



Compact-object Formation, Retention, and Growth through Accretion onto Gas-embedded White Dwarfs/Neutron Stars in Gas-enriched Globular Clusters

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Abstract

Observations of pulsars in globular clusters (GCs) give evidence that more than $>10\%$ – 20% of neutron stars (NSs) that ever formed in GCs were retained there. However, the velocity distribution of field pulsars peaks at 5–10 times the escape velocities of GCs. Consequently, only a small fraction of GC NSs should have been retained, which is potentially difficult to explain even accounting for low-velocity NSs formed through electron-capture supernovae (SNe). Thus, too few low-velocity NSs should have been retained, giving rise to the NS retention problem in GCs. Here we suggest a novel solution, in which the progenitors of most GC NSs were ONe white dwarfs (WDs) that accreted ambient intracluster gas and formed low-velocity NSs through accretion-induced collapse (AIC). The existence of an early gas-enriched environment in GCs is supported by observations of multiple stellar populations in GCs. It is thought that 10–100s of megayears after the formation of the first generation of stars, and after ONe WDs were already formed, GCs were replenished with gas, which formed a second generation of stars. Accretion of such replenished gas onto the ONe WDs catalyzed the AIC processes. The number of AIC-formed NSs is then sufficient to explain the large number of NSs retained in GCs. Similar processes might also drive CO WDs to produce Type Ia SNe or to merge and form NSs and similarly drive NSs to AIC and mergers producing BHs. Moreover, the wide variety of gas-catalyzed binary mergers and explosive transients suggested to occur in the gas-rich environments of an active galactic nucleus disk could similarly, and even more efficiently, occur in second-generation gas in GCs.

Unified Astronomy Thesaurus concepts: [Globular star clusters \(656\)](#); [Neutron stars \(1108\)](#); [White dwarf stars \(1799\)](#); [Stellar mass black holes \(1611\)](#); [Bondi accretion \(174\)](#); [Novae \(1127\)](#); [Young massive clusters \(2049\)](#)

1. Introduction

For decades, globular clusters (GCs) were thought to host simple stellar populations formed through a single star formation episode. However, detailed photometric and spectroscopic studies collected over the last decade (see, e.g., Carretta et al. 2009; Bastian & Lardo 2018, and references therein) have shown that the vast majority of galactic GCs host multiple stellar populations with different light-element contents. The exact origins of multiple stellar populations have been extensively studied, but no clear solution has yet been found (see Renzini et al. 2015; Bastian & Lardo 2018; Gratton et al. 2019, for a summary of the scenarios and their caveats). The general consensus is that GCs experienced two or more star formation episodes, in which second-population (2P) stars formed from processed gas lost by first-population (1P) stars and/or accreted external gas. Kinematics show that 2P stars are more centrally concentrated and were likely formed in the inner region of the GC where the second-generation gas likely accumulated.

While the exact source of the gas is debated, all suggested scenarios effectively require that tens up to hundreds of megayears after their formation, 1P stars had become embedded in a highly gas-rich environment that later produced the 2P stars. The evolution of stars, binaries, and compact objects embedded in gas could therefore be significantly altered. Such processes were little studied in the context of the early second-generation gas-enriched environment (Vesperini et al. 2010;

Maccarone & Zurek 2012; Leigh et al. 2013, 2014; Roupas & Kazanas 2019, but see works by us and others on some aspects of such evolution) but received much more attention in the context of gas-disk and active galactic nucleus (AGN) environments near massive black holes (e.g., Artymowicz et al. 1993; Baruteau et al. 2011; McKernan et al. 2012; Stone et al. 2017; McKernan et al. 2018; Tagawa et al. 2020, and references therein).

Here we explore the potential impact of the gas-enriched environment on the formation and evolution of neutron stars and their retention in clusters and discuss other aspects of stellar and binary evolution of gas-embedded environments in clusters.

