MULTIPLETY OF THE GALACTIC SENIOR CITIZENS: A HIGH-RESOLUTION SEARCH FOR COOL SUBDWARF COMPANIONS

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ABSTRACT

Cool subdwarfs are the oldest members of the low-mass stellar population. Mostly present in the galactic halo, subdwarfs are characterized by their low-metallicity. Measuring their binary fraction and comparing it to solar-metallicity stars could give key insights into the star formation process early in the Milky Way’s history. However, because of their low luminosity and relative rarity in the solar neighborhood, binarity surveys of cool subdwarfs have suffered from small sample sizes and incompleteness. Previous surveys have suggested that the binary fraction of red subdwarfs is much lower than for their main-sequence cousins. Using the highly efficient Robo-AO system, we present the largest high-resolution survey of subdwarfs, sensitive to angular separations ($\rho \geq 0.015$) and contrast ratios ($\Delta m \leq 6$) invisible in past surveys. Of 344 target cool subdwarfs, 43 are in multiple systems, 19 of which are newly discovered, for a binary fraction of $12.5 \pm 1.9\%$. We also discovered seven triple star systems for a triple fraction of $2.0 \pm 0.8\%$. Comparisons to similar surveys of solar-metallicity dwarf stars gives a $\sim 3\sigma$ disparity in luminosity between companion stars, with subdwarfs displaying a shortage of low-contrast companions. We also observe a lack of close subdwarf companions in comparison to similar-mass dwarf multiple systems.

Key words: binaries: close – instrumentation: adaptive optics – methods: data analysis – stars: late-type – subdwarfs – techniques: high angular resolution

1. INTRODUCTION

Cool subdwarfs are the oldest members of the low-mass stellar population, with spectral types of G, K, and M, masses between $\sim 0.6$ and $\sim 0.08 M_\odot$, and surface effective temperatures between 4000 and 2300 K (Kaltenegger & Traub 2009). First coined by Kuiper (1939), subdwarfs are the low-luminosity, metal-poor ([Fe/H] $< -1$) spectral counterparts to the main sequence dwarfs. On a color–magnitude diagram, subdwarfs lie between white dwarfs and the main sequence (Adams 1915). With decreased metal opacity, subdwarfs have smaller stellar radii and are bluer at a given luminosity than their main sequence counterparts (Sandage & Eggen 1959). These low-mass stars are members of the Galactic halo (Gould 2003) and have higher systematic velocities and proper motions than disk dwarf stars. Traditionally subdwarfs have been identified using high proper motion surveys. Although 99.7% of stars in the galaxy are disk main sequence, statistically there are more subdwarfs in these high PM surveys (Reid & Hawley 2005). Verification and precise spectral typing of cool subdwarfs can be performed by measuring molecular lines, as defined first by Gizis (1997). Lépine et al. (2007) introduced a refined system, using spectroscopic measurements of a large 1983 star survey to standardize the subdwarf metallicity subclasses and spectroscopic sequence.

The search for companions to stars of different masses gives clues to the star formation process, as any successful model must account for both the frequency of the multiple star systems and the properties of the systems. In addition, monitoring the orbital characteristics of multiple star systems yields information otherwise unattainable for single stars, such as relative brightness and masses of the components (Goodwin et al. 2007), lending further constraints to mass–luminosity relationships (Chabrier et al. 2000).

Old population II stars are important probes for the early history of star formation in the galaxy (Zhang et al. 2013). The formation process of low-mass stars remains less well understood than for solar-like stars. Although multiple indications suggest they form as the low-mass tail of regular star formation (Bourke et al. 2006), other mechanisms have been proposed for some or all of these objects (Goodwin & Whitworth 2007; Thies & Kroupa 2007; Basu & Vorobyov 2012). A firm binary fraction for low-metallicity cool stars could assist in constraining various formation models. This again motivates the need for a comprehensive binarity survey, sensitive to small angular separations.

The multiplicity of main sequence dwarfs has been well explored in the literature. A consistent trend that has pervaded is that the percentage of stars with stellar companions seems to depend on the mass of the stars. For AB-type stars, Peter et al. (2012) used a sample of 148 stars to determine a companion fraction of $\sim 70\%$. For solar type stars (FGK-type), around 57% have companions (Duquennoy & Mayor 1991), although Raghavan et al. (2010) have revised the fraction down to $\sim 46\%$. Fischer & Marcy (1992) looked at M-dwarfs and found a multiplicity fraction of $42 \pm 9\%$. More recently, Janson et al. (2012) found a binary fraction for late K- to mid-M-type dwarfs of $27 \pm 3\%$ from a sample of 701 stars. For late M-dwarfs, a slightly lower fraction was found by Law et al. (2006b) of $7\% \pm 3\%$. Extending their previous study for mid/late M-type dwarfs, M5–M8, Janson et al. (2014) find a multiplicity fraction of 21%–27% using a sample of 205 stars.

While the multiplicity of dwarf stars has been heavily studied with comprehensive surveys, detailed multiplicity studies of low-mass subdwarfs have, historically, been hindered by their low luminosities and relative rarity in the solar neighborhood. Within 10 pc, there are three low-mass subdwarfs, compared to...
243 main sequence stars (Monteiro et al. 2006). Subsequently, multiplicity surveys of cool subdwarfs have been relatively small. The largest, a low-limit angular resolution search by Zhang et al. (2013) mined the Sloan Digital Sky Survey (SDSS; York et al. 2000) to find 1826 cool subdwarfs, picking out subdwarfs by their PMs and identifying spectral type by fitting an absolute magnitude-spectral type relationship. They find 45 subdwarfs multiple systems in total, with 30 being wide companions and 15 partially resolved companions. When adjusting for the incompleteness of their survey, an estimate of the binary fraction of >10% is predicted. The authors note the need for a high spatial resolution imaging survey to search for close binaries (<100 AU) and put tighter constraints on the binary fraction of cool subdwarfs.

