White dwarfs, red dwarfs and halo dark matter

E García-Berro\textsuperscript{1,2}, S Torres\textsuperscript{1,2}, J Camacho\textsuperscript{1} and J Isern\textsuperscript{3,2}

\textsuperscript{1}Departament de Física Aplicada, Escola Politècnica Superior de Castelldefels, Universitat Politècnica de Catalunya, Av. del Canal Olímpic, s/n, 08860 Castelldefels, Spain
\textsuperscript{2}Institute for Space Studies of Catalonia, c/Gran Capità 2–4, Edif. Nexus 104, 08034 Barcelona, Spain
\textsuperscript{3}Institut de Ciències de l'Espai, CSIC, Campus UAB, Facultat de Ciències, Torre C-5, 08193 Bellaterra, Spain

E-mail: garcia@fa.upc.edu

Abstract. The nature of the microlensing events observed by the MACHO team towards the LMC still remains controversial. Low-mass substellar objects and stars with masses larger than $\sim 1 M_{\odot}$ have been ruled out, while stars of $\sim 0.5 M_{\odot}$ are the most probable candidates. This means that the microlenses should be either red or white dwarfs. Consequently, we assess jointly the relative contributions of both types of stars to the mass budget of the Galactic halo. We use a Monte Carlo code that incorporates up-to-date evolutionary sequences of both red dwarfs and white dwarfs as well as detailed descriptions of both our Galaxy and the LMC and we compare the synthetic populations obtained with our simulator with the results obtained by the MACHO and EROS experiments. We find that the contribution of the red dwarf population is not enough to explain the number of events measured by the MACHO team. Even though, the optical depth obtained in our simulations almost doubles that obtained when taking into account the white dwarf population alone. Finally, we also find that the contribution to the halo dark matter of the entire population under study is smaller than 10%, at the 95% confidence level.

1. Introduction
Since the pioneering proposal of Paczyński (1986) that gravitational microlensing could be an useful tool to study Galactic dark matter, considerable observational and theoretical efforts have been invested in this issue. The most likely candidates for building-up the baryonic dark matter are massive compact halo-objects (MACHOs). It has been suggested that MACHOs could be planets, brown and red dwarfs, primordial black holes, molecular clumps, and old white dwarfs. On the other hand the MACHO (Alcock et al. 1997, 2000), EROS (Lasserre et al. 2001; Goldman et al. 2002; Tisserand et al. 2007), OGLE (Udalski et al. 1994), MOA (Muraki et al. 1999), and SuperMACHO (Becker et al. 2005) teams have monitored millions of stars during several years, in both the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), to search for microlensing events. However, the MACHO and EROS teams have been the only ones that have published their results. Although there exist notable differences between the results reported by both teams there is as well agreement in some of the most important points. In particular, no microlensing candidates have been found by the MACHO team or the EROS group with event durations between a few hours and 20 days. This implies that the Galactic halo cannot contain more than a 10% of dark objects in the mass range $10^{-7} < M/M_{\odot} < 10^{-3}$, thus ruling out planets and brown dwarfs. Moreover, the MACHO
collaboration detected \( \sim 17 \) microlensing events during their 5.7 yr analysis of 11.9 million stars in the LMC (Alcock et al. 2000). However, the number of microlensing events has been the subject of some debate. After the publication of the first results (Alcock et al. 2000) in which 17 microlensing events were reported, it was discovered by the EROS collaboration that one of the MACHO events was caused by stellar variability rather than microlensing. This suggested that some of the other events might be variable stars, as well. Later, it was shown that most of the MACHO microlensing events were likely to be actual microlensing events (Bennett et al. 2005) and that 13 events were probably genuine events. Nevertheless, later on it has been shown that of these 13 events one is known to be a variable star, and it is most likely that another event is a variable star, as well. Thus, we are left with 11 microlensing events. Using their original data Alcock et al. (2000) derived an optical depth towards the LMC of \( \tau = 1.2^{+0.4}_{-0.3} \times 10^{-7} \) or, equivalently, a halo fraction \( 0.08 < f < 0.50 \), at the 95% confidence level, with a MACHO mass in the range \( 0.15 \leq M/M_\odot \leq 0.50 \), depending on the halo model. More recent calculations suggest (Bennett et al. 2005) that the optical depth is \( \tau = (1.0 \pm 0.3) \times 10^{-7} \). On the other hand, the non-detections reported by the EROS collaboration have provided an upper limit (Tisserand et al. 2007). Their results imply that, at the 95% confidence level, that the contribution of stars of \( \sim 0.5 M_\odot \) is less than 7%. All these findings have estimulated a vivid discussion about the location and nature of the lenses. A full variety of possible explanations have been proposed (and discarded) to reproduce the microlensing events. Some of these explanations are self-lensing by the LMC itself, tidal debris or a dwarf galaxy toward the LMC (Zhao 1998), a Galactic-extended shroud population of white dwarfs (Gates & Gyuk 2001), blending effects (Belokurov, Evans & Le Du 2003, 2004), biased mass-functions (Adams & Laughlin 1996) and spatially-varying mass-functions (Kerins & Evans 1998; Rahvar 2005). All in all, in spite of the numerous theoretical studies (Isern et al. 1998; Reylé et al. 2001; Flynn et al. 2003; García-Berro et al. 2004; Camacho et al. 2007) the mystery still remains unsolved. In this work, we analyze, in a comprehensive manner, a significant range of masses \( 0.08 < M/M_\odot < 10 \) likely to reproduce the observational microlensing results and, thus, to contribute to the halo dark matter. This mass range represents almost 90% of the stellar content. The paper is organized as follows. In Sect. 2 we describe in detail how the sample of microlensing events is built. In Sect. 3 we present our main results and we compare them with the observational results of the MACHO and EROS teams, whereas in Sect. 4 we discuss the significance of our results. Finally in Sect. 5 we summarize our major findings and we present our conclusions.

