MACHOS, WHITE DWARFS, AND THE AGE OF THE UNIVERSE

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ABSTRACT

A favored interpretation of recent microlensing measurements toward the Large Magellanic Cloud implies that a large fraction (i.e., 10%–50%) of the mass of the Galactic dark halo is composed of white dwarfs. However, a ground-based search by Liebert and a recent search of the Hubble Deep Field by Flynn did not detect a substantial dark halo population of white dwarfs; thus the putative halo population is either dim enough or sparse enough to have eluded detection. In this paper we compare model white dwarf luminosity functions to the data from the observational surveys in order to determine a lower bound on the age of any substantial white dwarf halo population (and hence possibly on the age of the universe). In the course of our analysis we pay special attention to the velocity bias in the Liebert and coworkers, survey; we show that (and quantify by how much) the velocity bias renders the survey significantly less sensitive to a cool white dwarf population.

We show that the minimum age of a white dwarf halo population depends most strongly on assumptions about three unknown quantities: (1) the white dwarfs’ total space density, (2) their atmospheric composition, and (3) the initial mass function (IMF) of their progenitors. We compare various theoretical white dwarf luminosity functions, in which we vary these three parameters, with the abovementioned survey results. From this comparison, we conclude that if white dwarfs do indeed constitute more than 10% (30%) of the local halo mass density and are candidates for explaining the microlensing events, then the universe must be at least 10 Gyr old (12 Gyr old) for our most extreme allowed values of the parameters. When we use cooling curves that account for chemical fractionation and more likely values of the IMF and the bolometric correction, we find tighter limits; a white dwarf MACHO fraction of 10% (30%) requires a minimum age of 14 Gyr (15.5 Gyr). Our analysis also provides evidence that the halo white dwarfs have helium-dominated atmospheres, although this conclusion may change after low-temperature white dwarf atmospheres have been calculated.

Subject headings: galaxies: halos — gravitational lensing — stars: luminosity function, mass function — stars: statistics — white dwarfs

1. INTRODUCTION

In this paper, we refine the process of using dark halo white dwarfs to derive a lower bound on the age of the universe. Our efforts are motivated by the second-year MACHO collaboration data (Alcock et al. 1996), which appear to indicate that objects of white dwarf mass may constitute a substantial fraction of the total mass of the Galactic dark halo.

If there is a profusion of white dwarfs in the galactic halo, one can naturally consider the prospects for detecting them optically. Kawaler (1996) predicted that halo white dwarfs might be present in the Hubble Deep Field (HDF). Flynn, Gould, & Bahcall (1996), Reid et al. (1996), and Elson, Santiago, & Gilmore (1996) searched the HDF for this population (with rigorous selection criteria) without notable success. Furthermore, the ground-based white dwarf luminosity function compiled by Liebert, Dahn, & Monet (1988; hereafter LDM) with stars from the Luyten Half-Second Catalogue (Luyten 1979) shows little evidence of a substantial population of halo white dwarfs. The immediate conclusion is that if the white dwarfs exist, then they are too dim to have been uncovered by the LDM and HDF surveys. Our intention in this paper is to provide a detailed quantification of this statement and its ramifications.

White dwarfs grow cooler and dimmer as they age. The cooling theory for white dwarfs is well developed (see, e.g., Winget 1987; Segretain 1994). Cooling models, in conjunction with star formation histories, initial mass functions (IMFs), and stellar evolution theory can be used to construct model luminosity functions for posited white dwarf halo populations. The luminosity function is defined to be the number density of stars with magnitude between $M$ and $M + dM$. By squaring the lack of observed faint white dwarfs in the HDF and LDM studies with model luminosity functions, it is possible to derive a lower bound on the age of the Galactic halo and hence on the age of the universe.

Unfortunately, the minimum age also depends on several loosely constrained parameters, notably the local density of halo white dwarfs, the present composition of the white dwarf atmospheres, and the mass distribution of the white dwarfs (which is in turn related to the IMF of the progenitor stars). The primary results of this paper are plotted in Figures 4 and 5; in obtaining these plots, we have used the cooling curves of Segretain et al. (1994) as communicated by Chabrier (1996). These figures indicate that if one takes the local mass density in white dwarfs to be at least 10% of the local halo mass density (as suggested by the microlensing data), then the white dwarfs must be at least 12 Gyr old. With the most reasonable mass function for the progenitors, the lower limit is 13 Gyr; if one also takes pure blackbody rather than the most extreme bolometric corrections, the lower limit rises to 14 Gyr. Although relatively young, a
universe of 12 Gyr is still in conflict with a Hubble constant of $H_0 > 55$ km s$^{-1}$ Mpc$^{-1}$ in a standard cosmological model.

In order to estimate the uncertainty in the minimum age due to white dwarf cooling models, we also consider a less sophisticated model without chemical fractionation for comparison. Chemical fractionation provides an additional source of energy for white dwarfs and allows them to cool more slowly. Models by Segretain et al. (1994) that do not include C/O chemical fractionation are about 2 Gyr younger than models with chemical fractionation. With these simpler cooling models, all the age limits in the previous paragraph become weaker by 2 Gyr. Thus the extreme minimum age one can consider for the white dwarfs is 10 Gyr.

If we assume that the age of the Galactic halo is less than 18 Gyr (Chaboyer et al. 1996), then we also find strong evidence that a substantial halo white dwarf population consists of white dwarfs with helium rather than hydrogen atmospheres. The remaining uncertainty on this issue is due to the fact that low-temperature white dwarf atmospheres have not been studied, although calculations by Méra & Allard (D. Méra 1997, private communication) are underway.

Please note that there is a potential source of confusion in our use of the word “halo.” We distinguish between two different types of Galactic halos: the visible halo, sometimes called the stellar halo or spheroid, which is dynamically insignificant in the outer Galaxy, and the dark halo, or corona, which dominates the dynamics of the outer Galaxy. If much of the mass of the dark halo is composed of white dwarfs, then it, along with the spheroid, is a stellar phenomenon; however, the two stellar populations would have greatly different IMFs and could thus be distinguished. Microlensing events toward the Large Magellanic Cloud (LMC) are sensitive to a dark halo population (Ansari et al. 1996). Thus, in this paper, unless otherwise stated, we are exclusively concerned with a dark halo population of white dwarfs.

1.1. Comparison with Previous Work on this Subject

The white dwarf luminosity function of the Galactic disk has been extensively studied. The LDM survey (discussed in more detail below) has been modeled by a number of groups, most significantly by Winget et al. (1987). There is a fairly robust consensus that the LDM survey is consistent with a disk population of white dwarfs having an age of 9–11 Gyr. A new survey of binary white dwarf companions to main-sequence stars, which is independent of the LDM survey, has separately confirmed this result and yields a measurement of $f_{disk} \approx 9.5$ Gyr (Oswalt et al. 1996).

