates are significantly different. Nonetheless, several different observational results and theories pointing to a possible dearth of subdwarf multiples are discussed.

Key words: binaries: close – instrumentation: high angular resolution – stars: late-type – subdwarfs – techniques: interferometric

1. INTRODUCTION

Studying stellar multiplicity is the key to understanding stellar formation, evolution, the true luminosity function (LF) of stellar objects, and is relevant to our understanding of stellar and planetary system stability. Many binary surveys have been carried out on varied populations, including the nearby Taurus star-forming region (Leinert et al. 1993), the Orion Nebula Cluster (Köhler et al. 2006), and Herbig Ae/Be Stars (Cordero et al. 2006), to name a few.

The multiplicity of various samples of main-sequence dwarfs has also been discussed in the last decade. Mason et al. (1998) found that more than 59% of O-type stars in clusters and associations have a visual, speckle, or spectroscopic companion. Duquennoy & Mayor (1991, hereafter DM91) found that 57% of solar-type binaries have mass ratios greater than 0.1 after considering their survey incompleteness. Henry & McCarthy (1990) and Fischer & Marcy (1992) found that the multiplicity fraction of M dwarfs drops to 34–42%. Thus, the overall trend is that the multiplicity rate of main-sequence stars decreases with mass.

Subdwarfs are lower-luminosity cousins of main-sequence stars on the H–R diagram. They are usually low-metallicity stars and are often referred to as either Population II or thick disk stars, making them astrophysically distinct from dwarfs. Given their formation in lower-metallicity environments, they might provide clues to the star formation process if we could know (1) their multiplicity fraction and (2) whether or not their multiplicity decreases with temperature, as it does for their dwarf counterparts. In this paper, we present results from our optical speckle survey for cool subdwarf companions. We then combine our results with other published subdwarf companion surveys spanning G to M types, and we discuss our current understanding of the multiplicity discrepancy between dwarfs and subdwarfs.

2. SAMPLE SELECTION

Our targets were selected from several different efforts, including lists of spectroscopically identified subdwarfs (Ryan & Norris 1991; Gizis 1997; Jao et al. 2008) and stars with metallicity measurements (Carney et al. 1994; Cayrel de Strobel et al. 2001; Nordström et al. 2004). In total, we selected 124 potential systems of interest, including 62 confirmed K- and M-type subdwarf systems and 62 others of earlier type. Of the 124 subdwarf systems, 118 have trigonometric distances within 60 pc (van Altena et al. 1995; ESA 1997; Jao et al. 2005; Costa et al. 2005, 2006) while the remaining six systems are beyond 60 pc (LHS 360, LHS 398, LHS 1481, LP907–080, HIP 101814, and HIP 101989). $V - K_s$ values greater than 2.0 are found for 188 systems, while six other systems have $V - K_s$ less than 2.0 (G 048–039, G 062–044, G 083–034, G 140–046, G 141–008, and LHS 322). The 62 subdwarfs within 60 pc have all been confirmed to have (1) K- or M-type, (2) subdwarf spectroscopic features (strong CaH and TiO band strength), and (3) $[m/H] \leq -0.5$ (if independent metallicity measurements are available) or at least one magnitude below the fitted main-sequence line (Jao et al. 2008). The 62 subdwarf systems are listed in Table 1.

3. OBSERVATIONS AND RESULTS

3.1. Observations and Calibrations of Speckle Interferometry

Three observing runs were carried out at Kitt Peak National Observatory (KPNO) and Cerro Tololo Inter-American Observatory (CTIO). From 2005 November 8–13 and 2007 August
## Table 1
Speckle Observations

| R.A.   | Decl.  | Name      | Site  | Binary Note | CPM Comp. | $\rho$ (′) | $\theta$ (°) | Epoch (yr) | Others |
|--------|--------|-----------|-------|-------------|-----------|------------|------------|------------|--------|
|        |        |           |       |             |           | (5)        | (6)        | (7)        | (8)    | (9)    |
| 00 09 16.46 | +09 00 41.9 | LHS0104 | K1   |             |           |            |            |            |        |        |
| 00 12 30.31 | +14 33 48.8 | G030−052 | K2   |             |           |            |            |            |        |        |
| 00 17 40.01 | −10 46 16.9 | LHS0109 | K2a  |             |           |            |            |            |        |        |
| 00 45 16.67 | +01 40 34.4 | G001−021B | K1a  |             |           |            |            |            |        |        |
| 00 45 17.80 | +01 40 43.3 | G001−021A | K1a  |             |           |            |            |            |        |        |
| 02 02 52.16 | +05 42 21.0 | LHS0012 | K1a  |             |           |            |            |            |        |        |
| 02 08 23.89 | +28 18 18.3 | G072−059 | K1   |             |           |            |            |            |        |        |
| 02 08 23.91 | +28 18 38.9 | G072−058 | K1   |             |           |            |            |            |        |        |

