LIMITS ON STELLAR OBJECTS AS THE DARK MATTER OF OUR HALO: NONBARYONIC DARK MATTER SEEMS TO BE REQUIRED

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Abstract. The nature of the dark matter in the Halo of our Galaxy remains a mystery. Arguments are presented that the dark matter does not consist of ordinary stellar or substellar objects, i.e., the dark matter is not made of faint stars, brown dwarfs, white dwarfs, or neutron stars. In fact, faint stars and brown dwarfs constitute no more than a few percent of the mass of our Galaxy, and stellar remnants must satisfy $\Omega_{\text{WD}} \leq 3 \times 10^{-3} h^{-1}$, where $h$ is the Hubble constant in units of 100 km $s^{-1}$ Mpc$^{-1}$. On theoretical grounds one is then pushed to more exotic explanations. Indeed a nonbaryonic component in the Halo seems to be required.

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, in the last few years, these candidates have been ruled out as significant components of the Galactic Halo. I will discuss limits on these stellar candidates, and argue for my personal conviction that: Most of the dark matter in the Galactic Halo must be nonbaryonic.

Until recently, stellar candidates for the dark matter, including faint stars, brown dwarfs, white dwarfs, and neutron stars, were extremely popular. 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 [11]; Graff and Freese [35]; Graff and Freese [36]; Mera, Chabrier and Schaeffer [38]; Flynn, Gould, and Bahcall [27]; and Freese, Fields, and Graff [28]). Specifically, using Hubble Space Telescope and parallax data (with some caveats mentioned in the text), we showed that faint stars and brown dwarfs contribute no more than 1% of the mass density of the Galaxy. Microlensing experiments, which
were designed to look for Massive Compact Halo Objects (MACHOs), also failed to find these light stellar objects and place strong limits on dark matter candidates in the \((10^{-7} - 10^{-2})M_\odot\) mass range.

Recently white dwarfs have received attention as possible dark matter candidates. Interest in white dwarfs has been motivated by microlensing events interpreted as being in the Halo, with a best fit mass of \(\sim 0.5M_\odot\). However, I will show that stellar remnants including white dwarfs and neutron stars are extremely problematic as dark matter candidates, due to a combination of mass budget issues and chemical abundances (Fields, Freese, and Graff 1998): A significant fraction of the baryons of the universe would have to be cycled through the white dwarfs (or neutron stars) and their main sequence progenitors; however, in the process, an overabundance of carbon and nitrogen is produced, far in excess of what is observed both inside the Galaxy and in the intergalactic medium. Agreement with measurements of these elements in the Ly\(\alpha\) forest would require \(\Omega_{WD}h \leq 2 \times 10^{-4}\). Throughout, \(h\) is the Hubble constant in units of \(100 \text{ km s}^{-1} \text{ Mpc}^{-1}\). Some uncertainty in the yields of C and N from low metallicity stars motivated us (Fields, Freese, and Graff 1999) to look also at D and He\(^4\), whose yields are far better understood. The abundances of D and He\(^4\) can be kept in agreement with observations only for low mass white dwarf progenitors \((m_{\text{prog}} \sim 2M_\odot)\) and \(\Omega_{WD} < 0.003\). In addition, another constraint arises from considering the contribution of white dwarf progenitors to the infrared background. If galactic halos contain stellar remnants, the infra-red flux from the remnant progenitors would contribute to the opacity of multi-TeV \(\gamma\)-rays. But the HEGRA experiment does see multi-TeV \(\gamma\)-rays from the blazar Mkn501 at \(z=0.034\). By requiring that the optical depth due to \(\gamma\gamma \rightarrow e^+e^-\) be less than 1 for a source at \(z=0.034\), we limit the cosmological density of stellar remnants (Graff, Freese, Walker, and Pinsonneault 1999), \(\Omega_{WD} \leq (1-3) \times 10^{-3}h^{-1}\). Hence white dwarfs, brown dwarfs, faint stars, and neutron stars are either ruled out or extremely problematic as dark matter candidates.

Then the puzzle remains: What are the 14 MACHO events that have been interpreted as being in the Halo of the Galaxy? Are some of them actually located elsewhere, such as in the LMC itself? These questions are currently unanswered. As regards the dark matter in the Halo of our Galaxy, one is driven to nonbaryonic constituents as the bulk of the matter. Possibilities include supersymmetric particles, axions, primordial black holes, or other exotic candidates.