Pfahl et al. (2002) pointed out a large number of pulsars and X-ray sources in GCs, suggesting a large population of NSs exist in GCs. They inferred that $>10\%$ – 20% of all NSs formed in GCs are retained there. Such high retention fractions are surprising and at odds with the observed velocity distribution of field pulsars, as GCs typically have low escape velocities of a few tens of km s^{-1} . Given the high natal-kick velocities of single pulsars observed in the field (Hobbs et al. 2005; Verbunt et al. 2017; Igoshev et al. 2021), only a fraction of NSs should have been retained in GCs. Such inconsistency, sometimes termed the NS retention problem, has been studied by various groups (e.g., Podsiadlowski et al. 2005; Ivanova et al. 2008). They and others suggested that a special population of low natal-kick velocity NSs is required in order to resolve the NS retention problem (Pfahl et al. 2002). Ivanova et al. (2008) proposed that NSs formed through electron-capture supernovae (SNe) that receive low natal-kick velocities could give rise to a few up to 10% retention fraction for typical GCs, somewhat lower than but potentially comparable with the inferred retention fractions. These results, however, were based on the assumption that

electron-capture SNe progenitors extend over mass ranges of $6.85\text{--}7.57 M_{\odot}$ ($6.17\text{--}6.76 M_{\odot}$) for single stars with GC-like metallicity of $Z = 0.005$ (0.0005). However, Willcox et al. (2021 and references therein) have recently suggested that the mass range for electron-capture SN progenitors cannot extend over a mass range larger than $\approx 0.2 M_{\odot}$ given the observed velocities of isolated pulsars in the field. This would result in at least three to five times smaller numbers of single NSs formed through electron-capture SNe and hence similarly lower retention fractions, exacerbating the NS retention problem. Accounting for the overall velocity dispersion of NS progenitors and the possibility of correlation between kick properties and pulsar properties that affects detectability could weaken these results, giving rise to a potential underestimate of the number of slow-kick pulsars. Nevertheless, these results challenge the electron-capture SNe solution for the retention problem.

Given the potential NS retention problem, but also irrespective of it, we suggest that a significant fraction, and possibly the majority of NSs in GCs, could have formed through efficient accretion of intracluster second-generation gas onto preexisting oxygen–neon white dwarfs (ONe WDs). The accretion could drive such WDs to sufficiently large masses as to become unstable and collapse to form NSs through accretion-induced collapse, AIC (e.g., Canal & Schatzman 1976; Nomoto & Kondo 1991). AIC-formed NSs are thought to receive no, or very low, natal kicks, allowing them to be retained in their host clusters.

In the following, we first discuss the gas-enriched environment formed through delayed gas replenishment in GCs and the expected conditions in such environments. We then discuss the accretion onto ONe WDs and its efficiency and estimate the numbers of NSs that could form and be retained through AICs of ONe WDs. We then briefly explore the implications for accretion onto other compact objects and stars. Finally, we discuss and summarize the results.

2. Early Gas Enrichment of Globular Clusters

The total mass of second-generation gas in GCs is highly uncertain, but given reasonable assumptions on the relation between the gas and the observed second-generation stars in GCs, one can provide an estimate of the amount of replenished gas and its density. The mass in 2P stars (M_{2P}) in clusters is of the order of half the GC mass (with some correlation between the GC mass and the 2P fraction, with higher-mass GCs having higher 2P fractions; Bastian & Lardo 2018a; Mastrobuono-Battisti & Perets 2020). Given the likely higher mass of newly formed GCs, compared with their inferred masses today, we consider the mass of 2P stars in a typical GC to be $M_{2P} \approx 10^5 M_{\odot}$ and given some efficiency of transforming gas into stars $\epsilon_g = 0.3$ (e.g., in models used by Bekki 2017), we find the gas mass to be $M_g \approx 3.3 \times 10^5 M_{\odot}$.

Observations suggest that the 2P stars concentrate in more compact configurations in the central part of GCs, consistent with the simulation of 2P star formation in GCs, suggesting they mostly form and are enclosed in the central parsec of the cluster (Bekki 2017), and likely in a disk configuration (Bekki 2010; Mastrobuono-Battisti & Perets 2013, 2016). Naturally, the densities in the cluster inner parts could be even higher, and the formation efficiency ϵ_g might be somewhat smaller or larger.