The high-resolution subdwarf surveys completed thus far have been comparatively small. Gizis & Reid (2000) detected no companions in a sample of eleven cool subdwarfs. Riaz et al. (2008) similarly found no companions in a sample of 19 M-subdwarfs using the Hubble Space Telescope. Lodieu et al. (2009) reported one companion in a sample of 33 M-type subdwarfs. Jao et al. (2009) found four companions in a sample of 62 cool subdwarf systems. With the high variance in small number statistics, the relationship between dwarf and subdwarf multiplicity fractions remains inconclusive.

We present here the largest high resolution cool subdwarf multiplicity survey yet performed, making use of the efficient Robo-AO system (Baranec et al. 2014). The Robo-AO system allows us to detect more cool and close companion stars in a much larger sample size than previously possible. This survey combines previously known wide proper-motion, spectroscopic binaries, and high angular resolution images able to detect companions with $\rho > 0.15$ arcsec and $\Delta m_i \leq 6$.

The paper is organized as follows. In Section 2 we describe the target selection, the Robo-AO system, and follow-up observations. In Section 3 we describe the Robo-AO data reduction and the companion detection and analysis. In Section 4 we describe the results of this survey, including discovered companions, and compare to similar dwarf surveys. The results are discussed in Section 5 and put in context of previous literature. We conclude in Section 6.

2. SURVEY TARGETS AND OBSERVATIONS

2.1. Sample Selection

We selected targets from the 564 spectral type F- through M-subdwarf candidates studied by Marshall (2007). These targets were selected from the New Luyten Two-Tenths catalog (NLTT; Luyten 1979; Luyten & Hughes 1980) of high proper motion stars (>0.18 arcsec yr$^{-1}$) using a reduced proper motion diagram (RPM). To distinguish subdwarf stars from their solar-metallicity companions on the main sequence, the RPM used a $(V - J)$ optical–infrared baseline, a technique first used by Salim & Gould (2002), rather than the shorter $(B - R)$ baseline used by Luyten. This method uses the high proper motion as a proxy for distance and the blueness of subdwarfs relative to equal luminosity dwarf stars to separate out main sequence members of the local disk and the halo subdwarfs (Marshall 2008). The RPM, $H_M$, is defined as

$$H_M = m + 5 \log \mu + 5$$

where $m$ is the apparent magnitude and $\mu$ is the proper motion in $\text{arcsec yr}^{-1}$. The discriminator, $\eta$, developed by Salim and Gould to separate luminosity classes, is defined as

$$\eta(H_V, V - J, \sin b) = H_V - 3.1(V - J) - 1.47 | \sin b | - 7.73$$

where $b$ is the Galactic latitude. The RPM diagram for the revised NLTT (rNLTT) catalog (Gould & Salim 2003) and our subdwarf targets is presented in Figure 1. The improved photometry of Marshall (2007) placed 12 of the original suspected subdwarfs outside the subdwarf sequence. These stars were not included in our sample. Possible dwarf contamination of our sample is expected to be small, as described in Section 3.3. Of the 552 subdwarfs confirmed by Marshall, a randomly selected sample of 348 G-, K-, and M-subdwarfs were observed by Robo-AO when available between other high priority surveys.

2.2. Observations

2.2.1. Robo-AO

We obtained high-angular-resolution images of the 348 subdwarfs during 32 separate nights of observations between 2012 September 3 and 2013 August 21 (UT). The observations were performed using the Robo-AO laser adaptive optics system (Riddle et al. 2012; Baranec et al. 2013, 2014) mounted on the Palomar 60 inch telescope. The first robotic laser guide star adaptive optics system, the automatic Robo-AO system can efficiently observe large, high-resolution surveys. All images were taken using the Sloan $i$-band filter (York et al. 2000) and with exposure times of 120 s. Typical seeing at the Palomar Observatory is between 0.8 and 1.8, with the median around 1.1 (Baranec et al. 2014). The typical FWHM (diffraction...
Detector format 1024 × 2 pixels
Field size 44″ × 44″
Observation dates 2012 Sep 1–2013 Aug 21
Targets observed/hour 20
Subdwarf targets 344
Exposure time 120 s
Pixel scale 43.1 mas/pix

Figure 2. (a) Histogram of magnitudes in V-band of the 348 observed subdwarfs. (b) Histogram of the (V−J) colors of the observed subdwarf sample, with approximate spectral types regions G, K, and M marked, using the spectral color indices of Ducati et al. (2001). Both plots use the photometry of Marshall (2007).

Table 1
The Specifications of the Robo-AO Subdwarf Survey

| Filter                | Sloan i'-band |
|-----------------------|---------------|
| FWHM resolution       | 0″15          |
| Field size            | 44″ × 44″     |
| Detector format       | 1024² pixels  |
| Pixel scale           | 43.1 mas/pix  |
| Exposure time         | 120 s         |
| Subdwarf targets      | 344           |
| Observation dates     | 2012 Sep 1–   |
|                       | 2013 Aug 21   |

limited) resolution of the Robo-AO system is 0″12–0″15. Images are recorded on an electron-multiplying CCD (EMCCD), allowing short frame rates for tip and tilt correction in software using a natural guide star (m_V < 16) in the field of view (FOV). Specifications of the Robo-AO system are summarized in Table 1.

The images were reduced by the Robo-AO imaging pipeline described in Law et al. (2009, 2014). The EMCCD output frames are dark-subtracted and flat-fielded and then, using the Drizzle algorithm (Fruchter & Hook 2002), stacked and aligned, while correcting for image motion using a star in the field. The algorithm also introduces a factor of 2 up-sampling to the images. Since the subdwarf targets are in relatively sparse stellar fields, for the majority of the images the only star visible is the target star and it was thus used to correct for the image motion.

