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AN IMPROVED CATALOG OF HALO WIDE BINARIES AND LIMITS ON HALO DARK MATTER (MACHOS)

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RESUMEN

A partir de una extensa búsqueda en la literatura, hemos construido un catálogo mejorado de binarias abiertas del halo galáctico. La probable pertenencia de nuestras binarias al halo galáctico fue verificada mediante el diagrama de movimiento propio reducido para 252 candidatos. Después de eliminar las estrellas del disco, subsisten 212 probables binarias del halo, para 150 de las cuales pudimos calcular órbitas galácticas y con ello, determinar la fracción de sus vidas que pasan en el disco. Estudiamos la distribución de separaciones angulares (o semiejes esperados) para la totalidad del catálogo, así como para distintas sub-muestras. Encontramos que, en todos los casos, la distribución se representa bien por una ley de potencias con exponente -1 (distribución de Oepik) hasta distintos límites para las separaciones angulares o semiejes esperados. Para las 50 binarias que pasan toda su vida en el disco (entre $z = \pm 500$ pc) el límite es de 19000 au, mientras que para el grupo de binarias que pasa sólo el 18% de su vida en el disco el límite que encontramos es de 63000 au. Empleamos este catálogo para encontrar límites superiores a las masas de los perturbadores masivos del halo (MACHOs). Tomando en cuenta los efectos dinámicos del disco galáctico, así como la densidad no uniforme del halo, encontramos una cota superior de 13 $M_\odot$ para la masa de los MACHOs. Esta cota, junto con las cotas inferiores encontradas en otros estudios, prácticamente excluye la existencia de MACHOs en el halo galáctico.

ABSTRACT

We constructed an improved catalog of halo wide binaries, compiled from an extensive literature search. Probable membership to the halo population was checked by means of reduced proper motion diagrams for 252 candidate halo binaries. After eliminating disk stars we end up with 212 probable halo binaries, for 150 of which galactic orbits could be computed, and the time they spend within the galactic disk calculated. Taking the full sample of 252 candidate halo binaries as well as several subsamples, we find that the distribution of angular separations (or expected major semiaxes) follows a power law with an exponent -1 (Oepik's relation) up to different limits. For the 50 most disk-like binaries, those that spend their lives entirely within $z = \pm 500$ pc, this limit is found to be 19000 au, while for the 50 most halo-like binaries, those that spend on average only 0.18 of their lives within $z = \pm 500$ pc, the limit is 63000 au. We employ this catalog to establish limits on the masses of the halo massive perturbers (MACHOs). We find that different subsamples of binaries give different upper limits for that MACHO mass. Taking into account the dynamical effects of the disk on the passing binaries, as well as the non-uniform density of the halo, we obtain 13 $M_\odot$ as an upper limit for the mass of the MACHOs. This limit, together with lower limits on their mass from other studies, practically excludes their existence in the galactic halo.

Key Words: binaries: general — binaries: visual — catalogs — Galaxy: halo — stars: Population II

1. INTRODUCTION

Old disk and halo binaries are relevant to the understanding of processes of star formation and early dynamical evolution. In particular, the orbital properties of the wide binaries remain unchanged after their formation, except for the effects of their interaction with perturbing masses encountered during their lifetimes, as they travel in the galactic environment. The widest binaries are quite fragile and easily disrupted by encounters with various perturbers, be they stars, molecular clouds, spiral arms or MACHOs (massive compact halo objects). For this reason, they can be used as probes to establish the properties of such perturbers (Wasserman & Weinberg 1991; Yoo, Chanamé, & Gould 2004; Jiang & Tremaine 2010).

An interesting application of halo wide binaries was proposed by Yoo et al. (2004) who used the catalog of Chanamé & Gould (2004) containing 116 halo binaries to try to detect the signature of disruptive effects of MACHOs in their widest binaries.