### Confirmed K and M subdwarfs within 60 pc

| R.A.   | Decl.  | Name      | Site  | Binary Note | CPM Comp. | $\rho$ (′) | $\theta$ (°) | Epoch (yr) | Others |
|--------|--------|-----------|-------|-------------|-----------|------------|------------|------------|--------|
| 01 40 60.60 | +45 01 06.4 | Kapteyn  | C1    |             |           |            |            |            |        |        |
| 11 10 24.26 | +33 49.6 | LHS2852 | C1a   |             |           |            |            |            |        |        |
| 11 38 15.70 | −11 29 13.5 | LHS0020 | K1a   |             |           |            |            |            |        |        |
| 11 42 29.45 | +12 31 33.8 | LHS0178 | K1a   |             |           |            |            |            |        |        |
| 04 04 20.30 | −04 49 2.3 | HD025673 | C1    |             |           |            |            |            |        |        |
| 04 25 42.97 | +14 54 36.0 | HIP2308 | K1    |             |           |            |            |            |        |        |
| 05 11 40.60 | +45 01 06.4 | Kapteyn  | C1    |             |           |            |            |            |        |        |
| 05 45 12.96 | −16 27 46.6 | LHS0052 | C1    | LHS0053     | 300.7     | 180.3      | 2000.0     |            |        |
| 07 02 36.44 | +31 33 54.7 | G087−019 | K1a   |             |           |            |            |            |        |        |
| 09 43 46.16 | −17 47 06.2 | LHS0272 | K1a   |             |           |            |            |            |        |        |
| 10 13 01.62 | −39 06 07.9 | LTT3743 | C1    |             |           |            |            |            |        |        |
| 11 10 02.64 | −02 47 26.4 | G010−003 | C1a   |             |           |            |            |            |        |        |
| 11 11 13.68 | −41 05 32.7 | LHS0300B | 4.3   | LHS0300B    | 4.3       | 62.0       | 2001.0     |            |        |
| 11 52 58.73 | +37 43 07.3 | LHS0044 | K1    |             |           |            |            |            |        |        |
| 11 58 28.02 | −41 55 19.3 | LHS2484 | 23.6  | LHS2484     | 23.6      | 312.4      | 2000.20    |            |        |
| 12 02 36.66 | +08 25 50.7 | LHS0320 | C1a   |             |           |            |            |            |        |        |
| 12 24 26.81 | −04 43 36.7 | LHS0326 | C1a   |             |           |            |            |            |        |        |
| 12 56 23.74 | +15 41 44.5 | LHS0343 | C1a   |             |           |            |            |            |        |        |
| 13 18 56.71 | −03 04 17.9 | LHS2715 | C1    |             |           |            |            |            |        |        |
| 14 02 46.66 | −24 31 49.6 | LHS2852 | C1    |             |           |            |            |            |        |        |
| 15 10 12.96 | −16 27 46.6 | LHS0052 | C1    | LHS0053     | 300.7     | 180.3      | 2000.0     |            |        |
| 15 10 13.08 | −16 22 46.0 | LHS0053 | C1    |             |           |            |            |            |        |        |
| 15 28 13.99 | +16 43 10.8 | LHS3073 | K2a   |             |           |            |            |            |        |        |
| 15 34 40.11 | +02 12 15.1 | LHS3084 | C1a   |             |           |            |            |            |        |        |
| 15 43 18.33 | −20 15 32.9 | LHS0406 | C1a   |             |           |            |            |            |        |        |
| 15 45 52.41 | +05 02 26.6 | G016−009 | K2    |             |           |            |            |            |        |        |
| 16 08 55.40 | +01 51 07.5 | G016−031 | C1a   |             |           |            |            |            |        |        |
| 16 20 17.97 | −48 13 32.8 | LHS3182 | C1    |             |           |            |            |            |        |        |
| 16 37 05.42 | −01 32 00.5 | LHS0424 | C1a   |             |           |            |            |            |        |        |
| 16 42 04.33 | +10 25 58.7 | LHS0425 | C1a   |             |           |            |            |            |        |        |
| 18 45 52.44 | +52 27 40.6 | LHS3409 | K2a   |             |           |            |            |            |        |        |
| 19 07 02.04 | +07 36 57.3 | G002−015 | K2a   |             |           |            |            |            |        |        |
| 19 09 00.52 | +41 38 04.5 | G125−004 | K1    |             |           |            |            |            |        |        |
| 19 39 57.41 | +42 55 50.7 | G125−026A| K2a   |             |           |            |            |            |        |        |
| 19 39 57.41 | +42 55 50.7 | G125−026B| K2a   |             |           |            |            |            |        |        |

* Resolved by speckle and see Table 2
Table 1 (Continued)

| R.A. (yr) | Decl. (′′) | Name | Site | Binary Note |
|-----------|------------|------|------|-------------|
| 22 14 24.01 | −08 44 42.0 | LHS3780 | K2<sup>a</sup> |
| 22 31 47.83 | +49 42 13.5 | G215−053 | K2 |
| 23 08 26.04 | +31 40 23.9 | LHS0536 | K1<sup>a</sup> |
| 23 25 11.31 | +34 17 14.0 | LHS3942 | K2<sup>a</sup> |
| 23 43 16.74 | −24 11 16.4 | LHS0073 | K2<sup>a</sup> |
| 23 55 04.17 | +20 23 05.5 | G129−042 | K1 |

