Forever young white dwarfs: when stellar ageing stops

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Abstract

White dwarf stars are the most common end point of stellar evolution. In particular, ultra-massive white dwarfs are expected to harbour oxygen-neon (ONe) cores as a result of single standard stellar evolution. However, a fraction of them could have carbon-oxygen (CO) cores and be born as a result of merger events. Recent observations provided by Gaia space mission, indicate that a fraction of the ultra-massive white dwarfs experience a strong delay in their cooling, which cannot be attributed only to the occurrence of crystallization, thus requiring an unknown energy source able to prolong their life for long periods of time. Here, we show that the energy released by 22Ne sedimentation in ultra-massive white dwarfs with CO cores is at the root of the long cooling delay of these stars. Our results provide solid sustain to the existence of CO-core ultra-massive white dwarfs and the occurrence of stellar mergers.

Introduction

White dwarfs are the most common fossil stars within the stellar graveyard[1]. It is well known that more than 95% per cent of all main-sequence stars will finish their lives as white dwarfs, earth-sized objects less massive than ~ 1.4 M_o—the Chandrasekhar limiting mass— supported by electron degeneracy[2]. A remarkable property of the white-dwarf population is its mass distribution, which exhibits a main peak at ~ 0.6 M_o, a smaller peak at the tail of the distribution around ~ 0.82 M_o, and a low-mass excess near ~ 0.4 M_o [3, 4]. White dwarfs with masses lower than 1.05 M_o are expected to harbour carbon(C)-oxygen(O) cores, enveloped by a shell of helium which is surrounded by a layer of hydrogen. Traditionally, white dwarfs more massive than 1.05 M_o (ultra-massive white dwarfs) are thought to contain an oxygen-neon(Ne) core, and their formation is theoretically predicted as the end product of the isolated evolution of intermediate-mass stars with an initial mass larger than 6–9 M_o, depending on the metallicity and the treatment of convective boundaries during core hydrogen burning [5, 6]. Once the helium in the core has been exhausted, these stars evolve to the super asymptotic giant branch (SAGB) phase, where they reach temperatures high enough to start off-centre carbon ignition under partially degenerate conditions. A violent carbon ignition eventually leads to the formation of an ONe core, which is not hot enough to develop further nuclear burning. During the SAGB phase, the star loses most of its outer envelope by the action of stellar winds, ultimately becoming an ultra-massive ONe-core white dwarf star.

On the other hand, the existence of a fraction of ultra-massive white dwarfs harbouring CO cores is supported by different piece of evidence [7,8,9]. This population could be formed through binary evolution channels, involving the merger of two white dwarfs [10]. Assuming that C is not ignited in the merger event, the merger of two CO-core white dwarfs with a combined mass below the Chandrasekhar limit is expected to lead to the formation of a single CO-core white dwarf substantially more massive than any CO-core white dwarf that can form from a single evolution (∼1.05 M_o) [11]. To the date, it has not been possible to distinguish a CO-core from a ONe-core ultra-massive white dwarf from their observed properties, although a promissory avenue to accomplish this is by means of white dwarf asteroseismology [12]. Recent studies reveal that 10% -30% of all white dwarfs are expected to be formed

as a result of merger events of any kind [7,8,13,14], and that this percentage raises up to 50% for massive white dwarfs ($M > 0.9M_o$) [9]. In particular [9] [15]and estimated that double white dwarf mergers contribute to the formation of massive white dwarfs in 20–30%. These results are in line with the existence of an excess of massive white dwarfs in the mass distribution [16]. However, the existence of ultra-massive CO white dwarfs remains to be proven, and their exact percentage is still unclear.

The formation of white dwarfs as a result of stellar mergers is particularly important given the persistent historical interest in the study of the channels that lead to the occurrence of type Ia Supernovae, which are thought to be the violent explosion of a white dwarf exceeding the Chandrasekhar limiting mass. The main pathways to type Ia Supernovae involve binary evolution, namely the single-degenerate channel in which a white dwarf gains mass from a non-degenerate companion, or the double-degenerate channel involving the merger of two white dwarfs [10]. Moreover, ultra-massive white dwarfs resulting from merger episodes are of utmost importance in connection with the formation of rapidly spinning neutron stars/magnetars [17]. Mergers of white dwarfs have also been invoked as the most likely mechanism for the formation of Fast Radio Bursts [18], which are transient intense radio pulses with duration of milliseconds. Since they have been localized at redshifts $z > 0.3$, it is thought that Fast Radio Bursts could replace Supernovae of type Ia to probe the expansion of the universe to higher redshifts [19].

