A Distant Sample of Halo Wide Binaries from SDSS

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ABSTRACT

Samples of reliably identified halo wide binaries are scarce. If reasonably free from selection effects and with a small degree of contamination by chance alignments, these wide binaries become a powerful dynamical tool, having provided one of the very few experiments capable of constraining the nature of dark matter in the Milky Way halo. Currently, however, the best available sample of halo wide binaries is confined to the solar neighborhood, and is plagued by small number statistics at the widest separations. We present the results of a program aimed to probe the wide binary population of the Galactic halo at significantly larger distances, and which informs future searches that could improve the statistics by orders of magnitude. Halo stars were taken from the Sloan Digital Sky Survey after analyzing the Galactic orbits of stars in the reduced proper motion diagram. We then select candidate binaries by searching for pairs with small differences in proper motion and small projected separation on the sky. Using medium-resolution spectroscopy, a subsample of candidates is validated via radial velocities, finding that about 68% of candidate pairs up to 20″ separation can be considered genuine halo wide binaries, to the limits of the available data. Photometric distance estimates show that the components of our validated candidates lie at the same distances, independently confirming the robustness of the selection method. These results should prove valuable to guide the optimal assembly of larger catalogs of halo wide binaries from upcoming large databases such as Gaia and LSST.

Key words: catalogues – astrometry – binaries: general – stars: kinematics and dynamics

1 INTRODUCTION

Observations have established that multiplicity is the principal product of star formation (Reipurth et al. 2014) and multiple systems of two or more bodies seem to be the norm at different stellar evolutionary stages and throughout stellar types. In consequence, stars in binary systems provide valuable information and influence almost all the branches in astronomy. However, most of this knowledge has come from the study of binary stars in close orbits, while the population of binaries with semi-major axes $a \gtrsim 100$ AU (often referred to as wide binaries) remains poorly explored, comparatively speaking (Chanamé 2007).

Wide binaries have low binding energies, which makes them easily disrupted by any inhomogeneity of the underlying gravitational potential (e.g., passing stars, molecular clouds, spiral arms, etc.) large scale tides, or even Massive Compact Halo Objects (MACHOs). If these encounters are frequent during the lifetime of the wide binaries in our Galaxy, one would expect the distribution of binaries to be depleted for the largest separations. Therefore, wide binaries can be used as probes to establish the properties of such perturbers. For example, they have been used to place constraints on the amount of halo dark matter composed of compact objects above some mass threshold (Bahcall et al. 1985; Yoo et al. 2004; Quinn et al. 2009;
Monroy-Rodríguez & Allen 2014; Peñarrubia et al. 2016). Additionally, the distribution of their semi-major axis might contain information about the dynamical history of the Galaxy.

Starting from the revised New Luyten Two Tenths catalog (rNLTT; Salim & Gould 2003), Chanamé & Gould (2004), hereafter CG04, assembled the first sample of halo wide binaries large enough for reliable population analyses. They cataloged 116 halo wide binaries with angular separations up to $\Delta \theta = 90^\circ$ (projected separations of $\sim 1$ pc). Using this sample, Yoo et al. (2004) set constraints on the mass and density of compact Galactic halo dark matter, excluding MACHOs with masses $M > 43 M_\odot$, at the local standard halo density. On the other hand, MACHOs with smaller masses ($M \lesssim 30 M_\odot$) had already been excluded by micro-lensing surveys (Udalski et al. 1992; Alcock et al. 1998, 1997; Afonso et al. 2003). Consequently, the combination of both experiments left only a small window for a Galactic halo composed entirely of MACHOs.

