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# ASSEMBLING THE LARGEST, MOST DISTANT SAMPLE OF HALO WIDE BINARIES FOR GALACTIC STRUCTURE AND DYNAMICS

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RESUMEN

Las muestras de binarias anchas ($a \gtrsim 100$ UA) son una mina de oro para estudios Galácticos. Han sido usadas en una larga lista de aplicaciones en muchos campos. Dinámicamente, las binarias anchas proporcionaron las primeras restricciones significativas en la masa y la naturaleza de la materia oscura en el disco y más recientemente fueron usadas para limitar el espacio de parámetros de materia oscura del halo en forma de MACHOs, algo que no es accesible a través de las campañas de microlente. Todas estas aplicaciones fueron posibles cuando las muestras de este tipo de objetos fueron lo suficientemente grandes como para no estar dominadas por alineamientos al azar de dos estrellas proyectadas en el cielo y que no están relacionadas. Sin embargo, aún hoy en día la muestra más grande de binarias anchas del halo que son realmente valiosas y libres de efectos de selección no contiene mucho más de 100 sistemas y las conclusiones que se pueden obtener sobre la materia oscura son muy sensibles a este hecho.

ABSTRACT

Samples of wide binaries ($a \gtrsim 100$ AU) are a gold mine for Galactic studies. They have been used on a large list of applications in a diversity of fields. In the dynamical arena, wide binaries provided the first meaningful constraints on the mass and nature of disk dark matter and, more recently, they were used to close the remaining parameter space of MACHO-like halo dark matter not accessible to the micro-lensing campaigns. All these applications were possible when samples of these objects became large enough to not be dominated by random, chance alignments of two unrelated stars projected on the sky. Nevertheless, still today the largest available sample of the particularly valuable halo wide binaries *free from selection biases*, contains not much more than 100 systems, and conclusions on dark matter are very sensitive to this fact.

*Key Words:* stars: binaries

## 1. INTRODUCTION

Binary stars provide information for a number of astrophysical studies and the fundamental data obtained from these stars can facilitate direct tests of structure models for stars of different mass on the Main Sequence, as well as models for the evolution of such stars throughout all the stages of their aging process. Nevertheless, most of this knowledge has come from the study of binary systems in close orbits, while the population of binaries with orbital separations with semi major axes $a \gtrsim 100$ AU remains poorly explored (Chanamé 2007). The main reason behind this bias is the much longer orbital timescale of very wide binaries, making their identification more difficult because it is a task that requires a relatively long timescale. In contrast to the case of close binaries where some kind of variability helps to uncover them, a reasonably large number of very wide binaries cannot be identified via the typical photometric or spectroscopic campaigns. Instead, wide binaries require accurate astrometry over longer timescales.

For some time now, the existence of very wide halo binaries with separations greater than 0.1 pc has been firmly established (Quinn et al. 2009; Chanamé & Gould 2004). These systems are intriguing for a number of reasons first, their formation remains a mystery. Parker et al. 2009 shows that wide binaries with semi major axis $a \gtrsim 10^4$ 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). On the other hand, 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). Second, the widest of the binaries are quite fragile and easily disrupted by encounters with perturbers (which can be passing stars, molecular clouds, spiral arms (Allen at al. 2007) or even Massive Compact Halo Objects known as MACHOS) . In