1.1. Microlensing Experiments

The MACHO (Alcock et al. [3], [4]) and EROS (Ansari et al. [8]) experiments have attempted to find the dark matter of our Galactic Halo by monitoring millions of stars in the neighboring Large Magellanic Cloud (LMC), which is approximately (45 – 60) kpc away; they have monitored stars in the Small Magellanic Cloud (SMC) as well. When a Macho crosses the line of sight between a star in the LMC and us, the Macho’s gravity magnifies the light of the background star. The background star gets temporarily brighter and then dims back down. The Macho acts as a lens for the background star. The duration of the event scales as \(\Delta t \propto \frac{m}{v}\), where \(m\) is the mass of the Macho and \(v\) is the velocity perpendicular to the line of sight. Thus there is a degeneracy in the interpretation of the data between \(m\) and \(v\). To break the degeneracy, one has to assume a galactic model, e.g., one has to assume that the lenses are in the Halo of our Galaxy. The three events in the first year MACHO data
had a typical timescale of 40 days, which corresponds (with the above assumption)
to a best fit mass for the Machos of $\sim 0.1M_\odot$. With reanalysis and more data, four
years of data yield 14 events of longer duration, 35-150 days (T. Axelrod [1]; this is
the Einstein diameter crossing time). Thus the new best fit mass is roughly

$$m \sim 0.5M_\odot.$$ 

From the experiments, one can estimate what fraction of the Halo is made of
Machos. Using isothermal sphere models for the Galaxy with the two year data, the
Macho group estimated that 50% (+30%, -20%) of the Halo could be made of Machos.
However, this estimate depends sensitively on the model used for the Galaxy. Gates,
Gyuk, and Turner [30] ran millions of models and found that the number of models vs.
Halo mass fraction peaks at Machos comprising (0-30)% of the Halo, with virtually
no models compatible with a 100% Macho Halo.

Hence there is evidence that a **nonbaryonic** component to the Halo of our Galaxy
is required. Microlensing experiments have ruled out a large class of possible baryonic
dark matter components. Substellar objects in the mass range $10^{-7}M_\odot$ all the way
up to $10^{-2}M_\odot$ are ruled out by the experiments. In this talk I will discuss the heavier
possibilities in the range $10^{-2}M_\odot$ to few $M_\odot$.

2. **Baryonic Candidates**

In this talk I will concentrate on baryonic candidates. Hegyi and Olive [41] ruled out
large classes of baryonic candidates. See also the work of Carr [16]. Until recently the
most plausible remaining possibilities for baryonic dark matter were

- Red Dwarfs ($0.2M_\odot > \text{mass} > 0.09M_\odot$). These are stars just massive enough to
  burn hydrogen; they shine due to fusion taking place in the core of the star. Thus
  these are very faint stars.

- Brown Dwarfs (mass $< 0.09M_\odot$). These are sub-stellar objects that cannot burn
  hydrogen. They are too light to have fusion take place in the interior.

- White Dwarfs (mass $\sim 0.6M_\odot$). These are the end-products of stellar evolution for
  stars of mass $< 8M_\odot$.

In this talk, I will present limits on red dwarfs (Graff and Freese 1996a), brown
dwarfs (Graff and Freese 1996b), and white dwarfs (Graff, Laughlin, and Freese [8];
Fields, Freese, and Graff [23]; Fields, Freese, and Graff [24]; Graff, Freese, Walker,
and Pinsonneault [37]) as candidates for baryonic dark matter.

3. **Faint Stars and Brown Dwarfs**

The number of stellar objects grows with decreasing stellar mass; Hence, until
recently, there was speculation that there might be a large number of faint stars
or brown dwarfs that are just too dim to have been seen. However, as I will argue
these candidates (modulo caveats below) have now been ruled out as dark matter
candidates. Faint stars and brown dwarfs constitute no more than a few percent of
the mass of our Galactic Halo.

3.1. **Faint Stars**

First we used Hubble Space Telescope data (Bahcall, Flynn, Gould, and Kirhakos
1994) to limit the mass density in red dwarfs to less than 1% of the Halo (Graff and
The data of Bahcall et al (1994) from HST examined a small deep field and measured the relative magnitudes of stars in the V and I bands. We used the six stars that were seen with $1.7 < V - I < 3$ to limit the density of red dwarfs in the Halo. First we obtained the distances to these stars, which are shown in Figure 1. One can see that the survey is sensitive out to at least 10 kpc. Note that the closest stars are likely disk contaminants and not included in our final analysis. We obtained estimates of the stellar masses of these objects from stellar models of Baraffe et al (1996); the masses are in the range $0.0875 M_\odot - 0.2 M_\odot$.

