Novae from isolated white dwarfs as a source of helium for second-generation stars in globular clusters

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ABSTRACT

We explore the possible contribution of classical and recurrent novae from isolated white dwarfs accreting from the intracluster medium to the abundances of ‘second-generation’ globular cluster stellar populations. We show that under reasonable assumptions the helium abundances of clusters can be enhanced substantially by these novae and argue that novae should be considered as an important, and perhaps even dominant, channel in the evolution of the intracluster medium. We also discuss a possible test for whether helium enhancement really is the cause of the multiple main sequences in globular clusters that is independent of the positions of stars in the colour–magnitude diagram.

Key words: stars: abundances – stars: formation – novae, cataclysmic variables – stars: Population II – ISM: general – globular clusters: general.

1 INTRODUCTION

Globular clusters have traditionally been taken to be almost perfect laboratories for studying the evolution of old stellar populations. Until recently, it was thought that globular clusters were truly simple stellar populations – made of stars of uniform age and chemical composition. Over the past decade, it has become increasingly clear that the chemical properties of globular clusters are more complicated, with clear evidence for multiple main sequences (Bedin et al. 2004) and giant branches, evidence for variations, correlations and anticorrelations among light metals (e.g. Norris 1981; Gratton, Quarta & Ortolani 1986; Ivans et al. 1999; Marino et al. 2008), and unusual horizontal branch (D’Antona et al. 2005) and subgiant branch (Milone et al. 2008; Marino et al. 2009; Moretti et al. 2009; Piotto 2009) morphologies that can be explained in straightforward ways by the presence of multiple stellar populations.

The apparent second-generation populations in the globular clusters tend to share a set of characteristics that are difficult to explain in terms of normal chemical evolution. In particular, the fact that the metal-rich population in $\omega$ Cen is bluer, not redder, than the metal-poor population argues for strongly enhanced helium abundances in the younger populations (e.g. Norris 2004; Piotto et al. 2007). In most other clusters, the age difference between the older and younger population seems to be no more than a few hundred million years and the metallicities appear to be very similar (e.g. Piotto 2009). In fact, enhanced helium abundances can explain nearly all the phenomenology of multiple stellar populations seen in globular clusters (e.g. D’Antona et al. 2010), and, largely speaking, most of the debate in recent years has been about how to produce such a large helium abundance, rather than whether enhanced helium abundances are really the proper solution to the problem, although there have still been suggestions that clusters with multiple stellar populations might have formed from mergers of two clusters (e.g. Mackey & Broby Nielsen 2007).

Two channels have been proposed and debated in recent years for producing large helium abundances in globular clusters’ second-generation stars. One is enrichment from the winds of fast-rotating massive stars (e.g. Prantzos & Charbonnel 2006; Decressin et al. 2007). The other is the enrichment from the ejecta of asymptotic giant branch (AGB) stars [first suggested by Cottrell & DaCosta (1981) in the context of sodium and cyanogen anomalies, and applied to the helium abundance problem by e.g. D’Antona & Ventura (2007) and D’Ercole et al. (2008, 2010)].

On the other hand, the most detailed model papers published to date invoke very unusual initial mass functions (IMFs) for the clusters in order to allow the production of a large enough amount of helium from a small enough number of first-generation stars (e.g. truncation at 9 M⊙ for the second generation (D’Ercole et al. 2010), or an IMF for the first generation considerably steeper than a Kroupa IMF (Prantzos & Charbonnel 2006)]. In some cases, substantial stripping of the stars on the outer part of the cluster is needed to produce enough helium enrichment in the second generation of stars, while also having a large enough ratio of the number of low-mass second-generation to first-generation stars in the present epoch (e.g. D’Ercole et al. 2008). While none of these issues is, on observational grounds, problematic (e.g. it is very easy to hide many first-generation cluster stars in the Galactic halo, and the combination of stellar and dynamical evolution in clusters makes it difficult to extract their IMFs from their present-day mass functions), the

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need for a series of potentially uncomfortable assumptions may indicate that the current theory does not tell the whole story of helium enhancement in globular clusters. As a result, alternative mechanisms for helium enrichment which might operate either instead of those already proposed or in conjunction with them are well worth consideration.