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this way, they can be used as probes to establish the properties of such perturbers, or to place constraints on the nature of the dark matter halo composed of massive compact bodies. Third, they are like mini clusters because they offer the possibility of studying two stars of different mass, but with the same age, distance and chemical composition. Early attempts to learn about dark matter in the solar neighborhood through wide binaries (Bahcall et al. 1985) did not achieve useful conclusions due to the small number of wide binaries available then, especially at large separations ($a \gtrsim 0.1$ pc). From the revised New Luyten Two Tenths catalog (rNLTT) (Salim & Gould 2003), the largest catalog of disk and halo wide binaries available to date (Chanamé & Gould 2004) was obtained. From the halo sample consisting of 116 secure wide binaries out to angular separations of $\Delta\theta = 900$ arcsec (projected separations of $\sim 1$ pc), constraints on the mass and density of dark matter were placed in the form of MACHOs present in the Galactic halo, the first of their kind completely independent of micro-lensing experiments. MACHOs with masses $M > 43 M_\odot$ (for a standard local halo luminosity function) were excluded at the 95% confidence level (Yoo et al. 2004). Sesar et al. (2008) also investigated wide binaries from the Sloan Digital Sky Survey (SDSS), but focusing on the disk population. Quinn et al. 2009 studied halo wide binaries in SDSS in Stripe 82 but their sample only contains separations between 0.007-0.25 pc and it is not large enough to improve constraints on dark matter in the halo. Finally, Allen & Monroy-Rodríguez (2014) recently compiled a list of 210 halo systems by joining existing catalogs. However, all those sources were built with different selection biases and degrees of completeness. We want to supersede these efforts and lay down the path to a significantly larger sample of genuine halo wide binaries.

## 2. HOW TO LOOK FOR THESE OBJECTS?

The wide binary distribution can be measured using the common proper motion method. This adds proper motion information to the astrometry and photometry. Because of the wide separations and correspondingly low orbital velocities, wide binaries should have very similar proper motions and, if available, they can be used to distinguish genuine binaries from the much more numerous pairs of unassociated stars in the field. However, this technique breaks down at large separations primarily because the number of field stars eventually becomes so large that some unassociated stars actually have similar proper motions, but ultimately because at sufficient large separations the observed proper motions represent substantially different projections of the common physical velocity.

With only proper motion and photometry on hand, the reduced proper motion (RPM) diagram is a common tool used to distinguish subdwarfs (halo) stars from disk stars (Quinn & Smith 2009). Although disk and halo dwarfs have similar absolute magnitudes, they have very different kinematics. As a consequence, the faster moving halo stars appear offset from the disk stars in an RPM diagram (Smith et al. 2009).

### 2.1. *Selecting the sample*

The candidate pairs were selected using color and reduced proper-motion criteria, with a query in Casjobs from the Data Release 7 (DR7) of the SDSS. The proper motions from Casjobs are derived by combining SDSS astrometry with USNO-B positions, recalibrated against SDSS (Munn et al. 2004), with statistical errors in the component proper motions of roughly 3-3.5 mas/yr, so these proper motions are good enough for our selection sample. We selected common proper-motion pairs moving faster than $|\vec{\mu}| > 40$ mas/yr (Figure 1) and with angular separations 10" $< \Delta\theta <$ 230". Therefore, the sample assembled from this program is a probe for regions several kpc away from the local neighborhood.

## 3. THE CHALLENGE

We want to produce a new sample of halo wide binaries that will be larger than the rNLTT sample at wide separations (~1pc), will probe the Galactic halo to distances never reached before with these sensitive objects, but which will still be free of selection effects as a function of separation. For the nearby Luyten stars, with proper motions $|\vec{\mu}| > 180$ mas/yr just the combination of photometry and astrometry was enough to do the selection. But with the more distant SDSS stars, moving at 40 mas/yr, the measured $\Delta\vec{\mu}$ alone does not reject all the apparent binaries. The challenge is then to be able to distinguish the truly bound systems from among the large number of false pairs that are inevitably present in such a large sample of stars with similar proper motions. Therefore, to assemble a catalog of genuine wide binaries from the SDSS we need the radial component of the space velocities.