For the 6 stars in the HST data with $1.7 < V - I < 3$, we thus obtained a Halo red dwarf mass density. We then compared this red dwarf mass density with virial estimates of the Halo density to see what fraction is composed of red dwarfs. We took a local Halo mass density of $\rho_0 \sim 9 \times 10^{-3} M_\odot/pc^3$. Bahcall et al (1994) had made this comparison by assuming that the red dwarfs had properties of stars at the edge of the high metallicity main sequence; these authors found that red dwarfs contribute less than 6% of the Halo density. However, Halo red dwarfs are low metallicity objects, and we were thus motivated to redo the analysis as outlined above. A ground-based search for halo red dwarfs by Boeshaar, Tyson, and Bernstein (1994) found a much smaller number. We felt that a careful reinterpretation of the Bahcall et al (1994) data was in order. Our result is that Red dwarfs with $1.7 < V - I < 3$ (i.e., mass $0.0875 < M/M_\odot < 0.2$), make up less than 1% of the Halo; our best guess is that they make up 0.14% - 0.37% of the mass of the halo. Subsequent examination of the Hubble Deep Field by Flynn, Gould, and Bahcall [27] and work by Mera, Chabrier,
and Schaeffer reiterated that low-mass stars represent a negligible fraction of the Halo dark matter.

3.2. Brown Dwarfs

With these strong limits on the contribution of faint stars to the Galactic Halo, we then obtained a Mass Function of these same red dwarfs in order to be able to extrapolate to the brown dwarf regime; in this way we were able to limit the contribution of brown dwarfs as well. We obtained the mass function from the following relation:

$$\text{MassFunction} = \frac{dM}{dm} \times \text{LuminosityFunction}. \quad (1)$$

Here, the Mass Function (hereafter MF) is the number density of stars with mass between $m$ and $m + dm$, and the Luminosity Function (hereafter LF) is the number density of stars in a magnitude range $M \rightarrow M + dM$ (note that $M$ refers to magnitude while $m$ refers to mass). The luminosity function is what is observed; we used parallax data taken by the US Naval Observatory (Dahn et al 1995) who identified 114 halo stars. We went from this observed luminosity function to the desired mass function via stellar models of $M_V(m)$ obtained by Alexander et al.

Figure 2. (taken from Dahn et al 1995): H-R diagram of nearby stars with measured parallax. The filled circles are high metallicity disk stars; the velocity dispersion of these disk stars is $\sim 30$ km/sec. The open circles are low metallicity halo “subdwarfs”; these stars have high proper motions $\sim 200$ km/sec. We have superimposed a solid line which indicates the theoretical model of Baraffe et al (1995) with $\log(Z/Z_\odot) = -1.5$.

The parallax data (Dahn et al 1995) are shown in Figure 2. This is an H-R diagram of nearby stars with measured parallax. The filled circles are high metallicity
disk stars. The open circles are red dwarfs which are known to be in the Halo because of their low metallicities and high velocities. It is these 114 Halo stars that we used to get a mass function. We always took the most “conservative” case, i.e., the steepest MF towards low mass; this case would give the largest number of brown dwarfs and low mass red dwarfs. For this reason, we considered a number of metallicities and used the lowest realistic value of $Z = 3 \times 10^{-4}$. There is a potential complication in that some of the stars in the survey may actually be unresolved binaries. If so, the observed light is the sum of the light from two stars. Then one may overestimate the mass of the star if one assumes the light is from a single star. We considered three models for binaries. The most extreme of these is that all the stars are really in binaries, with equal masses for the two stars in the binary system. Then the luminosity of each star is really half as big as if it had been a single star, each star has a smaller mass, and one obtains a steeper mass function towards low mass. This model is unphysical but simple, and we used it to illustrate an extreme for the largest number of stars at low mass that can be obtained from this data set. Figure 3 shows the mass functions that we obtained, for the case of no binaries and the extreme case of 100% binaries. In these plots we multiplied the vertical axis by $m^2$ for simplicity of interpretation. With this factor of $m^2$, a mass function (MF) that is decreasing to the left converges, an MF that is increasing to the left diverges, while an MF that is flat diverges only logarithmically. In figure 3a, the case of no binaries, we can see that the MF $\times m^2$ decreases to the left (convergent); in Figure 4c, the case of 100% binaries, the MF $\times m^2$ is flat (diverges logarithmically). Hence Figure 3 summarizes our results for the mass function for faint stars heavier than $0.09 M_\odot$.