Prior to our work, three groups constructed model luminosity functions for halo populations of white dwarfs and compared them to the LDM luminosity function. A precedent first investigation was made by Tamanaha et al. (1990), who addressed the problem prior to the advent of microlensing surveys. They recognized that a dark halo population of white dwarfs must necessarily arise from an old (in their analysis, older than 12 Gyr) population of predominantly high-mass (i.e., 2–6 $M_\odot$) stars. Motivated by the new MACHO results, Adams & Laughlin (1996) and Chabrier, Segretain, & Méra (1996) revisited the problem and produced new luminosity functions based on more sophisticated mass functions and cooling curves. Their work reinforced the conclusion that any significant white dwarf halo is the outcome of a very old population of high-mass progenitor stars. Adams & Laughlin (1996) obtained a lower limit of 14 Gyr and Chabrier et al. (1996) of 18 Gyr for the age of the white dwarfs. Our work revisits this problem and represents a substantial shift in that our results allow a considerably lower minimum age for the white dwarf population.

This paper continues in the spirit of the three halo white dwarf studies mentioned above. We share the overall goal of comparing theoretical model luminosity functions with observational surveys, and we have identified several specific areas for improvement in the comparison between observation and theory. Our aim is to address the following issues and incorporate them into a more refined analysis. These improvements lie in three areas: (1) the method of comparison with data, (2) the treatment of bolometric corrections, and (3) the comparison of theory with the combined results of the HDF and LDM surveys. In the course of this analysis we emphasize the importance of a little publicized velocity bias in the LDM survey. Each of these three areas of improvement is outlined below.

1.1.1. The Method of Comparison

Two of the groups that previously worked on this subject, Tamanaha et al. (1990) and Adams & Laughlin (1996), focused on the dimmest white dwarfs observed by LDM, which had a visual magnitude of $M_V \approx 16$. These two groups compared predictions from their luminosity functions with these observed white dwarfs. The third group, Chabrier et al. (1996), used the nondetection of white dwarfs by LDM at fainter magnitudes to compare with theory. We also use the nondetection, but in a more systematic way.

1.1.1.1. Comparison with the Coolest White Dwarfs Observed

Tamanaha et al. (1990) and Adams & Laughlin (1996) attempted to constrain the age and number density of the dark halo population by focusing on the dimmest white dwarfs that were actually uncovered in the LDM survey. The LDM luminosity function exhibits a sharp dropoff in number density for objects fainter than $M_V \approx 16$. Tamanaha et al. (1990) and Adams & Laughlin (1996) required their models to conform to the density of $M_V \sim 16$ stars from LDM data. Comparisons that focus on the coolest white dwarfs actually observed have two shortcomings: they are sensitive to small differences in the low-mass tail of the progenitor IMF, and they ignore the bulk of the posited halo white dwarfs, which would be dimmer than the faintest stars detected by LDM. We briefly discuss these two shortcomings here.

The sensitivity to the low-mass tail can be understood as follows. In Figure 1, the horizontal dotted line shows the bolometric luminosities of the dimmest white dwarfs observed by LDM (here we have assumed a blackbody bolometric correction; see the discussion below). The solid lines plot model white dwarf luminosities. We can see from Figure 1 that for a white dwarf population older than 10 Gyr, only the stars with the lowest initial masses would be bright enough to be limited by the LDM luminosity function at $M_V = 16$.

White dwarfs that emerged from progenitors of $M < 1.5$ $M_\odot$ are substantially brighter than white dwarfs that arose from heavier stars. (The lower mass progenitor stars were on the main sequence for a significant portion of a Hubble
cating the fictitious luminosity function that would have resulted had a single white dwarf been found in each of their unoccupied faint bins below $M_V = 16$. Chabrier et al. (1996) used this illustrative luminosity function to constrain the space density of white dwarfs fainter than $M_V = 16$. Although qualitatively reasonable, this method is not the best way to obtain an upper limit to the local white dwarf density. Requiring that model luminosity functions fall on or below the envelope of fictitious points does not provide a uniform constraint. Among the models presented by Chabrier et al. (1996), luminosity functions predicting nearly five stars among the dim bins are no more constrained than others in the same figure that predict only $\approx 1$. In addition, we will show that the LDM sensitivity to disk stars used by Chabrier et al. (1996) is up to 10 times too restrictive for a population of halo stars (see the discussion of the survey’s proper motion sensitivity in § 3.2); this fact led Chabrier et al. (1996) to overestimate the minimum age of the halo white dwarfs.

In this paper, we also use the nondetection of faint white dwarfs in the LDM survey with $M_V > 16.5$ to constrain the properties of prospective halo populations. However, we take a more rigorous statistical approach; we integrate over the entire low-luminosity region of the luminosity function to predict the number of stars that would be observed on average. Assuming that the white dwarfs are spatially uncorrelated, Poisson statistics indicate that the number of dwarfs predicted by a given model luminosity function must be $\mathcal{N} \leq 3$ in order to be consistent with a nondetection at the 95% confidence level. This statistical approach allows a systematic test for consistency, which can be applied automatically to a large number of trial model luminosity functions to efficiently determine the allowed region of parameter space.

1.1.2. Bolometric Corrections

Bolometric corrections are required in order to transform a white dwarf’s observed magnitude in the $V$, $R$, or $I$ band into a bolometric luminosity; it is this latter quantity that is predicted by theoretical models. Tamahana et al. (1990), Chabrier et al. (1996), and Adams & Laughlin (1996) compared their results to the bolometric luminosity function of LDM and thus made implicit use of bolometric corrections introduced by LDM. While fairly accurate for the brighter white dwarfs composing the disk population, these bolometric corrections cannot be used to extrapolate to visual magnitudes fainter than $M_V = 16$ and thus do not apply to the presumed halo white dwarf population. We apply a more sophisticated estimate of the bolometric corrections appropriate to extremely dim white dwarfs. We also focus discussion on the possibility that the putative halo dwarfs have hydrogen-dominated atmospheres. Hydrogen atmospheres imply very different bolometric corrections, as well as considerably longer cooling times. We show that a preponderance of hydrogen atmospheres is extremely unlikely in the event that the halo is younger than 18 Gyr.

1.1.3. Consolidation of Surveys

In addition to the LDM survey (which previous authors also compared with theoretical luminosity functions), we also examine the search of the HDF by Flynn et al. (1996). The HDF and the LDM survey can be used independently to place constraints on the age and number density of a halo white dwarf population. We put forth a detailed analysis of the effective volume searched by each of these...
surveys as a function of bolometric luminosity, which allows us to use the combined results of both surveys to place firmer limits than possible with either survey alone. In the course of our analysis, we discuss a little publicized velocity bias in the LDM survey that renders it less sensitive to the faint, high proper-motion stars that are characteristic of the population we are studying. In fact, taking the limit properly into account will admit considerably lower halo ages than found in prior analyses.

The organization of this paper is as follows: in § 2, we describe the theoretical issues involved in the construction of model white dwarf luminosity functions. These center mainly on the cooling theory and the star formation theory relevant for the original population. In § 3, we examine issues related to the comparison between observations and theory. We characterize the surveys, take stock of bolometric corrections, and discuss the question of faint white dwarf atmospheric composition. In § 4, we compare our theoretical luminosity functions with observations to constrain the age and number density of the putative halo population. In § 5, we discuss the ramifications of our work within a larger cosmological framework.