In this paper, we discuss a new scenario for enhancing the helium abundance of the gas that forms the second generations in globular clusters: novae powered by accretion of the intracluster medium by massive white dwarfs. Given the uncertainties in both the nova yields, and the likely properties of the clusters early in their lifetimes, we present only toy calculations at this stage to show that this mechanism is capable of producing a substantial yield of helium, rather than detailed calculations aimed at reproducing observed clusters. First, we outline our assumptions about the rate of accretion of material from the interstellar medium (ISM). Next, we show what the rates of helium production would be under those assumptions, based on existing estimates of nova yields. Additionally, we show that the helium-enhancement hypothesis is potentially testable by looking for mass segregation in clusters, since the helium-rich stars should be lighter than the helium-poor stars at the same luminosity.

2 THE AMOUNT OF ACCRETION FROM THE ISM

To date, there are no stellar mass compact objects which show clear evidence for strong accretion from the ISM. A few isolated neutron stars represent candidates for accretion from the ISM. They are most likely relatively young neutron stars still cooling from their initial formation (e.g. Perna et al. 2003; Kaplan et al. 2011), although in at least one case there is evidence for a hydrogen atmosphere on an isolated neutron star, which can be explained as evidence for accretion, but could also be due to diffusive nuclear burning (e.g. Chang, Arras & Bildsten 2004; Ho et al. 2007).

On the other hand, the Bondi accretion rate is expected to be highest for objects located deep within molecular clouds or in other regions where the ISM is especially dense – precisely the regions where foreground absorption and scattering of the accretion light would make sources hardest to observe. It has been suggested that such sources might be most easily detected in the radio, especially with the upcoming generation of wide-field, low-frequency radio arrays (Maccarone 2005), but at the present time adequate searches have not been made. The possibility that the nova rate in star clusters might be enhanced by accretion from intracluster gas has been discussed previously by Naiman, Ramirez-Ruiz & Lin (2011).

It is clear that the site of formation of second-generation populations in globular clusters must be a region of gas density comparable to that in molecular clouds (since the total amount of star formation must be of the order of $10^7-10^8 M_\odot$, and the size scale for the region must be of the order of 1 pc). Assuming one starts with $10^8 M_\odot$ within 1 pc of the cluster centre, the gas density will be about 10$^6$ particles per cubic centimetre.

We use the results of Dobbie et al. (2006) to estimate the birth masses of the white dwarfs present in the cluster:

$$M_{WD} = 0.7 + (M_\odot - 3.0)/8,$$

where $M_{WD}$ is the initial mass of the white dwarf and $M_\odot$ is the initial mass of the star, both in solar units. We can next estimate the fraction of the initial stellar population that will be in white dwarfs produced by progenitors of at least 3 $M_\odot$. By integrating over a Kroupa IMF from 0.08 to 80 $M_\odot$, we can get the total initial mass of the cluster. Then, by integrating the mass of the white dwarfs using the Dobbie et al. (2006) relation, we find that about 8 per cent of the initial mass of the first generation ends up in white dwarfs. We also find that about 50 per cent of the initial mass of the first generation is in main-sequence stars that still exist.

Rescaling the Bondi–Hoyle rate formula from Ho, Terashima & Okajima (2003), we find that

$$M_\text{b} = 7 \times 10^{-9} M_\odot \text{yr}^{-1} \left(\frac{M_{WD}}{M_\odot}\right)^2 \left(\frac{n}{10^6 \text{cm}^{-3}}\right) \left(\frac{c}{10^6 \text{cm s}^{-1}}\right)^{-3},$$

which gives mass accretion rates of the order of $10^{-5}$ $M_\odot$ yr$^{-1}$ over most of the cluster core. We compare the parameter values above with those in the figures in D’Ercole et al. (2008), who estimate that the central gas density should be $\sim 10^6$ cm$^{-3}$, with central temperatures of a few thousand K, yielding slightly higher expected mass accretion rates than $10^{-5}$ $M_\odot$ yr$^{-1}$ in the very centres of the clusters. They find that the gas density falls off a bit towards the outer part of the cluster core, but that the temperature does as well.

