A strip search for new very wide halo binaries

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ABSTRACT
We report on a search for new wide halo binary stars in Sloan Digital Sky Survey (SDSS) Stripe 82. A list of new halo wide binary candidates which satisfy common proper motion and photometric constraints is provided. The projected separations of the sample lie between 0.007 and 0.25 pc. Although the sample is not large enough to improve constraints on dark matter in the halo, we find the wide binary angular separation function is broadly consistent with past work. We discuss the significance of the new sample for a number of astrophysical applications, including as a testbed for ideas about wide binary formation. For the subset of candidates which have radial velocity information, we make use of integrals of motion to investigate one such scheme in which the origin of Galactic wide binaries is associated with the accretion/disruption of stellar systems in the Galaxy. Additional spectroscopic observations of these candidate binaries will strengthen their usefulness in many of these respects. Based on our search experience in Stripe 82 we estimate that the upcoming Pan-STARRS survey will increase the sample size of wide halo binaries by over an order of magnitude.

Key words: methods: data analysis – binaries: general – Galaxy: halo.

1 INTRODUCTION
The existence of very wide halo binaries with separations greater than 0.1 pc has now been firmly established (Chanamé & Gould 2004, hereafter CG04; Quinn et al. 2009). Such systems are intriguing objects for a number of reasons. First, their formation remains a mystery. Indeed, in a recent study Parker et al. (2009) show that wide binaries with semimajor axis \( a > 10^4 \) au are too fragile to survive in low- or high-density star cluster environments, i.e. the environments in which most star formation is thought to take place. It is not clear if isolated star formation could produce wide binaries either since isolated star-forming cores have radii of only about 0.1 pc (Ward-Thompson et al. 2007). Secondly, wide halo binaries are susceptible to disruption from massive compact bodies, so the distribution of wide halo binary separations can be used to place constraints on the fraction of the dark matter halo composed of massive compact bodies (Yoo, Chanamé & Gould 2004).

Our knowledge about wide halo binaries is still limited and derives mainly from the work of CG04, who compiled a list of common proper motion candidate binaries selected from the revised New Luyten Two-Tenths Catalogue (rNLTT) of stars with proper motions greater than 180 mas yr\(^{-1}\) (Gould & Salim 2003; Salim & Gould 2003). The sample listed 116 halo binary pairs, with only about 10 with projected separation greater than 0.1 pc. Follow up radial velocity measurement for four of these objects with separations greater than 0.1 pc confirmed that three are likely to be truly associated (Quinn et al. 2009).

Increasing the sample size of wide binaries is important to improve our understanding of these objects and quantify their implications for star formation and dark matter. As shown in Quinn et al. (2009), the existing constraints, derived from the distribution of wide halo binary separations, on compact massive bodies are not robust due to the small sample size. Larger samples are needed, moreover, to investigate the dependence of the wide binary separation distribution function on Galactic orbit. Also, with an expanded sample, the possibility of tracing the origin of groups of wide binaries to common recently disrupted Galactic satellites via integrals of motion (Allen, Poveda & Hernández-Alcázar 2007) is enhanced. In addition, a number of other astrophysical applications, such as testing and constraining photo-parallax relations (Sesar, Ivezić & Jurić 2008), would benefit from increasing the sample of wide binaries.

Here, we discuss results of a search in the recently published Sloan Digital Sky Survey (SDSS) Stripe 82 catalogue (Bramich et al. 2008) for new wide halo binaries. The outline of the paper is as follows. We first give an overview of the Strip 82 survey in Section 2; then in Section 3 we discuss how we select halo stars from the survey. Section 4 describes how we identify wide halo binaries and presents a list of new candidates. Finally, in Section 5 we outline applications for the new sample and summarize our results.

2 SDSS STRIPE 82
The SDSS (York et al. 2000) is a multicolour imaging and spectroscopic survey that has mapped more than one-fourths of the sky towards the North Galactic Pole. The imaging is done with the five photometric bands \( u, g, r, i \) and \( z \) (Fukugita et al. 1996). A 2.5
strip along the celestial equator (towards the South Galactic Pole) from right ascension $-49.5$ to $+49.5$, known as Stripe 82, has been repeatedly imaged by SDSS, from 1998 to 2005, to permit deeper studies and measure variability.

