Old White Dwarfs as a Microlensing Population

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Abstract. A popular interpretation of recent microlensing studies of the line of sight towards the Large Magellanic Cloud invokes a population of old white dwarf stars in the Galactic halo. Below I review the basic properties of old white dwarf stars and the ongoing efforts to detect this population directly.

1. Introduction

Other authors in this volume cover the microlensing motivations much better than I can, so I shall suffice to remind you that one possible explanation of the microlensing events towards the LMC invokes a population of objects in the range $0.3 - 0.8 M_{\odot}$. Potentially these could be either normal hydrogen-burning stars or white dwarfs, the burnt-out remnants of stellar evolution. To distinguish these populations, we turn to direct searches at optical wavelengths, since the latter population is $10^{-3} - 10^{-4}$ as bright as the former. The number counts of faint red stars suggest that hydrogen burning stars cannot account for the microlensing population (Bahcall et al 1994; Graff & Freese 1996). The question I wish to address is how well one can constrain the white dwarf hypothesis by similar means.

2. White Dwarf Cooling

To derive a constraint from direct optical searches, we need to know how to recognise white dwarfs. White dwarfs of moderate age ($< 10$ Gyr) emit approximately as black bodies. However, once the white dwarf cools to effective temperatures below $\sim 5000$ K, the atmospheric hydrogen resides in molecular form. This has dramatic consequences for the appearance of the white dwarf (Hansen 1998, 1999a; Saumon & Jacobsen 1999), because the dominant opacity source in such an atmosphere is collisionally induced absorption by $H_2$, which absorbs primarily in the near infra-red. For black bodies of effective temperatures $\sim 3000 - 5000$ K the peak of the spectrum lies in the same wavelength region, so that the increased absorption leads to dramatic deviations from the traditional assumption of black body colours. The general trend of the colour evolution is that the flux is forced to emerge preferentially blueward of $\sim 0.8 \mu$m. With the evolution of the black body flux redward, the peak of the spectrum for old white dwarfs lies around $0.6 \mu$m.
A correct quantitative analysis of the atmospheric conditions is not only important for determining the colours of the white dwarf, but is also of critical importance for the cooling evolution. For white dwarfs cooler than $T_{\text{eff}} \sim 6000$ K, the internal structure has no radiative zones. The bulk of the white dwarf mass resides in a degenerate core which is approximately isothermal due to the efficient thermal conduction by the electrons near the surface of the Fermi sea. This isothermal core is joined to a thin convective envelope which extends all the way to the photosphere. Thus, the entire white dwarf structure is critically dependant on the surface boundary condition and hence the atmospheric conditions. It must be noted that, while sophisticated analyses of white dwarf atmospheres have been around for several years (e.g. Bergeron, Saumon & Wesemael 1995), the white dwarf cooling calculations have lagged significantly behind, employing grey atmosphere boundary conditions. Thus, while one may trust the masses and gravities inferred in recent atmospheric analyses, one cannot completely trust the ages inferred for the older white dwarfs in most recent papers. To my knowledge, the only cooling calculations using boundary conditions based on proper atmosphere models are those of Hansen (1999a) and Salaris et al (2000). For isochrones and luminosity functions using the Hansen (1999a) models, see Richer et al (2000).

The models described above concern white dwarfs with pure hydrogen atmospheres. Empirically, a significant fraction of known white dwarfs appear to have no hydrogen in their atmospheres (Liebert et al 1979; Bergeron, Ruiz & Leggett 1997). When pure helium atmospheres reach effective temperatures $< 5000$ K, they have no molecular component to provide significant opacity and, as a result, the photosphere lies at much higher densities, where the beginnings of pressure ionization start to provide a small ionized component. This higher density and the concomitant difference in the boundary condition results in much faster cooling for old white dwarfs with helium atmospheres. Furthermore, these objects are expected to appear approximately as black bodies (contrary to the hydrogen atmosphere case) but will be hard to detect because they cool much faster.