2. MODEL LUMINOSITY FUNCTIONS

The white dwarf luminosity function (LF) describes the number density of stars per magnitude interval. We need to obtain a theoretical LF for the white dwarfs in order to compare with the LDM and HDF data. White dwarf LFs hinge on the physical properties of their component white dwarfs. The luminosity of a particular white dwarf is determined by its age, its mass, and its chemical composition. These properties in turn depend on the properties of the main-sequence progenitor star that led to the white dwarf.

We will assume that all the main-sequence progenitors of the present lensing population formed at a time $t_{tot}$ ago. Then we have

$$t_{evol}(m) + t_{c}(l, m_{WD}) = t_{tot}.$$  (2.1)

Here, $t_{evol}(m)$ is the time the progenitor spent on the main sequence, and $t_{c}$ is the time the star has spent as a white dwarf. We assume that the nuclear burning lifetime on the main sequence is a function only of the mass $m$ of the main-sequence progenitor, i.e.,

$$t_{evol} \equiv t_{evol}(m).$$  (2.2)

We will also use the fact that the mass of the white dwarf is a function of the mass of its main-sequence progenitor,

$$m_{WD} \equiv m_{WD}(m).$$  (2.3)

Note that lower mass stars spend a longer time on the main sequence, become white dwarfs later, and hence are brighter at any given time (see Fig. 1).

White dwarf progenitor lifetimes are assumed to conform to the relation

$$\log_{10} t_{evol} = 9.921 - 3.6648(\log_{10} m) + 1.9697(\log_{10} m)^2$$
$$- 0.9369(\log_{10} m)^3,$$  (2.4)

where $m$ is measured in units of solar mass. This result is taken from Iben & Laughlin (1989), who obtained the polynomial by extracting main-sequence lifetimes from the stellar evolution calculations of a number of different authors.

The cooling time of the white dwarf is a function of the white dwarf mass and of the particular luminosity interval $l$. We will assume that separate relations of the form

$$t_{c} \equiv t_{c}(l, m_{WD})$$  (2.5)

hold for white dwarfs with hydrogen and helium atmospheres. We primarily use the white dwarf cooling theory from the calculations of Segretain et al. (1994), as communicated by G. Chabrier (1996, private communication). The Segretain et al. (1994) model represents an advance over earlier cooling theories in that it accounts for gravitational energy release due to C/O differentiation at crystallization. Proper treatment of crystallization yields significantly longer white dwarf cooling times, which in turn imply an older age for any particular white dwarf halo population. These white dwarf models correspond to a mass sequence of initially unstratified white dwarfs composed of equal parts carbon and oxygen that have helium atmospheres.

To estimate the uncertainty in the age limits for white dwarfs due to cooling theory, we note that an extreme model presented by Segretain et al. (1994), which does not include the perhaps controversial C/O phase separation, and which allows an initial C/O stratification, predicts that cool white dwarfs will be $\sim 1$ Gyr younger than the homogeneous phase-separated models we use. These models would give rise to minimum white dwarf ages 2 Gyr younger than what is allowed by the Segretain et al. (1994) models and hence potentially allow a halo white dwarf age of 10 Gyr.

If we assume that all of the white dwarfs were formed within a relatively short period of time, then we can use equations (2.1) and (2.3) to derive a differential form for the LF (see Iben & Laughlin 1989 for details):
et al. (1997) have shown that although the derived MACHO mass fraction depends strongly on the choice of halo model, the MACHO fraction exceeds 0.1 with at least 90% confidence for every model they considered. Turner, Gates, & Gyuk (1996) have independently determined that the vast majority of otherwise plausible halo models must have \( f > 0.1 \) in order to be consistent with the microlensing result. For our working hypothesis we therefore adopt \( f > 0.1 \) as the minimum value in our analysis.

### 2.2. Initial Mass Function

As mentioned above, the mass- and main-sequence evolution of a white dwarf are determined by the mass of its main-sequence progenitor. Therefore we must examine possible IMFs, \( dN/dm \), for main-sequence stars that are capable of producing white dwarfs. Optical searches are more sensitive to brighter white dwarfs arising from low-mass progenitors than to the fainter dwarfs arising from high-mass progenitors; thus the limits that we will be able to place depend on the LF we choose. We compute a wide range of LF models to measure the sensitivity of our limits on the LF.

Adams & Laughlin (1996) argued that the initial masses of halo white dwarf progenitors had to be between 1 and 8 \( M_\odot \). The lower limit on the range of initial masses comes from the fact that stars with mass less than 1 \( M_\odot \) would still be on the main sequence. The upper bound arises from the fact that progenitor stars heavier than \( \approx 8 M_\odot \) explode as supernovae and do not form white dwarfs.

Because low-mass main-sequence halo stars are intrinsically scarce (Bahcall et al. 1994; Dahn et al. 1995; Graff & Freese 1996a, 1996b), an IMF similar to the disk IMF is not appropriate since it implies a gross overabundance of low-mass stars in the halo. We follow Adams & Laughlin (1996) and use a lognormal mass function motivated by Adams & Fatuzzo’s (1996) theory of the IMF

\[
\ln \frac{dN}{dm} (m) = A - \frac{1}{2\langle\sigma\rangle^2} [\ln(m/m_c)]^2. \tag{2.7}
\]

The parameter \( A \) sets the overall normalization. The mass scale \( m_c \) (which determines the center of the distribution) and the effective width \( \langle\sigma\rangle \) of the distribution are set by the star-forming conditions that gave rise to the present-day population of remnants. For our standard case, we take the parameters \( m_c = 2.3 M_\odot \) and \( \langle\sigma\rangle = 0.44 \), which imply warm, uniform star-forming conditions for the progenitor population. These parameters saturate the twin constraints required by the low-mass and high-mass tails of the IMF, as discussed by Adams & Laughlin (1996), i.e., this IMF is as wide as possible.

The IMF in equation (2.7) is different from the mass functions measured in the disk, the halo, globular clusters, and elliptical galaxies and justifiably seems to many people to be a sign of the fine tuning required for a white dwarf halo model. Indeed a MACHO IMF must be different from the standard IMFs and must be narrow. It is interesting to note, however, that the star formation theory of Adams & Fatuzzo (1996) predicts that a zero-metallicity primordial gas will form higher mass stars than the non-zero-metallicity gas that formed all the familiar stars; this prediction lends some plausibility to equation (2.7).

As an even more extreme possibility, we will also explore the effects of various single-valued (delta-function) IMFs, mainly for illustrative purposes. Such a delta-function mass function is undoubtedly too narrow and unphysical. However, it allows us to eliminate the poorly constrained low-mass tail of the IMF, which produces the most easily observed high-luminosity tail of the LF. Thus, delta-function mass functions enable us to focus on the effects of the initial mass of the majority of stars, without having to worry about about the shape of the wings of the IMF.

### 2.3. Initial/Final Mass Relations

The relation between the mass of a progenitor star and the mass of its resultant white dwarf is rendered uncertain by an imperfect understanding of mass loss from red giants. We follow Wood (1992) in adopting his standard transformation between the progenitor mass and the white dwarf mass,

\[
m_{\text{WD}} = A_x \exp (B_x m), \tag{2.8}
\]

where \( A_x = 0.49 \) and \( B_x = 0.095 \). With our choice of IMF in equation (2.7), this leads to an average white dwarf mass of 0.63 \( M_\odot \). Adopting other reasonable initial/final relations, such as the form \( m_{\text{WD}} = 0.45 + 0.1 m \) given by Iben & Tutukov (1984), has little qualitative effect on the results. We estimate that the uncertainty in the initial/final mass relation imparts an uncertainty of less than 0.5 Gyr to our final answer of the age of the white dwarf population.