2. Building the sample
A detailed description of our Monte Carlo simulator has been presented in Torres et al. (2002), García–Berro et al. (2004), and Camacho et al. (2007). Consequently, here we only summarize its most salient features. The Galactic halo was modeled assuming a spherically-symmetric halo. In particular, the model used here is an isothermal sphere of radius 5 kpc. The position of each synthetic star was randomly chosen according to this density profile. The mass distribution of synthetic stars was computed using two different initial mass functions, the standard initial mass function of Scalo (1998) and the biased log-normal initial mass function proposed by Adams & Laughlin (1996), which is representative of other non-conventional initial mass functions. We note, however, that these biased initial mass functions appear to be incompatible with the observed properties of the halo white dwarf population (Isern et al. 1998; García–Berro et al. 2004), and with other observations. The main-sequence mass is obtained by drawing a pseudo-random number, according to the adopted initial mass function. The time at which a star was born is randomly chosen assuming that the halo was formed 14 Gyr ago in an intense burst of star formation of duration \( \sim 1 \) Gyr. The main-sequence lifetime as a function of the main sequence mass is that of Iben & Laughlin (1989). Once the mass of a synthetic star is known, its main-sequence lifetime is inferred and we can determine which stars evolve into white dwarfs.
and which ones remain on the main sequence as red dwarfs. We considered red dwarfs to have masses in the range $0.08 < M/M_\odot < 1$. For these stars, we have adopted the evolutionary models of Baraffe et al. (1998). For stars that had time to enter the white dwarf cooling track effective temperatures, luminosities, and colors are derived using a set of theoretical cooling sequences and an initial-to-final-mass relationship (Iben & Laughlin, 1989). White dwarfs with masses smaller than $M_{WD} = 1.1 M_\odot$ are expected to have a CO core and for these we adopt the cooling tracks of Salaris et al. (2000). White dwarfs with masses larger than $M_{WD} = 1.1 M_\odot$ have ONe cores and for these, we adopt the cooling sequences of Althaus et al. (2007).

The kinematical properties of the halo population were modeled using Gaussian laws (Binney & Tremaine 1987) with radial and tangential velocity dispersions that reproduce the flat rotation curve of our Galaxy. We have adopted standard values for the circular velocity $V_c = 220$ km/s and the peculiar velocity of the Sun $(U_\odot, V_\odot, W_\odot) = (10.0, 15.0, 8.0)$ km/s (Dehnen & Binney 1998). We have discarded stars that had velocities smaller than 250 km/s, since these would not be considered halo members. We also have rejected stars of velocities larger than 750 km/s, because these velocities exceed 1.5 times the escape velocity. To compare simulated results with observations, a normalization criterion should be used. We have normalized our simulations to the local density of halo white dwarfs obtained from the halo white dwarf luminosity function of Torres et al. (1998), but taking into account the new halo white dwarf candidates reported by Vidrih et al. (2007).