We then estimate how much accretion could take place over the $\sim 300$ Myr during which white dwarfs exist, but before the second generation of stars has formed. One can see that it is not unreasonable for $\sim 3 M_\odot$ of gas to be processed by each solar mass of white dwarf – although only the heaviest white dwarfs will have existed for the full 300 Myr available, so it is more likely that the average white dwarf will process roughly its own mass rather than three times its own mass. According to the calculations of Yaron et al. (2005), for mass accretion rates of $10^{-8}$ $M_\odot$ yr$^{-1}$, the heaviest white dwarfs will be very near balance between the mass accreted and the mass lost in the nova shells, so the masses of the white dwarfs themselves can be assumed not to change substantially. This will remain true for white dwarf masses greater than about 0.8 $M_\odot$, which represent most of the white dwarf mass that will exist in a cluster with a Kroupa (2001) IMF over the allowed time-span.

We do note that in some cases there is evidence that the Bondi formula significantly overestimates the mass accretion rates of objects accreting from the ISM. Perna et al. (2003) find that the deficit of isolated neutron stars accreting from the ISM can be explained by suppressing accretion from the ISM due to magnetic pressure effects in the ISM (e.g. Igumenshchev & Narayan 2002), but also noted that propeller effects from the neutron stars’ own magnetic fields could be responsible for keeping the neutron stars from accreting substantially. Pellegrini (2005) shows that active galactic nuclei in elliptical galaxies are typically accreting at about 3 per cent of the Bondi rate – but a variety of processes may act to suppress accretion in galactic nuclei, included e.g. radiative and kinetic feedback from the accretor itself (e.g. Milosavljevic, Couch & Bromm 2009). On a more positive note, in high-mass X-ray binaries, the mass transfer rates are well modelled by the Bondi capture process (see e.g. Frank, King & Raine 2002). Finally, as we show below, our simple calculation gives an excess of helium compared to what is needed to match the observations if we make assumptions similar to those in D’Ercole et al. (2008) about the properties of the first generation and the gas reservoir that supplies the second generation, so it is easily possible to tolerate some mild suppression of the accretion rate below the Bondi capture rate.

3 THE EXPECTED NOVA YIELDS

It is generally well agreed that the properties of novae will depend strongly on the white dwarf mass, white dwarf temperature and...
the mass transfer rate on to the white dwarf. The yields of helium and metals and the ejected masses seem to depend only weakly on the composition of the white dwarf, while the specific composition of the metals in the ejecta can depend strongly on whether the white dwarf is a carbon–oxygen white dwarf or a neon–oxygen–magnesium white dwarf (see e.g. Yaron et al. 2005). The set of parameter values for which nova yields have been calculated has been steadily expanding over the past decade, but is still not detailed enough to account for details of the metal abundances of gas produced from novae [e.g. the calculation of Yaron et al. (2005), which is probably the most sophisticated treatment to date, treats ONeMg white dwarfs with a calculation assuming the white dwarf is only made of oxygen and neon]. Similarly, nearly all calculations done to date assume that the accreted material is of solar composition [although see also José et al. (2007), who do a calculation of the yields from very low metallicity gas as might be found in Population III].

Next, we consider the possibility that the novae are enriching largely pristine gas. This assumption allows for an arbitrarily large gas mass to be used to form the second generation of stars relative to the mass of the first generation. It also requires that the gas not be unbound entirely from the cluster by the core-collapse supernovae from the first generation, and also that the gas not be too strongly enriched by the core-collapse supernovae. Scenarios have been developed already in which the pristine gas can survive in this manner (e.g. Recchi, Matteucci & D’Ercole 2001). In this manner, if the gas can be sufficiently enriched by novae, then the second generation can have a similar stellar mass to that of the first generation if (i) only a small fraction of the mass in the first generation is turned into stars, (ii) most of the gas is blown from the core of the cluster by the first-generation core-collapse supernovae, but is not actually unbound from the cluster, so that the second generation is formed from a total gas mass similar to that from which the first generation is formed and (iii) the star formation efficiency (i.e. the stellar mass produced per unit gas mass) for the second generation is similar to that for the first generation. In this way, nova enrichment might solve the problems posed by having the helium-rich material been a small fraction of the gas released from first-generation stars (either through equatorial or AGB winds), but being a large fraction of the total mass of the first-generation stars which remain. The existent models (Decressin et al. 2007; D’Ercole et al. 2008) require a large fraction of the first-generation stars to be stripped from the outskirts of the clusters – a process which is plausible, but perhaps not as attractive as a model in which the mass evolution required of the clusters is not so extreme.

