Chemical Abundance Constraints on White Dwarfs as Halo Dark Matter

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ABSTRACT

We examine the chemical abundance constraints on a population of white dwarfs in the Halo of our Galaxy. We are motivated by microlensing experiments which have reported evidence for massive compact halo objects (Machos) in the Halo of our Galaxy, with an estimated mass of \((0.1 - 1)M_\odot\); the only conventional dark astrophysical candidates for objects in this mass range are white dwarfs. However, our work constrains white dwarfs in the Halo regardless of what the Machos are. We focus on the composition of the material that would be ejected as the white dwarfs are formed. This material would bear the signatures of nucleosynthesis processing, and contain abundance patterns which can be used to constrain white dwarf production scenarios. Using both analytical and numerical chemical evolution models, we confirm previous work that very strong constraints come from Galactic Pop II and extragalactic carbon abundances. We also point out that in some cases, depending on the stellar model, significant nitrogen is produced rather than carbon. The combined constraints from carbon and nitrogen give \(\Omega_{WD}h \lesssim 2 \times 10^{-4}\) from comparison with the low abundances of these elements measured in the Ly\(\alpha\) forest. We note, however, that these results are subject to uncertainties regarding the nucleosynthetic yields of low-metallicity stars. We thus investigate additional constraints from the light elements D and \(^4\)He, the nucleosynthesis of which is less uncertain. We find that these elements can be kept within observational limits only for \(\Omega_{WD} \lesssim 0.003\) and for a white dwarf progenitor initial mass function sharply peaked at low mass (\(2M_\odot\)). Finally, we consider a Galactic wind, which is required to remove the ejecta accompanying white
dwarf production from the galaxy. We show that such a wind can be driven by Type Ia supernovae arising from the white dwarfs themselves, but find that these supernovae also lead to unacceptably large abundances of iron. The only ways we know of to avoid these constraints are that (1) the ejecta from low-metallicity Macho progenitors are absent or completely unprocessed; or (2) the processed ejecta remain as hot ($\gtrsim 0.3$ keV) gas which is segregated from all observable neutral material to a precision of $\gtrsim 99\%$. Aside from these loopholes, we conclude that abundance constraints exclude white dwarfs as Machos.

*Subject headings:* dark matter — MACHOs
1. Introduction

The nature of the dark matter in the haloes of galaxies is an outstanding problem in astrophysics. Over the last several decades there has been great debate about whether this matter is baryonic or must be exotic. Many astronomers believed that a stellar or substellar solution to this problem might be the most simple and therefore most plausible explanation. However, recent analysis of various data sets has shown that faint stars and brown dwarfs probably constitute no more than a few percent of the mass of our Galaxy (Bahcall, Flynn, Gould, and Kirhakos 1996; Graff and Freese 1996a; Graff and Freese 1996b; Mera, Chabrier, and Schaeffer 1996; Flynn, Gould, and Bahcall 1996; Freese, Fields, and Graff 1999). Hence the only surviving stellar candidates of known populations are stellar remnants. In this paper we consider severe constraints on white dwarf stellar remnants. The situation for neutron stars is probably even more restrictive. If indeed stellar candidates are ruled out, one may be forced to more exotic nonbaryonic halo dark matter.

We have been particularly motivated to consider white dwarfs as Halo dark matter by recent results from microlensing experiments (Alcock et al. 1997a; Renault 1997), which have reported evidence for Massive Compact Halo Objects (Machos) in the Halo of our Galaxy. White dwarfs have been identified as plausible Macho candidates because of the best-fit Macho mass of \((0.1 - 1) \, M_{\odot}\). While some of our results are presented in the context of a possible Macho interpretation, our chemical abundance results constrain a white dwarf population in the Halo regardless of what the Machos are.

In a previous paper (Fields, Freese, and Graff 1998), we discussed the baryonic mass budget implied by a Galactic Halo interpretation of the LMC Macho events. We found that a simple extrapolation of the Galactic population (out to 50 kpc) of Machos to cosmic scales gives a cosmic density \(\rho_{\text{Macho}} = (1 - 5) \times 10^9 \, f_{\text{gal}} \, h \, M_{\odot} \, \text{Mpc}^{-3}\), which in terms of the critical density corresponds to

\[
\Omega_{\text{Macho}} = (0.0036 - 0.017) h^{-1} f_{\text{gal}}. \tag{1}
\]

Here the factor \(f_{\text{gal}} \geq 0.17\) is the fraction of galaxies that contain Machos, as we argued in Fields, Freese, and Graff 1998, and \(h\) is the Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\). This estimate applies regardless of the nature of the Machos, and shows that Machos (if indeed they are in the Galactic Halo) are a significant fraction of all baryons. Similar results have been obtained by Steigman & Tkachev (1999).

If one assumes—as we will hereafter—that the Machos are white dwarfs, then stronger constraints result. In particular, since white dwarfs are stellar remnants, their formation necessarily requires both the formation of progenitor stars, and ejection of the bulk of the progenitor mass when the white dwarf is formed. The simple requirement that the formation of white dwarfs is accompanied by the release of at least as much mass in the form of hot gas ejecta has profound consequences which constrain white dwarfs as Machos. For example, including progenitors in the Macho mass budget increases the cosmological density of material needed to
make Machos. If Machos are white dwarfs resulting from a single burst of star formation (without reprocessing of ejecta gas), then their main sequence progenitors would have been at least twice more massive: \( \Omega_\star \geq (0.007 - 0.034)h^{-1}f_{\text{gal}} \). Accounting for ejecta mass also has implications on the scale of our Galaxy. The gaseous ejecta produced along with the Galaxy’s Machos would have had a mass larger than what is measured in the known stellar and gaseous components of the Galaxy. Thus, mass budget considerations demand that most of the ejecta left the Galaxy, which in turn requires some kind of Galactic wind to remove it.

The ejecta produced by the white dwarf progenitors lead to constraints not only due to their mass, but also due to their composition. The latter is the focus of this paper: chemical abundance constraints on white dwarfs as Halo dark matter. The ejecta contain the products of nucleosynthesis–enrichment of some elements, depletion of others–which become signatures of white dwarf formation. We will show that current models for low-mass stellar nucleosynthesis predict a degree of processing which is so severe that it rules out white dwarf Machos.

The most powerful constraints on white dwarfs as halo dark matter come from carbon and nitrogen. However, the amount of these produced is also dependent on the stellar model. Hence we also consider the less powerful but unavoidable constraints from the light element abundances, deuterium and helium. We find that \(^4\text{He}\) can be kept within observational limits only for the lowest possible Macho density \( \Omega_{\text{Macho}} \) compatible with Eq. 1, together with high cosmic baryon density, and Macho progenitor initial mass function (IMF) peaked at \( 2M_\odot \) (so that there are very few progenitor stars heavier than \( 3M_\odot \)).

The carbon and nitrogen yields from white dwarf progenitors depend on the IMF of the stars and on the amount of Hot Bottom Burning, and are uncertain for zero metallicity stars. Still, best estimates for these yields are in excess of observations of these elements in our Galaxy (as first discussed for the case of carbon by Gibson and Mould (1997)). Hence a galactic wind would be required to eject these elements from the Galaxy along with the excess mass. We show that such a wind could be driven by Type Ia supernovae, which are produced by the same white dwarfs in binary orbits with other stars. To produce a successful wind, we find that at least 0.5% (by mass) of stars must to explode as supernovae. Such a scenario is reasonable, since a comparable fraction of stars become supernovae in the Disk of the Galaxy, if the star formation rate is \( \sim 1M_\odot/\text{yr} \) and the Type Ia rate is \( \sim 10^{-2}/\text{yr} \) (Tutukov, Yungelson, & Iben 1992). However, gas cooling may be rapid enough to keep the bulk of the ejecta from being evaporated. Furthermore, even if the C and N are ejected from the Galaxy, they are still constrained by extragalactic observations. Measurements of C and N in damped Lyman systems and the Ly\( \alpha \) forest are in excess of what would be produced by a white dwarf Halo. In addition, the Type Ia supernovae overproduce iron.