Maccarone & Zurek (2012) adapted a typical density of $n = 10^6 \text{ cm}^{-3}$ (Pflamm-Altenburg & Kroupa 2009) following

models by D’Ercole et al. (2008) for gas replenishment by asymptotic giant branch (AGB) stars. However, these models assume an exceedingly high star formation efficiency of 1, compared with, e.g., Bekki’s (Bekki 2017) models, taking the efficiency to be 0.3, and considered a spherical configuration. It is likely that the 2P gas formed in a disk-like configuration rather than a spherical distribution (Bekki 2010; Mastrobuono-Battisti & Perets 2013, e.g.). In order for stars to have formed, the temperatures and hence the sound velocity of the gas should have been sufficiently low, down to 10 km s^{-1} or lower (D’Ercole et al. 2008; Vesperini et al. 2010; Bekki 2010); if we adopt a sound speed of $c_s = 10 \text{ km s}^{-1}$ (D’Ercole et al. 2008) we get a disk height of $H_d \approx (c_s/v)R_c$, where v is the semi-Keplerian velocity in the cluster core and $R_c = 1 \text{ pc}$ is the adopted size of the enriched gas region. We should note that Pflamm-Altenburg & Kroupa (2009) explored external gas accretion rather than gas from AGB stars and found far higher gas densities in the central region of up to $10^8\text{--}10^{10}$ for $10^6 M_{\odot}$ clusters.

We can estimate the typical gas density by dividing the gas mass over the volume of a thick disk. Here we will adopt a fiducial gas mass of $3.3 \times 10^5 M_{\odot}$ to get the atomic gas density in the disk (with size 1 pc and a scale height of $H_d \approx 0.23 \text{ pc}$) to be $n = 1.9 \times 10^7 \text{ cm}^{-3}$. We briefly discuss the dependence on density and its possible implications for the growth of ONe WDs.

The timescales for 2P gas replenishment and depletion are unknown. Simulations (Bekki 2017) suggest gas replenishment can initiate on timescales of $\approx 50 \text{ Myr}$, if arising from winds of AGB stars, leading to star formation and gas depletion on the timescale of a few tens of megayears, up to $\approx 100\text{--}150 \text{ Myr}$. Observations and modeling of young GCs in the LMC showing multiple populations suggest potentially longer-replenishment timescales of a few hundred megayears (Li et al. 2016), with the gas originating from the accretion of external, galactic disk gas by the GCs. The latter study does not provide clear constraints on the gas-depletion timescales.

Here we adopt a simple model for gas depletion, assuming a constant gas density over a timescale τ_{acc} of 25 Myr , and a fast (e.g., exponential) depletion, modeled for simplicity as a strict immediate depletion at τ_{acc} .

3. Accretion onto ONe White Dwarfs

The accretion rate onto ONe WDs depends on the gas density in which they are embedded (discussed above), the relative velocity between the accretor and the gas, and the mode of accretion. In Leigh et al. (2013) we discussed the accretion rate on stars and the different processes involved. Here we briefly summarize the conclusions.

The Bondi–Hoyle–Lyttleton (BHL) approximation for accretion onto gravitating objects in gas should be regarded as a strict upper limit on the true accretion rate onto a compact object. It describes the rate at which material becomes bound and is captured by an object at least temporarily. Feedback effects could later unbind some of the captured material, giving rise to an effective lower mass accretion rate and growth of the accreting compact object (e.g., if the accretion is Eddington limited). Alternatively, or in addition, a WD accretor might not be able to efficiently grow in mass due to feedback from novae occurring on the accreting WDs, which could eject part or all of the accreted material.

Taking the fiducial gas densities discussed above and following Maccarone & Zurek (2012) and Leigh et al. (2013), the BHL accretion rate is given by rescaling the formula in Ho et al. (2003) to get

$$\begin{aligned} \dot{M}_{\text{BHL}} &= 6.8 \times 10^{-8} M_{\odot} \text{ yr}^{-1} \\ &\times \left(\frac{m}{1M_{\odot}} \right)^2 \left(\frac{n}{1.9 \times 10^7 \text{ cm}^{-3}} \right) \left(\frac{\sqrt{c_s^2 + v_d^2}}{14 \text{ km s}^{-1}} \right)^{-3} \\ &= Am^2, \end{aligned} \quad (1)$$