### 2.4. Atmospheric Composition

Tamanaha et al. (1990), Adams & Laughlin (1996), and Chabrier et al. (1996) all assumed that the putative white dwarf halo population is composed of dwarfs with helium atmospheres. Faint white dwarfs with helium atmospheres cool more quickly than dwarfs with hydrogen atmospheres (because of lower helium opacities below \( 1 \times 10^4 \) K), so any lower age limits derived with the assumption of helium atmospheres are firm. Nevertheless, hydrogen atmospheres are a possibility.

The chemical composition of cool white dwarf atmospheres is difficult to determine observationally, depends on the metallicity of the star (Iben & MacDonald 1986), and can change over the course of a white dwarf’s lifetime (Fontaine & Wesemael 1987). Until recently, it seemed that the most likely scenario for very cool white dwarfs in the disk is that they have helium atmospheres. Observations by LDM indicated that this is probably, and Fontaine & Wesemael (1987) suggested that hydrogen atmospheres could be diluted with the helium mantle through convection. However, a recent survey of the atmospheric type of cool white dwarfs (Bergeron, Ruiz, & Leggett 1997) found a substantial population of cool (4000 < \( T < 6000 \)) hydrogen atmosphere stars. These authors proposed a complex interaction of convection and accretion from the interstellar medium to allow the atmospheres of white dwarfs to rapidly evolve from helium to hydrogen and back to helium. It would be interesting to investigate the atmospheric properties of even cooler white dwarfs, including the ones we are considering as a halo population. The atmospheric structure of halo white dwarfs cooler than 4000 K has never been investigated.

The composition of white dwarf atmospheres is not yet certain even in the disk and certainly is unknown in the halo. The halo white dwarfs are likely to come from Population III, zero-metallicity stars, with a very different IMF than that which produced Population II stars, and are
much dimmer and cooler than any disk population of white dwarfs. Any hydrogen that is accreted from the disk interstellar medium may be pressure ionized at low temperatures, may not affect the total opacity, and may thus be invisible (Bergeron et al. 1997). (Note that a star that has a mixture of hydrogen and helium in its atmosphere behaves more like a helium white dwarf.) The metallicity can play an important role in determining the atmospheric composition, as illustrated by Iben & MacDonald (1986) for Population II stars. The halo white dwarfs are older, have lower metallicity precursors, and come from a different IMF than the disk white dwarfs. We feel that it is necessary to investigate both hydrogen and helium atmospheres for the dim halo white dwarfs. Our most important result will be our lower limit for the age of pure helium-atmosphere white dwarfs, since these white dwarfs cool the most slowly and hence have the lowest possible ages.

Oswalt et al. (1996) have recently illustrated that if the observed disk population of faint white dwarfs possesses predominantly hydrogen atmospheres, then the oldest observed disk dwarfs are several billion years older than currently assumed (i.e., \( t_{\text{disk}} \approx 13 \) Gyr as opposed to \( t_{\text{disk}} \approx 10 \) Gyr). Differences in bolometric corrections appropriate to the two atmospheric classes will exacerbate this age effect at the very low temperatures associated with halo dwarfs fainter than \( M_V \approx 16 \). In order to explore the broad effect of hydrogen-dominated atmospheres, we adopt the approximation that faint white dwarfs containing a thin hydrogen atmosphere above a helium mantle cool 30% more slowly than the Segretain et al. (1994) models, which have pure helium atmospheres (M. Wood 1996, private communication).

3. THE INTERPRETATION OF OPTICAL OBSERVATIONAL SURVEYS

In this section we discuss in detail how the LDM and HDF surveys can be used to constrain the true nature of the lensing population. In order to reconcile these two data sets with the MACHO data properly, several subtleties must be taken into account. These include bolometric corrections to observed \( V \), \( R \), and \( I \)-band magnitudes, and the oft-neglected proper-motion cutoff present in the LDM survey.

3.1. Bolometric Corrections

Bolometric corrections provide a basis of comparison between model LFs, most naturally expressed as bolometric (total) luminosity (\( M_{\text{bol}} \)), and observations made through specific bandpass filters. The HDF exposure was made in the \( I \) band; the original Luyten Half-Second Catalogue (Luyten 1979) (on which the LDM study is partially based) had an \( R \)-band magnitude limit; LDM’s follow-up photometry was done in the \( V \) band. Bolometric corrections are therefore necessary for our analysis.

With the usual definition,

\[
M_{(I,R,V)} = M_{\text{bol}} - BC_{(I,R,V)},
\]

(3.1)
a negative bolometric correction implies a larger value for \( M_{(I,R,V)} \) and hence an object that appears less luminous in the frequency band of interest. A conservative analysis (i.e., an analysis that obtains a conservative lower limit on white dwarf ages) should therefore adopt the most negative estimate of a particular bolometric correction.

LDM adopted two extreme bolometric corrections to bracket the range of possibilities for their dimmest white dwarfs (which they assumed had helium atmospheres). For a subset of their stars, they had measurements of both \( M_V \) and \( T_{\text{eff}} \). To produce a lower bound on the relevant bolometric correction, they assumed that the white dwarfs in this subset were blackbodies and then used the known values of \( T_{\text{eff}} \) and \( M_V \) to derive bolometric magnitudes. From the resulting plot of \( M_{\text{bol}} \) versus \( M_V \), they obtained the following relation:

\[
M_{\text{bol}} = -19.55 + 3.847M_V - 0.1042M_V^2.
\]

(3.2)

This fit is accurate for the range of magnitudes exhibited by the stars in their sample, but it cannot be extended beyond \( M_{\text{bol}} = 16 \) (the solution for \( M_V \) in eq. [3.2] becomes imaginary). As an upper bound to the bolometric correction for helium atmospheres, LDM adopted \( M_{\text{bol}} = M_V \) that is, in this case they took a zero value for the bolometric correction.

Bergeron, Saumon, & Wesemael (1995) have recently improved the estimation of bolometric corrections by computing new hydrogen- and helium-dominated white dwarf model atmospheres. Unfortunately their models only extend down to temperatures of 4000 K, whereas the bulk of the lensing population of halo dwarfs should have temperatures ranging between 2000 and 4000 K. We thus need to make conservative estimates of the bolometric corrections in this low-temperature regime in order to help put a firm lower bound on the age of the halo population.

3.1.1. Bolometric Corrections for Helium Atmospheres

The opacity in cool helium white dwarf atmospheres is dominated by \( \text{He}^{-} \) absorption. However, in a zero-metallicity, pure helium atmosphere, the free electrons required to make \( \text{He}^{-} \) are scarce. In the limit of a vanishing \( \text{He}^{-} \) fraction, the next largest opacity source is a very weak Rayleigh scattering (Bergeron et al. 1995). The essential point is that cool helium atmospheres have very low opacity, which causes white dwarfs with pure helium atmospheres to cool relatively quickly.