2.2.2. Keck LGS-AO

Six candidate multiple systems were selected for re-imaging by the NIRC2 camera behind the Keck II laser guide star adaptive optics system (van Dam et al. 2006; Wizinowich et al. 2006), on 2014 August 17 (UT) to confirm possible companions. The targets were selected for their low significance of detectability, either because of low contrast ratio or small angular separation. The observations were done in the K'- and H-bands with three 90 s exposures for two targets and three 30 s exposures for five targets in a three-position dither pattern that avoided the noisy, lower-left quadrant. We used the narrow camera setting (0″0099/pix), which gave a single-frame FOV of 10″ × 10″.

2.2.3. SOAR Goodman Spectroscopy

We took spectra of 24 of the subdwarfs using the Southern Astrophysical Research Telescope (SOAR) and the Goodman Spectrograph (Clemens et al. 2004) on 2014 July 15. We observed 12 targets with companions and 12 single stars from the subdwarf sample as reference. The spectra were taken using a 930 lines/mm grating with 0.42 Å/pixel, a 1″07 slit, and exposure times of 480 s.

3. DATA REDUCTION AND ANALYSIS

3.1. Robo-AO Imaging

3.1.1. Target Verification

To verify that each star viewed in the image is the desired subdwarf target, we created Digital Sky Survey cutouts of similar angular size around the target coordinates. Each image was then manually checked to assure no ambiguity in the target star. The vast majority of the targets are in relatively sparse stellar regions. Four of the target stars in crowded fields whose identification was ambiguous were discarded, leaving 344 verified subdwarf targets.

3.1.2. Point-spread Function (PSF) Subtraction

To locate close companions, a custom locally optimized PSF subtraction routine (Law et al. 2014) based on the Locally Optimized Combination of Images algorithm (Lafrenière et al. 2007) was applied to centered cutouts of all stars. Successful PSF subtraction requires similar reference images, taken at similar times, with similar instruments, and with reference stars of similar brightnesses. The set of subdwarf observations taken at similar times meet these criteria and were used as references, instead of dedicated reference observations, thus optimizing survey efficiency. This is made possible by the improbability of having a companion in the same position for two different targets.

For each target image and for 20 reference images selected as the closest to the target image in observation time, the region around the star was subdivided into polar sections, five up-sampled pixels in radius and 45° in angle. A locally optimized estimate of the PSF for each section was then generated using a linear combination of the reference PSFs. The algorithm begins with an average over the reference PSFs, then uses a downhill simplex algorithm to optimize the contributions from each reference image to find the best fit to the target image. The optimization is done on several coincident sections simultaneously to minimize the probability of subtracting out a real companion, with only the central region outputted to the final PSF. This also provides smoother transitions between adjacent sections as many of the image pixels were shared in the optimization.
After iterating over all sections of the image, the final PSF is an optimal local combination of all the reference PSFs. This final PSF is then subtracted from the original reference image, leaving residuals that are consistent with photon noise. Figure 3 shows an example of the PSF subtraction performance.

We ran the PSF subtraction algorithm on all our targets out to a radius of 2 ″. We subsequently reran the automated companion detection routine on the subtracted images to find significant (>5σ) close companions, and manually checked the results.

### 3.1.3. Automated Companion Detection

To efficiently find companions in the large data set, we developed a custom search algorithm, based on the method described in Law et al. (2014). The algorithm searches every four-pixel diameter aperture in the image and compares the signal inside the aperture to the average noise level at that radius from the target star. The detected companions were then manually checked, eliminating spurious detections with dissimilar PSFs to the target star and those having characteristics of a cosmic ray hit, such as a single bright pixel or bright streak. The detection significance of found companions is listed in Table 4.

### 3.1.4. Imaging Performance Metrics

The two dominant factors that effect the image performance of the Robo-AO system are seeing and target brightness. To further classify the image performance for each target an automated routine was ran on all images. Described in detail in Law et al. (2014), the code uses two Moffat functions fit to the PSF to separate the widths of the core and halo. We found that the core size was an excellent predictor of the contrast performance, and used it to group targets into three levels (low, medium, and high). Counter-intuitively, the PSF core size decreases as image quality decreases. This is caused by poor signal-to-noise ratio on the shift-and-add image alignment used by the EMCCD detector. The frame alignment subsequently locks onto photon noise spikes, leading to single-pixel-sized spikes in the images (Law et al. 2006b, 2009). The images with diffraction limited core size (∼0 ″15) were assigned to the high-performance group, with smaller cores assigned to lower-performance groups. For our target observations, 32% fall in the low performance group, 43% in the medium performance group, and 25% in the high performance group.

Using a companion-detection simulation with a group of representative targets, we determine the angular separation and contrast consistent with a 5σ detection. For clarity, the contrast curves of the simulated targets are fitted with functions of the form \( a - b(r - c) \) (where \( r \) is the radius from the target star and \( a, b, \) and \( c \) are fitting variables). Contrast curves for the three performance groups are shown in Section 5 in Figure 9 passing reference.

### 3.1.5. Contrast Ratios

For wide companions, the binaries’ contrast ratio was determined using aperture photometry on the original images. The aperture size was determined uniquely for each system based on separation and the presence of non-associated background stars.

For close companions, the estimated PSF was used to remove the blended contributions of each star before aperture photometry was performed. The locally optimized PSF subtraction algorithm attempts to remove the flux from companions using other reference PSFs with excess brightness in those areas. For detection purposes, we use many PSF core sizes for optimization, and the algorithm’s ability to remove the companion light is reduced. However, the companion is artificially faint as some flux has still been subtracted. To avoid this, the PSF fit was redone excluding a six-pixel-diameter region around the detected companion. The large PSF regions allow the excess light from the primary star to be removed, while not reducing the brightness of the companion.