Confirmed K and M Subdwarfs Beyond 60 pc

| R.A. (yr) | Decl. (′′) | Name | Site | Binary Note |
|-----------|------------|------|------|-------------|
| 02 58 10.24 | −12 53 05.9 | LHS1481 | K1<sup>a</sup> |
| 13 46 55.52 | +05 42 56.4 | LHS0360 | C1<sup>a</sup> |
| 23 08 26.04 | +31 40 23.9 | LHS0536 | K1 |
| 23 25 11.31 | +34 17 14.0 | LHS3942 | K2<sup>a</sup> |
| 23 43 16.74 | −24 11 16.4 | LHS0073 | K2<sup>a</sup> |
| 23 55 04.17 | +20 23 05.5 | G129−042 | K1 |

G or earlier than G-type Subdwarfs

| R.A. (yr) | Decl. (′′) | Name | Site | Binary Note |
|-----------|------------|------|------|-------------|
| 01 04 26.46 | −02 21 59.8 | G070−035 | K1 |
| 02 25 49.75 | +05 53 39.5 | G073−035 | K1 |
| 07 54 34.19 | −01 24 05.9 | G112−035 | K1, C1 SB1 |
| 12 06 00.94 | +14 38 56.8 | G012−035 | C1 |
| 13 31 39.95 | −02 19 02.5 | G062−035 | C1 |
| 16 13 48.56 | −57 34 13.8 | LHS0413 | C1 |
| 18 12 21.88 | +05 24 04.5 | G140−042 | K1 |
| 20 32 51.67 | +41 53 54.7 | G209−035 | K1 |

Possible Subdwarfs

| R.A. (yr) | Decl. (′′) | Name | Site | Binary Note |
|-----------|------------|------|------|-------------|
| 00 12 46.96 | +54 39 45.4 | LHS1039 | K1<sup>a</sup> |
| 00 38 29.17 | +42 59 59.8 | HIP003022A | K1 |
| 00 40 49.27 | +41 11 13.8 | HD003765 | K1 |
| 00 49 34.47 | +97 57 09.6 | G243−041 | K1 |
| 01 18 41.07 | −00 52 03.0 | G070−035 | K1 |
| 01 38 14.19 | +17 49 45.9 | G003−035 | K1 |
| 03 23 33.48 | +43 57 26.2 | HIP015797 | K1 |
| 03 26 04.26 | +45 27 28.4 | HIP015998 | K1 |
| 03 43 55.34 | −19 06 39.2 | HD023356 | K1 |
| 05 55 03.80 | +61 10 00.6 | G246−035 | K1 |
| 05 54 04.24 | −60 01 24.5 | HD040307 | C1 |
| 06 06 03.51 | −59 32 35.3 | LS18118 | C1 |
| 06 06 24.66 | +63 50 06.6 | G249−037 | K1 |
| 06 58 27.86 | +18 59 49.7 | G080−001 | K1 |
| 07 08 04.23 | +29 50 04.1 | HD053927 | K1 |
| 07 58 04.37 | −25 37 35.8 | HD065486 | C1 |
| 08 04 34.65 | +15 21 51.3 | G040−005 | K1 |
| 08 59 07.08 | +11 31 21.4 | G009−013 | K1, C1 |
| 08 40 33.55 | +13 33 23.4 | G009−014 | K1 |
| 08 53 18.03 | −38 52 56.5 | HD074576 | C1 |
| 09 00 47.41 | +21 27 13.8 | G009−014 | K1 |
| 09 49 48.53 | +11 06 22.9 | G048−008 | K1, SB1 |
| 10 41 02.02 | +03 35 46.6 | HIP052285A | K1 |
| 10 53 23.80 | +09 44 21.8 | HIP052285B | K1 |
| 11 58 27.19 | −27 40 09.8 | LP097−008 | C1<sup>a</sup> |
| 12 15 10.55 | −10 18 44.9 | LHS0322 | C1 |
| 12 55 15.97 | +07 49 57.6 | HIP03630 | C1 |
| 12 59 01.56 | −09 50 02.7 | HIP063366 | C1<sup>b</sup> |
| 13 16 51.05 | +17 01 01.8 | GJ0505A | C1<sup>b</sup> |
| 13 31 06.17 | −04 06 20.0 | HIP056940 | C1<sup>a</sup> |
| 13 52 35.87 | −50 55 18.3 | HIP077424 | C1<sup>b</sup> |
| 13 57 18.14 | +06 58 55.2 | HIP68165 | C1<sup>a</sup> |
| 14 10 02.68 | −61 31 18.5 | LHS2871 | C1 |
| 15 20 26.13 | +00 14 40.7 | G015−017 | C1 |
| 16 09 42.79 | −56 26 42.5 | HD144628 | C1 |
| 18 09 37.41 | +38 27 28.0 | HD166620 | K1 |
| 18 26 10.08 | +08 46 39.3 | G141−008 | K1 |
| 19 12 45.01 | +18 48 45.6 | G142−015 | K1 |
| 19 37 14.10 | +70 44 29.1 | G260−028 | K1 |
| 19 50 55.86 | +03 56 48.3 | G023−012 | K1 |
| 19 58 35.40 | +81 16 12.2 | HIP098322 | K1 |
| 20 03 52.12 | +23 20 26.4 | HD190404 | K1 |

Notes:
- CPM Comp. indicates the companion designation.
- ρ′′ and θ′′ are the position angles in arcseconds.
- Epoch (yr) and Others provide additional details.

