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Letter to the Editor

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. The ultramassive white dwarfs are of special interest as they are related to type Ia supernovae explosions, merger events, and fast radio bursts. Ultramassive 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. Recent studies, based on the new observations provided by the *Gaia* space mission, indicate that a small fraction of the ultramassive white dwarfs experience a strong delay in their cooling, which cannot be solely attributed to the occurrence of crystallisation, thus requiring an unknown energy source able to prolong their life for long periods of time. In this study, we find that the energy released by ^{22}Ne sedimentation in the deep interior of ultramassive white dwarfs with CO cores and high ^{22}Ne content is consistent with the long cooling delay of these stellar remnants. On the basis of a synthesis study of the white dwarf population, based on Monte Carlo techniques, we find that the observations revealed by *Gaia* can be explained by the existence of these prolonged youth ultramassive white dwarfs. Although such a high ^{22}Ne abundance is not consistent with the standard evolutionary channels, our results provide evidence for the existence of CO-core ultramassive white dwarfs and for the occurrence of ^{22}Ne sedimentation.

Key words. stars: evolution – stars: interiors – white dwarfs

1. Introduction

White dwarfs (WDs) are the most common fossil stars within the stellar graveyard (Althaus et al. 2010a). It is well known that more than 95% percent of all main-sequence stars will finish their lives as WDs, that is earth-sized objects less massive than ∼1.4 $M_\odot$, the Chandrasekhar limiting mass, supported by electron degeneracy (Chandrasekhar 1931). A remarkable property of the WD population is its mass distribution, which exhibits a main peak at ∼0.6 $M_\odot$, a smaller peak at the tail of the distribution around 0.82 $M_\odot$, and a low-mass excess near ∼0.4 $M_\odot$ (Rebassa-Mansergas et al. 2015; Kleinman et al. 2013; Jiménez-Esteban et al. 2018). WDs with masses lower than 1.05 $M_\odot$ are expected to harbour carbon (C)-oxygen (O) cores, enveloped by a shell of helium which is surrounded by a layer of hydrogen. WDs more massive than 1.05 $M_\odot$ are called ultramassive WDs and, conventionally, they are expected to contain an oxygen-neon (Ne) core.

The study of ultramassive WDs is motivated by their connection to type Ia supernova, double WD mergers, the occurrence of physical processes in the asymptotic giant branch, and the existence of high magnetic fields. Traditionally, the formation of ultramassive WDs is theoretically predicted as the end product of the isolated evolution of intermediate-mass stars with an initial mass larger than 6–9 $M_\odot$ (Siess 2007, 2010). However, in the recent years, the literature has been filled out with evidence supporting the idea that a large fraction of the single ultramassive WDs could be formed through binary evolutionary channels. Recent studies (Toonen et al. 2017; Maoz et al. 2018) suggest that binary mergers substantially contribute to the single WD population. The theoretical studies of Temmink et al. (2020) estimated that 30−45% of the WDs more massive than 0.9 $M_\odot$ are formed through binary mergers, mostly via the merger of two WDs, and Cheng et al. (2020) estimated observationally that the fraction of high-mass WDs (in the range of 0.8−1.3 $M_\odot$) that formed as a result of double WD mergers is nearly 20%.

The core chemical composition of an ultramassive WD is still a matter of debate. Traditionally, in the single evolution channel, once the helium in the core has been exhausted, massive intermediate-mass 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 (Doherty et al. 2017). A violent carbon ignition eventually leads to the formation of an ONe core, which will ultimately become an ultramassive ONe WD. Nevertheless, Althaus et al. (2021) show that rotation or a reduced mass loss rate during the SAGB would prevent carbon ignition, leading to the formation of ultramassive CO core WDs from single evolution. For the case of WDs that result from double WD mergers, Yoon et al. (2007) and Lorén-Aguilar et al. (2009) predict that the merger remnant avoids carbon burning and becomes a single CO-core ultramassive WD. In the opposite direction, the recent