Bramich et al. (2008) have created a Stripe 82 light-motion catalogue by cross-matching objects from the various imaging runs. The catalogue contains almost 4 million light and motion curves of stellar and galactic objects. Each light-motion curve consists of around 30 epochs over a baseline of 6 to 7 yr. In addition, a Higher-Level Catalogue (HLC) has been created by Bramich et al. (2008).\footnote{The Stripe 82 catalogue including the HLC is available for download from \url{http://das.sdss.org/value_added/strip82_variability/SDSS82_public/}} This provides a range of quantities derived from the light-motion catalogue, including mean position, proper motion and mean magnitudes in the five photometric bands. It is the HLC we mine in search of wide halo binaries.

The HLC is at present (2009) the deepest photometric and astrometric variability catalogue of its kind and is complete down to magnitude 21.5 in \textit{u}, \textit{r}, \textit{g} and \textit{i}, and 20.5 in \textit{z}. The photometric range is $14-21.5$ in \textit{r} with photometric rms scatter of 20 mmag down to $r \approx 19$ which rises exponentially to 100 mmag at $r = 21.5$. Typically proper motion errors are $\approx 4$ mas yr$^{-1}$.$^2$

The Stripe 82 survey provides a number of advantages over the rNLTT survey in the context of searching for wide halo binaries. The magnitude limits of Stripe 82 mean it probes much further away from the disc-dominated solar neighbourhood than the rNLTT survey (which is complete down to 250 pc from the solar position). Proper motion errors for objects in Stripe 82 are also slightly better and the proper motion threshold of 180 mas yr$^{-1}$ does not apply. Another advantage is that the Stripe 82 survey provides accurate photometry in two widely spaced colour bands, namely \textit{g} and \textit{i}, which is important for among other things selecting halo stars from the catalogue. In contrast, errors in the \textit{V} band used in rNLTT can be up to 0.25 mag. On the other hand, the rNLTT covers 44 per cent of the sky compared to 0.7 per cent for Stripe 82, so the density of random visual pairs is likely to be much higher in Stripe 82 searches.

We note another possible approach to search for new wide binaries is to match the single-epoch SDSS data ($14 < r < 20$) with older photometric/proper motion surveys. In fact, a number of groups have investigated this avenue by combining SDSS with USNO-B (Chanamé 2007; Sesar et al. 2008, with the latter focusing on wide disc binaries). While this approach covers a larger fraction of the sky, it is about 1.5 mag less deep than Stripe 82. The preliminary finding of Chanamé (2007) is that proper motions and photometry alone are not enough to define high-probability candidates constructed from the union of SDSS and USNO-B; follow up radial velocities are needed to prune the sample. Below, we show that it is possible to find a new robust sample of wide halo binaries in Stripe 82 with just proper motions and photometry.

3 SELECTING HALO STARS

The first problem to overcome in the search for halo binary stars from the Stripe 82 catalogue is the question of how to select a clean sample of halo stars (subdwarfs) from the mix of stellar populations in the catalogue.

1 The Stripe 82 catalogue including the HLC is available for download from \url{http://das.sdss.org/value_added/strip82_variability/SDSS82_public/}.
2 We use the clipped photometric and astrometric measurements in the catalogue which are calculated using an iterative algorithm that rejects the worst 4σ outlier in each iteration and terminates when there are no more outliers.

3.1 Reduced proper motion diagram

Subdwarfs can be identified directly by their position in the HR diagram or features in their spectra. For the vast majority of stars in Stripe 82 neither spectra (but see Section 4.3) nor accurate parallaxes are available. With only proper motion and photometry on hand, the reduced proper motion (RPM) diagram is a common tool employed to pick out subdwarfs from the disc stars. In this diagram, the RPM, which we take as $H_\mu = r + 5 \log \mu + 5$, with $r$ the apparent magnitude in the $r$ band and $\mu$ the proper motion in arcsec per year, is plotted against the stellar colour. The RPM exploits the differences in metallicity and kinematics between subdwarfs and disc stars. Since halo stars do not rotate about the Galaxy as fast as main-sequence disc stars and are fainter at the same colour, the RPM is typically larger for subdwarfs compared to disc main-sequence stars at a given temperature.

