IS GALACTIC DARK MATTER WHITE?

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ABSTRACT

We calculate the expected white dwarf luminosity functions and discovery functions in photometric passbands, assuming that 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 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 observed more than 12 events toward the LMC (Alcock et al. 1999). They confirm an optical depth of \( \tau = 2.9^{+0.4}_{-0.9} \times 10^{-7} \) and a mass of dark objects within 50 kpc of \( M_\odot = 2.0^{+1.3}_{-1.1} \times 10^{11} \ M_\odot \), which is at least 20% of the mass of the Galaxy within this limit. The time distribution of the microlensing events has a narrow range (\( t \approx 20–70 \) days), with \( (t_c) \approx 40 \) 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 \( (m) = 0.5^{+0.3}_{-0.2} \ M_\odot \).

Brown dwarfs and low-mass stars \( (m \lesssim 1 \ M_\odot) \) 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 \( \rho_{h_{\text{MAX}}} \leq 0.001 \rho_\odot \), where \( \rho_\odot \approx 10^{-5} \ M_\odot \ pc^{-3} \) is the dark halo local dynamical density (Chabrier & Méra 1997; Gould, Flynn, & 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 toward the LMC imply an initial mass function (IMF) different from a Salpeter one below \(~1 \ M_\odot\). 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 nondissipative 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 line of sight (Zaritsky & Lin 1997; Zhao 1998a, 1998b) is still controversial (Beaulieu & Sackett 1998; Alcock et al. 1997). Under these circumstances, white dwarfs (WDs) 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 \( (T_{\text{eff}} \leq 4000 \) K) H-rich–atmosphere WDs (Hansen 1998). In this Letter, 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, Segretain, & Méra 1996) by including new atmosphere models and spectral colors appropriate for the halo population.

2. HALO WHITE DWARF LUMINOSITY FUNCTION

For WDs to provide a mass fraction \( X_{\text{WD}} \) of the halo local dynamical density \( \rho_\odot \), the W DLF must be normalized as

\[
\int n \, dM_{\text{bol}} = \frac{X_{\text{WD}}}{(m_{\text{WD}})} \rho_\odot. \tag{1}
\]

The W DLF reads (Chabrier et al. 1996; Adams & Laughlin 1996)

\[
\frac{dn}{dM_{\text{bol}}} = \int_{m_{\text{WD}}}^{m_{\text{WD}}(t)} \psi(t, L) \phi(m) \left[ \frac{\partial t_{\text{cool}}(m, L)}{\partial M_{\text{bol}}} \right] dm \tag{2}
\]

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 \( \psi(t) = \delta(t - t_s) \). In that case, \( \psi(t) \) is simply the number of stars such that \( t_{\text{MS}} + t_{\text{cool}} = t_s \), where \( t_s \) is the halo age and \( t = t_{\text{MS}} + t_{\text{cool}} \) is the WD total age, i.e., its cooling time plus the main-sequence lifetime of its progenitor.

The IMF in equation (2) must fulfill several constraints: the HDF observations imply \( \rho_{h_{\text{MAX}}} \ll 0.01 \rho_\odot \) (see above) and the presence of Type II supernovae (SNe) at finite redshift (Miralda-Escudé & Rees 1997) imply a finite fraction of stars above \(~8 \ M_\odot\). We elected a truncated power-law function (Larson 1986; Chabrier et al. 1996):

\[
\phi(m) = \frac{dn}{dm} = A \exp(-t_{\text{bol}} m)^{\alpha} m^{-\beta}. \tag{3}
\]

