

CONTRIBUTION OF BROWN DWARFS AND WHITE DWARFS TO RECENT MICROLENSING OBSERVATIONS AND TO THE HALO MASS BUDGET

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ABSTRACT

We examine the recent results of the MACHO collaboration toward the Large Magellanic Cloud in terms of a halo brown dwarf or white dwarf population. The possibility that most of the microlensing events are due to brown dwarfs is totally excluded by large-scale kinematic properties. The white dwarf scenario is examined in detail in the context of the most recent white dwarf cooling theory which explicitly takes into account the extra energy source that derives from the carbon-oxygen differentiation at crystallization and the subsequent Debye cooling. We show that the observational constraints arising from the luminosity function of high-velocity white dwarfs in the solar neighborhood and from the recent *Hubble Space Telescope* deep field counts are consistent with a white dwarf contribution to the halo missing mass as large as 50%, provided there is (1) an initial mass function strongly peaked around $\sim 1.7 M_{\odot}$, and (2) a halo age older than ~ 18 Gyr.

Subject headings: dark matter — Galaxy: halo — stars: low-mass, brown dwarfs — stars: luminosity function, mass function — stars: white dwarfs

1. INTRODUCTION

There is compelling evidence for believing that a large amount, if not most of baryonic matter in the universe is under the form of dark, unobserved objects. On the other hand, there is also evidence that spiral galaxies are surrounded by a large amount of nonluminous mass which is responsible for their observed small- and large-scale kinematic properties (velocity dispersion and rotation curve). These two facts yield the natural conclusion that baryonic dark matter is a plausible candidate for halo dark matter. A breakthrough in this long-standing, unsolved problem has been accomplished recently with the development of microlensing experiments by inferring the presence of dark objects in the halo through their gravitational effect on luminous matter. A detailed analysis of the first year of the MACHO (Alcock et al. 1993) and EROS (Aubourg et al. 1993) observations toward the LMC, complemented by the determination of the mass function of low-mass halo stars, yielded an average mass for the dark objects $\langle m \rangle \approx 0.03 M_{\odot}$, well within the brown dwarf domain (Méra, Chabrier, & Schaeffer 1996a). The inferred maximum brown dwarf contribution to the halo mass budget was found to be $\sim 10\%$ – 20% (Alcock et al. 1995; Gates, Gyuk, & Turner 1995; Méra et al. 1996a). These results now have to be reconsidered in the light of the most recent analysis of the MACHO collaboration, which includes one more year of LMC data. This now yields a total of *seven* candidates for MACHO with *longer* durations, from 30 to 110 days (Alcock et al. 1996).

In this Letter, we re-examine the M dwarf, brown dwarf, and white dwarf contributions to the halo mass budget in light of the most recent observational constraints (star counts and MACHO results) and white dwarf cooling theory.

2. M DWARFS AND BROWN DWARFS

Hubble Space Telescope (HST) star counts at large magnitudes (Bahcall et al. 1994; Hu et al. 1994) show that the M dwarf contribution to the Galactic missing mass $M_{\text{dyn}} \approx 10^{12} M_{\odot}$ represents at most a few percent. A more precise deter-

mination can be obtained from the observed luminosity function (LF) of high-velocity M dwarfs in the solar neighborhood (Dahn et al. 1995). A detailed analysis of this LF shows that the mass function (MF) of the spheroid (characterized by a $\sim 1/r^3$ density profile) is reasonably well described by a power-law MF $\phi(m) \propto m^{-\alpha}$ with $\alpha \approx 2$ – 2.5 , from $0.6 M_{\odot}$ down to the hydrogen burning limit and a normalization $dN/dm(0.1 M_{\odot}) = 10^{-2.7} M_{\odot}^{-1} \text{pc}^{-3}$ (Méra et al. 1996a). This yields a *maximum* local density for the spheroid + halo M dwarf population $\sim 4 \times 10^{-5} M_{\odot} \text{pc}^{-3}$, and thus an optical depth $\tau_{\text{M dwarf}} < 4 \times 10^{-9}$. A comparison with the value inferred from the new MACHO results $\tau \approx 1.7 \times 10^{-7}$ shows convincingly that M dwarfs can be responsible for less than 0.1 of the microlensing events toward the LMC. On the other hand, reasonable estimates for the LMC characteristics yield an optical depth $\tau \approx 5 \times 10^{-8}$, a factor 3–4 smaller than the recent MACHO results (Sahu 1994).