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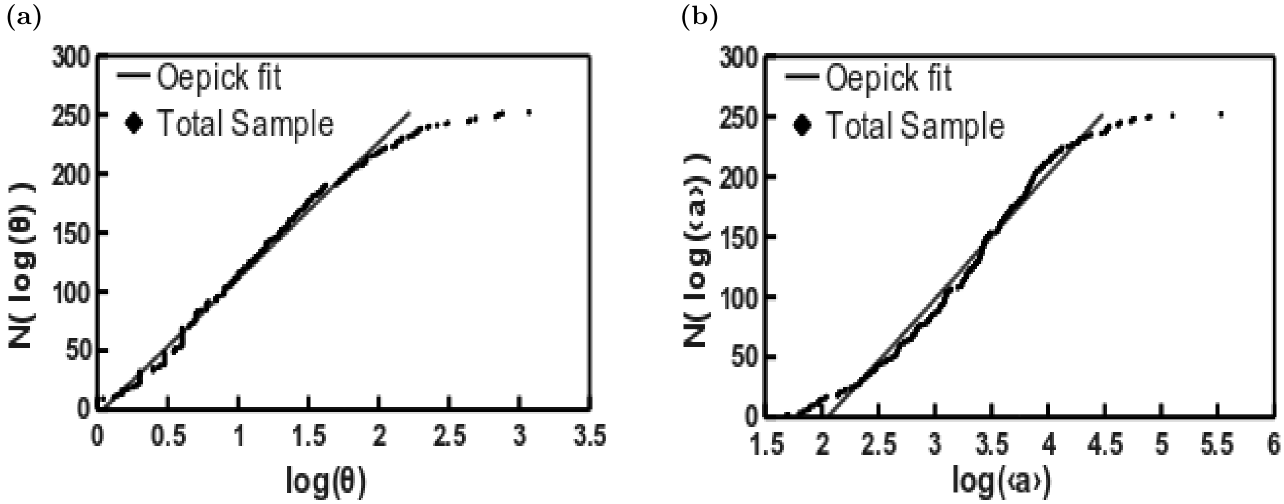

Fig. 1. Cumulative distribution of (a) angular separations and (b) expected major semiaxes for 252 halo binary candidates. The straight line is Oepik's distribution, which clearly holds up to about $\theta = 100'$ or $\langle a \rangle = 16000$ au.

Using their "clean" sample of 68 binaries they were able to constrain the masses of such perturbers to $m < 43\ M_{\odot}$, essentially excluding MACHOs from the galactic halo, since a lower limit of about 30 $M_{\odot}$ is found by other studies (Alfonso et al. 2003; Alcock et al. 1988, 2001) However, as was shown a few years later by Quinn et al. (2009) this result depends critically on the widest binaries of their sample, as well as on the observed distribution of the angular separations which, according to Chanamé & Gould (2004; their "clean sample" of 63 stars) shows no discernible cutoff between $5.5''$ and $900''$. Quinn et al. (2009) obtained radial velocities for both components of four of the widest binaries in the Chanamé & Gould catalog and found concordant values for three of them, thus establishing their physical nature. The fourth binary turned out to be optical, resulting from the random association of two unrelated stars. Excluding this spurious pair and assuming a power law distribution with exponents between 0.8 and 1.6 for the observed separations Quinn et al. (2009) find a limit for the masses of the MACHOs of $m < 500\ M_{\odot}$, much less stringent than that found previously. They conclude rather pessimistically that the currently available wide binary sample is too small to place meaningful constraints on the MACHO masses. They also point out that the density of dark matter encountered by the binaries along their galactic orbits is variable, and that this variation has to be taken into account when calculating constraints on MACHO masses.

Motivated by these concerns, we have constructed a catalog of 252 candidate halo wide binaries. We describe the way the catalog was compiled in § 2. In § 3 we present the distribution of angular separations and expected major semiaxes for different subsamples of binaries, and examine the galactic orbits for the 150 binaries with sufficient data. In § 4 we briefly discuss the dynamical model for the evolution of wide halo binaries and apply this model to several subgroups of binaries from our catalog in order to obtain new limits on the MACHO masses. We point out that for a total of 9 binaries concordant radial velocities for both components were found in the literature, thus confirming their physical nature. Our results are summarized in § 5. § 6 presents a brief discussion.