In Section 2 we discuss white dwarf properties; we discuss the initial mass function of the progenitor stars and the relation between the masses of progenitor stars and the resultant white dwarfs. In Section 3, we present our chemical evolution models which calculate the effect of white dwarf production on D, He, C, and O. In Section 4, we compare the expected chemical abundances
arising from white dwarf production with observed D and He abundances in various systems, and derive constraints on $\Omega_{WD}$; in section 5 we derive constraints from C and N, which in fact is more restrictive. In Section 6, we discuss the requirements for a Galactic wind to remove chemical debris from the Galaxy. We finish with a discussion in Section 7.

2. White Dwarf Properties: IMF and Initial/Final Mass Relation:

**Initial Mass Function:** The progenitor stars of any white dwarf halo had to arise from an initial mass function (IMF) that is strikingly different from any observationally inferred IMF: a white dwarf progenitor IMF must have very few stars less massive than $\sim 1 \, M_\odot$, many intermediate mass stars, and few high mass stars with mass greater than $\sim 8 \, M_\odot$. Adams and Laughlin (1996) argued that the initial masses of halo white dwarf progenitors have 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 $< 1 \, M_\odot$ would still be on the main sequence. The upper bound arises from the fact that progenitor stars heavier than $\sim 8 \, M_\odot$ explode as Type II supernovae, and leave behind neutron stars rather than white dwarfs. We can allow the IMF to have a small contribution to higher masses so that there are some Type II supernovae and corresponding remnant neutron stars, but not so many as to overproduce heavy elements.

Because low mass main sequence halo stars are intrinsically scarce (Bahcall et al. 1996; Graff & Freese 1996a,b), an IMF of the usual Salpeter (1955) type $dN/dm \propto m^{-2.35}$ is not appropriate, as it would imply a gross overabundance of low mass stars in the Halo. Adams & Laughlin (1996) propose a log-normal mass function motivated by Adams & Fatuzzo's (1996) theory of the IMF:

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

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 which gave rise to the present day population of remnants. Possible values of the parameters are $m_C = 2.3 \, M_\odot$ 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.

Stars in the mass range 2-4 $M_\odot$ will produce different abundances of He, C, and N than an IMF with most of the stars in the mass range 4-8 $M_\odot$. Thus we will also examine the effect of narrowly peaked IMFs chosen to highlight the different nucleosynthesis within the $1 - 8 \, M_\odot$ mass range.

**Initial/Final Mass Relation:** The relation between the mass of a progenitor star and the mass of its resultant white dwarf relies on an (imperfect) understanding of mass loss from red giants. We use the results of Van den Hoek & Groenewegen (1997); these are consistent with the results
of Iben & Tutukov (1984). At the progenitor mass limits of interest, we have white dwarf masses $m_{\text{WD}}(1M_\odot) = 0.55 \, M_\odot$, and $m_{\text{WD}}(8M_\odot) = 1.2 \, M_\odot$.

3. Chemical Evolution Calculations

It is our goal to compare light element abundances produced by white dwarf progenitors with the measurements of the these abundances. In this section we describe our approach to evolution calculations to estimate the element abundances arising from MACHO progenitors. First, in Section 3.1, we describe two different extreme approximations to bracket the possible abundances that can arise. This analytic approach is also useful in that it provides insight. Then, in Section 3.2, we discuss the numerical calculations. Below, in Sections 4 and 5, we will apply these calculations to D and He, and then C and N. There we will present the results of our calculations and compare them with observations of these elements.

Chemical evolution calculates the history of gas as it is processed into stars, which ultimately die, leaving remnants and ejecting processed material. Specifically, one calculates the time development of the gas and comoving remnant densities $\rho_{\text{gas}}$ and $\rho_{\text{Mach}}$, as well as the gas density $\rho_{\text{gas},i}$ in each isotope $i$. The abundances $i$ are expressed in terms of mass fractions $X_i = \rho_{\text{gas},i}/\rho_{\text{gas}}$. All of these components change according to star formation and the resulting star death. As initial conditions for all models, we take the baryons to be in gaseous form with density $\rho_B$. We take the primordial composition of elements to be the big bang nucleosynthesis abundances appropriate for the chosen $\rho_B$, $X_i^0 = \rho_{\text{gas},i}^0/\rho_{\text{gas}}^0 = \rho_{\text{gas},i}^0/\rho_B$. Here superscript 0 refers to primordial abundances.

**Homogeneity:** In both analytic and numerical calculations, we assume that at high redshifts the gas exists in a single “homogeneous” chemical phase; i.e., concentrations of various element abundances are independent of spatial position. A corollary of this assumption is that outflow from stars is instantly and evenly mixed with the primordial gas. This approximation allows us to use the average co-moving density of a chemical species as a useful parameter. We will refer to $\rho_B$ as the total co-moving baryon density, $\rho_g$ as the co-moving gas density, $\rho_{\text{WD}}$ as the comoving white dwarf density, $\rho_H$ as the comoving hydrogen density, etc. This picture thus amounts to a universal “post-processing” of baryons that occurs after primordial nucleosynthesis.

In reality some regions are likely to have abundances enhanced over the homogeneous levels, while other regions are likely to have abundances closer to primordial. For example, the numerical simulations of Cen and Ostriker (1999) suggest that the universe is far from being chemically homogeneous: high density regions tend to have higher metallicity than low density regions. If mixing is less efficient than we have assumed, the element abundances inside dense star forming galaxies due to progenitors of white dwarf Machos would be higher than our predictions, while the abundances outside these regions would be lower. Lack of homogeneity makes the measured galactic abundances harder to match and thus more constraining. In the simulations of Cen and Ostriker, the Ly$\alpha$ forest has a metallicity roughly equal to the mean metallicity of the universe.
Thus, these forest lines are representative of the mean metallicity results we calculate in our homogeneous models, and we will use these lines below to compare theory with observation. We do note, however, that a galactic wind which drives material out of galaxies is likely to exist and might be stronger than the one used in the Cen and Ostriker simulations; such a wind drives the system towards homogeneity. One can treat our results as constraints on the efficiency with which the enriched material is segregated from sites of subsequent star formation.

3.1. Abundances obtained with two Analytic Approximations

In this section we present analytic results of chemical abundances obtained with two extreme approximations. We consider two limits relating the star formation time-scale $t_{\text{SFR}}$ to the lifetime of a typical star $t_{\star}$ in our strongly peaked IMF. In the limit where $t_{\text{SFR}} \ll t_{\star}$, or the star burst limit, all the Machos are formed in a short time. Their ejecta mix into the IGM, but are not incorporated into any second generation of Machos. The opposite case where $t_{\text{SFR}} \gg t_{\star}$ is the instantaneous recycling limit. Here several generations of stars are created, and the ejecta from stars of one generation are mixed into the next generations of stars. Within this limit, we can use the instantaneous recycling approximation of chemical evolution which ignores the lifetime of stars. Note that a very efficient wind, which removes ejecta into the IGM as soon as they are produced, would make the recycling case look more like a burst; in this case the ejecta from a star are not mixed into the next generation of stars. These two limits bracket any possible star formation scenario.

