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 (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 5σ level. In the light of these measurements, we re-examine the implications for MA\textit{ssive Compact Halo Object (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: methods: numerical – methods: observational – binaries: visual – Galaxy: halo.

1 INTRODUCTION

Although convincing evidence for the existence of dark matter has been around for over 40 yr, its nature remains a mystery. If MA\textit{ssive Compact Halo Objects (MACHOs)} constitute a significant fraction of the dark matter budget, then a combination of observational and theoretical arguments constrains the properties of viable MACHO candidates to well-defined regions of parameter space. Microlensing experiments (e.g. Tisserand et al. 2007; Wyrzykowski et al. 2008) have, for instance, ruled out MACHOs with masses in the range 10−7–30 M⊙ 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 disc (Lacey & Ostriker 1985), evaporation of low mass gas clumps (‘snowballs’) (Rujula,Jetzer & Massao 1992), further reduce the parameter space available to baryonic Galactic MACHOs to ≈30–106 M⊙.

A recent analysis of the distribution of wide halo binaries in Yoo, Chaname & Gould (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 and 43 M⊙. 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 ≈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 reopen 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 unevolved 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 revisit the constraints on the MACHO content of the Milky Way halo based on our new data. Section 4 summarizes 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 per cent 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,
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).

| NLTT ID  | 1715 | 1727 | 10536 | 10548 | 15501 | 15509 | 16394 | 16407 |
|----------|------|------|-------|-------|-------|-------|-------|-------|
| Position |      |      |       |       |       |       |       |       |
| (°)      |      |      |       |       |       |       |       |       |
| (12000)  |      |      |       |       |       |       |       |       |
| Proper motion |      | |       |       |       |       |       |       |
| (arcsec yr\(^{-1}\)) |      |      |       |       |       |       |       |       |
| Magnitude |      |      |       |       |       |       |       |       |
| (V)      |      |      |       |       |       |       |       |       |
| Distance |      |      |       |       |       |       |       |       |
| (pc)     |      |      |       |       |       |       |       |       |
| Pair separation (arcsec) |      |      |       |       |       |       |       |       |
| Radial velocity (km s\(^{-1}\)) |      |      |       |       |       |       |       |       |
| $P(B|\Delta v_r)$ |       |       |       |       |       |       |       |       |

| 1715 | 7.98335 | 8.03731 | 49.62049 | 49.67233 | 85.91593 | 85.97542 | 94.91613 | 95.11188 |
| 10536 | −10.71683 | −10.83106 | −7.14044 | −7.13639 | 49.38367 | 49.37782 | −30.70087 | −30.60432 |
| 10548 | −0.034 | −0.035 | 0.171 | 0.164 | 0.081 | 0.081 | 0.328 | 0.325 |
| 15501 | −0.390 | −0.383 | −0.353 | −0.347 | −0.176 | −0.182 | −0.172 | −0.163 |
| 15509 | 17.6 | 16.1 | 11.22 | 15.8 | 17.2 | 17.6 | 12.22 | 15.33 |
| 16394 | 2.50 | 2.46 | 0.98 | 2.29 | 2.82 | 2.97 | 0.98 | 2.19 |
| 16407 | 209 | 209 | 219 | 219 | 210 | 210 | 348 | 348 |
| 453.4 | 453.4 | 185.7 | 185.7 | 141.0 | 141.0 | 698.5 | 698.5 |
| −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 |
| 0.001 | 0.993 | 0.991 | 0.99 | 0.999 |
measured radial velocities of the stars, $\Delta v_p$ dispersion from the observed triaxial dispersion tensor in Chiba & Catelan (2005) that CG04 estimated that about one false detection would be expected in their halo sample, we take $P(\text{B})$ 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 $P(\text{B})$ to the extremely conservative value of 0.5, the $P(\text{B}|\Delta v_r)$ is still greater than 0.9 for the three 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 spuriously on the basis of the pair’s position in the RPM diagram but was none the less used in the analysis of Yoo04. This result underscores the importance of conducting follow-up observations of the CG04 sample. However, we emphasize 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 preparation).

