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BARCELONATECH

White dwarfs: now and then

E. García-Berro & Santiago Torres

Hernanzfest, Tossa de Mar (Spain) – June 2017

1. Introduction

- White dwarfs are the most common fossil stars within the stellar graveyard.
- More than 90% of all main sequence stars will finish their lives as white dwarfs.
- On their way to become fossil remnants, half of the original mass is recycled back to the interstellar medium, contributing to its enrichment in metals.
- Supported by electron degeneracy, white dwarfs cool down for very long periods of time, allowing us to look back at early times.
- Their structural and evolutionary properties are now reasonably well understood (Althaus et al., 2010).

1. Introduction

- The Galactic population of white dwarfs carries essential information about several fundamental issues.
- The white dwarf luminosity function (García-Berro & Oswalt 2016) provides us with:
  - The age of the Galaxy.
  - The star formation history.
  - The structure and evolution of the Galaxy:
    - Thin and thick disks.
    - The galactic spheroid.
    - The system of open and globular clusters.
  - The evolution of stars off the main sequence.

1. Introduction

- White dwarfs are also important to:
  - Constrain non-standard theories of gravitation.
  - Can be used as astroparticle physics laboratories.
  - Compare different evolutionary numerical codes.
- To undertake these tasks two conditions must be fulfilled:
  - Excellent observational data to which compare the theoretical models.
  - Accurate and reliable cooling sequences.
- Here I will review the current status of the white dwarf cooling theory, from both the observational and the theoretical points of view.

2. Observations: now and then

- Large-scale automated surveys are revolutionizing the research field.
- The SDSS (York et al. 2000), the Pan-STARRS collaboration (Kaiser et al. 2002), the RAVE Survey (Zwitter et al. 2008), or the SuperCosmos Sky Survey (Hambly et al. 1998) have provided us with an unprecedented wealth of astrometric and photometric data.
- It is foreseen that the results of future massive surveys, of which Gaia is an example, will dramatically increase the number of white dwarfs with good observational data (Torres et al. 2005).

2. Observations: now and then

THE ASTROPHYSICAL JOURNAL, 308:176–189, 1986 September 1

THE LUMINOSITY FUNCTION OF DA WHITE DWARFS

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Received 1985 April 16; accepted 1986 February 18

ABSTRACT

We have expanded upon the earlier work of Green by analyzing a complete sample of 353 DA white dwarfs, spectroscopically identified from the Palomar-Green (PG) survey of ultraviolet excess objects. A breakdown by spectral type of the entire sample of ultraviolet-excess objects shows that the DA white dwarfs comprise 21% of the faint blue stars to a mean limiting magnitude of $B = 16.1$. The revised local space density for DA white dwarfs is 0.49 ± 0.05 per 1000 pc^3 for $M_v < 12.75$. This number is less than half of the previous one derived by Green and reflects the fact that a comparable fraction of the earlier sample have been reclassified as lower gravity objects. Depending upon the evolutionary cooling models used, the DA white dwarf formation rate lies in the range from 3.9 to 6.1×10^{-13} yr^{-1} pc^{-3}, and the total white dwarf rate including DB and DO stars is between 4.9 and 7.5×10^{-13} yr^{-1} pc^{-3}. Our observational data are compared to theoretical luminosity functions. The cool end ($M_v > 11.0$) is in excellent agreement with the data for a scale height of 250 pc. Fewer hot stars are found than are predicted by most theoretical curves. Better agreement is found with the recent models which assume a "thick" hydrogen envelope and hydrogen shell burning. The difficulties in assigning temperatures to these stars are discussed.

The ratio of the DA stars to the helium atmosphere DO/DB white dwarfs averages 4.3 ± 0.7 to 1 over 80,000 K $> T_{eff} >$ 12,000 K, but appears to be somewhat larger at the hot end of this range. The revised formation rate for all white dwarfs is somewhat lower than current values for the formation of planetary nebulae. However, the white dwarf rate excludes binaries, while the planetary rate is particularly uncertain. Extrapolation of our white dwarf formation rate over 12 billion years leads to a local mass density of only 0.006 $M_\odot$ pc^{-3}, far short of what is needed to satisfy the mass deficit in the local galactic disk.

Subject headings: luminosity function — stars: faint blue — stars: stellar statistics — stars: white dwarfs

2. Observations: now and then

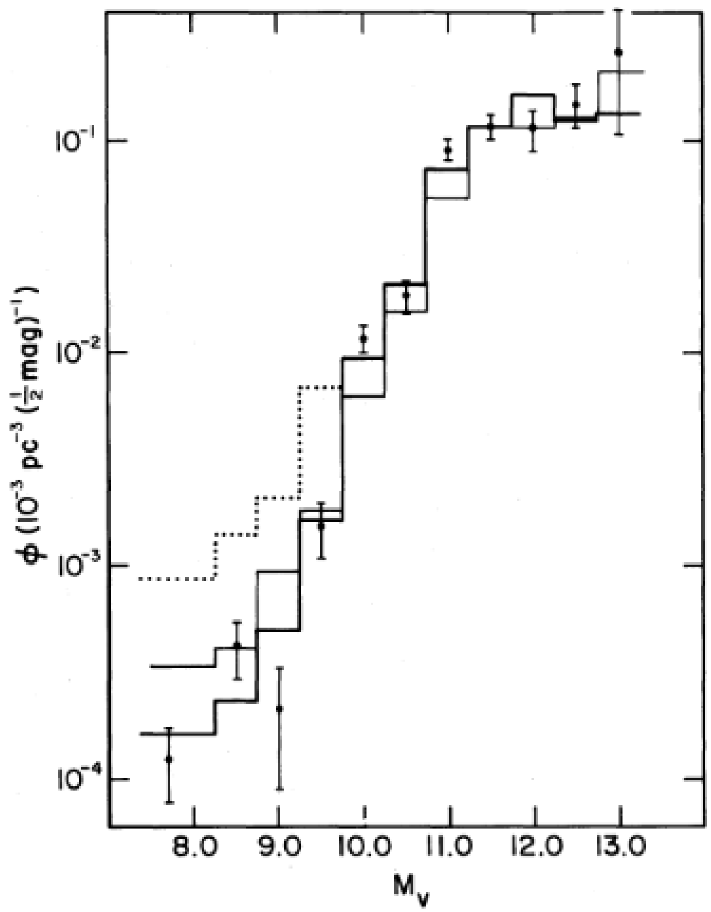

FIG. 2.—Luminosity function for DA white dwarfs presented in half-magnitude bins for convenience. The assumed scale height for the Galaxy, $z_0 = 250$ pc. Error bars represent statistical errors. Thick solid histogram represents the predicted luminosity function of Iben and Tutukov (1984), while the thin solid line represents that of Koester and Schönberner (1985). Dashed histogram represents the Mestel law.

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2. Observations: now and then

The Astronomical Journal, 153:10 (19pp), 2017 January

doi:10.3847/1538-3881/153/1/10

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A DEEP PROPER MOTION CATALOG WITHIN THE SLOAN DIGITAL SKY SURVEY FOOTPRINT. II. THE WHITE DWARF LUMINOSITY FUNCTION

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Received 2016 September 11; revised 2016 October 25; accepted 2016 October 25; published 2016 December 19

ABSTRACT

A catalog of 8472 white dwarf (WD) candidates is presented, selected using reduced proper motions from the deep proper motion catalog of Munn et al. Candidates are selected in the magnitude range $16 < r < 21.5$ over 980 square degrees, and $16 < r < 21.3$ over an additional 1276 square degrees, within the Sloan Digital Sky Survey (SDSS) imaging footprint. Distances, bolometric luminosities, and atmospheric compositions are derived by fitting SDSS *ugriz* photometry to pure hydrogen and helium model atmospheres (assuming surface gravities $\log\ g = 8$). The disk white dwarf luminosity function (WDLF) is constructed using a sample of 2839 stars with $5.5 < M_{\rm bol} < 17$, with statistically significant numbers of stars cooler than the turnover in the luminosity function. The WDLF for the halo is also constructed, using a sample of 135 halo WDs with $5 < M_{\rm bol} < 16$. We find space densities of disk and halo WDs in the solar neighborhood of $5.5 \pm 0.1 \times 10^{-3}\ {\rm pc}^{-3}$ and $3.5 \pm 0.7 \times 10^{-5}\ {\rm pc}^{-3}$, respectively. We resolve the bump in the disk WDLF due to the onset of fully convective envelopes in WDs, and see indications of it in the halo WDLF as well.