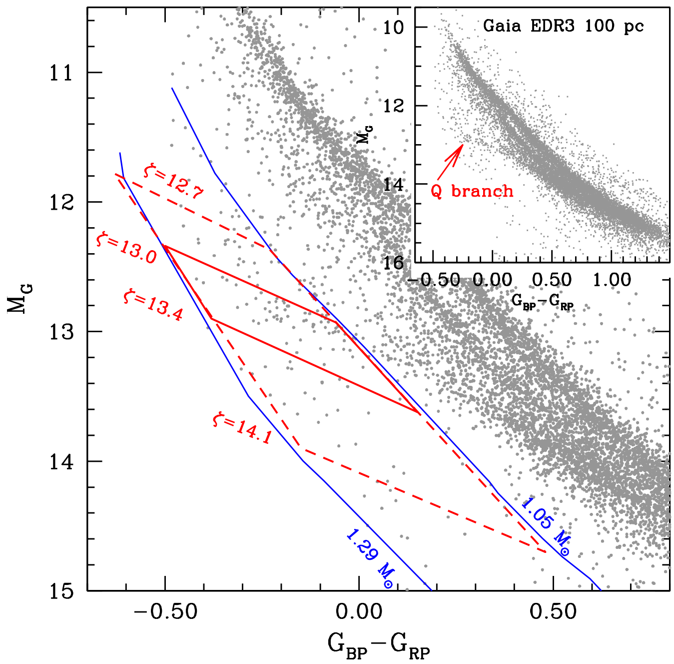

Fig. 1. WD sequence (grey points) in the *Gaia* Hertzsprung-Russell diagram. Theoretical ONe-core WD cooling tracks of 1.05 and 1.29 $M_\odot$ disregarding ^{22}Ne diffusion are shown as solid blue lines (Camisassa et al. 2019). The Q branch is represented as an observed overabundance of WDs below the standard cooling sequence. In order to mark off the Q branch, we have defined the parameter $\zeta = M_G - 1.2 \times (G_{\rm BP} - G_{\rm RP})$. The ultramassive Q branch is delimited by $\zeta = 13.4$ and $\zeta = 13.0$, and by the cooling tracks of 1.05 and 1.29 $M_\odot$. Dashed red lines delimit the region where we have counted WDs to prepare the histograms.

study of Schwab (2021), based on one-dimensional post merger evolutionary calculations, predicts the off-centre carbon burning in the merged remnant, leading to the formation of an ONe-core ultramassive WD. To date, it has not been possible to distinguish a CO-core from a ONe-core ultramassive WD from their observed properties, although a promissory avenue to accomplish this is by means of WD asteroseismology (Córsico et al. 2019).

Since April 2018, WDs have gathered a renewed interest in the scientific community as the Hertzprung-Russell (HR) diagram provided by *Gaia* Data Release 2 (Gaia Collaboration 2018) has revealed some unexpected features, which had been later reconfirmed by Early Data Release 3 (EDR3; Gaia Collaboration 2021). One of them corresponds to a transverse branch in the WD cooling sequence, called the Q branch, which can be seen by inspecting Fig. 1. Defining the parameter $\zeta = M_G - 1.2 \times (G_{\rm BP} - G_{\rm RP})$, which lies parallel to the Q branch, the ultramassive Q branch is delimited by $\zeta = 13.0$ and $\zeta = 13.4$ and by the cooling tracks of 1.05 and 1.29 $M_\odot$. Recently, the Q branch has been attributed to the crystallisation process occurring in the interior of WDs due to Coulomb interactions (Tremblay et al. 2019). The crystallisation process in a WD not only releases energy as latent heat, but it 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 WDs for long periods of time. However, crystallisation is expected to be a less relevant process in the evolution of ultramassive WDs (Camisassa et al. 2019). In fact, a more recent study of the ultramassive Q branch that considers the age velocity dispersion relation shows that models taking into account both the energy released by latent heat and phase separation due to crystallisation fail to account for the pile-up of ultramassive WDs on the Q branch (Cheng et al. 2019). In particular, it is estimated that a fraction of the ultramassive WD population should experience an unusual delay of 8 Gyr in their cooling times during their stay on the Q branch, when compared with evolutionary models that consider the energy released by the crystallisation process (Camisassa et al. 2019). This implies the need for an additional energy source able to produce strong delays in the WD cooling times. Horowitz (2020) tried, unsuccessfully, to explain these time delays as a result of electron capture and pycnonuclear reactions and dark matter heating. On the other hand, Bauer et al. (2020) claim that these strong delays could be the result of clustering-enhanced gravitational sedimentation. However, the recent paper of Caplan et al. (2020) questions these results using molecular-dynamics simulations, demanding new answers to this problem.