where m is the accretor mass, n is the gas density, c_s is the sound speed, and v_d is the relative velocity between the gas and accretor for stars embedded in the disk, assumed to be comparable to the gas sound velocity, $v_d = 10 \text{ km s}^{-1}$. We assume an atomic density of $n \approx 1.9 \times 10^7 \text{ cm}^{-3}$. The central temperatures were suggested to be a few thousand Kelvin, which translates into $c_s \approx 10 \text{ km s}^{-1}$ (D’Ercole et al. 2008), though they might be lower for star formation to occur (Bekki 2010). These values represent the 2P gas-disk region, yielding $A \approx 6.8 \times 10^{-8} M_{\odot}^{-1} \text{ yr}^{-1}$ for ONe WD masses and velocities. The velocity dispersion dictated by the stellar and gas mass is of the order of $\approx 43 \text{ km s}^{-1}$ but would be only about a quarter of that for stars embedded in the disk. Hence, only about a quarter of the stars reside in the disk region (but possibly higher, given that gas dynamical friction (GDF) would lead to migration and capture of higher inclination stars into the disk; e.g., Artymowicz et al. 1993).

3.1. Accretion Efficiency, Growth, and Accretion-induced Collapse

The accretion efficiency of WDs, i.e., the fraction of accreted material retained and not ejected in novae through its accretion evolution, depends on their mass, the accretion rate, and their temperature. Yaron et al. (2005) calculated a grid of models for WD accretion. Their models explored higher and lower accretion rates than our fiducial rate. For accretion rates closest to ours of $10^{-7} M_{\odot} \text{ yr}^{-1}$ they find that WDs in the mass range between 1.25 and $1.4 M_{\odot}$ (relevant for ONe WDs) accrete at 5%–30% efficiency (with only one model $M_{\text{WD}} = 1.25 M_{\odot}$ with core temperature $T = 3 \times 10^7 \text{ K}$, showing efficiency below 10%). Magnetic WDs could potentially accumulate mass at lower accretion rates (Ablimit 2022), but these are not considered here. We should also note that AIC formation of NSs could occur through mass transfer onto WDs in binaries. However, population studies suggest this channel produces at most $\sim 10\%$ of the inferred NS population (Ivanova et al. 2008). The final mass, M_f , of a WD with initial mass M_i is of the order of

$$M_f = \frac{M_i}{1 - M_i A \tau_{\text{acc}} f_{\text{acc}}} \quad (2)$$

following Leigh et al. (2013) (and accounting for the retention efficiency, not used there for accretion on BHs). This would diverge for too-long accretion times or initial masses, but significant accretion would deplete the gas (Leigh et al. 2013), e.g., before the scaling becomes unphysical.

Adapting a fiducial accretion time of $\tau_{\text{acc}} = 25 \text{ Myr}$ and accretion efficiency of $f_{\text{acc}} = 0.1$ (taking for simplicity a constant conservative low value between the highest and

lowest retention efficiencies), we find that WDs more massive than $\approx 1.15 M_{\odot}$ will collapse to NSs as they grow beyond $\approx 1.38 M_{\odot}$ during the gas-depletion timescale.

In other words, for the plausible conditions of 2P star formation in GCs, ONe WDs would accrete sufficient mass to grow to Chandrasekhar mass and transform to NSs through AIC.

4. Oxygen–Neon WD Progenitors

The formation and evolution of 1P ONe WDs depend on their progenitors’ stellar evolution. The evolution, in turn, depends on the metallicity of the stars. At lower metallicities, lower-mass stars can give rise to ONe WDs; the mass range of the progenitors then increases toward higher metallicities. Taking stellar evolution prescriptions (using the SSE population synthesis code; Hurley et al. 2000) we find that at low $Z = 0.05Z_{\odot}$ metallicity ($Z_{\odot} = 0.013$), ONe (NS) progenitors are stars in the mass range 5.13 – $6.58 M_{\odot}$ (compared with 6.58 – $18.44 M_{\odot}$ for NSs), which form ONe WDs after 60 – 100 Myr . The progenitors’ mass range increases up to the range of 6.2 – $7.9 M_{\odot}$ (compared with 7.9 – $19.95 M_{\odot}$ for NSs) for solar metallicity and formation timescales of the ONe WDs of 46 – 74 Myr . In these models, ONe WDs have masses $\gtrsim 1.2 M_{\odot}$; however, the lowest-mass ONe WDs might have masses of $1.1 M_{\odot}$, in which case the lower progenitor mass could be $\approx 0.4 M_{\odot}$ lower than assumed here (and progenitor lifetimes could extend up to 90 Myr even for solar metallicity).

Given the above discussion of the replenishment timescales, we find these are generally consistent with 1P ONe WDs already formed before, or at most during, the main gas-replenishment epoch, allowing them to interact with and accrete 2P gas.