Since April 2018, white dwarfs have gathered a renewed interest in the scientific community, as the Hertzprung-Russel (HR) diagram provided by *Gaia* Data Release 2 [20] has revealed some unexpected features. One of the them is a bifurcation that reveals a possible excess of massive white dwarfs that are located above the standard 0.6 M_o white dwarf cooling sequence. Some explanations have been proposed to explain this bifurcation, such as different atmospheric composition, the contribution of mergers or some peaks in the star formation history [4,14,21]. The second feature, to which this work is devoted, corresponds to a transverse branch in HR-diagram, called the Q branch that can be appreciated from inspecting Fig. 1. Defining the parameter $z = M_G - 1.2x(G_{BP} - G_{RP})$, which lies parallel to the Q branch, the ultra-massive Q branch is delimited by $z = 13.0$ and $z = 13.4$, and by the cooling tracks of 1.05 and 1.29 M_o. The red dashed lines delimit the regions between $z = 12.7$ and $z = 14.1$, which are the regions where we will focus our analysis of the population of ultra-massive white dwarfs. Recently, the Q branch has been attributed to the crystallization process occurring in the interior of white dwarfs due to Coulomb interactions [22]. The crystallization process in a white dwarf not only releases energy as latent heat, but also releases gravitational energy due to a phase separation process that alters the stellar chemical abundances in the core. These two energy sources delay the cooling of white dwarfs for long periods of time. However, models taking into account the energy released by crystallization fail in reproducing the observed white dwarf mass distribution [23]. Moreover, crystallization is expected to be a less relevant process in the evolution of ultra-massive white dwarfs [24]. In fact, a recent study of the Q branch that also considers the age velocity dispersion relation shows that models taking into account both the energy released by latent heat and phase separation due to crystallization fail in accounting for the pile-up of ultra-massive white dwarfs on the Q branch [25]. In particular, it is estimated that a fraction of the ultra-

massive white dwarf population should experience an unusual delay of ~ 8 Gyrs in their cooling times during their stay on the Q branch, when compared with evolutionary models that consider the energy released by the crystallization process [24]. This implies the need of an additional energy source, able to produce strong delays in the white dwarf cooling times. Here, we show that these strong delays in the cooling times reported for a selected population of the ultra-massive white dwarfs are caused by the energy released by the sedimentation process of ^{22}Ne occurring in the interior of CO-core ultra-massive white dwarfs with high ^{22}Ne content, providing strong sustain to the formation of CO-core ultra-massive white dwarfs through merger events.

Results

The neutron excess of ^{22}Ne, relative to the matter composing the white dwarf core that has equal number of protons and neutrons, results in a net downward gravitational force and a slow settling of ^{22}Ne in the liquid regions towards the centre of the white dwarf [26,27]. ^{22}Ne sedimentation process releases substantial energy to appreciably modify the cooling of white dwarfs, causing delays in their evolution [28]. The occurrence of this process in average-mass white dwarfs has been shown to be a key factor in solving the long-standing age discrepancy of the metal-rich cluster NGC 6791 [29] and to understand the cutoff regions of the local white dwarf luminosity function [30].

The diffusion coefficient of ^{22}Ne in the liquid core of white dwarfs has a strong dependence on the atomic charge Z of the background matter [31, 32]. Therefore, ^{22}Ne sedimentation turns out to be more efficient in a CO-core white dwarf than in a ONe-core white dwarf, thus resulting in a selective effect that produces strong delays in the cooling times of CO-core white dwarfs, but not in ONe-core white dwarfs. In Fig. 2, we show the effect of ^{22}Ne diffusion process on the evolution of selected 1.10 M_o ultra-massive white dwarf sequences with different core chemical compositions, i. e., CO-core and ONe-core white dwarfs. All these white dwarf sequences consider the energy released by latent heat and phase separation due to crystallization process. The white dwarf sequences displayed with dashed lines consider also the energy released by ^{22}Ne sedimentation process. This process was computed using the diffusion coefficients provided by [32], which are the result of molecular dynamic simulations. The strong dependence of the diffusion coefficients on the core chemical composition results evident by inspecting this Figure. For the CO-core white dwarf considering ^{22}Ne diffusion, the time delay compared to the ONe-core white dwarf sequence that disregards ^{22}Ne sedimentation is on average ~ 5 Gyr. For the ONe-core white dwarf sequence, the time delay caused by ^{22}Ne sedimentation process is negligible. Although ultra-massive white dwarfs are affected by ^{22}Ne sedimentation quite early in their evolution due to their large characteristic gravities, this process is abruptly interrupted in the crystallized core, and the energy released is reduced when crystallization process sets in. Coulomb interactions are weaker in nuclei with lower atomic charge, and thus, crystallization occurs at lower luminosities in CO-core white dwarfs than in their ONe-core counterparts, allowing ^{22}Ne diffusion to operate for a longer period of time. Furthermore, the total thermal content of a white dwarf is higher for lower atomic-mass chemical compositions. Hence,

the thermal energy stored in the ions is higher in CO-core white dwarfs than in ONe-core white dwarfs, reducing their cooling rate. This fact is reflected in the long cooling times experienced by the CO-core white dwarf model that does not consider ^{22}Ne sedimentation process in Fig. 2. However, the delays induced only by considering CO-core chemical composition and not including ^{22}Ne diffusion are not high enough to account for the new observations revealed by the *Gaia* space mission.

It is important to remark that the real C to O proportion in the core of ultra-massive white dwarfs is still unclear due to the high uncertainties on the C + α nuclear rate and due to the uncertainties in their past merger evolutionary history. Therefore, a C-enhanced chemical composition would provide even larger cooling delays induced by ^{22}Ne sedimentation process than the standard C-O proportions. Moreover, possible uncertainties in the ^{22}Ne diffusion coefficients could also enlarge the cooling delays induced by this process in CO-core white dwarfs.

