The formation of high-field magnetic white dwarfs from common envelopes

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The origin of highly-magnetized white dwarfs has remained a mystery since their initial discovery. Recent observations indicate that the formation of high-field magnetic white dwarfs is intimately related to strong binary interactions during post-main-sequence phases of stellar evolution. If a low-mass companion, such as a planet, brown dwarf, or low-mass star is engulfed by a post-main-sequence giant, the hydrodynamic drag in the envelope of the giant leads to a reduction of the companion's orbit. Sufficiently low-mass companions in-spiral until they are shredded by the strong gravitational tides near the white dwarf core. Subsequent formation of a super-Eddington accretion disk from the disrupted companion inside a common envelope can dramatically amplify magnetic fields via a dynamo. Here, we show that these disk-generated fields are sufficiently strong to explain the observed range of magnetic field strengths for isolated, high-field magnetic white dwarfs. A higher-mass binary analogue may also contribute to the origin of magnetar fields.

White Dwarfs | Magnetars | Magnetohydrodynamics

Abbreviations: HFMWD, high-field magnetic white dwarf; SDSS, Sloan Digital Sky Survey; MG, Megagauss; WD, white dwarf; CV, cataclysmic variable; CE, common envelope; MS, main sequence; AGB, asymptotic giant branch; BD, brown dwarf

Introduction

A significant fraction of isolated white dwarfs form with strong magnetic fields. These high-field magnetic white dwarfs (HFMWD), the majority of which were discovered via the Sloan Digital Sky Survey (SDSS; [1, 2, 3]), comprise $\sim$10% of all isolated white dwarfs [4]. Surface field strengths range from a few to slightly less than a thousand megagauss (MG) while the bulk of the isolated WD population have measured weak fields or non-detection upper limits of typically $\lesssim 10^4 - 10^5$ G [5, 6, 7].

In WD-binary systems, the companion's surface is an equipotential. In tight binaries, this equipotential extends toward the WD, leading to mass transfer from the companion onto the WD, a process called "Roche-lobe overflow." Among systems such as these, a possibly even larger fraction of the WD primaries are highly magnetic (i.e., $\sim$25% of cataclysmic variables; [8]). Magnetic cataclysmic variables (CVs) are generally divided into two classes: AM Herculis (polars) and DQ Herculis (intermediate polars). For reviews on AM Her and DQ Her systems see [9] and [10]. Generally, AM Her systems are those in which both components of the binary are synchronously rotating at the orbital period. In this scenario, the formation of an accretion disk is prevented and material is funneled onto the WD via the magnetosphere. Polars have strong magnetic fields ($\sim 10^7 - 10^8$ G), copious X-ray emission and stable pulsations in their lightcurves. On the other hand, DQ Her systems (intermediate polars) are not synchronously locked and have weaker magnetic fields than their polar counterparts, often by an order of magnitude or more. For these systems, an accretion disk forms from which the WD is spun up.

Remarkably, *not a single* observed close, detached binary system (in which the primary is a WD and the companion is a low-mass main-sequence star) contains a HFMWD [11, 12, 13]. If the magnetic field strengths of white dwarfs were independent of binary interactions, then the observed distribution of isolated WDs should be similar to those in detached binaries. In particular, within 20 pc, there are 109 known WDs (21 of which have a non-degenerate companion), and SDSS has identified 149 HFMWDs (*none* of which has a non-degenerate companion). Assuming binomial statistics, the maximum probability of obtaining samples at least this different from the same underlying population is 5.7×10^{-10}, suggesting at the 6.2-σ level that the two populations are different (for details on this kind of calculation, see Appendix B of [14]). Furthermore, SDSS identified 1253 WD+M-dwarf binaries (*none* of which are magnetic). As was previously pointed out, this suggests that the presence or absence of binarity is crucial in influencing whether a HFMWD results [15]. These results initially seem to indicate that HFMWDs preferentially form when isolated. However, unless there is a mechanism by which very distant companions prevent the formation of a strong magnetic field, a more natural explanation is that highly-magnetized white dwarfs became that way by engulfing (and removing) their companions.

In the binary scenario, the progenitors of HFMWDs are those systems that undergo a common envelope (CE) phase during post-MS evolution. In particular, magnetic CVs may be the progeny of common envelope systems that almost merge but eject the envelope and produce a close binary. Subsequent orbital reduction via gravitational radiation and tidal forces turn detached systems into those which undergo Roche-lobe overflow. For CEs in which the companion is not massive enough to eject the envelope and leave a tight post-CE binary, the companion is expected to merge with the core. It was suggested that these systems may be the progenitors of isolated HFMWDs [15].