<sup>a</sup>Confirmed K and M Subdwarfs Beyond 60 pc
<sup>b</sup>Confirmed G or earlier than G-type Subdwarfs
<sup>c</sup>Possible Subdwarfs

**Table 2**

Resolved by speckle and see Table 2
1–9, the United States Naval Observatory (USNO) speckle camera (Mason et al. 2006) was used on the KPNO 4 m Mayall reflector. The same USNO speckle camera was also used on the CTIO 4 m Blanco telescope from 2006 March 9–13. Observations with this camera are made in or near V band, usually with a Strömgren γ filter (5500 ± 240 Å).

Speckle interferometry is a technique that is very sensitive to changes in observing conditions, particularly when coherence length (\(\rho_0\)) and time (\(t_0\)) are degraded from nominal conditions. Under nominal conditions the camera is capable of resolving companions as close as 30 milliseconds of arc (mas) on these telescopes, provided the companion has a small to moderate magnitude difference relative to the primary star (\(\Delta V < 3\)). The \(\Delta m\) limit of the USNO speckle camera during the three observing runs for this survey was verified with nightly observations of pairs with known magnitude differences (Mason 1996) with a wide range of separations. This detection capability, both for large magnitude difference and resolution close to the Rayleigh limit of the telescope, is qualitatively established to be highly dependent on ambient seeing. The faint limit of the USNO camera (\(V \sim 16\)) was not approached for the targets observed in this survey.

The calibration of the KPNO data was determined through the use of a double-slit mask placed over the “stove pipe” of the 4 m telescope during observations of a bright single star (as described in Hartkopf et al. 2000). This application of the well-known Young experiment allows for the determination of scale and position angle zero point without relying on binaries themselves to determine calibration parameters. Multiple observations through the slit mask yield an error in the position angle zero point of 0.11° and a separation error of 0.17%. These “internal errors” are undoubtedly underestimates of the true errors of these observations, which we anticipate are no larger than 0.5° and 0.5% in separation.

Because the slit-mask option is not available on the CTIO 4 m telescope, we calibrated the southern hemisphere data using observations of numerous wide equatorial binaries obtained at both the KPNO and CTIO telescopes. The calibration errors for these southern observations were somewhat higher in position angle than those achieved using the slit mask. After removal of outliers, observations of 47 pairs, including subdwarfs, O-, B-, G-, and M-type stars, in common to both telescopes yielded a zero-point error in \(\theta\) of 0.67° and a separation error of 1.44%. A small part of this error may be attributed to such effects as orbital motion of pairs between epochs of observation. Regardless, the errors are rather larger than desired, so more calibrations and quality control systems are in preparation.

To verify companion detection limits a variety of known pairs with reliable measures of differential magnitude and well-determined ephemeris were observed. This allows us to map out detection space for both magnitude difference and resolution limit. For stars that were observed as single we can state with high confidence that in the regime 30 mas < \(\rho < 1\) these stars have no companions with a magnitude difference of 3.0 or less. This regime is relaxed to 50 mas < \(\rho < 1\)” for systems observed with a wider filter bandpass (see below). In total, 124 systems have been observed using 130 total pointings, as listed in Table 1 (in six cases, wide companions were observed with separate pointings). In Table 1, Columns 1–3 are coordinates and star identifiers, Column 4 indicates the observing run (run epochs are given in the table notes), and Columns 5–9 give details of multiplicity. Seven targets have also been observed by Gizis & Reid (2000) using the Hubble Space Telescope (HST)/Wide-Field Planetary Camera 2 (WFPC2) and by Riaz et al. (2008) using the HST/Advanced Camera for Surveys (ACS); these are noted as “W” = WFPC2 or “A” = ACS in Column 9 for the HST instruments used to make the observations.

### 3.2. Wide Companion Search

In addition to our optical speckle efforts, we have also blinked digital scans of photographic plates to reveal any wide common proper motion pairs. Images 10′ × 10′ on a side were extracted for each field from the Digitalized Sky Survey (http://archive.stsci.edu/cgi-bin/dss_form) for two

