Massive Compact Halo Objects Viewed from a Cosmological Perspective: Contribution to the Baryonic Mass Density of the Universe

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ABSTRACT

We estimate the contribution of Massive Compact Halo Objects (Machos) and their stellar progenitors to the mass density of the Universe. If the Machos that have been detected reside in the Halo of our Galaxy, then a simple extrapolation of the Galactic population (out to 50 kpc) of Machos to cosmic scales gives a cosmic density $\rho_{\text{Macho}} = (1 - 5) \times 10^9 h M_\odot \text{Mpc}^{-3}$, which in terms of the critical density corresponds to $\Omega_{\text{Macho}} = (0.0036 - 0.017) h^{-1}$. Should the Macho Halo extend out to much further than 50 kpc, then $\Omega_{\text{Macho}}$ would only be larger. Such a mass density is comparable to the cosmic baryon density implied by Big Bang Nucleosynthesis. If we take the central values of the estimates, then Machos dominate the baryonic content of the Universe today, with $\Omega_{\text{Macho}}/\Omega_B \sim 0.7 h$. However, the cumulative uncertainties in the density determinations only require that $\Omega_{\text{Macho}}/\Omega_B \geq \frac{1}{2} h f_{\text{gal}}$, where the fraction of galaxies that contain Machos $f_{\text{gal}} > 0.17$ and $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$. Our best estimate for $\Omega_{\text{Macho}}$ is hard to reconcile with the current best estimates of the baryonic content of the intergalactic medium indicated by measurements of the Lyman-$\alpha$ forest; however, measurements of $\Omega_{\text{Ly} \alpha}$ are at present uncertain, so that such a comparison may be premature.

If the Machos are white dwarfs resulting from a single burst of star formation (without recycling), then their main sequence progenitors would have been at least twice more massive: $\Omega_\star = (0.007 - 0.034) h^{-1}$. Thus, far too much gaseous baryonic material would remain in the Galaxy unless there is a Galactic wind to eject it. Indeed a Macho population of white dwarfs and the gas ejected from their main sequence progenitors accounts for a significant fraction of all baryons. This fact must be taken into account when attempting to dilute the chemical by-products of such a large population of intermediate mass stars. We stress the difficulty of reconciling the Macho mass budget with the accompanying carbon production in the case of white dwarfs. In the simplest picture, even if the excess carbon is ejected from the Galaxy
by a Galactic wind, measurements of carbon abundances in Lyman $\alpha$ forest lines with values $10^{-2}$ solar require that only about $10^{-2}$ of all baryons can have passed through the white dwarf progenitors. Such a fraction can barely be accommodated by our estimates of $\Omega_{\text{Mach}o}$ and would be in conflict with $\Omega_\ast$.

Subject headings: dark matter — MACHOs
1. Introduction

In recent years, microlensing experiments (Alcock et al. 1997a; Renault 1997) have reported evidence for Massive Compact Halo Objects (Machos) in the halo of our Galaxy. Candidates that have been considered as explanations for these events include faint stars, brown dwarfs, white dwarfs, and black holes. Other than the possibility of primordial black holes, all of these candidates are made of baryons. If these results are correct, then there may be a significant baryonic component of the Galactic halo. Although a 100% baryonic halo does not seem likely at this point, as much as 30-50% of the halo may be made of baryonic dark matter in the form of Machos (Alcock et al. 1997a).

It is the purpose of this paper to discuss the mass budget associated with such a discovery, by situating the discovery of Machos in a cosmological context. We will obtain a lower limit on the contribution of Machos to the mass density of the universe, and compare that contribution with the baryonic component in the Lyman-α forest and with the total baryonic mass density allowed by nucleosynthesis. We will see that, regardless of what the Machos are, $\Omega_{\text{Macho}}$ is comparable to $\Omega_B$ (where B refers to baryons). As an extreme lower limit, we find that $\Omega_{\text{Macho}} > \frac{h}{6} \Omega_B f_{\text{gal}}$, where $f_{\text{gal}}$ is the fraction of galaxies that contain Machos and $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$. Taking the central values for $\Omega_{\text{Macho}}$ and $\Omega_B$, we find that Machos are the dominant component of baryons in the universe. It is a remarkable consequence of a mere 6 events that they could imply such a large fraction of the baryonic mass budget of the universe. (At the Aspen Workshop on Microlensing in June 1997, Tim Axelrod presented preliminary results from the Macho group’s four year data, where there are about 14 events—see also Cook et al. 1997; these new numbers do not significantly change the conclusions of this paper.)

Then we turn to various candidates for the Machos, and examine the consequences for the mass budget of the universe. First we consider stellar and substellar candidates such as brown dwarfs, red dwarfs and ordinary stars. Next we examine stellar remnants: white dwarfs, neutron stars, and black holes. We focus especially on white dwarfs, as these have been identified as the most popular candidate because of the best-fit Macho mass of 0.5 $M_\odot$. With the hypothesis that the Machos are white dwarfs, we find a naïve estimate of the contribution of the progenitors to the mass density of the universe, i.e., we find $\Omega_*$ (where * refers to progenitors). Accounting for the progenitors increases the initial Galactic gas mass needed to give the present Macho observations. In fact, far too much baryonic material would remain in the Galaxy unless there is a Galactic wind to eject it. If the white dwarfs arise from a single burst of star formation, we find that the main sequence progenitor mass density was at least twice as large as the Macho mass density. We examine the range of overlap between $\Omega_*$ and $\Omega_B$. We also compare with the baryonic content of the intergalactic medium indicated by measurements of the Lyman-α forest. From these baryon abundance arguments alone, we will see that white dwarfs survive as viable Macho candidates, but only if one takes extreme values of the parameters. In addition, as we show below, the mass budget discussed in this paper is difficult to reconcile with the carbon abundance that would be produced by white dwarf progenitors (see also Gibson & Mould 1997).

2. Contribution of Machos to the Mass Density of the Universe

In this section, we make an extrapolation of the microlensing results to a cosmological context. As we argue below, we feel that this extrapolation provides a robust lower limit on the Macho contribution to the mass density of the universe. Microlensing results (Alcock et al. 1997a) predict that the total mass of
Machos in the Galactic halo out to 50 kpc is

\[ M_{\text{Macho}} = (1.3 - 3.2) \times 10^{11} M_\odot. \]  
\[ (1) \]

This result does not strongly depend on the halo model adopted. However, even with a fairly secure value of \( M_{\text{Macho}} \), one can only parlay it into a cosmological constraint by making some assumption about the cosmic distribution of Machos. This in turn requires one to commit at some level to a scheme for the origin and nature of Machos; we will make the different assumptions explicit as we proceed. Should the Halo extend to beyond the LMC at 50 kpc, the numbers in Eq. (1) may provide a lower limit to the total Macho mass in the Halo. Hence our results give a lower limit to \( \Omega_{\text{Macho}} \); still the values are quite large.

In order to determine a lower limit for the contribution of Machos to the mass density of the universe, we will take the following approach. We can obtain a “Macho-to-light ratio” for the Machos in the Galactic Halo; then assuming that the Macho content of our Galaxy is typical of the rest of the luminous universe\(^1\), we can multiply by the average luminosity density of the universe to determine \( \Omega_{\text{Macho}} \). Thus, if one can determine the “Macho-to-light” ratio for the Milky Way, then one can deduce their cosmic density.