Nevertheless, the Yoo et al. (2004) constraints rely heavily on the genuineness of the four widest binaries of the CG04 sample. Using radial velocity (RV) measurements, Quinn et al. (2009) showed that one of these four pairs is most likely a spurious one. Omitting this pair, the constraints on MACHO masses are substantially relaxed, increasing the unconstrained window to $\approx 30-500 M_\odot$. This sensitivity clearly means that larger samples of wide binaries with as little contamination as possible are needed to put stronger constraints on MACHOs. Recently, (Brandt 2016) put new constraints on MACHOs of $M \gtrsim 5 M_\odot$ as the main component of dark matter from the ultra-faint dwarf galaxy Eridanus II using the survival of one of its star clusters. However, this result is based on a single object, and, moreover, the subject is of such importance that it is desirable to contrast its validity against experiments from independent directions. Therefore, the test provided by wide halo binaries remains of high importance. Significant effort has been put during the past decade to search for halo wide binaries. For instance, Quinn & Smith (2009) searched for halo wide binaries in the stripe 82 of the Sloan Digital Sky Survey (SDSS) and found 16 pairs of candidates with projected separations between 0.01 and 0.25 pc. Although this sample on its own it is not enough to improve constraints on dark matter, it is a useful addition to the CG04 sample of wide binaries. More recently, Allen & Monroy-Rodríguez (2014) compiled a list of 210 halo systems by joining existing catalogs. However, their source catalogs were assembled independently, with different selection biases and degrees of completeness, most importantly as a function of semi-major axis. Therefore, since what matters for dynamical purposes is precisely the semi-major axis distribution of the population of binaries, the act of combining different catalogs does not produce a clean sample to draw robust conclusions regarding dark matter constraints.

Having precise astrometric data of a large number of stars is of paramount importance to assemble a significant sample of wide binaries belonging to our Galactic halo. This will be possible with the upcoming results from Gaia’s second data release (DR2), although some effort has already been done towards that goal using the Tycho-Gaia astrometric solution (TGAS) catalogue from Gaia’s first data release (DR1; Oh et al. 2017; Andrews et al. 2017, 2018). However, this release is mostly confined to the solar neighborhood, containing almost no halo population. The big challenge for these very large astrometric catalogs is then to be able to distinguish the truly bound systems from among the large number of false pairs that will inevitably be present in such a large sample of stars. With Gaia’s DR2 we will have access to better astrometric information and therefore we will be able to better discriminate genuine wide binaries from spurious associations. Nevertheless, since contamination grows rapidly with separation (see Andrews et al. 2017, 2018) the very widest samples will need radial velocity confirmation, albeit not necessarily selection. Hence, to assemble a catalog of highly reliable (i.e., genuine) halo wide binaries, which as demonstrated above is fundamental for deriving solid dark matter limits, the radial component of the space velocities is ultimately needed for the candidates that satisfy the proper motion, parallax, and/or photometry criteria.

In this paper, we present the results of a small-scale program for selecting reliable, genuine halo wide binaries using the SDSS, accounting properly for contamination from unassociated pairs. The outline of this work is as follows: In section 2 we present the selection of the candidate halo wide binaries, in section 3 the observations and data reduction, in section 4 the analysis of candidates and in section 5 the conclusions.

2 SELECTING THE SAMPLE

We selected our sample using proper motions and photometry from the SDSS, which is an imaging and spectroscopic survey that covers a large area of the sky in five optical bands $u,g,r,i,z$, to a depth of $g \approx 23$. The survey uses a dedicated 2.5 m telescope equipped with a large-format mosaic CCD camera to image the sky, and two digital spectrographs to obtain the spectra of about 1 million galaxies and 100,000 quasars selected from the imaging data (York et al. 2000).

SDSS astrometry is calibrated using observations by an array of astrometric CCDs in the imaging camera (York et al. 2000). Although it is a single-epoch survey, it can be combined with older photometric surveys in order to produce two epochs, necessary to compute proper motions of its stars. This was accomplished by Gould & Kollmeier (2004) and later by Munn et al. (2004) who derived proper motions by combining SDSS astrometry with USNO-B, with statistical errors of roughly 3-3.5 mas/yr. We use Data Release (DR) 9, which has the advantage of correcting errors in proper motions, previously present for DR7 stars at low Galactic latitudes. Proper motions in SDSS are available through the proper motions table in CasJobs¹, which provides a platform to query and access a large data collection in SDSS.

¹ http://skyserver.sdss.org/casjobs/
2.1 Selection of halo stars from SDSS

Using the aforementioned query, we choose stars from DR9 with $14 < r < 20$ and proper motions $|\mu| > 30$ mas/yr. This latter imposed criterion over the proper motions significantly decreases the density of stars, especially more distant ones, which in turn considerably decreases the probability of chance alignments (i.e. stars move together in the sky, but that are not physically related).

