Is Galactic Dark Matter White?

G. Chabrier
Centre de Recherche Astrophysique de Lyon (UMR CNRS 5574),
École Normale Supérieure de Lyon, 69364 Lyon Cedex 07, France
(chabrier@ens-lyon.fr)

Received _________________; accepted ___________________
ABSTRACT

We calculate the expected white dwarf luminosity functions and discovery functions in photometric passbands, if these stellar remnants provide a substantial fraction of the sought Galactic dark matter, as suggested on various observational grounds. We demonstrate the extremely rapid variation of the photometric signature of halo white dwarfs with time and thus the powerful diagnostic of white dwarf colors to determine the age of the Galactic halo. We also consider the various indirect constraints implied by a white dwarf dominated halo. These calculations will guide present and future observational projects at faint magnitudes. This will enable us to determine not only the nature of the Galactic dark matter but also the age and the initial conditions of the Galaxy formation.

Subject headings: dark matter — Galaxy: halo — Galaxy: stellar content — white dwarfs
1. Introduction

The nature of Galactic dark matter remains a major puzzle. The MACHO collaboration has now more than 12 events observed towards the LMC (Alcock et al., 1998). They confirm an optical depth \( \tau = 2.9^{+1.4}_{-0.9} \times 10^{-7} \) and a mass of dark objects within 50 kpc \( M_{50} = 2.0^{+1.2}_{-0.7} \times 10^{11} M_\odot \), at least 20% of the mass of the Galaxy within this limit. The time distribution of the microlensing events is narrow ranged (\( \bar{t} \sim 20-70 \) days) with \( \langle t_e \rangle \approx 40 \) days (for the Einstein radius crossing time). Assuming a standard \( 1/r^2 \) isothermal halo, this means that a fraction \( \sim 60 \pm 20\% \) of the sought Galactic dark mass might be in the form of objects with an average mass \( \langle m \rangle = 0.5^{+0.3}_{-0.2} M_\odot \).

Brown dwarfs and low-mass stars (\( m < 1 M_\odot \)) are excluded as a significant halo population both by the microlensing time distribution and by the star count analysis of the Hubble Deep Field (HDF) at faint magnitudes, yielding for the dark halo a maximum stellar plus brown dwarf density \( \rho_{h+BD} \lesssim 0.001 \times \rho_h \), where \( \rho_h \approx 10^{-2} M_\odot \text{pc}^{-3} \) is the dark halo local dynamical density (Chabrier and Méra, 1997; Gould, Flynn and Bahcall, 1998). It is important to stress that both these observational constraints on the stellar content of the Galactic dark halo and the narrow range of time distribution of the events observed towards the LMC imply an initial mass function (IMF) different from a Salpeter one below \( \sim 1 M_\odot \). The recent determination of the Galactic local volume density (Crézé et al., 1998) leaves essentially no room for dark matter in the disk, and thus strongly favors a non-dissipative component for the Galactic dark matter. The suggestion that the events might be due to an intervening stellar population (dwarf galaxy or tidal debris) along the light-of-sight (Zaritsky and Lin, 1997; Zhao, 1998) is still controversial (Beaulieu and Sackett, 1998; Alcock et al., 1997). Under these circumstances, WD’s remain the most favorable candidates for the observed microlensing events and the Galactic baryonic dark matter, in particular after the recent demonstration that some of the faint blue objects in the
HDF are consistent with very cool ($T_{\text{eff}} \lesssim 4000$ K) H-rich atmosphere WD’s (Hansen, 1998). In this paper we calculate the expected halo white dwarf luminosity functions (WDLF) and discovery functions for different halo ages, in various photometric passbands, for a halo WD population consistent with the dark mass inferred from the MACHO observations. This works extends beyond our initial work (Chabrier et al., 1996) by including new atmosphere models and spectral colors appropriate for the halo population.

