White Dwarfs in Globular Clusters – Progenitors, Successors and the Real Thing

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Abstract. I will start by discussing the evolutionary status of the white dwarf progenitors, the hot UV bright stars. Observations of UIT-selected UV bright stars in globular clusters suggest that a high percentage of them manage to evolve from the horizontal branch to the white dwarf region without passing through the thermally pulsing AGB phase, thereby avoiding the planetary nebula stage.

The white dwarf successors are stars experiencing a very late helium core flash while already on the helium white dwarf cooling curve. While they have been around theoretically for quite some time strong candidates could be verified only quite recently.

And, last not least, the white dwarfs themselves offer new opportunities to derive distances and ages of globular clusters, which I will discuss. For a discussion of white dwarfs in binaries see the reviews by Adrienne Cool and Frank Verbunt in this volume.

Being a spectroscopist at heart I concentrate in this review mainly on results that were obtained from spectroscopic analyses. However, as you will see in the last section of this review there are stars that manage to evade spectroscopic analyses even with the latest 8-10m class telescopes.

1. Progenitors: UV Bright Stars

UV bright stars have been classically defined as stars brighter than the horizontal branch and bluer than the red giant branch (Zinn et al. 1972). Such stars are also brighter in $U$ than any other cluster star. UV bright stars are produced by evolution from the

- horizontal branch (HB) towards the asymptotic giant branch (post-HB stars)
- extreme HB (EHB, $T_{\text{eff}} > 23,000$ K) directly towards the white dwarf domain (post-EHB stars)
- asymptotic giant branch towards the white dwarf domain (post-AGB stars), possibly showing up as central stars of planetary nebulae.

Ground based searches like the one of Zinn et al. (1972) found primarily cool UV bright stars ($T_{\text{eff}} \leq 9000$ K). Spectroscopic analyses of the few hot UV bright stars found this way turned up only post-AGB stars. This finding is puzzling as a minimum mass of 0.565 $M_\odot$ is required to reach the thermally
Figure 1. Results of spectroscopic analyses of UV bright stars compared to evolutionary tracks. Open circles mark stars detected by optical searches (Conlon et al. 1994; Dixon et al. 1994, 1995; Glaspey et al. 1985, Heber & Kudritzki 1986, Moehler et al. 1998b, Rauch et al. 2002), filled squares mark UV bright stars detected as such by UIT (Moehler et al. 1998a, Landsman priv. comm.). The post-AGB and post-early AGB tracks are from Schönberner (1983), the zero-age HB/EHB (ZAHB/ZAEHB) and post-EHB tracks are from Dorman et al. (1993). The numbers give the stellar mass of the track in units of 0.001 \(M_\odot\).

Pulsing AGB (Schönberner 1983), which makes this evolutionary stage difficult to reach for the low mass stars in today’s globular clusters. The post-AGB phase also has a shorter lifetime than the other channels producing UV bright stars, making the observation of such stars even further unlikely.

However, optical searches are obviously biased against finding hot stars, whose flux maximum moves ever farther to the ultraviolet with increasing temperature. Therefore searches in the satellite ultraviolet are much more promising and indeed the Ultraviolet Imaging Telescope (Stecher et al. 1997) found quite a few new hot UV bright stars in the globular cluster it surveyed. Spectroscopic analyses of these stars by ground based (ESO, Moehler et al. 1998a) and HST (Landsman, priv. comm.) observations showed stars evolving away from the extreme HB and also post-early AGB stars, that left the AGB before the thermal pulses started, but no new “classical” post-AGB stars (see Moehler 2001 for more details). These new results are in much better agreement with the expectations from stellar evolution theory with respect to evolutionary life times (and thus observability) and minimum masses. At the same time they also suggest
an explanation for the lack of planetary nebulae in globular clusters observed by Jacoby et al. (1997): None of the UV bright stars detected solely by UIT will produce a planetary nebula – post-EHB stars never reach the AGB and the evolution of post-early AGB stars proceeds so slowly that by the time they are hot enough to excite the remnants of their AGB envelopes these remnants have evaporated.

2. Successors: Blue Hook Stars

The globular clusters ω Cen and NGC 2808 show a large number of hot horizontal branch (HB) stars that populate a very long blue tail down to rather faint visual magnitudes. Observations of ω Cen (Whitney et al. 1998; D’Cruz et al. 2000) and NGC 2808 (Brown et al. 2001) in the far-UV revealed a puzzling feature: At the very hot end the HB shows a spread in UV brightness that cannot be explained by measuring errors. While stars brighter than the zero-age HB (ZAHB) might be understood by evolution away from the ZAHB, the stars fainter than the ZAHB cannot be explained by canonical HB evolution. The fainter stars appear to form a hook-like feature extending up to 0.7 mag below the ZAHB and are therefore called “blue hook” stars.