In this paper, we calculate the magnetic fields generated during the common envelope phase. We focus on low-mass companions embedded in the envelope of a post-MS giant. During in-spiral, the companion transfers orbital energy and angular momentum, resulting in differential rotation inside the CE. Coupled with convection, a transient $\alpha - \Omega$ dynamo amplifies the magnetic field at the interface between the convective and radiative zones where the strongest shear is avail-

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able. The fields produced from this interface dynamo are transient and unlikely to reach the white dwarf surface with sufficient strength to explain HFMWD observations. If, however, the companion tidally disrupts, the resultant super-Eddington accretion disk can amplify magnetic fields via a disk dynamo. The disk-generated fields are strong ($\sim 10^1 - 10^3$ MG) and accretion provides a natural mechanism with which to transport the fields to the WD surface. For a range of disrupted-companion masses, the fields generated in the disk are sufficient to explain the range of observed HFMWDs.

Common Envelope Evolution

Common envelopes are often invoked to explain short period systems in which one component of the binary is a compact star [16, 17, 18]. The immersion of a companion in a CE with a post-main sequence star can occur via direct engulfment or through orbital decay due to tidal dissipation in the giant's envelope [19, 20, 21]. Once engulfed, the companion in-spirals due to hydrodynamic drag until it either survives (ejects the envelope leaving a post-CE close binary) or is destroyed. While CEs can form for various mass-ratio binaries, we focus on low-mass stellar and substellar companions such that the remnant system is expected to be an isolated white dwarf. Since low-mass companions do not release enough orbital energy to eject the envelope, as the orbital separation is reduced, the differential gravitational force due to the proto-WD tidally shreds the companion. The disrupted companion then forms a disk inside the CE that subsequently accretes onto the proto-WD [22]. For more detail on the onset and dynamics of the CE phase for post-MS giants and low-mass companions (i.e. low, mass-ratio binaries), see [18] and [19].

Amplification of Magnetic Fields

As a consequence of common envelope evolution, the transfer of orbital energy and angular momentum during in-spiral generates strong shear. Coupled with convection, shear leads to large-scale magnetic field amplification via an $\alpha - \Omega$ dynamo. During in-spiral, the free energy in differential rotation available to the dynamo is proportional to the companion mass. In general, the more massive the companion, the more free energy in differential rotation [23]. The dynamo converts free energy in differential rotation into magnetic energy and therefore, strong shear leads to strong magnetic fields.

Some investigations of the dynamo in this context have imposed a velocity field to determine what steady-state magnetic field might arise if the velocity were steadily driven [24, 25, 26]. However, as the magnetic field amplifies, differential rotation decreases. In general, for systems in which shear is not resupplied, a transient dynamo and decay of the magnetic field result [27]. This scenario was investigated as a way to generate the strong fields necessary to power bipolar outflows in post-Asymptotic Giant Branch (post-AGB) and planetary nebulae (PNe) [28, 29]. A similar, but weaker, dynamo (akin to the Solar dynamo) may operate in isolated Red Giant Branch and Asymptotic Giant Branch stars [23].

Here, we investigate two scenarios for magnetic field generation during a CE phase between a post-MS giant and a low-mass companion. First, we calculate the magnetic fields at the interface between the convective and radiative zones in the CE (hereafter referred to as the envelope dynamo scenario) and show that this scenario, while potentially viable under special circumstances, is unlikely in general to explain the origin of HFMWDs. As an alternative, we estimate the magnetic fields generated in the disk of a tidally disrupted companion around the proto-WD. The disk-generated fields naturally accrete onto the WD surface and are sufficiently strong to match observations.

Envelope Dynamo. The shear profile in a giant star that is produced by a low-mass companion's CE-induced in-spiral leads to a dynamo in the presence of the turbulent convective zone. The field primarily amplifies at $R = R_{\rm conv}$, the interface between the convective and radiative regions. The back-reaction of field-amplification on the shear is included with differential rotation and rotation depleting via loss of Poynting flux and turbulent dissipation. For the precise equations solved, generic features of envelope dynamos, and a pictorial representation of the dynamo geometry in isolated stellar and CE settings see [28]. Here we calculate an upper limit to the magnetic field that may be generated by this mechanism, by taking the shear profile in the stellar envelope to be Keplerian (which produces stronger shear than could possibly be maintained in a spherical-hydrostatic star).