To correctly assess the white dwarf cooling delays induced by ^{22}Ne sedimentation, the exact amount of ^{22}Ne content in these stars is crucial, as higher ^{22}Ne abundances will lead to larger delays in the cooling times [33]. In the single-star evolution scenario, the abundance of ^{22}Ne expected in a white dwarf star is roughly equal to the initial stellar metallicity, and is created during the helium core burning phase from helium captures on ^{14}N, via the reactions ^{14}N(α, γ)^{18}F(β+)^{18}O(α, γ)^{22}Ne. ^{14}N is left from hydrogen burning via the CNO cycle. Hence, ^{22}Ne sedimentation will be more effective in those white dwarfs that result from high-metallicity progenitors [29], due to their larger ^{22}Ne content. On the contrary, the amount of ^{22}Ne remaining in the CO-core of a white dwarf that results of a merger event could be larger, depending on the hydrogen content of the binary components at the moment of merger. The study of [34] shows that the abundance in a merger episode of two white dwarfs could be as high as ~ 0.06. Therefore, we have also explored the ^{22}Ne sedimentation process considering a higher ^{22}Ne abundance ($X_{^{22}Ne}$=0.06), and we confirmed the strong dependence of the cooling delays of CO-core ultra-massive white dwarfs on the ^{22}Ne content. The impact of ^{22}Ne sedimentation process on the evolution of CO core ultra-massive white dwarfs is particularly strong for high ^{22}Ne content, where the delays in the cooling times reach 8 Gyrs at the Q branch, and 11 Gyrs by the faint end of the cooling sequence, when compared with the ONe-core cooling sequence (see Fig. 3). On the other hand, due to the larger mean atomic number in their core chemical composition, the cooling of ONe core ultra-massive white dwarfs is not substantially altered by ^{22}Ne sedimentation process, regardless of their ^{22}Ne content. The cooling age of a 1.10 M_o ultra-massive ONe white dwarf in the Q branch is of 2 Gyrs, whereas a CO-core white dwarf with $X_{^{22}Ne}$=0.06 of the same mass amounts to 10 Gyrs (see Fig. 3). These strong delays in the cooling times of CO-core ultra-massive white dwarfs imply that these stars will remain in the Q branch for longer periods of time, when compared with their ONe counterparts, that will rapidly age towards fainter absolute magnitudes.

In order to demonstrate the possible existence of these eternal youth ultra-massive CO-core white dwarfs, we have analyzed the effect of ^{22}Ne sedimentation on the local white dwarf population revealed by *Gaia* observations by means of an up-to-date population synthesis code. The code, based on Monte Carlo

techniques, incorporates the different theoretical white dwarf cooling sequences under study, as well as an accurate modeling of the local white dwarf population and observational biases.

We have performed a population synthesis analysis of the Galactic thin disk white dwarf population within 100 pc from the Sun under different input models. In order to minimize the selection effects, we chose the 100 pc sample, given that it represents the maximum size that the sample can be considered volume-limited and thus practically complete sample [4].

First, we considered that all the ultra-massive white dwarfs in the simulated sample have ONe core composition. This first synthetic population is shown in the *Gaia* HR diagram in the upper left panel of Fig. 4. The histogram of this synthetic population is shown in the upper right panel (black steps), together with the *Gaia* 100 pc white dwarf sample (red steps). The Q branch can easily be regarded as the main peak in the histogram of the *Gaia* 100 pc white dwarf sample, between z = 13.0 and z = 13.4. A first glance at these three histograms reveals that ultra-massive ONe white dwarfs fail to account for the pile-up in the Q branch, even though the ONe white dwarf sequences used include all the energy sources resulting from the crystallization process. A quantitative statistical reduced x^2-test analysis of the synthetic population distribution in the Q branch reveals a value of 11.18 when compared to the observed distribution.

The middle left panel of Fig. 4 illustrates the HR diagram of a typical synthetic white dwarf population realization, considering that 20% of the ultra-massive white dwarfs come from merger events. That is, 20% of the ultra-massive white dwarfs harbour a CO-core. In this model we also have assumed white dwarfs with high ^{22}Ne abundance, $X_{^{22}Ne}$=0.06. The histogram of this synthetic population, shown in black steps in the middle right panel, reveals that, although a mixed white dwarf population with both CO-core and ONe-core white dwarfs is in better agreement with the observations, the pile-up is still not fully reproduced. The reduced x^2 value of this synthetic population is 2.60.

Finally, we have also performed a population synthesis realization in which 50% of the ultra-massive white dwarfs have a merger origin and their core-chemical composition is CO. As in the previous model, the ^{22}Ne content of the white dwarf sequences with merger origin was set to $X_{^{22}Ne}$=0.06. The results of this synthetic population are shown in the lower panels of Fig. 4. We found that this simulation is in perfect agreement with the observed white dwarf sample, being its reduced x^2-test value 1.36.

The better agreement with the observations revealed by *Gaia* of the synthetic populations that include CO-core ultra-massive white dwarf sequences is in line with the longer cooling times that characterize these stars due to ^{22}Ne sedimentation process. We have also simulated a synthetic population that considers a fraction of merger of 50% and a ^{22}Ne abundance of 0.02, finding a better agreement when compared to simulations computed with only ONe-core white dwarfs, but not as good as the agreement we found for a population with high ^{22}Ne content (The reduced x^2 value of this synthetic population is 4.86). We have also generated synthetic populations considering different ^{22}Ne abundances in the white dwarf models and found that the best fit models are obtained for a high ^{22}Ne abundance ($X_{^{22}Ne}$=0.06), as

the one shown in the middle and lower panels of Fig. 4. Such a high ^{22}Ne abundance is not consistent with the isolated standard evolutionary history channel, because it would imply that these white dwarfs come from high-metallicity progenitors. However, merger events provide a possible scenario to create such a high ^{22}Ne abundance. If H were burnt in C-rich layers during the merger event, it would create a high amount of ^{14}N that could later capture He ions, creating a high ^{22}Ne abundance before the ultra-massive white dwarf is born.