3.1.1. Burst Model:

We take the baryons in the universe at any time to consist of three components, with comoving densities:

$$\rho_{\text{B}} = \rho_{\text{gas}} + \rho_{\text{star}} + \rho_{\text{WD}},$$

where subscripts “star” and “Macho” refer to stars and remnant white dwarfs respectively. Initially all the baryons are in gaseous form with different primordial abundances of various species. During the star burst, a fraction $f_{\text{pro}}$ of the gas goes into stars, reducing $\rho_{\text{gas}}$ from its initial density $\rho_{\text{B}}$ by an amount $f_{\text{pro}}\rho_{\text{B}}$. Once the stars die, a fraction $R$ of the progenitor mass is returned as processed gas. Given a white dwarf progenitor IMF $\xi_{\star}(m) = dN_{\star}/dm$, the gas return fraction is

$$R = \frac{\int_{1M_{\odot}}^{\infty} dm' m_{\text{ej}}(m') \xi_{\star}(m')}{\int_{0}^{\infty} dm' m_{\text{ej}}(m') \xi_{\star}(m)},$$

where $m$ is the mass of the progenitor, which upon its death produces a remnant of mass $m_{\text{rem}}$ and ejecta of mass $m_{\text{ej}} = m - m_{\text{rem}}$. Thus, the density of ejected, processed gas is $Rf_{\text{pro}}\rho_{\text{B}}$; there is no further processing of the ejecta. A portion of the progenitor stars is left in the form of white
dwarf Machos. These objects will have a cosmic density \( \rho_{WD} = f_{\text{pro}}(1 - R)\rho_B \). Thus a “white dwarf Macho fraction”

\[
f_{WD} \equiv \rho_{WD}/\rho_B = f_{\text{pro}}(1 - R) \tag{5}
\]

of the baryons is turned into white dwarfs. Note that in the burst scenario, \( f_{WD} \leq (1 - R) < 1 \). In terms of the Macho fraction, the gas density after the burst is just \( \rho_{\text{gas}} = \rho_B - \rho_{\text{Macho}} = [1 - f_{\text{pro}}(1 - R)]\rho_B \) by baryon conservation, and the gas fraction is \( \mu = 1 - f_{WD} = 1 - f_{\text{pro}}(1 - R) \). Hence, after the burst of star formation and the evolution of the stars to stellar remnants has ended, we are left with only gas and white dwarfs on the right-hand side of eqn. (3), with gas fraction \( \mu \) and white dwarf fraction \( f_M \).

**Gas Composition:** The initial gas density in each isotope \( i \) is given by \( \rho_{\text{gas},i}^0 = X_0^i \rho_B \) where \( X_0^i \) is the primordial abundance. As a result of star formation and the subsequent evolution of the stars, the composition of the gas has changed to:

\[
\rho_{\text{gas},i} = \rho_{\text{gas},i}^0 - f_{\text{pro}}X_0^i \rho_B + \rho_{\text{eject}}^i.
\]

The production of stars has lowered \( \rho_{\text{gas},i} \) by an amount \( f_{\text{pro}}X_0^i \rho_B \). The ejecta of these stars once they die has further changed it by \( \rho_{\text{eject}}^i \). The details of this latter quantity depend on the element. In the process of stellar evolution, some gas is turned into helium and some primordial deuterium is destroyed. In the remainder of this section we describe our analysis of specific element abundances in the burst model.

**Deuterium:** All deuterium that passes through a star is destroyed. Thus, \( \rho_{\text{gas},D}^0 = 0 \), and the post-Macho D density is just that in unprocessed material:

\[
\rho_{\text{gas},D} = (1 - f_{\text{pro}})X_D^0 \rho_B.
\]

Thus the deuterium mass fraction \( X_D \) after the burst is

\[
X_D = \frac{1 - f_{WD}/(1 - R)}{1 - f_{WD}} \tag{6}
\]

**Helium:** As our notation we use \( Y \equiv X_4^\text{He} \) to be the abundance of \(^4\text{He}\); we take the initial abundance to be \( Y^0 \). Some of this helium is removed from the Galaxy by Machos, while additional helium is added by the stellar evolution of the white dwarf progenitors. In the case of helium, the ejecta are enriched:

\[
\rho_{\text{gas},\text{He}}^{\text{eject}} = (Y^0R + Y_{\text{He}})f_{\text{pro}}\rho_B,
\]

where the first term is the fraction of the primordial helium that is returned as processed gas after the stars die and the second term is the He production during stellar evolution. The helium yield in the second term,

\[
Y_{\text{He}} = \frac{\int_{M_e/2}^\infty dm \left(m_{\text{ej,He}} - Y^0m_{\text{ej}}\right) \xi_s(m)}{\int_0^\infty dm \xi_s(m)}, \tag{7}
\]

measures the He production, over and above the initial abundance \( Y^0 \). Here \( m_{\text{ej,He}} \) is the mass of He ejected, and \( m_{\text{ej}} \) is the total mass ejected. For the Adams and Laughlin IMF (eq. 2), and the Halo metallicity stellar yields of Van Den Hoek & Groenewegen (1997), \( Y_{\text{He}} = 0.02 \). Since the helium yield is a roughly constant function of mass, \( Y_{\text{He}} \) is roughly independent of IMF for a range of white dwarf IMFs.

The final, post-Macho He abundance is thus

\[
Y = (Y^0\rho_B - f_{\text{pro}}Y^0\rho_B + \rho_{\text{gas,He}}^{\text{eject}})/\rho_{\text{gas}},
\]

which
simplifies to
\[ \Delta Y = \frac{Y_{\text{He}}}{1 - R} \frac{f_{\text{WD}}}{1 - f_{\text{WD}}} \]  

\[ (8) \]

_Carbon and Nitrogen:_ These elements have no primordial component, but are made by stars. Thus the production of C and N is formally similar to that of He (eq. 8), with the exception that the lack of a primordial component means that \( X_C^0 = X_N^0 = 0 \). Thus we have, after the burst,
\[ X_C = \frac{Y_C}{1 - R} \frac{f_{\text{WD}}}{1 - f_{\text{WD}}} \]  
\[ (9) \]
\[ X_N = \frac{Y_N}{1 - R} \frac{f_{\text{WD}}}{1 - f_{\text{WD}}} \]  
\[ (10) \]

where \( Y_C \) and \( Y_N \) are defined in a way analogous to eq. (7).

### 3.1.2. Instantaneous Recycling Approximation

Within the instantaneous recycling approximation (IRA), we have the well known results (e.g., Tinsley 1980)
\[ X_D = (1 - f_{\text{WD}})^{R/(1-R)} X_D^0 \]  
\[ (11) \]
\[ \Delta Y = \frac{Y_{\text{He}}}{1 - R} \ln \frac{1}{1 - f_{\text{WD}}} \]  
\[ (12) \]
\[ X_C = \frac{Y_C}{1 - R} \ln \frac{1}{1 - f_{\text{WD}}} \]  
\[ (13) \]
\[ X_N = \frac{Y_N}{1 - R} \ln \frac{1}{1 - f_{\text{WD}}} \]  
\[ (14) \]

Note that our \( Y_i \rightarrow (1 - R)Y_{\text{Tins},i} \) in Tinsley’s notation. In this approximation there is no restriction on \( f_{\text{WD}} \), unlike the burst case (see below eqn. (5)). Note also that as in the burst case, the ratios \( \Delta \text{He:C:N} \) are constant.

The burst and recycling solutions agree to first order in \( f_{\text{WD}} \), but disagree at higher orders. In particular, for a fixed \( f_{\text{WD}} \), the burst model always gives a larger \( \Delta Y \) and a smaller \( X_D/X_D^0 \) than the instantaneous recycling approximation does.

### 3.2. Numerical Models

The chemical evolution model used here is based on a code described in detail elsewhere (Fields & Olive 1998). The model allows for finite stellar ages prior to the stellar death and the concomitant remnant and ejecta production. Thus the model assumes neither instantaneous recycling nor the burst approximation, which are equivalent to zero and infinite stellar lifetimes.
respectively, relative to the timescale for star formation. The star formation rate is chosen as an exponential $\psi \propto e^{-t/\tau}$ with an $e$-folding time $\tau = 0.1$ Gyr. We have investigated other $e$-folding times up to $\tau = 1$ Gyr and find that the results are insensitive to details of the star formation rate. The initial mass function will vary as indicated.