We take the yields from the calculations of Yaron et al. (2005) as instructive, but not as definitive. The helium content of the nova ejecta are typically about 0.4–0.5 for high accretion rates. We then expect the final helium content of the gas to be about $0.21 \times M_{\text{WD}}/M_{\text{gas,sec}} + 0.24$, where $M_{\text{WD}}$ is the mass locked up in the white dwarfs from the first generation of star formation and $M_{\text{gas,sec}}$ is the mass of the gas that eventually produces the second generation. To reach $Y = 0.30$, we then need to have the mass processed in novae to be about (0.06/0.21) of the mass in the gas that will make up the second generation. This level is comfortably achieved in, e.g., the modelling currently used to produce second generations (e.g. D’Ercole et al. 2008). The white dwarfs represent about 8 per cent of the mass of the first generation by the time the $3M_\odot$ main-sequence stars form white dwarfs. Since a white dwarf can process roughly its own mass, and the first generation is a few to 10 times as massive as the second generation, it would be surprising if novae did not significantly enhance the helium content of clusters – in fact, the amount of helium we would naively expect to be produced in novae is so large that the fact that clusters are not routinely observed with $Y = 0.4$ suggests that perhaps the Bondi capture rate is an overestimate for white dwarfs accreting from the ISM. By providing an extra channel for helium enhancement, then, one can relax the assumptions about the second-generation IMF. Evaluating the effects of novae on the abundances of the light metals like oxygen, aluminium, sodium, carbon and nitrogen would require yield calculations far more complex than the ones which have been made to date. However, given the suggestions that some of the rarer isotopes of carbon, nitrogen and oxygen (i.e. $^{13}\text{C}$, $^{15}\text{N}$ and $^{17}\text{O}$) may be produced primarily in novae (e.g. Romano & Matteucci 2003), it may be worthwhile to check whether the isotopic abundances of these elements in red giants in globular clusters with multiple populations show anomalies. We note that gas must be cycled through multiple nova explosions before it becomes fully enriched – the ejecta of a single nova may reach a helium abundance of $\sim 0.3$–0.4, but the ejecta will travel over a distance of $10^3$ pc (see Section 4) before the nova shell stops expanding. As a result, the nova shell will sweep up many times its own mass, and the gas will not be sufficiently enriched by a single nova to form second-generation stars.

The nova yields of metals are particularly uncertain theoretically, but are likely to be keys to understanding whether novae are important contributors to the chemical enrichment of globular clusters’ second-generation stars. The relevant novae are likely to be novae from ONeMg white dwarfs. One can reach this conclusion through two lines of reasoning. First, the ONeMg white dwarfs are the heaviest and form first, so they will have the bulk of accretion take place on to them before the second generation of stars form (since the second generation must form fairly rapidly). Secondly, they produce the largest yields of helium and, in some accretion rate regimes, can account very nicely for a strong sodium–oxygen anticorrelation (Yaron et al. 2005). We note that the progenitors of these white dwarfs will predominantly be the same stars that are often taken to supply helium-enriched material to the ISM (D’Ercole et al. 2008). As a result, even if a substantial reservoir of pristine gas provides the bulk of material for accretion by the white dwarfs, its composition will be affected at least in part by the addition of the helium-rich AGB ejecta that are released as the white dwarfs are forming.

At the present time, only a few observational data sets have been obtained on ONeMg abundances (e.g. Schwarz et al. 2007). Generally, these novae produce very large enhancements of nitrogen and neon relative to solar composition, and frequently, they produce large magnesium enhancements as well. They also typically lead to a helium mass fraction of about 32 per cent, although with significant scatter. A potential problem is that mild oxygen enhancement is seen in most cases, while oxygen depletion is observed for the candidate helium-rich stars in globular clusters (e.g. Marino et al. 2011).