2. Halo white dwarf luminosity function

For WD’s to provide a mass fraction $X_{\text{WD}}$ of the halo local dynamical density $\rho_h$, the WDLF must be normalized as:

$$\int n \, dM_{\text{bol}} = \frac{X_{\text{WD}}}{\langle m_{\text{WD}} \rangle} \times \rho_h \quad (1)$$

The WDLF reads (Chabrier et al., 1996; Adams & Laughlin, 1996):

$$\frac{dn}{dM_{\text{bol}}} = \int_{m_{\text{inf}(L)}}^{m_{\text{sup}(L)}} \psi(t(m, L)) \times \phi(m) \times \left( \frac{\partial t_{\text{cool}}(m, L)}{\partial M_{\text{bol}}} \right) dm = \left( \frac{\partial t_{\text{cool}}}{\partial M_{\text{bol}}} \right) \frac{dm}{dt} \nu(t) \quad (2)$$

where $m$ is the WD progenitor mass and $\psi(t)$ and $\phi(m)$ denote the stellar formation rate (SFR) and the IMF. The second equality stems from the assumption that the star formation burst at the early epoch of the Galaxy is much shorter than the age of the halo, so that the SFR can be approximated by a Dirac function $\psi(t) = \delta(t - t_0)$. In that case $\nu(t)$ is simply the number of stars such that $t_{MS} + t_{cool} = t_h$, where $t_h$ is the halo age and $t = t_{MS} + t_{cool}$ is the WD total age, i.e. its cooling time plus the main sequence lifetime of its progenitor.

The IMF in (2) must fulfill several constraints: the HDF observations imply $\rho_{(m<1.0)} << 0.01 \times \rho_h$ (see above) and the presence of type II supernovae at finite redshift
Miralda-Escudé and Rees, 1997) imply a finite fraction of stars above \( \sim 8 M_\odot \). We elected a truncated power-law function (Larson, 1986; Chabrier et al., 1996):

\[
\phi(m) = \frac{dn}{dm} = A \exp\left(-\frac{m}{m_p}\right)^\beta m^{-\alpha}
\]

Equation (3) approaches a power-law form \( m^{-\alpha} \) at large masses and can easily be adjusted to reproduce any observed SNII rate, while the integral of the mass function, which is what matters in the present context, is determined essentially by the peak \( m_p = (\beta/\alpha)^{1/\beta} \bar{m} \) and by the parameter \( \beta \). In order to examine the dependence of the results upon the IMF parameters, the present calculations have been conducted with \( \bar{m} = 3.5 M_\odot \), \( \beta = 3.0 \), \( \alpha = 5.0 \), hereafter IMF1, which yields an average WD mass \( \langle m_{WD} \rangle \approx 0.8 M_\odot \) and \( \bar{m} = 2.4 M_\odot \), \( \beta = 3.0 \), \( \alpha = 5.0 \), hereafter IMF2, which yields \( \langle m_{WD} \rangle \approx 0.7 M_\odot \). The slightly larger average mass for halo WD’s than for disk WD’s is motivated by (i) the smaller mass-loss during evolution for metal-poor stars (Maeder, 1992) and (ii) by the fact that the faintest observed disk WD’s have masses \( \sim 0.7-0.8 M_\odot \) (Leggett, Ruiz and Bergeron, 1998). Both IMF1 and IMF2 yield a mass-to-light ratio \( M/L >> 100 \), as required for a dominantly baryonic halo. Note in passing that this type of IMF provides a natural explanation for the lack of zero-like metallicity stars in the Galaxy, the so-called G-dwarf problem.

The present calculations include the most recent atmosphere profiles and synthetic spectra calculations for pure hydrogen atmosphere (so-called DA) WD’s (Saumon and Jacobson, 1998), and the most updated WD interior physics, C/O profiles (Salaris et al., 1997), equation of state and crystallization along evolution (Segretain et al., 1994; Chabrier et al., 1996). To illustrate the rapid cooling of halo WD’s, we found out that although for \( t_h \lesssim 12 \) Gyr the entire WD population is brighter than \( M_V = 20 \), i.e. \( M_{bol} \approx 21-22 \), after 14, 15 and 16 Gyr, only \( \sim 80\% \), 60\% and 25\%, respectively, of the total WD population remains brighter than this magnitude. The more massive WD’s have cooled fainter. For
pure-He (more transparent) atmosphere WD’s, the situation is even more dramatic and after \( \sim 8 \) Gyr, the majority of these stars have cooled fainter than \( M_{\text{bol}} = 21 \) and will thus escape detection. However, using the Alcock and Illarionov (1980) accretion formula, \( dm/dt \approx 10^{-20} \left( \frac{m}{0.5 M_\odot} \right) M_\odot \text{yr}^{-1} \), these stars will accrete \( \sim 10^{-13} M_\odot \) of hydrogen, i.e. about a photosphere mass, during each disk crossing and will thus very likely cool like H-rich atmosphere WD’s.