The total luminosity of the Milky Way is nontrivial to determine because we are embedded in the Galaxy. One must rely on Galactic luminosity models extrapolated beyond the solar neighborhood, and/or comparisons to similar external galaxies. Estimates based on Galactic values give B-band results \( L_{\text{MW},B} \approx 1.4 \times 10^{10} L_\odot \) (e.g., Bahcall & Soniera [1980]). In addition, placing the Milky Way on the B-band Tully Fisher relation of, e.g., Yasuda, Fukugita, & Okamura (1997) with a Galactic circular velocity \( v_{\text{circ}} = 220 \text{ km s}^{-1} \) gives \( L_{\text{MW},B} = (1.9 \pm 0.6) \times 10^{10} L_\odot \). It is encouraging that these estimates are consistent. We will adopt a Milky Way B-band luminosity in the range

\[ L_{\text{MW},B} = (1.3 - 2.5) \times 10^{10} L_\odot. \]  
\[ (2) \]

Thus, we can derive a Macho mass/Milky Way luminosity ratio of the Macho component of the Milky Way as

\[ \Upsilon_{\text{Macho}} \equiv M_{\text{Macho}}/L_{\text{MW}} = (5.2 - 25) M_\odot/L_\odot. \]  
\[ (3) \]

More precisely, this ratio includes only the Macho mass by the LMC observations, i.e., out to 50 kpc. Any additional Macho population beyond this distance will increase \( \Upsilon_{\text{Macho}} \) and strengthen the arguments below; however, to be conservative we will adopt the lower bound of Eq. (3) as the appropriate value.

From the ESO Slice Project Redshift survey (Zucca et al. [1997]), the luminosity density of the Universe in the \( B \) band is

\[ L_B = 1.9 \times 10^8 h L_\odot \text{ Mpc}^{-3}, \]  
\[ (4) \]

where the Hubble parameter \( h = H_0/(100 \text{ km sec}^{-1} \text{ Mpc}^{-1}) \). If we assume that the \( M/L \) which we defined for the Milky Way is typical of the Universe as a whole, then the universal mass density of Machos is

\[ \rho_{\text{Macho}} = \Upsilon_{\text{Macho}} L_B = (1 - 5) \times 10^9 h M_\odot \text{ Mpc}^{-3}. \]  
\[ (5) \]

The corresponding fraction of the critical density \( \rho_c \equiv 3H_0^2/8\pi G = 2.71 \times 10^{11} h^2 M_\odot \text{ Mpc}^{-3} \) is

\[ \Omega_{\text{Macho}} \equiv \rho_{\text{Macho}}/\rho_c = (0.0036 - 0.017) h^{-1}. \]  
\[ (6) \]

\(^1\)We comment on this assumption below. For example, one might posit that Macho production is a precursor or byproduct of star formation, so that Machos exist in the neighborhood of luminous matter and the result in Eq. (4) is quite accurate. Alternatively one can interpret the result as a lower limit. Below we discuss how representative our Galaxy is of the objects contributing to the luminosity function.
Other alternative techniques for estimating $\Omega_{\text{Macho}}$ are possible as well. Thus far, we have explicitly assumed that Machos trace visible light. If Machos trace dark matter, then the total Macho density can be derived by comparing the total mass of Machos within 50 kpc to the total mass of dark matter within 50 kpc (we consider the additional possibility of biased galaxy formation later). The Macho group has estimated this fraction to be as high as 0.6; thus, $\Omega_{\text{Macho}}$ could be as high as 0.6$\Omega$, where $\Omega$ without a subscript refers to the total mass density of the universe. Clearly this approach is very dependent on the model of the Halo. We note that this estimate is higher than that of Eq. (6) for all reasonable values of $\Omega$, and so we will adopt the more conservative value of Eq. (6) as our lower limit.

After completion of our calculations, we learned of simultaneous and somewhat similar calculations by Fukugita, Hogan, & Peebles (1997), who note that the Macho mass of Eq. (1) is comparable to estimates of the Galactic disk mass: $M_{\text{Macho}} \sim 2M_{\text{disk}}$. This association of Machos with disks is similar to our consideration of the case where only spiral galaxies have Machos in them. They suggest extrapolation of this trend to estimate the minimum Macho fraction of the critical density and find a number which is quite similar to ours.

In any case, we will now proceed to compare our $\Omega_{\text{Macho}}$ derived in Eq. (6) with the baryonic density in the universe, $\Omega_{\text{B}}$, as determined by primordial nucleosynthesis. The compact nature of the Machos strongly suggests they are baryonic; we will assume this throughout this paper. Recently, the status of Big Bang nucleosynthesis has been the subject of intense discussion, prompted both by observations of deuterium in high-redshift quasar absorption systems, and also by a more careful examination of consistency and uncertainties in the theory. At present different groups report different D/H values, e.g. “high” D/H \( \simeq 2 \times 10^{-4} \) (Carswell et al. 1994, Songaila et al. 1994, Webb et al. 1997, Carsswell et al. 1994, Wampler et al. 1996); and “low,” D/H \( = (3.4 \pm 0.3) \times 10^{-5} \) (Burles & Tytler 1998a, Burles & Tytler 1998b). Using the “low” D/H values from Burles & Tytler, one obtains $\Omega_{\text{B}} = (0.019 \pm 0.0014) h^{-2}$ (1$\sigma$ stat error). To be conservative, we will allow for a systematic error equal to the statistical uncertainty; We will use the largest value in this range as our 1$\sigma$ upper limit: $\Omega_{\text{B}} \leq 0.022$. Our lower limit on $\Omega_{\text{B}}$ comes from consideration of observations of other elements. As emphasized by e.g., Fields et al. (1996), the most straightforward extrapolation of primordial $^4$He and $^7$Li from observations is consistent with high but not low D/H and gives $\Omega_{\text{B}} = 0.006^{+0.009}_{-0.001} h^{-2}$.

To conservatively allow for the full range of possibilities, we will therefore adopt

$$\Omega_{\text{B}} = (0.005 - 0.022) h^{-2}. \quad (7)$$

Note the different dependence on $h$ in equations (6) and (7). Despite this fact, we can still affirm that $\Omega_{\text{Macho}}$ and $\Omega_{\text{B}}$ are roughly comparable within this naive calculation. Thus, if the Galactic halo Macho interpretation of the microlensing results is correct, Machos make up an important fraction of the baryonic matter of the Universe. Specifically, the central values in eqs. (6) and (7) give $\Omega_{\text{Macho}}/\Omega_{\text{B}} \sim 0.7$. However, the lower limit on this fraction is considerably smaller and hence less restrictive. Taking the lowest possible value for $\Omega_{\text{Macho}}$ and the highest possible value for $\Omega_{\text{B}}$, we see that

$$\frac{\Omega_{\text{Macho}}}{\Omega_{\text{B}}} \geq \frac{1}{6} h \quad (8)$$

2A discrepancy of a factor of three between their results and ours stems from a different disk luminosity implied by their paper. Fukugita, Hogan, & Peebles (1997) also consider Macho halo fractions approaching 100%, and arrive at cosmic Macho densities which are quite large.
so that

\[ \frac{\Omega_{\text{Macho}}}{\Omega_B} \geq \frac{1}{12}. \tag{9} \]

For completeness, the corresponding upper limit is \( \Omega_{\text{Macho}}/\Omega_B \leq 3 h \). Note that if this were the case (i.e., high \( \Omega_{\text{Macho}} \), low \( \Omega_B \)), then one would conclude that Machos are non-baryonic.