Key words: stars: luminosity function, mass function – white dwarfs

Supporting material: data behind figures, machine-readable tables

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2. Observations: now and then

THE ASTRONOMICAL JOURNAL, 153:10 (19pp), 2017 January

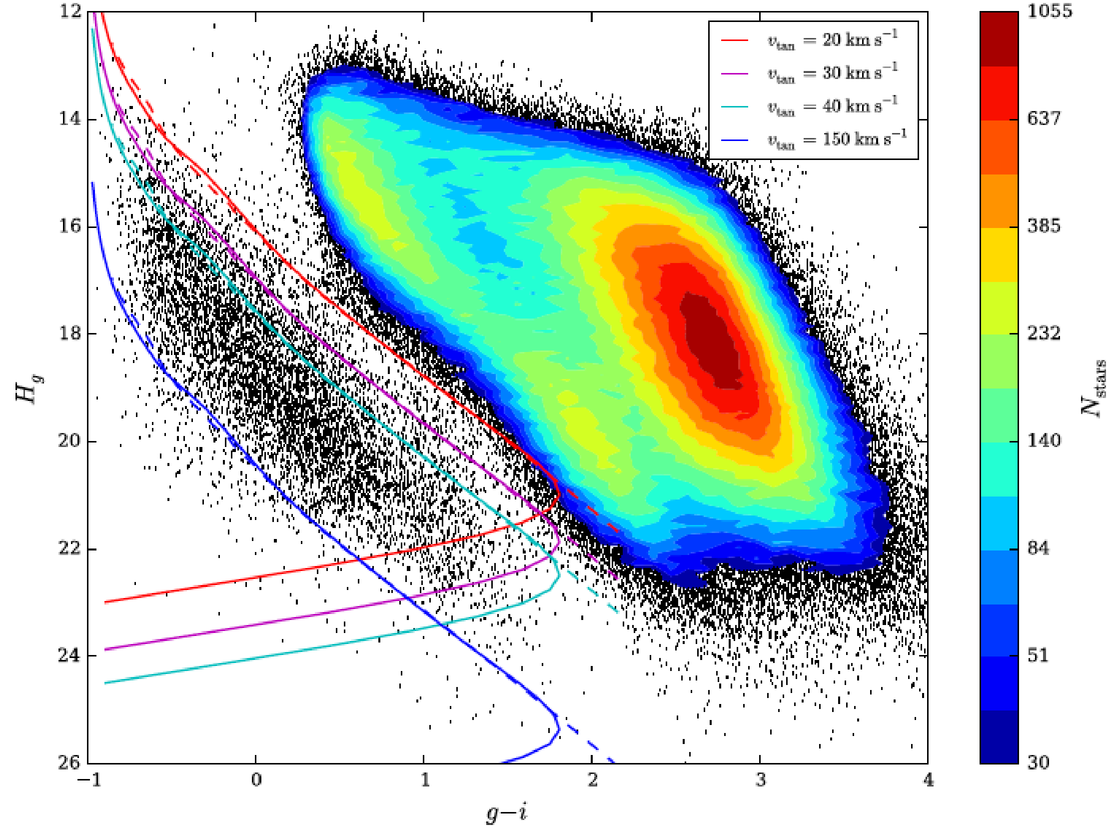

Figure 4. Reduced proper motion diagram for our 3.5σ proper motion sample. In the high-density portion of the diagram, density contours are plotted (number of stars per bin, where each bin is 0.1 mag in H_g by 0.1 mag in $g - i$). Outside the lowest density contour, individual stars are plotted. Evolutionary tracks for model WDs with different kinematics are plotted to indicate the expected position of WDs within the diagram. Solid lines are pure hydrogen atmosphere WDs, while dashed lines are pure helium atmosphere WDs. The red, magenta, cyan, and blue tracks are for WDs with tangential velocities of 20, 30, 40, and 150 km s^{-1}, respectively. Almost all objects below the v_{tan} = 30 km s^{-1} evolutionary tracks are expected to be WDs.

2. Observations: now and then

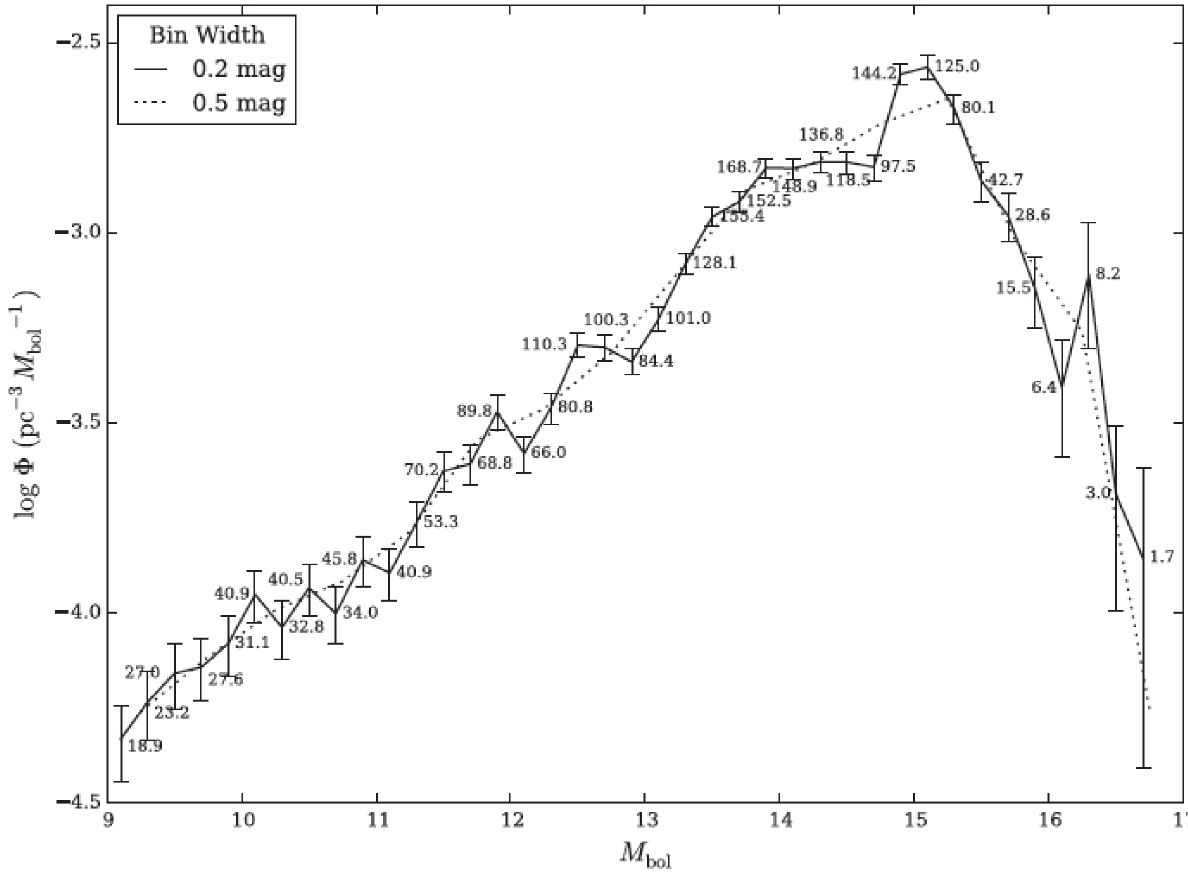

Figure 15. Preferred disk LF with 0.2 mag wide bins (solid line, with numbers indicating the number of weighted stars in each bin), compared to LF with 0.5 mag wide bins (dotted line). The data used to create this figure are available.