5. NS Retention Fraction

The NS retention fraction is typically defined as the fraction of NSs retained out of the NS formed in a cluster. However, in previously considered models, AIC-formed NSs contributed a negligible fraction of the NSs. In particular, the inferred retention fractions of 10%–20% calculated by Pfahl et al. (2002) referred to NSs formed from massive stars and not through the AIC of WDs. Consequently, in the following, we consider the fraction of retained NSs out of the NSs formed from massive stars, for consistent comparison.

Given the progenitor mass range for ONe WDs, we can find the relative numbers of initially formed ONe WDs and of NSs assuming typical initial mass functions (e.g., Miller-Scalo initial mass function; Miller & Scalo 1979). Given efficient accretion allowing the ONe WDs to form NSs through AIC, we find that the number of AIC-formed NSs is $\approx 61\%$ – 65% of the NSs formed from massive stars. Assuming, like Ivanova et al. (2008), that AIC-formed NSs get low-velocity kicks (10 times smaller than regular NSs, i.e., assuming a Maxwellian velocity distribution with a 10 times lower mean than inferred by Hobbs et al. 2005), about 85% of such AIC-formed low-velocity NSs were retained in our fiducial cluster.

If we extend ONe WD masses to as low as $1.15 M_{\odot}$ (such WDs would grow to $1.38 M_{\odot}$ and follow an AIC), these fractions could extend to $1.5\times$ larger. As mentioned above, only stars embedded in the disk will efficiently accrete. Assuming the relative fraction of stars in the disk goes like

the volumetric ratio of the disk volume of the central parsec, we obtain that only $\approx 17\%$ of the stars reside in the disk. Overall we then find a retention fraction of $9\%–14\%$ with these assumptions. Due to GDF, it is likely that a larger fraction of the stars could migrate into the disk (as suggested for AGN disks; e.g., Artymowicz et al. 1993), raising these fractions even higher. On the other hand, newly formed second-generation stars would dilute these fractions by up to a factor of 2. Taken together, we expect $\approx 5\%–15\%$ retention fractions, given the many uncertainties; these are generally consistent with the inferred NS retention fractions in GCs (Pfahl et al. 2002).

6. Discussion

6.1. Accretion, Growth, AIC, and Explosion of Gas-embedded WDs

We find that the AIC of ONe WDs due to accretion of intracluster gas could potentially produce the majority of NSs retained in GCs. AIC is likely to occur when an ONe WD approaches $\approx 1.38 M_{\odot}$, although the exact mass could depend on spin and/or other properties. Models suggest that at most $\approx 0.1 M_{\odot}$ of material is ejected during the collapse (e.g., Dessart et al. 2006; Sharon & Kushnir 2020, and references therein), and the AIC-formed NSs should therefore have typical initial masses close to the mass of the progenitor WD, of the order of $1.27–1.37 M_{\odot}$, although the newly born NS might continue to accrete, if still embedded in intracluster gas (Leigh et al. 2013), or if they later accrete from a binary companion.

The BHL accretion rate on lower-mass CO WDs is lower than the accretion rate on the more massive ONe WDs. However, their mass-retention rate is higher (Yaron et al. 2005), allowing them to grow in mass. Lower-mass CO WDs could therefore potentially grow, even up to the point they reach the Chandrasekhar mass, and explode as Type Ia SNe. However, the first CO WDs form only ≈ 100 Myr after the GC formation, and therefore, depending on the timing of the gas replenishment into the GC, only the most massive CO might form in time to accrete. Nevertheless, for gas replenishment occurring on longer timescales of 300 Myr, CO WDs as low as $\approx 0.95 M_{\odot}$ and down to ≈ 0.84 (for $Z = 0.05 Z_{\odot}$ and solar metallicity, respectively) could form, accrete, and potentially explode as Type Ia SNe, though the gas-depletion timescale required might be 1.2–1.5 times longer than 25 Myr.

Accretion onto gas-embedded WDs in AGNs was first discussed (to the best of our knowledge) by Ostriker (1983), who suggested such accretion could lead to Type Ia SNe. More recent studies by Grishin et al. (2021) and Zhu et al. (2021) explore the feedback and appearance of explosive thermonuclear explosions in AGN disks, suggesting that accretion can help drive such explosions, but with little discussion of the actual accretion rates. However, given the comparable gas densities, one can indeed expect to attain effective growth of WDs at least in some regions of AGN disks. Our proposed mechanism for low-kick NS formation in gas-embedded GCs should therefore be also applicable to the AIC production of NSs in AGN disks or in gas-replenished nuclear clusters, which could experience several epochs of star formation.