Classical HB stars burn helium in a core of about 0.5M⊙ and hydrogen in a shell. They have hydrogen-rich envelopes of varying mass and the more massive the envelope, the cooler is the HB star. The hottest HB stars with envelope masses below 0.02M⊙ do not have active hydrogen-burning shells (Teff > 23,000 K, extreme HB stars = EHB stars). The increase in bolometric correction with increasing temperature turns the horizontal branch into a vertical blue tail (in optical colour-magnitude diagrams) with the faintest blue tail stars being the hottest and least massive ones.

In the optical colour-magnitude diagram the blue hook stars show up at the very faint end of the blue tail in agreement with their high temperatures suggested by the UV photometry. They populate a range in visual magnitude (and thus effective temperature) beyond that of the hottest EHB stars analysed in globular clusters so far (NGC 6752, Moehler et al. 2000b), which already populate the canonical EHB to its very hot end. Even hotter EHB stars cannot be produced by simply reducing their envelope mass, since a minimum mass of the hydrogen envelope is required for canonical models to initiate the helium core flash at the tip of the red giants branch (see, e.g., Brown et al. 2001). Obviously other evolutionary channels are needed to produce the blue hook stars.

The concept of the delayed helium flash has been first suggested by Castellani & Castellani (1993). In this scenario a star loses so much mass on the red giant branch (RGB) that it fails to ignite helium core burning on the RGB and instead starts to evolve into a helium core white dwarf. During this evolution it may, however, still ignite helium burning in its core. Depending on when this happens one distinguishes between “early” (flash at the hot top of the white dwarf cooling curve) and “late” hot flashers (flash along the white dwarf cooling curve).

1EHB stars show up as subdwarf B stars in the field of the Milky Way and are considered good candidates for the cause of the UV excess in elliptical galaxies.
Cool flashers in this diction are stars igniting helium core burning on the RGB. D'Cruz et al. (1996, 2000) discussed in detail the evolution of early hot flashers in connection with the blue hook stars. The evolution of such an early hot flasher, however, proceeds rather similar to that of a canonical EHB star once it has settled down to stable helium core burning. It can therefore not explain the faint UV luminosities and high expected temperatures of the observed blue hook stars.

Brown et al. (2001) studied also the case of a late hot flasher which evolves quite differently: If the flash takes place late enough along the white dwarf cooling curve the hydrogen burning shell has weakened sufficiently to allow mixing between the helium core and the hydrogen envelope during the helium core flash. Thus hydrogen is mixed towards the interior of the star and mostly burned to helium, while the surface is highly enriched in helium and some carbon/nitrogen. Due to the lack of hydrogen in the star’s atmosphere absorption in the extreme UV is considerably reduced and thus less flux is emitted at far UV wavelengths, producing stars that lie below the canonical zero-age EHB in UV colour-magnitude diagrams. In addition the late hot flashers should lie at higher effective temperatures ($\approx 37,000$ K) and – due to the small difference in mass loss between early and late hot flashers – a gap should separate them from the early hot flashers and canonical EHB stars at and below $\approx 31,000$K. Such a gap is indeed observed in NGC 2808 (Walker 1999).

One of the easiest verifications of the late hot flasher scenario is the determination of temperatures and surface compositions for blue hook stars. The distinction between helium-rich late hot flashers and canonical EHB stars is facilitated by the diffusion active in EHB stars that makes their atmospheres helium-poor (e.g. Moehler et al. 2000b, see also review by Bradford Behr in this volume) with helium abundances generally below 0.1 solar.

Moehler et al. (2002) observed medium resolution spectra of blue hook stars with the New Technology Telescope of ESO. Indeed the stars turned out to be helium-rich with 9 of 12 stars showing at least solar helium abundance (i.e. more than a factor of 10 higher than the hottest canonical EHB stars observed in NGC 6752) and four even show helium abundances of $Y > 0.7$. There are also indications of super-solar carbon abundances, which would be consistent with predictions of the late hot flasher scenario. However, contrary to expectation the stellar atmospheres still contain quite some hydrogen. This may be understood by the results of Schlattl & Weiss (priv. comm.), who found that a small amount of hydrogen survives the flash mixing. While diffusion can enrich the atmospheres of the hot flashers in hydrogen and deplete them in helium more detailed calculations will be necessary to verify if this process is efficient enough to explain the observations. Recent observations with the ESO VLT of the blue hook stars in NGC 2808 also show helium-rich spectra, thus supporting the late hot flasher scenario, but no detailed analysis has been done so far.

