Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 17 May 2018 (MN LaTeX style file v2.2)

On the Reported Death of the Macho Era

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ABSTRACT

We present radial velocity measurements of four wide halo binary candidates from the sample in Chaname & Gould (2004; CG04) which, to date, is the only sample containing a large number of such candidates. The four candidates that we have observed have projected separations > 0.1 pc, and include the two widest binaries from the sample, with separations of 0.45 and 1.1 pc. We confirm that three of the four CG04 candidates are genuine, including the one with the largest separation. The fourth candidate, however, is spurious at the 5-sigma level. In the light of these measurements we re-examine the implications for MACHO models of the Galactic halo. Our analysis casts doubt on what MACHO constraints can be drawn from the existing sample of wide halo binaries.

Key words: Galaxy: Halo — stars: binaries — methods: observational — methods: numerical

1 INTRODUCTION

Although convincing evidence for the existence of dark matter has been around for over 40 years, its nature remains a mystery. If MAssive Compact Halo Objects (MACHOs) constitute a significant fraction of the dark matter budget, then a combination of observational and theoretical arguments constrain the properties of viable MACHO candidates to well-defined regions of parameter space. Microlensing experiments (eg Wyrzykowski et al. 2008; Tisserand et al. 2007) have, for instance, ruled out MACHOs with masses in the range $10^{-7} - 30$ M$_{\odot}$ as major constituents of the Milky Way's dark matter halo, thereby excluding dark matter candidates such as halo brown dwarfs or solar-mass black holes. In addition to microlensing, constraints from a number of indirect arguments such as the observed velocity dispersion in the disk (Lacey & Ostriker 1985), evaporation of low mass gas clumps ("snowballs") (Rujula et al. 1992), further reduce the parameter space available to baryonic Galactic MACHOs to $\approx 30 - 10^6$M$_{\odot}$.

A recent analysis of the distribution of wide halo binaries in Yoo et al. (2004; hereafter Yoo04), failed to detect a clear signature of the disrupting effect of MACHOs on the widest, and hence most weakly bound, binaries. Consequently, the study appeared almost to close the door entirely on the remaining region of viable MACHO parameter space, leaving only a small window between 30 $M_{\odot}$ and 43 $M_{\odot}$. A look, though, at Fig.5 in Yoo04 suggests that their results depend critically on the validity of the two widest binaries in the observed wide halo binary sample from Chaname & Gould (2004; hereafter CG04).

In this letter, we present radial velocity measurements of the stars in each of these candidate binaries along with two other large-separation halo binary candidates from CG04. Our radial velocities imply that three of these candidates are genuine binaries and we thus demonstrate directly that halo binaries with projected separations of $\approx$ 1 pc exist. However, our measurements also reveal that the second widest binary in CG04 is actually a spurious interloper. We update the constraints on MACHOs arising from these measurements. The removal of the spurious pair from the analysis eases the constraints significantly with the upper limit on MACHO mass increasing by an order of magnitude. In addition, the Galactic orbit we obtain for the widest binary raises questions on the validity of using this object in the analysis carried out by Yoo04. Its omission would re-open the region of parameter space closed in Yoo04. Furthermore, we also point out that, if the initial logarithmic slope of the binary separation function is set to -1, a choice with some theoretical foundation, then an un-evolved distribution is ruled out by the observations.

The outline of this letter is as follows. In Section 2 we present our spectroscopic data for the candidate binaries, and in Section 2.2 we derive radial velocities for the pairs and use these to determine which systems are genuine binaries. In Section 3, we re-visit the constraints on the MACHO content of the Milky Way halo based on our new data. Section 4 summarises our conclusions.