For the query, psf magnitudes were chosen, with their corresponding extinction coefficients. In order to have reliable photometry we follow Sesar et al. (2008) to select real sources. From this query 2,767,380 stars were obtained, with errors in photometry less than 0.05 mag.

The selection for this catalog so far is comprised of halo and disc stars, thus the next step is to separate both populations in order to select just halo stars. With only proper motion and photometry information, the Reduced Proper Motion (RPM) diagram can be used to distinguish between halo and disc stars. Salim & Gould (2003) first accomplished the task of constructing a clean RPM sample by improving the astrometry and photometry of the high proper motion ($|\mu| \geq 180$ mas/yr) stars from the New Luyten Two Tenths (NLTT) catalog.

The RPM diagram is a powerful tool to separate halo from disc stars because although these stars have similar absolute magnitudes, they have very different kinematics, and as a consequence, the faster-moving halo stars appear offset from the disc stars in an RPM diagram (Smith et al. 2009). They are also fainter (because in general more distant) and bluer, which also helps in the separation. The $V$-band RPM is defined as Eq. 1:

$$ V_{\text{RPM}} = V + 5 \log |\mu|, $$

and then plotted against a color, where $\mu$ corresponds to the proper motion. In this case, considering the SDSS $g$ band, we define the RPM as:

$$ g_{\text{RPM}} = g + 5 \log |\mu| - 1.47 |\sin(b)|, $$

where $|\sin(b)|$ is a correction factor that corrects for the vertical offset, introduced by different Galactic latitudes (Salim & Gould 2003).

In Fig. 1 we observe by simple inspection a separation between a more dense and populated disc extending from $3.0 < g - z < 4.5$ and the halo extending from $\sim 0.5 < g - z < 2.5$. As a first approach, the position and slope of the separating lines in this plot can be arbitrarily placed based on a visual analysis of the location of the halo and disc tracks in the diagram.

However, as it is crucial that our sample contains only halo stars, we want to determine a more robust limit. With this aim, we performed an analysis of the RPM diagram using radial velocity measurements obtained from SEGUE. This analysis was done by selecting only halo stars ($\sim 400,000$ stars) from the RPM diagram, and we found that only 30,000 of these had radial velocity measurements. Also, from this query, we requested the full parameter space information available for these stars to calculate the orbital parameters such as eccentricity, maximum height with respect to the disc plane ($z_{\text{max}}$) and maximum and minimum distance to the Galactic Centre.

Halo stars move on random, more eccentric orbits, therefore an analysis on the obtained orbits allowed to separate more clearly between halo and disc stars, as illustrated in Fig. 2. Here, we color code the RPM by
eccentricity and we clearly see a separation between halo and disc stars. This is the final criterion we apply to separate disc from halo in the RPM diagram and to place the dashed and solid lines in Fig. 1. In this figure the upper solid line is a relaxed limit separating both populations, the dashed line is a more confident limit and the third solid line, the one closest to the halo, is a confident separator between halo and disc.

2.2 Selection of common proper motion pairs

Once the catalog of halo and disc stars is assembled, we select halo stars applying the criterion described in §2. The next selection criterion is to consider pairs with angular separations between $5'' \leq \Delta \theta \leq 200''$. A lower limit of $5''$ is considered because of the limits in photometry; at smaller angular separations it is harder to distinguish between stars and blending can appear. Also, this avoids potential confusion that may be inherent to our source proper motions, which were obtained by comparing the SDSS and USNO-B epochs (Gould & Kollmeier 2004; Munn et al. 2004). The upper limit is considered because at larger angular separations, more contamination of unassociated stars is present. Since our sample is composed by stars from the Galactic halo, we expect our most distant pairs to be a few kpc from the Sun. An angular separation of 200'' corresponds to a projected separation of $\sim$1 pc at 1 kpc, and thus this upper limit still allows for very wide pairs, in principle, to be selected.

