IF THE MACHOS ARE OLD WHITE DWARFS

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\textbf{ABSTRACT.} The microlensing experiments in the direction of the LMC seem to be indicating that about 60\% of the dark matter in the Galactic halo is tied up in objects whose masses are about half the mass of the Sun. This mass is a natural one for old white dwarfs although other possibilities do exist. Using a grid of newly constructed models of cooling white dwarfs which incorporate for the first time the effects of molecular opacity in the stellar atmosphere, and assuming that such white dwarfs make up the entire Galactic dark matter, I predict the numbers of old white dwarfs expected in various surveys currently being conducted. In particular, I note the number to be expected in the Hubble Deep Field (HDF), the deepest image of the sky yet obtained.

1. Background – Can the MACHOs be Old White Dwarfs?

The microlensing experiments in the direction of the LMC seem to be indicating that 60\,\pm\,20\% of the dark matter in the Galactic halo is tied up in 0.5\,\pm\,0.3\,M\odot objects (Alcock \textit{et al.} 1997a, 1997b; Renault \textit{et al.} 1997). This mass is a natural one for old white dwarfs as this appears to be about the masses of white dwarfs found in globular clusters (Richer \textit{et al.} 1995, 1997) although other possibilities exist (e.g. neutron stars or primordial black holes). However, this scenario has numerous problems associated with it. Some of these are listed below together with their possible solutions.

1. \textit{Since these old white dwarfs represent roughly a quarter of the total mass of the original star, where is the rest of this mass?} The problem here is that if old white dwarfs represent about 2\,\times\,10^{11}\,M\odot of material in the Galaxy, where is the other 6\,\times\,10^{11}\,M\odot or so of gas ejected when the precursors formed the white dwarfs? One answer may be that it was blown out of the Galaxy early on by the first generation of supernovae. In a broader context, we see x-ray gas in large clusters of galaxies and in filaments between clusters and it seems clear now that this represents a substantial amount of mass, rivalling that in the cluster galaxies themselves. Further, much of this gas has been strongly enriched so it must have been cycled through stars. This gas may represent the material ejected by the stars from the initial burst of star formation in our Galaxy, the remnants from these stars, now in white dwarfs, making up the bulk of the Galactic dark matter. Another possibility is that this helium-enriched gas could possibly have condensed
into dark clouds. Such clouds would be very difficult to observe at any wavelength, even including CO.

2. If there were so many white dwarfs formed as a result of the first burst of star formation in our Galaxy, there must have been a huge tail of their precursors that had low mass and these should be producing bright white dwarfs in the halo today. Unfortunately, these bright white dwarfs are just not seen.

The potential answer to this objection is contained in the work of Chabrier 1999, Gibson and Mould 1997, Chabrier et al. 1996, and Adams and Laughlin 1996. These authors have investigated IMFs with log-normal or truncated power-law shapes to avoid this problem and also solve the chemical evolution problem wherein the massive stars would overproduce heavy elements. Such IMFs would have a peak near $2.5 M_\odot$, a virtual cut off at the high mass end near $6 M_\odot$, and at low mass just below $2 M_\odot$. Almost no low mass stars (that would be making white dwarfs today) are thus present.

3. We don't see stellar systems anywhere in which stars are currently being formed with this peculiar IMF.

This appears to be true but neither do we observe systems where the physical conditions are those of the early Universe. Our ignorance of star formation theory is such that at this stage such unusual IMFs can certainly not be excluded. It remains for theorists to try and understand how such an IMF could have resulted from star formation shortly after the Big Bang and for observers to try and find very metal-poor systems in which the IMF can be determined.

4. Calculations of the current chemical abundances under the white dwarf hypothesis have indicated that the Galaxy should be much more enriched in C and N than is currently observed (Gibson and Mould 1997).