Now, in order to proceed with an extrapolation of this red dwarf mass function past the hydrogen burning limit into the red dwarf regime, we need a brief theoretical interlude. Star formation theory indicates that, as one goes to lower masses, the MF rises no faster than a power law. The theories of Adams and Fatuzzo (1996), Larson (1992), Zinnecker (1984), and Price and Podsiadlowski (1995), while based on different physical principles, all find this same upper limit. Hence we looked for the power law describing the red dwarf mass function at the lowest masses, and then use this same power law to extrapolate into the brown dwarf regime. We took the mass function to scale as

$$MF \propto m^{-\alpha}.$$  \hspace{1cm} (2)

Then the total mass in the Halo is

$$m_{\text{tot}} = \int_0^{0.09 M_\odot} m \times MF \times dm.$$ \hspace{1cm} (3)

If $\alpha > 2$, then the total mass diverges. If $\alpha = 2$, then the total mass diverges only logarithmically. If $\alpha < 2$, then the total mass converges. We found

$$\alpha \leq 2,$$ \hspace{1cm} (4)

for all models. More specifically, for the extreme case of 100% binaries, we found $\alpha = 2$, i.e., each order of magnitude of mass range contains an equal total mass. Even for a lower limit $\sim m_{\text{moon}}$, the total mass in brown dwarfs is less than 3% of the Halo mass. For all other models, including the case of no binaries, we find $\alpha < 2$, and brown dwarfs constitute less than a percent of the Halo mass. Similar results were found by Mera, Chabrier, and Schaeffer [53].
Figure 3. (taken from Graff and Freese 1996b): The mass function of red dwarf halo stars (multiplied by $m^2$). Each of the four models is derived from the LF of Dahn et al. (1995) but assumes different metallicity and binary content. In all three panels, crosses without errorbars illustrate the mass function derived for stars with metallicity $Z = 3 \times 10^{-4}$ and no binary companions. The other model presented in panel (a) has $Z = 6 \times 10^{-4}$ (no binaries) for comparison. Panels (b) and (c) show binary models II and III for $Z = 3 \times 10^{-4}$. Binary model III has been designed to exaggerate the number of low mass stars compared to high mass ones and is unrealistic.

How might one avoid these conclusions? First, star formation theory might be completely wrong. Alternatively, there might be a spatially varying initial mass function so that brown dwarfs exist only at large radii and not in our locality, so that they were missed in the data (Kerins and Evans [44]).

The two year MACHO microlensing data have also shown that, for standard Halo models as well as a wide range of alternate models, the timescales for the events are not compatible with a population of stars lighter than $0.1M_\odot$ (Gyuk, Evans, and Gates 1998).

3.3. Punchline

The basic result of this work is that the total mass density of local Population II Red Dwarfs and Brown Dwarfs makes up less than 1% of the local mass density of the Halo; in fact, these objects probably make up less than 0.3% of the Halo.
4. Mass Budget Issues

This section (based on work by Fields, Freese, and Graff [23]) is general to all Halo Machos, no matter what kind of objects they are.

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

Dalcanton et al. were able to place strong limits on the cosmological mass density of Machos even before the galactic microlensing experiments produced their first results. They looked for a reduction in apparent equivalent width of quasar emission lines; such a reduction would be caused by compact objects. They found that $\Omega_m < 0.1$.

There is a potential problem in that too many baryons are tied up in Machos and their progenitors (Fields, Freese, and Graff [23]). We begin by estimating the contribution of Machos 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

$$M_{\text{Macho}} = (1.3 - 3.2) \times 10^{11} M_\odot.$$  \hspace{1cm} (5)

Now one can obtain a “Macho-to-light” ratio for the Halo by dividing by the luminosity of the Milky Way (in the B-band),

$$L_{MW} \sim (1.3 - 2.5) \times 10^{10} L_\odot.$$  \hspace{1cm} (6)

We obtain

$$(M/L)_{\text{Macho}} = (5.2 - 25) M_\odot / L_\odot.$$  \hspace{1cm} (7)

From the ESO Slice Project Redshift survey (Zucca et al. [68]), the luminosity density of the Universe in the $B$ band is

$$L_B = 1.9 \times 10^8 h L_\odot \text{ Mpc}^{-3}$$  \hspace{1cm} (8)

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

$$\rho_{\text{Macho}} = (M/L)_{\text{Macho}} L_B = (1 - 5) \times 10^9 h M_\odot \text{ Mpc}^{-3}.$$  \hspace{1cm} (9)

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

$$\Omega_{\text{Macho}} \equiv \rho_{\text{Macho}} / \rho_c = (0.0036 - 0.017) h^{-1}.$$  \hspace{1cm} (10)

Note: see also the discussion by Fukugita, Hogan, and Peebles [29].