2. Observations: now and then

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. 417, 93–113 (2011) doi:10.1111/j.1365-2966.2011.18976.x

White dwarfs in the SuperCOSMOS Sky Survey: the thin disc, thick disc and spheroid luminosity functions

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Accepted 2011 April 28. Received 2011 April 28; in original form 2011 February 14

ABSTRACT

We present a magnitude and proper motion limited catalogue of ~10 000 white dwarf candidates, obtained from the SuperCOSMOS Sky Survey by means of reduced proper motion selection. This catalogue extends to magnitudes $R \sim 19.75$ and proper motions as low as $\mu \sim 0.05$ arcsec yr^{-1}, and covers nearly three quarters of the sky. Photometric parallaxes provide distance estimates accurate to ~50 per cent. This catalogue is used to measure the luminosity functions for disc and spheroid white dwarfs, using strict velocity cuts to isolate subsamples belonging to each population. Disc luminosity functions measured in this manner are really a conglomerate of thin and thick disc objects, due to the significant velocity overlap between these populations. We introduce a new statistical approach to the stellar luminosity function for nearby objects that successfully untangles the contributions from the different kinematic populations, without the need for stringent velocity cuts. This improves the statistical power by allowing all stars to contribute to the luminosity function, even at tangential velocities where the populations are indistinguishable. This method is particularly suited to white dwarfs, for which population discrimination by chemical tagging is not possible. We use this technique to obtain the first measurement of the thick disc white dwarf luminosity function, while also improving constraint on both the thin disc and spheroid luminosity functions. We find that the thin disc, thick disc and spheroid populations contribute to the local white dwarf density in roughly 79 per cent/16 per cent/5 per cent proportions.

Key words: surveys – stars: luminosity function, mass function – white dwarfs – solar neighbourhood.

2. Observations: now and then

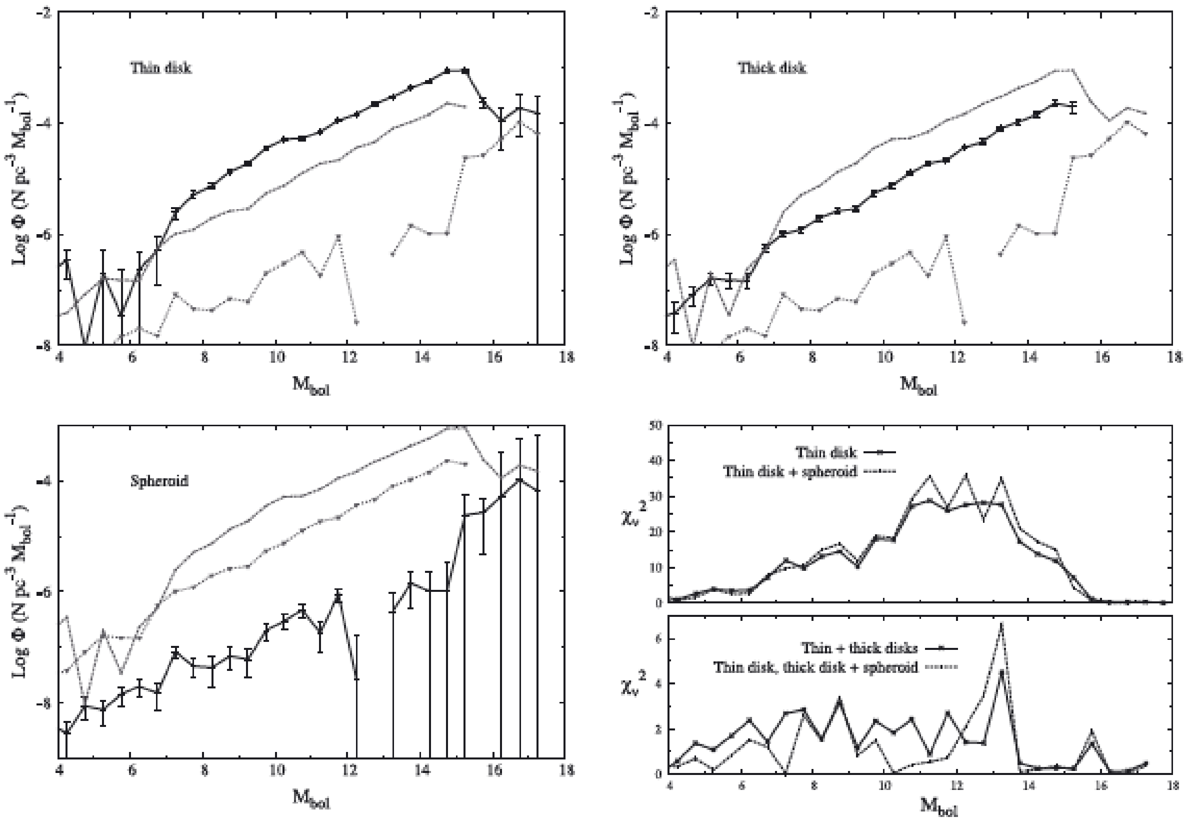

Figure 18. The luminosity functions for thin disc, thick disc and spheroid WDs, obtained from our catalogue using the effective volume method. The lower-right panel shows the χ^2 statistic for each luminosity bin, using different models to predict the observed star counts.

2. Observations: now and then

The Astrophysical Journal Supplement Series, 219:19 (35pp), 2015 August
doi:10.1088/0067-0049/219/2/19

PHYSICAL PROPERTIES OF THE CURRENT CENSUS OF NORTHERN WHITE DWARFS WITHIN 40 pc OF THE SUN

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Received 2015 January 23; accepted 2015 May 8; published 2015 July 30

ABSTRACT

We present a detailed description of the physical properties of our current census of white dwarfs within 40 pc of the Sun, based on an exhaustive spectroscopic survey of northern hemisphere candidates from the SUPERBLINK proper motion database. Our method for selecting white dwarf candidates is based on a combination of theoretical color–magnitude relations and reduced proper motion diagrams. We reported in an earlier publication the discovery of nearly 200 new white dwarfs, and we present here the discovery of an additional 133 new white dwarfs, among which we identify 96 DA, 3 DB, 24 DC, 3 DQ, and 7 DZ stars. We further identify 178 white dwarfs that lie within 40 pc of the Sun, representing a 40% increase of the current census, which now includes 492 objects. We estimate the completeness of our survey at between 66% and 78%, allowing for uncertainties in the distance estimates. We also perform a homogeneous model atmosphere analysis of this 40 pc sample and find a large fraction of massive white dwarfs, indicating that we are successfully recovering the more massive, and less luminous objects often missed in other surveys. We also show that the 40 pc sample is dominated by cool and old white dwarfs, which populate the faint end of the luminosity function, although trigonometric parallaxes will be needed to shape this part of the luminosity function more accurately. Finally, we identify 4 probable members of the 20 pc sample, 4 suspected double degenerate binaries, and we also report the discovery of two new ZZ Ceti pulsators.

Key words: solar neighborhood – stars: distances – stars: fundamental parameters – stars: luminosity function, mass function – surveys – white dwarfs

2. Observations: now and then

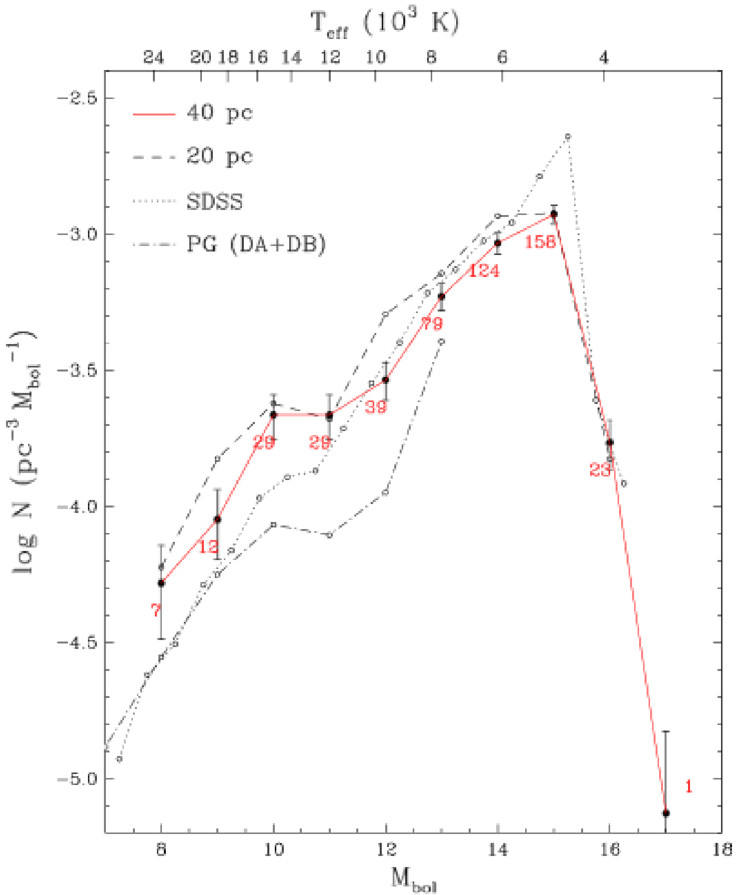

Figure 27. Luminosity function for our sample of white dwarfs within 40 pc of the Sun as a function of M_{bol} (red line), compared to the luminosity functions obtained by Giammichele et al. (2012) for the 20 pc sample, by Harris et al. (2006) for white dwarfs in the SDSS, and by Bergeron et al. (2011) for the DA and DB stars in the PG survey; the number of stars in each magnitude bin is given for the 40 pc sample only. The approximate temperature scale for a $M = 0.6\ M_{\odot}$ sequence is shown at the top of the figure.

