Death of Stellar Baryonic Dark Matter Candidates

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Abstract. The nature of the dark matter in the Universe is one of the outstanding questions in astrophysics. In this talk, I address possible stellar baryonic contributions to the 50-90% of our Galaxy that is made of unknown dark matter. First I show that faint stars and brown dwarfs constitute only a few percent of the mass of the Galaxy. Next, I show that stellar remnants, including white dwarfs and neutron stars, are also insufficient in abundance to explain all the dark matter of the Galaxy. High energy gamma-rays observed in HEGRA data place the most robust constraint, \( \Omega_{WD} < 3 \times 10^{-3} h^{-1} \), where \( h \) is the Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\). Overproduction of chemical abundances (carbon, nitrogen, and helium) provide the most stringent constraint, \( \Omega_{WD} < 2 \times 10^{-4} h^{-1} \). Comparison with recent updates of microlensing data are also made. According to the gamma-ray limit, all Massive Compact Halo Objects seen by the experiments (Machos) can be white dwarfs if one takes the extreme numbers; however, from chemical overproduction limits, NOT all Machos can be white dwarfs. Comments on recent observations of the infrared background and of white dwarfs are also made. In conclusion, a nonbaryonic component in the Halo seems to be required.

1 Introduction

My basic conclusions of this talk are the following:
I. It is looking very likely that 50-90% of our Galaxy is made of nonbaryonic dark matter.
II. Regarding the 13-17 microlensing events interpreted as being in our Halo: these are not yet understood.

The nature of the dark matter in the universe and in our Galaxy is one of the great unanswered questions in astrophysics. It is clear from rotation curves of galaxies including our own that most of the matter in galaxies is not in the form of bright stars and instead consists of an unknown component of dark matter. Ten years ago there were two different camps of people on this subject. In the first camp, there were those who believed that the simplest solution would be baryonic dark matter. In particular, the most likely solution appeared to be stellar or substellar objects including faint stars, brown dwarfs, white dwarfs, or neutron stars. In the second camp, there were physicists (particularly motivated by particle physics) who believed there must be a dominant nonbaryonic contribution due to particles such as massive neutrinos, axions, or supersymmetric particles. The main point of my talk is to show that the objects preferred
by the first camp, namely stellar baryonic dark matter candidates, are ruled out (see also my conference proceedings in [1], [2], [3] for a longer discussion). Thus nonbaryonic dark matter seems to be favored as explaining the mass of our Galaxy.

In 1986 Hegyi and Olive [4] ruled out many obvious candidates for baryons in the Halo of our Galaxy. They ruled out diffuse hot gas, cool neutral hydrogen, small lumps or snowballs of hydrogen, and rocks or dust. In the past decade, microlensing experiments including MACHO, EROS, and OGLE were designed to look for MACHOs, or Massive Compact Halo Objects, which are objects (probably baryonic) in the \((10^{-7} - 1)M_\odot\) mass range. Instead of resolving the dark matter puzzle, these experiments have raised new issues. The most recent results from the MACHO experiment are discussed by E. Aubourg in this volume. These experiments [5], [6], [7], [8] have the very strong result that they have ruled out a significant component in the Halo of objects in the mass range \((10^{-7} - 10^{-2})M_\odot\). These experiments have also found tens of objects not yet understood, with a best fit mass \(\sim 0.5M_\odot\), near the mass of a white dwarf. As a consequence, there has been a great deal of recent focus on a possible white dwarf component in the Halo.

In this talk, I will discuss work showing that stellar baryonic candidates for the dark matter are ruled out. The stellar candidates are:

1. Faint Stars. These are objects heavier than about \(0.1M_\odot\) that shine due to hydrogen burning in their cores.
2. Brown Dwarfs. These are objects lighter than about \(0.1M_\odot\) that do not have hydrogen burning in their cores; hence the easiest way to find these objects is to look for them gravitationally (such as with microlensing experiments).
3. White Dwarfs. These are objects with mass \(\sim 0.6M_\odot\) and are the remnants of \((1 - 8)M_\odot\) stars. As mentioned above, these are the best fit to the MACHOs found by the microlensing experiments.
4. Neutron Stars. These are the \(1.4M_\odot\) remnants of stars heavier than \(8M_\odot\).

As I will show in this talk, recent work has shown that none of these four candidates are found in sufficient abundance to explain the mass of our Galactic Halo.