There are two primary scenarios for avoiding C and N overproduction; either the gas is blown out by supernovae or these heavy elements are just not produced in $z = 0$ stars. The former hypothesis was the one favored by Fields et al. 1997, but there are difficulties with the premise. In their picture intermediate mass stars, regardless of $z$, undergo thermal pulses and eject large amounts of C$_{12}$ and N$_{14}$, but Type II SNe going off simultaneously blow everything out of the Galaxy into the inter-Local Group medium. One difficulty with this picture is that they had to adopt an instantaneous recycling approximation (IRA) to ensure the SNe went off at the same time as the AGB stars were returning ejecta, allowing a wind to develop before the ejecta could get incorporated into any subsequent generation of stars. In reality though there is (roughly) an order of magnitude difference in timescales for Type II SNe and thermally pulsing AGB stars, so the IRA is a poor assumption to make here.

If WDs are the solution to the Galactic dark matter problem, then it is more likely that the second option will prevail, i.e. primordial $z = 0$ (population III) $1 - 8 M_\odot$ stars simply do not behave like $[Fe/H] = -1.0$ stars. They may not undergo pulses
and the third dredge-up and hence will not return much, if anything, in the way of newly synthesized yields back to the interstellar medium. Even in the mid-1980s, there was a hint of such a possibility in the work of Chieffi and Tornambe 1984 who showed that a $z = 0, 5M_\odot$ star did not undergo thermal pulses. On the other hand, they inferred that all their $1 - 4M_\odot$ models should go through a thermally pulsing phase (but no detailed calculations were made), and for the IMFs we are considering here, it is only the $1 - 4M_\odot$ regime which is important. Still, this is perhaps a hint that there is a way to produce huge numbers of population III intermediate mass stars without polluting the Galaxy too much. Clearly much more theoretical work is required here.

5. Surely our Galaxy was not unique. Presumably, thus, most galaxies in the early Universe would have undergone a phase of similar star formation. Are the properties of high redshift galaxies consistent with this hypothesis? Charlot and Silk 1995 examined this question and concluded from the number counts of faint galaxies in deep surveys that current galactic halos could not contain more than about 10% of their mass in old white dwarfs formed from intermediate mass stars. It might be time to relook at these earlier calculations and include the effects of strong dust absorption, different IMFs for the first generation of stars, and very low metallicity stellar evolutionary models which could alter significantly the stellar lifetimes. New data in the submillimeter region of the spectrum from SCUBA on the JCMT (Smail et al. 1999) is indicating that there may be an important population of highly obscured young galaxies which could produce an important upward revision to the 10% figure.

2. New White Dwarf Cooling Models

Any search for old white dwarfs must be guided by theory – clearly we must know what we are looking for and design the experiments accordingly. Until recently all cooling white dwarf models predicted that these old objects would continue to fade and get cooler and redder as time progressed. However, recently new models (Hansen 1998, 1999; Saumon and Jacobson 1999) were developed that include the effects of molecular opacity which is critical in understanding the luminosity and emergent spectrum of white dwarfs whose temperatures fall below 4000K. Hydrogen molecules provide a very important opacity source which has the effect of redistributing the emergent radiation from the infrared in to the blue so that old white dwarfs are blue and not red.

Why is this important? Two potential observables are affected by this redistribution of energy; the colors and magnitudes of old white dwarfs.

First, cool white dwarfs are blue and not red. In deep images of the sky there are huge numbers of faint galaxies whose predominant color is red. At faint limits it is usually impossible to distinguish a star from an almost unresolved galaxy by image morphology alone. If old white dwarfs are blue they will move away from the galaxies in an optical color-magnitude diagram and be much easier to locate. For example, a typical faint galaxy has a $V - I$ color of about 1.0 whereas a 14 Gyr $0.5M_\odot$ white dwarf should have $V - I = -0.8$. There are almost no other objects expected at this color.
Secondly, even though the bolometric magnitude of the white dwarf continues to fall as it ages and cools, the absolute $V$ magnitude remains fairly constant at about $M_V = 17.0$ as more and more of the stellar flux is squeezed into the $V$ band due to an $H_2$ opacity minimum in this wavelength range.