We believe our lower limit on the contribution of Machos to the mass density of the universe to be quite robust. The only way that \( \Omega_{\text{Macho}} \) could be lower than the numbers presented in Eq. (6) would be if the luminosity density observed by Zucca et al. [1997] were dominated by galaxies which do not contain Machos. In other words, our Milky Way would have to be unrepresentative of other galaxies in that it contains exceptionally many Machos. However, the luminosity function observed by Zucca et al. [1997] has most of its light coming from galaxies similar to our own. Hence the lower limit to \( \Omega_{\text{Macho}} \) in Eq. (6) can be reduced by at most a factor of about five, as we will now show. To see this we will adopt the Zucca et al. [1997] luminosity function, which is well-fit by a Schechter function:

\[ \phi(L) dL = \phi_* \left( L/L_* \right)^\alpha \exp(-L/L_*) \frac{dL}{L_*}, \tag{10} \]

where \( \alpha = -1.22^{\pm 0.06}_-0.07 \), and \( L_* = (1.1 \pm 0.07) \times 10^{10} h^{-2} L_{\odot,B} \). Then, to obtain the fraction of Galaxies that do contain Machos, we must integrate this luminosity function over the range of luminosities that we believe are relevant to galaxies that do contain Machos. The fraction of galaxies that contain Machos would then be

\[ f_{\text{gal}} = \frac{L_{\text{Macho}}}{L} = \frac{\int_{L_1}^{L_2} dL \, L \phi(L)}{\int_0^{L_2} dL \, L \phi(L)}. \tag{11} \]

The choice of lower and upper limits of integration (\( L_1 \) and \( L_2 \) respectively) is a matter of taste. In the extreme case where only the Milky Way contains Machos, the range of integration would be so narrow as to obtain a negligible Macho fraction in the universe. However, a very narrow range is needed to make this fraction small: even if Machos only exist in Galaxies within one magnitude of the Milky Way (i.e., \( M_{\text{MW,B}} \pm 1 \text{ mag} \)), this still amounts to 26% of the luminosity density for \( h = 1/2 \) or 50% for \( h = 1 \). Of these galaxies roughly a fraction 0.65 are spiral (Postman and Geller 1985). Thus \( \Omega_{\text{Macho}} \) in Eq. (6) should be reduced by at most a factor of 0.17.

Regardless of the issue of which luminous galaxies contain Machos, there remains a strong possibility that galaxy halos suffer from cosmic biasing. Namely, it not all at clear that the mass-to-light ratio determined at the scale of galaxy halos is representative of the universe as a whole. Indeed, density determinations at the scale of clusters probably demand that mass does not trace light at the halo scale. If so, (and if \( \Omega_0 \approx 1 \)) then there could exist a population of stillborn, dark galaxies or intracluster gas with baryons in them. One possibility is that these dark galaxies contain no stars or Machos. Then, in this case, the amount of baryonic matter available to make Machos only becomes smaller; i.e., \( \Omega_{\text{Macho}} \) becomes an even larger fraction of \( \Omega_B - \Omega_{\text{dark}} \), where \( \Omega_{\text{dark}} \) refers to the dark galaxy component. Alternatively, a second possibility is that these dark galaxies do contain Machos (e.g. left over from an early generation of star formation). In this case Machos trace the dark matter and clearly the \( \Omega_{\text{Macho}} \) in Eq. (6), obtained on the scale of galactic halos, is again an underestimate of the true value. In summary, we feel that the results of Eq. (6-9) are hard to avoid.
3. Comparison with the Lyman-\(\alpha\) Forest

We can compare the Macho contribution to other components of the baryonic matter of the universe. In particular, measurements of the Lyman-\(\alpha\) (Ly\(\alpha\)) forest absorption from intervening gas in the lines of sight to high-redshift QSOs indicate that many, if not most, of the baryons of the universe were in this forest at redshifts \(z > 2\). It is hard to reconcile the large baryonic abundance estimated for the Ly\(\alpha\) forest with \(\Omega_{\text{Macho}}\) obtained previously (Gates, Gyuk, Holder, & Turner [1997]). Although measurements of the Ly\(\alpha\) forest only obtain the neutral column density, careful estimates of the ionizing radiation can be made to obtain rough values for the total baryonic matter, i.e. the sum of the neutral and ionized components, in the Ly\(\alpha\) forest. For the sum of these two components, Weinberg et al. [1997] estimate

\[ \Omega_{\text{Ly}\alpha} \sim 0.02 h^{-3/2}. \] (12)

This number is at present uncertain. For example, it assumes an understanding of the UV background responsible for ionizing the IGM, and accurate determination of the quasar flux decrement due to the neutral hydrogen absorbers. Despite these uncertainties, we will use Eq. (12) below and examine the implications of this estimate.

We can now require that the sum of the Macho energy density plus the Ly\(\alpha\) baryonic energy density do not add up to a value in excess of the baryonic density from nucleosynthesis:

\[ \Omega_{\text{Macho}}(z) + \Omega_{\text{Ly}\alpha}(z) \leq \Omega_B; \] (13)

this expression holds for any epoch \(z\). Unfortunately, the observations of Machos and Ly\(\alpha\) systems are available for different epochs. Thus, to compare the two one must assume that there has not been a tradeoff of gas into Machos between the era of the Lyman systems (\(z \sim 2 - 3\)) and the observation of the Machos at \(z = 0\). That is, we assume that the Machos were formed before the Ly\(\alpha\) systems.

Although Eq. (13) offers a potentially strong constraint, in practice the uncertainties in both \(\Omega_{\text{Ly}\alpha}\) and in \(\Omega_B\) make a quantitative comparison difficult. Nevertheless, we will tentatively use the numbers indicated above. We then have

\[ (\Omega_{\text{Macho}} = 0.007 - 0.04) + (\Omega_{\text{Ly}\alpha} = 0.06) \leq (\Omega_B = 0.02 - 0.09) \quad \text{for } h = 1/2, \] (14)

and

\[ (\Omega_{\text{Macho}} = 0.004 - 0.02) + (\Omega_{\text{Ly}\alpha} = 0.02) \leq (\Omega_B = 0.005 - 0.02) \quad \text{for } h = 1. \] (15)

These equations can be satisfied, but only if one uses the most favorable extremes in both \(\Omega_{\text{Macho}}\) and \(\Omega_B\), i.e., for the lowest possible values for \(\Omega_{\text{Macho}}\) and the highest possible values for \(\Omega_B\).