As mentioned above, the analysis of the previous MACHO + EROS results showed that the observed events were likely to be due to halo brown dwarfs, with an average mass $\langle m \rangle \approx 0.03 M_{\odot}$ (Méra et al. 1996a). These calculations must be re-examined in the context of the recent MACHO results. The new seven events yield $\langle t_e \rangle \propto \langle m^{1/2} \rangle \langle 1/v \rangle \approx 40$ days (Alcock et al. 1996).¹ Since the minimal tangential velocity $\langle v \rangle$ of the lens is bound by the rotation velocity of the line of sight ($\sim 220 \text{ km s}^{-1}$) (Méra, Chabrier, & Schaeffer 1996b), this totally excludes the possibility for these events to be caused by brown dwarfs and yields an average mass $\langle m \rangle \approx 0.5 M_{\odot}$. Since M dwarfs are excluded, the inferred optical depth $\tau \approx 1.7 \times 10^{-7}$ means that about 40% of the hidden mass consists of *halo white dwarfs*.²

¹ Note that the event timescale is defined here as the *Einstein radius* crossing time, whereas the MACHO group adopts the *Einstein diameter* crossing time in their definitions.

² Neutron stars and stellar black holes must be rejected as a significant halo population mainly on the basis of the severe constraints arising from the observed metallicity and helium abundances (Ryu, Olive, Silk 1990). In any case, neutron stars and black holes are likely to contribute considerably less than WDs to the dark mass fraction.

3. WHITE DWARFS

The white dwarf (WD) contribution to the halo missing mass has been examined over the past by different authors. These studies focused mainly on the constraint arising from the chemical evolution of the Galaxy (Olive 1986; Ryu et al. 1990). These authors show that WDs are unlikely candidates for providing the *entire* halo missing mass. Recent calculation of the expected radiation signature of the progenitors in galactic halos at large redshift (Charlot & Silk 1995) show that a white dwarf mass fraction larger than $\sim 10\%$ of the missing mass would be in conflict with observations. We will comment on these results below.

An independent, more stringent constraint comes from the observed white dwarf luminosity function (WDLF) in the solar neighborhood, as considered by Tamanaha et al. (1990). However, although pointing the way, these calculations were based on a simplified WD interior and a WD cooling theory aimed at describing the *disk* WDLF, appropriate for objects younger (and thus warmer) than the expected halo population. These calculations in particular do not include a *complete* treatment of crystallization (see below), which occurs around $\log(L/L_\odot) \approx -3.5$ in WD interiors. This substantially affects the cooling of halo WDs and will significantly modify the expected halo WDLF.³

In this Letter, we use the most updated WD cooling theory for carbon/oxygen WDs with the appropriate equation of state both in the classical and in the quantum (crystal) regime (Segretain et al. 1994; Chabrier 1993) and a helium-rich atmosphere (Wood 1992), characteristic of most cool ($T_{\text{eff}} \approx 6000$ K) so-called “DB” WDs. As first suggested by Stevenson (1980), the gravitational energy release, due to carbon-oxygen *differentiation* at crystallization, drastically affects the subsequent cooling time of the star, thus changing the luminosity for a given age (Segretain & Chabrier 1993). A consistent treatment of the crystallization phase diagram along WD evolution has been derived recently by Segretain et al. (1994). As shown by these authors, the crystallization processes appreciably modify the WD cooling time and then the WDLF for $\log(L/L_\odot) \approx -4$, characteristic of old disk and halo WDs. The LF derived with this theory yields an estimate for the age of the Galactic disk $\tau_{\text{disk}} \approx 10.5\text{--}12$ Gyr, depending on the bolometric correction used for the *observed* LF (Hernanz et al. 1994), about 20% larger than estimates based on cooling theories which do not include the *complete* crystallization process (Wood 1992; see Segretain et al. 1994 § 4.1 for details).