We will now proceed to compare our $\Omega_{\text{Macho}}$ derived in Eq. (10) with the baryonic density in the universe, $\Omega_B$, as determined by primordial nucleosynthesis. 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. To conservatively allow for the full range of possibilities, we will therefore adopt

$$\Omega_B = (0.005 - 0.022) h^{-2}.$$  \hspace{1cm} (11)
We can see that $\Omega_{\text{Macho}}$ and $\Omega_B$ 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. (10) and (11) give

$$\frac{\Omega_{\text{Macho}}}{\Omega_B} \sim 0.7.$$  \hspace{1cm} (12)

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 $\Omega_B$, we see that

$$\frac{\Omega_{\text{Macho}}}{\Omega_B} \geq \frac{1}{6} \geq \frac{1}{12}.$$  \hspace{1cm} (13)

The only way to avoid these conclusions is to argue that the luminosity density in eq. (8) is dominated by galaxies without Machos, so that the Milky Way is atypically rich in Machos. However, this is extremely unlikely, because most of the light contributing to the luminosity density $L$ comes from galaxies similar to ours. Even if Machos only exist in spiral galaxies ($2/3$ of the galaxies) within one magnitude of the Milky Way, the value of $\Omega_{\text{Macho}}$ is lowered by at most a factor of 0.17.

### 4.2. 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 [31]). 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. ([62]) estimate

$$\Omega_{\text{Ly} \alpha} \sim 0.02h^{-3/2}.$$  \hspace{1cm} (14)

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. (14) 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:

$$\Omega_{\text{Macho}}(z) + \Omega_{\text{Ly} \alpha}(z) \leq \Omega_B ;$$  \hspace{1cm} (15)

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

$$\Omega_{Mach} = 0.007 - 0.04 + (\Omega_{Ly} = 0.06) \leq (\Omega_B = 0.02 - 0.09)$$ for $h = 1/2$, (16)

and

$$\Omega_{Mach} = 0.004 - 0.02 + (\Omega_{Ly} = 0.02) \leq (\Omega_B = 0.005 - 0.02)$$ for $h = 1$. (17)

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

Recent measurements of Kirkman and Tytler (45) 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: $\Omega_{hot} \sim 10^{-2}h^{-1}$. If this estimate is correct, then Eq. (15) 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. A large, previously unknown population of stellar remnants could not have formed after redshift 2; we would see the light from the stars in galaxy counts (Charlot and Silk [18]) and in the Hubble Deep Field (Loeb [51]).

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. (15), this equation becomes harder to satisfy. However, we wish to reiterate that measurements of $\Omega_{Ly}$ are at present uncertain, so that it is possibly premature to conclude that Machos are at odds with the amount of baryons in the Ly$\alpha$ forest.

5. Machos as Stellar Remnants: White Dwarfs or Neutron Stars

In the last section on the mass budget of Machos, we assumed merely that they were baryonic compact objects. In this section (based on work by Fields, Freese, and Graff (23), Fields, Freese, and Graff (24), and Graff, Freese, Walker, and Ponsseault (37)): we turn to the specific possibility that Machos are stellar remnants white dwarfs, neutron stars, or black holes. The most complete microlensing data indicate a best fit mass for the Machos of roughly $(0.1 - 1)M_\odot$. Hence there has been particular interest in the possibility that these objects are white dwarfs. I will discuss problems and issues with this interpretation: in particular I will discuss the baryonic mass budget and the pollution due to white dwarf progenitors.

5.1. Mass Budget Constraints from the Macho Progenitors

In general, white dwarfs, neutron stars, or black holes all came from significantly heavier progenitors. Hence, the excess mass left over from the progenitors must be
added to the calculation of $\Omega_{\text{Macho}}$; the excess mass then leads to stronger constraints. Previously we found that any baryonic Machos that are responsible for the Halo microlensing events must constitute a significant fraction of all the baryons in the universe. Here we show that, if the Machos are white dwarfs or neutron stars, their progenitors, while on the main sequence, are an even larger fraction of the total baryonic content of the universe. The excess mass is then ejected in the form of gas when the progenitors leave the main sequence and become stellar remnants. This excess mass is quite problematic, as there is more of it than is allowed by big band nucleosynthesis and it is chemically enriched beyond what is allowed by observations of Halo stars and the intergalactic medium.