Before presenting details of these calculations, we note a few generic features of this type of scenario that might make the envelope dynamo an unlikely explanation of HFMWDs, irrespective of details. There are a few reasons why a field generated at the radiative-convective boundary may not be able to produce strongly magnetized material in the vicinity of the WD. First, as shown below, a robust upper limit to the magnitude of the envelope dynamo generated field is a few times 10^4 G. To explain megagauss fields at the WD surface, this requires an inwardly increasing gradient of $\mathbf{B}$ (e.g. via field amplification from flux freezing), which might lead the highest-field regions to rise buoyantly, therefore never reaching the WD surface. Second, since the envelope is transient (operates for $\sim$100 years) and the typical AGB lifetime is $\sim 10^5$ years, the envelope would need to be ejected at the time of formation of a HFMWD. Without fine tuning, this results in a tight, post-CE binary with an under-massive white dwarf – the exact opposite of the observed HFMWDs. Finally, even if the field could penetrate to the WD surface, some mass would need to remain and/or fallback during envelope ejection to anchor the field. A further subtlety is that the transport of magnetic flux into the radiative layer is likely to involve not merely isotropic diffusion but anisotropic diffusion, as a downward pumping of magnetic flux involves anisotropic convection. We are led to what seems to be a more natural formation explanation, which is described in the next section. Nevertheless, despite the aforementioned potential difficulties, we now investigate the viability of the envelope dynamo scenario.

Our stellar evolution models were computed using the "Evolve Zero-age Main Sequence" (EZ) code [30].[1] We employ a zero-age main-sequence progenitor of 3 $M_\odot$, with solar metallicity at the tip of the AGB. Under the assumption of Keplerian rotation, the saturated toroidal field strength at the base of the 3-$M_\odot$ progenitor's convective zone ($R_{\rm conv} \sim 6 \times 10^{11}$ cm) is roughly $B_\phi \sim 2 \times 10^4$ G. To survive past the PN stage, the fields must reach the WD surface (which is the core of the AGB star, a distance $L \simeq R_{\rm conv}$ interior to the base of the convective zone; see Fig. 3 of [18] for a pictorial representation), anchor, and sustain or induce a field in the WD. The latter scenario has been investigated by [31], who conclude that an ordered external field (potentially generated from a dynamo) can induce a surface field on the WD that decays to a few percent of its initial value after a million years.

[1] http://www.astro.wisc.edu/∼townsend/static.php?ref=ez-web

For the fields to reach the WD surface, radially inward diffusion of magnetic flux must act on a faster timescale than magnetic buoyancy, which transports flux outward. The buoyant rise velocity, u, is found by equating the upward buoyancy force on a flux tube to the downward viscous drag, thereby obtaining the upward terminal velocity. It may be represented as $u \sim (3Q/8)\,(a/H_{\rm p})^2\,\left(v_a^2/v\right)$, where $v_a = B/(4\pi\rho)^{1/2}$ is the Alfvén velocity, v is the convective fluid velocity, a is the flux tube radius, $H_{\rm p}$ is a pressure scale height, and Q is a dimensionless quantity of order unity [32]. The time to buoyantly rise a distance L from $R_{\rm conv}$, assuming $a \sim L/2$, is $t_{\rm b} = L/u \sim 0.1$ years. The diffusion timescale to traverse a distance L, given a turbulent diffusivity β_ϕ, is $t_{\rm d} = L^2/\beta_\phi$ and must be less than the buoyant-rise time $t_{\rm b}$. This implies a constraint on the turbulent diffusivity: $\beta_\phi > Lu$. For the buoyant-rise velocity of a 2×10^4-G flux tube in an AGB star, this requires a diffusivity of at least a few times 10^{17} cm^2 s^{-1}; a very large and physically unlikely value. Note however that if weaker fields are generated, the requirement on the diffusivity would lower correspondingly. Furthermore, during one cycle half-period $\tau_{0.5}$ (defined as the time for one reversal of the field), magnetic flux of a given sign (positive or negative) can diffuse into the radiative layer.[2] After reversal, field of the opposite sign amplifies and diffuses in the radiative layer. Therefore, the diffusion timescale must not be greater than the cycle half-period: $t_{\rm d} \leq \tau_{0.5}$. This implies another a theoretical constraint on the turbulent diffusivity for consistency of our dynamo model, namely $\beta_\phi \geq L^2/\tau_{0.5}$. This latter constraint yields $\beta_\phi \gtrsim 4\times10^{17}$ cm^2 s^{-1}. A subtlety is that the transport would not be a strictly isotropic diffusion but could be the result of down pumping by anisotropic convection [33].