The model results are only as reliable as the nucleosynthesis yields used. For stars of $1 - 8M_\odot$ we use the yields of Van den Hoek & Groenewegen (1997), which allow for metallicity-dependence (but the lowest calculated metallicity is $Z = 0.001$, i.e., 1/20 solar). For higher mass stars we use the yields of Woosley & Weaver (1995), though the IMFs we examine put very little mass into these stars.

For the initial D and He abundances of our calculations, we have adopted the results of big bang nucleosynthesis calculations, which relate these quantities directly to $\rho_B$ and the number of light neutrino species $N_\nu$. We shall assume that $N_\nu = 3$.

As we will illustrate below, we find that our numerical calculations yield results very similar to those of the burst approximation. The reason for this similarity is that many of the stars are in the low mass range, so that they have long lifetimes compared to reasonable star formation rates. By the time they die, they can no longer contribute to recycling in other stars.

4. Deuterium and Helium

A large white dwarf component in the Galactic Halo may lead to possible overproduction of helium and depletion of deuterium. The results of our calculations for these two elements are presented in this section, and compared with observations. We will find that these elements can be kept within observational limits only for $\Omega_{WD} \leq 0.003$ and for a white dwarf progenitor initial mass function sharply peaked at low mass ($2M_\odot$).

The problem of helium overproduction has previously been investigated by Ryu, Olive, and Silk (1990). In their work, they took the Galaxy to be a closed box, in which there is no infall of unprocessed gas to the Galaxy from the intergalactic medium (IGM), and no outflow of processed gas from the Galaxy into the IGM. They concluded that, in this closed box model, the Halo could contain only a few white dwarfs, or else the Galaxy would have no hydrogen left; all the hydrogen would have been turned into helium. We will generalize their work here: we will move beyond the closed box model and consider the possibility that the processed gas is able to leave the Galaxy via a galactic wind. The details of such a wind will be discussed in a later section.

As we will see in Section 5, the overproduction of C and N provide by far the severest chemical abundance constraint on a white dwarf population in the Halo. However, this statement assumes that we understand the dredge-up of C and N from the core of the low-metallicity white dwarf progenitors (Chabrier 1999). Hence, in this section we consider D and He, whose yields are far less uncertain. Of all of the elements considered here, the evolution of D is the cleanest:
D is always destroyed by stars and is not produced in significant amounts by any astrophysical process other than the big bang (1976). Although He is produced by stars, as are C and N, He production is farther out from the core of the star so that the He yields are thus less uncertain than those of C and N. On the other hand, Fields & Olive (1998) found that published He yields have trouble with the $Y - Z$ slope in dwarf galaxies. However, the difficulty was that the model predictions underestimate the slope compared to the observations, suggesting that in fact the He yields themselves may be an underestimate. In this sense, therefore, the constraints on He production are conservative.

4.1. Observational Constraints

With the assumption of homogeneous abundances, D and He are universally altered from their primordial values. In this view, then, the apparently “primordial” abundances of D and He used to constrain BBN are really “pregalactic” abundances which have already had some processing from their initial values. We want to quote D and He abundances in different environments and use these as constraints on processing by white dwarf progenitors.

**Deuterium:** The best available Galactic measurement of deuterium is the abundance in the present day local ISM. Linsky (1998) find $D/H = (1.5 \pm 0.1) \times 10^{-5}$. The present day value has been depleted by an unknown amount from the original low metallicity value by galactic disk stars, and thus provides a very conservative lower limit on the D abundance and thus on pre-Galactic processing.

A stronger limit arises from measurements of D in quasar absorption line systems. At present, different groups report different D/H values. The strongest claims include “high” $D/H \approx (8 - 25) \times 10^{-5}$ (Webb et al. 1997; Tytler et al. 1999) measured in a system at $z = 0.701$; and “low” $D/H = (3 - 5) \times 10^{-5}$ (Burles & Tytler 1998a; Burles & Tytler 1998b) measured in two systems at $z > 3$. These measurements are difficult and subject to systematic errors (principally affecting H, rather than D). It is thus unclear which (if either) of these values best represents the primordial abundance. Thus we will allowing a very generous range:

$$D/H_p = (3 - 25) \times 10^{-5}. \quad (15)$$

**Helium:** A best estimate of pre-galactic (i.e., normally “primordial”) helium comes from extragalactic HII regions, the lowest metallicity cases of which are in blue compact dwarf galaxies. The data are summarized in, e.g., Fields & Olive (1998). The large number of measurements now lead to a small statistical error, so that systematic errors are now the limiting factor. Again, we will take generous limits, adding the systematic error linearly with the statistical errors (both at 1σ):

$$Y_p = 0.231 - 0.245 \quad (16)$$
4.2. Model Results and Constraints

The results of our calculation depend on several parameters: the IMF of the white dwarf population, the total density of white dwarfs $\rho_{WD}$, the Hubble constant, and the total baryon density $\rho_B$. In general, the departure from the big bang nucleosynthesis initial conditions increases as $f_{WD} = \rho_{WD}/\rho_B$ increases, i.e., as white dwarfs become a larger fraction of the baryons. We can see this in the analytical results. As the white dwarf fraction increases in Eqs. 8 and eq. 11, helium and CNO enrichment increases, and more deuterium is depleted.

We present results for four different sets of parameter choices here. In the first model, we take $\Omega_{WD} h = 0.0036$, the lowest value allowed by a simple extrapolation of the Galactic Macho results to a cosmic scale in Eq. (1) (Fields, Freese, & Graff 1998). In this model we take the white dwarf IMF of Adams and Laughlin (eq. 2). Figure 1 summarizes the nucleosynthetic processing in two panels. In Figure 1a, we show the values of $Y$ and $\text{D/H}$ which result from our calculations (for various values of $\rho_B$, and with $h = 0.7$). Shown are the full numerical model, as well as the burst and instantaneous recycling models. Also shown are the initial values from big bang nucleosynthesis and the (very generous) range of primordial values from eqs. (15) and (16). Note that the numerical model falls between the burst and IRA, as expected. It is interesting to see that the full model falls very close to the burst case. Thus we can conclude that the burst model well-approximates the full results; also, as the burst model gives stronger constraints, the IRA results are in fact the most generous (and thus the most conservative) bounds.

Since the previous model is obviously not consistent with measurements, we also present, in Figure 2, a threshold model with results barely consistent with measurements of deuterium and helium. For this model, we have kept the log-normal IMF suggested by Adam and Laughlin, but with different parameters: our IMF is centered at $M_c = 2 M_\odot$ instead of $2.3 M_\odot$, and is narrower, with an effective width $\sigma = 0.05$ instead of 0.44. This IMF contains far fewer stars with initial mass $M > 5 M_\odot$, and so produces less helium enriched gas, represented by the fact that $R$ drops slightly from 0.69 to 0.66. We also drop $\Omega_{WD} h$ down to 0.002, somewhat below the lower bound of what is suggested by the simple extrapolation in eq. 1 for $f_{gal} = 1$. This model is most constrained by the upper limit of the He data. The allowed range in $\Omega_B$ is 0.01 – 0.03 (for $h = 0.7$). Note that to prevent over-production of helium, Machos are a relatively modest $\sim 10\%$ of Baryons.

Figures 3 and 4 represent the minimum cosmic processing required if Machos are contained only in spiral Galaxies of luminosities similar to the Milky Way: $\Omega_{WD} h = 6.1 \times 10^{-4}$ (Fields, Freese, & Graff 1998). Figure 3 uses an IMF peaked at $2 M_\odot$, designed to minimize the effect on deuterium and helium abundances. Figure 3(a) shows that the effect on D and He is small and permissible (but see the following section for discussion of C and N production in this model). Figure 4 uses the same $\Omega_{WD}$, but adopts an IMF peaked at $4 M_\odot$. Note the increased D and He processing now becomes unallowably large. Thus we are driven to a low initial progenitor mass by the helium and deuterium abundances alone.