### Table 1

(Continued)

| R.A.  | Decl.       | Name       | Site | CPM Comp. | \(\rho(\degree)\) | \(\theta(\degree)\) | Epoch (yr) | Others |
|------|-------------|------------|------|-----------|-------------------|-------------------|------------|--------|
| 20 13 59.85 | −00 52 00.7 | HD192263   | K1   |           |                   |                   |            |        |
| 20 37 58.49 | +77 14 02.3 | HIP101814  | K1   |           |                   |                   |            |        |
| 20 40 07.90 | +41 15 10.7 | HIP101989  | K1   |           |                   |                   |            |        |
| 22 35 13.31 | +18 06 20.1 | G083–034   | Cl   |           |                   |                   |            |        |
| 23 13 16.98 | +57 10 06.0 | HD219134   | K1, K2 |          |                   |                   |            |        |
| 23 19 58.19 | +28 52 03.9 | HD219953   | K1   |           |                   |                   |            |        |
| 23 35 49.27 | +00 26 43.6 | G029–050   | K1   |           |                   |                   |            |        |
| 23 36 26.80 | +33 02 15.1 | G128–084   | K1   |           |                   |                   |            |        |
| 23 50 40.40 | +17 20 40.5 | G030–024   | K1   |           |                   |                   |            |        |
| Notes. The site codes, K1, K2, and Cl, indicate that targets are observed at KPNO (2005.8625–2005.8692), KPNO (2007.5876–2007.6076), and CTIO (2006.1882–2006.2001), respectively. “WDS” in Column 7 indicates the CPM binary separations are from Washington Double Catalog (Mason et al. 2001). “SB1” and “SB2” in Column 8 indicate a single-line spectroscopic binary reported in Latham et al. (2002) and a double-line spectroscopic binary reported in Goldberg et al. (2002). “SB” indicates a spectroscopic binary from Dawson & De Robertis (2005), but no orbital elements are available. “SB?” for LHS 169 indicates a large \(V\) variation observed in Dawson & De Robertis (2005), and this system needs to be re-observed. “A” and “W” in Column 8 indicates targets have also been observed by HST/ACS and HST/WFPC2 in Riaz et al. (2008) and Gizis & Reid (2000).

a Observed with a wider filter (Johnson V: 545 ± 85 nm) and a lower microscope objective due to the character of target. Resolution limit for this observation is estimated at \(\rho < 0.05\).

b Known companion is too wide for detection here.

c Known companion has too large a \(\Delta\)m for detection here.
epochs corresponding to POSS-I red and POSS-II UKSTU red plates. No new companions were found through this effort. We have also cross-checked our target list on the Lépine Shara Proper Motion-North (LSPM-North) catalog to search for any recently discovered companions detected in that work. The search limits of LSPM-North are fully discussed in Lépine & Shara (2005), and all the wide companions are listed on LSPM-North catalog.

3.3. Results

Table 1 presents the complete list of targets observed during the three observing runs. The targets are sorted into four different categories: (1) confirmed K and M subdwarfs within 60 pc, (2) confirmed K and M subdwarfs beyond 60 pc, (3) G or earlier than G type subdwarfs, and (4) probable, but unconfirmed by spectroscopy, subdwarfs. Most are null detections. In some cases, known companions were not detected because the binary separation is larger than the speckle field of view (3′′ × 3′′) or the magnitude difference is larger than detectable with the optical speckle camera. For ~40% of the targets, an interference filter with a significantly larger FWHM was used to allow enough signal through the system for a companion search, at some cost in resolving the closest pairs. Specific stars for which the wider-band filter was used are noted. All of the observations are also available in the Fourth Interferometric Catalog (Hartkopf et al. 2001), which is updated frequently online.

We found two new companions (LHS0182B and G125−026B) and confirm two known companions (LHS0189B and G062−044B) and they are also listed in Table 2. The remaining 120 systems, including previously known double-line and single-line spectroscopic binaries (Latham et al. 2002; Goldberg et al. 2002) and HST (ACS/WFPC2) targets, have no companions detected by optical speckle interferometry. Table 2 lists the astrometric measures of the four detected companions, where Columns 1–3 identify the systems by providing the epoch-2000 coordinates, discovery designations (Washington Speckle Interferometer (WSI)) and alternate designations, and Columns 4–8 give the epoch of observation (expressed as a fractional Besselian year), the position angle (in degrees), the separation (in arcsec), and the magnitude difference. Note that the position angles have not been corrected for precession, and are thus based on the equinox for the epoch of observation. The differential magnitudes were determined by direct comparison of other pairs with known magnitude differences and are probably accurate to ±0.5mag.

LHS 182 is type M0.0VI (Gizis 1997) at 43.3 pc (van Altena et al. 1995). The newly resolved companion with ρ = 0′62 lies at a projected separation of 27 AU. LHS0189/LHS0190 is a common proper motion binary and their combined spectral type is an M3.0VI (Jao et al. 2008). The 2′81 projected separation is equivalent to 62 AU at a distance of 22.1 pc (Costa et al. 2006). Because this system is fainter than G 125−026 (discussed below), no speckle work was done on individual components.

G062−044 is a G-type subdwarf with [m/H] = −0.69 (Carney et al. 1994) and is a single-line spectroscopic binary (Latham et al. 2002) with a period of 3.3 years. Balega et al. (2006) used their speckle camera on the 6 m telescope of the Special Astrophysical Observatory to resolve this system with ρ = 0′′082 at 62.5 in 2001.271. Our data show the companion at ρ = 0′13 and 147′6 in 2006.192, implying significant orbital motion.

Carney et al. (1994) reported G125−026 to have [m/H] = −1.5, while its V − K = 2.5 indicates it is a mid-K type subdwarf. Because this system has a wide separation (3′′29 along the diagonal of our field of view, corresponding to a projected separation of 181 AU at 55.2 pc), both components were observed. No companion was detected for either component. However, G125−026 is in a crowded field, so the companion is possibly optical. A follow-up observation is necessary to confirm common proper motions.