In this Letter, we study the sedimentation of ^{22}Ne occurring in the interior of ultramassive WDs, both with a CO and ONe composition. We have performed a population synthesis study and we found that these strong delays in the cooling times reported for a selected population of the ultramassive WDs can be explained as a consequence of the energy released by the sedimentation process of ^{22}Ne occurring in the interior of CO-core ultramassive WDs with a high ^{22}Ne content.

2. Methods

We have calculated a complete set of ultramassive WD models for both a CO and ONe core composition of 1.10, 1.16, 1.22, and 1.29 $M_\odot$, varying the ^{22}Ne mass fractions from $X_{^{22}\rm Ne} = 0.001$ to $X_{^{22}\rm Ne} = 0.06$. The evolutionary calculations presented in this Letter were done with an updated version of the LPCODE stellar evolutionary code (see Althaus et al. 2005 and references therein). This code has been well tested and calibrated with other stellar evolutionary codes in different evolutionary phases, such as the red giant phase (Silva Aguirre et al. 2020; Christensen-Dalsgaard et al. 2020) and the WD cooling phase (Salaris et al. 2013), and it has been amply used in the study of different aspects of low-mass star evolution (Camisassa et al. 2017; Miller Bertolami 2016).

The energy contribution resulting from the gravitational settling of ^{22}Ne was treated in a similar way as it was done in Camisassa et al. (2016) and Althaus et al. (2010b), 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 (Ze) are defined by the average A and Ze 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 García-Berro et al. 2008 for details). In particular, in the liquid interior, we have considered the diffusion coefficients from Hughto et al. (2010), which are the result of molecular dynamic simulations. For those regions of the WD models that are crystallised, the viscosity is expected to abruptly increase, preventing the ^{22}Ne sedimentation process from operating in these solid regions. Therefore, we have set the diffusion coefficient $D = 0$ in the crystallised regions.

We have also considered the energy sources resulting from the crystallisation of the WD core, that is, the release of latent heat and the release of gravitational energy associated with a phase separation process induced by crystallisation. In LPCODE, these energy sources are included self-consistently and are locally coupled to the full set of equations of stellar evolution (see Camisassa et al. 2019; Althaus et al. 2010b). The crystallisation temperature and the changes in the chemical abundances due to crystallisation in CO-core WDs are taken from the phase diagram of Horowitz et al. (2010), and from the phase diagram of Medin & Cumming (2010) for ONe-core WDs.

For the ONe ultramassive WD models, we have considered the initial chemical profiles that result from the full computation of previous evolutionary stages, calculated in Siess (2007, 2010). For the ultramassive CO-core WDs, we have considered the chemical profiles of Althaus et al. (2021). The initial ^{22}Ne chemical abundance of our WD models has been artificially set at the beginning of the WD cooling sequence.