Five years ago, many astronomers believed that the numbers of faint stars and brown dwarfs in the Halo could be quite substantial; in fact these appeared to be the most plausible candidates for the Halo dark matter. It appeared that, as one looked at lower and lower masses, the number of stars seemed to increase such that there could be very many low mass stars and substellar objects. Instead, my work of the last few years with David Graff as well as the work of other authors has shown that the first two candidates, faint stars and brown dwarfs, add up to less than 3% of the mass density of the Galactic Halo. Hubble Space Telescope data found faint stars, and one \([9], [10], [11], [12], [13]\) can use these data to constrain the mass density of faint stars in the Halo. We showed that faint stars are seen to comprise roughly 1% of the Halo. Brown dwarfs are constrained by both the microlensing experiments (as discussed above) and by our work using
a combination of parallax data and theory. We ([11]) looked at the faint stars in the parallax data of [14] and used theory to extrapolate down into the brown dwarf regime. We found that brown dwarfs account for at most a few percent of the Halo. I don’t have time for further discussion of the constraints on these two classes of candidates. I recommend the reader to my previous conference proceeding ([18]) for a fuller discussion.

2 White Dwarfs

Next I will proceed to discussion of white dwarfs as dark matter candidates. These are the most interesting stellar candidates currently as they have the masses best fit to the MACHOs seen by microlensing data (if one assumes that these MACHOs are indeed in the Galactic Halo). Is the dark matter made of white dwarfs? There are four problems and issues that need to be addressed:

1. Infrared Radiation
2. Initial Mass Function
3. Baryonic Mass Budget
4. Element Abundances (C, N, He$^4$)

We will see that, for each of these topics, none of the expected signatures of a significant Halo white dwarf population is found.

2.1 Constraints from multi-TeV $\gamma$-rays seen by HEGRA

The mere existence of multi-TeV $\gamma$-rays seen in the HEGRA experiment places a powerful constraint on the allowed abundance of white dwarfs. This arises because the progenitors of the white dwarfs would produce infrared radiation that would prevent the $\gamma$-rays from getting here. The $\gamma$-rays and infrared photons would interact via $\gamma\gamma \rightarrow e^+e^-$. Multi-TeV $\gamma$-rays from the blazar Mkn 501 at a redshift $z=0.034$ are seen in the HEGRA detector. The cross section for (1-10)TeV $\gamma$-rays peaks at infrared photon energies of (0.03-3)eV. Photons in this energy range would be produced in abundance by the progenitor stars to white dwarfs and neutron stars. 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 [15]),

$$\Omega_{\text{WD}} \leq (1 - 3) \times 10^{-3}h^{-1}. \quad (1)$$

This constraint is quite robust and model independent, as it applies to a variety of models for stellar physics, star formation rate and redshift, mass function, and clustering. In addition, we can be absolutely certain the main sequence progenitors of the white dwarfs produced light!

Note that recent direct observations of infrared light ([16], [17]) give comparable constraints on the white dwarf abundance.
2.2 Mass Budget Issues

First, I discuss the mass budget issues (based on work by Fields, Freese, and Graff [18]) general to all Halo Machos, regardless of the type of object.

**Contribution of Machos to the Mass Density of the Universe:** There is a potential problem in that too many baryons are tied up in Machos and their progenitors. We begin by estimating the contribution of Machos to the mass density of the universe. Microlensing results [6] predict that the total mass of Machos in the Galactic Halo out to 50 kpc is $M_{Macho} = (6 - 16) \times 10^{10} M_\odot$ (note that the new numbers are a factor of two lower than the previous estimates of [5] and in agreement with [7]). 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), $L_{MW} \sim (1.3 - 2.5) \times 10^{10} L_\odot$, to obtain $(M/L)_{Macho} = (2.6 - 13) M_\odot/L_\odot$.

From the ESO Slice Project Redshift survey [19], the luminosity density of the Universe in the B band is $L_B = 1.9 \times 10^8 h L_\odot ~ \text{Mpc}^{-3}$. 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

$$\Omega_{Mach} \equiv \rho_{Mach}/\rho_c = (0.002 - 0.01) h^{-1} \quad (2)$$

where the critical density $\rho_c \equiv 3H_0^2/8\pi G = 2.71 \times 10^{11} h^2 M_\odot ~ \text{Mpc}^{-3}$.

We will now proceed to compare our $\Omega_{Mach}$ derived in Eq. (2) with the baryonic density in the universe, $\Omega_B$, as determined by primordial nucleosynthesis. To conservatively allow for the full range of possibilities, we will adopt $\Omega_B = (0.005 - 0.026) h^{-2}$. 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 give

$$\Omega_{Mach}/\Omega_B \sim 0.4 h \quad (3)$$

However, the lower limit on this fraction is considerably less restrictive,

$$\frac{\Omega_{Mach}}{\Omega_B} \geq 0.1 h \quad (4)$$

where we have used the lowest $\Omega_{Mach}$ and the highest $\Omega_B$.