2. CONSTRUCTION OF THE CATALOG

A search of the literature was conducted, looking for high velocity, metal-poor wide binaries, since such samples are likely to be rich in halo stars. Most of the binaries in the new catalog stem from the lists of Ryan (1992), Allen et al. (2000), Chanamé & Gould (2004) and Zapatero-Osorio & Martín (2004). All data were checked and updated when necessary. We selected the most reliable data for the distances, metallicities and radial velocities. All proper motions were checked, and non-common proper motion companions were eliminated. The catalog includes 111 binaries from Allen et al. (2000), 110 halo binaries from Chanamé & Gould (2004), 23 from Zapatero-Osorio & Martín (2008), and 8 from Ryan (1992), to give a total of 252 halo binary candidates.

In order to check the sample, we constructed a reduced proper motion diagram, following Salim &

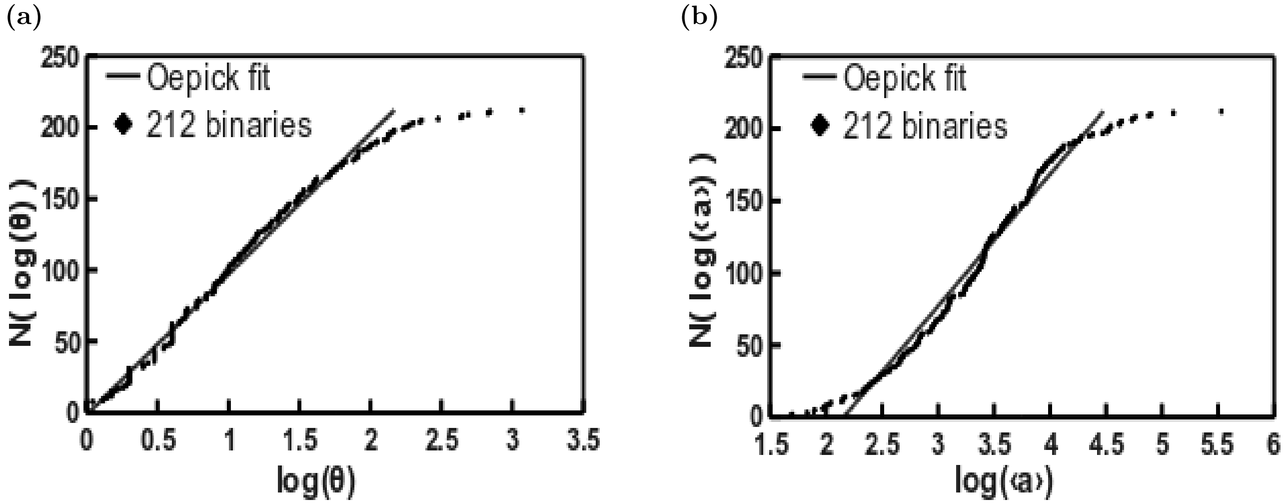

Fig. 2. Same as Figure 1, but for 212 halo binaries.

Gould (2003). Taking into account also the information available from the galactic orbits, we end up with 212 binaries most likely to belong to the galactic halo or thick disk.

To carry out the dynamical model of the evolution of halo binaries, the most useful quantity is the fraction of its lifetime that each binary spends far from the galactic disk. Thus, galactic orbits were calculated for all binaries with available radial velocities (at least for their primaries), a total of 150 systems. The Allen & Santillán (1991) galactic potential was used, and the orbits were calculated for 13 Gyr. This allowed us to compute for each system Td/t, the fraction of time spent within $z = \pm 500$ pc.