The observed sample consists in 11 707 WDs belonging to the thin disk population. The sample has been selected from *Gaia* EDR3 and later classified in its Galactic components by means of artificial intelligent techniques based on an accurate random forest algorithm (see Torres et al. 2019 for the classification technique, whereas an update to the EDR3 sample will be published in a forthcoming paper). 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 Torres et al. (2019) and Jiménez-Esteban et al. (2018).

Our population synthesis code based on Monte Carlo techniques has been widely used in the study of the WD population during the last decades. A comprehensive explanation of the ingredients can be found in Torres et al. (2019) and Jiménez-Esteban et al. (2018), and references therein. Here we just mention the major physical inputs. Our modelling 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. For each star, a metallicity value was adopted following a metallicity dispersion law centred at a solar metallicity value of $Z_{\odot} = 0.014$. Once the mass and the metallicity of each star was known, we derived its main-sequence lifetime from the models of Hidalgo et al. (2018) and the WD mass using the initial-to-final mass relationship of Catalán et al. (2008). It was then possible to compute which stars had become WDs and its corresponding cooling age. For the ultramassive WDs, we set the percentage of the CO-core and ONe-core of the synthetic population and randomly adopted a chemical composition for each artificial WD. We also set different ^{22}Ne abundances to model the effect of ^{22}Ne sedimentation on the *Gaia* 100 pc WD population. Once the mass, the cooling time, the core chemical composition, and the ^{22}Ne abundance were known, the magnitudes in *Gaia* filters were derived by interpolating the evolutionary models with the grid of synthetic WD atmospheres detailed by Koester (2010), including a number of more recent unpublished improvements. Finally, observational uncertainties were added to each of our simulated objects by introducing photometric and astrometric errors in concordance with *Gaia* performances[1].

3. Results

3.1. The cooling age delay caused by ^{22}Ne settling

The neutron excess of ^{22}Ne, relative to the matter composing the WD core that has an 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 WD (Deloye & Bildsten 2002; Isern et al. 1991). The ^{22}Ne sedimentation process releases substantial energy to appreciably modify the cooling of WDs, causing delays in their evolution (Camisassa et al. 2016). The occurrence of this process in average-mass WDs has been shown to be a key factor in solving the long-standing age discrepancy of the metal-rich cluster NGC 6791 (García-Berro et al. 2010).

The diffusion coefficient of ^{22}Ne in the liquid core of WDs has a strong dependence on the atomic charge Ze of the background matter (Bildsten & Hall 2001; Hughto et al. 2010). Therefore, ^{22}Ne sedimentation turns out to be more efficient in a CO-core WD than in a ONe-core WD, thus resulting in a selective effect that produces strong delays in the cooling times of CO-core WDs, but not in ONe-core WDs. In Fig. 2, we show the effect of the ^{22}Ne diffusion process on the evolution of selected $1.10\,M_{\odot}$ ultramassive WD sequences with different core chemical compositions, that is, CO-core and ONe-core WDs. All these WD sequences consider the energy released by latent heat and phase separation due to the crystallisation process. The WD sequences displayed with dashed lines also consider the energy released by the ^{22}Ne sedimentation process. The strong dependence of the diffusion coefficients on the core chemical composition results is evident upon inspection of this figure. For the CO-core WD considering ^{22}Ne diffusion, the time delay compared to the ONe-core WD sequence that disregards ^{22}Ne sedimentation is 5 Gyr on average. For the ONe-core WD sequence, the time delay caused by the ^{22}Ne sedimentation process is negligible. Although ultramassive WDs are affected by ^{22}Ne sedimentation quite early in their evolution due to their large characteristic gravities, this process is abruptly interrupted in the crystallised core, and the energy released is reduced when the crystallisation process sets in. Coulomb interactions are weaker in nuclei with a lower atomic charge, and thus, crystallisation occurs at lower luminosities in CO-core WDs than in their ONe-core counterparts, allowing ^{22}Ne diffusion to operate for a longer period of time. We have performed artificial calculations in order to test if the longer cooling delays obtained for CO WDs are mainly