Recent measurements of Kirkman and Tytler [1997] of the ionized component of a Lyman limit system at \(z=3.3816\) towards QSO HS 1422+2309 estimate an even larger value for the mass density in hot and highly ionized gas in the intergalactic medium: \(\Omega_{\text{hot}} \sim 10^{-2} h^{-1}\). If this estimate is correct, then Eq. (13) becomes even more difficult to satisfy.

One way to avoid this mass budget problem would be to argue that the Ly\(\alpha\) baryons later became Machos. Then it would be inappropriate to add the Ly\(\alpha\) plus Macho contributions in comparing with \(\Omega_B\), since the Machos would be just part of the Ly\(\alpha\) baryons. However, the only way to do this would be to make the Machos at a redshift after the Ly\(\alpha\) measurements were made. Since these measurements extend down to about \(z \sim 2 - 3\), the Machos would have to be made at \(z < 2\). However, this would be difficult to
maneuver. Stellar remnants could not have formed after redshift 2; we would see the light from the stars in galaxy counts (Charlot and Silk 1995) and in the Hubble Deep Field (Loeb 1997).

Until now we have only considered the contribution to the baryonic abundance from the Machos themselves. Below we will consider the baryonic abundance of the progenitor stars as well, in the case where the Machos are stellar remnants. When the progenitor baryons are added to the left hand side of Eq. (13), this equation becomes harder to satisfy. However, we wish to reiterate that measurements of $\Omega_{\text{Ly}}$ are at present uncertain, so that it is possibly premature to imply that Machos are at odds with the amount of baryons in the Ly$\alpha$ forest.

4. On Stellar and Brown Dwarf Macho Candidates

The arguments we presented in the previous sections have been quite general, independent of the nature of the Machos. In particular, they apply to stellar and brown dwarf Macho candidates. Here we outline the existing stellar and substellar candidates. In the next section we discuss stellar remnants, where the mass budget constraints become even more severe.

Before microlensing experiments reported their first results, the community had arrived at a general consensus that the most plausible candidates for baryonic dark matter in the halo of our Galaxy were brown dwarfs (e.g., Hegyi & Olive 1986) or very low mass faint stars (red dwarfs). The low mass tail of the mass function of halo stars was ill-known and it seemed natural that it would rise steeply enough to include large numbers of brown dwarfs (e.g., Carr 1994). This conclusion was strengthened by the analysis of the first microlensing events towards the LMC (Alcock et al. 1996) which had a short time-scale (typically $\leq 40$ days) suggesting that a decent fraction of the halo was composed of objects with mass about $0.1 M_\odot$, very plausibly brown dwarfs.

However, a significant population of red dwarfs (faint low mass hydrogen burning stars) has been ruled out by Hubble Space Telescope data and by parallax data, which simply did not see large numbers of these objects (Bahcall, Flynn, Gould & Kirhakos 1996; Graff & Freese 1996a, 1996b; Dahn et al. 1995). In addition, measurements of the mass function of halo stars showed that the mass function does not rise fast enough (towards low mass) to allow a significant population of brown dwarfs (Méra, Chabrier & Schaeffer 1996; Graff & Freese 1996b). In fact, we found that red dwarfs and brown dwarfs do not constitute more than $\sim 3\%$ of the mass density of the Halo of the Galaxy. These bounds follow from the simple assumption that halo red dwarfs are distributed isotropically. Kerins (1997, 1997) discussed how these bounds on the mass density are weakened if halo red dwarfs are clustered. Kerins has also suggested (reported at the 1998 International Workshop on Gravitational Microlensing) that brown dwarf candidates might remain if their orbits keep them predominantly at large radii (far from the center of the Galaxy).

In addition, all subsequent microlensing events had time-scales longer than the first LMC microlensing event. After two years, the time scales of the events were long enough that the estimated mass of Machos grew to $0.5 M_\odot$, clearly inconsistent with a brown dwarf population (which must have masses $\leq 0.1 M_\odot$; Alcock et al. 1997a). Now, after four years of Macho group runs, events continue to have the large time scales consistent with white dwarfs (D. Bennett, reported at the 1997 Notre Dame microlensing conference).

There are still several other possible stellar or substellar explanations for the microlensing results: A brown dwarf halo in which the component brown dwarfs are on radial orbits would mimic the long time scale events measured by the microlensing groups (Evans 1996). A population of ordinary stars lying on the
line of sight to the LMC could also explain the microlensing signal. Such a population could be due to a tidal tail of the LMC (Zhao 1997; Zaritsky & Lin 1997; but see Gould 1997; Alcock et al. 1997b; Beaulieu & Sackett 1997). However, if we examine only microlensing evidence and Galactic dynamics, white dwarfs are the most promising candidate Machos.

5. Machos as Stellar Remnants: the Mass Budget Constraints from the Macho Progenitors

In this section we will investigate the possibility that Machos are stellar remnants: white dwarfs, neutron stars, or black holes. We will now define and relate a few useful quantities: \( m \) will refer to the initial mass of the main sequence star, which is the progenitor of a remnant having mass \( m_{\text{rem}}(m) \). Unless otherwise specified, all masses are in solar units.

For the Macho mass density contribution discussed above, we here estimate the contribution of Macho progenitors to the mass density of the Universe. We find it useful to define \( r \) to be the ratio of the total mass in Machos to the total mass in progenitors. To do this requires specification of an initial mass function for the Macho progenitors; we will denote this IMF as \( \xi_\star(m) = dN_\star/dm \). The IMF we choose will be different depending on whether the dominant remnant component is a white dwarf or a neutron star. Given a Macho progenitor IMF, we can define

\[
\langle r \rangle = \frac{\int_{M_\odot}^\infty dm \, m_{\text{rem}}(m) \, \xi_\star(m)}{\int_0^\infty dm \, m \, \xi_\star(m)}.
\]  

Equation (16) is closely related to the usual gas return fraction \( R \) by \( \langle r \rangle = 1 - R \). Here \( R \) is the fraction of the progenitor mass returned as gas (i.e., not swept up into the remnant). Our lower limit in the integral in the numerator arises because stars with mass \( M < \sim 1 M_\odot \) will not have completed their stellar evolution in a Hubble time.

5.1. The Case of White Dwarfs

In this section, we focus on the case where the Machos are mostly white dwarfs with a smattering of neutron stars. This choice allows us to be concrete and to evaluate the integrals above. As mentioned previously, white dwarfs appear to be the best fit candidates to the mass estimates of the Macho group. We will show that the ratio of the mass in Machos to progenitors can be at most \( r < 1/2 \) (e.g., \( r = 1/4 \) for the log-normal mass function described below), so that (in a single burst model) the progenitor mass density is at least twice as large as the Macho mass density we have already computed.

Initial Mass Function: The nature and plausibility of the white dwarf progenitor mass function (for brevity, “white dwarf IMF”) is a central issue for (and a major source of objections to) a white dwarf halo scenario. Unfortunately, it is always difficult to derive the IMF empirically, as emphasized in the excellent review by Scalo (1986). An IMF of the usual Salpeter (1955) type, \( \xi_\star(m) \propto m^{-2.35} \) extending to \( m_{\text{min}} \sim 0.1 M_\odot \), is not appropriate, as it would imply a gross overabundance of low mass stars still in the halo. Any white dwarf IMF must be sharply different from any observationally inferred IMF. This difference justifiably strikes many as being a sign of fine tuning required for a white dwarf halo model. However, one should bear in mind the significant model-dependences inherent in deriving any IMF. Also, the star formation theory of Adams and Fatuzzo (1996) predicts that a zero metallicity primordial gas, such as was
present at the time of star formation in the Halo, would form higher mass stars than a nonzero metallicity gas, which formed all the familiar stars.