To reproduce the microlensing experiments towards the LMC, we have followed the detailed LMC descriptions of Gyuk et al. (2000) and Kallivayalil et al. (2006). This model provides a synthetic population of stars representative of the monitored point sources. After each simulation was completed, we evaluate which star of the Galactic halo could be responsible for a microlensing event. We have considered only stars that fulfilled certain criteria. First, the lensing star should be fainter than a given magnitude limit. Secondly, we also checked whether the lens was inside the Einstein tube of the monitored star. Finally, we filter those stars that are candidates to produce a microlensing event with the detection efficiency function, which depends on the particular characteristics of the experiment. In the case of the MACHO project, we have adopted $1.1 \times 10^7$ stars during 5.7 yr over $13.4$ deg$^2$, whereas the detection efficiency has been modeled using the fit of Alcock et al. (2000). For the EROS experiment, we have used $0.7 \times 10^7$ stars over a wider field of $84$ deg$^2$ and a period of 6.7 yr. To evaluate the detection efficiency, we have adopted a numerical fit to the results of Tisserand et al. (2007).

3. Results

3.1. The MACHO experiment

In the left panels of Fig. 1, we show the contribution of the different simulated populations to the optical depth, for the two initial mass functions studied here, as a function of the adopted magnitude cut. The value of the optical depth obtained in our simulations has been normalized to the value of the optical depth derived by Alcock et al. (2000), $\tau_0 = 1.0 \times 10^{-7}$. The white dwarf populations are represented by solid and open squares for the CO and ONe white dwarfs, respectively. Open triangles indicate the contribution of red dwarfs, while the contribution of the three populations is represented by open circles. The combined contribution of red dwarfs and white dwarfs is at most one third of the observed optical depth, when a totally-unrealistic magnitude cut is adopted, $m_V \sim 15$mag. In addition, it should be noted that there is a clearly decreasing trend as the adopted magnitude cut is increased. This is because fewer objects contribute to the optical depth as the magnitude cut increases. Furthermore, the slope of the distributions is different for the three types of objects considered. For instance, the contribution of red dwarfs decreases faster than the contribution of CO white dwarfs as the magnitude cut increases, which, in turn, decreases faster than the contribution of ONe white dwarfs. This reflects the fact that, in general, red dwarfs are brighter than regular, CO white dwarfs. Finally,
ONe white dwarfs cool rapidly (Althaus et al. 2007) and thus, for realistic halo ages, are faint objects. Consequently, their contribution remains almost constant.

In Table 1 we summarize the average values of parameters of the entire population for two initial mass functions and four magnitude cuts, that is, present the number of microlensing events, the average mass of the microlenses, their average proper motion, distance and tangential velocity, the corresponding Einstein crossing times and, finally, the contribution to the microlensing optical depth. As can be seen, the average distance of the sample increases as the magnitude cut increases. This is a natural consequence of selecting more distant objects which, in turn, implies longer Einstein crossing times. This behavior is independent of the assumed initial mass function. Note as well that the expected number of events or the average mass of the sample do not depend on the adopted magnitude cut. In the case of a standard initial mass function, no more than one microlensing event should be expected at the 1σ confidence level, while for a log-normal mass function up to 5 events might be expected. In any case, the expected number of microlensing events is far from the 11 events claimed by the MACHO experiment.

We have also evaluated the fraction of microlenses for the different populations as a function of the adopted magnitude cut. The results are shown in the right panels of Fig. 1 for both the standard initial mass function (top panel) and the log-normal initial mass function (bottom panel). For the standard initial mass function, the relative contribution of red dwarfs decreases with increasing value of magnitude cuts, while that of the CO white dwarfs increases. Both

Figure 1. Left panels: microlensing optical depth towards the LMC as a function of the limiting magnitude. Solid and open squares represent the CO and ONe white-dwarf populations, respectively. Red dwarfs are represented using open triangles, while the entire population is shown using open circles. Right panels: fraction of microlenses with respect to the entire population, as a function of the magnitude cut.
Table 1. Summary of the results obtained for the entire simulated population of microlenses in the direction of the LMC for a halo age of of 14 Gyr, different model initial mass functions, and several magnitude cuts.