The models of Yaron et al. (2005) predict oxygen depletion and sodium enhancement for most ONe novae. Whether the discrepancy exists because of problems with the theoretical nova models or observational errors or selection biases in the small number of ONeMg novae which have been observed is difficult to determine at the present time. However, if a large number of high accretion rate novae from massive ONeMg white dwarfs are seen to produce excesses of oxygen relative to solar values, this should be taken as a point against the nova enrichment scenario – although there will still remain the point that the chemical composition of the gas in globular clusters early in their lifetimes will be rather different than the gas accreted for most present-day novae.
4 STABILITY OF THE CLUSTER AGAINST NOVAE CLEARING OUT THE GAS

It has recently been suggested by Moore & Bildsten (2011) that most globular clusters today may have low gas content because novae frequently sweep out all the gas from the cluster. The clusters we are considering should be robust to having even the high rate of novae we are considering here from sweeping out their gas. The momentum carried by a shell of $10^{-3} M_\odot$ at about $1000 \text{ km s}^{-1}$ (typical numbers for a $1.2 M_\odot$ WD accreting at about $10^{-3} M_\odot \text{ yr}^{-1}$) should be large enough to evacuate a bubble of radius about $10^{3} \text{ pc}$ in gas with random motions of the order of $10 \text{ km s}^{-1}$, before the outflow speed is comparable to the random motions of the gas. The refilling time-scale of the bubble would be of the order of $30–100$ years. As a result, the nova would provide some energy input into the cluster, but would not blow gas out of the cluster. This is unsurprising, since D’Ercole et al. (2008) have already pointed out that a single Type Ia supernova would represent only a mild perturbation on the cluster’s gas reservoir, and the sum of energy injections from all the novae would be significantly less than that from a single supernova – although they also went on to point out that a large rate of supernovae would have severe effects on the gas reservoir of the cluster.

One can alternatively look at the filling factor of the bubbles that are expected to be created by nova explosions. With $\sim 10^5$ white dwarfs in the cluster, each undergoing a nova explosion every $\sim 1000$ years, there should be about $100$ novae per year in the cluster. Since the lifetimes of the nova bubbles are $\sim 100$ years, there should be about $10^4$ active bubbles at a time, each of which has a radius of $\sim 10^{3} \text{ pc}$, and hence a volume of about $10^{-4} \text{ pc}^3$. Therefore, $10^{-4}$ of the cluster core volume should be filled by the bubbles, and they can be neglected in terms of the effects of interactions of bubbles with one another and the fact that the accretion rates within a bubble will be much lower than those outside a bubble.

5 EFFECTS OF ACCRETION ON THE FIRST-GENERATION STARS

One can also consider whether the first-generation stars can be expected to be affected significantly by accretion of interstellar gas. In considering this, it is important to bear in mind two points: first, in most clusters, nearly all the stars below the turnoff mass at the present time are fully convective. Furthermore, none is more than about half the mass of the heavy white dwarfs from which the recurrent novae that are expected to pollute the ISM are produced. The former effect means that whatever gas has been accreted by a main-sequence star in a globular cluster should have been well mixed by the present time [see e.g. the discussion in Briley, Cohen & Stetson (2002) of why accretion is unlikely to lead to the unusual abundances of some M13 subgiants]. One can then consider what fraction of the mass of the present-day main-sequence stars would have come from accretion. Integrating equation (1), we find that in the inner parts of the cluster, $M_f - M_i = 2M_f/M_i$, where $M_f$ is the initial mass of the star and $M_i$ is the initial mass of the star, with both quantities divided by the solar mass. Over most of the first-generation main sequence, stars should have acquired about half their masses by accretion, much of which will have taken place before much enrichment of the gas, so the deviations of their abundances from those of stars which formed from first-generation material and did not accrete at all should be only about a quarter as big as the differences between the first- and second-generation stars, meaning that these stars should probably be hard to identify with current data quality.

6 WHAT NOVAE CANNOT EXPLAIN

It is also important to consider what observed phenomena cannot be explained by nucleosynthesis taking place in classical novae. Largely speaking, classical novae do not burn beyond chlorine. Therefore, some of the heavier s-process elements recently shown to have unusual abundances (e.g. NGC 6656 – Milone et al. 2011) cannot be produced by novae. On the other hand, Milone et al. (2011) suggest that some supernova enrichment was probably likely for the second generation in NGC 6656, as some of the stars also show enrichment in elements such as europium, which are not thought to be produced except in supernovae – but of course these elements represent a challenge also to the scenarios in which the enrichment comes from stellar winds. Additionally, we again emphasize the possibility that novae may act in concert with other mechanisms to change the composition of the gas from which second-generation stars form.