Equation (3) approaches a power-law form \( m^{-\alpha} \) at large
masses and can easily be adjusted to reproduce any observed Type II SN rate, while being the integral of the mass function, which is what matters in the present context, is determined essentially by the peak $m_p = (\beta \alpha)\frac{\dot{m}}{\dot{\alpha}}$ 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 $\dot{m} = 3.5 \ M_{\odot}$, $\beta = 3.0$, and $\alpha = 5.0$ (hereafter IMF1), which yields an average WD mass $\langle m_{\text{WD}} \rangle \approx 0.8 \ M_{\odot}$, and $\dot{m} = 2.4 \ M_{\odot}$, $\beta = 3.0$, and $\alpha = 5.0$ (hereafter IMF2), which yields $\langle m_{\text{WD}} \rangle \approx 0.7 \ M_{\odot}$. The slightly larger average mass for halo WDs than for disk WDs is motivated by (1) the smaller mass loss during evolution for metal-poor stars (Maeder 1992) and (2) the fact that the faintest observed disk WDs have masses ~$0.7$–$0.8 \ M_{\odot}$ (Leggett, Ruiz, & Bergeron 1998). Both IMF1 and IMF2 yield a mass-to-light ratio $M/L \gg 100$, 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) WDs (Saumon & Jacobson 1999), 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 WDs, we found out that although for $t_e \leq 12$ Gyr the entire WD population is brighter than $M_v = 20$, i.e., $M_{\text{WD}} \approx 21$–$22$, after 14, 15, and 16 Gyr, only ~$80\%$, $60\%$, and $25\%$, respectively, of the total WD population remains brighter than this magnitude. The more massive WDs have cooled faster. For pure He (more transparent) atmosphere WDs, the situation is even more dramatic, and after ~8 Gyr, the majority of these stars have cooled fainter than $M_{\text{bol}} = 21$ and will thus escape detection. However, using the Alcock & Illarionov (1980) accretion formula, $\dot{m} \sin i \approx 10^{-20} [m/(0.5 \ M_{\odot})] M_{\odot} \ \text{yr}^{-1}$, these stars will accrete ~$10^{-10} \ M_{\odot}$ of hydrogen, i.e., about a photosphere mass, during each disk crossing and will thus very likely cool like H-rich–atmosphere WDs.

Figure 1 displays the expected halo WDLF for DAs with the IMF1 (solid line), normalized to $X_{\text{WD}} = 50\%$, in the most favored $V$ band for $t_e = 14$, 15, and 16 Gyr, about the age of the oldest globular clusters (Pont et al. 1998). The end of the observed disk WDLF is also displayed, as well as the observed WDs with halo-like kinematics, i.e., $V_{\text{hel}} \geq 250$ km s$^{-1}$ (Liebert, Dahn, & Monet 1988). It is important to mention the sensitivity of the calculations upon the different input parameters, namely (1) the progenitor mass-WD mass relationship, (2) the progenitor main-sequence lifetime, and (3) the IMF. All of the present calculations were done with the disk characteristic relationships (Iben & 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 Figure 1, which displays the results of the same calculations with the IMF2. Although the peak of the WDLF is not affected significantly (shifted by ~$0.5$–$1$ 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 observe 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 and illustrates the rapid variation of halo WD optical colors with time. The photometric observation of identified halo WDs 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 Figure 1, a very small number of objects at $M_v \approx 20$ might reflect either a negligible fraction of halo WDs or a halo age older than $\sim 20$ Gyr.

Note that $t \approx 15$ Gyr corresponds to the age of the universe for $\Omega_{\text{matt}} = 0.24$, $\Omega_{\Lambda} = 0.62$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, the presently most favored parameters.
than 16 Gyr. The color-magnitude diagram 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 WDs 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):

\[ R(t) = \frac{\int_{0.5 M_\odot}^{M_\star} (m - m_{\text{WD}}(m))\phi(m) \, dm}{\int_{0.5 M_\odot}^{M_\star} m_{\text{WD}}(m)\phi(m) \, dm}. \]  (4)

The IMF1 and IMF2 yield \( R(t) = 3.5 \) and 2.7, respectively. The total mass of returned gas is thus \( M_{\text{gas}} \approx 1.5 \times 10^{12} M_\odot \) if \( X_{\text{WD}} = 0.5 \). Most of this gas will appear in the Ly\( \alpha \) forest, and the total mass of baryons in the leftovver gas in and the stellar remnants is bound by the total baryon density, \textit{for the same redshift value}: \( \Omega_{\text{b, tot}}(z) + \Omega_{\text{tot}}(z) \leq \Omega_{\Lambda} \approx 0.019 \pm 0.002 \) \( h^2 \) (Fields, Freese, & Graff 1998). Present determinations yield \( \Omega_{\text{tot}} \approx 0.02 \) at \( z \approx 2 \) (Petitjean et al. 1993). The leftover gas is likely to be ejected in the intergalactic medium by a wind due to Type II SNe or by the more efficient merging mechanism (Gnedin 1998). This implies the presence of some hot (\( \sim 10^4 \)–\( 10^8 \) K) 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 and in the intracluster medium (see, e.g., Mushotzky et al. 1996). The total mass of metals ejected during the envelope ejection phase of the WD progenitors is

\[ M_x = y_z \int m\phi(m) \, dm, \]  (5)