The analysis of the ultra-massive white dwarf population revealed by *Gaia* shows that ONe-core white dwarfs alone are not able to account for the pile-up in the ultra-massive Q branch. Indeed, energy sources as latent heat and phase separation process due to crystallization, and ^{22}Ne sedimentation can not prevent the fast cooling of these stars. According to our study, the Q branch is the observational evidence of the presence of white dwarfs with CO core, that experience a stronger delay in their cooling due to the combination of three effects: crystallization, ^{22}Ne sedimentation and higher thermal content.

Conclusions

In this study, we find that CO-core ultra-massive white dwarfs with high ^{22}Ne content are long-standing living objects, that should stay on the Q branch for long periods of time. Indeed, their CO core composition, combined with a high ^{22}Ne abundance, provides a favorable scenario for ^{22}Ne sedimentation to effectively operate, producing strong delays in the cooling times, and leading to an eternal youth source. Our study indicates that the observed evidence of these delays from *Gaia* provides valuable sustain on their CO chemical composition, and their past history involving merger events, whilst ONe core white dwarfs are unable to predict these delays. Moreover, the high percentage of observed carbon-rich atmosphere stars (DQ white dwarfs) on the Q branch [20] supports the hypothesis that a large fraction of the white dwarfs on the Q branch would certainly have been formed through merger events [35].

Methods

White dwarf cooling models

We have calculated a complete set of ultra-massive white dwarf models for both CO and ONe core composition of 1.10, 1.16, 1.22 and 1.29 M_o, varying the ^{22}Ne mass fractions from $X_{^{22}Ne}$=0.001 to $X_{^{22}Ne}$=0.06. The evolutionary calculations presented in this paper were done with an updated version of the LPCODE stellar evolutionary code (see [36] and references therein). This code has been well tested and calibrated and has been amply used in the study of different aspects of low-mass star evolution [28,33,37,38,39]. LPCODE has been tested and callibrated with other stellar evolutionary codes in different evolutionary phases, such as the red giant phase [40,41] and the white dwarf cooling phase [42]. In LPCODE convection is treated within the standard mixing length formulation, as given by the ML2 parameterization [43]. Radiative and conductive opacities are taken from OPAL [44] and from [45], respectively. For the low-temperature regime, molecular radiative opacities with varying C-to-O ratios are used [46,47].

The equation of state for the low-density regime is taken from [48], whereas for the high-density regime, we employ the equation of state of [49], which considers all the important contributions for both the solid and liquid phases. LPCODE takes into account neutrino emission for pair, photo,and bremsstrahlung processes using the rates of [50], while for plasma processes we follow the treatment presented in [51]. LPCODE considers a detailed treatment of time-dependent element diffusion, including gravitational settling, chemical and thermal diffusion, that shapes the surface and the inner chemical abundances. Outer boundary conditions for both H-rich and H-deficient evolving models are taken from non-gray model atmospheres [39,52,53]. Moreover, these non-gray model atmospheres allow us to obtain the magnitudes in the *Gaia* bands of our white dwarf models.

^{22}Ne sedimentation process and crystallization

The energy contribution resulting from the gravitational settling of ^{22}Ne is treated in a similar way as it was done in [28 33]and, assuming that the liquid behaves as a single-background one-component plasma plus traces of ^{22}Ne. The background matter consists of a fictitious element in which the atomic mass (A) and the atomic charge (Z) are defined by the average A and Z in each layer. The changes in the ^{22}Ne chemical profile and the associated local contribution to the luminosity equation are provided by an accurate treatment of time-dependent ^{22}Ne diffusion; see [54] for details. In particular, in the liquid interior we have considered the diffusion coefficients from [32], which are the result of molecular dynamic simulations. For those regions of the white dwarf models that are crystallized, the viscosity is expected to abruptly increase, preventing ^{22}Ne sedimentation process to operate in these solid regions. Therefore, we have set the diffusion coefficient D = 0 in the crystallized regions.

We have also considered the energy sources resulting from the crystallization of the white dwarf core, i.e., the release of latent heat and the release of gravitational energy associated with a phase separation process induced by crystallization. In LPCODE, these energy sources are included self-consistently and are locally coupled to the full set of equations of stellar evolution (see [24] and [33]). The crystallization temperature and the changes in the chemical abundances due to crystallization in CO-core white dwarfs are taken from the phase diagram of [55], and from the phase diagram of [56] for ONe-core white dwarfs.