4. Multiplicity Comparison with Similar Surveys

Our sample is a mixture of confirmed K/M subdwarfs, G subdwarfs, and subdwarf candidates. Here we use the 62 systems in the confirmed K/M-type subdwarf category as the benchmark sample for our multiplicity discussion. For these 62 systems, the (single:double:triple:quadruple) ratios are 46:12:2:2. Hence, the fraction of K/M type subdwarf multiple systems for this sample is 26 ± 6%.

A few recent subdwarf companion surveys have also yielded relatively low multiplicity fractions. Gizis & Reid (2000) used HST/WFPC2 to observe 11 cool subdwarfs and failed to detect any companions. We observed five of those targets, and also detected no companions. Lépine et al. (2007) observed 18 subdwarfs from Lick Observatory using the AO-laser guide star system and resolved only one system, LSR 1530 + 5608. Recently, Riaz et al. (2008) reported no companions detected by HST/ACS for 19 m-subdwarfs, other than the known wide common proper motion system LHS2139/2140 (ρ = 6′2). We observed two of those targets, LHS 161 and LHS 482, and also detected no companions. However, C. R. Gelino (2007, private communication) used the Keck AO-natural guide star system to observe 54 low metallicity stars of spectral type from G to M, and detected seven possible companions, five of which are new. Recently, a late-type subdwarf, LSR 1610−00 (Dahn et al. 2008, V − I = 4.05, and d = 32.5 pc), has been discovered to be a binary through parallax observations, not through a high-resolution companion survey.

The binary rate from the combined samples of Gizis & Reid (2000), Lépine et al. (2007), Riaz et al. (2008), and Dahn et al. (2008), which had no stars in common, is only 6% (3/49). Gelino’s work yields a higher binary rate of 13%, but the sample
is a mixture of G-, K- and M-type subdwarfs, so the results are not immediately comparable to the other surveys. Our survey is the largest available to date, and so far is the only survey for which all targets have trigonometric parallaxes, in a volume-limited sample reaching to 60 pc (details will be included in the next paper of this series).

5. MULTIPlicity COMPARISON WITH K- AND M-TYPE DWARFS

Binary surveys have been carried out for M dwarfs, the main-sequence counterparts of the stars surveyed here, and comparisons between dwarf and subdwarf multiplicities are now possible. Henry & McCarthy (1999) used an infrared speckle camera to survey for stellar and brown dwarf companions to 27 known M dwarfs within 5 pc north of decl. = −30°, and found a multiplicity fraction of 34 ± 9%. Henry (1992) expanded the sample to 99 m dwarfs within 8 pc north of decl. = −25°, and found a consistent multiplicity fraction of 31 ± 6%. Fischer & Marcy (1992) did a complete analysis of companion searches around 100 m dwarfs within 20 pc, including radial velocity, visual (astrometric), infrared imaging, and the infrared speckle efforts. They found a multiplicity fraction of 42 ± 9% after considering the incompleteness of the surveys. Reid & Gizis (1999, hereafter RG97) compiled a sample of 106 low-mass stars (80% of which were M dwarfs) north of decl. = −30° and found a multiplicity fraction of 35 ± 5%. More recently, Delfosse et al. (2004) observed 100 m dwarfs within 9 pc using radial velocity and AO observations, and found a multiplicity fraction of 26 ± 3%. Many of the studies include the same stars, and all reach the same conclusion—the multiplicity of M dwarfs is roughly 30%–40%.

Here we compare our results to the work of RG97. In order to match our sample of K/M subdwarfs, non-K/M-type dwarfs are excluded from RG97, leaving 92 stars. Of these, 58 are single and 34 are multiples (counting only companions with stellar masses, i.e., masses greater than 0.08 $M_{\odot}$), yielding a multiplicity fraction of 37 ± 5%. Hence, the multiplicity rate difference between cool dwarfs and subdwarfs is 11%.

Table 3 compares the techniques used for our sample and the RG97 sample. All of our subdwarf targets have been searched using the optical speckle camera, which will detect companions in the separation regime 50 mas < $\rho$ < 1′′ with a magnitude differences of 3.0 or less, and by blinking photographic plates for wide common proper motion companions. Although 43 targets in our sample have radial velocity measurements, only six systems have been observed for spectroscopic binaries using radial velocity surveys, so spectroscopic companions are almost certainly underrepresented. Only two other stars (LHS 64 and LHS 482) in Table 1 are reported to be spectroscopic binaries (Dawson & De Robertis 2005), but no orbital elements are available.6

Among the 92 systems selected from the RG97 work, 68 were observed by Henry (1992) using an infrared speckle camera, which detects companions in the regime 0.2″ < $\rho$ < 2.0″ on the Steward Observatory 90 inch telescope used for the observations at 2.2 μm. In addition, 36 systems were observed by Marcy & Benitz (1989) and Delfosse et al. (1999) during long-term radial velocity surveys covering orbital periods of a few days to a few years. More details about the companion search for this sample are discussed in RG97. Consequently, many of the 92 stars in our comparison sample have been searched for companions with separations of a few AU to thousands of AU.