Note that white dwarf progenitors would lead to a raised floor in the $^4\text{He}$ abundance. From
Eq. (8), one can see that, to obtain the primordial helium abundance from the measured values, one should really subtract the contribution due to white dwarf progenitors. This would complicate the usual big bang nucleosynthesis comparison of observed pregalactic abundances with the primordial yields.

5. Carbon and Nitrogen

We illustrate here the difficulties of reconciling the carbon and nitrogen production with the abundance of white dwarfs in the Halo suggested by the microlensing experiments.

5.1. Production of C and N

White dwarf progenitors are expected to produce prodigious amounts of C and N. Here we discuss the relative production of these two elements. The relative amounts of C and N produced in the asymptotic giant branch (AGB) phase are determined by a process known as Hot Bottom Burning (hereafter HBB). During HBB, the temperature at the bottom of a star’s convective envelope is sufficiently high for nucleosynthesis to take place (Sackmann et al. 1974, Scalo et al. 1975, Lattanzio 1989). One of the main effects of HBB is to take the $^{12}\text{C}$ which is dredged to the surface and process it into $^{14}\text{N}$ via the CN cycle. Significant destruction of $^{12}\text{C}$ together with production of $^{13}\text{C}$ and $^{14}\text{N}$ requires temperatures of at least $80 \times 10^6\text{K}$. For low mass AGB stars ($m < 4M_\odot$), the effect of HBB is negligible due to the low temperature at the bottom of their envelopes. For high mass AGB stars ($m > 4M_\odot$), the effect of HBB depends on the amount of matter exposed to the high temperatures at the bottom of their envelopes, the net result being the conversion of carbon and oxygen to nitrogen (Boothroyd et al. 1993). Yields of H, He, are not affected by HBB; moreover, the total CNO yields also remain the same. Since the CNO production is dominated by C and N, this means that the sum C+N is independent of Hot Bottom Burning. Thus, the main effect of Hot Bottom Burning is to determine the degree to which C is processed into N, but the sum remains the same.

With Hot Bottom Burning, progenitor stars less massive than about $4M_\odot$ produce significant amounts of carbon and negligible nitrogen, while heavier stars produce significant amounts of nitrogen and negligible carbon. Van den Hoek & Groenewegen (1997) find that a star of mass $2.5M_\odot$ and metallicity $Z = 0.001$ will produce $1.76 M_\odot$ of ejecta of which $0.012 M_\odot$ is new carbon, for an ejected mass fraction of $7 \times 10^{-3}$. In comparison, the solar system composition has a carbon mass fraction of $3.0 \times 10^{-3}$. In other words, the ejecta of a typical intermediate mass star have more than twice the solar enrichment of carbon. If a substantial fraction of all baryons pass through $1 - 4M_\odot$ stars, the carbon abundance in this model will be near solar. These stars also produce $2.2 \times 10^{-4}M_\odot$ of N, leading to an ejected mass fraction $1.25 \times 10^{-4} \approx X_{N,\odot}/8$, a much lower enrichment. On the other hand, a $5M_\odot$ progenitor at the same metallicity produces...
\[ X_C = 7.2 \times 10^{-4} = 0.24 X_{C, \odot} \quad \text{and} \quad X_N = 8.2 \times 10^{-3} = 7.4 X_{N, \odot}. \] Hence, with Hot Bottom Burning, a white dwarf IMF with stars in the mass range 1-4 \( M_\odot \) produces a twice-solar enrichment of carbon, whereas a white dwarf IMF with stars in the mass range 4-8 \( M_\odot \) produces seven times solar enrichment of nitrogen. An IMF with stars in both regimes, such as the Adams and Laughlin IMF in Eq. (2), produces both elements.

For comparison, van den Hoek and Groenewegen (1997) considered the case of no HBB. Then stellar yields of carbon are seen to dominate the total CNO-yields over the entire mass range, with carbon production at the level of solar enrichment. Models with HBB are favored as they are in excellent agreement with observations, e.g. for AGB stars in the Magellanic Clouds (Plez et al. 1993, Smith et al. 1995). In the next section we will present results from our models without Hot Bottom Burning; however, the presence of HBB would not change our results as it merely trades a C overproduction problem for a N overproduction problem.

A possible loophole to C and N overproduction stems from the primordial, zero-metallicity composition that the Macho progenitors would have. Stellar carbon and nitrogen yields for zero metallicity stars are quite uncertain, and have not been systematically calculated for the 1 – 8\( M_\odot \) mass range of interest to us here. Thus we use the yields of Van den Hoek & Groenewegen (1997), at the lowest metallicity, \( Z = 0.001 = Z_\odot / 20 \), and as an approximation of the true \( Z = 0 \) yields. However, it is possible (although not likely) that carbon never leaves the white dwarf progenitors, so that carbon overproduction is not a problem (Chabrier 1999). Carbon is produced exclusively in the stellar core. In order to be ejected, carbon must convect to the outer layers in the “dredge up” process. Since convection is less efficient in a zero metallicity star, it is possible that no carbon would be ejected in a primordial star. In that case, it would be impossible to place limits on the density of white dwarfs using carbon abundances. On the other hand, the 1\( M_\odot \) model of Fujimoto et al. (1995) suggests that C and N are in fact highly enriched due to strong mixing. Indeed, there is evidence (Norris, Ryan, & Beers 1997) for very strong C enrichment in some Halo giants, suggesting a mixing effect.

The basic result of typical models with HBB is then that a white dwarf IMF with stars in the mass range 1-4 \( M_\odot \) produces a twice-solar enrichment of carbon, whereas a white dwarf IMF with stars in the mass range 4-8 \( M_\odot \) produces seven times solar enrichment of nitrogen. An IMF with stars in both regimes, such as the Adams and Laughlin IMF in Eq. (2), produces both elements. Without HBB, a solar enrichment of C is produced by all WD progenitor stars.

5.2. Model Results

In the figures, in panels b), we show CNO abundances from the same four models discussed previously for deuterium and helium. The CNO abundances are presented relative to solar via the usual notation of the form

\[ [C/H] = \log_{10} \frac{C/H}{(C/H)_\odot}. \]
For example, in this notation \([C/H] = 0\) represents a solar abundance of C, while \([C/H] = -1\) is 1/10 solar, etc. Our C and N abundances were obtained without including Hot Bottom Burning, which would exchange a C overproduction problem for a N overproduction problem. The effect of HBB would be to increase N at the expense of C, keeping the sum C+N constant.

In Figure 1, we have \(\Omega_{WD} h = 0.0036\), the lowest value allowed by Eq. (1). We take \(h = 0.7\) and the Adams-Laughlin IMF in Eq. (2). We see that, even after dilution with the primordial baryons, the C and N abundances are still both greater than 1/10 solar (e.g. \([C/H] > -0.8\)) over the entire range of \(\Omega_B\). Lower values of \(\Omega_B\) correspond to higher C abundances because there are fewer primordial baryons to dilute the C emerging from the white dwarf progenitors. In Figure 2, we have \(\Omega_{WD} h = 0.002\), \(h = 0.7\), and an IMF peaked at 2\(M_\odot\) as described previously. In Figures 3 and 4, we have \(\Omega_{WD} h = 0.00061\), the minimum amount of WD required to explain the microlensing results if only Galaxies similar to ours produce WD Machos. Figure 3 uses an IMF peaked at 2\(M_\odot\) while Figure 4 uses an IMF peaked at 4\(M_\odot\). In all cases there is substantial C and N production: in particular, the resultant C abundance is above 1/10 solar.

In the next section, we will show that, with or without HBB, C and N exceed by at least 2 orders of magnitude the levels seen in halo stars in our own Galaxy as well as by an order of magnitude those in quasar absorbers.

5.3. Observational Constraints

White dwarf progenitors produce a huge amount of C and/or N. With the assumption of homogeneity, the C and N produced would give rise to a universal “floor”, i.e., an apparent Pop III component which might even be mistaken as primordial. If the abundances are not homogeneous, then the observations of C and N in various sites can be used to obtain the required segregation of these elements to keep them out of certain regions. In addition, if one argues that C and N are underrepresented in some region, then they must be enhanced elsewhere.