Figure 1 displays the expected halo WDLF for DA’s with the IMF1 (solid line), normalized to \( X_{WD} = 50\% \), in the most favored V-band, for \( t_h = 14, 15 \) and 16 Gyr, about the age of the oldest globular clusters (Pont et al., 1998)\(^1\). The end of the observed disk WDLF is also displayed, as well as the observed WD’s with halo-like kinematics, i.e. \( v_{\text{tan}} \geq 250 \text{ km.s}^{-1} \) (Liebert, Dahn and Monet, 1988). It is important to mention the sensitivity of the calculations upon the different input parameters, namely (i) the progenitor mass - WD mass relationship, (ii) the progenitor main sequence lifetime and (iii) the IMF. All the present calculations were done with the disk characteristic relationships (Iben and Tutukov, 1984). Although modifications of the two first relationships were found to affect only moderately the WDLF, the IMF is determinant. This is illustrated by the dashed line in Fig. 1, which displays the results of the same calculations with the IMF2. Although the peak of the WDLF is not affected significantly (shifted by \( \sim 0.5-1 \) mag), the bright part of the WDLF, which stems from the low-mass tail of the IMF, has changed by orders of magnitude. This shows the extreme sensitivity of the bright part of the halo WDLF to the ill-constrained low-mass end of the IMF and thus the necessity to observed the bulk of the halo WDLF in order to constrain the IMF of the Galactic halo.

Figure 2 shows WD evolution in a color-magnitude diagram (CMD) and illustrates

\(^1\)Note that \( t \approx 15 \) Gyr corresponds to the age of the universe for \( \Omega_{\text{matter}} = 0.24 \), \( \Omega_\Lambda = 0.62 \) and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), the presently most favored parameters.
the rapid variation of halo WD optical colors with time. The photometric observation of identified halo WD’s will thus provide a powerful diagnostic to determine the age of the Galactic halo. It also provides complementary information to the observation of the WDLF. As shown in Fig. 1, a very small number of objects at $M_V \lesssim 20$ might reflect either a negligible fraction of halo WD’s or a halo age older than 16 Gyr. The CMD will resolve this ambiguity by providing a determination of the age of the objects.

3. Indirect constraints

A Galactic halo composed dominantly of stellar remnants like WD’s implies several constraints on the Galaxy genesis and evolution. The mass fraction of returned gas between the progenitor and the WD with respect to the remnant mass can be written (still assuming a Dirac-function for the SFR):

$$R(t) = \frac{\int_{0.5M_{\odot}}^{8M_{\odot}} \{m - m_{WD}(m)\} \phi(m) dm}{\int_{0.5M_{\odot}}^{8M_{\odot}} m_{WD} \phi(m) dm}$$

(4)

The IMF1 and IMF2 yield $R(t) = 3.5$ and 2.7, respectively. The total mass of returned gas is thus $M_{gas} \approx 1.5 \times 10^{12} M_{\odot}$ if $X_{WD} = 0.5$. Most of this gas will appear in the Lyman-$\alpha$ forest and the total mass of baryons in the leftover gas and in the stellar remnants is bound by the total baryon density, for the same redshift value:

$$\Omega_{rem}(z) + \Omega_{Ly\alpha}(z) \leq \Omega_B \approx (0.019 \pm 0.002) h^{-2} \text{ (Fields et al., 1998). Present determinations yield } \Omega_{Ly\alpha} \approx 0.02 \text{ at } z \sim 2 \text{ (Petitjean et al., 1993). The leftover gas is likely to be ejected in the intergalactic medium (IGM) by a wind due to the primordial generation of SNII or by the more efficient merging mechanism (Gnedin, 1998). This implies the presence of some hot } (\sim 10^8-10^6 \text{ K}) \text{ X-ray gas in the Local Group (LG). Although there are only hints for the presence of such gas in the LG, its presence has been established in other galaxy groups}$$
The total mass of metals ejected during the envelope ejection phase of the WD progenitors is:

\[ M_Z = y_Z \times \int m \phi(m) \, dm \tag{5} \]

where \( y_Z \) denotes the metal stellar yields. As noted by Gibson and Mould (1997), a strongly peaked IMF around \( 2 \, M_\odot \) will produce \([C, N/O]\) abundances during the AGB phase about 10 times the observed value in halo stars. This result, however, depends entirely on the assumed stellar yields \( y_Z \). Gibson and Mould used yields appropriate for \( Z > 10^{-2} \times Z_\odot \).