One way to infer the turbulent diffusivity in evolved stars is to note that isotopic anomalies in low-mass Red Giant Branch and AGB stars require that material from the base of the convective zone be transported to near the H-burning shell, processed, and returned to the convective envelope [34, 35]. This so-called "cool bottom processing" (CBP) is thought to be magnetically driven [36, 23]. In the magnetic mixing scenario, a lower bound on the turbulent diffusivity is $\sim 7\times10^{15}$ cm^2 s^{-1} [23]. While the actual diffusion coefficients in evolved star interiors are unknown, the values inferred from CBP are more than an order of magnitude lower than what are required for the envelope dynamo scenario to transport $\sim 10^4$-G fields all the way to the WD surface. Higher field strengths (in particular, $\sim$MG fields) lead to shorter buoyant-rise times and smaller cycle half-periods, and therefore require even greater diffusivity. In short, a substantial macroscopic diffusivity would be needed to transport megagauss fields to the WD surface in AGB stars. We presently do not have independent constraints on these coefficients.

Disk Dynamo. If the field generated in the envelope cannot diffuse to the WD surface, an alternative possibility is amplification in an accretion disk that forms when the companion is tidally disrupted inside the common envelope [22]. As shown below, this scenario is attractive because it provides a natural mechanism for transporting the field to the proto-WD surface.

We consider disks formed from companions spanning the range from sub-Jupiter-mass planets (see below) to low-mass stars (i.e. $M_{\rm c}$ between $\sim 0.1 M_{\rm J}$ and a few times $10^2 M_{\rm J}$).[3] Tidal disruption of the companion results in formation of a disk inside the AGB star. This occurs at the tidal shredding radius, which we estimate as $R_{\rm s} \simeq R_{\rm c}(2M/M_{\rm c})^{1/3}$, where $r_{\rm c}$ and $M_{\rm c}$ are the radius and mass of the companion and M is the stellar mass interior to $R_{\rm s}$ [19]. We note that, since planetary and low-mass stellar companions to solar-type stars are significantly more plentiful than brown dwarfs [38, 39, 40], disks at the upper or lower mass range may be more common than those in the intermediate mass range.

The disk is ionized and susceptible to the development of magnetized turbulence (e.g. via the magneto-rotational instability [41]). Accretion towards the central proto-WD occurs on a viscous timescale given by $t_{\rm visc} \simeq R^2/\nu \simeq P_{\rm orb}/\alpha(H/R)^2$, where $P_{\rm orb}$ is the Keplerian orbital period at radius R, $\nu = \alpha_{\rm ss} c_{\rm s} H = \alpha_{\rm ss}(H/R)^2 R^2\Omega$ is the effective kinematic viscosity, H is the disk scaleheight, $c_{\rm s} = H\Omega$ is the midplane soundspeed, $\Omega = 2\pi/P_{\rm orb}$ is the Keplerian orbital frequency, and $\alpha_{\rm ss}$ is the dimensionless Shakura-Sunyaev parameter that characterizes the efficiency of angular momentum transport [42]. The initial accretion rate can be approximated as

$$\dot{M} \sim \frac{M_{\rm c}}{t_{\rm visc}|_{r_{\rm s}}} \approx 7 M_\odot\,{\rm yr}^{-1} \times \left(\frac{\alpha_{\rm ss}}{10^{-2}}\right)\left(\frac{M_{\rm c}}{30M_{\rm J}}\right)^{3/2}\left(\frac{r_{\rm c}}{r_{\rm J}}\right)^{-1/2}\left(\frac{H/R}{0.5}\right)^2, \quad [\mathbf{1}]$$

where we have scaled $r_{\rm c}$ to the radius of Jupiter[4] and have scaled H/R to a large value ~ 0.5 because the disk cannot cool efficiently at such high accretion rates and would be geometrically thick. Since the companions under consideration lead to disks much more dense than the stellar envelope, it is reasonable to ignore any interaction between the disk and the star.