Initial models

For the ONe ultra-massive white dwarf models, we have considered the initial chemical profiles that result from the full computation of previous evolutionary stages. Specifically, the chemical composition of our models is the result of the entire progenitor evolution calculated in [5,6], from the ZAMS to the thermally pulsating SAGB phase. This allows us to assess the core chemical composition, the mass of the helium-rich mantle and the hydrogen-helium transition. Conversely, the total mass of the hydrogen envelope left by the prior evolutionary phases is quite uncertain, as it depends on the occurrence of carbon enrichment in the envelope during the thermally pulsing AGB phase [57] and the occurrence of late thermal pulses [58]. Since we are interested in getting long cooling times, we have adopted the maximum expected hydrogen

envelope for ultra-massive white dwarfs, of about $\sim 10^{-6}$ M_o. Larger values of the total hydrogen mass would lead to unstable nuclear burning and thermonuclear flashes on the white dwarf cooling track.

On the other hand, we have considered the formation of an ultra-massive CO-core white dwarfs resulting from the merger of two equal-mass white dwarfs and assumed the extreme situation of complete mixing between the two white dwarfs [11]. To this end we adopt the internal distribution of carbon, oxygen, and helium of the 0.58 M_o white dwarf model from [28] and assume the complete mixing between both white dwarfs.

The initial ^{22}Ne chemical abundance of our white dwarf models has been artificially set at the beginning of the white dwarf cooling sequence. This abundance varies from $X_{^{22}Ne}$=0.001 in the lowest ^{22}Ne abundance models to $X_{^{22}Ne}$=0.06 in the highest ^{22}Ne abundance ones.

The observational sample

The observed sample consists in 12,227 white dwarfs belonging to the thin disk population. The sample has been selected from *Gaia* DR2 data [20], and later classified in its Galactic components by means of artificial intelligent techniques based on an accurate Random Forest algorithm [59]. Only objects with accurate astrometric and photometric measurements (relative error lower than 10%) and within 100 pc from the Sun were considered. The complete set of selecting criteria can be consulted in [4, 59]. The observed sample extracted guarantees the larger and complete sample to date available of the single thin disk white dwarf population.

Population synthesis code: Our population synthesis code based on Monte Carlo techniques has been widely used in the study of the white dwarf population during the last decades. A comprehensive explanation of the ingredients can be found in [4, 59] and references therein. Here we just mention the major physical inputs. Our modeling of the thin disk population consists in a constant star formation history which lasts 9.2 Gyr. Main-sequence stars are randomly drawn according to a Salpeter law, with standard slope α=-2.35. For each star a metallicity value is adopted following a metallicity dispersion law centered at solar metallicity value $Z_\odot$=0.014. Once the mass and the metallicity of each star is known, we derive its main-sequence lifetime using the models of [60] and the white dwarf mass using the initial-to-final mass relationship of [61]. It is possible then to compute which stars have become white dwarfs and its corresponding cooling time. It is worth saying that the cooling sequences adopted in our code have been self-consistently calculated, that is, following all the stellar evolutionary phases starting from the zero-age main sequence, through the red giant and the thermally pulsing phases to the planetary nebula and cooling stages of the white dwarf. For those objects that become white dwarfs we randomly adopt a hydrogen-rich atmosphere in 80% of the cases, while the rest of the white dwarfs are considered as hydrogen-deficient objects. Magnitudes are then evaluated in *Gaia* filters according to these atmospheric models (R. Rohmann, private communication). Finally, observational uncertainties are added to each of

our simulated object by introducing photometric and astrometric errors following *Gaia*'s performance (http://www.cosmos.esa.int/web/gaia/science-performance).

A single simulation thus created has a number of objects of the order of the observed sample, i.e. ~13,000. For the distributions presented in this work, an average of 50 single simulations are performed, thus guaranteeing statistical significance.

Declarations

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Author Contributions M.E.C., L.G.A., and S.T. conceived the study. M.E.C., L.G.A. and S.T. wrote the paper. M.E.C. and L.G.A. computed the theoretical expressions for the time delays introduced by ^{22}Ne sedimentation processes. M.E.C., L.G.A., and A.H.C. computed the white dwarf cooling sequences. M.E.C., S.T., A.R.M, and performed the population synthesis study and analyzed the results. All authors discussed the results and made substantial contributions to the manuscript.