The dearth of stars in the dark Halo provides a lower limit on the mass of the white dwarf progenitors. The most solid constraint simply demands that the white dwarf progenitors all lived less than the age of the universe ($t_\odot \simeq 11 - 17$ Gyr for most plausible cosmologies). With the mass-lifetime relation of, e.g., Scalo (1986), this translates to a hard lower cutoff mass of $m_{low} \simeq 0.85 - 0.95 M_\odot$. In addition, the white dwarfs themselves have to cool off in the age of the universe in order to explain why they are not seen in a recent search of the Hubble Deep Field (Flynn, Bahcall, and Gould 1996) and in a ground based search by Liebert, Dahn, and Monet (1988). Looking at Figure 6 in Graff, Laughlin, and Freese (1997), one can see that white dwarfs with progenitors lighter than $1 M_\odot$ would not have been able to cool off enough in 18 Gyr to avoid detection in these two surveys, unless white dwarfs constitute less than $4 \times 10^{-4} M_\odot$ pc$^{-3}$, roughly 4% of the Halo. The precise lower limit on the progenitor mass in order for the white dwarfs to have cooled sufficiently depends on the correct number for the age of the universe as well as on the Halo model. For example, white dwarfs that constitute at least $10^{-3} M_\odot$ pc$^{-3}$ would have cooled off sufficiently in 13 Gyr if their progenitors were more massive than $1.5 M_\odot$. Because of these uncertainties, we will consider a range of lower limits on the progenitor mass in our calculations below.

The upper limit to the white dwarf IMF is not as strong. By assumption, we wish white dwarfs to be the most numerous halo remnants. Thus we want an IMF with most of the progenitors less massive than $m_{WD,max} \simeq 8 M_\odot$, since progenitor stars heavier than $\sim 8 M_\odot$ explode as supernovae and become neutron stars. Adams and Laughlin (1996) take this mass as an upper bound, since they view neutron stars as unwanted. However, having some high mass stars is permissible and even desirable (Miralda-Escudé & Rees 1997; Gnedin & Ostriker 1997): high redshift supernovae are required to produce the metals $Z \sim 10^{-2} Z_\odot$ seen in quasar absorption lines of quasars at redshift $z < \sim 5$. The supernovae may also provide a Galactic wind to eliminate excess metals and mass ($\S$ 5.2). The upper limit is thus model-dependent, aside from the basic requirement of white dwarf (rather than neutron star) dominance.

Within these general mass limits, there remains considerable freedom for the form of the white dwarf IMF. Fortunately, we find that one can already make interesting statements about the white dwarf progenitors just using these limits. Further constraints must rely on theoretically derived IMFs, or on the details of the halo white dwarf scenario one adopts. For example, Adams and Laughlin (1996) use a log-normal mass function motivated by Adams & Fatuzzo’s (1996) theory of the IMF:

$$\ln \xi_*(\ln m) = A - \frac{1}{2\langle \sigma \rangle^2} \left\{ \ln (m/m_C) \right\}^2. \quad (17)$$

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. For illustration, we adopt their white dwarf IMF 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 if supernovae are to be excluded (but see above).

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 $m_{WD}(1 M_\odot) = 0.55 M_\odot$, and
\( m_{WD}(8M_\odot) = 1.2M_\odot \). The key point we will use below is that the “remnant fraction” relative to the progenitor mass, \( m_{\text{rem}}/m \), is a monotonically decreasing function of \( m \).

**White Dwarf Progenitor Mass Budget:** Our goal is to estimate the contribution of the white dwarf progenitors to the mass density of the universe. Given \( \Omega_{\text{Macho}} \) from the previous sections, we now need to compute the remnant fraction \( \langle r \rangle \) of Eq. (16). Despite the freedom in choosing the white dwarf IMF as discussed above, interesting and general limits to \( \langle r \rangle \) still emerge. We will bound the possible values for \( \langle r \rangle \) in the following way. Consider the remnant fraction at a given mass, \( r(m) = m_{\text{rem}}(m)/m \). One can rewrite Eq. (16) as

\[
\langle r \rangle = \frac{\int dm \, r(m) \, m_{\xi}(m)}{\int dm \, m_{\xi}(m)}.
\]

In this form one can see that \( \langle r \rangle \) is a weighted average of \( r(m) \) where \( m_{\xi}(m) \) is the weighting function. Then if \( r(m) \) has a maximum (minimum) at some \( m \), then the weighted average \( \langle r \rangle \) is always greater than (less than) this extremum. But \( m_{\text{rem}}(m)/m \) is maximized for the lowest allowed progenitor mass, \( m_{\text{min}} \). If \( m_{\text{min}} = (1,1.5,2)M_\odot \), then correspondingly \( r_{\text{max}} = (0.55,0.38,0.33) \), i.e., white dwarfs are at most about half of the progenitor mass. Similar arguments apply to finding a minimum value for \( \langle r \rangle \); we find \( \langle r \rangle > r_{\text{min}} = 0.15 \), for \( m_{\text{max}} = 8M_\odot \). The most conservative case is the one that gives the lowest progenitor mass density \( \Omega_* \), as would be obtained with \( r_{\text{max}} \), the largest possible value for \( \langle r \rangle \). We have found the range of possible values for \( \langle r \rangle \), and we see that \( M_* = M_{\text{Macho}}/\langle r \rangle \geq 2M_{\text{Macho}} \). Thus, for every unit mass of Machos formed, at least as much mass is ejected as gas as swept into remnant Machos. For comparison, if we use the Adams & Laughlin (1996) log-normal IMF in Eq. (17), we find \( R = 0.75 \) and \( \langle r \rangle = 0.25 \), which implies that three times as much mass is ejected as gas as is swept into remnants.

We note that Fields, Mathews & Schramm (1997) used an IMF of the same log-normal form as Eq. (17), but with a larger width: \( \langle \sigma \rangle = 1.6 \). This gave a return fraction of \( R = 0.375 \). In their model, the quantity of gas ejected was only about half the total Macho mass. Thus, for a given total mass in Machos, the Fields, Mathews and Schramm model produced only one fifth as much returned gas as would be produced by the canonical Adams & Laughlin mass function. This comes about largely due to the assumption that the white dwarf IMF extends above \( 8M_\odot \) to include a significant fraction of massive stars that are above the Bethe & Brown (1995) 18\( M_\odot \) cutoff for direct black hole formation. While these black holes are rare in number compared to white dwarfs, in fact they carry a significant fraction of the mass from the Fields, Mathews & Schramm (1997) IMF.

Having derived constraints on \( \langle r \rangle \), we must still specify more information about the white dwarf formation to constrain the progenitor mass. Specifically, we must address the issue of reprocessing of the gas ejected when the white dwarfs are formed.