### 3.1.6. Separation and Position Angles

Separation angles were determined from the raw pixel positions. Uncertainties were found using estimated systematic errors due to blending between components. Typical uncertainty in the position for each star was 1–2 pixels. Position angles were calculated using a distortion solution produced using Robo-AO measurements for a globular cluster.\(^\text{5}\)

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\(^\text{5}\) S. Hildebrandt (2013, private communication).
3.2. Previously Detected Binaries

To further realize our goal of a comprehensive cool subdwarf survey, we included in our statistics previously confirmed binary systems in the literature with separations outside of our FOV. Common proper motion is a useful indicator of wider binary systems. Wide (>30") common proper motion companions among our target subdwarfs were previously identified in the Revised New Luyten Two-Tenths catalog (rNLTT; Sahim & Gould 2002; Chanamé & Gould 2004), and a search by López et al. (2012) of the Lepine and Shara Proper Motion-North catalog (LSPM) (Lépine & Shara 2005). None of our target stars overlap with the large survey of (Zhang et al. 2013), as our targets are several magnitudes brighter on average.

The target list was also cross-checked against the Ninth Catalogue of Spectroscopic Binary Orbits (SwP; Pourbaix et al. 2004), a catalog of known spectroscopic binaries available online. While these systems were included in the total subdwarf binary numbers, the compilatory nature of this catalog leaves some uncertainty in the completeness of the spectroscopic search.

3.3. Spectroscopy

To further verify that the targets selected are cool subdwarfs, we took spectra of 7% of the total survey and 31% of the candidate companion systems. Past spectroscopic studies of cool subdwarfs at high resolution have proven difficult as, at the low temperatures present, a forest of molecular absorption lines conceals most atomic lines used in spectral analysis. Subdwarfs can be classified spectroscopically using two molecular lines (Gizis 1997). Comparing titanium oxide (TiO) bands to metal hydride bands (typically CaH in M-subdwarfs), Gizis classified two groups, the intermediate and extreme subdwarfs. As the metallicity decreases, the TiO adsorption also decreases, but the CaH remains largely unaffected for a given spectral type. This classification system was expanded and revised to include ultra subdwarfs by Lépine et al. (2007), who introduced the new useful parameter 

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right ascension and declination of \(>8 \text{ mas yr}^{-1}\). To locate possible fake companions, we use the high-proper motion survey LSPM (Lépine & Shara 2005), which is estimated over 99\% complete in high galactic latitudes \(|b| > 15^\circ\), where most of our targets lie. Out of approximately 21 million possible associations, we identified 12,451 pairs of stars, one of our subdwarf targets and an LSPM star, which have similar (below our dissociation threshold) proper-motion magnitude and direction. Known associated stars were removed from this sample. With our relatively small FOV and the large sky coverage of the LSPM, the probability of any of these pairs falling within our FOV is a remote \(9.1 \times 10^{-8}\).

**Figure 4.** Extracted spectra for NLTT 52532 showing subdwarf characteristics, most apparent the weakness of the 7050 Å TiO band and strength of the 6380 Å CaH band. The y-axis is given in normalized arbitrary flux units.

**Table 2**

| NLTT  | \(m_v\) | ObsID | Companion? |
|-------|--------|-------|------------|
| 2205  | 14.0   | 2014 Jul 14 | Yes        |
| 7301  | 14.9   | 2014 Jul 14 | Yes        |
| 7914  | 14.3   | 2014 Jul 14 | Yes        |
| 9597  | 12.0   | 2014 Jul 14 | ...        |
| 9898  | 14.2   | 2014 Jul 14 | ...        |
| 10022 | 15.8   | 2014 Jul 14 | ...        |
| 10135 | 15.7   | 2014 Jul 14 | ...        |
| 33971 | 12.8   | 2014 Jul 14 | ...        |
| 37342 | 14.4   | 2014 Jul 14 | Yes        |
| 37807 | 12.0   | 2014 Jul 14 | ...        |
| 40022 | 13.9   | 2014 Jul 14 | ...        |
| 40313 | 13.7   | 2014 Jul 14 | ...        |
| 41111 | 13.7   | 2014 Jul 14 | ...        |
| 44039 | 11.5   | 2014 Jul 14 | ...        |
| 44568 | 12.3   | 2014 Jul 14 | ...        |
| 49486 | 16.0   | 2014 Jul 14 | Yes        |
| 50869 | 15.8   | 2014 Jul 14 | ...        |
| 52377 | 14.5   | 2014 Jul 14 | Yes        |
| 52532 | 15.5   | 2014 Jul 14 | Yes        |
| 53255 | 15.0   | 2014 Jul 14 | Yes        |
| 53603 | 12.1   | 2014 Jul 14 | Yes        |
| 56818 | 14.0   | 2014 Jul 14 | Yes        |
| 57038 | 13.9   | 2014 Jul 14 | Yes        |
| 58812 | 14.9   | 2014 Jul 14 | Yes        |

In addition, since our stars appear in relatively sparse stellar regions in the sky, well outside the Galactic disk, the probability of a background star appearing in a close radius to our observed star is low. Using the total number of known non-associated stars in our images, than at 95\% confidence 7 of the 10 stars found within 2\" of any of our background stars are associated, with 9 of 10 being the most likely number of associated stars. The small number of probable unassociated background stars in our fields and the DSS proper-motion confirmations suggest a high-likelihood for true association for all of our companion stars.