The overproduction of carbon and nitrogen can be a serious problem, as emphasized by Gibson & Mould (1997). They noted that white dwarf progenitors are expected to be the main source of carbon. Thus the production of a white dwarf population would be accompanied by a copious production of carbon, without a corresponding enrichment of oxygen, which is made predominantly by Type II supernovae. The expected signature of white dwarf production would be anomalously high ratios of C/O and N/O, i.e., \(C/O \gtrsim 3(C/O)_\odot\) and \(N/O \gtrsim 3(N/O)_\odot\). However, metal-poor stars in our galactic halo have C/O and N/O that are about 1/3 solar, i.e., below and not above levels in Population I disk stars. Thus Gibson & Mould (1997) concluded that the gas which formed these stars cannot have been polluted by the ejecta of a large population of white dwarfs.

In using Galactic Halo star abundance ratios as constraints, the Gibson & Mould (1997) analysis assumes that 1) the Halo stars form at the same time as the white dwarf progenitors, and
2) the Galaxy’s Macho progenitor ejecta would remain in situ. It is possible that the observed low C spheroid stars formed before the white dwarf progenitors, in which case they would not be affected by the metals produced later on by the white dwarf progenitors. The authors note that galactic winds could intervene but argue these to be unlikely. However, they did not consider the effect of Type Ia supernovae, which may in fact be a natural engine to drive such winds (though at the price of iron production; see §6). Thus, in order to be generous to the white dwarf scheme, we will examine C and N production in terms of the absolute abundances produced, and use these as constraints on the degree of efficiency of the winds.

If the spheroid stars do not predate the white dwarf progenitors, then, in our own Galaxy, the metal-poor Halo stars provide a strong constraint: in these stars, neither C nor N has a detectable “floor” that would indicate a pre-Galactic component. However, there is no evidence for such a floor, which would appear as a constant C and/or N abundance as, e.g., Fe decreases. C has been observed with abundances at least as low as $10^{-3} C/H_\odot$; and, N has been observed with abundances as low as $10^{-3} N/H_\odot$. Thus if the production of these elements is of order solar, as we have seen in the previous section, the segregation between white dwarf progenitor ejecta and these Halo stars must be very effective. Mixing must be prevented with a $\sim 99\%$ efficiency. A way to achieve this segregation is with a Galactic wind, which can remove C and N from the Galaxy.

If the C and N are expelled from the Galaxy, the abundances of these elements are constrained by measurements in the intergalactic medium. Carbon abundances in intermediate redshift Ly$\alpha$ forest lines have been measured to be quite low. Carbon is indeed present, but only at the $\sim 10^{-2}$ solar level, (Songaila & Cowie 1996) in the Ly$\alpha$ forest at $z \sim 3$ with column densities $N \geq 3 \times 10^{15}$ cm$^{-2}$. Ly$\alpha$ forest abundances have also been recently measured at low redshifts with HST (Shull et al. 1998) to be less than $3 \times 10^{-2}$ solar.

The forest lines sample the neutral intergalactic medium. With HBB, white dwarf progenitors in the mass range $(1 - 4) M_\odot$ typically produce solar abundances of carbon; without HBB, all white dwarf progenitors do so. If we assume that the nucleosynthesis products of the white dwarf progenitors do not avoid the neutral medium, then these observations offer strong constraints on scenarios for ubiquitous white dwarf formation. In order to maintain carbon abundances as low as $10^{-2}$ solar, only about $10^{-2}$ of all baryons can have passed through the intermediate mass stars that were the predecessors of Machos. Such a fraction can barely be accommodated by the results in our previous paper (Fields, Freese, and Graff 1998) for the remnant density predicted from our extrapolation of the Macho group results, and would be in conflict with $\Omega_\gamma$ in the case of a single burst of star formation. Note that, while the Halo star limit is not absolutely robust, in that it could be avoided if the Halo stars predate the Machos, the Ly$\alpha$ constraint cannot be avoided. Hence, below, in obtaining numbers, we use the Ly$\alpha$ constraint.

Furthermore, in an ensemble average of systems within the redshift interval $2.2 \leq z \leq 3.6$, with lower column densities ($10^{13.5}$ cm$^{-2} \leq N \leq 10^{14}$ cm$^{-2}$), the mean C/H drops to $\sim 10^{-3.5}$ solar (Lu, Sargent, Barlow, & Rauch 1998). One can immediately infer that, however carbon is
produced at high redshift, the sources do not enrich all material uniformly. Any carbon that had been produced more uniformly prior to these observations (i.e., at still higher redshift) cannot have been made above the $10^{-3.5}$ solar level. These damped Ly$\alpha$ systems are thought to be possible precursors to today’s galaxies.

While measurements of nitrogen abundance have not been made in the Ly$\alpha$ forest, there are measurements in damped Ly$\alpha$ systems. The value of N/H in these systems is measured to be typically $< 10^{-2}$ of solar, and in one case at $z_{\text{DLA}} = 0.28443$ reported to be as low as $N/H = 10^{-3.79\pm0.08} N/H_\odot$ (Lu et al. 1998). In contrast, with HBB, white dwarf progenitors in the mass range $(4-8) M_\odot$ produce seven times the solar abundance of nitrogen. In order to reconcile measurements of C and N in damped Lyman systems with the much higher abundances predicted by white dwarf progenitors, one would have to argue that these elements are ejected from the damped Ly$\alpha$ systems, which may be protogalaxies. Again a wind may be operative here. However, the segregation requirements are even stronger, particularly if N/H of $10^{-4}$ solar is to be taken seriously.

**Comparison with Model Results:** We can compare these observations with our model results to obtain more quantitative constraints when specific parameter choices are made. Again, our models have no HBB included. First let us assume that the abundances we obtained in the figures apply homogeneously throughout the universe. We will compare our results to the Ly$\alpha$ carbon measurements of $10^{-2}$ and the Halo measurements of $10^{-3}$. Then in order to obtain agreement of the C and N abundances we find in our Model 1 (see Fig. 1) with the Ly$\alpha$ observations described above (which are a factor of 30 below the predicted values), we must reduce the white dwarf densities by a factor of 30. Hence we require $\Omega_{\text{WD}} h \leq 0.0036/30 = 1 \times 10^{-4}$. Alternatively, we require an actual abundance distribution that is quite heterogeneous: those regions in which the observations are made must be underprocessed. This implies departure from the mean of a factor of at least 30, i.e., there must be segregation efficiency of $1 - 1/30 = 97\%$.

The other figures confirm the results of Figure 1. While the parameter choices of Figures 2 and 3 give acceptably low D and He reprocessing, the C and N abundances are again 10-100 times what is observed. In Fig. 2 and 3, agreement with Ly$\alpha$ forest requires $\Omega_{\text{WD}} h \leq 1 \times 10^{-4}$. Figure 4, with an IMF peaked at $4 M_\odot$, overproduces all four elements. This last model is the least restrictive when comparing with the Ly$\alpha$ measurements, $\Omega_{\text{WD}} h \leq 2 \times 10^{-4}$. Note that if C and N remain inside the Galaxy and Halo stars do not predate the white dwarf progenitors, then all these limits would be an order of magnitude more powerful; the abundances must match the measured C values of $10^{-3}$ solar of the Halo stars.

Our results are mildly dependent on the redshift when C and N are expelled into the IGM. If the C and N are not expelled until low redshifts, then they would not be seen in intermediate redshift ($z = 2-3$) absorbers. Our limits at low redshifts will be $\sim 3$ times less restrictive since the observational limits are less restrictive. However, removing the C and N from the Galaxy requires supernovae. Since large numbers of SN Type Ia are not seen out to $z \sim 1$ (Hardin et al. 1999),
one must ensure that the supernovae have mostly gone off by $z \sim 1$. Thus the stronger bounds quoted previously in the session apply unless the supernovae that ejected the material take place precisely at $z \sim (1 - 2)$. Hence the low measurements of C and N in the damped Ly$\alpha$ systems are hard to reconcile with the higher predictions of C and N from white dwarf progenitors.