Stellar evolution calculations for zero-like metallicities (Chieffi and Tornambé, 1984; Fujimoto et al., 1984) show that for a central degenerate core \( M > 0.77 \, M_\odot \), thermal pulses along the asymptotic giant branch do not occur, so that the bottom of the convective envelope never reaches the carbon-enriched region and remains unpolluted. This leads to no C-enhancement of the interstellar medium during the planetary nebulae phase. For zero-like metallicities, this core mass corresponds to \( m > 3 \, M_\odot \), a condition satisfied for most of the stars with IMF1 and marginally satisfied by the IMF2. The C-enrichment constraint might thus be relaxed for primordial stars, depending on the IMF. On the other hand, the presence of an unexpected level of heavy-element enrichment in the IGM at high redshift has been established observationaly (Cowie and Songaila, 1998). The identification of AGB stars as the origin of some of these elements would bring immediate support to the halo WD scenario.

The halo WD scenario seemed to have been excluded on the basis of the observed rate of type Ia SN in galaxies (Smecker & Wyse, 1991). These calculations, however, assumed that the merging of two WD’s whose total mass exceeds the Chandrasekhar mass would produce a SNIa. Recent calculations (Segretain, Chabrier and Mochkovitch, 1997) seem to exclude, or at least strongly unfavor the formation of SNI by this scenario. These calculations seem to be supported on various observational grounds, suggesting that
the rate of SNIa from merging WD’s has been significantly overestimated (see Segretain et al., 1997; Maxted and Marsh, 1998). Note also that usual assumptions about binary parameters in the Galactic disk (mass loss, orbital radius, rate) are likely to be irrelevant under the completely different primordial halo conditions. Charlot and Silk (1995) showed that a halo WD population such that $X_{WD} > 10\%$ would correspond to a progenitor light at redshift $z \leq 3.5$ at odd with the observational constraints. These calculations, however, were done for a halo age $t_h = 13$ Gyr and for stellar evolution models with solar metallicity. Low metallicity stars are brighter for the same mass and thus evolve more quickly. This - and an older halo age - weakens the Charlot-Silk constraint or at least pushes it to larger redshifts. The background light of the progenitors of a WD-dominated halo is constrained also by the total amount of energy distribution in the universe determined by the DIRBE observations (Guiderdoni et al., 1997). The IMF1 (resp. IMF2) yields $\langle m \rangle \sim 4 M_\odot$ (resp. $\sim 3 M_\odot$) for the progenitors, i.e. $\langle L \rangle \sim 80 \times L_\odot$ (resp. $\sim 30 \times L_\odot$) over $\sim 1$ Gyr. Since the mass of the LG is $M_{LG} \sim 2 \times 10^{12} M_\odot$, this yields $\langle L_{LG} \rangle \lesssim 10^{47}$ erg/s. The radius of the LG protogalactic region was $R \sim 1$ Mpc (Peebles, 1993), which yields a surface brightness at redshift $z$, $\mu_z \lesssim (2.6 \times 10^{-4})/(1+z)^4$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. For a halo formed at redshift $z \gtrsim 4$, this yields a peak distribution $\mu_z \lesssim 4.0 \times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ at $\lambda_z = \lambda_0(1+z) \gtrsim 1 \mu$m, about a factor 50 below the DIRBE limit.