**Single Burst Model:** If we assume that Machos were born in a single burst, then that portion of the mass of the progenitor stars which does not go into the remnants cannot be used for subsequent formation of Machos. Then we can immediately infer the progenitor density \( \rho_* \) from the Macho density via Eq. (16): \( \rho_* = (\langle r \rangle)^{-1} \rho_{\text{Macho}} \). Thus, the upper limit \( r_{\text{max}} = 0.55 \) (for \( m_{\text{min}} = 1M_\odot \)) now gives a lower limit to the progenitor density,

\[
\rho_* \geq \frac{1}{r_{\text{max}}} \rho_{\text{Macho}} = (2 - 9) \times 10^9 h \ M_\odot \ Mpc^{-3}
\]

which corresponds to

\[
\Omega_* \geq (0.007 - 0.034)h^{-1}.
\]

If we adopt \( m_{\text{min}} = 1.5M_\odot \) as suggested by white dwarf cooling arguments, this bound increases by 30%. If the white dwarf IMF is specified, these expressions become equalities. For example, with the IMF of Eq.
(17), we have \( R = 0.75 \) and \( \langle r \rangle = 0.25 \) so that the total mass density of the progenitors was roughly four times higher than the mass density of the remnant Machos, and \( \Omega_* = (0.016 - 0.08) h^{-1} \).

The highest \( \Omega_B \) from BBN in Eq. (7) would be consistent with the lowest \( \Omega_* \) from the simple extrapolation above if \( h < 0.9 \). Thus there is a range of overlap between the two estimates, if one takes the low estimates of \( D/H \) and low total Macho mass \( \Omega_{\text{Macho}} \). Since these ranges for the Hubble constant and \( D/H \) are, if anything, currently favored, this situation is not so unattractive. Of course, the mass budget must include all types of baryons, in particular, those in the IGM (Eq. 13). However, the relationship between \( \Omega_* \) and \( \Omega_{\text{IGM}} \) depends on the scenario for white dwarf formation; if the white dwarf progenitors are born at high redshift, the net ejecta \( \Omega_* - \Omega_{\text{Macho}} \) becomes part of the IGM, and thus should not be double counted in the mass budget (but see also nucleosynthesis issues in §5.3).

**Recycling:** As an alternative to the model discussed above in which all of the Machos were created in a single burst, there is the possibility of recycling. In the recycling scenario, much of the mass let out by high mass Macho progenitors is incorporated in the next generation of stars. This would allow us to make more Machos with less gas, and have less intergalactic gas left over too. However, packing most of the gas into white dwarfs through several star formation generations could create too much helium (Ryu, Olive & Silk 1990). In addition, as discussed earlier, \( \Omega_{\text{IGM}} \sim 0.02 h^{-3/2} \) of gas should be left over after the Macho formation epoch to form the intergalactic medium (Weinberg, Miralda-Escudé, Hernquist & Katz 1997). The chemical evolution of a recycling scenario should be considered further. The fact that a large fraction of baryons must be cycled through the Machos and their progenitors must be taken into account when attempting to dilute the chemical by-products of such a large population of intermediate mass stars. Further discussion of this issue follows shortly.

### 5.2. Galactic Winds

The white dwarf progenitor stars return most of their mass in their ejecta, i.e., planetary nebulae composed of processed material. Both the mass and the composition of the material are potential problems. As we have emphasized, the cosmic Macho mass budget is a serious issue; here we see that it is significant even when one considers only the Milky Way.

One can use \( \langle r \rangle \) to derive not only cosmological limits, but also local ones. Given the \( M_{\text{Macho}} \) of Eq. (1), a burst model requires the total mass of progenitors in the Galactic Halo (out to 50 kpc) to have been at least twice the total mass in remnant white dwarfs, i.e., \( M_* \geq M_{\text{Macho}}/r_{\text{max}} = (2.4 - 5.8) \times 10^{11} M_\odot \). The gas that is ejected by the Macho progenitors is collisional and tends to fall into the Disk of the Galaxy. But the mass of the ejected gas \( M_{\text{gas}} = M_* - M_{\text{Macho}} \sim M_{\text{Macho}} \) is at least as large as the mass \( \sim 10^{11} M_\odot \) of the Disk and Spheroid of the Milky Way combined. For a value of \( \langle r \rangle \) less than \( r_{\text{max}} \), the gas ejected by the Macho progenitors exceeds the mass of the Disk and Spheroid. Thus the Galaxy’s baryonic mass budget—including Machos—immediately demands that some of the ejecta be *removed* from the Galaxy.

This requirement for outflow is intensified when one considers the composition of the stellar ejecta. It will be void of deuterium, and will include large amounts of the nucleosynthesis products of \((1 - 8) M_\odot\) white dwarf progenitors, notably: helium, carbon, and nitrogen (and possibly s-process material). To reduce these abundances to acceptably low levels requires some degree of *dilution*: mixing the ejecta with material that has not gone into stars. In other words, the efficiency of star formation (in terms of mass into stars compared to total available mass) must be small. This implies that there is additional gas mass associated with the white dwarfs, but not coming from the white dwarfs or their progenitors. This mass too
must be partially (mostly!) removed to respect the observed disk and bulge baryon budget. Thus we see that a “closed box” model of white dwarf Macho formation fails for the Galaxy. Some means of gas outflow is needed.

A possible means of removing these excess baryons is a Galactic wind. 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 Lyα forest. Thus, it seems mandatory that many galaxies do manage to shed hot, processed material. Of course, it is considerably more difficult to construct a detailed scenario which quantitatively shows that the gas temperatures and compositions, generated concurrently with white dwarf Machos, are consistent with the observations. There are serious problems in matching the carbon abundances arising from white dwarf progenitors with the carbon abundances in the Lyα forest and elsewhere, as we discuss in §5.3.

Before constructing a detailed model, one can deduce several necessary features of a white dwarf + wind scenario. (1) Outflow presumably requires massive stars as an energy source; these must be included in the halo IMF. They will thus contribute supernova products to the wind composition. Indeed, such elements are present in observed, wind-ejected material: intracluster X-ray gas contains iron, oxygen, and other α-chain elements coming from supernovae (e.g., Mushotzky et al. 1996). (2) For the wind to be effective, it must remove material ejected from a large fraction of the planetary nebulae formed. But the winds are driven by shorter-lived, massive stars which explode as supernovae. This implies that the progenitors cannot have all formed simultaneously, so that some massive stars are left to explode as the planetaries appear. Such an arrangement requires an extended burst of star formation, lasting roughly $t_{\text{burst}} \sim \tau(m_{\text{min}})$, the age of the longest lived white dwarf progenitor. This could be as long as 1 Gyr (for $m_{\text{min}} = 2M_\odot$), unless $m_{\text{min}}$ is larger (reducing the timescale but raising the total progenitor mass that must then be removed). (3) It is clear solely from considerations of the implied progenitor mass budget, and from the further need to dilute the ejecta composition, that white dwarf halos cannot be where most of the universe’s baryons reside. Thus, white dwarf halos, if they exist, would be only the tip of the baryonic iceberg—i.e., the white dwarfs themselves would represent only a minority of the baryons needed to accommodate their formation and associated pollution.