**Mass Budget constraints from Machos as Stellar Remnants: White Dwarfs or Neutron Stars** 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 $\Omega_{Mach}$; the excess mass then leads to stronger constraints. Typically we find the contribution of Macho progenitors to the mass density of the universe to be

$$\Omega_{prog} = 4\Omega_{Mach} = (0.008 - 0.04) h^{-1}. \quad (5)$$
The central values of all the numbers now imply
\[ \Omega_{\text{prog}} > \Omega_B, \]  
which is obviously unacceptable. One is driven to the lowest values of \( \Omega_{\text{Macho}} \) and highest value of \( \Omega_B \) to avoid this problem.

### 2.3 On Carbon and Nitrogen

The overproduction of carbon and/or nitrogen produced by white dwarf progenitors is one of the greatest difficulties faced by a white dwarf dark matter scenario, as first noted by Smecker and Wyse ([20]) and Gibson and Mould ([21]). Stellar carbon yields for zero metallicity stars are quite uncertain. Still, according to the Van den Hoek & Groenewegen (1997) yields, a star of mass \( 2.5M_\odot \) will produce about twice the solar enrichment of carbon. However, stars in our galactic halo have carbon abundance in the range \( 10^{-4} - 10^{-2} \) solar. Hence the ejecta of a large population of white dwarfs would have to be removed from the galaxy via a galactic wind.

However, carbon abundances in intermediate redshift Ly\( \alpha \) forest lines have recently been measured to be quite low, at the \( \sim 10^{-2} \) solar level [22], for Ly\( \alpha \) systems at \( z \sim 3 \) with column densities \( N \geq 3 \times 10^{15} \text{cm}^{-2} \) (for lower column densities, the mean C/H drops to \( \sim 10^{-3.5} \) solar [23].

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 (Fields, Freese, and Graff [18]). 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 \( \Omega_{\text{prog}} \) in the case of a single burst of star formation. Note that stars heavier than \( 4M_\odot \) may replace the carbon overproduction problem with nitrogen overproduction [25] [26].

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 [27] to obtain our numerical results. Our results are presented in the figure.

In the figure, 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 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 addition (see the figures in Fields, Freese, and Graff [24]) we have considered a variety of other parameter choices. By comparing with the observations, we obtain the limit,
\[ \Omega_{\text{WD}\ h} \leq 2 \times 10^{-4}. \]  

As a caveat, note that it is possible that carbon never leaves the (zero metallicity) white dwarf progenitors, so that carbon overproduction is not a problem [28].
Fig. 1. (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 $\Omega_B$. The C and N production in particular are greater than $1/10$ solar.
2.4 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. Panel a) in the figure displays 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. From D and He alone, we can see that the white dwarf progenitor IMF must be peaked at low masses, \(~2M_\odot\). We obtain

\[ \Omega_{WD} \leq 0.003. \]  

(8)

2.5 Is Dark Matter Made of White Dwarfs?

To reiterate, there are four major problems with a white dwarf Halo: 1) infrared radiation, 2) initial mass function, 3) baryonic mass budget, and 4) element abundances (C, N, He\(^4\)). We have found that of the expected signature of a white dwarf population is found. Hence white dwarfs cannot explain the full dark matter of the Halo.

A second question remains: can the Macho data be explained by white dwarfs? If one compares \(\Omega_{\text{Macho}}\) with the HEGRA limit presented above in eq.(1), all MACHOs can still be white dwarfs if one takes the extreme numbers. However, according to the limit in eq.(7), NOT all Machos can be made of white dwarfs, even with the most extreme numbers. Gates and Gyuk (29) have proposed the following explanation of the Macho data: white dwarfs in an enlarged protodisk can explain the Macho events with \(M = 7 \times 10^{10}M_\odot\) and \(\Omega_{\text{Macho}} \sim 3 \times 10^{-3}\). These white dwarfs would comprise (3-4)% of the Halo density. Even such a small Halo fraction is hard to reconcile with eq.(7) above.

Recent observations (30) (31) have found evidence of direct optical detections of objects that may be Halo white dwarfs. The situation regarding these objects is unclear. The objects found in the Hubble Deep Field (30) are in conflict with what was found earlier in the Luyten survey; if the new observations are correct, large numbers of these objects should have been found in the Luyten survey (32). Regarding the two white dwarfs found in (31), if one takes into account the Poisson statistics, these two white dwarf are consistent with white dwarfs from known stellar populations (33).

In any case the bulk of the dark matter has not yet been found.

3 Zero Macho Halo?

The possibility exists that the 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. In particular, it is possible that the LMC is thicker than previously thought so that the observed events are due to self-lensing of the LMC. All these possibilities are being investigated. More data are required in order to identify where the lenses are.