2 RADIAL VELOCITIES OF WIDE HALO BINARY CANDIDATES IN CG04 SAMPLE

The search for wide halo binaries is still in its infancy as a number of difficult observational challenges need to be overcome. First, halo stars are rare, constituting less than 0.2% of local stars (Helmi 2008). Second is the problem of distinguishing wide binary stars in samples of halo stars from mere chance associations. To date there has been one keynote study (CG04), which detected a large number of local (sample median distance is 240 pc), high probability candidate wide halo binaries (namely 116). The angular separation function of these binaries followed a power law distribution out to angular separations corresponding to ≈1 pc which was the detection limit of their survey.

The candidate binaries in the CG04 sample were chosen from the revised New Luyten Two-Tenths Catalog (NLTT) of high proper motion stars, (Gould & Salim 2003; Salim & Gould 2003). Candidate halo pairs were required to satisfy proper motion consistency tests and to lie along what are essentially isochrones in the halo region of the reduced proper motion (RPM) diagram. As the angular separation, $\Delta\theta$, between the members in a candidate binary increases, the probability that the candidate pair is merely a random association increases roughly in proportion to $(\Delta\theta)^2$. CG04 argue that their halo binary sample is unlikely to be contaminated out to $\Delta\theta = 900''$. While the CG04 candidate binaries have angular separations smaller than this value, their importance for placing restrictions on viable MACHO candidates for dark matter demands that they be subject to further tests, in particular the candidate binaries with the widest angular separations which run the largest risk of misidentification.

One useful test to further explore the nature of these objects is to measure their radial velocities: both members of the candidate binaries should have essentially identical velocities on account of the long period of wide binaries. For example, the magnitude of the relative velocity for a binary of mass m with separation a (assuming circular orbits) is given by

$$v = 0.2\text{km/s}\sqrt{\frac{m}{M_\odot}}\left(\frac{a}{0.1\text{pc}}\right)^{-1/2}. \quad (1)$$

Combined with the other information, radial velocities also enable the Galactic orbital properties of these objects to be studied.

A search in SIMBAD of the 11 objects with separations $> 100''$ reveals radial velocity data for each member of the candidate binary NLTT 39456/39457. The radial velocities agree at the 3σ level and the members also have consistent parallaxes - thus, this candidate is almost certainly a binary. The orbit of this object has been analysed in detail in Allen et al. (1987) and provides strong evidence that wide halo binaries with separations out to at least ≈ 0.05pc exist.

In order to probe further the other candidate wide binaries we set out to obtain spectra for a representative sample of the CG04 sample with angular separations $> 100''$ that includes the 2 widest halo binary candidates. We obtained spectra for four candidate pairs, listed in Table 1 and referenced by their identifiers in the NLTT catalog. Using the colour-absolute magnitude relation given in CG04 the 4 candidates NLTT 1715/1727, 10536/10548, 15501/15509 and 16394/16407 have projected separations of 0.45, 0.2, 0.14 and 1.1 pc, respectively. The observations of NLTT 1715/1727, 10536/10548, 15501/15509 were carried out on the William Herschel Telescope (WHT, La Palma) as part of the Isaac Newton Group (ING) service observing program. NLTT16394/16407 was observed with the Magellan telescope.

2.1 Data Reduction

2.1.1 WHT spectra

The pairs NLTT 10536/10548 and NLTT 15501/15509 were observed with the single-slit, Intermediate dispersion Spectrograph and Imaging System (ISIS) mounted on the WHT, on November 27, 2007 while the pair NLTT 1715/1727 was observed on July 23, 2008. The red and blue arm of the spectrograph were used to provide a resolution of about 1Å and spectral coverage over $3587 - 5412$Å and $7587 - 8812$Å, the latter to cover the Ca II triplet. (The blue region suffered from vignetting and was ignored in the analysis).