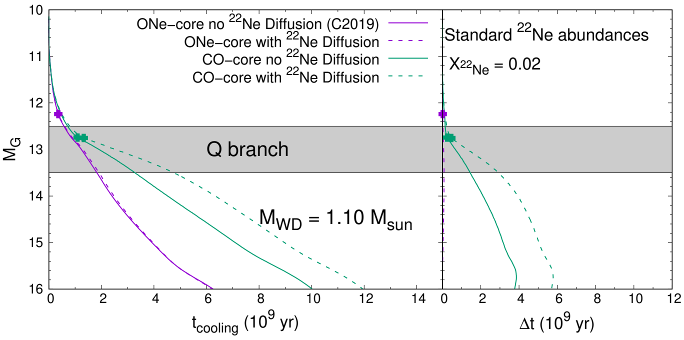

Fig. 2. Impact of ^{22}Ne diffusion on the WD cooling times, defined as the time since the star reaches its maximum effective temperature at the beginning of the WD phase, for cooling sequences with standard ^{22}Ne abundances and different core chemical compositions. Solid lines indicate the ONe- and CO-core cooling sequences of $1.10\,M_{\odot}$ disregarding ^{22}Ne diffusion, whilst dashed lines illustrate the behaviour of $1.10\,M_{\odot}$ sequences with ONe and CO cores that consider the impact of ^{22}Ne diffusion. *Right panel*: resulting time delays (in gigayears) relative to the $1.10\,M_{\odot}$ ONe-core WD cooling track of Camisassa et al. (2019) that disregards the ^{22}Ne diffusion process. Filled squares indicate the onset of core crystallisation in each WD sequence and the shaded area indicates when the model overpasses the Q branch, that is, the region where the cooling delays are revealed by the observations of *Gaia*.

[1] http://www.cosmos.esa.int/web/gaia/science-performance

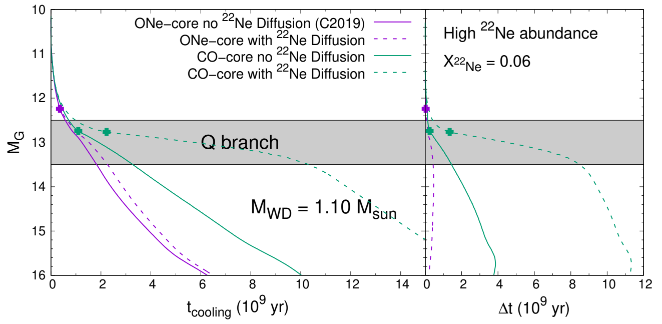

Fig. 3. Same as Fig. 2, but for ultramassive WD models with high ^{22}Ne initial abundances, i.e. $X_{^{22}Ne} = 0.06$.

due to the fact that these WDs crystallise at lower luminosities or due to the fact that the diffusion coefficient in these stars is larger, and we found that this last factor was crucial.

On the other hand, the total thermal content of a WD is higher for lower atomic-mass chemical compositions. Hence, the thermal energy stored in the ions is higher in CO-core WDs than in ONe-core WDs, reducing their cooling rate. This fact is reflected in the long cooling times experienced by the CO-core WD model that does not consider the ^{22}Ne sedimentation process in Fig. 2. However, the delays induced by only considering the CO-core chemical composition and not including ^{22}Ne diffusion are not long enough to account for the observations revealed by the *Gaia* space mission.