Maccarone & Zurek (2012) first explored the role of accretion onto WDs in gas-embedded GCs. In particular, they focused on the role of novae arising from the accretion process and its potential pollution of the 2P gas and stars. Their paper is

in many ways complementary to our proposed accretion processes. They focus on the ejected mass through novae rather than on the growth of the WDs. The main difference is in the assumptions regarding the accretion and retention rates.

Maccarone & Zurek (2012) assume a gas density of 2P gas which is a few times lower than in our models, while also suggesting a much longer lifetime of the gas in the GC before its dispersal through star formation and feedback processes. These differences could have significant implications. In particular, the transition between efficient retention of material by accretion WDs and inefficient retention (Yaron et al. 2005) effectively occurs in between the accretion rate taken by Maccarone & Zurek (2012) and the accretion rate we discuss above. Nevertheless, given the uncertainty in the amount of 2P gas, it is quite plausible that a range of gas densities could exist in different GCs and even in different regions in the same GC. It is therefore possible for both Maccarone & Zurek (2012) and our scenario to operate at different clusters, or even in the same cluster at different regions/times, allowing for both inefficient accretion on some WDs and the pollution of GCs by novae, and the growth and AIC of other WDs and the production and retention of low-velocity AIC-formed NSs.

6.2. Accretion, Growth, AIC, and Explosion of Gas-embedded NSs and BHs

Although we focused on the accretion, growth, and AIC of WDs, similar processes could potentially operate for NSs (Collin & Zahn 1999). Perna et al. (2021) explored the possibility of accretion onto gas-embedded NSs in AGN disks. Most of their results would therefore be generally applicable to NSs embedded in 2P gas in GCs, including spin-up of NSs and the AIC formation of low-mass BHs from accretion NSs. However, we point out some important differences. First, NSs that formed through core-collapse SNe could be retained in nuclear clusters near MBHs, where the escape velocities are far higher than in GCs or migrate there through slow mass-segregation processes (e.g., Aharon & Perets 2016 and references therein). Therefore, NSs could reside in AGN disks and accrete there. Such NSs, however, would mostly be expelled from GCs, as discussed above, and would not be able to participate in such processes. Nevertheless, as mentioned earlier, if 2P gas-depletion timescales are sufficiently long (e.g., 100–300 Myr), NSs formed and retained through the proposed accretion and AIC of WDs discussed here could then have sufficient time to further grow after their formation and follow the evolution discussed by Perna et al. (2021). In other words, our proposed WD accretion and AIC model are also a prerequisite for wide-scale NS growth and AIC of NSs into BH to occur in GCs.

Stochastic isotropic accretion onto NSs might only lead to growth, without spinning-up NSs, but if the NSs are embedded in a more coherent disk-like structure in GCs (e.g., Bekki 2010; Mastrobuono-Battisti & Perets 2013, 2016, and references therein), accretion could be more coherent in term of angular momentum accretion and lead not only to growth but also to spin-up of NSs.

The growth and evolution of BHs through accretion in gas-embedded GCs is also possible, as we discussed in Leigh et al. (2013), potentially giving rise to the formation of very-high-mass BHs, even beyond the pair-instability mass cutoff (Roupas & Kazanas 2019). Again, the level of spin-up from such accretion would depend on the structure of the gaseous

component and the orbits of the stars in comparison with the gas.

6.3. Accretion onto Main-sequence Stars

The role of environmental cluster gas accretion on non-compact-object stars was first discussed by Artymowicz et al. (1993), with more recent studies by Davies & Lin (2020) and Cantiello et al. (2021) (and references therein). As already discussed by us in Leigh et al. (2013), more massive stars can accrete significantly and grow. We point out that similar processes would occur in second-generation gas in GCs. In particular, less-massive stars (e.g., $<2-5 M_{\odot}$ stars), which could still be on the main sequence (MS) during the gas replenishment could sufficiently grow, as to effectively change the mass function of 1P stars in GCs and even end their life in core-collapse SN and form NSs/BHs, i.e., produce NSs from stars that would otherwise have only formed WDs. As with NSs, stochastic isotropic accretion onto stars might lead to growth, without spinning them up. If stars are embedded in a more coherent disk-like structure in GCs as discussed above, stars could be spun up and thereby affect their stellar evolution and the core-collapse SN of the more massive stars and the formed NSs/BHs, and in turn the possibility of producing an electron-capture SN producing low-velocity natal kicks or long GRBs following the core collapse of fast-rotating massive stars.