Since \( \text{He}^{-} \) opacity is largely frequency independent, one expects that, to first approximation, the spectrum of a pure helium atmosphere will resemble a blackbody distribution. Therefore, for pure helium atmospheres with \( T < 4000 \) K, we adopt blackbody bolometric corrections (Allard 1990) with a multiplicative “safety” factor of 0.8:

\[
BC_{\text{He}}(T_{\text{eff}}) = BC_{\text{bb}}(0.8T_{\text{eff}}).
\]

(3.3)

The multiplicative factor ensures that we are underestimating the bolometric correction and placing a conservative lower limit on the halo age. We will also make calculations for blackbody bolometric corrections (without the correction factor of 0.8), since these are more likely to be representative of a helium atmosphere. The differences in our results will illustrate the range of uncertainty that comes from the fact that there are still no calculations of model atmospheres for such cool white dwarfs.

3.1.2. Bolometric Corrections for Hydrogen Atmospheres

Saumon et al. (1994) have published models of zero-metallicity, red dwarf atmospheres that span the 2000–4000 K temperature range. In the Saumon et al. (1994) models, strong \( \text{H}_2 \) absorption in the infrared forces the bulk of the radiation to emerge in the \( R \) and \( I \) bands. The far-infrared

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4 All BCs were defined so that \( M_{\text{bol}}(\odot) = 4.72 \).
absorption becomes more significant for cooler atmospheres as more H$_2$ is formed and as the blackbody peak moves into the far infrared, with the odd result that, as the temperature drops, the peak of the emission spectrum moves to higher frequencies. Very dim zero-metallicity red dwarfs therefore radiate quite efficiently in the $R$ and $I$ bands. In the Saumon et al. (1994) models, as the surface gravity is raised by 2 orders of magnitude, the atmospheres radiate more and more efficiently in the $R$ and $I$ bands and become less like blackbody atmospheres. Therefore, we expect hydrogen-atmosphere white dwarfs, which have surface gravities approximately 3 orders of magnitude larger than the highest gravity Saumon et al. (1994) models, to emit an even higher proportion of their radiation in the $R$ and $I$ bands, exactly the bands of the observations. We thus choose to adopt the bolometric corrections appropriate to the Saumon et al. (1994) red dwarf atmospheres as the lower limits to the corrections appropriate to high-surface-gravity white dwarfs. As shown in Figure 2 (in which all of our bolometric correction estimates are plotted) red dwarf bolometric corrections are less than the white dwarf bolometric corrections in the region of overlap, $4000 \, \text{K} < T_{\text{eff}} < 5000 \, \text{K}$, and it is encouraging that the red dwarf and hydrogen white dwarf atmospheres show a similar trend of behavior in this regime.

Since white dwarf atmospheres have a surface gravity 3 orders of magnitude higher than the red dwarf atmospheres that we use, it is possible that new physics will govern the white dwarf hydrogen atmospheres. In this case, we expect their bolometric corrections to be very different from the red dwarf bolometric corrections that we have adopted. We reserve the right to alter our conclusions once white dwarf atmospheres of this low temperature have been calculated.

We do wish to emphasize, however, that the lower age limits obtained from the pure helium-atmosphere white dwarfs discussed in § 3.1.1 are firm; our estimates of bolometric corrections for the case of helium atmospheres that are discussed in § 3.1.1 are extremely conservative and the age limits for helium-atmosphere white dwarfs are expected to become more constrained in the future.

White dwarfs with hydrogen-dominated atmospheres are far more detectable than dwarfs with helium atmospheres. The strong H$_2$ absorption keeps the opacity of the hydrogen-atmosphere white dwarfs relatively high and thus forces them to cool relatively slowly. Thus hydrogen dwarfs are inherently brighter. In addition, as discussed above, they also emit their radiation preferentially in the frequency bands to which the surveys are sensitive. Since hydrogen-atmosphere dwarfs are so much easier to see, the limit that we can place on the number density of these stars is considerably more severe. In order to be in agreement with the observed paucity of white dwarfs in the HDF and LDM data, hydrogen dwarfs would have to be very old, as discussed below. In fact the brightness difference between hydrogen and helium white dwarfs leads to an astounding difference of more than 8 Gyr in the inferred age of a population.

3.2. The Effective Volume of the LDM Luminosity Function

LDM culled their LF from a survey of high proper-motion stars carried out by Luyten (1979). The Luyten survey was sensitive to stars with $R$ magnitudes brighter than 18 and proper motions in the range $0'8 < \mu < 2'5$ (Liebert et al. 1979). In order to minimize computer time, very high proper motion stars with $\mu > 2'5$ were not cataloged.

The velocity bias present in the Luyten (1979) survey has little consequence for the LF of disk white dwarfs. As a result, it has been scantily documented. For a high-velocity halo population, however, it is significant. The proper motion cutoff in Luyten’s survey implies that the tangential velocity of a white dwarf detected by the survey must be

$$V_{\text{tan}} < 121 \, \text{km s}^{-1}(d \, \text{10 pc}^{-1}).$$

Thus a white dwarf with a typical halo tangential velocity of 270 km s$^{-1}$ must be at least 22 pc away to have been registered in the survey. This distance corresponds to $M_R = 16.4$, since the maximum distance a star with absolute magnitude $M_R$ can be seen is $d_{\text{max}} = 100.2 \, (18 - M_R) + 1 \, \text{pc}$. If we assume blackbody atmospheres, we have very roughly $(V-R) \sim 1$ so that the corresponding visual magnitude is $M_V < 17$. Thus the velocity bias against high-velocity stars in the LDM survey becomes significant at $M_V \sim 17$, while some of the white dwarfs predicted by the Adams & Laughlin (1996) LF have magnitudes down to $M_V \sim 18$. Because of the upper limit on the proper motions, a significant number of the white dwarfs predicted by the previously described model LFs would have been missed by the LDM survey.

To assess the degree of incompleteness introduced by the proper-motion cutoff, we have calculated the effective volume probed by the Luyten (1979) survey. Effective volume is defined to indicate the actual volume probed,
weighted by the probability that a halo star will have a sufficiently low proper motion to appear in the survey; i.e.,

$$V_{\text{eff}}^{\text{LDM}} = \int_{x \in \text{(vol)}} d^3 x P(x) ,$$

(3.5)

where (vol) is the northern third of the sky, to a distance $d_{\text{max}}$, which is a function of luminosity. $P(x)$ is the probability that a halo star at location $x$ would have the appropriate proper motion,

$$P(x) = \int_{0.8 < \mu(x, v) < 2.5} d^3 v Q(v) .$$

(3.6)

Here $Q(v)$ is the probability density that a halo star has velocity $v$. We assumed that the local halo stars have an isotropic Maxwellian velocity distribution with a dispersion $\sigma_v = 270$ km s$^{-1}$, and that the Sun moves through this distribution with a velocity $v_\odot = 220$ km s$^{-1}$. $\mu(x, v)$ is the proper motion, $\mu_x / |x|$. The analysis of et al. was sensitive to stars in the magnitude range $24.6 < I < 26.3$, where the bright cutoff was made to avoid a foreground contamination of the sample by disk stars. (The discarded volume constituted only 10% of the total sample volume.) Within their sample, Flynn et al. (1996) found one stellar object with $(V-I) \approx 1.32$ and $I \approx 23.71$. They saw none that were either redder or dimmer. If the single detected starlike object is a white dwarf with a helium atmosphere, the atmospheric models of Bergeron (1995) indicate an effective temperature of 4050 K. For a 0.6 $M_\odot$ white dwarf, this corresponds to a luminosity of $\log (L/L_\odot) = -4.0$.