A criterion in proper motion is also applied, selecting small differences in proper motion $\Delta \mu$ for the pairs. We choose candidates with $\mu / \Delta \mu > 10$. Larger values of $\mu / \Delta \mu$ could imply several possibilities; that the difference in proper motion of the halo wide binary candidate is very small, that these move with very high proper motions, or a combination of both. This sets strong constraints on the selection of the candidates given that if both stars move with high proper motions the probability that these stars are not related is very low, and in the case that both have very similar proper motions (hence, smaller differences in $\mu$), then the probability that both are related is very high. Therefore, for all possibilities, the larger the quantity, the more likely the real association between the two stars. Indeed, the high rate of success after radial velocity vetting (Section 4) demonstrates the reliability of this quantity for the selection of good candidates. The specific threshold was chosen because larger values of $\mu / \Delta \mu$ leave too few candidates and smaller values increase the possibility of contamination.

Applying the criteria in proper motion and angular separation, selecting pairs that satisfied this condition the catalog is now composed of $\sim$5000 pairs. In Fig. 3 we present the distribution of these pairs in equal logarithmic bins of angular separation. We clearly see an excess with respect to the random distribution (dashed line) of pairs at close angular separations $5'' < \theta < 32''$, which already suggests the presence of genuine binaries. At larger separations we see that the number of pairs steeply increases, indicating the presence of contamination by chance alignments, as was already noted by Sesar et al. (2008) and Quinn & Smith (2009) who also analyzed the angular distribution of pairs in SDSS.

Figure 2. RPM color coded by eccentricity. We can see a clear separation between stars in eccentric orbits, belonging to the halo, and stars with eccentricities closer to circular orbits, typical of disc stars.

Figure 3. Distribution of angular separations for our initial sample of halo wide binary candidates ($\sim$ 5000 pairs). This distribution shows the number of pairs in equal logarithmic bins of angular separation and it is obtained by just counting pairs. The error bars show Poisson uncertainties. We note an excess of pairs at close angular separations, indicating the presence of true bound systems. The dashed line has slope 2, since random association of stars increase $\propto \theta^2$. 

$\log (N)$
2.3 Assessing the binarity of our candidates

If we want to determine the binarity of our candidates, i.e. the confidence to which we can say a system is a genuine binary, we need to establish a method to disentangle the true bounded systems from line-of-sight chance alignments. To this end, we first explore in detail the distribution in angular separation of our entire initial catalog \( \sim 5000 \) pairs as showed in Fig. 3 without including radial velocity information.

As we can see from this figure, the last two bins lie on top of the dotted line that shows how the contamination fraction increases with angular separation. The last two bins of Fig. 3 follow closely the behaviour of random pairs, making the identification of true pairs impossible. Therefore, we can use the last bin to account for contamination from chance alignments in our catalog. In order to do this we plot in the lower panel of Fig. 4 the slope and height from the isotachs connecting pairs in the RPM for the last bin in Fig. 3. We define the height as the difference in the \( y \)-axis of each pair in the RPM diagram.

In Fig. 4 we show the height and slope of the third bin from Fig. 3, which is comprised by a large fraction of likely genuine binary systems. Here we observe that most points are distributed along a narrow stripe, therefore we use this region to define a rectangle with height \( > 0.4 \) and slope between 2.1 and 3.2. This narrow region contains pairs with isotachs that lie parallel to the halo track in the RPM diagram. In principle, based on the isotach criterion alone, these pairs could be regarded as good candidates. However, this is not true for the last few bins of Fig. 4, where there is no information on true binaries, as the distribution of pairs in this region is consistent with random alignments. Consequently, if we assume that these last two bins are pure contamination, we can use them to find the normalization of the random distribution, i.e. the zero-point of the dashed line in Fig. 5.

In Fig. 5 we now see the distribution of angular separation for the pairs that fall into the enclosed region from the lower panel in Fig. 4. The dashed line shows again the number of random pairs, and they increase with angular separation. At separations less than \( 25'' \) there is a clear excess of true pairs. For separations between \( 25'' \) and \( 63'' \) there may be some excess of genuine binaries, but for separations larger than \( 63'' \) the pairs are consistent with random, chance alignments. We then define the fraction of true binaries as \( \varepsilon = 1 - n_{\text{obs}}/n_{\text{rand}} \) following Sesar et al. (2008), where \( n_{\text{obs}} \) corresponds to the number of observed pairs, and \( n_{\text{rand}} \) is the number given by the dashed line. We show this fraction as a function of the angular separation in Fig. 6. Here we can see that \( \varepsilon \) decreases steeply from the fourth bin onwards, at separations larger than \( \sim 20'' \). At separations larger than \( 63'' \) we see that this fraction reaches 0.