Thus, C and N indeed prove to be very restrictive; in all models the mean cosmic production is unacceptably large if it is homogeneously distributed. As mentioned above, however, the abundances could well be inhomogeneous due to galactic winds, which would blow the C, N, and other products of the white dwarf progenitors out of galaxies. The D, He, C, and N measurements could be avoided as constraints only if there is not much mixing, e.g. of hot outflowing gas and cool infalling gas; with mixing, the material essentially reenters the galaxies with a universal proportion.

In summary, low mass stellar progenitors produce a solar enrichment of carbon; high mass stellar progenitors produce either a solar abundance of carbon (without HBB) or a ten times solar enrichment of nitrogen (with HBB). Both elements are in conflict with measurements inside our Galaxy and must be ejected from the Galaxy if white dwarfs are to survive as Macho candidates. Even outside our Galaxy, these abundances are hard to reconcile with measurements of the Ly$\alpha$ systems. We do wish to repeat the caveat, however, that the C and N yields from low metallicity stars are still uncertain.

We close this section by pointing out that extragalactic HII regions cannot contain a substantial number of white dwarf Machos. These regions are observed to have N and C increasing as the oxygen abundance increases. White dwarf progenitors, on the other hand, produce C and/or N without producing O enrichment. One would have to argue that extragalactic HII regions missed out in white dwarf formation.

6. Galactic Wind

We have seen that the progenitors of a substantial white dwarf Halo population would have produced a significant amount of pollution, in conflict with observations. In general one could avoid these constraints by arguing for strong segregation between the hot gas emerging from the progenitors and the cold gas where the element abundances are measured. Then one views the incompatibility of the predicted abundances with the observations as a measure of the required efficiency of segregation of the hot ejecta from the rest of the universe.

A possible means of removing excess abundances from the Galaxy is a Galactic wind. As discussed in the Introduction, such a wind is required to remove the excess gaseous baryonic material left over from the Macho progenitors; this excess material has more mass than the Disk and Spheroid combined, is extremely polluted (with carbon, nitrogen, etc.) and must be ejected from the Galaxy. Indeed, as pointed out by Fields, Mathews, & Schramm (1997), such a wind may be a virtue, as hot gas containing metals is ubiquitous in the universe, seen in galaxy clusters and
groups, and present as an ionized intergalactic medium that dominates the observed neutral Ly\(\alpha\) forest. Thus, it seems mandatory that many galaxies do manage to shed hot, processed material. Here a galactic wind could remove helium, carbon and nitrogen from the star forming regions and mix it throughout the universe.

Such a wind could be produced by supernova explosions providing the energy source. The white dwarf IMF must therefore include the stars responsible for the supernovae. Possibilities include Type II supernovae from neutron stars arising from massive progenitor stars; in this case the IMF must contain some stars heavier than \(8 \, M_\odot\). The disadvantage of such a scenario is that these heavy stars evolve more quickly than the lighter stars that give rise to the white dwarfs; i.e., the supernovae explosions would naturally take place before the white dwarf progenitors have produced their polluting materials. Then it would be hard to see how the excess carbon and nitrogen could be ejected from the Galaxy.

We therefore propose the alternate possibility of Type Ia supernovae. Here the same white dwarfs that are Macho candidates would also be responsible for the supernova explosions. These white dwarfs are in binary systems. Smecker & Wyse (1991) have shown a problem with a binary system of two merging white dwarfs as being responsible for the supernova explosions: too few such explosions are seen in haloes today to allow us to have enough of these earlier on to provide the required wind. However, a scenario in which the white dwarf has a red giant companion can be quite successful. The red giant loses mass onto the white dwarf. When the white dwarf mass approaches the Chandrasekhar mass, then there is a supernova explosion. The timing is just right, since the supernova and accompanying galactic wind takes place when low mass stars become red giants. Thus the explosion and wind take place after the white dwarf progenitors pollute the Galaxy with excess element abundances, so that the wind is able to eject any excess helium, carbon and/or nitrogen from the galaxy.

Here we now show that about 0.5\% (by mass) of the stars must explode as Type Ia supernovae in order to provide sufficient energy to produce the required Galactic wind. Such a number is very reasonable, as it is comparable to the number of Type Ia supernovae per white dwarf in the disk of Galaxy.

Consider a protogalaxy with a baryonic mass \(M_B\), total mass \(M_{\text{tot}} = M_B + M_{\text{DM}} \sim 10^{12} M_\odot\), and size \(R \sim 100 \, \text{kpc}\). The escape velocity is thus

\[
v_{\text{esc}}^2 = 2 \frac{GM_{\text{tot}}}{R} \sim (300 \, \text{km} \, \text{s}^{-1})^2
\]  

(18)

For a supernova wind to be effective in evaporating gas from the protogalaxy, it must heat the gas to a temperature \(T_{\text{gas}}\) such that the wind condition

\[
\frac{3}{2} k T_{\text{gas}} = \frac{1}{2} m_p v_{\text{gas}}^2 > \frac{1}{2} m_p v_{\text{esc}}^2
\]

is satisfied, or \(k T_{\text{gas}} \gtrsim 0.3 \, \text{keV}\) for the \(v_{\text{esc}}\) value in eq. (18).
This condition sets a lower limit to the number (and fraction) of supernovae needed, as follows. We envision a scenario wherein some baryons (i.e., gas) become stars and ultimately their remnants and refuse, while other gas remains unprocessed. We thus write

\[ M_B = M_\star + M_{\text{unpro}} \]  

and we will denote the “processed fraction” \( f_\star = M_\star / M_B \). Furthermore, we note that some of the white dwarfs will occur in binaries and will lead to Type Ia supernovae. Consequently, some (most) of the stars will meet their demise as white dwarfs and planetary nebulae (PN), while some will die as supernovae: \( M_\star = M_{\text{PN}} + M_{\text{SN}} \). We thus denote the “supernova fraction” \( f_{\text{SN}} = M_{\text{SN}} / M_\star \); our goal here is to constrain \( f_{\text{SN}} \).

To get the constraint, we assume that the three gas components—unprocessed, planetary nebulae, and supernova ejecta—are mixed, and come to some temperature \( T_{\text{gas}} \). Since the unprocessed and planetary nebula components are much cooler than the supernova ejecta, we can, to good approximation, put their temperatures to zero. In this case, the temperature of the mixed gas is just given by energy conservation:

\[ \frac{3}{2} N_{\text{gas}} k T_{\text{gas}} = E_{\text{SN}} N_{\text{SN}} \]  

where \( N_{\text{gas}} = M_{\text{gas}} / m_p \) is the number of gas molecules, \( N_{\text{SN}} \) is the number of supernovae that have gone off. Also, \( E_{\text{SN}} \sim 10^{51} \) erg is the mechanical energy of the supernova, which is ultimately thermalized. Furthermore, since \( N_{\text{SN}} = M_{\text{SN}} / \langle m_{\text{SN}} \rangle \), we have

\[ \frac{3}{2} M_B k T_{\text{gas}} = m_p \varepsilon_{\text{SN}} M_{\text{SN}} \]  

where \( \varepsilon_{\text{SN}} \equiv E_{\text{SN}} / \langle m_{\text{SN}} \rangle \) is the specific energy per supernova. For Type Ia supernovae, \( \varepsilon_{\text{SN}} \sim 10^{51} \) erg/5M\(_\odot\) = (3000 km s\(^{-1}\))^2.