Of course, we have only considered the need for outflow in the burst approximation, in which all progenitors are formed before any have died and returned their ejecta. In cases with recycling, the total mass budget is reduced since the ejecta of successive generations become grist for new stars. However, where recycling alleviates the mass problem, it exacerabates chemical composition problems. That is, the contamination of the gas due to stellar nucleosynthesis processing is compounded as the gas is recycled. Thus abundance constraints (§5.3) work to require dilution and to limit recycling, at odds with the need for baryonic parsimony. The result is that outflow is still needed even in a recycling model.

5.3. On Carbon

The issue of carbon (Gibson & Mould 1997) produced by white dwarf progenitors is complex. We present here a simple estimate of the difficulties of reconciling the carbon production with the baryonic abundance of Machos. Stellar carbon yields for zero metallicity stars are quite uncertain. Still, according to the Van den Hoek & Groenewegen (1997) yields, a star of mass 2.5 will produce $1.26M_\odot$ of ejecta of which 0.012$M_\odot$ is carbon, for an ejected mass fraction of $10^{-2}$. In comparison, the sun has a carbon enrichment
of $4.4 \times 10^{-3}$. In other words, the ejecta of a typical intermediate mass star has about twice the solar enrichment of carbon. If a substantial fraction of all baryons pass through intermediate mass stars, the carbon abundance in this model will be near solar.

It is possible (although not likely) that carbon never leaves the white dwarf progenitors, so that carbon overproduction is not a problem (Chabrier, private communication). 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. For the remainder of this section, we will assume that carbon does leave the white dwarf progenitor stars.

Then overproduction of carbon can be a serious problem, as emphasized by Gibson & Mould (1997). They noted that stars in our galactic halo have carbon abundance in the range $10^{-4} - 10^{-2}$ solar, and argued that the gas which formed these stars cannot have been polluted by the ejecta of a large population of white dwarfs. The galactic winds discussed in the previous section could remove carbon from the star forming regions and mix it throughout the universe.

However, carbon abundances in intermediate redshift Lyα forest lines have recently been measured to be quite low. Carbon is indeed present, but only at the $\sim 10^{-2}$ solar level, (Songaila & Cowie 1996) for Lyα systems at $z \sim 3$ with column densities $N \geq 3 \times 10^{15}$ cm$^{-2}$. Furthermore, in an ensemble average of systems within the redshift interval $2.2 \leq z \leq 3.6$, with lower column densities $(10^{13.5} \text{ cm}^{-2} \leq N \leq 10^{14} \text{ cm}^{-2})$, the mean C/H drops to $\sim 10^{-3.5}$ solar (Lu, Sargent, Barlow, & Rauch 1996). 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.

The forest lines discussed in these references sample the high-z neutral intergalactic medium. 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. We will use the more conservative $10^{-2}$ solar values, which provide the weaker constraints. These values are quite plausible as well, since the higher column density systems are more typical of regions of high star formation, wherein white dwarf progenitors might be formed. 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 our results in section 2 for the remnant density predicted from our extrapolation of the Macho group results, and would be in conflict with $\Omega_*$ in the case of a single burst of star formation. The simple discussion we have presented here has considered only the simplest (but most plausible) white dwarf formation and evolution scenario. More detailed investigation is required. However, we stress the difficulty of reconciling the Macho mass budget with the accompanying carbon production in the case of white dwarfs.

5.4. Neutron Stars

The first issue raised by neutron star Macho candidates is their compatibility with the microlensing results. Neutron stars ($\sim 1.5M_\odot$) and stellar black holes ($\gtrsim 1.5M_\odot$) are more massive objects, so that one would typically expect longer lensing timescales than what is currently observed in the microlensing experiments (best fit to $\sim 0.5M_\odot$). As discussed by Venkatesan, Olinto, & Truran (1998), one must posit
(1) that the microlensing events observed thus far only detect the low-mass tail of a distribution that includes significantly more massive objects; and (2) that as the experiments continue to take measurements, longer timescale events should begin to be seen. In this regard, it is intriguing that the first SMC results (Palanque-Delabrouille et al. 1998; Alcock et al. 1997c) suggest lensing masses of order $\sim 2M_\odot$. If indeed the present microlensing results miss a higher mass lensing population, then the halo Macho mass has been underestimated; thus the baryonic budget constraints we have derived would be strengthened.

Even with the Galactic Macho mass we adopt in Eq. (1), the central issues for neutron stars are the baryonic budget, and the chemical composition of the stellar ejecta. One expects the progenitor mass requirements to be significantly worse than for white dwarfs, since for neutron stars, $r(m) = m_{\text{rem}}/m \leq m_{\text{NS}}/m_{\text{SN,min}} \sim 1.5M_\odot/8M_\odot = 0.2$; thus the mass density in progenitors must be at least 5 times the neutron star mass density (cf. Eq. (19), and consistency with the upper bounds on $\Omega_B$ become hard to satisfy. However, Venkatesan, Olinto, & Truran (1998) note that this limit is reduced in some scenarios of stellar black hole formation. The models they consider have remnant masses that smoothly increase with the progenitor mass; to give a rough example of the effect, we note that allowing ejecta-free black holes to form at masses $> 30M_\odot$, increases the mean remnant mass so that $\langle r \rangle = 0.24 - 0.36$. The composition of the ejecta will be highly metal rich, in a situation similar to the carbon problem with white dwarfs. Here, however, the higher yields are also directly associated with explosive heating that could drive winds.

Venkatesan, Olinto, & Truran (1998) discuss a scenario wherein a burst of early, massive ($\gtrsim 10M_\odot$) star formation leads to neutron star, black hole, and metal production. The metallicity of the ejecta is typically much larger than solar, with the best case being a zero initial metallicity model, which has ejecta abundances of 1.3 times solar. Venkatesan, Olinto, & Truran (1998) compute the mass dilution needed to reduce the mean metallicity to solar, which is at the high end of the metallicities found in intracluster and intragroup gas. The total initial mass needed for this dilution is found to be compatible with $\Omega_B$ if most baryons participated either in this star formation burst or in the associated dilution. Furthermore, most of the baryons end up in intragroup hot gas, so the Local Group mass budget constraints could be met as well. However, assuming this evolution history is typical, it is not clear how to reconcile this scenario with the IGM abundances as determined by the Ly$\alpha$ absorption systems. As discussed in §5.3, these systems show typical abundances at least two orders of magnitude below solar. If one requires that the massive star ejecta be diluted to this level, then the baryonic requirements become prohibitive. More baryons are required to dilute the ejecta than are allowed by nucleosynthesis.