| Magnitude | Standard | AL |
|-----------|----------|----|
|           | 17.5     | 22.5 | 27.5 | 32.5 | 17.5 | 22.5 | 27.5 | 32.5 |
| ⟨NWD⟩    | 0 ± 1    | 0 ± 1 | 0 ± 1 | 0 ± 1 | 3 ± 2 | 2 ± 1 | 1 ± 1 | 0 ± 1 |
| ⟨m⟩ (M/M⊙) | 0.421 | 0.411 | 0.427 | 0.443 | 0.638 | 0.636 | 0.640 | 0.684 |
| ⟨µ⟩ (yr⁻¹) | 0.020 | 0.017 | 0.008 | 0.004 | 0.036 | 0.025 | 0.011 | 0.003 |
| ⟨d⟩ (kpc) | 2.48 | 3.79 | 6.62 | 13.08 | 1.39 | 2.15 | 5.13 | 19.6 |
| ⟨Vtan⟩ (km s⁻¹) | 240 | 247 | 262 | 241 | 240 | 252 | 263 | 261 |
| ⟨tE⟩ (d) | 41.2 | 49.3 | 63.3 | 82.8 | 34.7 | 46.6 | 76.4 | 126.8 |
| ⟨τ/τ0⟩ | 0.283 | 0.214 | 0.139 | 0.055 | 0.302 | 0.204 | 0.140 | 0.129 |

contributions are equal for a magnitude cut of ≈ 24 mag. Finally, the contribution of ONe white dwarfs remains roughly constant and only becomes significant for large magnitude cuts. These trends can be attributed to the fact that red dwarfs are more numerous at bright magnitudes than white dwarfs, for which typical luminosities are of the order of log(L/L⊙) ≃ −3.5. The situation is completely different when the log-normal initial mass function of Adams & Laughlin (1996) is used. As can be seen the number of microlenses is practically dominated by the CO white dwarf contribution, while the contribution of red dwarfs and ONe white dwarfs is negligible.

We have also performed a Z² statistical test of the compatibility of the different populations with the observed data. The Z² statistical test (Lucy 2000) is an improvement to the standard χ² statistical test, especially designed for meagre data sets. In Table 2, we show the Z² probability that the different simulated populations are compatible with the distribution of Einstein times obtained by the MACHO experiment. It is convenient to clarify that this probability is an estimate of the degree to which the observed event-rate distribution can be derived from a single population of stars. As can be seen in Table 2, the CO white dwarf population provides the most appropriate description of the observational data, given that its compatibility is as high as 0.90 for the faintest magnitude cut. Moreover, the compatibility of this population with the observational data increases at fainter magnitude bins. In sharp contrast, the population of red dwarfs presents a decreasing trend as the magnitude cut increases and, additionally, the compatibility with the observational data is, at most, 0.70. With regard to the ONe white dwarf population, the compatibility presents an almost constant value of around 0.70, independently of the magnitude cut. These results indicate that the CO white-dwarf population can reproduce the observed distribution of microlensing event-rates. Even more, they dominate the behavior of the entire population, as can be seen from the final row of Table 2, in which we analyze the compatibility of the entire population of simulated stars.

3.2. The EROS experiment
While the MACHO team has claimed the identification of up to 11 observed events, the EROS collaboration has not found any microlensing event towards the LMC and only one candidate event towards the SMC. Adopting a standard halo model and assuming τ_SMC = 1.4τ_LMC, the EROS results imply an optical depth τ₀ = 0.36 × 10⁻⁷ (Tisserand et al. 2007), which is four times smaller than that obtained by the MACHO team. We have performed a set of simulations emulating the conditions of the EROS experiment with inputs similar to those of the MACHO experiment. Our simulations show that, for the standard initial mass function, the expected
Table 2. Compatibility, as obtained using the $Z^2$ statistical test, of the observed MACHO distribution of Einstein crossing times and those of the different simulated populations.

