Volume Title
*ASP Conference Series, Vol. **Volume Number***
Author

On the origin of high-field magnetic white dwarfs

E. García–Berro,[1,2] S. Torres,[1,2] P. Lorén–Aguilar,[1,2] G. Aznar–Siguán,[1,2] J. Camacho,[1,2] B. Külebi,[2,3] J. Isern,[2,3] L.G. Althaus,[4] and A.H. Córsico[4]

[1]*Departament de Física Aplicada, Universitat Politècnica de Catalunya, c/Esteve Terrades, 5, 08860 Castelldefels, Spain*

[2]*Institute for Space Studies of Catalonia, c/Gran Capità 2–4, Edif. Nexus 104, 08034 Barcelona, Spain*

[3]*Institut de Ciències de l'Espai (CSIC), Facultat de Ciències, Campus UAB, Torre C5-parell, 08193 Bellaterra, Spain*

[4]*Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque s/n, (1900) La Plata, Argentina*

Abstract. High-field magnetic white dwarfs have been long suspected to be the result of stellar mergers. However, the nature of the coalescing stars and the precise mechanism that produces the magnetic field are still unknown. Here we show that the hot, convective, differentially rotating corona present in the outer layers of the remnant of the merger of two degenerate cores is able to produce magnetic fields of the required strength that do not decay for long timescales. We also show, using an state-of-the-art Monte Carlo simulator, that the expected number of high-field magnetic white dwarfs produced in this way is consistent with that found in the solar neighborhood.

1. Introduction

High-field magnetic white dwarfs have field strengths larger than 10^6 G and up to 10^9 G (Schmidt et al. 2003). The galactic population of these white dwarfs exhibits two remarkable peculiarities. The first one is that very few of them belong to a non-interacting binary system (Kawka et al. 2007), while the second one is that they are more massive than average (Silvestri et al. 2007). Generally speaking there are two competing scenarios to explain the formation of these stars. One possibility is that these white dwarfs descend from single stars, so the magnetic field is a fossil of previous evolution (Angel et al. 1981). However, this scenario cannot explain why they are preferentially massive, and why they are not found in non-interacting binary systems. Recently, it has been suggested (Tout et al. 2008; Nordhaus et al. 2011) that strong magnetic fields can be produced during a common envelope episode in a close binary system in which one of the components is degenerate. During this phase, spiral-in of the secondary in the extended envelope results in differential rotation in the convective envelope, which in turn produces a stellar dynamo which could give raise to strong magnetic fields. However, it has been shown that the magnetic field produced in this way does not penetrate in the white dwarf, but instead decays rapidly when the common envelope is ejected (Potter & Tout 2010).

The coalescence of double degenerate objects has been the subject of numerous theoretical studies during the last years. Large computational efforts have been devoted to study this intrinsically three-dimensional problem because it is thought to be at the heart of several interesting astrophysical phenomena, among which we mention Type Ia supernova (Webbink 1984; Iben & Tutukov 1984), magnetars (King et al. 2001), and hydrogen-deficient carbon stars and of R Corona Borealis stars (Longland et al. 2011, 2012). Also, the large metal abundances found around some hydrogen-rich white dwarfs with dusty disks around them could also be explained by the merger of a carbon-oxygen and a helium white dwarf (García-Berro et al. 2007). Finally, during the phase previous to the coalescence of a double white-dwarf close binary system gravitational waves are emitted, and it has been shown that LISA will be able to detect them (Lorén-Aguilar et al. 2005). Here we quantitatevely show that the merger of two degenerate cores can also explain the presence of very high magnetic fields in some white dwarfs — a scenario initially suggested by Wickramasinghe & Ferrario (2000).

2. An $\alpha\omega$ dynamo in the merger remnant

Full three-dimensional simulations of the merger of two white dwarfs (Guerrero et al. 2004; Lorén-Aguilar et al. 2009) have shown that the final remnant of the coalescence is a central white dwarf containing all the mass of the undisrupted primary. On top of this white dwarf there is a hot corona made of about half of the mass of the disrupted secondary. Finally, surrounding this structure a rapidly rotating Keplerian disk can be found. This disk contains nearly all the mass of the secondary which has not been incorporated to the hot corona, since little mass ($\sim 10^{-3}\, M_\odot$) is ejected from the system during the merger process. The structure of the system is shown in Fig. 1.