Accretion onto stars could potentially deplete the gas as discussed by us in Leigh et al. (2013), however, it is quite possible that once grown to become very massive feedback (e.g., winds and radiation) may quench further accretion. The general aspects of the stellar evolution of and accretion onto MS stars embedded in 2P gas in GCs are beyond the scope of this paper and will be discussed elsewhere. We do note that if the 2P gas originates from winds of evolved stars, suggested to explain the chemical differences between 1P and 2P clusters, it could pollute the envelopes of MS stars. Given the very low mass of the outer convective envelope of low-mass stars, even slight pollution (e.g., accretion of only $0.01 M_{\odot}$) onto 1P stars would make them appear as 2P stars, masquerading their true 1P nature, at least until other processes, such as thermohaline mixing, could dilute the low-mass convective envelope from the polluted material. One might therefore expect a much larger fraction of 2P stars during the early evolution of GCs on the thermohaline mixing timescales. We leave the discussion on this somewhat disconnected topic to further studies.

6.4. Gas-catalyzed Compact Binary Mergers

The role of gas-catalyzed mergers of compact objects and their implications was discussed by us in the context of binary planetesimals embedded in protoplanetary disks (Perets & Murray-Clay 2011; Grishin & Perets 2016) and later in the context of compact-object binaries embedded in AGN disks (McKernan et al. 2012), where the latter have been extensively studied since then (e.g., Stone et al. 2017; McKernan et al. 2018; Roupas & Kazanas 2019; Tagawa et al. 2020, and references therein). The 2P gas environment in GCs could provide similar and even more favorable conditions for gas-catalyzed mergers (e.g., a larger fraction of hard binaries, lower velocity dispersions, and far larger numbers of massive clusters compared with nuclear clusters in AGNs). Here we focus on accretion processes on WDs and their implications for NS formation and production; a dedicated study of binary mergers

in such environments is explored in a companion paper (Rozner & Perets 2022). However, we should note here that mergers of ONe WDs with CO or other ONe WDs could also give rise to a merger-induced collapse of the remnant merged object, which, similar to the AIC case, would likely involve no, or very little, natal kicks, hence providing another channel for NS formation and retention in gas-embedded GCs. Such a process could produce more massive NSs, with typical masses of the combined masses of the merging WDs, $\approx 1.8-2.4 M_{\odot}$, given that only massive WDs should exist at the time of 2P gas replenishment.

6.5. Potential Observable Signatures

6.5.1. NS Fractions Dependence on Cluster Properties

Larger gas reservoirs would give rise to larger gas densities and faster and more efficient accretion and growth. If the fractions of 2P stars could correspond to the size of the gas reservoir, then one would expect some correlation between the NS fractions and the 2P star fractions. The NSs (effectively known mostly from millisecond pulsars and X-ray sources) are known to correlate with the collisional parameter of the cluster, which in turn correlates with the cluster mass. The 2P stellar population is also known to correlate with the cluster mass (e.g., Mastrobuono-Battisti & Perets 2020 and references therein). Consequently, a correlation between the NS population and the 2P population is expected but would be difficult to disentangle from the formation processes of 2P stars and the collisional dynamics that play a role in the formation of millisecond pulsars used to assess the NS population. That being said, with sufficient future statistics and a better understanding of 2P star formation, one might be able to differentiate between the various dependencies in the future. In particular, in cases where clusters show no 2P population, such as low-mass GCs and open clusters, the NS population should be significantly smaller, if our proposed channel serves as the main channel for NS formation and retention in GCs. Currently, low-mass X-ray binaries and pulsars have not yet been found in such clusters (van den Berg 2020); however, the statistics are still too low as to infer a significant depletion of such sources in these environments.