Although the HDF survey probes far deeper than the Luyten survey, its 4.4 arcmin$^2$ field of view is much smaller. Employing both hydrogen and helium $I$-band bolometric corrections, we computed the maximum and minimum distances surveyed as

$$d_{\text{min}}^3 = 10^{0.2(M_I - I_{\text{min}}) + 1} \text{ pc} ,$$

(3.7)

and calculated the effective volume of the HDF search as

$$V_{\text{HDF}} = (\Omega/3)(d_{\text{max}}^3 - d_{\text{min}}^3) ,$$

(3.8)
for a range of white dwarf bolometric luminosities. The results are shown in Figure 3.

As mentioned above, the surveys are much more sensitive to white dwarfs with hydrogen-dominated atmospheres. For hydrogen atmospheres, the LDM survey is always much more sensitive than the HDF. For the more likely case of helium atmospheres, the LDM survey is more sensitive than the HDF search for luminosities roughly greater than \( \log L_L \) despite the proper-motion limit, while HDF is more sensitive at lower luminosities. (The exact location of the transition depends on the age of the halo population.)

We are now able to take both the LDM and the HDF surveys into account by using the total effective volume searched, \( V_{\text{eff}} = V_{\text{LDM}} + V_{\text{HDF}} \). In § 4, we discuss how the combined survey results, in comparison with model theoretical LFs, can constrain the age of the putative halo population.

4. RESULTS: COMPARISON OF MODEL LUMINOSITY FUNCTIONS WITH OBSERVATIONS

Here we compare the combined observational data from LDM and HDF discussed in § 3 with theoretical model LFs for white dwarfs. The number of stars that should, on average, appear in a sample is

\[
n_{\text{th}} = \int dM_{\text{bol}} \Phi(M_{\text{bol}}) V_{\text{eff}}(M_{\text{bol}}). \tag{4.1}
\]

As discussed in § 2.1, the LFs \( \Phi(M_{\text{bol}}) \) are normalized to give a local halo white dwarf number density \( n_{\text{WD}} \) appropriate to the choice of MACHO fraction \( f \). The \( d_{\text{max}} \) value for the HDF, 2 kpc, is substantially smaller than the radius of the solar circle. Thus, to first order, we can ignore details of the spatial distribution of white dwarfs and work with a single local density \( n_{\text{WD}} \).

As mentioned in § 1, we are employing the absence of dim white dwarfs in the LDM and HDF surveys to determine lower bounds on the age of a white dwarf halo population. If one assumes that the white dwarfs are spatially uncorrelated, then in order to be consistent with a nondetection at the 95% confidence level, the number of dwarfs predicted by a given model LF must be \( n_{\text{th}} \leq 3 \). In this way, equation (4.1) can be used for any model white dwarf LF to restrict the local white dwarf halo density as a function of (1) the age of the white dwarfs, (2) the initial progenitor mass function, and (3) the atmospheric composition. Variations in model LFs depend primarily on these three factors.

Figures 4 and 5 show the minimum age of a white dwarf halo population, \( t_{\text{halo}} \), as a function of local white dwarf halo density \( n_{\text{WD}} \). In these figures, the regions above and to the left of a particular curve are excluded at the 95% confidence level. Excluded models predict at least three stars distributed through the effective volume of the LDM and HDF surveys. Figure 4 shows our results when we use a lognormal IMF (following Adams & Laughlin 1996) for the main-sequence progenitors as motivated by star formation theory. In Figure 5, on the other hand we used delta-function mass functions. In both figures, we show the results obtained with both helium and hydrogen atmospheres. In obtaining these figures, we have used the cooling curves of Segretain et al. (1994). In both figures, alternate cooling models without C/O fractionation would make all age limits younger by 2 Gyr.

Since we are investigating the consequences of white dwarfs providing an explanation for the MACHO data, as our lower limit for the MACHO fraction we take \( f > 0.1 \) (i.e., MACHOs make up at least 10% of the halo). We take the total local density of the halo to be \( 10^{-2} M_\odot \) pc\(^{-3} \). In Figure 4, with the lognormal IMF, we then find that the youngest allowed age for the white dwarfs is \( \approx 13 \) Gyr. This minimum age is obtained for the case of helium atmospheres with blackbody bolometric corrections containing the “safety factor” (eq. [3.3]). Using the less conservative, but more likely, blackbody bolometric correction without the “safety factor,” we find that the minimum age rises to 14 Gyr. If the local halo white dwarf density were as high as \( 3 \times 10^{-2} M_\odot \) pc\(^{-3} \), which is near the midpoint of the MACHO results (\( \approx 30\% \) of the local halo density), the minimum age rises further to 15.5 Gyr. Our minimum age is younger than what appeared to be allowed in Chabrier et al. (1996), who obtained 18 Gyr halo ages for \( f = 0.25 \) as the approximate lower limit on the white dwarf age (in the text of their paper, Chabrier et al. 1996 obtained a minimum age of 16 Gyr for \( f = 0.08 \)). The surprisingly low minimum age that we find (notice the discrepancy with other authors) is a consequence of (1) admitting MACHO fractions as low as \( f = 0.1 \) to be marginally consistent with the lensing result, (2) the proper motion limit in the Luyten Survey, (3) conservative bolometric corrections, and (4) the statistical process...
of excluding models at the 95% confidence level. Nevertheless, the general result of Figure 4 is still suggestive of a white dwarf halo age commensurate with the age of the globular clusters, as discussed below.

Figure 5 shows how the limits on $\rho_{WD}$ and $t_{\text{halo}}$ depend on the form of the progenitor IMF. We have again plotted the allowed halo age as a function of local halo white dwarf density, and in this plot we have assumed $\delta$-function IMFs for the white dwarf progenitors. As before, we have considered the two cases of helium and hydrogen atmospheres. Specifically, we have assumed that all white dwarf progenitor stars in the sample had the same initial masses, $M = 1.0$, 1.5, 2.0, 3.0, 4.0, 5.0, and 6.0 $M_\odot$. Such extremely sharp IMFs are of course unrealistic. However, our results do illustrate that the surveys are not particularly sensitive to higher mass, cooler white dwarfs, while being extremely sensitive to white dwarfs of initial mass $1-1.5 M_\odot$. Thus, an IMF weighted toward these low-mass stars is the most constrained. For example, helium-atmosphere white dwarfs from $1 M_\odot$ progenitors must be older than about 18 Gyr if they are to contribute 10% of the local halo density and still be consistent with the combined survey results. On the other hand, it is quite clear that an IMF weighted almost entirely toward high-mass initial stars is consistent with a younger halo. As seen in Figure 5, if all the main-sequence progenitors of the white dwarfs initially were 6 $M_\odot$ stars with helium atmospheres, then the halo could be less than 12 Gyr old. Discussion of these age limits with possible cosmological implications is presented in the § 5.