The temperature gradient in the hot corona is high, and thus it is convective. Using the Schwarzschild criterion we found that the inner and outer edges of the convective region are located at $R \approx 0.012\, R_\odot$, and $R \approx 0.026\, R_\odot$, respectively, and that the total mass inside this region is $\sim 0.24\, M_\odot$. Assuming energy equipartition, the resulting $\alpha\omega$ dynamo produces a magnetic field $B^2/8\pi \approx \rho(\omega R)^2/2$. For the typical values found in our simulations the magnetic field is $B \sim 3.2 \times 10^{10}$ G. For this mechanism to be efficient the dynamo must work for several convective turnovers before the energy of the hot corona is radiated away. The temperature of the corona is very high, and hence it is preferentially cooled by neutrinos. Typical luminosities are $L_\nu \sim 4.0{\times}10^2\, L_\odot$, while the total thermal energy of the corona is $U \sim 8.8 \times 10^{48}$ erg. Consequently, the convective shell lasts for $\tau_{\rm hot} \sim 1.8{\times}10^5$ yr. The convective turnover timescale is $\tau_{\rm conv} \approx H_P/v_{\rm conv}$, where $H_P \approx 2.7 \times 10^8$ cm is the pressure scale height and $v_{\rm conv} \approx 8.0 \times 10^7$ cm/s is the convective velocity. Thus, $\tau_{\rm conv} \sim 3.3$ s, and during the lifetime of the hot corona the number of convective cycles is sufficiently large. Thus, the $\alpha\omega$ mechanism is able to produce strongs magnetic fields.

Now that we have proved that large magnetic fields can be established in the aftermath of a double degenerate merger, it is necessary to assess if during the lifetime of the resulting white dwarf the magnetic field diffuses outwards, to the surrounding disk, or inwards, to the degenerate primary. Thus, we solved the diffusion equation for both the disk and the degenerate core, and we found that the timescale for diffusion of the magnetic field across the disk is $\tau_{\rm disk} \sim 2.0 \times 10^{11}$ yr, while for the diffusion timescale