The calculations proceed as in Hernanz et al. (1994). The WDLF reads:

$$n(L) = \int_{m_{\text{inf}}(L)}^{m_{\text{sup}}} \tau_{\text{cool}}(L, m) \psi[t_h - t_{\text{cool}}(L, m) - t_{\text{ms}}(m)] \phi(m) dm \quad (1)$$

Here $\tau_{\text{cool}} = dt_{\text{cool}}/dM_{\text{bol}}$ is the *characteristic* cooling time, where t_{cool} is the WD cooling time. t_{ms} and t_h denote, respectively, the age spent on the main sequence for the WD progenitor and the age of the halo. The function $\phi(m)$ is the

³ After the present calculations were completed, we became aware of similar studies by Adams & Laughlin (1996). These calculations, however, are based on crude (pure carbon) WD interior and the aforementioned cooling theory, without accurate treatment of crystallization and Debye cooling.

initial mass function and m_{inf} and m_{sup} denote, respectively, the minimum and the maximum mass of the WD progenitors which contribute at luminosity L . Since the age of the halo is much larger than any time associated with star formation, the initial stellar formation rate $\psi(t)$ is well approximated by a burst at $t = 0$, i.e., a $\delta(t = 0)$ function. In that case equation (1) reduces to:

$$n(L) = \frac{dt_{\text{cool}}}{dM_{\text{bol}}} \nu(t_h - t_{\text{cool}}) \frac{dm}{dt} \quad (2)$$

where $\nu(t_h - t_{\text{cool}})$ represents the number of WDs formed at $t = t_h - t_{\text{cool}}$, i.e., the number of stars with a main-sequence lifetime $t_{\text{ms}} = t_h - t_{\text{cool}}$. We verified that finite-time SFR (e.g., a constant SFR along $\Delta t \neq 0$, a reasonable representation of a continuous series of burst SFRs) or an exponential SFR yield very similar results. The progenitor-WD mass relation is $m_{\text{WD}} \approx 0.45 + 0.1 m$ (Iben & Tutukov 1984). The WDLF is normalized to

$$\int n dM_{\text{bol}} = -2.5 \int n d \log(L/L_\odot) = X_{\text{WD}} \rho_{\text{dyn}} / \langle m_{\text{WD}} \rangle \text{ pc}^{-3} \quad (3)$$

where X_{WD} is the (sought) mass fraction under the form of WDs in the halo of the Galaxy. As shown in equation (2) the most essential parameter in this calculation is the white dwarf cooling time t_{cool} . We use the aforementioned WD cooling sequences calculated in Segretain et al. (1994) and Garcia-Berro et al. (1996).

The second important parameter to be determined in equation (1) is the IMF $\phi(m)$. As mentioned in § 2, a severe constraint arises from the recently determined mass function (slope and normalization) of halo M dwarfs. The predicted star counts obtained with this MF for a spheroid ($1/r^3$) + halo ($1/r^2$) density profile are in perfect agreement with the observations of the *HST* at large magnitude ($I \geq 25$) (Méra et al. 1996a). On the other hand, the observed halo metallicity implies that stars above $m \approx 8 M_\odot$, believed to be Type II supernovae progenitors, represent at most $\sim 1\%$ of the halo initial stellar population (Ryu et al. 1990). These observational constraints show that for WDs to contribute significantly to the mass of the halo the IMF must exhibit a strongly *bimodal* behaviour and peak around some characteristic mass in the range ($M_{\text{inf}}, \sim 8 M_\odot$). The minimum mass corresponds to a main-sequence lifetime of the progenitor equal to the age of the halo, i.e., $m_{\text{inf}} \approx 0.9 M_\odot$ for $t = 10\text{--}25$ Gyr. Several functional forms can be advocated for such an (unknown) IMF. We elected a simple cut-off power-law function $\phi(m) = dN/dm = A e^{-(\bar{m}/m)^{\beta_1}} m^{-\beta_2}$ (see, e.g., Larson 1986). This form mimics adequately a strongly peaked IMF and is very similar to functional forms based on stellar formation theory (Adams & Laughlin 1996). The IMF is normalized to