The colour adopted in the RPM diagram is a proxy for temperature and is chosen to enhance the separation of the halo subdwarfs from the disc main-sequence stars. After some experimentation, we found that the $g-i$ colour leads to a reasonable division. This choice for colour and the form for $H_\mu$ have appeared before in the literature to construct RPM diagrams for Stripe 82 in order to search for new white dwarf candidates (Vidrih et al. 2007) and to study the kinematics of the stellar halo (Smith et al. 2009a; Smith, Wyn Evans & An 2009b), while Sesar et al. (2008) constructed a similar RPM diagram from the union of SDSS and USNO-B across the entire SDSS footpath to define a sample in which to search for wide disc binaries.

Errors in proper motion measurements and also the intrinsic spread of velocities for a given population will mask the separation in the diagram. We limit the influence of proper motion errors by selecting stars in the catalogue with proper motions larger than 40 mas yr$^{-1}$ and with proper motion errors less than 5 mas yr$^{-1}$, the latter corresponding to an error of about 0.3 in $H_\mu$. Errors in photometry also blur the separation in the RPM diagram. We require that the error of the mean photometry in the $r$, $g$ and $i$ bands to be less than 0.05 mag. These introduce an error in $H_\mu$ of less than 0.05 and 0.07 in the colour.

The RPM diagram is plotted for the 32644 stars in the HLC that met the above criteria in Fig. 1. We can see that stars are found in three groups: white dwarfs; subdwarfs and disc stars. The white dwarfs to the lower-left side of the diagram are clearly separated from the other groups. We use the separators put forward in Vidrih et al. (2007) to divide the white dwarfs from the rest of the stars. For $g-i \leq 1.6$ the separator is defined as $H_\mu = 2.68(g-i) + 15.21$. For $g-i > 1.6$ it is defined as $H_\mu = 10(g-i) + 3.5$.

It is not as clear cut where to draw the boundary between the disc main-sequence stars and the subdwarfs, but since the RPM is equivalent to combining the absolute magnitude and the logarithm of the magnitude of the tangential velocity of the star, we can use a photo-parallax relation to define a boundary in the RPM diagram for a given tangential velocity. Ivezic et al. (2008a, hereafter I08) provide a photometric parallax relation for stars observed in SDSS colours. The relation gives the absolute magnitude in the $r$ band, $M_r$, as a function of colour, $g-i$ and metallicity, [Fe/H], as follows:

$$M_r = -5.06 + 14.32(g-i) - 12.97(g-i)^2$$
$$+ 6.127(g-i)^3 - 1.267(g-i)^4 + 0.0967(g-i)^5$$
$$+ 4.5 - 1.1[\text{Fe/H}] - 0.18[\text{Fe/H}]^2.$$  \hspace{1cm} (1)

Using this relation with the metallicity set to be $-1.5$ dex (corresponding to the median halo metallicity as reported in I08) and
82. The regions of the RPM diagram predominately occupied by white dwarfs, subdwarfs and disc main-sequence stars are labelled and the boundaries, as discussed in the text, between the different regions are drawn.

Figure 1. RPM diagrams of high proper motion stars throughout the Stripe 82. The distributions, for stars in equally spaced bins in galactic latitude, of the differences between the RPM of the star and the value of the subdwarf–disc separator evaluated at the colour of the star, are shown. A vertical offset is applied to each distribution for clarity.  

220 km s$^{-1}$ for the tangential velocity we find that, as shown in Fig. 1, the resultant RPM boundary does a good job of defining a disc/subdwarf divider consistent with the apparent division discernible by visual inspection. CG04 made similar use of the RPM diagram to classify binaries as disc or subdwarfs. The definition of their disc/subdwarf separator contained a dependence on Galactic latitude, $b$. We assess the need for such a dependence in our sample, which covers a narrower range in $b$ than the CG04 sample, by plotting the distribution of the differences between the value of $H_i$ and the value of our separator at the colour of the star for groups of stars binned in $b$. If the separator has a significant dependence on $b$ we can expect to see a systematic shift in the distribution of these differences as $b$ changes. As Fig. 2 shows, there is no indication that we are detecting such a shift. Therefore, we define the halo subdwarf sample as the stars in the RPM diagram lying between the white dwarf and photo-parallax-based divisions. This selection produces a sample of 6419 subdwarfs.

4 SEARCHING FOR HALO BINARY STARS

With the sample of halo stars now defined, we can proceed to search for binary pairs. The simplest approach is to count the number of subdwarf pairs as a function of angular separation, $\Delta \theta$, on the sky. However, this fails to deal with the problem of chance close pairs of stars. The contamination due to these random pairs, $N_{RP}$, depends on the surface density of stars in the catalogue, and for small $\Delta \theta$ we can expect roughly that $N_{RP}(\Delta \theta) \propto (\Delta \theta)^2$.