If all the Machos formed in $< 1$Gyr (the burst model), then (for different choices of the initial mass function) we can determine the additional contribution of the excess gas to the mass density of the universe. Typically we find the contribution of Macho progenitors to the mass density of the universe to be

$$\Omega_{\text{prog}} = 4\Omega_{\text{Macho}} = (0.016 - 0.08)h^{-1}. \quad (18)$$

(As an extreme minimum, we find an enhancement factor of 2 rather than 4). From comparison with $\Omega_B$, we can see that a very large fraction of the baryons of the universe must be cycled through the Machos and their progenitors. In fact, the central values of all the numbers now imply

$$\Omega_{\text{prog}} \sim 3\Omega_B, \quad (19)$$

which is obviously unacceptable. One is driven to the lowest values of $\Omega_{\text{rmMacho}}$ and highest value of $\Omega_B$ to avoid this problem.

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. The amount of mass ejected by the progenitors is far in excess of what can be accommodated by the Galaxy. Given the $M_{\text{Macho}}$ of Eq.(5), 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_{\text{prog}} \geq 2M_{\text{Macho}} = (2.4 - 5.8) \times 10^{11}M_\odot. \quad \text{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_{\text{prog}} - M_{\text{Macho}} \sim M_{\text{Macho}} \text{ is at least as large as the mass (} \sim 10^{11}M_\odot \text{) of the Disk and Spheroid of the Milky Way combined. We see that 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).

A possible means of removing these excess baryons is a Galactic wind. Indeed, as pointed out by Fields, Mathews, & Schramm (26), 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.

Such a wind may be driven by some of the white dwarfs themselves (Fields, Freese, and Graff [24]). Some of the white dwarfs may accrete from binary red giant companions and give rise to Type I Supernovae, which serve as an energy source for Galactic winds. However, excess heavy elements such as Fe are overproduced in the process (Canal, Isern, and Ruiz–Lapuente [15]).

5.3. On Carbon and Nitrogen

The issue of carbon (Gibson & Mould [33]) and/or nitrogen produced by white dwarf progenitors is the greatest difficulty faced by a white dwarf dark matter scenario. 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\(M_\odot\) will produce 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.

Then overproduction of carbon can be a serious problem, as emphasized by Gibson & Mould ([33]). 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 [61]) for Lyα systems at \(z \sim 3\) with column densities \(N \geq 3 \times 10^{15}\) cm\(^{-2}\). Lyα forest abundances have also been recently measured at low redshifts with HST (Shull et al. [59]) to be less than \(3 \times 10^{-2}\) solar. 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 [52]).

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 4.1 for the remnant density predicted from our extrapolation of the Macho group results, and would be in conflict with \(\Omega_{prog}\) in the case of a single burst of star formation.

We note that progenitor stars lighter than 4\(M_\odot\) overproduce Carbon; whereas progenitor stars heavier than 4\(M_\odot\) may replace the carbon overproduction problem with nitrogen overproduction (Fields, Freese, and Graff [24]). The heavier stars may have a process known as Hot Bottom Burning, in which the temperature at the bottom of the star’s convective envelope is high enough for nucleosynthesis to take place, and carbon is processed to nitrogen (Lattanzio [8], Renzini and Voli [8], Van den Hoek and Groenewegen (1997), Lattanzio and Boothroyd [8]). In this case one gets a ten times solar enrichment of nitrogen, which is far in excess of the observed nitrogen in damped Lyman systems. In conclusion, both C and N exceed what’s observed.

Using the yields described above, we calculated the C and N that would result from the stellar processing for a variety of initial mass functions for the white dwarf progenitors. We used a chemical evolution model based on a code described in Fields
& Olive to obtain our numerical results. The star formation rate is chosen as an exponential \( \psi \propto e^{-t/\tau} \) with an e-folding time \( \tau = 0.1 \) Gyr, although we have found that the results are insensitive to details of the star formation rate up to \( \tau = 1 \) Gyr. Our results are presented in panels b) of figures 4 and 5. The CN 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. Our C and N abundances were obtained without including HBB, which would exchange a C overproduction problem for a N overproduction problem.

In Figure 4, we make the parameter choices that are in agreement with D and He\(^4\) measurements (see the discussion below) and are the least restrictive when comparing with the Ly\(\alpha\) measurements. We take \(\Omega_{\text{WD}} h = 6.1 \times 10^{-4}\), the minimum amount of WD required to explain the microlensing results if only galaxies similar to ours produce WD Machos. We take \(h = 0.7\) and an initial mass function (IMF) sharply peaked at \(2M_\odot\), so that there are very few progenitor stars heavier than \(3M_\odot\) (this IMF is required by D and He\(^4\) measurements). In Figure 5, we have the same values for \(\Omega_{\text{WD}}\) and \(h\) but have taken an IMF peaked at \(4M_\odot\). In both cases, by comparing with the observations, we obtain the limit,

\[
\Omega_{\text{WD}} h \leq 2 \times 10^{-4}.
\]

We also considered a variety of other parameter choices, and obtained the same limit (see the figures in Fields, Freese, and Graff 1999).