To correctly assess the WD cooling delays induced by ^{22}Ne sedimentation, the amount of ^{22}Ne content in these stars is crucial as higher ^{22}Ne abundances lead to larger delays in the cooling times (García-Berro et al. 2010). In the single-star evolution scenario, the abundance of ^{22}Ne expected in a WD star is roughly equal to the initial stellar metallicity, and it is created during the helium core burning phase from helium captures on ^{14}N, via the reactions $^{14}N(\alpha,\gamma)^{18}F(\beta+)^{18}O(\alpha,\gamma)^{22}Ne$. The ^{14}N is left from hydrogen burning via the CNO cycle. Hence, ^{22}Ne sedimentation is more effective in those WDs that result from high-metallicity progenitors due to their larger ^{22}Ne content. On the contrary, the amount of ^{22}Ne remaining in the core of a WD that results from a merger event could be larger, depending on the hydrogen content of the binary components at the moment of the merger. The study of Staff et al. (2012) shows that the abundance in a merger episode of two WDs could be as high as 0.06. In order to maximise the effect of ^{22}Ne sedimentation, we have also explored this 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 ultramassive WDs on the ^{22}Ne content. The impact of the ^{22}Ne sedimentation process on the evolution of CO core ultramassive WDs is particularly strong for a high ^{22}Ne content, where the delays in the cooling times reach 8 Gyr at the Q branch and 11 Gyr 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 ultramassive WDs is not substantially altered by the ^{22}Ne sedimentation process, regardless of their ^{22}Ne content. The cooling age of a 1.10 $M_\odot$ ultramassive ONe WD in the Q branch is small, whereas a CO-core WD with $X_{^{22}Ne} = 0.06$ of the same mass amounts to 10 Gyr (see Fig. 3). These strong delays in the cooling times of CO-core ultramassive WDs imply that these stars will remain in the Q branch for longer periods of time, when compared to their ONe counterparts, which will rapidly age towards fainter absolute magnitudes.

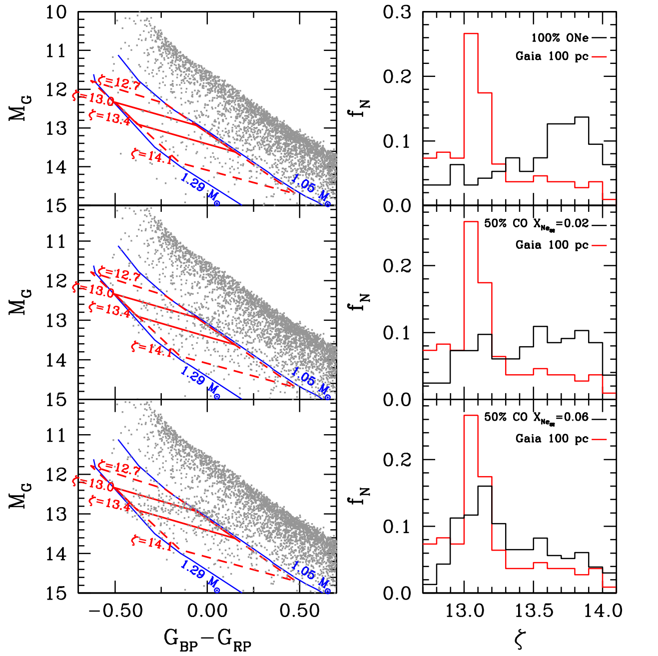

Fig. 4. *Left panels*: synthetic WD populations (grey points) in the *Gaia* Hertzsprung-Russell diagram considering different prescriptions. The ultramassive Q branch is delimited by solid red lines. Dashed red lines mark the region where we have counted WDs to prepare the histograms. *Right panels*: synthetic (black line) and observed (red line) histograms for the 100 pc WD population. The observed Q branch can be regarded as the red peak between $\zeta = 13.0$ and $\zeta = 13.4$ in the 100 pc WD sample observed by *Gaia*.