Two exposures for each science image were taken. S/N at 8600Å varied from ≈ 20 for the fainter objects to ≈ 60 for the bright objects. The spectra were reduced following standard steps using IRAF. Each science image was bias-subtracted and flat-fielded. The iraf task `apall` was used to extract the sky-subtracted image along with a spectrum of the sky taken from regions of the slit adjacent to, but not dominated by, the light of the target. Typically 5-6 un-blended sky lines spanning the wavelength range of the Ca II triplet were identified with the help of the sky-line catalog in Osterbrock et al. (1996) and used to define a wavelength solution (using the `identify` and `reidentify` tasks in IRAF). A Chebyshev function of order 2 was used in this step to map from pixels to wavelength; the typical error on the wavelength solution was about 0.2Å i.e., about 7 km/s at the wavelengths of the triplet. After applying the appropriate wavelength solution to each science image, the wavelength shifts in the Ca II triplet lines were determined. This step was carried out interactively within the IRAF tool `splot`; the prominent triplet lines were identified and the `d` function in splot was used to find the center of each of the lines (by fitting a Gaussian to the line). An average of the velocity shifts of the 3 lines for each of the 2 exposures was used to determine the radial velocity; the standard deviation of the measurements was used to define the velocity error. We convert these to heliocentric velocities using IRAF task `rvcorrect`. The results are listed in Table 1 and sample spectra are given in the top 3 panels of Figure 1.

2.1.2 Magellan Spectra

Observations of the NLTT 16394/16407 pair were taken on November 13, 2008 with the Magellan Inamori Kyocera Echelle (MIKE) spectrograph at the 6.5-m Magellan2/Clay Telescope. We used a slit width of $0.7''$ and a binning of 2×2 CCD pixels in the spatial and spectral dimensions, from which we obtain a spectral resolving power of R∼30,000. As for the WHT data, we employed the red and blue CCDs of the instrument, yielding a total wavelength coverage of 3340–9150Å. While NLTT 16394 was exposed for 2×300 s, we acquired 2×900 s exposures of the fainter NLTT 16407. The pipeline reduction package of Kelson et al. (2000; 2003) was used to reduce and extract the spectra from the raw data. Wavelength calibration was carried out via built-in Th-Ar lamp exposures, taken between each pair of science exposures. As a result, we reach signal-to-noise (S/N) ratios of 115 (55) per pixel at 6500Å (4000Å) for NLTT 16394 and 60 (10) per pixel for NLTT 16407. We determined the radial velocity again by averaging the Doppler shift of the CaII triplet lines.

2.2 Diagnosis from Radial Velocities

If the objects are genuine binaries with separation $a > 0.1$ pc, the measurement errors will dominate the differences between the measured radial velocities of the stars, Δv_r, so the probability of measuring a particular value of Δv_r for a true binary, P(Δv_r|B), will be a Gaussian with mean zero and dispersion given by the radial velocity measurement error. If we assume the objects are halo stars (i.e. the CG04 classification is correct) and, furthermore, that the stellar halo relative velocity distribution is a Gaussian with dispersion $\sqrt{2} \times 116$ km/s (i.e. we use the root mean square dispersion from the observed triaxial dispersion tensor in Chiba & Beers

NLTT ID		1715	1727	10536	10548	15501	15509	16394	16407
Position	α	7.98335	8.03731	49.62049	49.67233	85.91593	85.97542	94.91613	95.11188
(J2000)	δ	-10.71683	-10.83106	-7.14044	-7.13639	49.38367	49.37782	-30.70087	-30.60432
Proper motion	$\mu_\alpha \cos(\delta)$	-0.034	-0.035	0.171	0.164	0.081	0.081	0.328	0.325
(arcsec/yr)	$\mu_{\rm Dec}$	-0.390	-0.383	-0.353	-0.347	-0.176	-0.182	-0.172	-0.163
Magnitude	V	17.6	16.1	11.22	15.8	17.2	17.6	12.22	15.33
Colour	V-J	2.50	2.46	0.98	2.29	2.82	2.97	0.98	2.19
Distance	pc	209	209	219	219	210	210	348	348
Pair Separation	arcsec	453.4	453.4	185.7	185.7	141.0	141.0	698.5	698.5
Radial Velocity	km/s	-123.2±13.7	-45.6±9.1	121.6±6.8	122.6±7.2	262.3±10.5	265.2±7	268.2±1.7	268.3±1.4
P(B$\|\Delta v_r$)		0.001		0.993		0.991		0.999	