$$\int_{m_{\text{inf}}}^{\sim 8M_\odot} \phi(m) m_{\text{WD}}(m) dm = X_{\text{WD}} \rho_{\text{dyn}},$$

which determines A [for a given X_{WD} and $m_{\text{WD}}(m)$ relation]. The parameter space for ($\bar{m}, \beta_1, \beta_2$) is constrained by the required negligible number of stars outside the mass range ($\sim 0.9 M_\odot, \sim 8 M_\odot$), but different values yield quantitatively different mass distributions. A large number of masses $\geq 2 M_\odot$ would raise severe problems for the fraction of ejected gas and

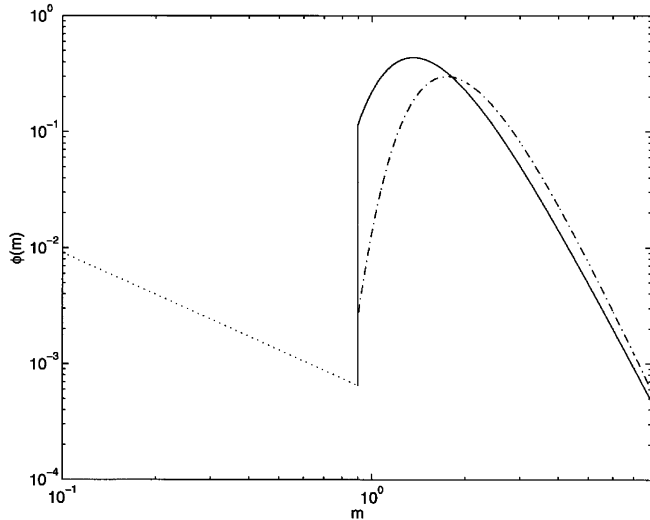


FIG. 1.—Halo initial mass function. The dotted line illustrates the M dwarf MF $dM/dm \propto m^{-2.2}$ (Méra et al. 1996a). The solid line is the IMF $\phi(m) = Ae^{-(\bar{m}/\text{min})\beta_1} m^{-\beta_2}$ with $\bar{m} = 2.0$, $\beta_1 = 2.2$, $\beta_2 = 5.15$ (IMF1). The dot-dashed line is the same IMF with $\bar{m} = 2.7$, $\beta_1 = 2.2$, $\beta_2 = 5.75$ (IMF2).

the subsequent helium and metal galactic enrichment (Hegyi & Olive 1986; Ryu et al. 1990). In order to examine the dependence of the IMF on the results, we thus considered two functions, namely, $\bar{m} = 2.0$, $\beta_1 = 2.2$, $\beta_2 = 5.15$ peaked around $\sim 1.3 M_\odot$ (hereafter IMF1), and $\bar{m} = 2.7$, $\beta_1 = 2.2$, $\beta_2 = 5.75$ peaked around $\sim 1.7 M_\odot$ (hereafter IMF2). The complete M dwarf + WD IMF's fulfilling all the aforementioned constraints are shown in Figure 1.

We note the following observational constraints. The LF of field WDs has been obtained by Liebert, Dahn, & Monet (1988) up to $M_V \approx 19$ (i.e., $L/L_\odot \gtrsim 10^{-5} - 10^{-6}$, depending on the bolometric correction BC_V). The LF declines abruptly for $M_V \approx 16$ which corresponds to $\log(L/L_\odot) \approx -4.2$ to -4.6 . As stated by these authors, *no* WD was found at fainter magnitudes, either with this or with other proper-motion samples, whereas stars up to $M_V = 19$ (i.e., 3 magnitudes fainter) have been observed with similar programs (Liebert et al. 1988; Monet et al. 1992). Interestingly enough, five WDs in the Liebert et al. sample have tangential velocities $v_{\text{tan}} > 250 \text{ km s}^{-1}$ and $M_V \geq 13$, and are thus assignable to the halo sample (shown by filled circles in Figure 2).