**4.2. Photometric Parallaxes**

Very few subdwarfs in our sample have accurate parallax measurements. Only 43 of the targets have published parallaxes, most with significant measurement errors. To estimate the distances to our subdwarf targets, we employed an expression for \(M_R = \frac{1}{2} (R - I)\) estimated by Siegel et al. (2002) using a color–magnitude diagram and the photometric measurements by Marshall (2007).

The polynomial fit found by Siegel for subdwarfs with measured parallaxes and an estimated mean \([\text{Fe/H}]\) of \(-1.2\), and with the Lutz & Kelker (1973) correction, is

\[
M_R = 2.03 + 10 \times (R - I) - 2.21 \times (R - I)^2.
\]

The color-absolute magnitude relation has an uncertainty of \(\sim0.3\) mag. In all cases, the published parallax errors are much larger than photometric errors of \(<0.03\) mag. The estimated distances for the primary stars in the subdwarf multiple systems are listed in Table 4.

**5. DISCUSSION**

**5.1. Comparison to Main-sequence Dwarfs**

With comparable sample size and spectrum types, the cool dwarf survey of Janson et al. (2012) is a useful metal-rich analog to this work. The study used the Lucky Imaging technique on a sample of 761 stars, sensitive to companion separations of 0\"08–6\"0. The most striking disparity between the two samples is the lack of low-contrast (\(\Delta m_i \leq 2\)), close (\(\rho \leq 1\") companions to the subdwarf stars, a regime heavily populated by solar-metallicity dwarf companions. This is clearly seen in a plot of the companion’s magnitude difference versus angular separation for the two populations, as in Figure 9.

The dissimilarity between contrast ratios between dwarfs and subdwarfs is further illustrated in Figure 10. A two sample Kolmogrov–Smirnov test rejects the null hypothesis that the two populations are similar at a confidence of \(\sim2.8\sigma\).
The lack of close subdwarf companions has been noted previously by Jao et al. (2009) and by Abt (2008), but with significantly smaller samples. A direct comparison of orbital separations is biased by the distance variation in the two samples. With their rarity in the solar neighborhood, the subdwarf sample is overall approximately a factor of 4 further distant than the dwarf sample. If the populations were similar, this would result in a relative abundance of tight dwarf binaries, while the 6″ limit of the Janson et al. survey reduces the number of observed wide dwarf binaries. Attempts to pick out similar systems by relative distance or by orbital separation from the two surveys results in a small statistical sample. Nonetheless, the relative lack of close stars in the subdwarfs sample, as illustrated in Figure 11, and confirmed at high-confidence in our survey, warrants further investigation.

5.2. Binarity and Metallicity

The binary fraction we have found further confirms what has been suspected by past studies: that the binary fraction of subdwarfs is substantially lower than their dwarf cousins. The largest survey of cool subdwarfs, although limited by the low angular resolution of the SDSS, Zhang et al. (2013), find a multiplicity for type late K and M-subdwarfs of 2.41%, with an estimated lower bound of 10% when adjusting for survey incompleteness. This estimate and our work leave subdwarfs multiplicity rates approximately a factor of 2–4 lower than solar-metallicity stars of the same spectral types.

Historically, it has been a widely held view that metal-poor stars possess fewer stellar companions (Batten 1973; Latham 2004). A deficiency of eclipsing binaries was found in globular clusters by Kopal (1959), while Jaschek & Jaschek (1959) discovered a deficiency of spectroscopic binaries in a sample of high-velocity dwarfs. Abt & Willmarth (1987) used higher resolution CCD spectra to conclude that the frequency of spectroscopic binaries in high-velocity stars was half of metal-rich stars. Recently, however, this view has come under attack. Carney et al. (1994) used radial velocity measurements of 1464 stars, along with metallicity data (Carney et al. 1987), and found the difference in binary frequency of metal-rich and metal-poor stars to not be significant. Likewise, Grether & Lineweaver (2007) found a ∼2σ anti-correlation between metallicity and companion stars.

In recent years, the relationship between planetary systems and metallicity has also been explored. Fischer & Valenti (2005) found a positive correlation between planetary systems and the metallicity of the host star. This correlation has been reinforced to ∼4σ by Grether & Lineweaver (2007). Recently, Wang et al. (2014) found that planets in multiple-star systems occur $4.5 \pm 3.2$, $2.6 \pm 1.0$, and $1.7 \pm 0.5$ times less frequently when the companion star is separated by 10, 100, and 1000 AU, respectively.

The solution may lie in the differences between halo and thick disk stars. Latham et al. (2002) found no obvious difference between the binary fraction of the two populations;
however Chiba & Beers (2000) found a 55% multiplicity rate for thick disk stars and 12% for halo stars. Grether & Lineweaver also find that the thick disk shows a ~4 times higher binary fraction than halo stars, further hypothesizing that the mixing of the populations is the explanation for the perceived anti-correlation of metallicity and binarity. Similarly, Bovy et al. (2012) use spectroscopic data to chart the disk thickness, finding, instead of a bi-modal separation of the thin and thick disks, a smooth, continuous distribution. This suggests the absence of a distinct thick disk in the Milky Way.

The large difference between the M-subdwarfs and thick-disk M-dwarfs, apparent in our work in this paper and Janson et al. (2012), seems to imply the two populations formed under different initial conditions. Star formation in less dense regions appears to lower binary rates. Köhler et al. (2006) found a factor 3–5 difference in binary fraction between the low-density Taurus star-forming region and the dense Orion cluster. It is also possible that, as forming earlier than solar-abundance stars, the metal-poor subdwarfs could have suffered more disruptive encounters with other stars and the Galactic tide (Kaib et al. 2013). These disturbances could separate companions with separations larger than a few AU, with the tighter, more highly bound systems being less affected (Sterzik & Durisen 1998; Abt 2008), a theory derived from N-body simulations (Aarseth & Hills 1972; Kroupa 1995; Jiang & Tremaine 2010). This, however, is contrary to our tentative result of a lack of close subdwarf companions, and the similar observations of Jao
et al. (2009) and Abt (2008) that close subdwarf binaries are rare. This implies that metal-poor subdwarfs had shorter lifetimes in clusters than their younger, metal-rich cousins, either being ejected or formed in a disrupted cluster.