Finally, a subsample of these 5000 pairs was selected based on their observability from the southern hemisphere as the final catalog. This is composed of \( \sim 400 \) halo wide binary candidates, and their positions in the RPM diagram can be seen in Fig. 1.

Figure 4. Height and slope of the isotach connecting candidate pairs in the RPM diagram. In the upper panel we show pairs from the third bin in Fig. 3, while the lower panel shows the pairs that fall in the last bin of the same figure. Both samples represent two different regimes – where we expect to find mostly genuine binaries and the latter where we are dominated by contamination. The red rectangle shows the region of this plot where we should have well behaved pairs connected by a parallel line with respect to the halo track in the RPM.

3 OBSERVATIONS AND DATA REDUCTION

For the candidates that passed our selection criteria we obtained long-slit spectra. Observations were carried with the COSMOS instrument at the Blanco telescope in Cerro Tololo Inter-American Observatory (CTIO) with the blue VPH grism covering a wavelength range of 5600-9600 Å and a 0.9'' slit reaching a spectral resolution of \( \sim 2100 \). Also with the EFOCS2 spectrograph at the NTT in La Silla with grism \#20 covering a wavelength range of 6047-7147 Å and a 0.5'' slit reaching a spectral resolution of \( \sim 3200 \). Finally with the KOSMOS instrument at the Kitt Peak National Observatory (KPNO) with the red VPH grism covering a wavelength range of 5600-9600 Å and a 0.9'' slit reaching a spectral resolution of \( \sim 2200 \). From the initial sample of 400 candidate pairs we obtained spectra for 88 pairs.

We highlight the fact that we do not need high resolution spectra given that we carefully select pairs that
Figure 5. Distribution of angular separations as seen in Fig. 3 but now counting the pairs that fall inside the region defined in Fig. 4 for each bin. The dashed line has the same slope as Fig. 4, but with a different zero point. This was obtained by using the fraction of pairs from the last bin that fall into the rectangle region from Fig. 4 compared to the total number of pairs in that bin. Again, at close angular separations, 5′′ < θ < 32′′ we see an excess of true pairs. The error bars show Poisson uncertainties.

Figure 6. Fraction of true binaries, ε using bins from Fig. 5. At separations larger than 60″ the fraction reaches 0, so no useful information can be obtained for larger separations.

are close and move together in the sky. Therefore, we only need radial velocities within a few km/s in precision to confirm their association, given that the dispersion in the Galactic halo is of ~ 140 km/s (Bland-Hawthorn & Gerhard 2016).

For the lowest resolution spectrograph used (R ~ 2100) the precision in radial velocity measurements is Δv_r ~ 15 km/s.

On the other hand, our sample is composed of halo stars which are faint targets with magnitudes in the range 14 < V ≤ 20, hence long exposure times were necessary. We planned our observations aiming for a minimum signal-to-noise ratio of SN ~ 10, which is sufficient to resolve the general spectral features we need to estimate the radial velocities via cross-correlation techniques.

For the faintest targets (V > 17) combined exposures were obtained, taking 2 or 3 spectra per object depending on how faint the target was. In order to save time, for the cases where this was possible, stars of a pair were observed together placing both of them in the slit. This was done for the cases where angular separations were small enough in order to be able to observe them at the same time in the slit. Generally for cases where Δθ was larger than 70″ this was not possible. We always observed stars of a pair with the same instrument.

The process of data reduction involved all the standard procedures for cosmetics correction, extraction of the spectra and a final wavelength calibration which was done for each of the 88 pair candidates of wide binaries using ccdproc and apextract from IRAF.