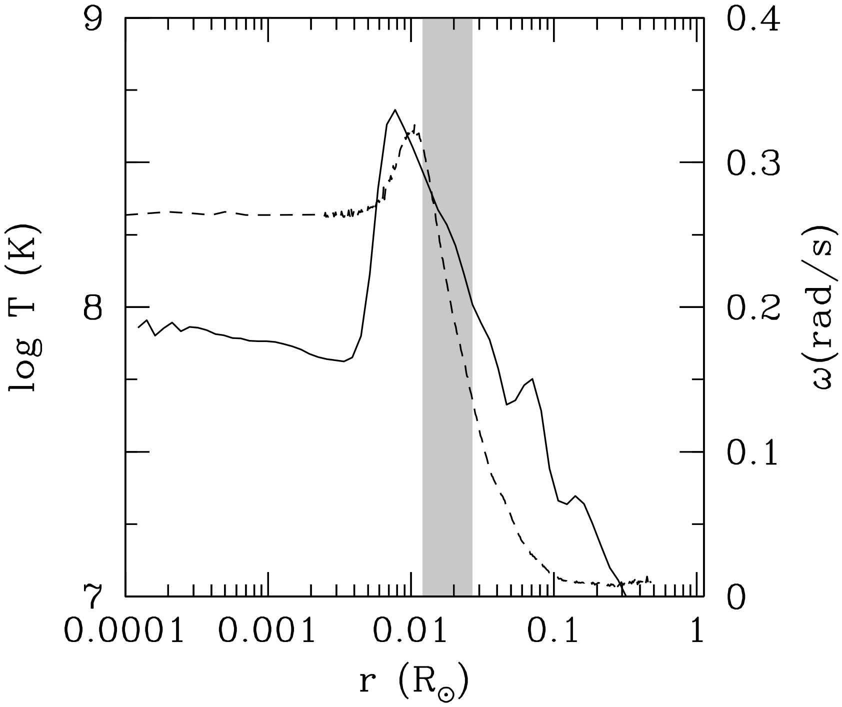

Figure 1. Temperature (solid line, left scale) and rotational velocity (dashed line, right scale) stratifications in the final remnant of a double white dwarf merger in which the binary system is composed of two stars of 0.6 and 0.8 $M_\odot$. The central spinning white dwarf rotates as a rigid body with a rotational velocity $\omega \sim 0.26$ s^{-1}, and the corona rotates differentially, with a peak rotation rate $\omega \sim 0.33$ s^{-1}. These velocities arise from energy and angular momentum conservation, since little mass is ejected from the system, so the orbital angular momentum of the binary system is invested in spinning up the remnant, while the available energy is primarily invested in heating the corona. The location of the convective region is displayed by the shaded area.

for the central white dwarf turns out to be $\tau_{\rm WD} \sim 4.3 \times 10^9$ yr. Thus, it can safely stated that as the white dwarf cools, the magnetic field is not allowed to diffuse across the keplerian disk nor to penetrate in the degenerate core, and consequently remains confined to the surface layers.

Our model predicts that the masses of high-field magnetic white dwarfs should be larger than the average of field white dwarfs and that they should be observed as single white dwarfs, as observationally found. However, high-field magnetic white dwarfs are generally found to be slow rotators (Wickramasinghe & Ferrario 2000). Nevertheless, this apparent shortcoming can be easily solved. If the rotation and magnetic axes are misaligned, magneto-dipole radiation rapidly spins down the white dwarf. The evolution of the rotational velocity (Benacquista et al. 2003) is given by $\dot{\omega} = -2\mu^2\omega^3 \sin^2\alpha/(3Ic^3)$, where I is the moment of inertia of the white dwarf, α is the angle between the magnetic and rotation axes and $\mu = BR^3_{\rm WD}$. Adopting typical values resulting from our SPH simulations we obtain a spin-down timescale $\tau_{\rm MDR} \sim 2.4 \times 10^8 / \sin^2\alpha$ yr, when a field strength $B = 10^7$ G is adopted. Hence, if both axes are perfectly aligned the remnant of the coalescence will be a high-field, rapidly rotating magnetic white dwarf. On the contrary, if both axes are nearly perpendicular magneto-dipole radiation efficiently brakes the remnant. Consequently, very young, hot, ultramassive, slowly rotating high-field magnetic white dwarfs can also be easily accommodated in our model.

On the other hand, spectro-polarimetric observations show that in most cases high-field magnetic white dwarfs have fields with both toroidal and poloidal components. Our scenario can also account for this observational fact, since in the $\alpha\omega$ mechanism, convection is responsible for the generation of poloidal fields, whereas rotation is responsible for the generation of toroidal fields. In particular, the energy available to generate the poloidal field component is $\rho v^2_{\rm conv}/2 \sim 4.0 \times 10^{20}$ erg, which is $\sim$ 10% of the energy available to build the toroidal component, $\rho(\omega R)^2/2 \sim 5.5 \times 10^{21}$ erg. Thus, we expect that the magnetic field geometry of the remnant of the merger will be complex.

3. The number of high-field magnetic white dwarfs in the solar neighborhood

To assess the number of mergers that could occur in the solar neighborhood we expanded an existing Monte Carlo code (García-Berro et al. 1999; Torres et al. 2002; García-Berro et al. 2004) designed to study the galactic population of single white dwarfs to deal with that of double degenerates. The population synthesis code is described in full depth in García-Berro et al. (2012), where all the necessary ingredients are detailed. Here, for the sake of conciseness, we only present the most significant results of our calculations.