Table 1. Table listing, for convenience, the properties of the four candidate wide binaries, taken from the compilation given in CG04. Also included are the measured heliocentric radial velocities, an estimate of the distance to the putative binary based on applying the CG04 photoparallax relation to the brightest member of each candidate, and the probability P(B$|\Delta v_r$) that the pair is a genuine binary (equation 2).

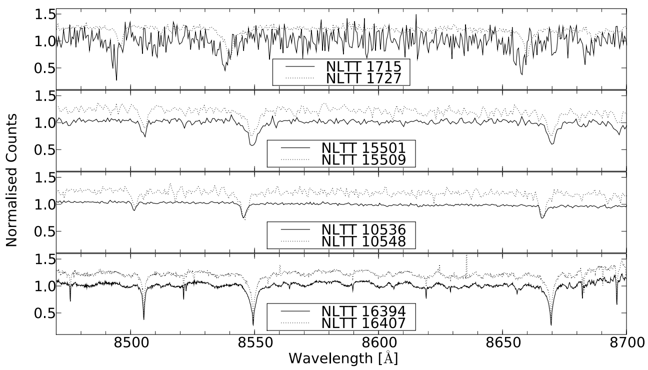

Figure 1. Spectra for the four candidate binary systems we have observed. The top three panels show data from our WHT observations, while the bottom panel shows the data for the pair NLTT 16394/16407 taken with the Magellan telescope. In each panel, the spectra are centred on the Ca II triplet region. The spectra for each member of a candidate binary are plotted together. The second component is shifted slightly upwards for clarity.

2000), then the probability of measuring Δv_r if it is a spurious binary, P(Δv_r|Not B), will also be Gaussian with dispersion dominated by the relative halo radial velocity dispersion. We can write the probability that the binary is real given the new data as

$$P(\mathrm{B}|\Delta v_r) = \frac{P(\Delta v_r|\mathrm{B})}{P(\Delta v_r|\mathrm{B})P(\mathrm{B}) + P(\Delta v_r|\mathrm{Not\ B})P(\mathrm{Not\ B})} P(\mathrm{B}) \quad (2)$$

where P(B) is the prior probability that the object is a binary. Given that CG04 estimated that about one false detection would be expected in their halo sample, we take P(B) to be 10/11. Using Equation 2 we list the probabilities that the objects are binaries in Table 1.

The results show that we have at high probability confirmed the binary nature of three of the pairs in the CG04 sample. Even if we reduce $P(\mathrm{B})$ to the extremely conservative value of 0.5, the $P(\mathrm{B}|\Delta v_r)$ is still greater than 0.9 for the 3 objects. NLTT 1715/1727, the second widest pair, turns out to have inconsistent radial velocities (at the 5σ level). This was flagged by CG04 as potentially spurious on the basis of the pair's position in the RPM diagram but was nonetheless used in the analysis of Yoo et al. (2004). This result underscores the importance of conducting follow-up observations of the CG04 sample. However, we emphasise that our results are entirely consistent with the estimation of one false detection in CG04.

Most importantly, the observation of the widest halo binary candidate in CG04, with projected separation 1.1 pc, reveals that it is in fact a true halo binary. Its Galactic orbit, discussed below, is also consistent with this interpretation. This result provides strong evidence that wide halo binaries with $a \gtrsim 1$ pc can exist. In the next section we consider implications of our measurements for the constraints on the MACHO content of the Milky Way halo. An investigation of the origin of binaries with such wide separations is deferred to a future paper (Quinn et al., in prep.).

