Searching for the Microlenses: The Observational Signatures of Old White Dwarfs

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The recent discovery of microlensing of stars in the Large Magellanic Cloud\(^1\,^2\) has excited much interest in the nature of the lensing population. Detailed analyses indicate that the mass of these objects ranges from \(0.3 - 0.8 \, \text{M}_\odot\)^3, suggesting that they might be white dwarfs, the faint remnants of stellar evolution. The confirmation of such an hypothesis would yield profound insights into the early history of our galaxy and the early generations of stars in the universe\(^4\,^5\,^6\). Previous attempts have been made to place theoretical constraints on this scenario\(^6\,^7\,^8\), but were unduly pessimistic because they relied on inadequate evolutionary models. Here we present the first results from detailed evolutionary models appropriate for the study of white dwarfs of truly cosmological vintage. We find that the commonly held notion that old white dwarfs are red to hold only for helium atmosphere dwarfs and that hydrogen atmosphere dwarfs will be blue, with colours similar to those of the faint point sources found in the Hubble Deep Field. Thus, any direct observational search for the microlensing population should search for faint blue objects rather than faint red ones.

The issue of old white dwarf observability is inextricably linked to the age of the object, since white dwarfs fade with time. The primary uncertainty in the calculation of accurate cooling models is the description of energy transport in the stellar atmosphere, which affects both the cooling rate\(^9\) and observational appearance\(^10\). Old white dwarfs have luminosities \(\log L/L_\odot < -4\) and effective temperatures \(T_{\text{eff}} < 6000\, \text{K}\). The atmospheric constituents at these temperatures are neutral, so that the primary opacity sources are the collisionally induced absorption of molecular hydrogen (for hydrogen atmospheres) or Rayleigh scattering (for helium atmospheres). The molecular opacities are strongly wavelength dependent and require a detailed radiative transfer calculation. The calculation of such atmosphere models\(^10\) has led to advances in the study of the basic physical parameters of old white dwarfs\(^11\). However, previous cooling models have used outer boundary conditions calculated using simplified atmosphere calculations, so that the self-consistent determination of cooling ages from atmospheric models was not possible for the oldest white dwarfs. The cooling models described here aim to rectify that uncertainty.

Our calculations use a white dwarf cooling code originally developed for the study of the companions to millisecond pulsars\(^12\). To this we have added a detailed atmospheric model using the Feautrier and Avrett-Krook methods\(^13\) to solve the radiative transfer at the surface. The atmospheric model provides an outer boundary condition (taken to be the photosphere) for the interior model which describes the cooling of the white dwarf. The position of the photosphere for helium and hydrogen atmospheres differs dramatically because neutral helium does not form molecules so that the opacity \(\kappa\) is much lower and hence the density at the photosphere \(\rho \propto 1/\kappa T_{\text{eff}}\) is much larger. Figure 1 shows the location of the photosphere for hydrogen and helium atmospheres respectively. In both cases the photospheric density increases as the star cools and \(T_{\text{eff}}\) drops. This trend ends when both atmospheres reach \(T_{\text{eff}} \sim 3000\, \text{K}\), but for different reasons. For helium atmospheres, pressure ionization of helium increases the opacity dramatically, halting the inward motion of the photosphere. For hydrogen atmospheres, the molecular hydrogen opacity is stronger at long wavelengths \(\lambda > 1\, \mu\text{m}\), so that the opacity increases when the peak of the black-body \(\lambda_{\text{bb}} \sim 1.7\, \mu\text{m}/(T_{\text{eff}}/3000\, \text{K})\) moves into that range, and hence the photospheric density moves outwards again. The molecular opacity is strongly wavelength-dependent, so that the observational appearance of these old stars deviates significantly from a black-body spectrum, in a similar fashion to that seen in brown dwarf atmospheres\(^14\).

Figure 2 shows the comparison of our cooling results with the best extant models in the literature\(^15\,^16\). The agreement with the hydrogen atmosphere models is excellent until the models reach \(T_{\text{eff}} \sim 6000\, \text{K}\), at which point our improved treatment of the atmospheric physics results in slower cooling. The difference in the helium models is more dramatic, with the new models cooling rather more rapidly. This is a result of the extremely low opacity of neutral helium. Application of the new models to the white dwarf luminosity function shows that previous age estimates for disk hydrogen dwarfs were reasonably accurate, although disk helium dwarf ages were somewhat overestimated. However, for white dwarfs residing in the galactic halo or in globular clusters, the differences are very important. In particular, previous efforts to place constraints...
on white dwarf dark matter\textsuperscript{6,7,8} have been unduly pessimistic because they use inappropriate white dwarf models.

The observational constraints on local white dwarf dark matter centre on two sources, the luminosity function determined from proper motions\textsuperscript{17} and searches for point sources in the Hubble Deep Field\textsuperscript{18,19,20}. Unfortunately, the proper motion sample suffers from poorly constrained incompleteness at the fainter magnitudes (the luminosity function declines much more rapidly than the luminosity function based on white dwarfs in binaries\textsuperscript{21}). Thus, inferring how many objects could have been seen at fainter magnitudes is a particularly dangerous endeavour. More robust estimates must rely on the Hubble Deep Field (HDF) alone. Figure 3 shows the point sources detected by various groups in the HDF along with cooling tracks for both hydrogen and helium atmospheres. The first result that one can glean from this is that the HDF places no limits on helium atmosphere dwarfs, because the rapid cooling means that they become unobservable within 6 Gyr, which is approximately half their expected age. The second and most interesting result is that the hydrogen atmosphere dwarfs are potentially observable and would lie in the region of the faint blue objects that were indeed detected. This is contrary to the conventional wisdom which states that white dwarfs should become redder with age because that is the trend shown by a black body (and indeed that is what happens to the helium dwarfs). The blueward deviation shown by the hydrogen atmosphere dwarfs is again a consequence of the strong molecular hydrogen opacity which also causes the photosphere to move to lower densities in Figure 1. The strong opacity at longer wavelengths (red) forces the stellar flux to emerge at shorter wavelengths (blue) where the opacity is smaller. Thus, hydrogen atmosphere white dwarfs may have already been detected in the halo!