Another possible explanation is that a large number of low-metallicity stars in the Milky Way could have resulted from past mergers with satellite galaxies. Simulations from Abadi et al. (2006) predict that the early Galaxy underwent a period of active merging. From these mergers, the Galaxy would inherit large numbers of metal-poor stars. Meza et al. (2005) observe a group of metal-poor stars with angular momenta similar to the cluster ω Cen, long theorized to be the core of a
dwarf galaxy that merged with the Milky Way. The environment of these foreign galaxies is unknown, so star formation could be quite different than our own Galaxy. It is also possible that during the merger multiple close stellar encounters and perturbations could alter their primordial binary properties.

6. CONCLUSIONS

In the largest high-resolution binary survey of cool subdwarfs, we observed 344 stars with the Robo-AO robotic laser adaptive optics system, sensitive to companions at $\rho \geq 0'15$ and $\Delta m_i \leq 6$. Of those targets, we observed 16 new multiple systems and five new companions to already known binary systems. When including previously recorded multiple systems, this implies a multiplicity rate for cool subdwarfs of $12.5 \pm 1.9\%$ and a triplet fraction of $2.0 \pm 0.8\%$. This is significantly lower than the observed cool subdwarf binarity of $26 \pm 6\%$ by Jao et al. (2009) and in agreement with the completeness adjusted estimate of $>10\%$ of Zhang et al. (2013). When comparing our results to similar surveys of non-subdwarf binarity, we note a $\sim 2.8\sigma$ difference in relative magnitude differences between companions. An apparent lack of close binaries is noted, as has been previously observed in the literature. The high efficiency of Robo-AO makes large, high-angular resolution surveys practical and will in the future continue to put tighter constraints on the properties of stellar populations.