3. Theory: now and then

- Reliable cooling sequences aimed at reproducing the characteristics of the observed populations of white dwarfs are also needed.
- All the relevant sources and sinks of energy must be carefully evaluated, and a detailed and realistic treatment of the energy transport in their atmospheres is required.
- A full end-to-end treatment of all the stellar evolutionary phases from the zero-age main sequence (ZAMS), through the red giant and the thermally pulsing phases to the planetary nebula and cooling stages is also needed.
- Only in this way state-of-the-art and realistic initial models for the cooling sequences can be obtained.

3. Theory: now and then

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3. Theory: now and then

- Finally, it is also essential to have state-of-the-art population synthesis codes to account for the selection procedures and the known biases.
- Significant progress has been made in three directions:
  - Physical inputs (model envelopes and separation processes, including diffusion and phase diagrams).
  - Evolutionary sequences.
  - Population synthesis models.

2. Theory: now and then

Astron. Astrophys. 193, 141–147 (1988)

ASTRONOMY AND ASTROPHYSICS

Theoretical white-dwarf luminosity functions for two phase diagrams of the carbon-oxygen dense plasma

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Received June 22, accepted August 6, 1987

Summary. The white dwarf luminosity function is obtained for two phase diagrams of the carbon-oxygen dense plasma. In the first case, carbon and oxygen are totally mixed in solid phase and we obtain results that are in good agreement with recent calculations of Iben and Tutukov (1984). In the second case, either pure carbon or pure oxygen crystallizes, depending on the composition of the liquid mixture compared to an eutectic having a carbon mass fraction $X_c \approx 0.6$. Due to the larger density of solid oxygen, this leads to the formation of an oxygen core surrounded by a carbon rich mantle. The redistribution of elements releases as substantial amount of energy which slows down the cooling. The resulting theoretical luminosity function falls abruptly at $\log(L/L_\odot) \approx -4.6$, this value corresponding to a cooling time of 15 Gyr, assumed to be the age of the galactic disk. Carbon-oxygen separation can therefore explain the low luminosity cut-off observed in the white dwarf luminosity function which is not predicted by standard cooling theory.

Key words: white dwarfs – luminosity function – dense matter – dark matter

Recently, Iben and Tutukov (1984) have carefully rediscussed the cooling of a 0.6 $M_\odot$ carbon-oxygen white dwarf. The luminosity function they have obtained is in excellent agreement with the observations down to $\log(L/L_\odot) \approx -4$ but a discrepancy appears at lower luminosities where the paucity of observed white dwarfs contrasts with a still flat luminosity function. Possible loop-holes to this problem have been considered by Iben and Tutukov (1984), one of which being what they call the "delay" solution where a physical process increases the time necessary to reach luminosities smaller than $10^{-4} L_\odot$ to a value which is larger than the age of the galactic disk. An example of such a process is the separation of carbon and oxygen which occurs if these two elements cannot coexist in solid phase (Stevenson, 1980). Denser solid oxygen accumulates at the star center, which releases gravitational energy and then decreases the cooling rate. The effect is of major importance since the energy released per gram of deposited oxygen represents about ten times the latent heat (Mochkovitch, 1983). A disadvantage of the delay solution is, however, to increase the number of white dwarfs with luminosities larger than $10^{-4} L_\odot$ which can produce a bump in the luminosity function, in contradiction with the observations. The purpose of this paper is to show that carbon-oxygen separation during crystallization can

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2. Theory: now and then

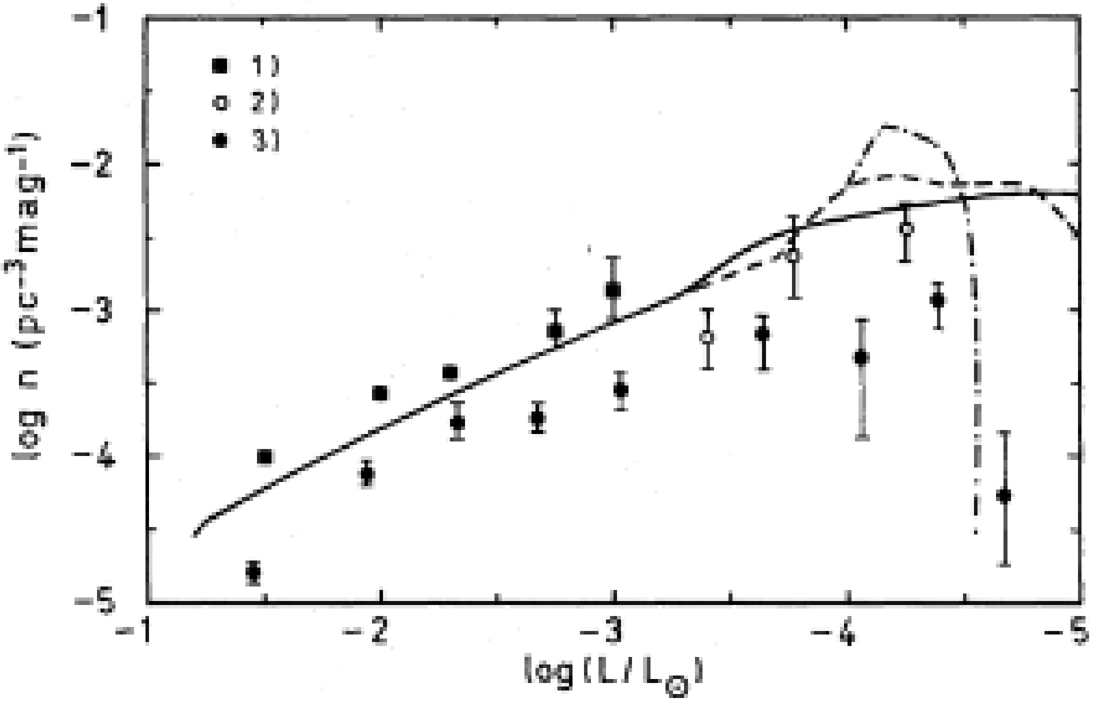

Fig. 5. White dwarf luminosity functions in case (*a*) — solid line, (*b*) — dashed line and (*c*) — dot-dashed line, assuming a constant white dwarf birth rate $\nu_{wd} = 0.5\, yr^{-1}$ over the age of the Galaxy. Observational data are 1) from Green (1977); 2) from Sion and Liebert (1977); 3) from Winget et al. (1987)

2. Theory: now and then

Properties of high-density binary mixtures and the age of the Universe from white dwarf stars

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The luminosity of white dwarf stars can be attributed to the cooling process of their degenerate cores. The simple relationship existing between their luminosity and their age, together with the lack of white dwarfs fainter than log $(L/L_\odot) \approx -4.5$, provides a method of measuring the age of the disk and consequently that of the Universe[1,2]. Winget *et al.*[2] have derived an age of the galactic disk of 9.3 Gyr and have then found that the Universe is young: 10.3 Gyr. These values depend on the assumption that completely ionized carbon and oxygen (the most abundant elements in white dwarf interiors) are miscible in solid phase. It is possible, however, that completely ionized carbon and oxygen separate during the process of crystallization[3,4]. The consequences of this behaviour on the evolution of mass-accreting carbon–oxygen white dwarfs in stellar binary systems[5–7] and on the cooling process of white dwarfs[8,9] have been already described. Here, we attempt to show that a galactic disk age of 15 Gyr cannot be excluded by the white dwarf observations if carbon and oxygen are immiscible in solid phase.