Both Figure 4 and Figure 5 emphasize that white dwarfs with hydrogen atmospheres (or at least with atmospheres whose bolometric corrections are similar to those we have adopted) cannot provide more than a few percent of the mass of the halo. Here we have taken 18 Gyr as the upper limit on the age of the Galactic halo, since this is the oldest possible age of globular clusters (Chaboyer et al. 1996). As discussed earlier in the text, hydrogen-atmosphere white dwarfs are much brighter than those with helium atmospheres and are thus far more constrained. Hence our results suggest that if white dwarfs are indeed present at the level suggested by the MACHO survey, the majority must have helium atmospheres. To reiterate, the absolute lower limit on the age of the white dwarfs is provided by the pure helium-atmosphere white dwarfs; these lower limits will potentially be revised upward in the future as uncertainties are reduced.

4.1. A Note on Uncertainties

Uncertainties in the white dwarf ages come from a number of factors. We have tried to be very careful to take into account the three factors that lead to the biggest uncertainties: the nature of the white dwarf atmospheres, the bolometric corrections, and the progenitor IMF. As we have seen, hydrogen atmospheres in the white dwarfs lead to ages that are larger than those for helium atmospheres by more than 8 Gyr. The IMF leads to at least several Gyr of uncertainty, as indicated by the $\delta$-function IMF exercise shown in Figure 5. For helium atmospheres, we have compared blackbody bolometric corrections with and without the safety factor of 0.8 and have seen that this imparts about 1 Gyr of uncertainty. Here we have been extremely conservative in allowing such a large safety factor, which leads to ages 1 Gyr younger.

As mentioned previously, there may be uncertainty associated with the white dwarf cooling theory; this uncertainty is $\sim 1$ Gyr. In obtaining the figures we have used the models of Segretain et al. (1994); alternate models without chemical fractionation lead to minimum ages that are 2 Gyr younger. The initial/final mass relation imparts less than 0.5 Gyr of uncertainty. This additional source of uncertainty has therefore not been added into our final numbers.

5. Discussion

The second year MACHO events give a very provocative result. If a lensing population of dim white dwarfs really accounts for a substantial fraction of the missing halo mass, there are ramifications of tremendous interest to cosmology, Galactic evolution, star formation, and white dwarf physics. As a test of this white dwarf interpretation of the MACHO data, we have considered the implications of non-detections of white dwarfs inoptical searches of the HDF (Flynn et al. 1996) as well as the ground-based survey of LDM. As long as MACHOs are indeed white dwarfs that make up 10% of the local halo density, we are able to conclude that (1) the halo must be at least 10 Gyr old (probably at least 14 Gyr) and (2) the halo white dwarfs are likely to have helium dominated atmospheres.
5.1. Cosmological Implications

These ages are consistent with the ages of the oldest globular clusters in the Galaxy, 11.6–18.1 Gyr (95% confidence; Chaboyer et al. 1996). Observations of halo white dwarfs provide an important and largely independent estimate of the age of the Galactic halo and hence a lower bound of the age of the universe. Such an old Galaxy is difficult to reconcile with the Hubble age of the universe. For a Hubble constant \( H_0 = 100 \) km s\(^{-1}\) Mpc\(^{-1}\), in a flat, matter-dominated universe without a cosmological constant,

\[
t_0 = 2/3H_0^{-1} = 6.5 \, \text{h}^{-1} \, \text{Gyr}
\]

For an age limit \( t_0 > 12 \) Gyr, we have \( h < 0.55 \). For a stronger age limit of 14 Gyr, we have \( h < 0.46 \).

There are several competing observations of the Hubble constant. Madore et al. (1996) measured the distance to Cepheids in the Fornax Cluster using the Hubble Space Telescope (HST) and derived \( 0.63 < h < 0.97 \). Measurements of Type Ia supernovae have set the Hubble constant to be \( 0.6 < h < 0.74 \) (Riess, Press, & Kirshner 1995). On the other hand, Tammann et al. (1997) have also measured distances to Cepheids in the Virgo Cluster with HST and have derived a value \( 0.45 < h < 0.65 \). Measurements of time delays in a gravitationally lensed quasar yield estimates for \( h \) (for \( \Omega = 1 \)) of 0.63 ± 0.12 (Kundic et al. 1997).

Only the low range of these values of \( h \) is consistent with an age limit of 12 Gyr. If \( h > 0.6 \), and if our estimate of the local halo white dwarf density is correct, we would be forced to abandon the standard, flat, matter-dominated cosmology. One possible alternate cosmology is an open universe, in which the factor of \( \frac{\Omega}{2} \) in equation (5.1) is closer to unity. For a lower limit of 12 Gyr, \( h < 0.67 \) is required for \( \Omega = 0.3 \), and \( h < 0.83 \) is required for \( \Omega = 0 \). These higher values of \( h \) are somewhat easier to reconcile with all the data. A cosmological constant might also imply an older universe.

5.2. Other Implications of, and Problems with, a White Dwarf Halo

5.2.1. Chemical Evolution

A large halo white dwarf population would affect the chemical evolution of the Milky Way. The primary difficulty with the hypothesis that the lensing MACHOs are white dwarfs appears to lie with the copious quantities of enriched gas that the stars that were formed in an early wave of star formation would later have deposited into the interstellar medium. Stars that become white dwarfs change the chemical composition of the interstellar medium. A 2 \( M_\odot \) star will become a 0.6 \( M_\odot \) white dwarf, spitting out 70% of its mass in the form of hot, helium-rich, carbon- and nitrogen-rich, deuterium-depleted gas. This gas has long been used to place limits on white dwarfs as baryonic dark matter candidates (see Carr 1994 for a review; also see Smecker & Wyse 1991). In addition, a recent chemical evolution study carried out by Gibson & Mould (1997) shows that the nucleosynthetic yield of a Population III halo white dwarf precursor population would produce a CNO abundance ratio of \([C, N/O] \approx +0.5\), which stands in stark disagreement with the \([C, N/O] \approx -0.5\) ratio observed in present-day halo stars (Timmes, Woosley, & Weaver 1995).

It appears that a large quantity of the enriching gas would have to have been driven from the halo in order to explain current Population II abundance ratios; i.e., the “closed box” model of the Galaxy would have to be abandoned. Such scenarios for ejecting metals from the Galaxy have been outlined by Scully et al. (1996) and Fields, Matthews, & Schramm (1996). It is also intriguing to note that studies of chemical evolution in rich clusters of galaxies suggest that these galaxies had an early burst of star formation that produced high-mass stars (e.g., Elbaz, Arnaud, & Vangioni-Flam 1995). According to these models, supernovae from these high-mass stars generated a Galactic wind that blew most of the metals out into the intergalactic medium.

5.2.2. Ionizing the Intergalactic Medium

The light from all the white dwarf progenitors would also help ionize the intergalactic medium and could thus contribute to an understanding of the Gunn-Peterson test (Gunn & Peterson 1965), which showed a dearth of background neutral hydrogen. Miralda-Escudé & Ostriker (1990) and Giroux & Shapiro (1996) showed that the light from even the disk population of stars can make a significant contribution to the ionization of the intergalactic medium. The additional light from a large, high-initial-mass halo population of white dwarf progenitors would make a much greater contribution to the ionization than the disk population alone.