3.2. Population synthesis analysis

In order to demonstrate the possible existence of these eternal youth ultramassive CO-core WDs, we have analysed the effect of ^{22}Ne sedimentation on the local *Gaia*-selected WD population of the Galactic thin disk, within 100 pc from the Sun, by means of an up-to-date population synthesis code. Accounting for a range of input conditions, we first considered that all the ultramassive WDs in the simulated sample have an ONe core composition. This first synthetic population is shown in the simulated *Gaia* HR diagram in the upper left panel of Fig. 4. The histogram distribution of ζ of this synthetic population is shown in the upper right panel (black steps), together with the *Gaia* 100 pc WD sample (red steps). The Q branch can easily be regarded as the main peak in the histogram of the *Gaia* 100 pc WD sample, between $\zeta = 13.0$ and $\zeta = 13.4$. A first glance at these histograms reveals that ultramassive ONe WDs fail to account for the pile-up in the Q branch, even though the ONe WD sequences used include all the energy sources resulting from the crystallisation process. A quantitative statistical reduced χ^2-test analysis of the synthetic population distribution in the Q branch reveals a value of 4.27 when compared to the observed distribution.

The middle left panel of Fig. 4 illustrates the HR diagram of a synthetic WD population realisation, considering that 50% of the ultramassive WDs harbour a CO-core. In this model we also have assumed WDs with a standard ^{22}Ne abundance, $X_{^{22}Ne} = 0.02$. The histogram of this synthetic population reveals that, although a mixed WD population with both CO-core and ONe-core WDs is in better agreement with the observations, the pile-up is still not fully reproduced. The reduced χ^2 value of this synthetic population is 3.37.

Finally, we have performed another population synthesis realisation in which 50% of the ultramassive WDs have a CO core-chemical composition, but this time considering that the ^{22}Ne content of the CO-core WD sequences is $X_{^{22}Ne} = 0.06$. The results of this synthetic population are shown in the lower panels of Fig. 4. We found that this simulation is in a much better agreement with the observed WD sample, being its reduced χ^2-test value 2.01.

The better agreement with the observations revealed by *Gaia* of the synthetic populations that include CO-core ultramassive WD sequences is in line with the longer cooling times that characterise these stars due to the ^{22}Ne sedimentation process. We have also simulated a synthetic population that considers a fraction of CO-core WDs of 80% and a ^{22}Ne abundance of 0.02, finding a better agreement when compared to simulations computed with only ONe-core WDs, but not as good as the agreement we found for a population with a high ^{22}Ne content. We have also generated synthetic populations considering different ^{22}Ne abundances in the WD models and found that the best fit models are obtained for a high ^{22}Ne abundance ($X_{^{22}Ne} = 0.06$). We would like to remark that such a high ^{22}Ne abundance is not consistent with the isolated standard evolutionary history channel because it would imply that these WDs come from high-metallicity progenitors. However, merger events could 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 ultramassive WD is born.

The analysis of the ultramassive WD population revealed by *Gaia* shows that ONe-core WDs alone are not able to account for the pile-up in the ultramassive Q branch. Indeed, energy sources such as latent heat and the phase separation process due to crystallisation as well as ^{22}Ne sedimentation cannot prevent the fast cooling of these stars. According to our study, the Q branch might be explained by the presence of WDs with a CO core, which experience a stronger delay in their cooling due to the combination of the following three effects: crystallisation, ^{22}Ne sedimentation, and a higher thermal content.

4. Conclusions

In this study, we find that CO-core ultramassive WDs with a high ^{22}Ne content are long-standing living objects, which 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 favourable 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 cooling delays observed by the *Gaia* space mission provide valuable sustain to the existence of ultramassive WDs with a CO chemical composition, whilst ONe core WDs are unable to predict these delays. This work is the first population synthesis study based on Monte Carlo techniques that uses the luminosities of the ultramassive WDs measured by *Gaia*, and it reveals that *Gaia* observations are consistent with a population in which 50% of the ultramassive WDs show strong delays in their cooling times. Unfortunately, the CO chemical composition in the core of ultramassive WDs still needs to be proven, and the high ^{22}Ne content that we demand to fit the observations is not consistent with the standard evolutionary channels. We hope that new mechanisms that lead to the formation of ultramassive WDs with a higher ^{22}Ne content can be found in the future.

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