The luminosity function of white dwarf stars (the number of

in solid phase, the situation changes dramatically. Oxygen, being denser than carbon, sinks towards the centre, releasing gravitational energy. This process is dominant during the late stages of the cooling of white dwarfs. For instance, for a $0.6 M_\odot$ white dwarf, with equal mass fractions of carbon and oxygen, the gravitational energy released this way is $\epsilon_{grav} \approx 10^{14}$ ergs g^{-1}, which is larger than the latent heat of oxygen ($\sim 5.2 \times 10^6\, T$ ergs g^{-1}, where T is the solidification temperature). Furthermore, this process happens when the central temperature is $\sim 2 \times 10^6$ K, which corresponds to a luminosity of ~log $L/L_\odot \approx -4$.

The confirmation of either carbon and oxygen miscibility or immiscibility in solid phase is a difficult problem as it requires the knowledge of the free energy of the completely ionized carbon–oxygen plasma in both liquid and solid phases. Using the Monte Carlo method, it is possible to compute the thermodynamic properties of the liquid phase. The free energy of the liquid can be well approximated by assuming ion-sphere charge averaging and an ideal entropy of mixing[14]. In solid phase the situation is more complex, as a given configuration has to be assumed for the alloy before computing the free energy. If we assume that ion-sphere charge averaging and ideal entropy of mixing are simultaneously valid for the solid, carbon and oxygen are miscible in solid phase. Stevenson[3] has pointed out, however, that both requirements cannot be satisfied simultaneously and adopted a model in which the solid alloy had an ideal entropy of mixing and the electrostatic energy of a random alloy. Because of the larger electrostatic energy of the alloy, the mixture tends to separate in soliJ phase. In the case of a completely ionized carbon–oxygen mixture, the phase diagram shows a eutectic for a carbon mass fraction $X_c^e = 0.6$, and total immiscibility in solid phase. The freezing temperature for different chemical compositions can be approximated on each side of the eutectic by: $T/T_c = 0.925 X_c^l + 0.075$ $(X_c^l \geq X_c^e)$; $T/T_c = 1.615 - 1.642 X_c^l$ $(X_c^l \leq X_c^e)$, where X_c^l is the carbon mass fraction in the liquid phase and $T_c = 2.3 \times 10^4 \rho^{1/3}$ (where ρ is the density) is the freezing temperature of pure carbon. Of course, this phase diagram is an oversimplification and its theoretical confirmation needs more detailed calculations. Recently, Barrat *et al.*[4] have calculated the phase diagram of binary hard-sphere mixtures (which accounts for the geometrical packing aspects of solubility) as a function of α, the ratio of sphere diameters. They have

2. Theory: now and then

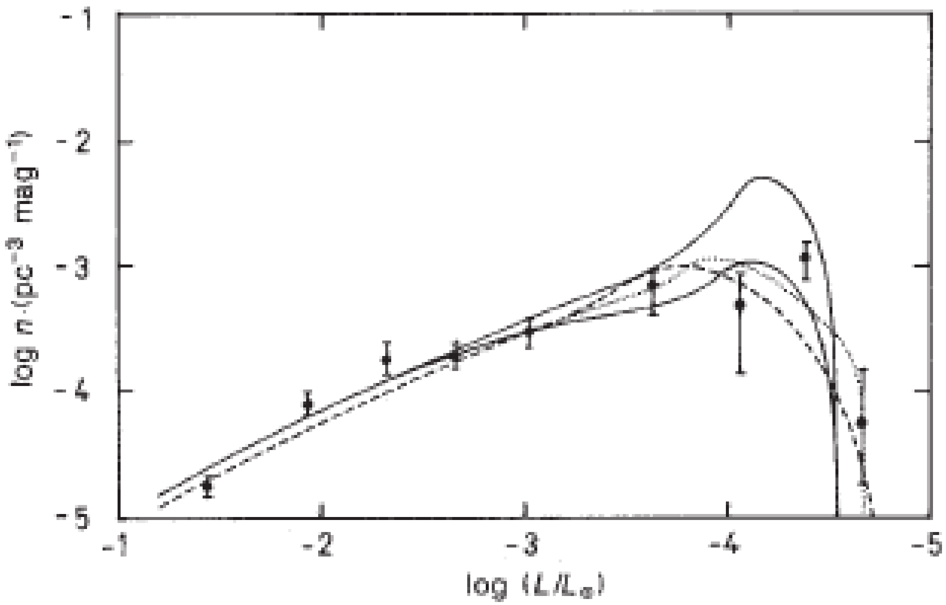

Fig. 1 White-dwarf luminosity functions in the three cases shown in Table 1. Model 1, dashed line; model 2, dotted line; model 3, continuous lines (the upper continuous line has been obtained neglecting the dilution effect introduced by the scale height of white dwarfs). The first three curves are normalized to give the observed number of white dwarfs at $\log(L/L_\odot) = -3$. The normalization factor for the upper continuous line is the same as for the lower one. Observational data are from Winget *et al.*[2]

2. Theory: now and then

Volume 58A, number 4 PHYSICS LETTERS 6 September 1976

MISCIBILITY GAPS IN FULLY PRESSURE-IONIZED BINARY ALLOYS

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Received 7 July 1976

Binary alloys in which all the electrons form a uniform, degenerate, non-relativistic gas are predicted to exhibit miscibility gaps. Approximate analytical formulae are given for the critical temperatures and compositions. Astrophysical implications are mentioned.

2. Theory: now and then

Astron. Astrophys. 122, 212–218 (1983)

ASTRONOMY AND ASTROPHYSICS

Freezing of a carbon-oxygen white dwarf

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Received October 6, 1982; accepted January 24, 1983

Summary. We describe the cooling and solidification of a carbon-oxygen white dwarf assuming a ^{12}C–^{16}O mixture phase diagram which exhibits an oxygen poor eutectic. Freezing is then an efficient mechanism of chemical differentiation. An almost pure "oxygen snow", denser than the liquid, crystallizes first and settles at the center as the carbon left behind is mixed to the rest of the star by convective motions resulting from an unstable concentration gradient. When the fluid at the boundary of the oxygen core has reached the eutectic composition solid carbon begins to form. However, the high gravity may ensure further differentiation since the carbon snow, less dense than the liquid, will rise to lower density regions and melt.

We compare the evolution of the white dwarf to the case where carbon and oxygen can coexist in an alloy. The crystallizing star has a smaller luminosity and must radiate the binding energy release due to the differentiation process. These two combined effects increase strongly the cooling time.

We finally discuss these results for a white dwarf in a binary system in relation with type I supernova models.

Key words: dense matter – stellar evolution – white dwarfs – supernovae

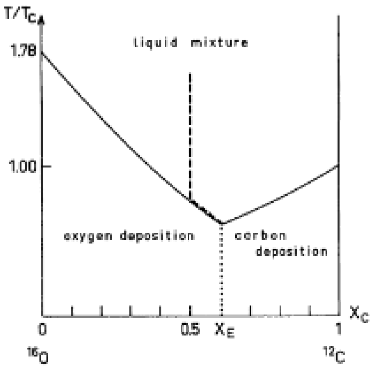

Fig. 1. The phase diagram of Stevenson. The solidification temperature of the liquid mixture compared to that of pure carbon is represented as a function of X_c, the carbon mass fraction. On the oxygen (carbon) rich side of the eutectic $-X_c<0.6$ ($X_c>0.6$) the solid phase is pure oxygen (carbon). The dashed line corresponds to the cooling at constant density of a liquid mixture with $X_c=0.5$. The solidification temperature decreases as oxygen freezes until the eutectic composition is reached in the fluid phase

1. Introduction

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2. Theory: now and then

PRL 104, 231101 (2010) PHYSICAL REVIEW LETTERS week ending 11 JUNE 2010

Crystallization of Carbon-Oxygen Mixtures in White Dwarf Stars

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(Received 21 February 2010; published 7 June 2010)

We determine the phase diagram for dense carbon-oxygen mixtures in white dwarf (WD) star interiors using molecular dynamics simulations involving liquid and solid phases. Our phase diagram agrees well with predictions from Ogata *et al.* and from Medin and Cumming and gives lower melting temperatures than Segretain *et al*. Observations of WD crystallization in the globular cluster NGC 6397 by Winget *et al.* suggest that the melting temperature of WD cores is close to that for pure carbon. If this is true, our phase diagram implies that the central oxygen abundance in these stars is less than about 60%. This constraint, along with assumptions about convection in stellar evolution models, limits the effective S factor for the $^{12}C(\alpha,\gamma)^{16}O$ reaction to $S_{300} \leq 170$ keV b.