| Magnitude | 17.5$^{\text{mag}}$ | 22.5$^{\text{mag}}$ | 25.0$^{\text{mag}}$ | 27.5$^{\text{mag}}$ | 30.0$^{\text{mag}}$ |
|-----------|------------------|------------------|------------------|------------------|------------------|
| Red dwarfs | 0.58             | 0.67             | 0.65             | 0.55             | 0.40             |
| CO white dwarfs | 0.61             | 0.70             | 0.80             | 0.87             | 0.90             |
| ONe white dwarfs | 0.76             | 0.55             | 0.68             | 0.68             | 0.72             |
| Whole population | 0.59             | 0.69             | 0.75             | 0.82             | 0.89             |

optical depth could be 70% of the value found by the EROS team. The value obtained when only the white-dwarf population was considered was previously found to be 50% (Camacho et al. 2007). The simulations presented here show a better agreement with the results of the EROS experiment. Obviously, the reason for this is the inclusion of the red dwarf population. However, when a non-standard initial mass function is considered, the results are only marginally different of those obtained for a white dwarf population, given the fact that in this case the role of red dwarfs is limited. In summary, our results are in fair agreement with those obtained by the EROS experiment, and appear to indicate that the microlensing optical depth, obtained by the MACHO collaboration, is probably an overestimate.

4. Discussion
Based on their $\sim$15 microlensing events, the MACHO collaboration has derived an estimate of the halo fraction of dark matter $f$, as well as the MACHO mass $m$, using maximum-likelihood techniques. A similar analysis was completed by the EROS team, but with the significant difference that, in this case, no event was reported for the LMC, which implies that only an upper limit to the halo mass fraction can be obtained. To compare the results of the MACHO and EROS collaborations with our Monte Carlo simulations we have adopted as our reference model the isothermal sphere of core radius 5 kpc, with a value of $\rho_0 = 0.0079 M_\odot \text{pc}^{-3}$ for the local dark matter density and disregarding the contribution of the LMC halo. Using this model, we have obtained that the optical depth towards the LMC is $\tau_{\text{LMC}} = 5.1 \times 10^{-7} f$. The different estimates of the halo mass fraction $f$, as a function of mass, are plotted in Fig. 2. We show using a solid line the curve of the MACHO 95% confidence level, as taken from Alcock et al. (2000), and the EROS 95% confidence-level upper-limit, based on no observed events in the EROS-1 and EROS-2 data (Tisserand et al. 2007). We also represent the individual contributions of each population studied and the entire population, in addition to the corresponding 95% confidence level error bars. It is noticeable that the value obtained for the entire halo simulated population agrees within the 95% confidence level curves of both observational estimates. Our results therefore predict that the range of stellar masses within 0.08 and 10 $M_\odot$, provides $f = 0.05$ and an average mass of 0.411 $M_\odot$ to the halo dark matter, in agreement with the observational data.

5. Conclusions
We have extended our previous studies of the contribution to the halo dark matter of the white dwarf population and included the Galactic population of red dwarfs, we have estimated as well the contribution of these objects to the microlensing optical depth towards the LMC and compared our estimate with the measurements of the MACHO and EROS collaborations. Our estimate is based on a series of Monte Carlo simulations that incorporate the most up-to-date evolutionary tracks for red dwarfs, CO white dwarfs, and ONe white dwarfs, and reliable models of our Galaxy and the LMC. In a first set of simulations, we have found that the contribution of the red dwarf population practically doubles the contribution found so far for the white
dwarf population. Our results indicate that the entire population of these stars can account for at most $\sim 0.3$ of the optical depth found by the MACHO team. This value implies that the contribution of the full range of masses between 0.08 and $10 M_\odot$ represents 5% of the halo dark matter with an average mass of 0.4 $M_\odot$. Although this result is in partial agreement with the 95% confidence level MACHO estimate for a standard isothermal sphere and no halo LMC contribution, the expected number of events obtained by our simulations (3 events at the 95% confidence level) is substantially below the 11 observed MACHO events. These arguments reinforce the idea, previously pointed out by other studies, that the optical depth found by the MACHO team is likely an overestimate, probably due to contamination of self-lensing objects, variable stars and others. Moreover, we have assessed the compatibility between the observed event rate distribution and the ones obtained for the different populations under study. Our results show that the CO white dwarf population can reproduce fairly well the observed event-rate distribution although, as mentioned earlier, the expected number of events is considerably smaller. On the other hand, the negative results obtained by the EROS team towards the LMC are in agreement with our standard halo simulation. Finally, and for the sake of completeness, we have studied the effects of a log-normal biased initial mass function. In this case, the contribution of the red dwarf population is only marginal given that the production of low-mass stars is strongly inhibited. Accordingly, the total contribution to the microlensing optical depth is not different from that found in previous studies of the white dwarf contribution.

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