6. Conclusions

If Machos are indeed found in halos of galaxies like our own, we have found that the cosmological mass budget for Machos requires $\Omega_{\text{Macho}}/\Omega_B \geq \frac{1}{4}h f_{\text{gal}}$, where $f_{\text{gal}}$ is the fraction of galaxies that contain Machos, and quite possibly $\Omega_{\text{Macho}} \approx \Omega_B$. Thus a stellar explanation of the microlensing events requires that a significant fraction of baryons cycled through Machos and their progenitors. If the Machos are white dwarfs that arose from a single burst of star formation, we have found that the contribution of the progenitors to the mass density of the universe is at least a factor of two higher, probably more like three or four. We have made a comparison of $\Omega_B$ with the combined baryonic component of $\Omega_{\text{Macho}}$ and the baryons in the Ly$\alpha$ forest, and found that the values can be compatible only for the extreme values of the parameters. However, measurements of $\Omega_{\text{Ly} \alpha}$ are at present uncertain, so that it is perhaps premature to imply that Machos are at odds with the amount of baryons in the Ly$\alpha$ forest. In addition, we have stressed the difficulty in
reconciling the Macho mass budget with the accompanying carbon production in the case of white dwarfs. The overproduction of carbon by the white dwarf progenitors can be diluted in principle, but this dilution would require even more baryons that have not gone into stars. At least in the simplest scenario, in order not to conflict with the upper bounds on $\Omega_B$, this would require an $\Omega_{\text{Macho}}$ slightly smaller than our lower limits from extrapolating the Macho results. Only $10^{-2}$ of all baryons can have passed through the white dwarf progenitors, a fraction that is in conflict with our results for $\Omega_\ast$.

There is a certain amount of irony in the following: There is as yet no detection of nonbaryonic dark matter, yet there is an abundance of attractive candidate particles and galaxy formation scenarios for these particles. Here, on the other hand, we have been taking seriously the possibility that a baryonic dark matter component has been detected as Machos, yet no candidates seem able to convincingly explain both local and cosmological observations, though white dwarf candidates still survive at the limits of the uncertainties. Should stellar candidates be definitively ruled out, this would be a very interesting state of affairs—indeed more so than if the Halo is made of brown dwarfs or even white dwarfs. If it becomes clear that the stellar or remnant contributions to the mass density of the Halo are small, then either (1) Machos are insignificant in the Halo, which means the Halo is made of non-baryonic dark matter, or (2) Machos are significant in the Halo, but they are in an exotic form of baryons or are not baryonic (e.g., primordial black holes). Either way, the halo could well be made of very different stuff than we are. At present, however, a stellar explanation (including white dwarfs) for Machos survives as a possibility, albeit with the difficulties pointed out in the paper.

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REFERENCES

Adams, F.C., & Fatuzzo, M. 1996, ApJ, 464, 256
Adams, F.C., & Laughlin, G.P. 1996, ApJ, 468, 58
Alcock, C., et al. 1996, ApJ, 461, 84
———. 1997a, ApJ, 486, 697
———. 1997b, ApJ 490, L59
———. 1997c, ApJ, 491, L11
Bahcall, J.N. & Soniera, R. 1980, ApJS, 44, 96
Bahcall, J.N., Flynn, C., & Gould, A., & Kirhakos, S., 1994, ApJ, 435, L51
Beaulieu J.P. & Sackett, P.D. 1997, AJ submitted (astro-ph/9710156)
Bethe, H.A., & Brown, G.E., 1995, ApJ, 445, L12
Burles, S. & Tytler, D. 1998, ApJ, in press [astro-ph/9712108]
———. 1998, ApJ, in press [astro-ph/9712109]
Carr, B. 1994, ARAA, 32, 531
Carswell, R., Rauch, M., Weymann, R.J., Cooke, A.J., & Webb, J.K. 1994, MNRAS, 268, L1
Carswell, R.F., et al. 1996, MNRAS, 278, 518
Charlot, S., & Silk, J. 1995, ApJ, 445, 124
Cook, K., et al. 1997, BAAS, 191, 83.01
Copi, C.J., Schramm, D.N., & Turner, M.S. 1994, Science, 267, 192
Dahn, C.C., Liebert, J., Harris, H.C., & Guetter, H. H. 1995, in The Bottom of the Main Sequence and Beyond, ed. C.G. Tinney (Heidelberg: Springer), 239.
Evans, N.W. 1996, MNRAS, 278, L5
Fields, B.D., Kainulainen, K., Olive, K.A., & Thomas, D. 1996, New Astronomy, 1, 77
Fields, B.D., Mathews, G.J., & Schramm, D.N., 1997, ApJ, 483, 625
Flynn, C., Bahcall, J., and Gould, A. 1996, ApJ, 466, L55
Fukugita, M., Hogan, C.J., & Peebles, P.J.E. 1997, ApJ, submitted [astro-ph/9712020]
Gates, E.I., Gyuk, G., Holder, G.P., & Turner, M.S. 1997, ApJL, submitted [astro-ph/9711110]
Gnedin, N.Y., & Ostriker, J.P. 1997, ApJ, 474, 223
Gibson, B.K., & Mould, J.R., 1997, ApJ, 482, 98
Gould, A. 1997, ApJL, submitted [astro-ph/9709263]
Graff, D.S., & Freese, K. 1996a, ApJ, 456, L49
———. 1996b, ApJ, 467, L65
Hegyi, D.J., & Olive, K.A. 1986, ApJ, 300, 492
Iben, I., & Tutukov, A.V. 1984, ApJS, 54, 335
Kerins, E.J. 1997, A&A, 322, 709
———. A&A, 328, 5
Kirkman, D. & Tytler, D. 1997, ApJ, 489, L123
Liebert, J., Dahn, C. C., & Monet, D.G. 1988, ApJ, 332, 891
Loeb, A. 1997 [astro-ph/9704290]
Lu, L., Sargent, W.L.W., Barlow, T.A., & Rauch, M. 1998, AJ, submitted (astro-ph/9802189)
Méra, D., Chabrier, G., & Schaeffer, R. 1996, Europhys. Lett., 33, 327
Miralda-Escudé, J., & Rees, M.J. 1997, ApJ, 478, 57
Mushotzky, R., et al. 1996, ApJ, 686, 694
Palanque-Delabrouille, et al. 1998, A&A, in press (astro-ph/9710194)
Persic, M., & Salucci, P. 1988, MNRAS, 234, 131
Renault et al. 1997, A&A, 324, 69
Ryu, D., Olive, K.A., & Silk, J. 1990, ApJ, 353, 81
Salpeter, E.E., 1955, ApJ, 121, 161
Scalo, J.M. 1986, Fund. Cosmic Phys., 11, 1
Songaila, A., Cowie, L.L., Hogan, C., & Rugers, M. 1994, Nature, 368, 599
Songaila, A., & Cowie, L.L. 1996, AJ, 112, 335
Wampler, E.J., et al. 1996, A&A 316, 33
Webb, J.K., et al. 1997, Nature, 388, 250
Weinberg, D.H., Miralda-Escudé, J., Hernquist, L., & Katz, N. 1997, ApJ, 564
van den Hoek, L.B., & Groenewegen, M.A.T. 1997, A&AS, 123, 305
van der Kruit, P.C., in The Milky Way as a Galaxy, (University Science, Mill Valley), 331
Venkatesan, A, Olinto, A.V., & Truran, J.W. 1998, ApJ submitted (astro-ph/9705091)
Yasuda, N., Fukugita, M., & Okamura, S. 1997, ApJS, 108, 417
Zaritsky, D., & Lin, D.N.C. 1997, AJ in press (astro-ph/9703097)
Zhao, H. 1997 (astro-ph/9703097)
Zucca, E., et al. 1997, A&A, 326, 477

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