DOI: 10.1103/PhysRevLett.104.231101 PACS numbers: 97.20.Rp, 52.25.Kn, 64.70.dg

2. Theory: now and then

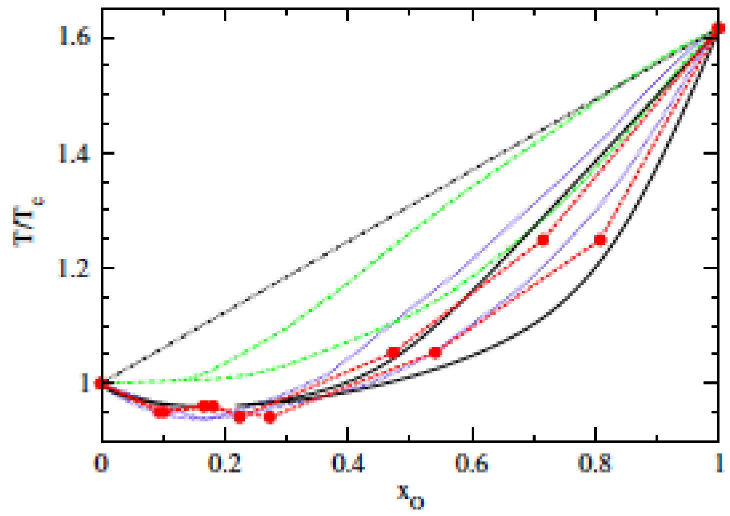

FIG. 2 (color online). Melting temperature T of carbon-oxygen mixtures over the melting temperature T_c of pure carbon, versus oxygen number fraction $x_o = 1 - x_c$. Simulation results of Table I are plotted as filled red circles connected by dashed lines. The x_o in the liquid and in the solid are shown as two separate lines. Also shown are the phase diagram results of Medin and Cumming [13] as solid black lines, the Ogata *et al.* results [7] as dotted blue lines and the Segretain *et al.* results [6] as dot-dashed green lines. Finally the black dot-dot-dashed line corresponds to $\Gamma = 178.4$ in Eq. (1).

2. Theory: now and then

The Astrophysical Journal, 717:183–195, 2010 July 1 doi:10.1088/0004-637X/717/1/183

NEW COOLING SEQUENCES FOR OLD WHITE DWARFS

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Received 2010 March 23; accepted 2010 May 7; published 2010 June 9

ABSTRACT

We present full evolutionary calculations appropriate for the study of hydrogen-rich DA white dwarfs. This is done by evolving white dwarf progenitors from the zero-age main sequence, through the core hydrogen-burning phase, the helium-burning phase, and the thermally pulsing asymptotic giant branch phase to the white dwarf stage. Complete evolutionary sequences are computed for a wide range of stellar masses and for two different metallicities, $Z = 0.01$, which is representative of the solar neighborhood, and $Z = 0.001$, which is appropriate for the study of old stellar systems, like globular clusters. During the white dwarf cooling stage, we self-consistently compute the phase in which nuclear reactions are still important, the diffusive evolution of the elements in the outer layers and, finally, we also take into account all the relevant energy sources in the deep interior of the white dwarf, such as the release of latent heat and the release of gravitational energy due to carbon–oxygen phase separation upon crystallization. We also provide colors and magnitudes for these sequences, based on a new set of improved non-gray white dwarf model atmospheres, which include the most up-to-date physical inputs like the Lyα quasi-molecular opacity. The calculations are extended down to an effective temperature of 2500 K. Our calculations provide a homogeneous set of evolutionary cooling tracks appropriate for mass and age determinations of old DA white dwarfs and for white dwarf cosmochronology of the different Galactic populations.

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2. Theory: now and then

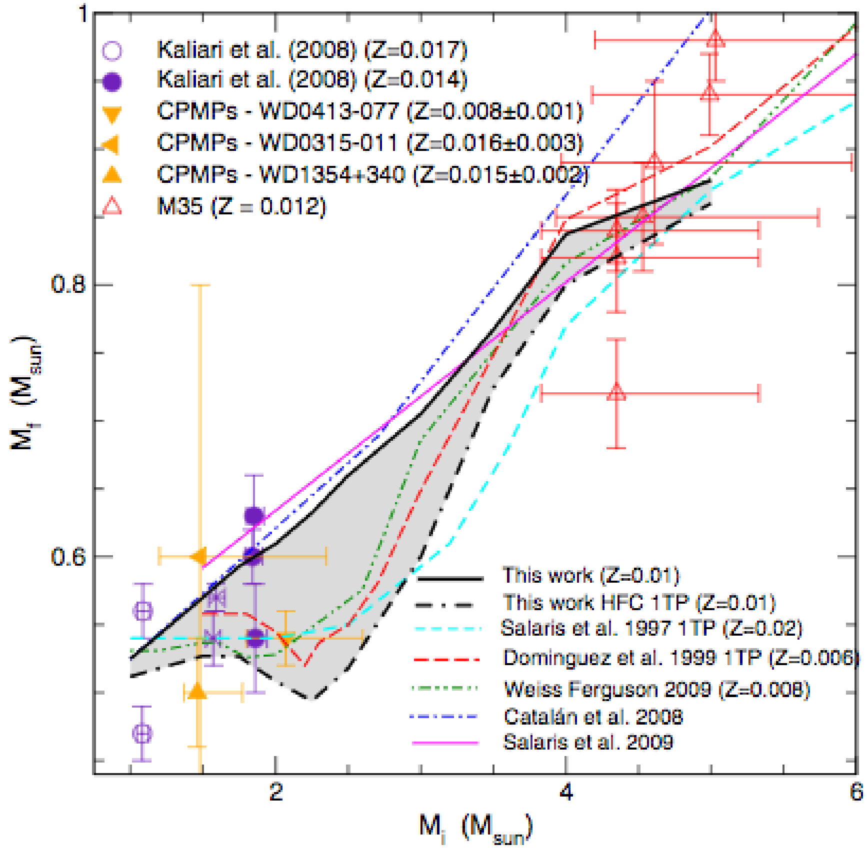

Figure 2. Theoretical initial-to-final mass relationship (thick solid line) and mass of the degenerate core at the beginning of the first thermal pulse (thick dot-dashed-dashed line) obtained in this work, both for the case in which the solar composition is adopted. The initial-to-final mass relationships of Salaris et al. (1997; short dashed line), of Domínguez et al. (1999; long dashed line), and of Weiss & Ferguson (2009; dot-dot-dashed line) are also shown. The observational initial-to-final mass relationship of Catalán et al. (2008a) and Salaris et al. (2009) are the dot-dashed and solid lines, respectively.