The matter of a component of the white dwarf population sporting helium atmospheres is one that is often not mentioned in the recent studies attempting to tie direct searches to microlensing populations. It is important to note that this represents an essentially unobservable (due to their much more rapid cooling) component and, as such, will always introduce some uncertainty into the comparison.

3. Observational Progress

3.1. The story thus far

The last couple of years have been fun for those interested in the question of halo white dwarfs. The realisation that old white dwarfs would appear somewhat bluer than black bodies meant that previous constraints on the local number density based on Hubble Deep Field point source counts were somewhat overstated. Much excitement was generated by the detection of proper motions of several faint blue point sources in the HDF North (Ibata et al 1999). The colours and magnitudes of these objects are consistent with old white dwarfs $\sim 12$ Gyr old.
Figure 1. The source of all the fuss. The five points are the magnitudes & colours of the 5 proper motion objects of Ibata et al (1999). The solid curves describe the cooling of a 0.6 solar mass white dwarf with hydrogen atmosphere located at 1 and 2 kpc. Representative ages are indicated along the lower curve. The dashed curves are the same but for a pure helium atmosphere. The much more rapid cooling is evident.
at distances $\sim 1$ kpc. Given the radical consequences of this observation, some kind of confirmation would be nice. A third epoch, to confirm the measurement, has been approved but was postponed due to the HST gyro problems in December 1999. Nevertheless, the veracity of the HDF proper motions should be addressed within the next year or so.

In the interim, several other interesting results have come to light. Most importantly, Hodgkin et al (2000) presented a near-infrared spectrum of a nearby cool white dwarf, demonstrating the reality of the flux-suppression due to molecular hydrogen absorption. This provides a welcome check that the theory behind the predicted colour change is at least qualitatively correct. The high proper motion of this object also suggests membership of the Galactic halo. Another object showing such a long wavelength depression is LHS 3250 (Harris et al 1999)

A further interesting indirect argument supporting the white dwarf hypothesis comes from Mendez & Minniti (2000), who assert that the number counts of faint blue point sources (the class amongst which Ibata et al discovered proper motions) in the Hubble Deep Field South is approximately twice that in the HDF North. This is consistent with the objects (whatever they are) being Galactic in origin, since the southern field looks in a direction closer to the Galactic centre and consequently the stellar density is expected to be higher.

A note of caution, however, is sounded by Flynn et al (2000), who find little evidence for a population equivalent to that of Ibata et al in the Luyten proper motion survey. They conclude that hydrogen atmosphere white dwarfs cannot comprise a significant fraction of the Galactic halo. On the other hand, a new search of wide field photographic plates by Ibata et al (2000) has uncovered several high proper motion objects, at least two of which are spectroscopically confirmed to be white dwarfs and with some modicum of IR flux suppression.

In my not-completely-unbiased interpretation of the above, the evidence in favour of the white dwarf hypothesis is encouraging, although not conclusive. The recent results of Hodgkin et al and Ibata et al (2000) have demonstrated at least the existence of a population of high proper motion (and thus probably halo) white dwarfs. The question is now a matter of number density. It is on this point that we must await further data.

3.2. Future prospects

While the above results indicate that some white dwarfs do show halo kinematics, the fact that there is little evidence for a large halo white dwarf population in existing large-scale proper motion surveys casts some doubt that this population may be responsible for the microlensing results. This last statement relies heavily on the data set of Luyten (1979), so it would be nice to check this with another large scale survey.

Towards this end, a program led by Peter Stetson has begun at CFHT to image almost 20 square degrees to $V \sim 25$. Repeated with an interval of 2-3 years, this program should provide a conclusive test of the white dwarf halo hypothesis. Using the new MACHO mass fraction estimate ($\sim 20\%$) and assuming only half of all white dwarfs have hydrogen atmospheres, this program is still expected to find about 8 white dwarfs per square degree.
Figure 2. The left hand panel shows the SDSS stellar locus (York et al. 2000) in the g-r/r-i plane, with the evolution of a representative white dwarf shown by the dashed line. Thus, it is possible to select very cool white dwarfs by colour alone. However, objects that cool are also faint. The right hand panel shows the apparent magnitudes of the stars with g-r > 0.8 as well as the dashed line for the cooling of a 0.6 $M_\odot$ white dwarf at 10 pc (i.e. the absolute magnitude). The dotted line shows the apparent magnitude of a 3500 K white dwarf at various distances.