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Figures

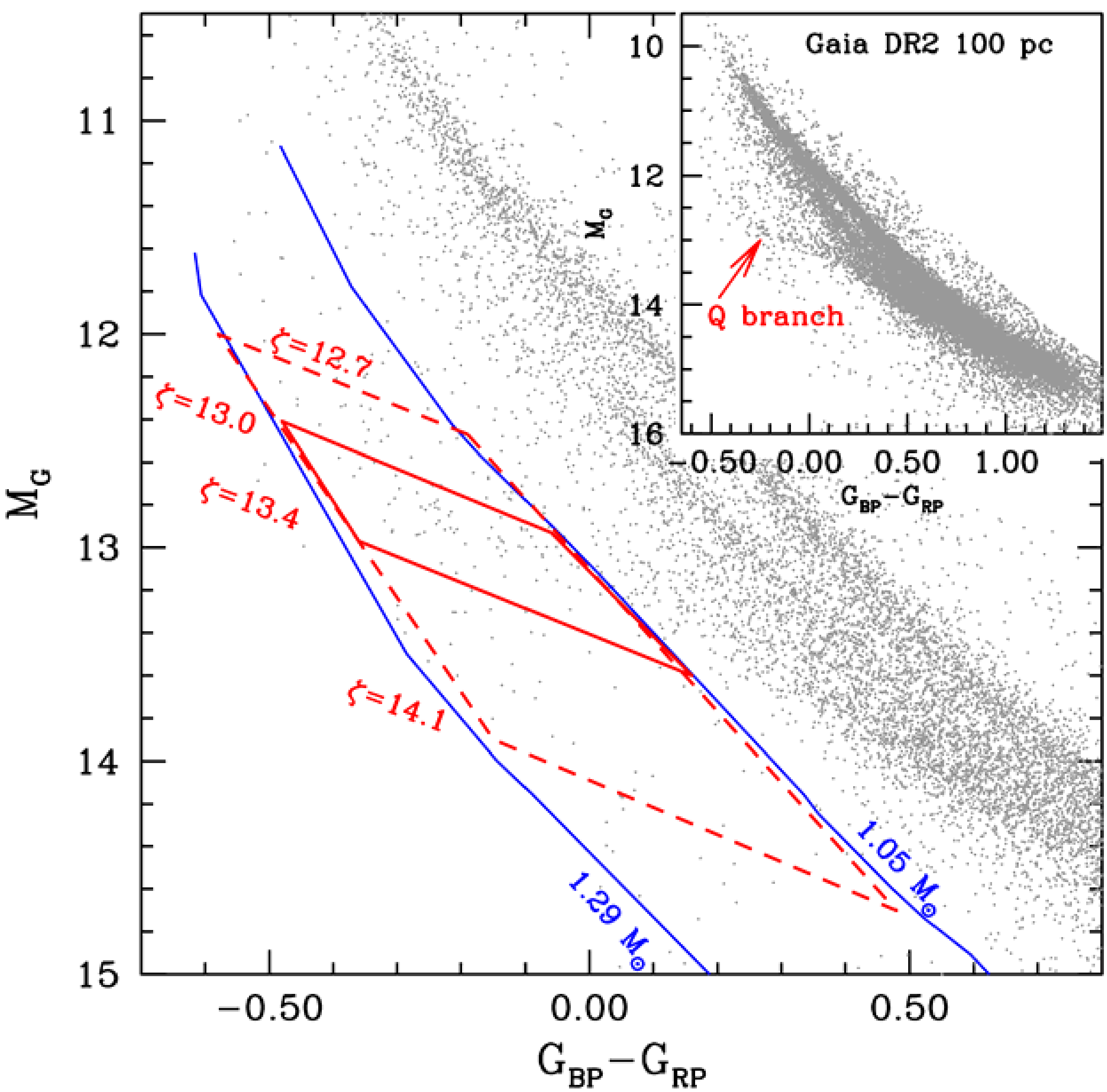

Figure 1

The white dwarf sequence (gray points) in the Gaia Hertzsprung-Russell diagram. Theoretical ONe-core white dwarf cooling tracks of 1.05 and 1.29 Mo disregarding ^{22}Ne diffusion are shown as solid blue lines 24. The Q branch is represented as an observed overabundance of white dwarfs below the standard cooling sequence 20. In order to mark off the Q branch, we have defined the parameter z=MG-1.2x(GBP-GRP). The ultra-massive Q branch is delimited by z=13.4 and z=13.0, and by the cooling tracks of 1.05 and 1.29 Mo. Dashed red lines delimite the region where we have counted white dwarfs to prepare the histograms.