4 Conclusions

Microlensing experiments have ruled out a large class of possible baryonic dark matter components. Microlensing experiments have ruled out objects in the mass range $10^{-7} M_\odot$ all the way up to $10^{-2} M_\odot$. In this talk I discussed the heavier possibilities in the range $10^{-2} M_\odot$ to a few $M_\odot$. Brown dwarfs and faint stars are ruled out as significant dark matter components; they contribute no more than 1% of the Halo mass density. Stellar remnants are not able to explain the dark matter of the Galaxy either; none of the expected signatures of stellar remnants, i.e., infrared radiation, large baryonic mass budget, and C, N, and He abundances, are found observationally.

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, nonbaryonic Machos (Machismos?), mirror matter Machos, or perhaps a no-Macho Halo?

5 References

References

1. K. Freese, B. Fields, D. Graff: “Limits on Stellar Objects as the Dark Matter of our Galaxy: Nonbaryonic Dark Matter seems to be Required,” Proceedings of the Nineteenth Texas Symposium on Relativistic Astrophysics, eds. E. Aubourg, T. Montmerle, J. Paul, and P. Peter, Nucl. Phys. B (Proc. Suppl.) 80 (2000), contr. 03/05, astro-ph/9904401 (2000)
2. K. Freese, B. Fields, D. Graff: “What are Machos? Limits on Stellar Objects as the Dark Matter of our Halo,” Proceedings of the International Workshop on Aspects of Dark Matter in Astro-Particle Physics (DARK ’98), eds. H.V. Klapdor-Kleingrothaus and L Baudis (World Scientific), astro-ph/9901178 (1999)
3. K. Freese, D. Graff: Proceedings of the International Workshop on Dark Matter in Astro- and Particle Physics (DARK ’96), eds. H.V. Klapdor-Kleingrothaus and Y. Ramachers (World Scientific) (1997)
4. D. Hegyi, K. Olive: Proceedings of Inner Space/Outer Space I, eds. Kolb, Turner, Lindley, Olive, and Seckel, (Chicago: University of Chicago Press) p. 112 (1986)
5. C. Alcock, et al.: ApJ, 486, 697 (1997a)
6. C. Alcock, et al.: astro-ph/0001272 (2000)
7. R. Ansari, et al.: A&A, 314, 94 (1996)
8. T. Laserre: astro-ph/9909503 (1999)
9. J.N. Bahcall, C. Flynn, A. Gould, S. Kirkahos: ApJ, 435, L51 (1994)
10. D.S. Graff, K. Freese: ApJ, 456, L49 (1996a)
11. D.S. Graff, K. Freese: ApJ, 467, L65 (1996b)
12. D. Méra, G. Chabrier, R. Schaeffer: Europhys. Lett., 33, 327 (1996)
13. C. Flynn, J. Bahcall, A. Gould: ApJ, 466, L55 (1996)
14. C.C. Dahn, J. Liebert, H.C. Harris, H.H. Guetter: in Proceedings of the ESO workshop “The bottom of the Main sequence and Beyond” ed. C.G. Tinney (Springer Verlag, Heidelberg) p. 239 (1995)
15. D.S. Graff, K. Freese, T.P. Walker, M.H. Pinsonneault: in press, ApJ Lett. astro-ph/9903181 (1999)
16. V. Gorjian, E.L. Wright, R.R. Chary: astro-ph/9909425 (2000)
17. E.L. Wright, E.D. Reese: astro-ph/9912523 (1999)
18. B. Fields, K. Freese, D. Graff: New Astron, 3, 347 (1998)
19. E. Zucca, et al.: A&A, 326, 477 (1997)
20. T. Smecker, R. Wyse: ApJ, 372, 448 (1991)
21. B.K. Gibson, J.R. Mould: ApJ, 482, 98 (1997)
22. A. Songaila, L.L. Cowie: AJ, 112, 335 (1996)
23. L. Lu, W.L.W. Sargent, T.A. Barlow, M. Rauch: astro-ph/9802189 (1998)
24. B. Fields, K. Freese, D. Graff: in press, ApJ (1999)
25. L.B. van den Hoek, M.A.T. Groenewegen: A&AS, 123, 305 (1997)
26. J.C. Lattanzio, A.I. Boothroyd: astro-ph/9705186 (1997)
27. B.D. Fields, K.A. Olive: ApJ, 506, 177 (1998)
28. G. Chabrier: ApJ Lett. in press: astro-ph/9901147 (1999)
29. E. Gates, G. Gyuk: astro-ph/0004399 (2000)
30. R. Ibata, H. Richer, R. Gilliland, D. Scott: astro-ph/9908270 (1999)
31. R. Ibata, et al.: astro-ph/0002138 (2000)
32. C. Flynn, et al.: astro-ph/9912264 (1999)
33. D. Graff: astro-ph/0005521 (2000)
34. B. Carr: ARAA, 32, 531 (1994)
35. K. Jedamzik: Phys. Rev. D, 55, 5871 (1997)
36. R.N. Mohapatra, V.L. Teplitz: astro-ph/9902085 (1999)