3. THE DISTRIBUTION OF ANGULAR SEPARATIONS AND EXPECTED MAJOR SEMIAXES

Figure 1a shows the cumulative distribution of angular separations for the full sample of 252 binaries low-metallicity high-velocity stars. The straight line is a fit to Oepik's distribution (1924) $f(s) = k\ s^{-1}$. Figure 1b shows the same fit for the expected major semiaxes. We choose to display the distributions in cumulative form, as we did in Allen et al. (1994), since in this way we can apply directly the Kolmogorov-Smirnov (KS) test to quantitatively assess the probability that the observed distribution stems from a given theoretical distribution. This choice of presentation was criticized by Chanamé & Gould, who found a different exponent for the power law. For a discussion of this issue see Allen & Monroy-Rodríguez (2013).

After eliminating stars clearly belonging to the disk we ended up with 212 candidate halo binaries. The cumulative frequency distribution of their angular separations is shown in Figure 2a, that of their expected major semiaxes in Figure 2b. Again, the KS test for both distributions supports an exponent of -1 up to a limiting separation of 160 arcsec, corresponding to an expected major semiaxis of 12600 au.

To further refine our sample of halo candidates we integrated galactic orbits for all binaries with available radial velocities (150). The orbits were integrated over 13 Gyr using the Allen & Santillán (1993) galactic potential model. These computations allowed us to determine the time each binary spends within the galactic thin disk (defined as $z = \pm 500$ pc), where most of the non-halo perturbations are expected to occur. The cumulative frequency distribution of major semiaxes for the sample of 150 binaries with computed galactic orbits shown in Figure 3a, the KS test in Figure 3b. These figures clearly show that Oepik's distribution holds for all these subsamples, although it does so up to different values of the separations or major semiaxes.

Next, we separated the 150 binaries into three equal groups, according to the time they spend within the galactic disk, as defined above. We refer to these groups as the most disk-like, the intermediate, and the most halo-like binaries. The average fraction of their lifetime the 50 most disk-like binaries spend in the disk is 1.0, that of the most halo-like binaries is 0.18. To maximize the contrast we disregarded the intermediate group.

Figures 4 and 5 show the cumulative frequency distribution of the expected major semiaxes for the most disk-like and the most halo-like groups, along with the corresponding KS tests. We see that the

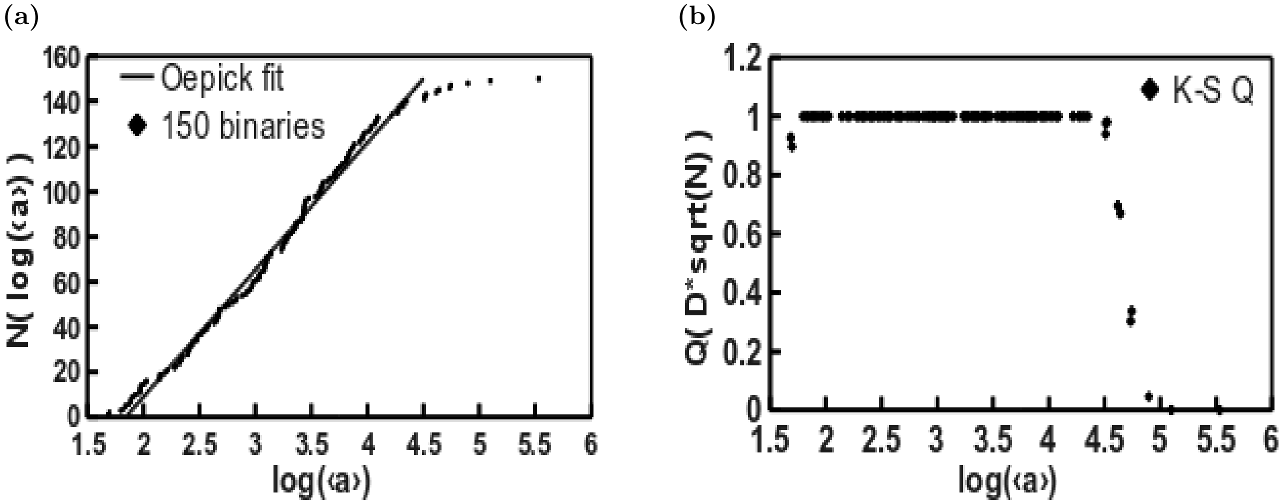

Fig. 3. (a) Same as Figures 1 and 2, but for 150 binaries with computed galactic orbits. (b) Kolmogorov-Smirnov test for 150 binaries. The test shows that Oepik's distribution holds up to 25000 au.