To quantitatively connect these findings to the observational searches one also requires a model for the relative populations of hydrogen and helium atmosphere white dwarfs. Recent advances in asteroseismological investigations of white dwarfs\textsuperscript{22} have confirmed that many hydrogen atmosphere white dwarfs have hydrogen surface layers of mass $\sim 10^{-4} \, M_\odot$. This suggests that such stars will survive as hydrogen atmosphere dwarfs despite the mixing effects of surface convection zones. Although these estimates are for disk white dwarfs, the mechanisms for removing hydrogen from the surface of a white dwarf\textsuperscript{9,23,24} should become less efficient in stars with lower metallicity, such as those in the halo and in globular clusters. The relative proportion of hydrogen atmospheres amongst the cool white dwarfs in the disk appears to be $> 50\%$, so we will adopt this as a conservative estimate. In the future, the effect of advanced age and lower progenitor metallicity can be empirically tested by examining the faint white dwarfs in globular clusters\textsuperscript{25}.

How many white dwarfs would we expect to see in the Hubble Deep Field? The HDF probes great distances, but only over a very small portion of sky, so that the total galactic volume sampled is quite small. Given a limiting magnitude $m_V \sim 28$ and an absolute magnitude for old white dwarfs $M_V \sim 17$, the corresponding volume probed is only

$$V_{\text{HDF}} \sim (5.4 \, \text{pc})^3 10^{0.6((m_V-28)-(M_V-17))}.$$  (1)

Thus, even if the white dwarfs constitute the entire local dark matter ($\sim 0.01 \, M_\odot \, \text{pc}^{-3}$\textsuperscript{26}), their space density is only $\sim 0.02 \, \text{pc}^{-3}$ and hence we expect to find only 3 even if all the white dwarfs have hydrogen atmospheres and are 12 Gyr old (an age appropriate for globular cluster and halo stars). Our most realistic estimate invokes only 50% of the total number in hydrogen atmosphere white dwarfs and requires that only 50% of the dark matter is in the form of white dwarfs\textsuperscript{3}. In this case, the volume probed by the HDF is too small to reliably detect even one object. Nevertheless, as one can see in Figure 3, several points sources have been detected in the HDF. Given the relative profusion of these objects, most must have another origin, such as extragalactic star forming regions\textsuperscript{19}.

The implications of these results for the search for dark matter are twofold. The first result is that deep surveys for very red objects are unlikely to be successful in the near future because the red population (helium atmosphere dwarfs) will be very faint. However, searches for faint blue objects could be much more successful. The second implication is that the hydrogen atmosphere dwarfs are observable but that the HDF results suggest that there are other unresolved populations of objects with similar colours and magnitudes. Thus, proper motions will be essential for identifying galactic objects from extragalactic ones.
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Caption: Figure 1

Location of the Photosphere: The solid and dotted lines indicate the evolution of the photospheres for hydrogen and helium atmospheres respectively. The solid and open circles are the same quantities from the work of Bergeron et al.

Caption: Figure 2

Cooling curves: a) The solid line from this work is compared with the dashed line from the models of Wood (1995). The model is for a 0.6 M⊙ white dwarf with an oxygen core and a hydrogen mass fraction of 10⁻⁴. The improved boundary condition leads to a slight flattening of the cooling curve at log L/L⊙ ∼ −4 and longer cooling times thereafter. b) The solid line from this work is compared with the dashed line from the models of Salaris et al (1997). The model is for a 0.6 M⊙ carbon/oxygen model with a helium mass fraction of 10⁻³. The much longer cooling of the Salaris model is because of the outdated atmospheric model used in that work. In both panels the horizontal dotted lines enclose the location of the turnover in the disk white dwarf luminosity function. The vertical dotted lines indicate the mean age of the globular clusters, indicating the expected age of any halo white dwarf population. The large variations in the different models at these ages indicate how important accurate atmosphere models are.

Caption: Figure 3

Stellar Objects in the Hubble Deep Field: The filled circles are the unresolved objects detected by Elson et al. The open circles are the point sources from Mendez et al. Although Flynn et al did not publish a table of detections, the dotted line encloses their ‘halo region’, which they used to constrain the halo white dwarf population. The dashed lines show the cooling behaviour of a helium atmosphere white dwarf at a distance of 1 kpc (upper line) and 2 kpc (lower line). The upper curve is labelled with ages in Gyrs at appropriate points. The solid lines represent the corresponding evolution of a hydrogen atmosphere white dwarf at 1 and 2 kpc. The dwarf ages are shown on the lower curve in this case. The bandpasses are the hubble telescope bandpasses from Holtzmann et al. The blueward shift for ages 10-12 Gyr is due to the presence of molecular hydrogen in the atmosphere.