More recent constraints arise from the *HST* counts up to $I = 26.3$ (Flynn, Gould, & Bahcall 1996). For a WD mass fraction $X_{\text{WD}} \sim 10\%$, it is easy to show that the observed number of WDs in the *HST* field implies that *halo* WDs must have $M_V \approx M_{\text{bol}} \gtrsim 14$. This is consistent with the observed high-velocity WDs. The colors of the disk and halo WDs were taken to be $0 \lesssim V - I \lesssim 2$, as suggested by the observations (Liebert et al. 1988; von Hippel, Gilmore, & Jones 1995), and the bolometric correction $0 \lesssim BC_V \lesssim 1$ (Liebert et al. 1988; Bergeron, Saumon, & Wesemael 1995).

The observed WDLF is represented in Figure 2, with different halo WDLFs. The dotted line is the *disk* WDLF from Segretain et al. (1994) for an age $\tau_d = 10.5 \text{ Gyr}$.⁴ The crosses correspond to a 90% exclusion confidence level in the limit of detection, i.e., the possibility to see at least two WDs above

⁴ Based on a blackbody bolometric correction BC_V for the observed LF (see Liebert et al. 1988). A zero BC_V will yield $\sim 1.5 \text{ Gyr}$ older ages (see Hernanz et al. 1994) for both the disk and the halo.

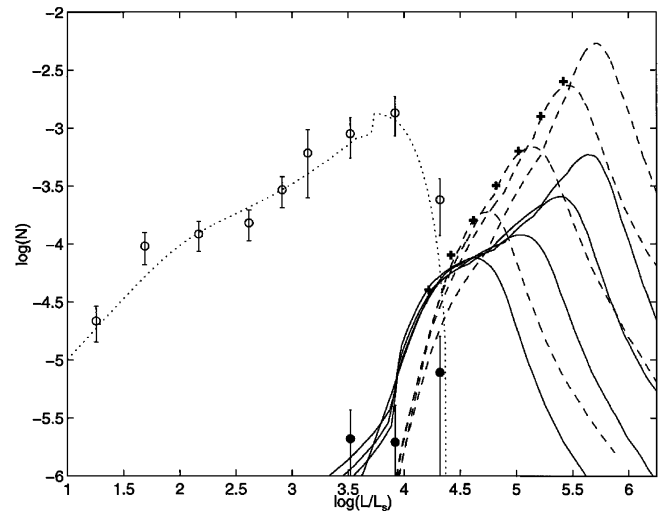


FIG. 2.—White dwarf luminosity function ($\text{pc}^{-3} M_{\text{bol}}^{-1}$). *Open circles*: Liebert et al. (1988). *Filled circles*: high-velocity WDs (Liebert et al. 1988). *Crosses*: limit of detection at the 2σ level (see text). *Dotted line*: disk WDLF for $t_d = 10.5 \text{ Gyr}$. *Solid lines*: halo WDLF for $t_h = 14, 16, 18, 20 \text{ Gyr}$ and $X_{\text{WD}} = 1\%, 2\%, 4\%, 8\%$, from left to right, with IMF1. *Dashed line*: halo WDLF for $t_h = 14, 16, 18, 20 \text{ Gyr}$ and $X_{\text{WD}} = 1.7\%, 8\%, 25\%, 50\%$, with IMF2.