Another example of something which is difficult to explain in the scenario we propose is the observation of a strong sodium–oxygen anticorrelation in M3 (Cohen & Meléndez 2005), with no evidence for a helium enhancement (Catelan et al. 2009). Because the results of Cohen & Meléndez (2005) extended the discovery of the sodium–oxygen anticorrelation down to masses on the red giant branch below where dredge-up should have taken place, they argue that some form of pollution must be necessary for these systems, and the lack of such correlations for field stars (Gratton et al. 2000) suggests that the origin of the pollution must be inherently related to the dense stellar environments, but attempts to model such pollution have not, to date, been successful (e.g. Fenner et al. 2004). These observations remain a problem in the context of all current models of the chemical evolution of globular cluster stars.

7 MASS SEGREGATION AS A TEST OF THE HELIUM HYPOTHESIS

We also discuss a possible test for the helium enrichment hypothesis for producing the multiple main sequences and the other anomalies seen in evolved stars in globular clusters. No direct measurements of the helium contents of stars suspected to be helium enhanced have been possible to date, leaving the helium enhancement scenario largely untested, except based on its effects in colour–magnitude diagrams. An alternative indirect test for the helium enrichment scenario is that the masses of stars at a given luminosity should be quite different. For example, D’Antona & Caloi (2004) calculate three tracks with the metallicity and age of NGC 2808, but with helium abundances of 0.24, 0.28 and 0.32. They find that the turnoff luminosities for the three tracks are the same, but that the turnoff masses are 0.82, 0.77 and 0.72, respectively. It should be expected, then, that the core radius for the helium-rich stars will be larger than the core radius for the stars with normal helium abundances due to mass segregation (see e.g. Gunn & Griffin 1979), since all globular clusters in the Galaxy are older than their core relaxation timescales (Harris 1996, and references therein). On the other hand, a few clusters do have relaxation time-scales at their half-light radii which are longer than their ages (Harris 1996, and references therein), so searching for mass segregation of the second generation well outside the core could lead to spurious results, especially since most models predict that the second generation formed in a more centrally concentrated manner than the first generation.

We note that because the mass functions may differ for the different generations, a straight test of the spatial profile of the red sequence versus that of the blue sequence could potentially be
misleading. Additionally, because the clusters may not be fully relaxed at radii observable from the ground, ground-based data are unlikely to be useful. We have tested the feasibility of this mechanism by drawing stars at random from a King (1966) model distribution. We take a King model with $W = 7$ (corresponding to a ratio of tidal core radius of about 33 or a concentration parameter in the units of the Harris catalogue of about 1.5) and repeatedly draw about 1400 stars at random (because we draw the stars in each spherical shell as a Poisson distribution, the number varies a bit from simulation to simulation). Typically about 100 of those stars have projected radii less than the core radius of the cluster. We then compute the mean value for the distance of these stars from the cluster centre, and find that it is about $0.48 \pm 0.02$. Assuming that the stars really fit to a Gunn & Griffin (1979) model, groups of 100 stars in the red and blue sequences should then yield $\approx 3\sigma$ differences in terms of their mean distances from the centre of the cluster if they have masses of 0.82 and 0.72 $M_\odot$, respectively. Many such bins can be constructed in the clusters, massive enough to show multiple main sequences, in a manner that keeps the luminosity bins having small mass ranges within themselves, and then one can look to see whether a consistent trend holds up. Previous approaches have typically looked at the spatial profiles of the different main sequences as a whole, rather than breaking the stars down into luminosity bins (e.g. Sollima et al. 2007; D’Ercole et al. 2008).

At the present time, we are aware only of observations of the outer part of $\omega$ Cen which have been used to compare the red and blue main sequences (Sollima et al. 2007). $\omega$ Cen shows that the blue (i.e. likely helium rich) main sequence is centrally concentrated. On the other hand, the observations compare the spatial profiles of the two main sequences on physical scales with relaxation time-scales of the order of or greater than a Hubble time (the half-light radius relaxation time for $\omega$ Cen is about 12 Gyr – Harris 1996), so one would not expect the mass segregation effects to have taken place yet.

8 DISCUSSION

We have shown that the production of a substantial amount of helium from novae triggered by accretion of intracluster medium by isolated white dwarfs is a necessary consequence of having a large amount of gas available in a globular cluster’s core well after the white dwarfs have started forming. We have also outlined a method that can be used for testing whether the second-generation populations of globular clusters really are helium enhanced.

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