4 ANALYSIS

In this section we will present the results from our radial velocity measurements for our catalog comprised of 88 candidate pairs. In Sec. 2.3 we presented a method to analyze the contamination in our catalog due to chance alignments without including radial velocity information. Here we want to establish if the pairs that have small Δv_r are consistent with being genuine binaries.

4.1 Radial velocity measurements

We measure the radial velocities of our sample using the xcmoa, rvsa o IRAF task, which is part of a package for obtaining radial velocities of stars and galaxies from optical spectra using the cross-correlation method developed by Kurtz et al. (1992). The correlation procedure compares each spectrum with an input template. Given the importance of having templates with a high signal-to-noise ratio we use the PHOENIX library, which is a collection of synthetic spectra that covers effective temperatures from 2300 to 12000K and a wavelength range from 3000 to 25000 Å with a high resolution of R ≈ 500,000 (Husser et al. 2013).

We applied the conversion from vacuum to air wavelength to the synthetic spectra using the refractive index from Edlén (1966).

Given the low-resolution of our data, we lack detailed spectral information (i.e., precise spectral type and metallicity for each star), and thus we were not in a position to choose a single best template in advance for
any given target. Therefore, we developed a procedure that involved the cross-correlation with the full library of spectra. However, as we selected only halo stars from the RPM diagram, we assume that our entire sample is composed of dwarfs. In consequence, we select templates with log g between 3.5 and 4.5 and [Fe/H] of -1.5 and effective temperatures in the range $2300 \lesssim T_{\text{eff}} K \lesssim 8000$.

Once the cross-correlation with each template is done, we have to select a velocity from all the results obtained from this. Besides the velocity, $z_{\text{csao}}$ gives a reliability factor $R$ which depends on the amplitude of the cross-correlation peak, hence at larger values of $R$, the correlation is better. We plotted the obtained $R$ values from the cross-correlation as a function of the effective temperature of each template and adopted a Gaussian fit for this distribution, as can be seen in Fig.A1. This allowed us to select a range of effective temperatures to consider (and for which the cross-correlation was better) and then, for the velocities that fell in that same range in effective temperature, the final velocity was taken from the median of all of these values.

To determine how well the cross-correlation method is performing, we plot the error given by this method and its corresponding $R$ value, which can be seen in Fig.A2. For larger $R$’s the error decreases until converging to the value of the spectral resolution of the spectograph. Thus, choosing higher values of $R$ also gives small errors in the cross-correlation.

The result of all our radial velocity measurements for our 88 candidate pairs and their corresponding uncertainties can be seen in Fig. 7. In this figure the velocity components of the primary versus the secondary star of the selected candidates can be seen in blue dots, therefore each point in this plot corresponds to a pair. The background is the result of a query in SEGUE for halo stars from the RPM diagram for which radial velocity measurements were available. Approximately 3000 stars with RV measurements were found, none of them belonged to our catalog. Then, in order to be able to plot them in Fig. 7 a random selection of pairs for these stars was made. This was done considering that these velocities follow the velocity distribution of halo stars and assigning random velocities for a pair following this distribution. Note that the width of the random distribution of points, in both axes is consistent with the expected velocity dispersion of the Galactic halo which is is $\sim 140$ km/s.

It is expected that, because of low orbital velocities, wide binaries should have very similar proper motions and radial velocities, thus they should follow a 1-to-1 slope, which is the central solid line in Fig. 7. Most of the candidates follow this trend, also the candidates follow the distribution of velocities expected for halo stars, with $\sim 140$ km/s of dispersion in velocity. Hence, we can say that the independent radial velocity vetting confirms that our criterion in proper motion alone already seems to select a large fraction of genuine halo wide binaries, given the velocity distribution of our candidates in this plot. However, we have to further analyze our sample in order to establish a quantitative result of binarity for our candidate pairs in the catalog.

Besides our criteria in proper motion and angular separation, we did not apply any extra criterion on photometry besides the cut in $r < 20$ to select the candidates for our catalog. Nonetheless, in Fig. 8 we see that if we connect our candidates with a line most of them lie parallel with respect to the halo track in the RPM diagram. This isochrone (Chanamé & Gould 2004) is an isochrone vertically displaced due to velocity (proper motion) in the RPM diagram. We should expect this behavior since both members of a binary should have similar metallicities and essentially the same proper motion but with different luminosities. Therefore, the line connecting their positions in the RPM diagram should be approximately parallel to the stellar halo track. There are a few cases in Fig. 8 where this is not the case, which can occur for two reasons: (1) either the wide binary is real but its photometry has been compromised, or (2) there is contamination of systems that are not real pairs, therefore we have to find a way to establish the amount of chance alignments in our catalog.