4. Predicted counts

The number of WD’s of absolute magnitude $M_\lambda$ per arcmin$^2$ observable in a field of longitude and latitude $(l, b)$, for a limit magnitude $m_l$ reads:

$$N_{WD} = \frac{1}{3600} \left(\frac{\pi}{180}\right)^2 R_0^2 \times \left\{ \int_{M_\lambda}^{M_{\lambda}} ndM \int_{0}^{d_{max}(M_\lambda)} \frac{r^2 dr}{R_0^2 + r^2 - 2rR_0 \cos b \cos l} \right\}$$

(6)
where \( R_0 = 8.5 \) kpc is the galactocentric position of the Sun and \( \log d_{\text{max}}(M_\lambda) [pc] = 0.2(m_I - M_\lambda) + 1 \). Using the WDLF’s determined in the present calculations for pure DA WD’s and \( X_{WD}=50\% \), at most \( N \sim 2 \) WD’s should have been expected in the HDF (4.4 arcmin\(^2\)) at \( V \approx I \approx 28 \) for \( t_h = 14 \) Gyr, whereas less than 1 is expected with the FORS1 VLT telescope (\( V = 26; 6.8 \) arcmin\(^2\)). In the total available field of the french EROSII survey (250\(^2\)), about \( N \sim 26, 2 \) and 0.01 WD’s are expected for halo ages \( t_h = 14, 15 \) and 16 Gyr, respectively at \( I_{\text{lim}} = 20 \) in the appropriate (age-dependent) colors (see Fig. 2). These numbers are multiplied by a factor \( \sim 4 \) for \( I_{\text{lim}} = 21 \), a factor \( \sim 15 \) for \( I_{\text{lim}} = 22 \), and a factor \( \sim 1000 \) for \( I_{\text{lim}}=25 \). Note that for \( t_h \geq 16 \) Gyr, the expected number of WD’s remains essentially zero or a few. A useful tool for observers is the so-called discovery function \( D(M_\lambda) \), i.e. the number of WD’s observable over the whole sky. For a survey limited to nearby halo WD’s, the density can be considered as constant, and \( D(M_\lambda) = \frac{4 \pi}{3} d_{\text{max}}^3(M_\lambda) n(M_\lambda) \). Figure 3 shows the expected discovery functions in the V-band for \( X_{WD} = 0.5 \) and different halo ages and magnitude limits.

5. Conclusion

We have shown in this paper that most of identified baryonic components are unlikely to provide a substantial contribution to the Galactic missing mass, except if they are distributed inhomogeneously, which implies a varying mass-to-light ratio in the Galactic dark halo. White dwarfs, although raising important issues about the Galaxy formation and evolution, remain the most plausible candidates to explain the observed microlensing events and might provide a substantial fraction of the sought baryonic dark matter. The luminosity functions, discovery functions and star counts calculated in the present paper will guide ongoing and future observational projects at faint magnitudes. As shown in Fig. 2, the photometric observation of halo WD’s will provide a powerful diagnostic to determine
the age of the Galactic halo. If WD's do indeed account for a large fraction of the Galactic missing mass, they solve the dilemma of the missing baryons at $z = 0$. In that case the baryonic missing mass is composed essentially of these stellar remnants in galactic halos and of the intergalactic left-over gas from the progenitors.

Acknowledgments: I am deeply indebted to D. Saumon and G. Fontaine for allowing me to use results prior to publication, and to P. Petitjean and U. Fritze for very useful conversations. My gratitude to M. Hernanz for sending the C/O profiles. I am also grateful to the ESO, where most of this work was accomplished, for a visiting scientist position.
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FIGURE CAPTIONS

Fig. 1.— Expected halo WDLF for pure H-atmosphere WD’s in the V-band, for three different halo ages and for $X_{WD}=50\%$. Solid line : IMF1; dashed line : IMF2 for $t_h = 14$ and 16 Gyr. The solid circles correspond to the faint end of the disk WDLF (Liebert et al., 1998) while the squares correspond to the WD’s in the sample with $v_{tan} > 250 \text{ km.s}^{-1}$.

Fig. 2.— $M_V$ vs (V-I) color-magnitude diagram for three different WD masses scanning the standard C/O WD mass range with ages in Gyr indicated by the filled circles for the mean value $0.8 \, M_\odot$.

Fig. 3.— Discovery functions in the V-band for 2 magnitude limits, namely $m_V = 22$ (top lines) and $m_V = 20$ (bottom lines), and for 2 halo ages, for $X_{WD}=50\%$. Solid and long-dash lines : IMF1; dot and short-dash lines : IMF2. Note that a kinematically selected sample might reduce the explored volume and thus the density of observable WD’s as a function of the magnitude.