5.2.3. Light Emitted by High-Redshift Galaxies

The large population of halo white dwarfs would have been very bright when it was composed of main-sequence stars and should dominate the light emitted by high-redshift galaxies. It may be that the detected excess population of distant blue galaxies (Tyson 1988) is due to the light emitted during the main-sequence phase of what later became white dwarf MACHOs. Charlot & Silk (1995) examined the evolution of light emitted by white dwarf halos and found that for most of their models they predicted dimmer galaxies than are observed. New and higher quality data on the LFs of high-redshift galaxies is pouring in. For example, Steidel et al. (1996) found a population of blue star-forming galaxies at redshift \( z = 3 \). The contribution of the white dwarf progenitors to the light of high-redshift galaxies will remain an interesting subject.

5.3. A Case in Which our Bounds Would Not Apply

The only way to have white dwarfs younger than the bounds presented in our paper is to have white dwarfs that are more massive than about 1.2 \( M_\odot \), a mass range not yet probed by the microlensing experiments. In that case, quantum effects (Chabrier 1993; Hansen 1997) due to the zero energy of protons may take place even in the fluid stage before crystallization. This effect would speed up cooling so that it would be easy to hide white dwarfs even if they were quite young. Again, this effect is only possible for white dwarfs that are close to the Chandrasekhar limit in mass and does not apply to current microlensing experiments.

5.4. Proposed Improvements

Our main goal in this paper was to reevaluate the age limits on the halo population. A significant new aspect of our analysis is the specific recognition of the importance of the velocity bias in the LDM survey. The result of this bias is that the LDM survey places considerably less strict limits...
on the number of dim white dwarfs than previously believed. Indeed, the effect of the bias is so important that it renders the LDM survey less sensitive than the HDF for luminosities below \( \log (L/L_\odot) = -4.8 \). At white dwarf luminosities of \( \log (L/L_\odot) = -5.0 \), the bias reduces the effective LDM search volume by nearly a factor of 10.

There is still a great deal of room for progress in the art of limiting the density of halo white dwarfs, both theoretically and observationally. Because of its proper-motion biases, the Luyten survey used by LDM was clearly not an ideal place to search for a population of halo white dwarfs. However, a new survey could quite feasibly be done with ground-based telescopes. Modern CCDs are sensitive in the infrared where Luyten’s survey was not, and one could easily search for stars with proper motions greater than \( \mu = 2.5 \, \text{yr}^{-1} \). Although such a search would not necessarily go deep as the HDF survey, it could potentially cover 4\( \pi \) sr arcmin\(^{-2} \) of 3.4 \( \times 10^7 \) times as much solid angle. We mention here three such searches that are ongoing or proposed: Lidman et al. (1998) observed and are now processing 3 deg\(^2\) down to \( I = 22 \). The EROS team is presently observing 200 deg\(^2\) down to \( I = 21 \). A very promising survey has been proposed as a project to be undertaken with the forthcoming Subaru 8 m telescope (C. Alcock, 1996 private communication), which would observe a large area of the sky in the \( V \) and \( I \) bands down to limiting magnitude of 29 or 30.

Beyond possibly explaining the lensing results, the optical identification of exceedingly dim white dwarfs in a deep proper motion survey of this type would be of great importance. From a purely astronomical point of view, these would be the oldest, coolest white dwarfs yet seen. They would allow us to test white dwarf cooling theory into the Debye crystallization regime and calibrate models of extremely cool white dwarf atmospheres.

While there has been recent progress in extending white dwarf cooling curves down to very low temperatures, the computation of very cool, frequency-dependent white dwarf atmosphere models has lagged considerably. Now that the microlensing searches suggest that a hitherto undetected population of very cool white dwarfs is lurking in the Galactic halo, new atmosphere models are needed for temperatures cooler than 4000 K. As can be seen by comparing the blackbody curve with our conservative helium-atmosphere curve in Figure 4, uncertainty in the bolometric correction adds about 1 Gyr of uncertainty to the interpreted age of a population of white dwarfs. A project is currently underway by D. Mérar & F. Allard (1996, private communication) to generate these cool model white dwarf atmospheres. The peak emission of these cool white dwarfs is in the infrared; the exact peak wavelength of emission depends on the white dwarf and properties and will be easier to predict once theoretical advances occur in understanding white dwarf atmospheres and bolometric corrections.

5.4.1. Binaries

Another possibility for refining the theoretical model LFs is to take into account binary systems; the white dwarfs may have binary companions. Roughly half of Population I stars are in binary systems; thus it is plausible that some fraction of the halo white dwarf stars may also be in binary systems. (Of course, the halo white dwarf stars we are considering here come from a very different IMF than do the Population I stars; thus the binary distribution could also be different.) In order to examine how much binaries can change our final result, we have considered the extreme case in which all white dwarfs have unresolved binary companions and both companions are identical. Each unresolved binary acts like a “star” that is twice as bright as the luminosity of the component stars. In a pure magnitude-limited sample, doubling the luminosity increases the volume searched by a factor of \( 2^{3/4} \). Because of the velocity biases of the LDM survey, the volume actually increases somewhat faster in that survey; it increases by a factor roughly of 4. Since these binary systems are theoretically expected to be brighter at a given age, they must be older to have escaped detection. On the other hand, each binary system has twice the mass of a single star, so that half as many are needed to account for the local halo white dwarf mass density. Thus a MACHO density that is 10% of the halo could be accounted for by a density of white dwarf binary system that is only 5% of the halo. When we redid our calculations using this extreme binary model, we found that the lower limits on ages increased by about 0.6 Gyr.

Some of these binary systems may be in very close orbits. Such a population may cause Type Ia supernovae (SNe Ia). Smeecker & Wyse (1991) estimated the SN Ia rate from a halo full of binary white dwarfs and concluded that their models predicted 100s of times too many SNe Ia. While theirs is a severe constraint when it applies, their assumptions about mass loss, orbital radius, and binary fraction may not apply to a zero-metallicity population. Gravitational radiation from a population of close binaries would be detectable with the proposed Omega experiment.

5.5. Conclusion

Our work was motivated by microlensing measurements that suggest that MACHOs have masses consistent with the fact that they are white dwarfs. Of course it is always possible that the MACHOs that are being seen are in fact different objects entirely; however, in this paper we examined the possibility of a substantial white dwarf halo. In conclusion, we have found an age constraint on white dwarfs that are candidates for explaining the microlensing events. If white dwarfs comprise at least 10% of the halo of the galaxy then, with extreme parameters, the minimum age we obtain for the white dwarf population is 10 Gyr. With more likely parameters and up-to-date cooling curves, the white dwarfs must be at least 14 Gyr old to be marginally consistent with the joint results of the LDM, HDF, and MACHO surveys. We used the recent theoretical cooling curves of Segretain et al. (1994) and considered a variety of progenitor IMFs, bolometric corrections, and atmospheric compositions to come to this conclusion. Analysis of the effects of the velocity bias in the LDM survey also played a significant role in our results. Potentially the most serious problem with a white dwarf halo lies with the enriched gas the progenitors would have produced.

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