### 4.2 Distances

Our sample is composed of stars moving at relatively small proper motions ($\mu > 30$ mas/yr) and of relatively faint stars covering the range in magnitudes $14 < r < 20$ therefore, we could think that these are distant stars. In order to

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{The upper and lower panels show the radial velocity measurements for all the candidates of our catalog. Each point in this plot corresponds to a pair. The central solid line corresponds to the 1-1 slope, and dashed lines show $\pm \sigma$ of the precision in radial velocity from the instruments used. The lower panel shows that the difference in radial velocity of our candidates is mostly concentrated in velocities less than 45 Km/s. $\Delta v_r > 200$ km/s are omitted in the lower panel.}
\end{figure}
4.3 Candidates with RV measurements

Now that we have established a reliable method to quantify the degree of contamination, and to determine the fraction of true bounded systems, we proceed to test it by applying it to the candidates in our catalog with RV measurements. In Fig. 9 we show the height and slope from the RPM diagram for this sample, color coded by their difference in radial velocity. In the upper panel of this figure we see that there are some candidates with large $\Delta v_r$ inside the red rectangle. As we are including our entire catalog, which has pair with large angular separations, this result is consistent with our previous findings, where we expect to have significant contamination from random alignments. In the lower panel of this figure we show the subsample of pairs with $\theta < 18.25"$, where we expect to have mostly genuine binaries, as can be seen from Fig. 6. We observe that less than ~20% of pairs have large differences in $v_r$, implying much less contamination. In consequence, these results are consistent with what we already obtained, and it shows the robustness of our previous analysis.

We now proceed to determine the fraction of true binaries in our catalog with RVs using our proposed method. In Fig. 10 we show the distribution in angular separation for our candidates. The colored regions indicate the pairs that have up to 68% and 20% of confidence of being truly bounded in light pink and blue, respectively. These regions were determined based on the results shown in Fig. 6. From the distribution shown in Fig. 10, we observe that at angular separations larger than 25" we expect to have less than 20% of true binaries.

With the calculated distances for our candidates we proceed to calculate their projected distances in the sky in Astronomical Units (AU). In Fig. 11 we show the distribution of projected distance for our complete catalog of halo wide binary candidates with RV measurements, as well as the candidates that have 68% or more probability of being genuine binaries. The entire sample has a roughly flat distribution up to $r_\perp \sim 6 \times 10^4$ AU, where the number
of pairs sharply drops. Conversely, the candidates with large probabilities of being true binaries are concentrated at smaller distances, as most of the contamination comes from large projected distances.

Our complete catalog with RV measurements reaches up to $\sim 0.9$ parsecs in projected distance according to Fig. 11. However, once we analyze the contamination from chance alignments, this sample decreases and reaches only up to $\sim 0.1$ parsecs in projected distance. We obtain for this subsample a 68% probability or more of \textit{binarity}. For larger separations we have no reliable information on genuine pairs, as shown by Fig. 5.

Finally, for the pairs with $\theta < 18.25''$ for which we find a 68% of probability of \textit{binarity} we show their connecting \textit{isotachs} in the RPM diagram. We present these pairs in Fig. 12 connected by pink lines. Clearly our criterion selects the well connected pairs in this diagram. For comparison, we show the entire sample with RVs connected by black lines.