The top two plots of Figure 1 illustrate the distribution of companion separations from the dwarf and subdwarfs samples. It appears that cool subdwarf binaries tend to have larger separations. However, as discussed above, our subdwarf sample has not yet been systematically searched for close companions via long-term radial velocity surveys. Note that the optical and infrared speckle efforts search similar spatial regimes—the factor of roughly 5 difference in resolution limit is compensated for because the dwarfs are closer than the subdwarfs by about a factor of 5. Although the dearth of close binaries in our sample may be due to lack of observational coverage, Abt (2008) offered a possible scenario to explain why metal-poor stars might have lower multiplicity fractions than more metal-rich stars. According to N-body simulations, binaries become tighter if they survive interactions in dense clusters. This implies that the metal-poor field subdwarfs we see today may have had shorter lifetimes in clusters than generally younger, more metal-rich stars. Clearly, a subdwarf radial velocity survey of K/M subdwarfs needs to be done to confirm or refute our tentative conclusion that subdwarfs have fewer binaries.

The bottom of Figure 1 plots the LFs from both surveys to see if there are any significant differences. The LF of K/M subdwarfs has two prominent peaks, in the $M_{K_s} = 4$–5 bin and in the $M_{K_s} = 7$–8 bin. In contrast, the LF of dwarfs looks more like a normal distribution. There are several reasons for these differences. First, our sample lacks K-type subdwarfs. As discussed in Jao et al. (2008), K-type subdwarfs are difficult to separate spectroscopically from dwarfs using low-resolution spectra covering from 6000 Å to 9000 Å (the region widely used to identify cool subdwarfs). Consequently, our current K-type subdwarfs within 60 pc are undersampled. Second, most of the subdwarfs with $M_{K_s} < 6.0$ in our sample were selected spectroscopically from Carney et al. (1994), so few subdwarfs with $M_{K_s} = 5$–6 were included in our survey. Third, very few subdwarfs fainter than $M_{K_s} = 9$ within 60 pc are yet known. Thus, the LFs of the two samples appear different. Will subdwarf multiplicity be the same as that of dwarfs if we increase the 60 pc sample to smooth out the LF, and we expand our companion searches? While only future efforts can answer this question for K/M stars, we can make some comparisons now by discussing the multiplicity fractions of A- to G-type stars for both dwarf and subdwarf samples.

6 Dawson & De Robertis (2005) reported LHS 169 has a large radial velocity variation, so it is flagged as a “possible” spectroscopic binary by them; we count it as a binary in this analysis.

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Table 3

| Samples | $V_{rad}$ Survey (%) | Speckle Interferometry (%) | Blinking Plates (%) |
|---------|----------------------|-----------------------------|---------------------|
| This work | 14                   | 100 (at V band)             | 100                 |
| RG97    | 39                   | 74 (at near-IR band)        | 100                 |

6 Dawson & De Robertis (2005) reported LHS 169 has a large radial velocity variation, so it is flagged as a “possible” spectroscopic binary by them; we count it as a binary in this analysis.
Figure 1. Top: comparison of the secondary projected separations of our sample and RG97. Because two of the objects in our sample, G016−009 and G129−042, are SB2, they are plotted at their minimum separations \((a \sin i, \text{ where } i = 90^\circ)\), as is also done for two SB2 (GJ 268 and GJ 829) in RG97. Three spectroscopic binaries in our sample (LHS 64, LHS 482, and 169) and two in RG97 (G 041−014 and G 203−047) do not have \(a \sin i\) available in publications, so they are not shown in these top two plots. Bottom: comparison of the LFs of our sample and RG97. In this figure we plot the primary stars only. The black bars indicate primary stars in binary systems and gray bars indicate single star systems. Because SB2 systems do not have magnitude differences available at \(K\) band, SB2 systems are plotted using combined photometry, instead of using deconvolved single star photometry. For systems with only \(\Delta V\) available, we use the approximate relation \((\Delta m_K/\Delta m_V = 0.53)\) discussed in Probst (1981) to convert it to \(\Delta K\).

Table 4
Comparison of Multiplicity Results

| Stellar Type | A–G or G-type (%) | K- and M-type (%) |
|--------------|-------------------|------------------|
| Dwarfs       | 57 (DM91)         | 37 (RG97)        |
| Subdwarfs    | 15–30 (Mixed)     | 26 (This work)   |

CCD images. (3) Zinnecker et al. (2004) used optical speckle interferometry, AO and direct imaging methods and found the binary fraction of the combined Carney–Latham (Carney et al. 1994) and Norris (1986) samples to be up to 15%, depending on the flux ratio \(F_{primary}/F_{secondary}\) cutoff assigned. Again, most of their targets were A, F, and G subdwarfs as well. (4) Rastegaev et al. (2007) observed 106 systems from the Carney–Latham sample also using optical speckle, and they found their multiple star fraction to be 33\% (75 singles and 35 multiples). Based on these four surveys, the multiplicity rate is between 15\% and 33\%.