3. The Real Thing

As white dwarfs are the final stage in the evolution of all low mass stars many are expected to exist in globular clusters. Their faintness, however, allowed
them to escape detection until 1995: That year not only saw detections of a few stars that could be white dwarfs in M 15 (de Marchi & Paresce 1995) and ω Cen (Elson et al. 1995), but also of prominent white dwarf sequences in NGC 6397 (Paresce et al. 1995) and M 4 (Richer et al. 1995). Later observations managed to hunt down white dwarfs also in NGC 6752 (Renzini et al. 1996) and 47 Tuc (Zoccali et al. 2001).

3.1. The bright end – Nonflickerers

Cool et al. (1998) detected several faint but UV bright stars in NGC 6397. While some of those showed light variations and colours consistent with being cataclysmic variables three remained blue in all filters and did not show any variations. This earned them the name “nonflickerer” and their faintness suggested an identification with low-mass helium core white dwarfs of about 0.25 M⊙. A spectrum obtained by Edmonds et al. (1999) showed a hydrogen-rich atmosphere and yielded parameters consistent with a 0.25 M⊙ white dwarf. The radial velocity obtained from the spectrum deviated from that of the cluster indicating a binary nature of the star, which would be consistent with its low mass.

3.2. Distance determinations and spectral types

Renzini et al. (1996) suggested to use the white dwarf sequence for distance determinations in the same way as the main sequence: comparing the white dwarf sequence of a globular cluster to an appropriate cooling sequence of local white dwarf with well determined trigonometric parallaxes yields the distance of the globular cluster. While it may seem strange to use the faintest objects in a globular cluster to derive its distance white dwarfs offer considerable advantages as standard candles when compared to main sequence stars:

- They come in just two varieties - either hydrogen-rich (DA) or helium-rich (DB) independent of their original metallicity. So the problem of finding local stars of the same metallicity as the metal-poor globular clusters vanishes.
- White dwarfs are locally much more numerous than metal-poor main sequence stars allowing to define a better reference sample.

However, there are also some problems (for details see Salaris et al. 2001). The brightness of white dwarfs depends on their

- **mass**
  
  There are so far no observational mass determinations available for any white dwarfs in globular clusters. Renzini et al. (1996) argue on theoretical grounds for a mean mass of 0.53±0.02 M⊙ for white dwarf in globular clusters. Unfortunately, there are no local white dwarfs in this mass range with directly determined masses. All masses for local white dwarfs in this range are derived from effective temperatures and surface gravities in combination with evolutionary models. Masses derived this way depend on the assumed mass of the remaining hydrogen layer – changing the mass of this layer from 0 to 10^{-4} M⊙ changes the resulting white dwarf mass by 0.04 M⊙.
Figure 2. VLT spectra of white dwarfs in M 4 (ESO proposal 65.H-0531(A), 1.5 hours exposure time) and NGC 6752 (ESO proposal 67.D-0201(B), 9 hours exposure time). All spectra show the strong Balmer lines typical for DA white dwarfs. More details will be given in Moehler, Heber, Napiwotzki, Koester & Renzini (in prep.)

- spectral type
DB stars are fainter than DA stars at a given colour, with the offset depending on the filter combination (i.e. the offset is greater in $V$ vs. $B-V$ than in $I$ vs. $V-I$). However, more massive stars are also fainter at a given colour and the best way to verify the spectral types of white dwarfs is obviously by spectroscopy. This has been done with VLT observations of white dwarfs in NGC 6397 (Moehler et al. 2000a), M 4 and NGC 6752 (see Fig. 2). All observed candidates turned out to be hydrogen-rich DA white dwarfs as was assumed for the distance determinations of NGC 6752 (Renzini et al. 1996) and 47 Tuc (Zoccali et al. 2001).

The distance moduli derived from white dwarfs for NGC 6752 and 47 Tuc are in good agreement with other methods, esp. since the distance to 47 Tuc
derived from main sequence fitting has been shortened recently by Percival et al. (2002).

3.3. The faint end – age determination

Recent very deep HST observations allowed to detect the white dwarf cooling sequence in M 4 to unprecedented depths of $V \approx 30$ (Richer et al. 2002). Using proper motions to separate field and globular clusters stars (a method first used by King et al. 1998 for NGC 6397) the globular cluster sequences were isolated from field stars. The luminosity function of the globular cluster white dwarfs shows a much more sudden increase towards fainter magnitudes than that of the disk white dwarfs, suggesting that star formation in M 4 took place over a very short time (Hansen et al. 2002). Assuming that the photometry really reaches the end of the white dwarf sequence one can derive the age of the globular cluster from the age of its oldest and faintest white dwarfs. Aside from the observational uncertainty also uncertainties in the cooling tracks affect the result (see Chabrier et al. 2000 for more details). As a preliminary result Hansen et al. (2002) derive an age of $12.7 \pm 0.7$ Gyr from the white dwarf luminosity function of M 4, consistent with other independent age estimates.

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