2. Theory: now and then

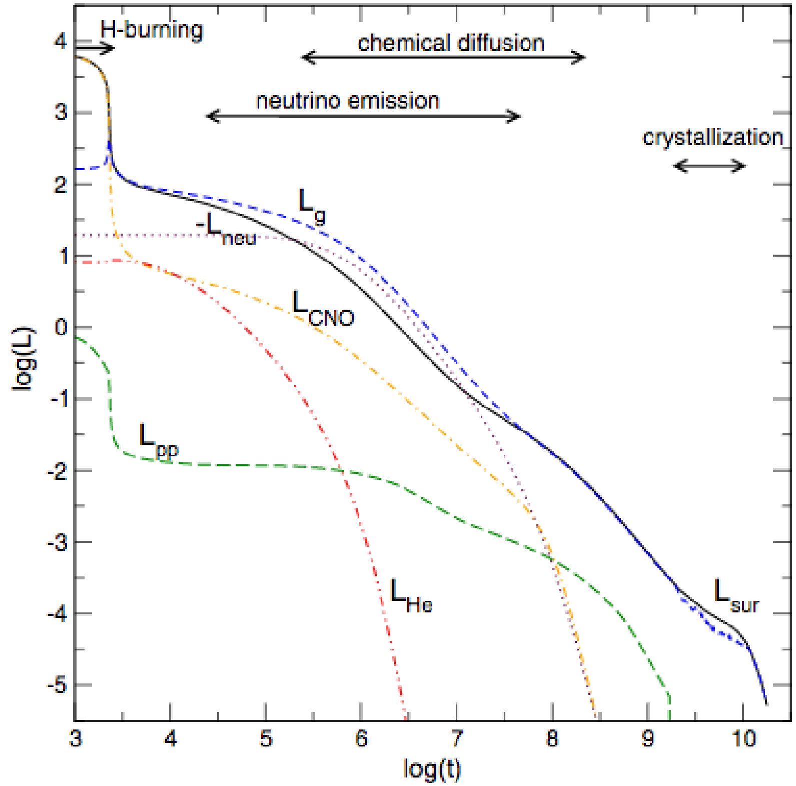

Figure 3. Time dependence of the different luminosity contributions for our 0.609 $M_\odot$ white dwarf sequence when carbon–oxygen phase separation is included. We show the photon luminosity, $L_{\rm sur}$ (solid line), the luminosities due to nuclear reactions—proton–proton chains, L_{pp} (long dashed line), CNO bi–cycle, $L_{\rm CNO}$ (dot-dashed line), helium-burning, $L_{\rm He}$ (dot-dot-dashed line)—the neutrino losses, $L_{\rm neu}$ (dotted line) and the rate of gravothermal (compression plus thermal) energy release, $L_{\rm g}$ (dashed line). Time is expressed in years counted from the moment at which the remnant reaches $\log T_{\rm eff} = 4.87$ at high luminosity. The various physical processes occurring as the white dwarf cools down are indicated in the figure. The progenitor corresponds to a solar-metallicity 2.0 $M_\odot$ star.

2. Theory: now and then

Astron. Astrophys. 241, L29–L32 (1991)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

The role of the minor chemical species in the cooling of white dwarfs

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Received August 7, accepted September 27, 1990

Abstract. White dwarf interiors are made of a mixture of carbon, oxygen and other minor species, ^{22}Ne being the most abundant one. In this Letter we compute a preliminary phase diagram for the C-Ne and O-Ne mixtures and we show that ^{22}Ne can settle down at the center as an outcome of solidification. The gravitational energy released by this process keeps the white dwarf warm for 2 Gyr, thus delaying the cooling process by a similar amount.

Barrat, Hansen and Mochkovitch (1988), which is of the spindle form, is adopted. This delay amounts to 1.5 Gyr if the phase diagram of Ichimaru et al. (1988), which displays an azeotropic behavior, is adopted (Hernanz et al., 1990). The discrepancies in the results come from the differences in the freezing temperatures and, given the uncertainties involved in the calculations, they are irrelevant.

The existence of an azeotrope in the phase diagram opens, however, new and very interesting possibilities for obtaining

2. Theory: now and then

nature
Vol 465|13 May 2010|doi:10.1038/nature09045

LETTERS

A white dwarf cooling age of 8 Gyr for NGC 6791 from physical separation processes

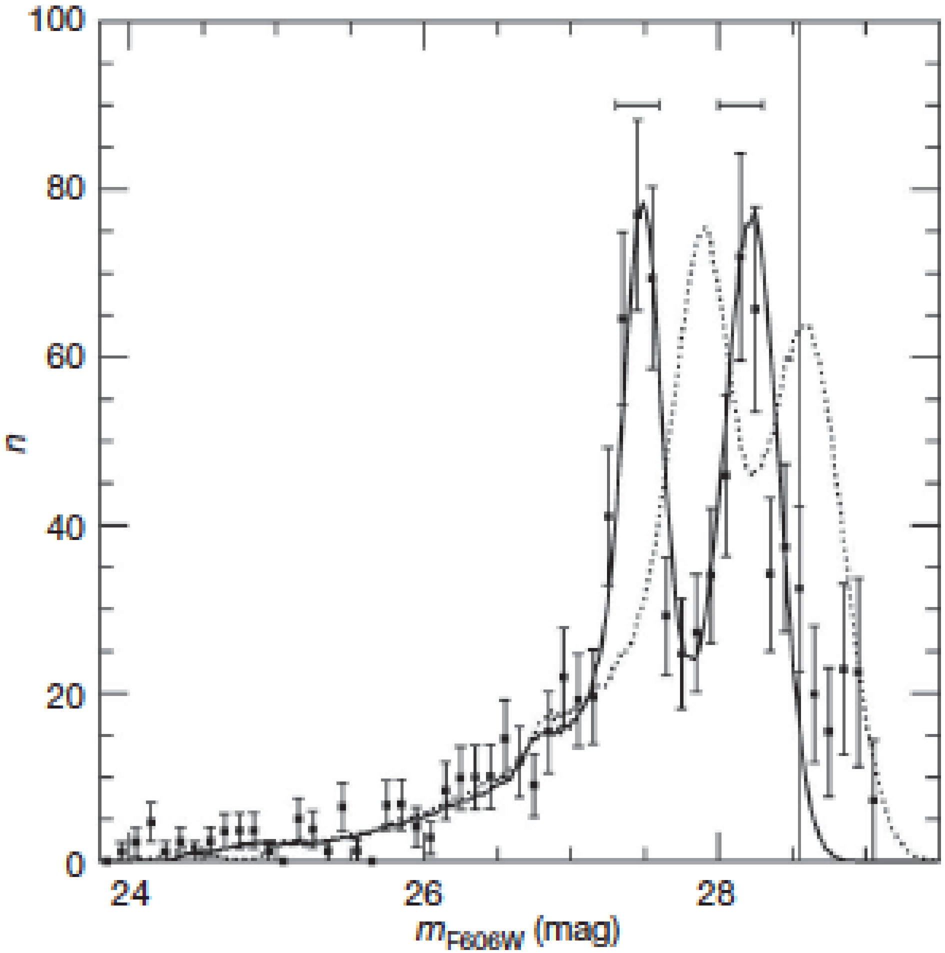
Enrique García-Berro[1,2], Santiago Torres[1,2], Leandro G. Althaus[1,3,4], Isabel Renedo[1,2], Pablo Lorén-Aguilar[1,2], Alejandro H. Córsico[3,4], René D. Rohrmann[5], Maurizio Salaris[6] & Jordi Isern[2,7]

NGC 6791 is a well studied open cluster[1] that it is so close to us that can be imaged down to very faint luminosities[2]. The main-sequence turn-off age (~8 Gyr) and the age derived from the termination of the white dwarf cooling sequence (~6 Gyr) are very different. One possible explanation is that as white dwarfs cool, one of the ashes of helium burning, ^{22}Ne, sinks in the deep interior of these stars[3–5]. At lower temperatures, white dwarfs are expected to crystallize and phase separation of the main constituents of the core of a typical white dwarf (^{12}C and ^{16}O) is expected to occur[6,7]. This sequence of events is expected to introduce long delays in the cooling times[8,9], but has not hitherto been proven. Here we report that, as theoretically anticipated[5,6], physical separation processes occur in the cores of white dwarfs, resolving the age discrepancy for NGC 6791.

sequences which include both physical processes. The final white-dwarf masses were 0.5249, 0.5701, 0.593, 0.6096, 0.6323, 0.6598 and 0.7051 solar masses.