Table 4 outlines the differences noted to date between main-sequence and subdwarf multiplicities. From this table, there are two ways to interpret the results. We can either compare the multiplicity rate (horizontally) between A–G and K- and M-type stars, or we can compare the multiplicity difference (vertically) between dwarfs and subdwarfs in each type. Before we compare horizontally or vertically, we choose the multiplicity fractions of dwarfs as reference frames. In other words, we assume the multiplicity studies for dwarfs are comprehensive and complete. Note that the multiplicity rate for late-type stars should be less than for the early-type stars, because of the decreased companion mass range. The results of companion surveys of subdwarfs should also follow this trend.

**Horizontal comparison.** Given that the quantity of M dwarf multiples is roughly 65\% that of G dwarfs for main-sequence stars, we might expect either (1) A–G-type subdwarfs should be as high as 40\%, or (2) the K and M subdwarfs multiplicity fraction should be no larger than 20\%, if we assume the binary formation theory is independent of the metallicity. The first expectation implies that the multiplicity rate of subdwarfs shown in the Table 4 could be underestimated. The second expectation implies that our volume-limited sample contains more binaries than it should, so more single stars within 60 pc are missing from this sample. Because most of these early-type subdwarfs have been searched for companions from close to wide separations, we think the multiplicity rate for them will not be much different. However, we are sure that the sample of K and M subdwarfs within 60 pc is incomplete, because (1) historically these stars have been neglected from trigonometric parallax observations and (2) we have not completed the optical speckle survey of the entire cool subdwarfs within 60 pc. Consequently, a census of nearby K and M subdwarf sample is necessary to understand this horizontal comparison, and we are continuing to make subdwarf parallax observations through the Cerro Tololo Inter-American Observatory Parallax Investigation (CTIOPI) project.

**Vertical comparison.** It appears that the multiplicity rate for subdwarfs is less than for dwarfs, but the differences are not equal between early and late type stars. For A–G-type stars, the
subdwarf multiplicity rate is only about 34% of dwarfs. For K- and M-type stars, the subdwarf multiplicity rate is about 34% of that of dwarf. This shows they are different, but recent studies do not all support this trend.

Latham et al. (2002) found in their high proper motion sample, which contains both old and young populations, that there is no significant difference in the binary fraction of the two populations. Grether & Lineweaver (2007) argued stellar companions tend to be more abundant around low-metallicity hosts (see their Figure 15) when they examined the relation between frequency close companions and the metallicity of F, G, and K stars.

Theoretical work is also in conflict with this trend. Bate (2005) had investigated how the metallicity of a molecular cloud affects fragmentation. By setting the critical density of the equation of state a factor of 9 lower than normal calculation (Bate et al. 2003), he tried to mimic the thermal dynamics for molecular gas that has a lower metallicity. He found this does not affect the ability to form close binaries. However, this low-density (metallicity) calculation generates slightly more binaries (17%, 19 singles, and four multiples) than the other calculation (13%, 26 singles, and four multiples).

Fischer & Valenti (2005) also found the number of stars with planets decreases as a power law when primary stars decrease their metallicity (see their Figure 5). If we assume there is some degree of similarity between planet formation and binary formation as a function of metallicity, fewer subdwarf companions are expected.

Apparently, these multiplicity comparisons are still unsettled, no matter if they are compared horizontally or vertically in Table 4. Consequently, the following investigations are necessary to better understand the multiplicity differences between cool dwarfs and subdwarfs:

1. As we discussed above, increasing the total number of nearby cool subdwarfs is one of the keys to understanding their multiplicity. We can select these subdwarfs through reduced proper motion diagram, then observe spectroscopically to confirm their luminosity classes. Parallax observations can then be carried out to secure their distances.

2. Abt (2008) concluded that the multiplicity discrepancy between metal-poor and metal-rich stars depends mainly on the equipment/techniques used. He said using high spectral resolution spectra for finding spectroscopic binaries tends to conclude there is no difference in the binary frequency, but while using low spectral resolution spectra in radial velocity survey concludes that the metal-poor stars have fewer binary than metal-rich stars. As Figure 1 shows, currently there are only two cool subdwarf companions (2/16 ≈ 13%) within 10 AU and both of them are plotted in projected minimum separations (i = 90°). Hence, these K and M subdwarfs need to have a completed radial velocity survey to detect any possible close binaries.

On the other hand, Chanamé & Gould (2004) and Lépine & Shara (2005) have reported many wide common proper motion (CPM) subdwarf binaries on the reduced proper motion diagram. Unfortunately, all of these CPM binaries need to have spectroscopic follow-up to confirm their luminosity classes, and need parallax observations. If the radial velocity surveys for cool subdwarfs fail to detect companions closer than 10 AU, it will give an important observational support to the theory that metal-poor stars lack short-period binaries.

3. Tokovinin (2004) concluded that systems of multiplicity three and higher are frequent, accounting for about 20% of the total population of stellar systems, so forming hierarchical multiples is not a rare phenomenon. Currently, our sample contains four systems (6%) with three or more components. Among these four systems, there is only one system with $V - K_s > 2.6$, and the rest of these systems are K-type subdwarfs. Supposedly, those hierarchical multiples of M-type subdwarfs should exist, but have not been identified.

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