Another fascinating prospect is the hope of finding such old white dwarfs in the Sloan Digital Sky Survey (SDSS). Although this comprehensive large scale survey will not provide proper motions as a matter of course, some proper motion information is potentially available from comparison with Palomar Sky Survey plates. Furthermore, there will be a strip of sky in the southern hemisphere that will be multiply imaged. Even without proper motions, very old white dwarfs are potentially detectable by colours alone in the SDSS five-band photometric system. Photometric selection alone is unlikely to provide a complete census as only the oldest white dwarfs will stand out from the locus of other stars (the problem is that even the reddest bandpass doesn’t extend significantly beyond 1 $\mu$m). Nevertheless, very old white dwarfs are interesting in their own right.

Figure 2 shows a representative stellar locus and how one might select old white dwarfs based on colours. The colour selection suggests that only white dwarfs cooler than 3500 K can be selected in this manner. Using an i-band detection limit of 18, we find such objects can be detected to distances ~ 30 pc. If the entire MACHO fraction (taken to be 20%) were in 0.5 $M_\odot$ white dwarfs, 50% of whom had hydrogen atmospheres, and all had 3500 K temperatures, we would expect approximately 43 white dwarfs in the Sloan survey, or 1 every 480 square degrees. This is probably an overestimate. Hotter white dwarfs cannot be distinguished from the stellar locus (it is worth noting that the Hodgkin et al. and Ibata et al. detections all correspond to $T_{\text{eff}}$ ~ 3500 – 4000 K, so in the marginal region) and cooler objects are fainter and thus the effective volume is smaller. Nevertheless, this simple estimate offers encouragement that at least
some white dwarfs are potentially detectable in this manner. More detailed calculations are underway to provide a more robust estimate.

Another large scale proper motion survey that should offer interesting constraints is that being undertaken by the EROS project (Goldman 1998). With a survey area of 350 square degrees and an I-limit of 20.5, we can use the same approximate scenario as above to estimate $\sim 23$ white dwarfs in their sample. This is a somewhat more realistic ballpark number in this case as the proper motion selection will allow detection of hotter objects.

The bottom line of the above is that, although uncertainty about mass distributions and chemical compositions make prognostication difficult, the fact that naive estimates lead to predictions of 10-100 detections in ongoing surveys suggests that we should see something if the hypothesis of a significant white dwarf halo is correct.

4. Beige Dwarfs

Although it was not my intention to address this subject at the conference, it was raised a couple of times, so I will conclude with a few remarks about “Beige” dwarfs (Hansen 1999b). Given that brown dwarfs are strongly ruled out by the microlensing timescales, red dwarfs by direct observations and white dwarfs (as well as neutron stars) are an uncomfortable fit due to issues of chemical pollution, it appears that there are no surviving baryonic candidates for halo MACHOs. However, there is one remaining possibility. Lenzuni, Chernoff & Salpeter (1992) demonstrated that one could circumvent the traditional hydrogen burning limit by starting with a brown dwarf and accreting material slowly enough that it could cool. In this fashion one could construct a degenerate hydrogen/helium object with mass $> 0.1 M_\odot$. If one could build such objects to masses $> 0.3 M_\odot$, they would make ideal MACHO candidates as they would be faint and would have no nuclear burning history and thus no chemical pollution problem. The term “Beige” dwarf comes from the superposition of brown dwarf and white dwarf characteristics. The primary problem for this scenario is that there is little evidence that this mode of “star” formation was ever important.

The existence of Beige dwarfs is observationally testable. They have similar radii to white dwarfs but can only exist at effective temperatures $T_{\text{eff}} < 2000$ K, so the detection of hotter objects would suggest white dwarfs. Indeed, the spectroscopically confirmed objects of Hambly et al and Ibata et al (2000) indicate temperatures $\sim 3500 – 4000$ K. Therefore these are unlikely to be Beige dwarfs.

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