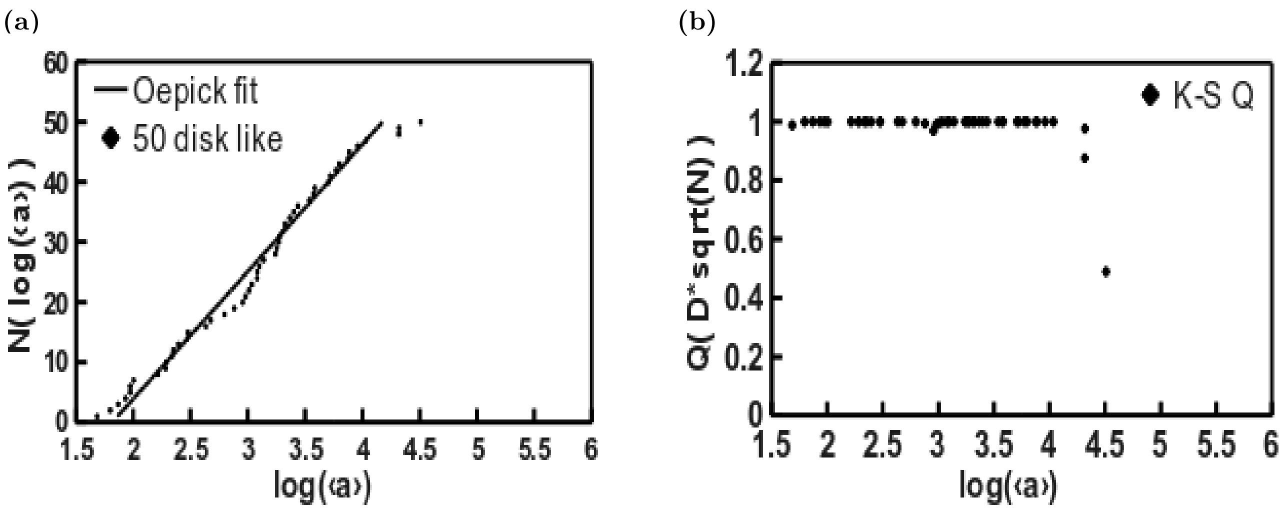

Fig. 4. Same as Figure 3 but for the 60 most disk-like binaries. The KS test shows that Oepik's distribution holds up to 10000 au.

most disk-like binaries follow Oepik's distribution up to an expected major semiaxis of 10000 au, while the most halo-like binaries do so up to an expected semiaxis of 63000 au.

These results confirm and reinforce the conclusions obtained in Poveda et al. (1997), Poveda & Allen (2004), and Allen et al. (2000), namely that (a) Oepik's distribution is followed by many different samples of wide binaries; (b) the maximum semiaxis up to which Oepik's distribution holds is a function of the age of the group studied, as well as of the galactic environment traversed by the binaries. The departure from Oepik's distribution has been interpreted as due to the effects of dynamical perturbations, which tend to decrease the binding energy and thus increase the separation of the binary, until its ultimate dissolution. These effects will, with the passage of time, tend to eliminate the widest systems. Weinberg et al. (1987) and more recently Jiang & Tremaine (2010) have modeled the evolution of disk binaries subject to perturbations by molecular clouds. The results of Weinberg et al. were found to be consistent with the distributions of the youngest and oldest systems of the solar vicinity (Poveda et al. 1997). For the samples studied here, the departure sets in at much larger values than those obtained for