Quinn et al. (2009) confirmed the physical nature for three of the four widest halo binary candidates from the sample of Chanamé & Gould (2004) using radial velocity (RV) measurements, thereby confirming that binaries with separations $\sim 1$ pc can

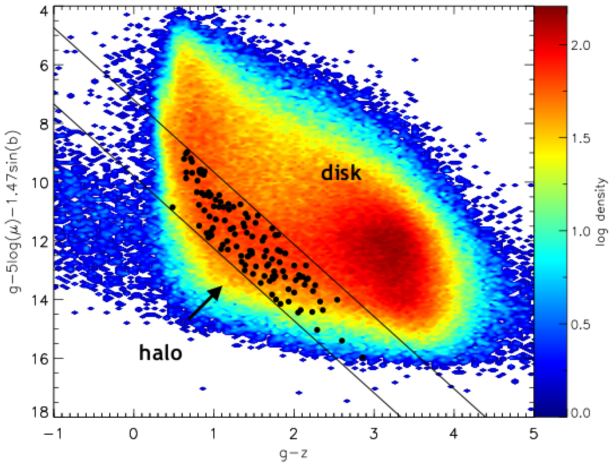


Fig. 1. Reduced Proper Motion (RPM) diagram, clearly separating the disk and the halo tracks. Black dots within the two solid black lines correspond to our pre-selected candidates. We selected stars moving at $|\vec{\mu}| > 40$ mas/yr with separations of 10" $< \Delta\theta <$ 230".

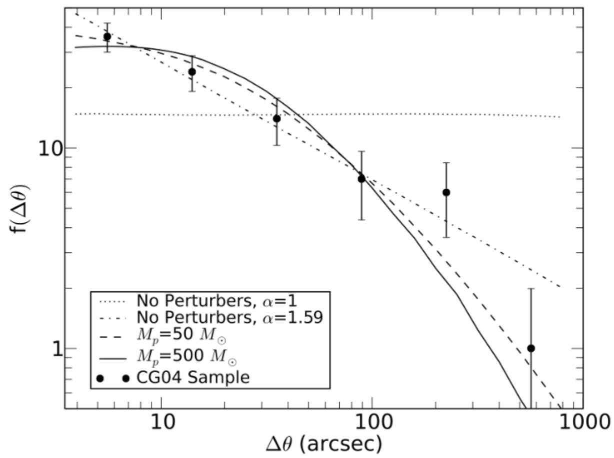


Fig. 2. A comparison of the predicted observable angular separation function for a number of models (Quinn et al. 2009). The observed distribution, from the Chanamé & Gould (2004) homogeneous sample less the spurious pair, is also shown with associated Poisson errors.

exist. However, the spurious nature of the second widest pair undermines the existing constraints on MACHOs and shows that the obtained limits are highly dependent on the number of binaries at the widest separations (Figure 2). Therefore, the best wide binary sample today is too small to place meaningful constraints on MACHOs, being extremely sensitive to the widest of the binaries in the sample.

## 4. RADIAL VELOCITIES

For the candidates that passed the first tests (consisting of photometry and proper motions) we have long-slit spectra from Bollers and Chivens (B&C) spectrograph at the du Pont 2.5m telescope for $\sim 50$ pairs. Their radial velocities will allow us to clean the initial sample and select the real binaries. The ultimate goal is to determine how easily can we tell the difference between real bound systems and chance alignments when the three components of the space velocity are known for both stars in any given pair, and to establish the fraction of real binaries among the total number of candidate pairs that are selected based on photometry and proper motions alone, i.e, with no radial velocity information. Radial velocity for the candidates were calculated using the cross-correlation technique with the task *xcsao* from the *rvsao* external package of IRAF (Figure 3). Errors for this task are calculated using the Tonry & Davis (1979) definition. The correlation was done using templates from the ELODIE spectral library (Prugniel & Soubiran 2001). The ELODIE library includes 1962 spectra of 1388 stars (of different spectral types) obtained with the ELODIE spectrograph at the Observatoire de Haute-Provence 193cm telescope in the wavelength range 390 to 680 nm. The cross-correlation is performed using each template of the library. As a preliminary result we are considering that in the cross-correlation with each template spectrum the best fit (given by a reliability factor in *xcsao* task) gives the best velocity.