Both these effects can be seen in Figure 1 where I plot Hansen’s cooling model for a $0.5M_\odot$ white dwarf with a hydrogen-rich atmosphere compared to an earlier model that does not include the molecular opacity. The difference is quite dramatic and shows why there might be some optimism that very old white dwarfs could be observed – at least compared to what one expected from the earlier models.

3. Number of White Dwarfs Expected in Surveys

Under the scenario that old white dwarfs make up the bulk of the Galactic dark matter, they will be plentiful but difficult to detect because of their intrinsic faintness. The local number of such objects can be determined simply from the mass density required to produce a flat Galactic rotation curve ($0.0079M_\odot/\text{pc}^3$; Alcock et al. 1997a; Chabrier and Méra 1997; Gould, Flynn and Bahcall 1996) and the mean white dwarf mass $<M_{WD}>$. With the assumption that old white dwarfs are 100% of the Galactic dark matter, the local number density of these objects will then be

![Fig. 1. A $0.5M_\odot$ white dwarf cooling model of Hansen 1998, 1999 compared with a similar mass model constructed from the interiors of Wood 1992, 1995 and Bergeron et al. 1995 atmospheres (W-B). The age of the white dwarf is indicated on the diagram in Gyr. The main differences set in at around 8 Gyr where the effects of atmospheric $H_2$ opacity become important.](image-url)
Richer et al. 1999 have constructed synthetic halo white dwarf luminosity functions for ages of 10, 14 and 16 Gyr and limiting magnitude $V_{lim} = 28$ under the assumption that hydrogen-rich white dwarfs make up 100% of the Galactic dark matter. That is, the functions were normalized by the known local dark matter mass density. The following Table indicates some results from this work.

| Number of White Dwarfs | HDF: $V_{lim} = 28$ (C) | HDF: $V_{lim} = 28$ (S) | Field: $V_{lim} = 24$ (C) |
|------------------------|--------------------------|--------------------------|--------------------------|
| 10 Gyr                 | 15                       | 125                      | 68                       |
| 14 Gyr                 | 3                        | 89                       | 14                       |
| 16 Gyr                 | 2                        | 92                       | 10                       |

In this Table the second and third columns are the expected number of old white dwarfs in the Hubble Deep Field (area 4.4 square arc minutes) to a limiting magnitude of $V_{lim} = 28$. These numbers were calculated under 2 assumptions for the IMF of the white dwarf precursors; a Chabrier-type IMF (C) and a Salpeter IMF (S). The last column is the number of halo white dwarfs per square degree expected to a limiting magnitude of $V_{lim} = 24$ using a Chabrier IMF. This will be approximately the 100% completion limit of deep ground-based surveys which are already in progress at CFHT, ESO and NOAO.

Some conclusions can already be drawn from Table 1. In particular, we can eliminate the hypothesis that old white dwarfs with hydrogen-rich atmospheres, formed with a Salpeter IMF make up the bulk of the Galactic dark matter. From the third column we see that this would have yielded about 100 such objects in the HDF to $V_{lim} = 28$ no matter what the age of the halo. Ibata et al. 1999 have shown that there are at most 12 such candidates in the HDF. The suggestion that the dark matter consists of white dwarfs formed with a Chabrier IMF cannot as yet be excluded by the observations.

For ground-based surveys the numbers are interestingly high - 68 are expected per square degree to a limiting magnitude of $V_{lim} = 24$ for a 10 Gyr halo and about a dozen for a halo with an age of 14 – 16 Gyr. It will thus prove to be quite straightforward to test the white dwarf hypothesis with ground-based data and eventually even use the statistics to provide an accurate age for the halo. Discovery of such objects from the ground will be critical as they will be bright enough that the current generation of 8m class telescopes will be able to obtain spectra of them to confirm that they are indeed old white dwarfs.
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