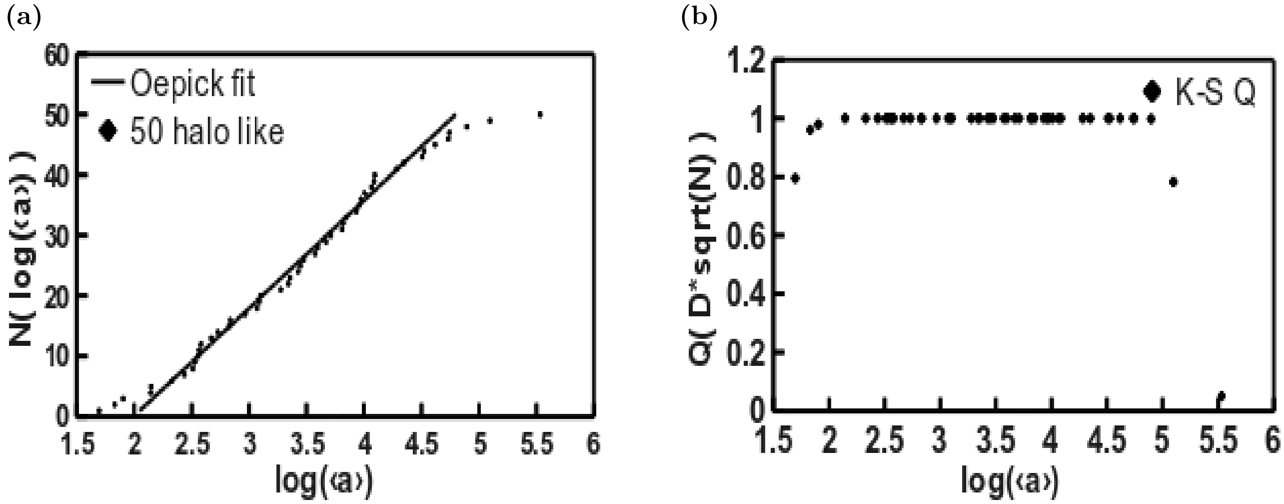

Fig. 5. Same as Figure 4, but for the 50 most halo-like binaries. The KS test shows Oepik's distribution to hold up to 63000 au.

even the oldest binaries of the solar vicinity. Similarly as was done in Allen et al. (2000) and Poveda & Allen (2004) we interpret these larger values as due mainly to the relatively small time spent by our binaries within the galactic disk, where most of the perturbations occur. The most halo-like binaries in Allen et al. (2000) spent on average 0.26 of their lifetimes within the disk, and were found to follow Oepik's distribution up to $\langle a \rangle = 20000$ au. The most halo-like binaries of our improved catalogue spend on average only 0.18 of their lifetime within the disk, and follow Oepik's distribution up to 63000 au.

4. THE DYNAMICAL MODEL

To model the dynamical evolution of our sample of halo wide binaries we follow closely the procedure of Yoo et al. (2004). In this approach, the impulse approximation is used, and effects of large-scale galactic tides, molecular clouds and dissolved binaries are neglected. We temporarily assume a constant halo density, and attribute to MACHOs the total local density, taken as $\rho = 0.007\ M_\odot\ \mathrm{pc}^{-3}$. We then evaluate the effects of the 100 closest encounters in the tidal regime.

We start the Monte Carlo simulations by drawing initial semiaxes uniformly from a power law distribution with arbitrary exponent. The mass of each binary component is taken as 0.5 $M_\odot$, and the velocity distribution of the perturbers is assumed to be isotropic with $\sigma = 200$ km s^{-1}. In each simulation we let 100,000 binary systems evolve for 10 Gyr. For each model (with a fixed M and ρ, we construct a scattering matrix to simultaneously investigate large sets of initial power law distributions. This scattering matrix gives the probability that a binary with initial semiaxis a will have a semiaxis a' after 10 Gyr of evolution. For each model we fix the normalization so that the expected number of binaries with separations between 3.5$''$ and 900$''$ (or their corresponding semiaxes) is equal to the observed number of binaries within these limits. Then, the binary population resulting from the evolved model is fitted to the observed sample of binaries. The goodness of fit is evaluated either computing the standard deviation σ, or by means of the maximum likelihood method. The best fit fixes the value of the mass of the perturbers and the initial value of the power law exponent. The most conservative estimate (largest MACHO mass) is obtained with an initial exponent $\alpha = -1$ (Oepik).