Collecting, then, we have

\[ \frac{M_{\text{SN}}}{M_B} = \frac{3}{2} \frac{k T_{\text{gas}}}{m_p \varepsilon_{\text{SN}}} \]  

and since \( M_{\text{SN}} / M_B = f_{\text{SN}} M_\star / M_B = f_{\text{SN}} f_\star \), we have

\[ f_{\text{SN}} f_\star = \frac{3}{2} \frac{k T_{\text{gas}}}{m_p \varepsilon_{\text{SN}}} \]  

Thus the condition of eq., (19) gives

\[ f_{\text{SN}} f_\star > \frac{1}{2} \frac{v_{\text{esc}}^2}{\varepsilon_{\text{SN}}} \]  

\[ \Rightarrow f_{\text{SN}} > \frac{1}{2} \frac{v_{\text{esc}}^2}{\varepsilon_{\text{SN}}} f_\star^{-1} \]  

\[ \approx 5 \times 10^{-3} f_\star^{-1} \]
Thus we see that we need at least about 0.5% (by mass) of the stars to explode as Type Ia supernovae; more, if the processed fraction $f_\star$ is significantly lower than unity.

Thus far, we have only accounted for gas heating due to the Type Ia supernovae, ignoring any cooling processes. However, cooling processes will operate; for the temperatures of interest, the dominant cooling mechanism is bremsstrahlung. We can estimate the importance of cooling by computing the cooling rate, $\tau_{\text{cool}} = E/\dot{E}$, where $E \sim kT \sim 0.3$ keV is the energy per gas particle, and $\dot{E}$ is the cooling rate per particle. The cooling rate is $\dot{E} = \Lambda n$, with $\Lambda \approx 10^{-23}$ erg cm$^3$s$^{-1}$, and $n$ the gas density. Assuming a constant density, we have $n = \frac{M_{\text{gas}}}{4\pi R^3}$, where $M_{\text{gas}}$ and $R$ are the mass and radius respectively of the WD gaseous ejecta. Thus

$$\tau_{\text{cool}} = 0.2 \text{ Gyr} \left( \frac{M_{\text{gas}}}{10^{11}M_\odot} \right)^{-1} \left( \frac{R}{50 \text{kpc}} \right)^3$$

(28)

for the fiducial gas mass and radii indicated. We see that the cooling timescale is shorter than longest stellar lifetime considered, $\tau(2M_\odot) = 1$ Gyr. Thus cooling can be effective if the Type Ia supernova burst is not rapid or the WD progenitors have masses $\lesssim 3M_\odot$. Furthermore, the cooling will be all the more effective if the gas is inhomogeneous, as denser regions will cool much faster. On the other hand, the cooling is very sensitive to the assumed total radius $R$ of the WD gaseous ejecta. Hence, cooling cannot rule out such a wind, but it does demand that the wind be driven out on timescales more rapid than $\sim 0.2$ Gyr.

Thus, if the cooling is indeed inefficient, it is quite reasonable to use some of the white dwarf Macho candidates as Type Ia supernovae to remove excess carbon and nitrogen from the Galaxy. However, SN Ia make prodigious amounts of iron, about $m_{\text{ej}}(\text{Fe}) \sim 1M_\odot$ per event, i.e., a large fraction of the mass going into Ia’s becomes iron (Canal, R., Isern, J., & Ruiz-Lapuente 1998). Thus we will expect a mass fraction of iron of order

$$X(\text{Fe}) \sim M_{\text{SN}}/M_B = f_\star f_{\text{SN}} \sim 5 \times 10^{-3} \sim 4X(\text{Fe})_\odot$$

(29)

i.e., a very large enrichment. Thus, while the SN Ia’s can remove the gas from the galaxies, they add their own contamination which must be kept segregated from the observable neutral material at a high precision. (And the iron makes things all the worse as it also adds to the cooling of the hot gas.)

7. Conclusions and Discussion

In conclusion, we have found that the chemical abundance constraints on white dwarfs as candidate Machos are formidable. The D and $^4$He production by the progenitors of white dwarfs can be in agreement with observation for low $\Omega_{\text{WD}}$ and an IMF sharply peaked at low masses $\sim 2M_\odot$. Unless carbon is never dredged up from the stellar core (as has been suggested by Chabrier 1999), overproduction of carbon and/or nitrogen is problematic. The relative amounts of these elements that is produced depends on Hot Bottom Burning, but both elements are
produced at the level of at least solar enrichment. Such enrichment is in excess of what is observed in our Galaxy and must be removed. A Galactic wind may have been driven by Type Ia supernovae, which emerged from some of the same white dwarfs that are the Machos. However, Lyα measurements in the IGM are extremely restrictive and imply that these elements must somehow be kept out of damped Lyα systems. In addition these Type Ia supernovae overproduce iron (Canal, R., Isern, J., & Ruiz-Lapuente 1998).

In sum, there is no evidence in Galactic halo stars, in external galaxies, or in quasar absorbers for the patterns of chemical pollution that should be formed along with a massive population of white dwarfs. While this debris does carry the seeds of its own removal in the form of Type Ia supernovae, the required galactic winds must be effective in all protogalaxies, must arise at redshifts 1 < z < 2, and the debris must remain hot and segregated from cooler neutral matter. Given these requirements, we conclude that white dwarfs are very unlikely Macho candidates unless they are formed in an unknown and unconventional manner.

With the failure of known stellar candidates as significant sources of dark matter, one may be driven to exotic candidates. These include Supersymmetric particles, axions, massive neutrinos, primordial black holes (Carr 1994; Jedamzik 1997) and mirror matter Machos (Mohapatra 1999).

We thank Elisabeth Vangioni-Flam, Grant Mathews, Scott Burles, Joe Silk, Julien Devriendt, Michel Cassé, Jim Truran, Nick Suntzeff, Sean Scully, and Dave Spergel for helpful discussions. We especially wish to thank Dave Schramm, without whom none of us would be working in the field of cosmology. We are grateful for the hospitality of the Aspen Center for Physics, where part of this work was done. DG acknowledges the financial support of the French Ministry of Foreign Affairs’ Bourse Chateaubriand and the Physics and Astronomy Departments at Ohio State University. KF acknowledges support from the DOE at the University of Michigan. The work of BDF was supported in part by DoE grant DE-FG02-94ER-40823.

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FIGURE CAPTIONS

1. (a) The D/H abundances and helium mass fraction $Y$ for models with $\Omega_{WD}h = 0.0036$, $h = 0.7$, and the Adams-Laughlin IMF. The red curves show the changes in primordial D and He as a result of white dwarf production. The solid red curve is for the full chemical evolution model, the dotted red curve is for instantaneous recycling, and the long-dashed red curve for the burst model. The short-dashed blue curve shows the initial abundances; the error bars show the range of D and He measurements. We see that the processing drives D and He out of the measured range.

(b) CNO abundances produced in the same model as a, here plotted as a function of $\Omega_B$. The C and N production in particular are greater than 1/10 solar (e.g., $[\text{C/H}] > -0.8$) over the entire range of $\Omega_B$. These models do not include Hot Bottom Burning; the effect of Hot Bottom Burning would be to increase N at the expense of C, keeping the sum C+N constant.

2. As in Figure 1, for $\Omega_{WD}h = 0.002$, $h = 0.7$, and IMF peaked at $2M_\odot$. This is the absolute largest $\Omega_{WD}$ compatible with data for the light elements.

3. As in Figure 1, for $\Omega_{WD}h = 0.00061$, $h = 0.7$. This represents the minimum cosmic processing required if Machos are contained only in spiral Galaxies of luminosities similar to the Milky Way. The IMF is peaked at $2M_\odot$, designed to minimize the effect on abundances. We see in (a) that the effect on D and He is small and permissible, but in (b) we see that even here the C and N production is significant.

4. As in Figure 2, for $\Omega_{WD}h = 0.00061$, $h = 0.7$. To show the effect of the IMF choice, here the IMF is peaked at $4M_\odot$. Note the increased D and He processing now becomes unallowably large.