Alternatively, we require an actual abundance distribution that is quite heterogeneous: those regions in which the observations are made must be underprocessed. This implies segregation efficiency of 97%.

Note that it is possible (although not likely) that carbon never leaves the white dwarf progenitors, so that carbon overproduction is not a problem (Chabrier). 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. We have here assumed that carbon does leave the white dwarf progenitor stars.

### 5.4. Deuterium and Helium

Because of the uncertainty in the C and N yields from low-metallicity stars, we have also calculated the D and He\(^4\) abundances that would be produced by white dwarf progenitors. These are far less uncertain as they are produced farther out from the center of the star and do not have to be dredged up from the core. We use both the numerical model discussed above, in which the stars have finite lifetimes, and also two extreme analytical models to bracket the possible results. We consider a burst model, in which the timescale for star formation is much shorter than the lifetimes of the stars. We also consider the opposite limit, the instantaneous recycling approximation, in which the stellar lifetime is short compared to the star formation timescale. In the figures we present results from both analytical approaches and from the numerical
Figure 4. (taken from Fields, Freese, and Graff 1999): (a) The D/H abundances and helium mass fraction $Y$ for models with $\Omega_{\text{WD}} h = 6.1 \times 10^{-4}$, $h = 0.7$, and IMF peaked at $2 M_\odot$. The red curves show the changes in primordial D and He and 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. This is the absolute minimum $\Omega_{\text{WD}}$ compatible with cosmic extrapolation of white dwarf Machos if Machos are contained only in spiral galaxies with luminosities similar to the Milky Way.

(b) CNO abundances produced in the same model as a, here plotted as a function of $\Omega_B h^2$. The C and N production in particular are greater than 1/10 solar.

Panels a) in Fig. 4 and 5 display our results. Also shown are the initial values from big bang nucleosynthesis and the (very generous) range of primordial values of D and He$^4$ from observations. One can see right away that Fig. 4 obtains abundances compatible with the measurements, while the model in Fig. 5 fails to match the D and He$^4$ measurements. Thus, from D and He alone, we can see that the white dwarf model; we can see that the numerical results are closely approximated by the burst model.
progenitor IMF must be peaked at low masses, $\sim 2M_\odot$. We obtain
\[
\Omega_{WD} \leq 0.003. \tag{22}
\]

5.5. Background Light

If galactic halos contain stellar remnants, the infrared flux from the remnant progenitors would contribute to the opacity of multi-TeV $\gamma$-rays (Konopelko et al. [46]). The multi-TeV $\gamma$-ray horizon is established to be at a redshift $z > 0.034$ by the observation of the blazar Mkn501. By requiring that the optical depth due to $\gamma\gamma \rightarrow e^+e^-$ be less than one for a source at $z = 0.034$ we limit the cosmological density of stellar remnants (Graff, Freese, Walker, and Pinsonneault [37]),
\[
\Omega_{WD} \leq (1 - 3) \times 10^{-3}h^{-1}. \tag{23}
\]

In other words, if the density of white dwarfs exceeds this value, the infrared radiation from the progenitors would have prevented TeV $\gamma$-rays from Mkn501 from ever reaching us.
5.6. Neutron Stars

The first issue raised by neutron star Macho candidates is their compatibility with the microlensing results. Neutron stars ($\sim 1.5 M_\odot$) and stellar black holes ($\gtrsim 1.5 M_\odot$) 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 $\sim 0.5 M_\odot$). As discussed by Venkatesan, Olinto, & Truran ([64]), one must posit 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. [56]; Alcock et al. [6]) suggest lensing masses of order $\sim 2 M_\odot$. Note that these long timescales could be explained if the SMC events are due to SMC self lensing (Palanque-Delabrouille et al. [56]; Graff & Gardiner [38]).

However, the same issues of mass budget and chemical enrichment arise for neutron stars as did for white dwarfs, only the problems are worse. In particular, the higher mass progenitors of neutron stars eject even more mass, so that $\Omega_{\text{prog}}$ is even bigger than for the case of white dwarfs. The ejecta are highly metal rich and would need a great deal of dilution (as much as for the case of white dwarfs) in order to avoid conflict with observations. However, most of the baryons in the universe have already been used to make the progenitors (even more than for the case of white dwarfs); there are no baryons left over to do the diluting.