Our population synthesis calculations predict that the fraction of merged double degenerate cores in the solar neighborhood is $\sim$ 2.9% of the total population. This number includes not only white dwarf mergers ($\sim$ 0.3%), but also the coalescence of a white dwarf and a giant star with a degenerate core ($\sim$ 1.1%), and the merger of two giants with degenerate cores ($\sim$ 1.5%). In these two last cases the mergers obviously occur during the common envelope phase, while for the cases in which two white dwarfs coalesce gravitational wave radiation is the final driver of the merger. Finally, it is important to mention as well that the distribution of remnant masses is nearly flat, in agreement with the observed distribution of masses of magnetic white dwarfs (Nalężyty & Madej 2004).

Within 20 pc of the Sun there are 122 white dwarfs (Holberg et al. 2008), and contains 14 magnetic stars (Kawka et al. 2007). Although scarce, this sample is 80% complete, and allows reliably determine the true incidence of magnetism in white dwarfs. Mass determinations are available for 121 of them. Of the 14 magnetic white dwarfs in local sample, 8 have magnetic fields larger than 10^7 G, and 3 have masses larger than $0.8\,M_\odot$ — a value which is $\sim 2.5\sigma$ away from the average mass of field white dwarfs. This mass cut is chosen to cull only white dwarfs that are expected to be the result of stellar mergers. Actually, our calculations predict that $\sim$ 4 white dwarfs are the result of double degenerate mergers, and have masses larger than $0.8\,M_\odot$, in agreement with observations. Additionally, our simulations predict that the fraction of white dwarfs more massive than $\sim 0.8\,M_\odot$ resulting from single stellar evolution is $\sim$ 10%. Consequently, the expected number of massive white dwarfs in the local sample should be $\sim$ 12. Instead, the local sample contains 20, pointing towards a considerable excess of massive white dwarfs, which could be the progeny of mergers. The rest of the population of magnetic white dwarfs (~ 5) — those with small magnetic field strengths — would be well the result of the evolution of single stars (Aznar Cuadrado et al. 2004).

4. Conclusions

It has been shown that the hot, convective, differentially rotating corona predicted by detailed Smoothed Particle Hydrodynamics simulations of the coalescence of two degenerate stellar cores can produce very high magnetic fields. We have also shown that these magnetic fields are confined to the outer layers of the remnant of the coalescence, and do not propagate neither to the interior of the white dwarf or to the debris region. Our model has two clear advantages, which meet the requirements imposed by observations. The first one is that it naturally predicts that high-field magnetic white dwarfs should preferentially have high masses. The second advantage is that it explains why high-field magnetic white dwarfs are found to be single stars. Moreover, our scenario predicts that if the rotation and magnetic axes are not aligned the magnetic white dwarf rapidly spins down due to the emission of magnetodipole radiation. Thus, we expect that high-field magnetic white dwarfs should have different rotation periods, depending on their evolutionary status and on the geometry of the magnetic field. Moreover, in the case in which the masses of the merging objects white dwarfs are not equal the keplerian disk can eventually form a second-generation planetary system. Disruption of small bodies in this planetary system could contaminate the atmospheric layers of the magnetic white dwarf. This finding is important, as it can explain the recently discovered population of metallic magnetic white dwarfs. If, on the contrary, the masses of the merging white dwarfs are similar the remnant has spherical symmetry and rotates very rapidly, as observed in some high-field magnetic white dwarfs. Also, the geometry of the surface magnetic fields can be well explained by our model. Finally, we have also shown that the expected number of double degenerate mergers is roughly consistent with the number of high-field magnetic white dwarfs in the local sample. In summary, our calculations indicate that a sizable fraction of all high-field magnetic white dwarfs could be the result of double degenerate mergers, a hypothesis previously anticipated by Wickramasinghe & Ferrario (2000), but not hitherto demonstrated by a quantitative analysis.

Acknowledgments. This research was supported by AGAUR, by MCINN grants AYA2011–23102 and AYA08-1839/ESP, by the European Union FEDER funds, by the ESF EUROGENESIS project (grant EUI2009-04167), by AGENCIA: Programa de Modernización Tecnológica BID 1728/OC-AR, and by PIP 2008-00940 from CONICET.

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