Our sequences start from stellar models on the zero-age main sequence with masses between 1 and 3 solar masses. These sequences were followed through the thermally pulsing and mass-loss phases on the asymptotic giant branch to the white dwarf stage. Evolutionary calculations were done using a state-of-the-art stellar evolutionary code[12]. Issues such as the simultaneous treatment of non-instantaneous mixing and burning of elements, and the modelling of mixing during core nuclear burning, of relevance for the carbon–oxygen stratification of the resulting white dwarf core, have been considered with a high degree of detail. Particularly relevant for the present study is the treatment of the release of gravitational energy resulting from ^{22}Ne sedi-

2. Theory: now and then



2. Theory: now and then

The Astrophysical Journal, 823:158 (8pp), 2016 June 1
doi:10.3847/0004-637X/823/2/158

THE EFFECT OF ^{22}Ne DIFFUSION IN THE EVOLUTION AND PULSATIONAL PROPERTIES OF WHITE DWARFS WITH SOLAR METALLICITY PROGENITORS

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Received 2016 February 3; accepted 2016 March 22; published 2016 June 1

ABSTRACT

Because of the large neutron excess of ^{22}Ne, sedimentation of this isotope occurs rapidly in the interior of white dwarfs. This process releases an additional amount of energy, thus delaying the cooling times of the white dwarf. This influences the ages of different stellar populations derived using white dwarf cosmochronology. Furthermore, the overabundance of ^{22}Ne in the inner regions of the star modifies the Brunt–Väisälä frequency, thus altering the pulsational properties of these stars. In this work we discuss the impact of ^{22}Ne sedimentation in white dwarfs resulting from solar metallicity progenitors ($Z = 0.02$). We performed evolutionary calculations of white dwarfs with masses of 0.528, 0.576, 0.657, and 0.833 $M_\odot$ derived from full evolutionary computations of their progenitor stars, starting at the zero-age main sequence all the way through the central hydrogen and helium burning, the thermally pulsing asymptotic giant branch (AGB), and post-AGB phases. Our computations show that at low luminosities ($\log(L/L_\odot) \lesssim -4.25$), ^{22}Ne sedimentation delays the cooling of white dwarfs with solar metallicity progenitors by about 1 Gyr. Additionally, we studied the consequences of ^{22}Ne sedimentation on the pulsational properties of ZZ Ceti white dwarfs. We find that ^{22}Ne sedimentation induces differences in the periods of these stars larger than the present observational uncertainties, particularly in more massive white dwarfs.

Key words: asteroseismology – dense matter – diffusion – stars: evolution – stars: interiors – white dwarfs

2. Theory: now and then

PHYSICAL REVIEW E **82**, 066401 (2010)

Diffusion of neon in white dwarf stars

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(Received 21 September 2010; published 1 December 2010)

Sedimentation of the neutron rich isotope ^{22}Ne may be an important source of gravitational energy during the cooling of white dwarf stars. This depends on the diffusion constant for ^{22}Ne in strongly coupled plasma mixtures. We calculate self-diffusion constants D_i from molecular dynamics simulations of carbon, oxygen, and neon mixtures. We find that D_i in a mixture does not differ greatly from earlier one component plasma results. For strong coupling (coulomb parameter $\Gamma >$ few), D_i has a modest dependence on the charge Z_i of the ion species, $D_i \propto Z_i^{-2/3}$. However, D_i depends more strongly on Z_i for weak coupling (smaller Γ). We conclude that the self-diffusion constant D_{Ne} for ^{22}Ne in carbon, oxygen, and neon plasma mixtures is accurately known so that uncertainties in D_{Ne} should be unimportant for simulations of white dwarf cooling.

DOI: 10.1103/PhysRevE.82.066401 PACS number(s): 94.05.−a, 97.20.Rp, 97.60.−s, 66.10.C−

2. Theory: now and then

letters to nature

Old and blue white-dwarf stars as a detectable source of microlensing events

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The analysis[1] of gravitational microlensing events of stars[2,3] in the Large Magellanic Cloud places the masses of the lensing objects in the range 0.3–0.8 solar masses, suggesting that they might be old white-dwarf stars. Such objects represent the last stage of stellar evolution: they are the cooling cores of stars that have lost their atmospheres after nuclear fusion has ceased in their centres. If white dwarfs exist in abundance in the halo of our Galaxy, this would have profound implications for our understanding of the early generations of stars in the Universe[4–6]. Previous attempts to constrain theoretically[6–8] the contribution of white dwarfs to microlensing indicate that they can account for only a small fraction of the events. But these estimates relied on models of white-dwarf cooling that are inadequate for describing the properties of the oldest such objects. Here I present cooling models appropriate for very old white dwarfs. I find, using these models, that the widely held notion that old white dwarfs are red applies only to those with a helium atmosphere; old white dwarfs with hydrogen atmospheres, which could be a considerable fraction of the total population, will appear rather blue, with colours similar to those of the faint blue sources in the Hubble Deep Field. Observational searches for the population of microlensing objects should therefore look for faint blue objects, rather than faint red ones.

2. Theory: now and then

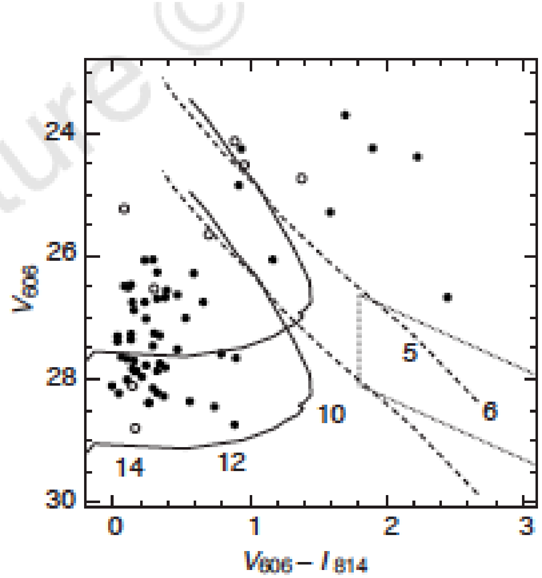

Figure 3 Stellar objects in the Hubble Deep Field. The filled circles are the unresolved objects detected by Elson *et al.*[19]; the open circles are the point sources from Mendez *et al.*[20]. Although Flynn *et al.*[18] did not publish a table of detections, the dotted line encloses their 'halo region', which they used to constrain the halo white-dwarf population. The dashed lines show the cooling behaviour of a helium atmosphere white dwarf at a distance of 1 kpc (upper line) and 2 kpc (lower line). The upper curve is labelled with ages in Gyr at appropriate points. The solid lines represent the corresponding evolution of a hydrogen-atmosphere dwarf at 1 and 2 kpc. The dwarf ages are shown on the lower curve in this case. The bandpasses are the Hubble Telescope bandpasses from Holtzman *et al.*[28]. The blueward shift for ages 10–12 Gyr is due to the presence of molecular hydrogen in the atmosphere.

2. Theory: now and then

Mon. Not. R. Astron. Soc. **302,** 173–188 (1999)

Monte Carlo simulations of the disc white dwarf population

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Accepted 1998 September 3. Received 1998 August 4; in original form 1998 March 24

ABSTRACT

In order to understand the dynamical and chemical evolution of our Galaxy it is of fundamental importance to study the local neighbourhood. White dwarf stars are ideal candidates to probe the history of the solar neighbourhood, since these 'fossil' stars have very long evolutionary time-scales and, at the same time, their evolution is relatively well understood. In fact, the white dwarf luminosity function has been used for this purpose by several authors. However, a long-standing problem arises from the relatively poor statistics of the samples, especially at low luminosities. In this paper we assess the statistical reliability of the white dwarf luminosity function by using a Monte Carlo approach.

Key words: stars: luminosity function, mass function – white dwarfs – solar neighbourhood – Galaxy: stellar content.

3. Final thoughts

- I have reviewed the current status of the research field, paying attention only to its most crucial breakthroughs.
- I have not gone into the (very interesting) details of the calculations, and on the abundant literature of the white dwarf cooling theory and its many applications.
- Also, I have not mentioned whatsoever the myriad of papers on pulsating white dwarfs, nor on evolutionary calculations of cooling white dwarfs with helium-dominated atmospheres.
- The selection of papers is product of my own research trajectory, interests, and personal biases. I apologize for any unintentionally missed relevant reference.

3. Final thoughts

- Finally, a few words about Margarita's contributions to the theory of white dwarf cooling.
- Margarita and me started to work on white dwarf cooling when I was still struggling with my PhD. She obtained her degree 2 years before I did.
- I owe her gratitude for her invaluable help, but more importantly, for her long-lasting friendship.
- Margarita left the field approximately in 2000, and focused on novae, but her work remains, and is considered a milestone within the white dwarf community.
- Thank you very much, Margarita.

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White dwarfs: now and then

E. García-Berro & Santiago Torres

Hernanzfest, Tossa de Mar (Spain) – June 2017