5.7. Mass Budget Summary

If Machos are indeed found in halos of galaxies like our own, we have found that the cosmological mass budget for Machos requires $\Omega_{\text{Macho}}/\Omega_B \geq \frac{1}{6} h f_{\text{gal}}$, where $f_{\text{gal}}$ is the fraction of galaxies that contain Machos, and quite possibly $\Omega_{\text{Macho}} \approx \Omega_B$. Specifically, the central values in eqs. (10) and (11) give $\Omega_{\text{Macho}}/\Omega_B \sim 0.7$. Thus a stellar explanation of the microlensing events requires that a significant fraction 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 and/or nitrogen production in the case of white dwarfs. The overproduction of carbon or nitrogen 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 $\Omega_{\text{prog}}$.

6. Zero Macho Halo?

The possibility exists that the 14 microlensing events that have been interpreted as being in the Halo of the Galaxy are in fact due to some other lensing population. One
of the most difficult aspects of microlensing is the degeneracy of the interpretation of the data, so that it is currently impossible to determine whether the lenses lie in the Galactic Halo, or in the Disk of the Milky Way, or in the LMC. Evans et al. (22) proposed that the events could be due to lenses in our own Milky Way Disk. Gould (40) showed that the standard model of the LMC does not allow for significant microlensing.

Zhao (1998) has proposed that debris lying in a tidal tail stripped from the progenitor of the LMC or SMC by the Milky Way or by an SMC-LMC tidal interaction may explain the observed microlensing rate towards the LMC. Within this general framework, he suggests that the debris thrown off by the tidal interaction could also lead to a high optical depth for the LMC. There have been several observational attempts to search for this debris. Zaritsky & Lin (1997) report a possible detection of such debris in observations of red clump stars, but the results of further variable star searches by the macho group (Alcock et al. 1997b), and examination of the surface brightness contours of the LMC (Gould 1998) showed that there is no evidence for such a population. A stellar evolutionary explanation for the observations of Zaritsky & Lin (1997) was proposed by Beaulieu & Sackett (1998). However, possible evidence for debris within a few kpc of the LMC along the line of sight is reported by the eros group (Graff et al. in preparation). These issues are currently unclear and are under investigation by many groups.

Note that a recent microlensing event towards the SMC, MACHO-98-SMC-1, was due to a binary lens. In this case it was possible to clearly identify that the lens is in the SMC and not in our Halo (Albrow 2). Parallax analysis of event MACHO-97-SMC-1 shows that this event also is likely to be in the SMC (Palanque-Delabrouille et al. 1998). Analysis of the binary lensing event MACHO-LMC-9 shows that this event lies in the LMC. So far, all the events which can be located lie in the Magellanic Clouds. However, the cause of the remaining events of the LMC remains ambiguous and awaits further observations.

7. Conclusions

Microlensing experiments have ruled out a large class of possible baryonic dark matter components. Substellar objects in the mass range $10^{-7} M_\odot$ to $10^{-2} M_\odot$ are ruled out by the experiments. In this talk I discussed the heavier possibilities in the range $10^{-2} M_\odot$ to a few $M_\odot$. I showed that brown dwarfs and faint stars are ruled out as significant dark matter components; they contribute no more than 1% of the Halo mass density. White dwarfs and neutron stars are also extremely problematic. The chemical abundance constraints are formidable. The D and He$^4$ production by the progenitors of the white dwarfs can be in agreement with observation for low $\Omega_{WD}$ and an IMF sharply peaked at low masses $\sim 2 M_\odot$. Unless carbon is never dredged up from the stellar core (as has been suggested by Chabrier 17), 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, in conflict with what is seen in our Halo and in Ly$\alpha$ systems. One must either abandon stellar remnants as dark matter or argue that the debris have remained hot and segregated from cooler neutral matter. However, the observations of TeV $\gamma$-rays from Mkn501 at $z=0.034$ restrict the infrared background of the universe and hence the white dwarf progenitors that would have produced infrared light. In sum, we have a constraint on the remnant density, $\Omega_{WD} \leq (1 - 3) \times 10^{-3} h^{-1}$. 
Hence, in conclusion,

1. Nonbaryonic dark matter in our Galaxy seems to be required, and

2. The nature of the Machos seen in microlensing experiments and interpreted as the dark matter in the Halo of our Galaxy remains a mystery. Are we driven to primordial black holes (Carr 1994; Jedamzik [42]), nonbaryonic Machos (Machismos?), mirror Machos (Mohapatra and Teplitz [55]) or perhaps a no-Macho Halo?

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