### 4.1. *Preliminary results*

In Figure 4 we plot the velocity components of the primary versus the secondary star of our pre-selected candidates in blue dots. We expect 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 dashed line in this plot. We see that most of our candidates follow this trend within the precision in radial velocity of the B&C spectrograph, which is roughly 25 km/s (represented by the two external dashed lines). The outliers are probably not genuine wide binary systems.

As a comparison, we also plot in Figure 4 the velocity of random pairs from Xue et al. (2008), which is a sample of 2401 Blue Horizontal Branch halo stars. We notice that if the sample of candidates were not related they would follow the random distribution and they clearly do not. From this we can state that most of the candidates of our sample appear to be genuine wide binaries.

## 5. CONCLUSIONS

From this work so far we have obtained the radial velocities of $\sim$50 pre-selected pairs from our sample using proper motion criteria. Our preliminary

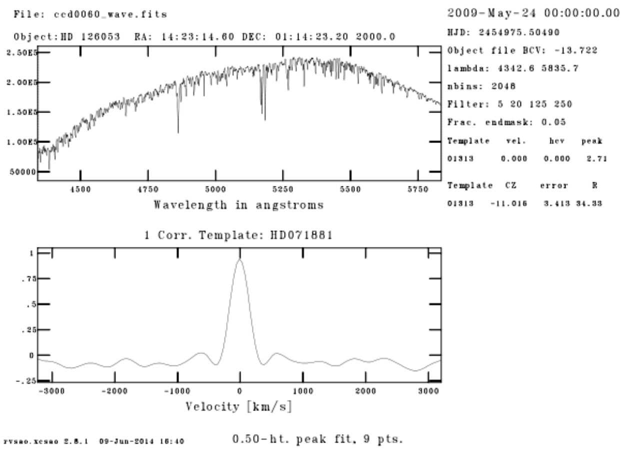


Fig. 3. Example of the cross correlation using *xcsao* in IRAF with a template spectrum from ELODIE library. In the bottom panel we see the cross-correlation peak which gives the velocity and in the upper panel is the spectrum of one of the candidates.

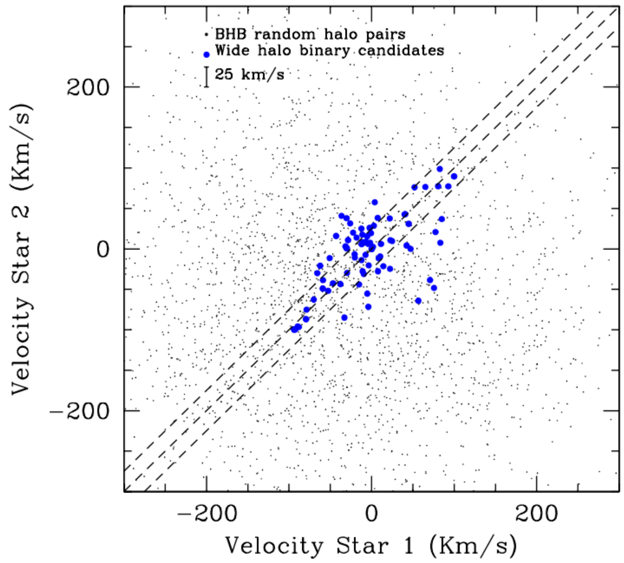


Fig. 4. Plot showing the radial velocities of pairs of our pre-selected candidates in blue dots, and the background in black dots shows pairs selected randomly from Xue et al. (2008).

results are encouraging and show that the proper motion selection alone already selects many genuine wide binaries. We still have to work on the remaining 50% of our sample, because we have echelle spectra from the MagE spectrograph of the Clay 6.5m telescope. As a future work we would like to perform a contamination analysis as a function of relevant parameters such as total proper motion, angular separation, and magnitude.

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