The actual number of stellar pairs, $f(\Delta \theta)$, for the Stripe 82 subdwarf sample, in equal logarithmic bins of angular separation, is shown in the left-hand panel of Fig. 3. In order to estimate the signal from chance pairs, we fit a power law using a maximum likelihood method to the distribution of pair separations with $100 < \Delta \theta < 1000$ arcsec. We see this adequately fits the data beyond $\approx 10$ arcsec. The signal in excess of the fit inside $\Delta \theta < 10$ arcsec is most likely attributable to genuine binaries. This signal though is clearly not well described by a power law with an index $\sim 1.57$, as observed for the binary angular separation function in CG04. This could be due to blending which reduces the efficiency of detecting pairs closer than $\approx 3$ arcsec when good photometry is demanded, as noted in Sesar et al. (2008) and Longhitano & Binggeli (2009). According to the I08 relation with metallicity $\sim -1.5$ dex, the subdwarf sample lies at median distance of 1.3 kpc, so the plot implies that the direct search for candidate wide binaries becomes dominated by the signal from random pairs at separations of around 0.05 pc and suffers from blending for binaries with separations less than about 0.01 pc.

4.1 Common proper motion pairs

Since our goal is to generate a reliable list of candidates rather than a complete list with many false contaminants, we must exploit the proper motion and photometric information to cut down on the signal from random pairs. As the typical distances to the binaries is around 1 kpc, the proper motion differences for wide binaries, arising from relative orbital velocity and projection effects due to the angular separation in the sky, fall below the typical proper motion error. Consequently, we incorporate a proper motion constraint in our wide binary selection procedure by requiring that the magnitude of the vector proper motion differences for candidate pairs is less than 5 mas yr$^{-1}$ (roughly the typical relative proper motion error). The middle panel of Fig. 3 displays the outcome for $f(\Delta \theta)$ on imposing this constraint. The effect is to reduce the amplitude of the signal from random pairs, found using the same technique as before, by over an order of magnitude, without seriously compromising the genuine binary signal in the inner region.

4.2 Photometric constraints

We can go further and apply photometric constraints in the selection process. Unfortunately, there are no well-defined SDSS colour–magnitude relations that cover the entire colour range for halo subdwarfs which means we cannot fully exploit the excellent Stripe 82 photometry. The source of the problem is the fact that SDSS has a bright magnitude limit greater than the faint magnitude limit of the Hipparcos survey, which measured accurate distances to nearby bright stars permitting photo-parallax relations to be constructed from them.
As mentioned above, I08 presented a photo-parallax relation for SDSS colours. The blue end \((g - i \lesssim 1)\) of this relation is grounded on observations of stars in globular clusters with known distances. However, the red end has been constrained only with disc stars. The photo-parallax relation from I08 should predict that each member of a genuine binary has a similar value for the difference between the model absolute magnitude and the apparent magnitude, i.e. the quantity \(\delta = M_\Delta (g - i) - m_\Delta - (M_\Delta (g - i) - m_\star)\) should be centred about zero, where \(M_\Delta (g - i)\) and \(m_\Delta\) are the absolute magnitudes from the I08 relation and the observed apparent magnitude of one of the components in the binary, and ditto for \(M_\Delta (g - i)\) and \(m_\star\). We test the relation of I08 on the 14 pairs with \(\Delta \theta < 15\) arcsec satisfying the common proper motion criterion, which we assume for the moment are all genuine binaries. We find the median and standard deviation in the distribution of \(\delta\) for the binary sample turn out to be 0.04 and 0.55 mag, respectively. The scatter is larger than the formal error in \(\delta\) which is less than 0.1 mag, as the median photometric errors of the 14 pairs are smaller than 0.01 mag in \(r, g\) and \(i\). The large scatter might point to the limitations of the photo-parallax relation. Alternatively, the wide binary sample may include a number with an unresolved triplet. We get similar scatter if we use the binary candidates to fit a quadratic polynomial colour–magnitude relationship, \(M_\Delta (g - i)\). (It turns out that attempting to fit higher order polynomials leads to unphysical colour–magnitude relations.) Of course, in this approach the constant term is not constrained, so distances to the objects cannot be directly determined.