where \( y_z \) denotes the metal stellar yields. As noted by Gibson & 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 & Mould used yields appropriate for \( Z \approx 10^{-5} Z_\odot \). Stellar evolution calculations for zero- to metal-like metallicities (Chieffi & Tornambé 1984; Fujimoto et al. 1984) show that for a central degenerate core \( M \geq 0.77 M_\odot \), 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 unprocessed. This leads to no C enhancement of the interstellar medium during the planetary nebula phase. For zero- to metal-like metallicities, this core mass corresponds to \( m \approx 3 M_\odot \), 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 intergalactic medium at high redshift has been established observationally (Cowie & 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 SNe in galaxies (Smecker & Wyse 1991). These calculations, however, assumed that the merging of two WDs whose total mass exceeds the Chandrasekhar mass would produce a Type Ia SN. Recent calculations (Segreani, Chabrier, & Mochkovitch 1997) seem to exclude, or at least strongly disfavor, the formation of Type I SNe by this scenario. These calculations seem to be supported on various observational grounds, suggesting that the rate of Type Ia SNe from merging WDs has been significantly overestimated (see Segreani et al. 1997; Matched & 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 & Silk (1995) showed that a halo WD population such that \( X_{\text{WD}} \approx 10\% \) would correspond to a progenitor light at redshift \( z \approx 3.5 \) at odds 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 (IMF2) yields \( m \approx 4 M_\odot \) \( (~3 M_\odot) \) for the progenitors, i.e., \( (L_\odot) \approx 80 L_\odot \) \( (~30 L_\odot) \) over \( \sim 1 \) Gyr. Since the mass of the LG is \( M_{\text{IG}} \approx 2 \times 10^{12} M_\odot \), this yields \( (L_{\odot}) \approx 10^{42} \) ergs \( s^{-1} \). The radius of the LG protogalactic region is \( R \approx 0.1 \) Mpc (Peebles 1993), which yields a surface brightness at redshift \( z \) of \( \mu \approx 2 \times 10^{-2} \) ergs \( s^{-1} \) \( cm^{-2} \) \( sr^{-1} \) at \( \lambda_0 = \lambda_0(1 + z) \approx 1 \mu m \), about a factor 50 below the DIRBE limit.

4. PREDICTED COUNTS

The number of WDs of absolute magnitude \( M_r \) per square minute of arc observable in a field of longitude and latitude \( (l, b) \), for a limit magnitude \( m_r \), reads

\[ N_{\text{WD}} = \frac{1}{3600} \left( \frac{\pi}{180} \right)^2 R_0^2 \int_0^{M_r} n \, dM \times \int_{\Omega} \frac{r^2 \, dr}{R_0^2 + r^2 - 2R_0 \cos b \cos l}. \]  (6)

where \( R_0 = 8.5 \) kpc is the Galactocentric position of the Sun and \( \log d_{\text{max}}(M_r) \) [pc] \( = 0.2(m_r - M_r) + 1 \). Using the WDLFs determined in the present calculations for pure DA WDs and \( X_{\text{WD}} = 50\% \), at most \( N \sim 2 \) WDs should have been expected in the HDF (4.4 arcmin\(^2\)) at \( V \approx l \approx 28 \) for \( t_h = 14 \) Gyr, whereas less than 1 is expected with the FORS1 Very Large Telescope \( (V = 26; 6.8 \) arcmin\(^2\)). In the total available field of the French EROS II survey (250 deg\(^2\)), about \( N \approx 26, 2, \) and 0.01 WDs are expected for halo ages \( t_h = 14, 15, \) and 16 Gyr, respectively at \( l_{\text{lim}} = 20 \) in the appropriate (age-dependent) colors (see Fig. 2). These numbers are multiplied by a factor \(~4\) for \( l_{\text{lim}} = 21 \), a factor \(~15\) for \( l_{\text{lim}} = 22 \), and a factor \(~1000\) for \( l_{\text{lim}} = 25 \). Note that for \( t_h \geq 16 \) Gyr, the expected number of WDs remains essentially zero or a few. A useful tool for observers is the so-called discovery function \( D(M_r) \), i.e., the number of WDs observable over the whole sky. For a survey limited to...
nearby halo WDs, the density can be considered as constant, and $D(M_*) = \frac{4\pi}{3} M_\odot^2 \rho_\odot (M_*) n(M_*)$. 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 Letter that most 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 Letter will guide ongoing and future observational projects at faint magnitudes. As shown in Figure 2, the photometric observation of halo WDs will provide a powerful diagnostic to determine the age of the Galactic halo. If WDs 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 leftover gas from the progenitors.

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