3 RE-EXAMINING DARK MATTER CONSTRAINTS FROM THE CG04 SAMPLE

Weakly-bound wide binaries are vulnerable to disruption from encounters with massive compact objects. Depending on the properties of the perturbers and the fragility of the binary star, encounters fall into two regimes: a diffusive regime in which the typical change in binding energy of the binary induced by an encounter is small in magnitude relative to its binding energy, and a catastrophic regime in which the energy change from the closest encounter can disrupt the binary. Expressed in terms of fiducial values of potential MACHO parameters, the disruption timescales for a solar mass binary with separation of order 0.1 pc in each of these regimes, $t_{\rm diff}$ and $t_{\rm cat}$, are (see Equations 8.65a and b of Binney & Tremaine 2008)

$$t_{\rm diff} \approx \frac{v_p}{200\ \mathrm{km/s}} \frac{100 M_\odot}{M_p} \frac{0.01 M_\odot \mathrm{pc}^{-3}}{\rho_p} \frac{0.1\mathrm{pc}}{a}\ \mathrm{Gyr} \quad (3)$$

and

$$t_{\rm cat} \approx 3 \left(\frac{0.01 M_\odot \mathrm{pc}^{-3}}{\rho_p}\right) \left(\frac{0.1\mathrm{pc}}{a}\right)^{3/2}\ \mathrm{Gyr} \quad (4)$$

where v_p is the relative velocity dispersion between MACHO perturbers and binaries, M_p is the mass of the perturber and ρ_p is the density of perturbers. The perturber mass, $m_{\rm crit}$, which marks the transition between the two regimes is

$$m_{crit} \approx 30 M_\odot \frac{v_p}{200\mathrm{km/s}} \left(\frac{a}{0.1\mathrm{pc}}\right)^{1/2} \quad (5)$$

Evaluating the timescales at the fiducial values we find that the disruption timescale for binaries with separation of 0.1 pc or more is shorter than 10 Gyr if the perturber mass is greater than about 10 $M_\odot$. We can thus expect to see a signature on the binary separation function at these scales if a population of MACHOs with masses above this threshold exists.

The study by Yoo04 found no strong signature in the sample of CG04 and consequently was able to rule out MACHOs with masses above 43 $M_\odot$. In this section we reassess that analysis and the constraints on MACHOs from the CG04 dataset in the light of our measurements. We focus on exploring how the MACHO mass and the fraction of the halo composed of MACHOs affect the observed binary separation function.

As our treatment follows closely the analysis in Yoo04 we only briefly summarize our analysis procedure. We assume the original binary separation function is a power law of the form $f(a) \propto a^{-\alpha}$, with α to be determined from the observations. The final binary separation function is determined by simulating encounters between perturbers and binaries, using the impulse approximation to work out the change in binding energy induced by each encounter. We assume the total mass of the binary is 1 $M_\odot$, take the 1-D relative velocity dispersion between MACHO perturbers and the binaries to be 200 km/s and assume that the binaries are subject to encounters for a period of 10 Gyr. These assumptions are consistent with the choices in Yoo04. We also assume that the binaries move through a constant halo density which we take to be the local dark matter density assumed to be $0.01 M_\odot \mathrm{pc}^{-3}$, the value in Milky Way Mass Model 1 of Dehnen & Binney (1998) which was one of their best-fit models. The value of the local dark matter density and velocity dispersion are within 3σ of the values found in a recent Bayesian analysis of Milky Way models by Widrow et al. (2008), which indeed also re-affirmed the Milky Way models of Dehnen & Binney (1998). As we can see from the timescales above, the choice of background perturber density is crucial; in the catastrophic regime this parameter sets the disruption timescale for a given total binary mass.

We adopt the procedure given in Yoo04 to generate the model wide binary angular separation function, P($\log(\Delta\theta)|M_p, \rho_p, \alpha$) (i.e. depending on perturber mass, density of perturbers and power law exponent for the initial binary distribution) from the model separation function; this involves convolving the model binary separation function with the distance distribution of the observed wide binaries.