### 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 time-scales for a solar mass binary with separation of order 0.1 pc in each of these regimes, $t_{\text{diff}}$ and $t_{\text{cat}}$, are (see equations 8.65a and b of Binney & Tremaine 2008)

$$t_{\text{diff}} \approx \frac{v_p}{200 \text{ km s}^{-1}} \frac{100 M_\odot}{M_p} \frac{0.01 M_\odot \text{ pc}^{-3}}{\rho_p} \frac{0.1 \text{ pc}}{a} \text{ Gyr}$$

and

$$t_{\text{cat}} \approx 3 \left( \frac{0.01 M_\odot \text{ pc}^{-3}}{\rho_p} \right)^{1/3} \left( \frac{0.1 \text{ pc}}{a} \right)^{3/2} \text{ Gyr},$$

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

$$m_{\text{crit}} \approx 30 M_\odot \left( \frac{v_p}{200 \text{ km s}^{-1}} \right)^{1/2} \left( \frac{a}{0.1 \text{ pc}} \right)^{1/2}.$$
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 \( \alpha \) 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 \( \text{km s}^{-1} \) 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 \( M_\odot \text{pc}^{-3} \), the value in Milky Way Mass Model 1 of Dehnen & Binney (1998) which was one of their best-fitting models. The values of the local dark matter density and velocity dispersion are within \( 3\sigma \) of the values found in a recent Bayesian analysis of Milky Way models by Widrow, Brent & Dubinski (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, \( P(\log (\Delta \theta)|M_p, \rho, \alpha) \) (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 normalization so that the sum of \( P(\log \Delta \theta)\Delta(\log \Delta \theta) \) over 24 angular separation bins, equally spaced logarithmically between 3.5 and 900 arcsec (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

\[
\log L = \sum_{k=1}^{24} n_k \log P(\log \Delta \theta_k),
\]

with \( n_k \) the number of halo binaries from CG04 in the bin centred on \( \log \Delta \theta_k \).

We explore the combined constraints on the mass and the density of a putative perturber population by maximizing the likelihood over \( \alpha \). In Fig. 2, we plot the model predictions for the angular separation distribution assuming a MACHO halo mass fraction of unity and values of 50 and 500 for \( M_p \), for which we find \( \alpha \) to be 1.06 and 0.80, respectively. We also show a model with no perturbers finding in this case 1.59 for \( \alpha \). 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.

Fig. 2 also shows the unraveled case for \( \alpha = 1 \). This is the value favoured by observations of disc 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 unraveled distribution with an initial value of \( \alpha = 1 \).

3.1 Updating the constraints on MACHOs

The analysis of the CG04 sample by Yoo04 favoured 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 per cent confidence level, only a small window, \( 30 \text{M}_\odot < M_p < 43 \text{M}_\odot \) was left open for haloes composed entirely of MACHOs.

In Fig. 3, we replot the constraints on MACHO mass and halo fraction from the complete CG04 homogeneous sample. We show contours for the joint 95 per cent 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 \( \approx 3\sigma \) of 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 \( \approx 500 \text{M}_\odot \).

Fig. 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 per cent confidence 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 (Fig. 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 per cent of the local dark matter density. (Even if we assume the distance to this binary is 20 per cent less than predicted by the CG04 relation the average dark matter density is still only 40 per cent 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 per cent of the local density, while for...
Using the constraints discussed above but the contours defined by the object eases the constraints on MACHOs; the window increases to $\approx 30$–$500 M_{\odot}$. In addition, the effect on the constraints of omitting the widest binary in CG04 is shown at the 90 per cent confidence level: the constraints at the 2$\sigma$ level vanish. The regions of parameter space shaded in grey are joint confidence levels.

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Figure 4. Orbits over 10 Gyr for the three 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.

NLTT 39456/39457 it is 11 per cent. 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 Fig. 3 need to be shifted upwards by a factor of 5. 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 $\gtrsim 1$ pc 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 Sloan Digital Sky Survey 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.

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