this line whereas none has been detected is rejected at the 2σ level (see, e.g., § IV of Liebert et al. 1988). The solid lines show the *halo* WDLFs for halo ages $t_h = 14, 16, 18,$ and 20 Gyr , normalized to $X_{\text{WD}} = 1\%, 2\%, 4\%$, and 8% , respectively, for calculations done with IMF1. For the distribution of progenitors corresponding to this IMF, differentiation at crystallization in the WD interiors leads to a bump in the halo WDLF in the range $-5 \lesssim \log(L/L_\odot) \lesssim -4$, therefore ruling out substantial WD mass fractions. This shows convincingly the importance of a *complete* treatment of crystallization in WD cooling. Calculations with no carbon/oxygen differentiation will underestimate the number of WDs by more than a factor ~ 5 for a given age and luminosity. Conversely they will yield halo ages $\sim 2 \text{ Gyr}$ younger for a given LF. In the same vein, an incorrect Debye treatment will change significantly the shape of the WDLF. The dashed lines correspond to the same calculations when using IMF2. The normalizations correspond now to $X_{\text{WD}} = 1.7\%, 8\%, 25\%$, and 50% , for the same halo ages. Clearly, for the IMF2, a halo WD mass fraction $\gtrsim 30\%$, in agreement with the MACHO results, cannot be excluded, *provided* a halo age $\gtrsim 18 \text{ Gyr}$.

We have compared the star counts predicted by these WDLFs with the recent *HST* observations at large magnitudes (Flynn et al. 1996), for a $1/r^3$ spheroid and a $1/r^2$ halo. *All* WDLFs predict *at most* (depending on BC_V) ~ 1.4 WD in the *HST* field at the limit magnitude $I = 26$ for a 100% WD halo, and thus are consistent with the *HST* counts. This shows that for these scarce and faint objects, large nearby surveys put more severe constraints than deep pencil searches.

4. CONCLUSION

In this Letter, we have examined the possibility for the recent MACHO events (assuming these events are genuine microlensing events) to be due either to brown dwarfs or to white dwarfs. This determination directly affects the contribution of these objects to the missing mass in the halo of the

Galaxy. Brown dwarfs are clearly excluded as a significant halo population. The luminosity function of *halo* white dwarfs has been calculated with the most accurate white dwarf cooling theory presently available. This WDLF is compared to *all* available observational constraints on halo objects. We show that, under the two *necessary conditions* (1) the IMF in the halo differs totally from the one in the disk and exhibits a strongly peaked behavior around $m \sim 1.5\text{--}2 M_{\odot}$, and (2) the halo is older than ~ 18 Gyr, the white dwarf mass fraction in the halo can represent $\sim 25\%$ – 50% of the dark matter density, in agreement with the recent MACHO results. This would imply an initial *stellar* mass fraction greater than 50% and thus an essentially *baryonic* halo. These results are consistent with the ones obtained from Galactic chemical evolution (Ryu et al. 1990), though they are in conflict with the conclusion obtained by these authors that the disk must form no later than the halo. However, as stated by these authors, alternative scenarios in the disk formation can still be advocated: the left-over gas fraction might have been ejected into the intergalactic medium, as suggested by recent observations of metal-rich hot gas

in the local group (Suto et al. 1996).⁵ The present results are also consistent with the ones obtained by Charlot & Silk (1995), based on the expected radiation signature in high-redshift Galactic halos. These authors considered a Hubble time less than 13 Gyr and solar metallicity (i.e., slowly evolving) stars. The evolution of significantly older, i.e., highly redshifted, low-metallicity stellar populations will certainly be consistent with these observational constraints.

Therefore, although providing a plausible explanation for the MACHO observations and the halo missing mass, the present scenario relies on the necessary use of a *very peculiar*, fine-tuned IMF. These calculations illustrate the difficulty to reconcile the recent MACHO results with other observational constraints. A detailed analysis of the OGLE, MACHO, and EROS results, in the context of a consistent model for the Galaxy, will be presented in a forthcoming paper (Méra, Chabrier, & Schaeffer 1996b).

⁵ Note also that, given the low-metallicity and thus the probably less efficient mass-loss, halo WDs may have larger masses than disk WDs, resulting in a smaller fraction of gas ejecta.

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