4.4 Selection effects as a function of separation

If this catalog is intended to be used to improve constraints on dark matter in the halo of the Galaxy in the form of MACHOs, we need to have a complete selection of candidates covering a certain parameter range to draw conclusions that will be statistically significant from the sample. Our selection criterion $\mu/\Delta\mu$ is substantial and already eliminates contamination from pairs that are chance alignments. Moreover, it is a selection criterion independent of angular separation, crucial for dynamical population studies. In Fig. 13 we plot the quantity $1/\mu\Delta\mu$, where smaller values imply that the criterion is stronger and that the halo wide binary candidate has more chance of being an actual
bound system. After applying our selection criteria, the sample we assembled is still fairly large consisting of ~ 400 pairs, as we mentioned in Sec. 2.2. However, if we consider further constraints, we can have a more or less complete observed sample of halo wide binaries. In Fig. 13 we show the candidates that could be observed from the southern hemisphere, and with magnitudes for the primary and secondary star, \(v_1\) and \(v_2\) ≤ 19. From this selection, our final radial velocity-vetted sample is shown as blue opened circles, and black crosses are the candidate halo wide binaries that could not be observed due to weather conditions. We note in this figure that up to angular separations of 70' we observed most of the pairs in that region.

5 CONCLUSIONS

We report a new method to find genuine wide binaries from the halo of our Galaxy. We also report a new assembled catalog of halo wide binaries using photometry and proper motion information from SDSS, complemented by ground-based radial velocities from medium-resolution spectra. Wide binaries have low binding energies, which makes them easily disrupted by encounters with different perturbers (MACHOs being one of them). Therefore, one of their applications is that they can be used to place constraints on the amount of halo dark matter composed of these compact objects. With this new catalog we expand the current small and local sample of genuine halo wide binaries (until today, best represented by that of CG04) and therefore we produce a new one probing the Galactic halo to distances never reached before with these objects, and free of selection effects as a function of separation.

Because there are a large number of false pairs present in such a large sample of stars with similar proper motions, radial velocity measurements were obtained in order to confirm which of the candidates selected with proper motion criteria were genuine binaries. From the radial velocity measurements it was possible to test the adopted criterion in proper motion to select the halo wide binary candidates, and according to our results ~ 68% of the sample with separations up to \(\theta < 18.25'\) is composed of true bound systems, having consistent proper motions and consistent velocities. From the results obtained with the radial velocity measurements, we show that proper motion alone already selects many genuine halo wide binaries at close angular separations.

We find pairs up to ~ 0.9 parsecs in projected distances, but once we analyze the contamination fraction, we find that the sample reaches only up to 0.1 parsecs. For larger separations we cannot reliably establish a fraction of true bounded systems. Future work includes the calculation of Galactic orbits for the candidate pairs, given that all the information necessary for them is available in this catalog (proper motions, radial velocities, positions and photometric distances). Finally, this new assembled catalog will certainly help in the future goal of statistically selecting even larger samples from the entire SDSS for example, as well as from Gaia and Panstarrs.

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Figure 13. \(1/(\mu/\Delta\mu)\) criterion vs the angular separation for the candidates between \(5' < \Delta\theta < 200'\), \(\delta_1\) and \(\delta_2 < 25\) deg, \(v_1\) and \(v_2\) ≤ 19. The dashed line shows the limit of 70" in angular separation, where our sample is complete.
Appendix A: Radial Velocities: Template Fitting

In this section we present some of our results of the cross-correlation method we used to calculate the radial velocities in our catalog. In Fig. A1 and Fig. A2 each red dot in the plot is the result of the correlation of the spectrum of the star and a different template. As was noted in Sec. 4.1, a cross-correlation with the complete range of templates covering $3.5 < \log g < 4.5$ is necessary because we do not have the stellar parameters of the wide halo binary candidates. The synthetic spectra have effective temperature information, which is used to plot Fig. A1. This is the first step in the determination of the velocity. Besides the velocity, $xcsao$ gives a reliability factor $R$ which depends on the amplitude of the cross-correlation peak, hence at larger values of $R$, the correlation is better. We expect the candidates to be dwarfs because of their location in the RPM diagram their effective temperatures should be around $2300 \lesssim T_{eff} \lesssim 8000$ just as Fig. A1 shows, and we adopt a Gaussian fit to select the best $R$ values. The errors obtained by the cross-correlation are illustrated in Fig. A2, where we observe that for larger values of $R$ the error decreases until converging into $\sim 5$ km/s. Finally, once it has been established the range of $R$ and temperature, we consider which velocities fall into this range, and this is how we select the velocity for each candidate pair.

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