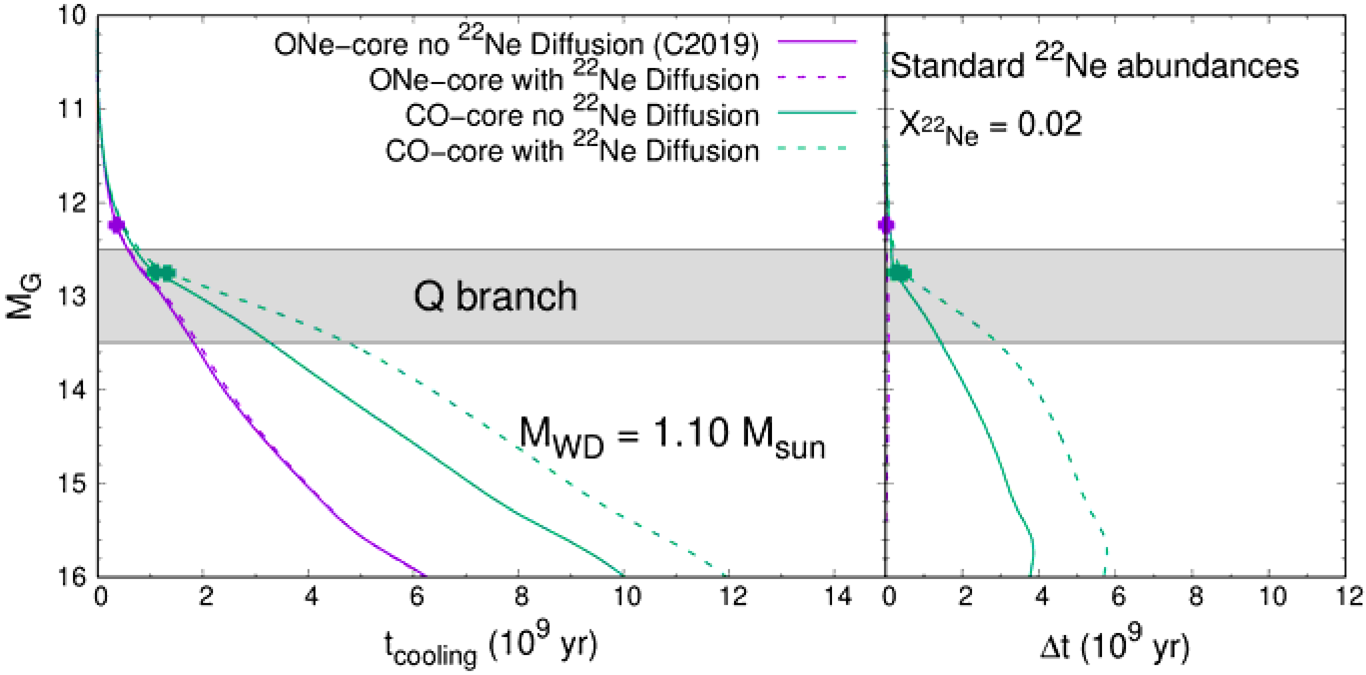

Figure 2

Impact of ^{22}Ne diffusion on the white dwarf cooling times, defined as the time since the star reaches its maximum effective temperature at the beginning of the white dwarf phase, for cooling sequences with standard ^{22}Ne abundances and different core chemical compositions. Solid lines indicate the ONe- and CO-core cooling sequences of 1.10 Mo disregarding ^{22}Ne diffusion, whilst dashed lines illustrate the behaviour for 1.10 Mo sequences with ONe and CO cores that consider the impact of ^{22}Ne diffusion. The right panel displays the resulting time delays (in Gyrs) relative to the 1.10 Mo ONe-core white dwarf cooling track of 24 that disregards ^{22}Ne diffusion process. Filled squares indicate the onset of core crystallization in each white dwarf sequence and the shaded area indicates when the model is overpassing the Q branch 20 , i.e., the region where the cooling delays are revealed by the observations of Gaia 25. ^{22}Ne diffusion becomes more efficient for lower atomic charge chemical compositions, leading to larger cooling times in CO-core white dwarf models, as compared with the ONe counterparts. Moreover, the specific heat per gram is higher for lighter ions, resulting in CO-core sequences with longer cooling times. Also note that crystallisation sets in at higher luminosities when a higher atomic charge composition is considered, due to stronger Coulomb interactions.

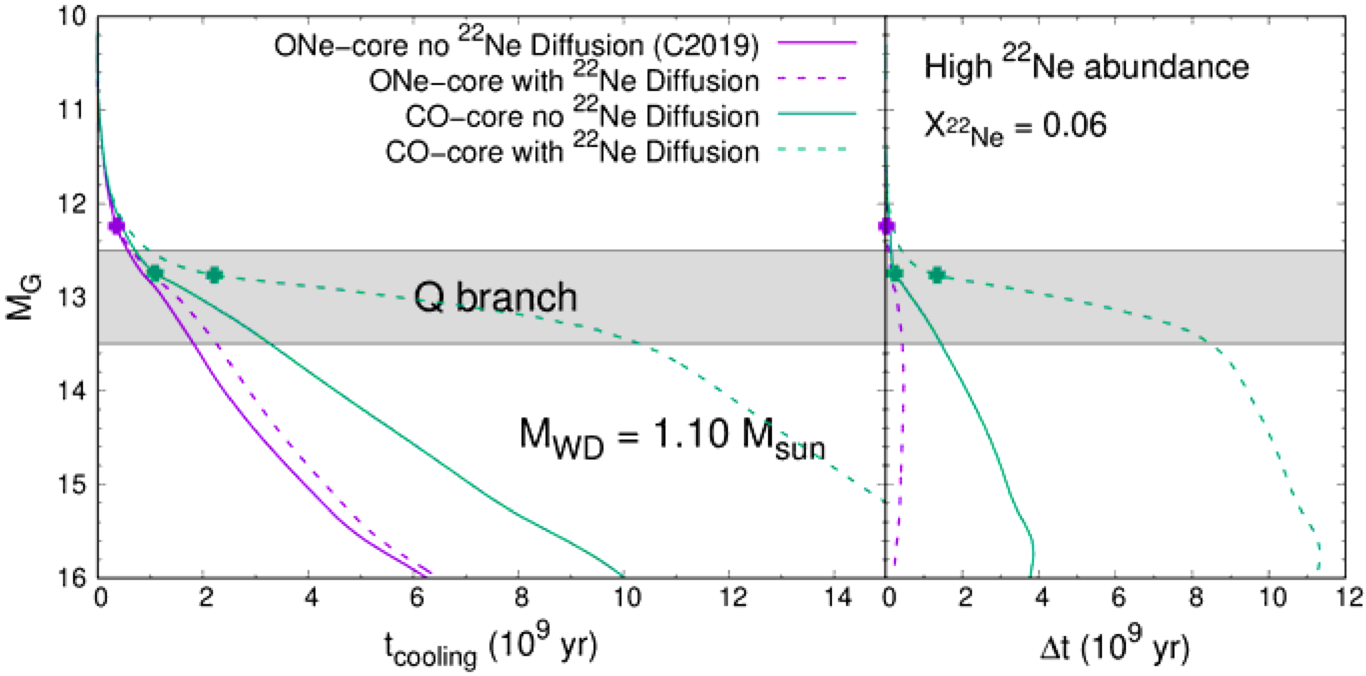

Figure 3

Same as Figure 2, but for ultra-massive white dwarf models with high ^{22}Ne initial abundances, i.e., $X_{^{22}Ne}=0.06$. In this case, ^{22}Ne diffusion process produces substantial delay for CO white dwarfs. However, note that the cooling times of the ONe sequences are barely altered by the occurrence of this process, even in the case of very high ^{22}Ne content. Indeed, the process of ^{22}Ne diffusion is almost irrelevant in white dwarfs with ONe cores. Also note that for this high ^{22}Ne content, an ultramassive CO-core white dwarf would stay in the Q branch for more than about 10 Gyrs.