We produce a final homogeneously selected sample of wide binary candidates by requiring that in addition to the proper motion constraint, \(\delta\) from the I08 relation should be less than 0.8 mag \((\approx 1.5\) times the scatter and corresponding to a distance uncertainty of around 400 pc at 1 kpc). The right-hand panel of Fig. 3 shows the improvement on applying this requirement. We see that the amplitude of the signal from random pairs falls by a factor of about 2. Wide binaries can be detected now with little contamination out to \(\approx 40\) arcsec. In Table 1, we provide a list of the 15 new candidate halo binaries with \(\Delta \theta < 40\) arcsec that meet the proper motion and photometric constraints. We estimate that the sample contains about one contaminant based on the cumulative distribution of the fit to the random pairs.

The photo-parallax proviso removed two pairs with \(\Delta \theta < 15\) arcsec that met the proper motion constraint. One of these which has \(\Delta \theta = 11.23\) arcsec is probably spurious because the bluest star in this pair is almost a magnitude fainter than its apparent partner. The other object has \(\Delta \theta = 4.54\) arcsec with one of the components close to the magnitude limit in \(r\). We also list this object in Table 1, as the signal from random pairs is negligible at its angular separation (see the middle panel of Fig. 3).

In an effort to boost the sample size further, we have considered reducing the proper motion threshold, but tightening the photo-parallax constraint to compensate for the increase in contamination from spurious pairs. However, these experiments failed to produce a larger sample of robust wide binary candidates. Lowering the threshold, as alluded to in Section 3.1, also runs the risk of increasing the contamination from the disc stars as the separation between components in the RPM diagram is not as well defined.

### 4.3 Radial velocities in Stripe 82

We have mentioned above that SDSS is also a spectroscopic survey and a large sample of stellar spectra has been taken across the SDSS footprint (Yanny et al. 2009, and references therein), so it is important to investigate if we can factor in radial velocity or metallicity information into the binary search. On cross-matching with the SDSS catalogue of stellar spectra, we find that 781 objects, about 12 per cent of the subdwarf sample, including five stars from the homogeneous selected new wide binaries which we list in Table 2, have radial velocities with errors less than 15 km s\(^{-1}\). While a non-negligible fraction, the available radial velocity information is not ideal for improving the detection efficiency or characterizing the distribution of wide binaries. This is because of a restriction in the SDSS spectroscopic plate which requires targets to be separated on the sky by at least an arcmin (Yanny et al. 2009, see also Fig. 4). So, for \(\Delta \theta < 60\) arcsec where the signal for wide binaries is strongest we cannot make use of a common radial velocity constraint on candidate pairs analogous to the common proper motion one. Not surprisingly, if we none the less repeat the search as before but include a radial velocity constraint\(^3\) for any pairs in which both components have radial velocity measurements, we find that the fits to the distribution of random pairs are virtually identical to the corresponding ones in Fig. 3. We also carried out a search in the subsample of 781 objects with radial velocities for wide binaries. This failed to produce any candidates, in fact the proper motion and

\(^3\) For the radial velocity consistency test, a conservative requirement that the relative velocities are less than 20 km s\(^{-1}\) is imposed (most of the radial velocity errors are actually less than 10 km s\(^{-1}\)).
This plot shows the number of subdwarf pairs, similar to the right-hand panel of Fig. 3 except we restrict the sample to pairs with radial velocity measurements. Beyond an arcmin (projected separation $\approx 0.4$ pc) the distribution is well matched by the distribution of random pairs. The absence of pairs with separations less than around an arcmin is simply a reflection of the target spectroscopic selection effects.

CG04 sample of wide binaries. Over the interval 3 and 40 arcsec, the sample obtained with the proper motion and photometric constraints is clean and likely free from selection effects as a function of $\Delta \theta$, so we can use it to find the power law that best characterizes the observed angular separation function. Our best fit leads to a power-law index of $-1.25 \pm 0.4$. This is not as steep as the power law found in CG04 but they are consistent within the uncertainty of the value of the fitted index. The deficit of pairs just outside 40 arcsec would appear to be inconsistent with a flatter power law unless it steepens, for example due to the action of compact dark matter bodies. However, for the moment this must remain a speculation, as the small size of our new sample relative to CG04 precludes any improvements on current dark matter constraints from wide halo binaries.