6.5.2. X-Ray Sources and NS Masses

During accretion, AIC progenitors could potentially produce supersoft X-ray sources and/or cataclysmic variables (e.g., Kahabka & van den Heuvel 1997; Wang & Liu 2020, and references therein). Unfortunately, because the sources are embedded in a large-scale gaseous environment, they are likely to be obscured. Moreover, one needs to observe a young massive cluster during the 2P gas-replenishment epoch, and such clusters are likely to be rare, especially in the very close-by universe where extragalactic X-ray sources are observable.

As discussed above the masses of the resulting NSs are likely to be slightly smaller than their post-accretion WD progenitors, i.e., around $1.32 \pm 0.05 M_{\odot}$. However, such properties could be difficult to pinpoint and smeared, given that NSs may continue to accrete after their formation, and given that most NSs in GCs are found as recycled pulsars, potentially affected by accretion from a companion star. Nevertheless, AIC-formed NSs from this channel are likely to generally have a different mass function than NSs in the field. In particular, spectroscopic observations of binaries in

clusters may start to find fully unrecycled neutron stars and be able to determine their masses (e.g., see the approach of Giesers et al. 2019 using the MUSE spectrograph).

6.6. Potential Caveats and Uncertainties

Most of the main potential caveats and uncertainties involved in the proposed scenario have been discussed in previous sections. These can be briefly summarized as follows:

1. Potentially large uncertainties exist with regard to the gas densities and hence the accretion rates and mass retention and growth rate of WDs. Too low densities would not allow for efficient WD growth, as also discussed in Maccarone & Zurek (2012).
2. The accretion rate was calculated assuming a BHL accretion; the accretion rate could, however, be more limited due to feedback effects (e.g., Eddington limited), leading to lower accretion rates; see further discussion of this in Leigh et al. (2013).
3. The timescales for gas replenishment and the timescale for gas depletion are not known. The former would affect which compact objects will be able to accrete (longer timescales allow for lower-mass compact objects to form before 2P gas replenishment ensues). The latter would affect the timescale for the accretion and hence the overall mass growth of compact objects. Furthermore, accretion onto stars and compact objects might lead to faster depletion of gas and/or give rise to feedback effects, e.g., from SNe of newly grown massive stars.

7. Summary

In this paper, we explored the effect of accretion of second-generation intracluster gas onto WDs in GCs (or young massive clusters), and its implication for producing and retaining NSs in GCs. The observations of multiple stellar populations in GCs gave rise to various models for gas replenishment in GCs that could form two or more stellar populations separated by tens up to hundreds of megayears. The evolution and interaction of 1P stars and compact objects (formed during the first epoch of star formation) with the large gas reservoirs that later form the 2P stars could lead to accretion of replenished intracluster gas onto the stars and compact objects.

Considering plausible gas densities and timescales for the gas replenishment and depletion (motivated by observations and simulations of multiple population GCs) we find that massive WDs, and in particular ONe WDs, would already form and then accrete up to a few $\times 0.1 M_{\odot}$ of material, allowing them to reach the Chandrasekhar limit and form low-velocity NSs through AIC. The numbers of such intracluster gas-catalyzed AIC-formed NSs could explain the origin of most NSs in GCs and their retention there, alleviating potential challenges raised to previously proposed solutions to the GC NS retention problem. Although we considered plausible gas densities and accretion rates, we should note that lower gas densities and/or lower accretion rates might give rise to inefficient accretion and growth of WDs, which could then limit the proposed channel for AIC formation of NSs.

Similar gas accretion processes onto NSs and BHs could give rise to the production of BHs both in the low-mass BH gap-mass regime ($<3-5 M_{\odot}$ from AIC and gas-catalyzed

mergers of NSs, as well as very massive BHs in the upper (pair-instability) BH mass-gap region. Accretion onto main-sequence 1P stars can pollute low-mass stars and change the mass function of intermediate stars.

Massive reservoirs of second-generation intracluster gas have strong observational support from the existence of multiple stellar populations in GCs. Our findings (Leigh et al. 2013, 2014, and Rozner & Perets 2022) and the current discussion on accretion onto compact objects and the novel channel for NS formation and retention suggest major revision is needed in the modeling of the early evolution of GCs. The early gas-embedded GC evolution would give rise to major differences in both the overall dynamics of GCs and the stellar and compact-object populations in these environments. These in turn would directly propagate into the modeling of various stellar exotica, X-ray binaries, millisecond pulsars, and gravitational-waves sources expected to form in GCs.

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