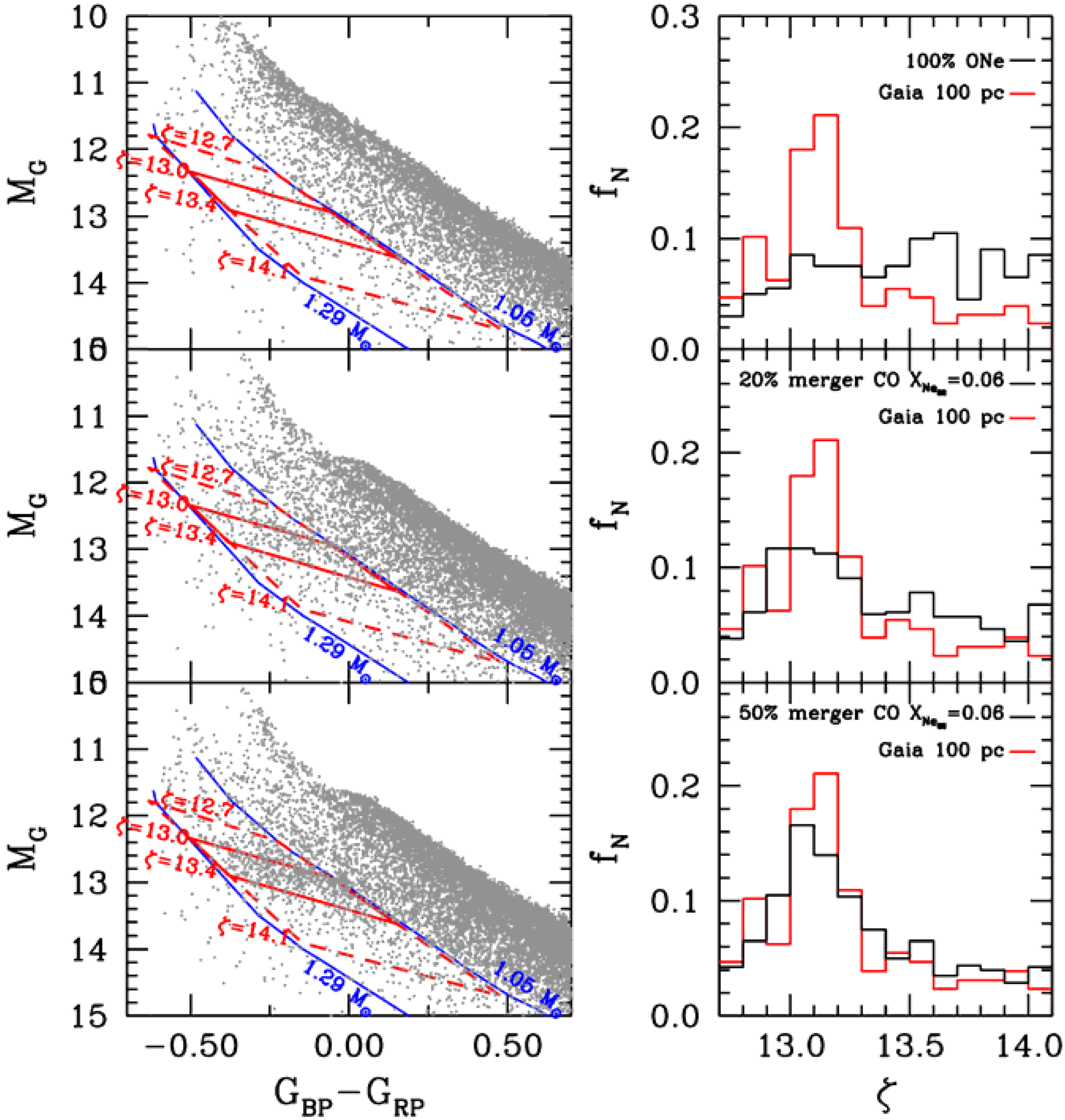

Figure 4

Left panels: Synthetic white dwarf populations (gray points) in the Gaia Hertzsprung-Russell diagram considering different prescriptions. The ultra-massive Q branch is delimited by solid red lines. Dashed red lines mark the region where we have counted white dwarfs to prepare the histograms. Right panels: synthetic (black line) and observed (red line) histograms for the 100pc white dwarf population 4. The observed Q branch can be regarded as the red peak between z=13.0 and 13.4 in the 100 pc white dwarf sample observed by Gaia. Note that, in order to theoretically reproduce the peak in the observed

population, it is necessary to assume a high merger fraction leading to ultra massive white dwarfs with CO core composition and a high ^{22}Ne abundance.