### 5 DISCUSSION AND CONCLUSIONS

In this paper, we have described a search for wide halo binaries in SDSS Stripe 82. Our main result is given in Table 1, which provides the first set of high probability wide halo binary candidates observed in SDSS colours. As the projected separations lie between roughly 0.01 and 0.25 pc, the new sample serves as a useful addition to the

### Table 1.

| SDSS Obj1 | SDSS Obj2 | $\mu_\alpha \cos(\delta)$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $\mu_\alpha \cos(\delta)$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $r_1$ | $r_2$ | $g - i_1$ | $g - i_2$ | $\Delta \theta$ (arcsec) | Proj Sep (pc) |
|-----------|-----------|-----------------------------------|-----------------------------|-----------------------------------|-----------------------------|-------|-------|------------|------------|-----------------|---------------|
| J002255.45+005427.6 | J002255.81+005423.7 | 69.21 | 70.98 | -17.01 | -19.55 | 14.20 | 19.27 | 0.42 | 1.98 | 6.69 | 0.030 |
| J010740.28-004724.2 | J010740.33-004725.2 | -37.80 | -37.86 | -64.05 | -64.35 | 15.65 | 15.30 | 0.72 | 0.59 | 7.20 | 0.029 |
| J011447.79-002339.0 | J011448.38-002331.2 | 40.73 | 39.25 | -14.88 | -14.56 | 18.47 | 19.00 | 1.05 | 1.60 | 11.73 | 0.098 |
| J013335.18-002552.3 | J013335.26-002549.8 | 35.15 | 36.06 | -31.71 | -27.79 | 20.64 | 20.87 | 1.97 | 2.04 | 2.83 | 0.029 |
| J014026.17-003229.8 | J014026.33-003231.4 | 74.84 | 73.76 | -3.47 | -1.41 | 19.44 | 17.50 | 1.86 | 1.09 | 2.95 | 0.018 |
| J030126.09-004049.2 | J030126.10-004053.3 | 105.83 | 107.99 | 5.35 | 0.86 | 16.59 | 19.43 | 1.24 | 2.09 | 4.08 | 0.016 |
| J212546.23-002939.1 | J212546.46-002939.0 | 8.85 | 6.71 | -51.29 | -48.40 | 18.93 | 17.89 | 1.67 | 1.16 | 3.24 | 0.021 |
| J213457.20-002505.6 | J213457.58-002504.9 | 0.05 | 2.33 | -51.61 | -50.29 | 14.90 | 19.62 | 0.40 | 2.08 | 5.44 | 0.029 |
| J220549.2+002738.2 | J220551.43+002731.3 | -14.60 | -17.76 | -38.62 | -41.49 | 15.32 | 19.93 | 0.38 | 2.03 | 34.18 | 0.230 |
| J221549.22+005737.0 | J221549.63+005732.9 | -5.45 | -3.01 | -142.00 | -142.22 | 18.16 | 17.49 | 2.22 | 2.06 | 7.38 | 0.015 |
| J222937.88+000505.3 | J222938.02+000503.7 | -34.57 | -36.73 | -88.64 | -86.43 | 17.16 | 16.44 | 1.57 | 1.17 | 2.19 | 0.007 |
| J233659.49-010744.4 | J233700.42+010725.0 | 55.70 | 55.77 | -54.73 | -54.78 | 15.95 | 16.28 | 0.69 | 0.74 | 23.91 | 0.113 |
| J242145.05-003736.1 | J242145.99-003734.3 | 4.31 | 4.43 | -40.55 | -42.39 | 18.73 | 20.21 | 1.44 | 1.94 | 14.16 | 0.112 |
| J242515.39-005706.5 | J242517.43-005709.2 | 25.32 | 25.59 | -38.00 | -38.54 | 17.18 | 17.41 | 0.90 | 0.80 | 30.71 | 0.210 |
| J235153.62+000240.8 | J235153.91+000237.5 | 47.43 | 45.65 | -94.63 | -93.58 | 17.34 | 16.71 | 1.48 | 1.03 | 5.73 | 0.023 |
| J024131.67-010959.3 | J024131.70-010954.7 | 2.16 | -0.13 | -54.46 | -51.83 | 21.18 | 17.27 | 2.12 | 0.97 | 4.54 | 0.035 |