We choose the normalisation so that sum of P($\log \Delta\theta$)$\Delta(\log \Delta\theta)$ over 24 angular separation bins, equally spaced logarithmically between 3.5$''$ and 900$''$ (corresponding to the interval in angular separation over which CG04 claim to have a clean and complete sample of wide halo binaries), equals the number of observed binaries in this range. The log likelihood, $\log L$, of the model parameters given the data is then

$$\log L = \sum_{k=1}^{24} n_k \log \mathrm{P}(\log \Delta\theta_k) \qquad (6)$$

with n_k the number of halo binaries from CGO4 in the bin centered on $\log \Delta\theta_k$.

We explore the combined constraints on the mass and the density of a putative perturber population by maximising the likelihood over α. In figure (2) we plot the model predictions for the angular separation distribution assuming MACHO halo mass fraction of unity and values of 50 and 500 for M_p for which we find α to be 1.06 and 0.80, respectively. We also show a model with no perturbers finding in this case 1.59 for α. The plot clearly shows that the main question at stake is whether the data favour a flat power law in the inner regions that becomes steeper through the action of perturbers or essentially a featureless power law for the case without perturbers.

Figure 2 also shows the unevolved case for $\alpha = 1$. This is the value favoured by observations of disk binaries with separation greater than 100 AU and could be the outcome of energy relaxation processes in the formation of wide binaries (Lepine & Bongiorno 2007). The data are clearly inconsistent with an unevolved distribution with an initial value of $\alpha = 1$.

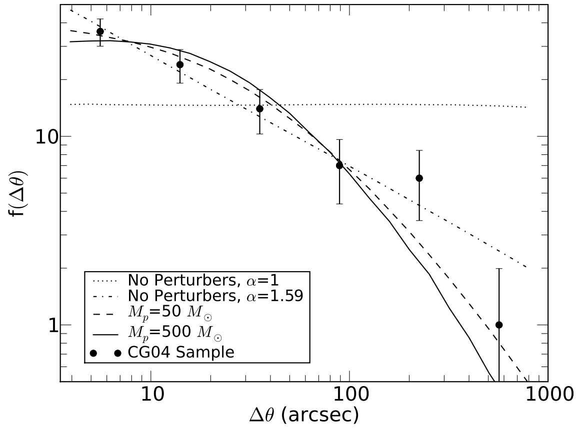

Figure 2. A comparison of the predicted observable angular separation function for a number of models. See text for details. The observed distribution, from the CG04 homogeneous sample less the spurious pair, is also shown with associated Poisson errors.

3.1 Updating the constraints on MACHOs

The analysis of the CG04 sample by Yoo04 favored a model with no perturbers. In conjunction with microlensing experiments their results rule out most of the available parameter space for halo models which have a significant contribution from baryonic MACHOs. At the 95% percent confidence level only a small window, $30 M_\odot < M_p < 43 M_\odot$ was left open for haloes composed entirely of MACHOs.

In Figure 3 we replot the constraints on MACHO mass and halo fraction from the complete CG04 homogeneous sample. We show contours for the joint 95% confidence levels using the definition adopted in Yoo04 (which strictly only holds for 1d confidence levels) and using the standard definition (i.e. region within ≈3 log likelihood units of the likelihood maximum). Since we are following closely the approach of Yoo04 these should, and in fact do, turn out to be broadly similar to those given in Yoo04. More importantly, we show how the joint confidence levels change if we neglect the candidate which we have shown is a spurious binary. The constraints on MACHOs are eased substantially, the upper limit on MACHO mass has moved out to $\approx 500 M_p$.

Figure 3 shows that the exclusion of just one binary has a significant effect on the MACHO constraints. To explore this effect further, we also examined the impact of removing NLTT 16394/16407 from the sample and find in this case the constraints from binaries at the 95% level vanish. Such sensitivity clearly means larger samples of wide binaries are urgently needed to solidify the constraints on MACHOs.