Our implementation of the dynamical model was tested applying it to the samples of Yoo et al. (2004) and Quinn et al. (2009). We were able to closely reproduce their results, an thus we consider our model validated.

5. RESULTS

We now apply the dynamical model to several subgroups of binaries taken from our catalog. Using our full sample of low metallicity high velocity binaries, but omitting those with disk-like orbits we obtain an upper limit for the MACHO mass $m = 164\ M_\odot$. Using 150 binaries with computed galactic orbits the limit is $M = 134\ M_\odot$. The 100 most halo-like binaries give $m = 105\ M_\odot$.

However, we still have to take into account the effects on these limits of both the non-uniform halo

TABLE 1

HALO BINARY SUB-SAMPLES

# binaries	$\langle\rho\rangle$	$\langle T_d/T_b\rangle$
25	1.24	0.08
30	1.39	0.10
35	1.62	0.12
40	1.75	0.14
45	1.76	0.16
50	1.72	0.18
55	1.73	0.21
60	1.77	0.24
65	1.77	0.27
70	1.80	0.30
80	1.85	0.37
90	1.94	0.44
100	1.95	0.50
110	1.95	0.55

TABLE 2

UPPER BOUNDS TO MACHO MASSES

$\langle T_d/T_b\rangle$	M limit $M_\odot$	$\mathcal{M}$ limit $M_\odot$
0.08	17	13
0.10	24	16
0.12	34	17
0.14	37	18
0.16	43	22
0.18	48	28
0.21	50	33
0.24	56	36
0.27	59	40
0.30	63	41
0.37	67	43
0.44	72	46
0.50	78	51
0.55	81	54

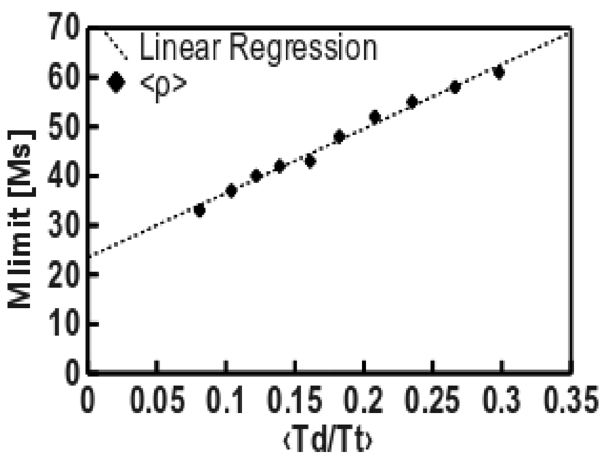

Fig. 6. Trend of the upper limit to the MACHO mass as the binaries spend progressively less time within the disk, assuming a constant halo density. The ordinate displays the limiting MACHO masses, in units of solar mass, the abscissa for each group of binaries the average fraction of their lifetimes spent within the disk $\langle T_d/T\rangle$.

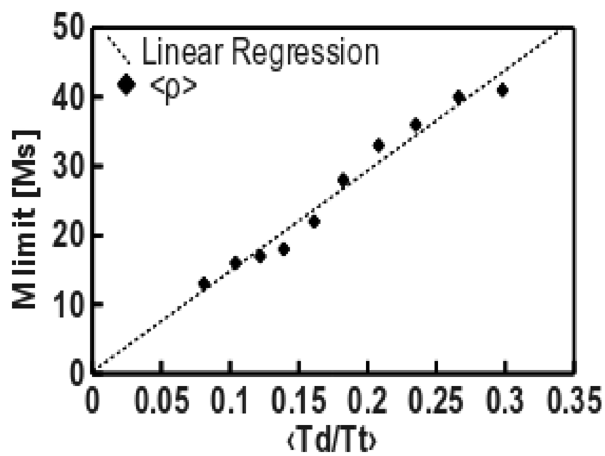

Fig. 7. Trend of the upper limit to the MACHO mass as the binaries spend progressively less time within the disk, taking into account a non-uniform halo density. The last point plotted corresponds to 13 $M_\odot$. The extrapolation of the trend tends to zero. Ordinate and abscissa as in Figure 6.

density and the perturbations suffered during the passage of the binaries through the galactic disk. To estimate these effects, we will use different subsamples of binaries, as shown in Table 1. In this table, Column 1 lists the number of binaries in each subsample, Column 2 the orbit-averaged halo density for each group, and Column 3 the average fraction of the lifetime each group spends within the disk.