### Table 2.

| SDSS Obj | Radial velocity (km s$^{-1}$) | [Fe/H] (dex) |
|-----------|-----------------------------|-------------|
| J007140.28-004732.4 | 9.5 ± 2.0 | -1.81 ± 0.07 |
| J030126.09-004049.2 | 142 ± 2 | -1.35 ± 0.22 |
| J221549.63+005732.9 | -108 ± 2 | NA |
| J222451.39-005706.5 | -244 ± 3 | -1.48 ± 0.08 |
| J235153.62+000240.8 | -75 ± 4 | -2.17 ± 0.17 |

radial velocity constraints together are powerful enough to eliminate any of the potential pairs with separations out to 1000 arcsec ($\approx 10$ pc), which make up the signal shown in Fig. 4.

By lowering the original proper motion threshold of 40 mas yr$^{-1}$, it is possible to get a larger sample of Stripe 82 subdwarfs with radial velocities. Indeed, Smith et al. (2009a) have created a sample of 1717 subdwarfs from Stripe 82 with radial velocities and proper motions without imposing a proper motion threshold in order to study the kinematics of the stellar halo. We have looked also in this sample but found no high probability candidates. The proper motion and radial velocity cuts leave a pair distribution consistent with a random distribution of pairs. Adding a photo-parallax constraint and/or a common metallicity constraint just reduces the amplitude of this signal without revealing any excess that might be due to very wide binaries. The significance of these null detections of wide binaries with $\Delta \theta > 60$ arcsec is not easy to interpret since for these samples we have no handle on the number of wide binaries at smaller $\Delta \theta$ because of the spectroscopic target-selection effects.
Future surveys though, such as Pan-STARRS (Kaiser et al. 2002) or the Large Synoptic Survey Telescope (Ivezic et al. 2008b), will enable vaster samples of wide binaries to be selected with the aid of more stringent proper motion and trigonometric or photoparallax constraints. For example, the 3.5-yr Pan-STARRS PS1 3σ survey, which is due to begin this year, will observe three-fourths of the sky in the five stellar filters (grizY) with a predicted proper motion accuracy of 1.2 mas yr\(^{-1}\) (Magnier et al. 2008). If we simply scale up the numbers found in Stripe 82 by this increased sky coverage, then the PS1 survey will yield at least 2000 wide halo binaries over an order of magnitude greater than CG04 sample size. Such a sample would be hugely influential for advancing our understanding of these objects and placing robust constraints on the nature of dark matter.

In the meantime spectroscopic observations of our new binary candidates for radial velocities and metallicities could be scientifically fruitful. As Fig. 5 shows, many of the binaries span a wide range in spectral type and are of particular importance in testing and constraining SDSS subdwarf photo-parallax relations. Indeed, we pointed out that the scatter in the δ values in our sample is larger than expected for the I08 photo-parallax relation for subdwarf stars. If this is due to unresolved triplets, spectroscopic observations could uncover evidence for this. In any case, metallicities for the new sample would allow more complicated colour–magnitude relations that change systematically with metallicity, to be tested.

With radial velocities from spectra, it will be possible to analyse the Galactic orbits of the objects, allowing one to address questions such as whether there is a trend in binary separation and the Galactic orbit averaged dark matter density. Another application that could be carried out, following spectroscopic observations of the sample, is to search for associations of wide binaries in integral of motion and metallicity parameter space, testing the idea put forward by Allen et al. (2007) that wide halo binaries may have survived disruption in the Galaxy on account of being recently accreted from disrupted satellites.

We give a foretaste of such a test using the five new binaries with spectra from our sample, along with the CG04 wide halo binaries with projected separations larger than 0.01 pc and for which radial velocities have been measured for one or both components. This is given in Fig. 6, which shows the components of the angular momentum perpendicular and parallel to the symmetry axis of the Galactic plane for the new binaries with spectra from our sample (circles), along with the CG04 wide halo binaries (projected separation >0.01 pc) with radial velocity measurements of both components (triangles) and those with radial velocities for just one component (squares). Also included in this figure are the contours from Smith et al. (2009a) showing the 1σ, 3σ, 5σ, 10σ overdensities in this space for halo subdwarfs within 2.5 kpc. Typical errors in \(J_z\) are around 200–250 kpc km s\(^{-1}\). Radial velocities for the CG04 wide binaries were obtained from the compilation in Quinn et al. (2009) and by searching in SIMBAD.

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