3.1.1 Orbits: A Note of Caution

With proper motions, radial velocity and an estimate of the distance we can plot the orbit for the confirmed binaries (Figure 4). The orbits confirm that the binaries belong to the halo. For NLTT 16394/16407 we find that along the orbit the average dark matter density experienced by the object over a 10 Gyr period is 10% of

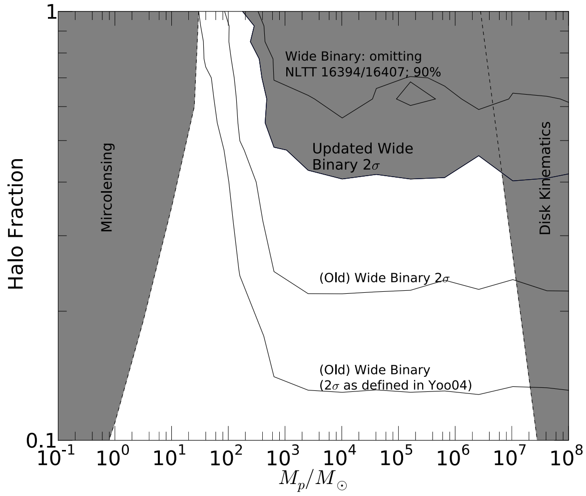

Figure 3. Confidence regions for the MACHO mass $M_{\rm p}$ and MACHO halo fraction. For comparison to past work we show the 2σ joint confidence levels as defined in Yoo04 and using the standard definition, respectively, when the whole CG04 homogeneous sample is included. We also show the updated 2σ confidence levels omitting the spurious candidate binary. The omission of this object eases the constraints on MACHOs; the window increases to $\approx 30-500\,{\rm M}_{\odot}$. In addition, the effect on the constraints of omitting the widest binary in CG04 is shown at the 90% confidence level: the constraints at the 2σ level vanish. The regions of parameter space shaded in grey are ruled out at the 2σ level by binaries and microlensing data – an upper limit on the MACHO mass and halo fraction from disk kinematics is also shown. We stress that the constraints from the binaries are based on the assumption that the time-averaged dark matter density experienced by each binary is the local halo density at the position of the Sun – the actual Galactic orbits of the confirmed wide binaries suggest much lower time-averaged dark matter densities. See text for a detailed discussion.

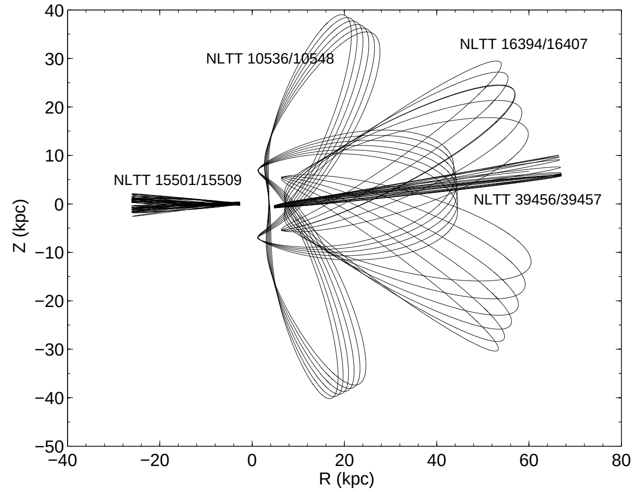

Figure 4. Orbits over 10 Gyrs for the 3 wide binaries that we confirmed and wide binary NLTT 39456/39457. The Milky Way Mass model 1 of Dehnen & Binney (1998) is assumed and for clarity we have flipped the sign of R for NLTT 15501/15509.