In order to eliminate the effect caused by the galactic disk we will use binary samples that spend progressively shorter times within the disk, and extrapolate the result. This is shown in Figure 6.

In order to obtain a rough estimate of the effects of the non-uniform halo density we assume a near-isothermal halo and average the density over each of the computed galactic orbits. Then, we average over the group studied. The results of these estimates are shown in Figure 7 and Table 2. Column 1 lists again the average time spent by the group of binaries

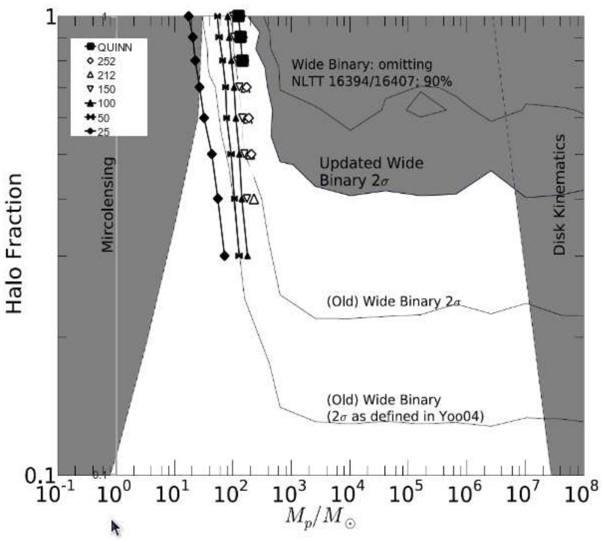

Fig. 8. Exclusion contours using a 1σ fit for various subsamples of binaries. The lef-most sample (25 binaries) excludes the existence of MACHOs in the galactic halo.

within the disk. Column 2 shows the upper limit to the MACHO mass assuming a constant halo density, and Column 3 the limit found using the halo density averaged over the galactic orbits for each group. Table 2 and Figure 7 show that as we approach zero time spent within the disk the upper limit for the MACHO mass tends essentially to zero. The last point gives a limit $m = 13\ M_\odot$, but, of course, corresponds to the smallest sample. Figure 8 shows the exclusion contours found using 1σ fits for various subgroups of binaries superposed on the corresponding figure of Quinn et al. (2009). For comparison, the figure shows that the left-most sample (25 binaries) essentially excludes the existence of MACHOs, while larger samples permit only a very narrow range of MACHO masses. We should point out that this group of 25 binaries includes 6 objects with concordant radial velocities for both components, which can thus be considered to be physical systems.

6. DISCUSSION AND CONCLUSIONS

We have compiled a list of 252 candidate halo wide binaries. The distribution of separations and major semiaxes for all the subgroups studied follows Oepik's up to different limits. We computed galactic orbits for 150 binaries and obtained the fraction of their lifetimes spent within the galactic disk. Separating the binaries into three groups, most disk-like, intermediate and most halo-like we find that the most disk-like binaries begin to depart from Oepik's distribution at $\langle a \rangle = 10000$ au, whereas the most halo-like do so at $\langle a \rangle = 63000$ au.

These results are consistent with those found in Allen et al. (2000), but the most halo-like group follows Oepik up to $\langle a \rangle = 63000$ au. They are used to obtain better estimates of upper limits for the mass of massive perturbers in the galactic halo (MACHOs). The mass limits we find are significantly smaller than those of previous studies, and essentially exclude the existence of such massive perturbers in the galactic halo.

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