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| ObsID   | m_v   | Obs. Qual | Companion? |
|---------|-------|-----------|------------|
| 9653    | 15.6  | 2013 Aug 16 | Low       |
| 9727    | 15.8  | 2013 Aug 15 | Medium    |
| 9734    | 15.0  | 2012 Sep 04 | Medium    |
| 9799    | 15.4  | 2012 Sep 13 | Low       |
| 9848    | 16.6  | 2013 Aug 19 | Low       |
| 9898    | 14.2  | 2013 Aug 19 | Low       |
| 9938    | 16.2  | 2013 Aug 15 | Low       |
| 10018   | 15.4  | 2013 Aug 17 | Low       |
| 10022   | 15.8  | 2013 Aug 16 | Medium    |
| 10135   | 15.7  | 2012 Sep 04 | Low       |
| 10176   | 15.8  | 2013 Aug 20 | Low       |
| 10234   | 14.1  | 2012 Sep 04 | Medium    |
| 10401   | 14.6  | 2013 Aug 18 | Low       |
| 10517   | 14.5  | 2012 Sep 04 | Medium    |
| 10536   | 11.2  | 2013 Aug 15 | High      |
| 10548   | 15.9  | 2013 Aug 15 | Low       |
| 10850   | 10.7  | 2012 Sep 04 | High      |
| 10883   | 15.9  | 2012 Sep 04 | Low       |
| 11007   | 12.2  | 2013 Aug 21 | High      |
| 11010   | 14.1  | 2012 Sep 04 | Medium    |
| 11015   | 16.3  | 2013 Aug 16 | Low       |
| 11032   | 14.2  | 2012 Sep 04 | Medium    |
| 11068   | 15.4  | 2013 Aug 21 | Low       |
| 11938   | 14.3  | 2012 Sep 04 | Medium    |
| 12017   | 12.3  | 2013 Aug 17 | High      |
| 12026   | 15.8  | 2013 Aug 18 | Low       |
| 12044   | 15.8  | 2012 Sep 13 | Low       |
| 12227   | 14.2  | 2013 Aug 18 | Medium    |
| 12350   | 12.1  | 2013 Aug 18 | Medium    |
| 12489   | 14.6  | 2012 Oct 10 | Low       |
| 12537   | 14.5  | 2013 Aug 21 | Medium    |
| 12704   | 15.4  | 2012 Oct 10 | Low       |
| 12769   | 14.1  | 2013 Aug 18 | Medium    |
| 12829   | 14.6  | 2012 Oct 03 | Medium    |
| 12845   | 10.6  | 2012 Oct 03 | High      |
| 12856   | 10.8  | 2013 Aug 18 | High      |
| 12876   | 15.6  | 2012 Oct 03 | Low       |
| 12923   | 15.2  | 2013 Aug 18 | Low       |
| 13022   | 15.9  | 2012 Oct 03 | Low       |
| 13344   | 13.8  | 2012 Oct 03 | Medium    |
| 13368   | 15.5  | 2012 Oct 03 | Low       |
| 13402   | 14.7  | 2012 Oct 03 | Low       |
| 13469   | 15.1  | 2013 Aug 18 | Low       |
| 13470   | 13.8  | 2012 Oct 03 | Medium    |
| 13641   | 12.9  | 2012 Oct 06 | High      |
| 13660   | 12.4  | 2012 Oct 03 | High      |
| 13694   | 15.4  | 2013 Aug 20 | Medium    |
| 13706   | 14.5  | 2012 Oct 03 | Low       |
| 13770   | 12.4  | 2012 Oct 03 | High      |
| 13811   | 13.4  | 2012 Oct 03 | Medium    |
| 13920   | 14.4  | 2013 Aug 20 | Medium    |
| 13940   | 14.4  | 2012 Oct 05 | Medium    |
| 14091   | 13.9  | 2012 Oct 05 | Medium    |
| 14131   | 13.4  | 2012 Oct 03 | Medium    |
| 14169   | 13.4  | 2012 Oct 05 | Medium    |
| 14197   | 12.4  | 2012 Oct 04 | Low       |
| 14391   | 13.5  | 2012 Oct 04 | Low       |
| 14450   | 14.7  | 2012 Oct 04 | Low       |
| 14549   | 14.5  | 2012 Oct 10 | Low       |
| 14822   | 12.7  | 2012 Oct 03 | Medium    |
| 14864   | 14.3  | 2012 Oct 07 | Low       |
| 15039   | 14.8  | 2012 Oct 10 | Low       |
| 15183   | 12.6  | 2012 Oct 07 | Medium    |
| 15218   | 12.3  | 2012 Oct 06 | High      |
| NLTT | $m_v$ | ObsID  | Obs. Qual | Companion? |
|------|-------|--------|-----------|------------|
| 15973| 9.3   | 2012 Oct 07 | High      | Yes        |
| 15974| 13.8  | 2012 Oct 07 | High      | ...        |
| 16030| 13.9  | 2012 Oct 07 | Low       | ...        |
| 16185| 14.4  | 2012 Oct 10 | Low       | ...        |
| 16242| 10.6  | 2012 Oct 06 | Medium    | ...        |
| 16579| 12.3  | 2012 Oct 09 | High      | ...        |
| 16606| 12.3  | 2012 Oct 10 | High      | ...        |
| 16849| 15.3  | 2012 Oct 10 | Low       | ...        |
| 16869| 13.2  | 2013 Jan 20 | High      | ...        |
| 16986| 15.8  | 2013 Jan 20 | Low       | ...        |
| 17039| 12.9  | 2012 Oct 10 | Medium    | ...        |
| 17485| 11.9  | 2012 Oct 10 | High      | Yes        |
| 17680| 13.6  | 2013 Jan 20 | Medium    | ...        |
| 17786| 12.0  | 2013 Jan 20 | High      | ...        |
| 17872| 10.7  | 2013 Jan 20 | High      | ...        |
| 18019| 13.3  | 2012 Oct 10 | Medium    | ...        |
| 18131| 14.4  | 2013 Jan 20 | Medium    | ...        |
| 18424| 12.7  | 2013 Jan 18 | High      | ...        |
| 18463| 13.8  | 2013 Jan 20 | High      | ...        |
| 18502| 12.2  | 2013 Jan 19 | High      | Yes        |
| 18731| 13.1  | 2013 Jan 19 | High      | Yes        |
| 18798| 14.5  | 2013 Jan 19 | High      | Yes        |
| 18799| 11.0  | 2013 Jan 19 | High      | ...        |
| 19037| 14.9  | 2013 Jan 20 | Medium    | ...        |
| 19210| 11.2  | 2013 Jan 19 | High      | Yes        |
| 19301| 14.7  | 2013 Jan 19 | Low       | ...        |
| 19570| 14.4  | 2013 Apr 22 | Medium    | ...        |
| 19614| 15.7  | 2013 Apr 22 | Medium    | ...        |
| 19643| 11.9  | 2013 Jan 19 | High      | ...        |
| 19824| 14.6  | 2013 Jan 19 | Medium    | ...        |
| 20252| 14.9  | 2013 Apr 22 | Medium    | ...        |
| 20288| 14.9  | 2013 Apr 22 | Medium    | ...        |
| 20392| 13.8  | 2013 Jan 22 | Low       | ...        |
| 20476| 13.2  | 2013 Apr 22 | High      | ...        |
| 20492| 13.3  | 2013 Jan 19 | High      | ...        |
| 20684| 12.0  | 2013 Jan 19 | High      | ...        |
| 20691| 9.6   | 2013 Jan 19 | High      | Yes        |
| 20768| 14.0  | 2013 Jan 19 | Medium    | ...        |
| 21039| 14.0  | 2013 Jan 19 | Medium    | ...        |
| 21112| 15.3  | 2013 Apr 22 | Medium    | ...        |
| 21333| 12.7  | 2013 Jan 19 | High      | ...        |
| 21341| 14.3  | 2013 Jan 19 | Low       | ...        |
| 21370| 13.7  | 2013 Jan 19 | Medium    | Yes        |
| 21449| 12.6  | 2013 Apr 22 | High      | ...        |
| 21601| 14.6  | 2013 Apr 22 | Medium    | ...        |
| 22026| 12.6  | 2013 Apr 22 | High      | ...        |
| 22053| 12.1  | 2013 Jan 19 | High      | ...        |
| 22520| 10.8  | 2013 Jan 19 | High      | ...        |
| 22752| 13.9  | 2013 Jan 19 | Medium    | ...        |
| 22945| 13.2  | 2013 Apr 22 | Medium    | ...        |
| 23894| 14.6  | 2013 Jan 18 | Low       | ...        |
| 24006| 15.5  | 2013 Apr 22 | Medium    | ...        |
| 24082| 13.1  | 2013 Jan 19 | Medium    | Yes        |
| 24353| 13.2  | 2013 Jan 18 | Medium    | ...        |
| 24371| 14.2  | 2013 Jan 18 | Low       | ...        |
| 24718| 13.1  | 2013 Jan 18 | Medium    | ...        |
| 24984| 12.5  | 2013 Apr 21 | High      | ...        |
| 25006| 14.1  | 2013 Apr 21 | Medium    | ...        |
| 25177| 12.2  | 2013 Apr 22 | High      | ...        |
| 25190| 13.9  | 2013 Jan 18 | Low       | ...        |
| 25234| 13.2  | 2013 Jan 18 | Medium    | Yes        |
| 25475| 13.9  | 2013 Apr 21 | Medium    | ...        |
| 25776| 13.8  | 2013 Apr 22 | Medium    | ...        |
| 25909| 13.5  | 2013 Apr 22 | High      | ...        |
In Table A1, we list our Robo-AO observed subdwarfs, including date the target was observed, observation quality as described in Section 3.1.4, and the presence of detected companions.