the local dark matter density. (Even if we assume the distance to this binary is 20% less than predicted by the CG04 relation the average dark matter density is still only 40% of the local dark matter density.) This implies that the inclusion of this object in the sample and the use of the local solar density are incompatible. In fact, the two other binary pairs in our sample experience time-averaged dark matter densities of 45% and 16% of the local density, while for NLTT 39456/39457 it is 11%. If these orbits are representative of the orbits of the widest binaries in the sample then this trend could be a sign that the widest binaries can only survive by spending most of the orbit away from the inner regions of the Galaxy. If we take the mean of the time-averaged halo density experienced by the four binaries as a more representative value for the dark matter encountered by a typical halo binary along its orbit, we can still use the constraints discussed above but the contours defined by the binary constraints plotted in Figure 3 need to be shifted upwards by a factor of five. This would seriously undermine the constraints that can be drawn from wide binaries.

4 CONCLUSION

A population of MACHOs with masses beyond the current microlensing detection threshold could have a marked effect on the separation distribution of wide halo binaries. While the actual number of observed candidate wide halo stellar binaries is small, strong constraints on MACHOs have been drawn from their distribution. We have measured the radial velocities of four of the widest candidate wide halo binaries from the sample used to place the existing constraints. These measurements provide a consistency test on the binarity of these objects and provide the data needed to examine their Galactic orbits. Our data confirm that three of the four widest halo binary candidates in the CG04 sample are real, thereby vindicating the search strategy of CG04 and demonstrating explicitly that binaries with separations of $\gtrsim 1pc$ can exist. However, the spurious nature of the second-widest pair and the orbit of the widest object undermines the existing constraints on MACHOs from analysis of wide halo binaries. The current wide binary sample is too small to place meaningful constraints on MACHOs; in particular the constraints are extremely sensitive to the widest binary in the sample which, as we have shown, experiences a much lower dark matter density than the value in the analysis leading to the constraints. Increasing the size of the wide binary sample, for example using the SDSS proper motion data or, in the longer term, using *Gaia*, is thus essential if we are to constrain the clumpiness of the dark matter distribution in the Milky Way and determine whether our results are just a reprieve for MACHOs.

ACKNOWLEDGMENTS

Our WHT data were obtained as part of the ING service program and we gratefully acknowledge the ING staff for taking these data. We thank J. Yoo and J. Chaname, in particular, for providing information about the original CG04 data set. We thank L. Wyrzykowski for providing microlensing data.We also thank the anonymous referee for a prompt and insightful report. MIW is supported by the Royal Society.

REFERENCES

Allen C., Martos M. A., Poveda A., 1987, Revista Mexicana de Astronomia y Astrofisica, 14, 213
Binney J., Tremaine S., 2008, Galactic Dynamics: Second Edition. Princeton University Press, Princeton, NJ USA.
Chaname J., Gould A., 2004, ApJ, 601, 289
Chiba M., Beers T. C., 2000, AJ, 119, 2843
Dehnen W., Binney J., 1998, MNRAS, 294, 429

Gould A., Salim S., 2003, ApJ, 582, 1001
Helmi A., 2008, A&AR, 15, 145
Kelson D. D., 2003, PASP, 115, 688
Kelson D. D., Illingworth G. D., van Dokkum P. G., Franx M., 2000, ApJ, 531, 137
Lacey C. G., Ostriker J. P., 1985, ApJ, 299, 633
Lepine S., Bongiorno B., 2007, AJ, 189, 889
Osterbrock D., et al., 1996, PASP, 108, 277
Rujula A., Jetzer P., Massao E., 1992, A&A, 254, 99
Salim S., Gould A., 2003, ApJ, 582, 1011
Tisserand P., et al., 2007, A&A, 469, 387
Widrow L., Brent P., Dubinski J., 2008, ApJ, 679, 1239
Wyrzykowski L., et al., 2008, MNRAS, submitted
Yoo J., Chaname J., Gould A., 2004, ApJ, 601, 311