### APPENDIX

In Table A1, we list our Robo-AO observed subdwarfs, including date the target was observed, observation quality as described in Section 3.1.4, and the presence of detected companions.

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table A1

| NLTT | $m_e$ | ObsID | Obs. Qual | Companion? |
|------|------|-------|-----------|------------|
| 48391 | 15.2 | 2012 Oct 05 | Medium | ... |
| 48592 | 12.2 | 2012 Oct 04 | Medium | ... |
| 48866 | 12.7 | 2012 Oct 04 | Medium | ... |
| 49486 | 16.0 | 2012 Oct 04 | Medium | Yes |
| 49487 | 12.3 | 2012 Oct 04 | Medium | ... |
| 49488 | 14.9 | 2013 Aug 19 | Medium | ... |
| 49618 | 12.2 | 2012 Oct 04 | Medium | ... |
| 49726 | 15.9 | 2013 Aug 19 | Low | ... |
| 49749 | 14.8 | 2012 Oct 03 | Medium | ... |
| 49819 | 14.0 | 2013 Aug 19 | High | Yes |
| 49821 | 12.8 | 2013 Aug 19 | High | ... |
| 49897 | 15.8 | 2012 Oct 04 | Low | ... |
| 50257 | 13.8 | 2013 Aug 18 | Low | ... |
| 50376 | 13.9 | 2012 Sep 13 | Medium | Yes |
| 50556 | 15.7 | 2012 Sep 13 | Low | ... |
| 50759 | 15.9 | 2012 Sep 13 | Low | Yes |
| 50869 | 15.8 | 2013 Aug 19 | Low | ... |
| 50911 | 11.6 | 2012 Sep 13 | High | ... |
| 51006 | 14.1 | 2013 Aug 19 | Medium | Yes |
| 51153 | 15.1 | 2012 Sep 13 | Low | ... |
| 51740 | 15.3 | 2013 Sep 13 | Low | ... |
| 51754 | 15.0 | 2012 Sep 13 | Low | ... |
| 51824 | 11.9 | 2013 Aug 18 | Medium | ... |
| 51856 | 13.4 | 2012 Sep 04 | Medium | ... |
| 52089 | 14.9 | 2012 Sep 04 | Medium | ... |
| 52377 | 14.5 | 2012 Sep 04 | Medium | Yes |
| 52532 | 15.5 | 2012 Sep 04 | Low | Yes |
| 52573 | 15.3 | 2013 Aug 18 | Low | ... |
| 52666 | 15.0 | 2013 Aug 19 | Low | ... |
| 52816 | 15.7 | 2012 Sep 13 | Low | ... |
| 52894 | 16.0 | 2012 Sep 13 | Low | ... |
| 53190 | 15.4 | 2013 Aug 16 | Medium | ... |
| 53254 | 14.7 | 2013 Aug 16 | Medium | Yes |
| 53255 | 15.0 | 2013 Aug 16 | Medium | Yes |
| 53274 | 11.9 | 2013 Aug 17 | High | Yes |
| 53316 | 15.4 | 2013 Sep 13 | Low | ... |
| 53346 | 13.8 | 2013 Aug 17 | Medium | ... |
| 53480 | 12.6 | 2013 Aug 17 | High | ... |
| 53702 | 15.3 | 2012 Sep 13 | Medium | ... |
| 53707 | 12.1 | 2013 Aug 18 | Medium | ... |
| 53781 | 13.8 | 2013 Aug 17 | Medium | ... |
| 53801 | 11.8 | 2012 Sep 13 | High | ... |
| 53823 | 13.8 | 2013 Aug 18 | Low | ... |
| 54027 | 13.3 | 2013 Aug 19 | Medium | ... |
| 54088 | 14.1 | 2013 Aug 18 | Low | ... |
| 54168 | 13.4 | 2013 Aug 17 | Medium | ... |
| 54184 | 14.0 | 2013 Aug 17 | Medium | ... |
| 54349 | 14.4 | 2012 Sep 13 | Medium | ... |
| 54450 | 15.6 | 2013 Aug 16 | Low | ... |
| 54578 | 15.8 | 2013 Aug 18 | Low | ... |
| 54608 | 16.0 | 2013 Aug 16 | Low | ... |
| 54620 | 15.2 | 2013 Aug 17 | Medium | ... |
| 54699 | 15.1 | 2012 Sep 13 | Low | ... |
| 54710 | 15.2 | 2012 Sep 13 | Low | ... |
| 54730 | 11.5 | 2012 Sep 13 | High | ... |
| 55411 | 15.9 | 2013 Aug 16 | Low | ... |
| 55603 | 12.1 | 2013 Aug 18 | Medium | Yes |
| 55732 | 13.4 | 2013 Aug 17 | Medium | ... |
| 55733 | 14.5 | 2012 Sep 03 | Medium | ... |
| 55942 | 13.5 | 2013 Aug 16 | Medium | ... |
| 56002 | 14.4 | 2012 Sep 03 | Medium | ... |
| 56290 | 12.6 | 2013 Aug 16 | High | ... |
| 56420 | 15.6 | 2012 Sep 03 | Low | ... |

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