Equation (1) illustrates that for $M_{\rm c} \sim 0.1 - 500 M_{\rm J}$, and for typical values of $\alpha_{\rm ss} \sim 0.01 - 0.1$, $\dot{M}$ is $\sim$3 to 9 orders of magnitude larger than the Eddington accretion rate of the proto-WD (i.e., $\dot{M}_{\rm Edd} \sim 10^{-5} M_\odot$ yr^{-1}). At first, it might seem apparent that inflow of mass onto the WD surface would be inhibited by radiation pressure in such a scenario. However, this neglects the fact that, at sufficiently high accretion rates, photons are trapped and advected to small radii faster than they can diffuse out [43, 44, 45, 46, 47]. In this 'hyper-critical' regime, accretion is possible even when $\dot{M} \gg \dot{M}_{\rm Edd}$.

We evaluate the possibility of hyper-critical accretion by estimating the radius interior to which the inward accretion timescale, $t_{\rm visc}$, is less than the timescale for photons to diffuse out of the disk midplane, $t_{\rm diff}$ (which is approximately $H\tau/c$, where τ is the vertical optical depth [44, 48, 45]). This "trapping radius" is given by $R_{\rm tr} = \dot{M}\kappa H/4\pi Rc$ where κ is the opacity. An important quantity is the ratio of the trapping radius to the outer disk radius $R_{\rm s}$ (coincident with the tidal shredding radius) :

$$\frac{R_{\rm tr}}{R_{\rm s}} \approx 1.0\times10^4\left(\frac{\alpha_{\rm ss}}{10^{-2}}\right)\left(\frac{\kappa}{\kappa_{\rm es}}\right) \times \left(\frac{M_{\rm c}}{30M_{\rm J}}\right)^{11/6}\left(\frac{M_{\rm WD}}{0.6M_\odot}\right)^{-1/3}\left(\frac{r_{\rm c}}{r_{\rm J}}\right)^{-3/2}\left(\frac{H/R}{0.5}\right)^3, \quad [\mathbf{2}]$$

where we have used equation (1) and scaled κ to the electron scattering opacity $\kappa_{\rm es} = 0.4$ cm^2 g^{-1}. If $R_{\rm s} < R_{\rm tr}$, then $t_{\rm visc} < t_{\rm diff}$ and photons are advected with the matter.

From equation (2) we conclude that $R_{\rm tr} > R_{\rm s}$ for $M_{\rm c} \gtrsim 0.1 M_{\rm J}$. This implies that photon pressure will be unable to halt accretion, at least initially. Truly steady-state accretion, though, (i.e., on timescales greater than the viscous timescale) may not be possible. The inflowing material becomes very hot, such that thermal pressure may eventually

[2] Though the cycle period does increase in the dynamical regime, it does not deviate significantly from the half-cycle kinematic value we use here ($\tau \sim 0.03$ years) ; [28]). Note that while the radiative layer is convectively stable it may still possess non-negligible turbulence.

[3] $M_{\rm J}$ is the mass of Jupiter. This classification as planet or brown dwarf is based solely on mass [37]

[4] $r_{\rm J}$ is the radius of Jupiter. Note that $r_{\rm c}$ depends only weakly on mass for the companions we consider.

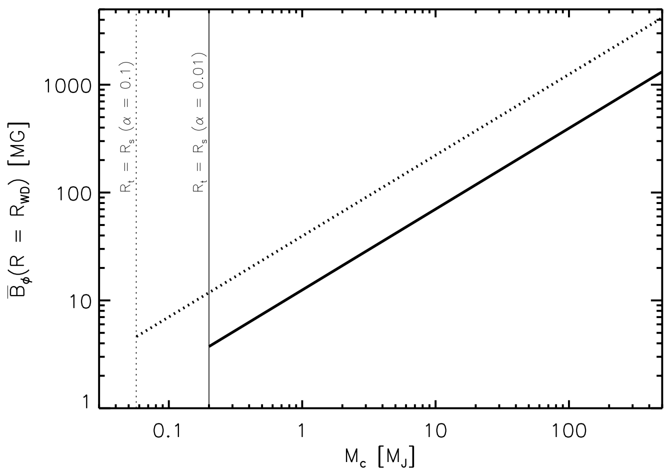

Fig. 1. Toroidal magnetic field strength, $\overline{B}_\phi$ (eq. [3]), at the WD surface as a function of the mass of the tidally disrupted companion M_c. Toroidal field strengths are presented for two values of the viscosity, $\alpha_{ss} = 0.01$ (*solid line*) and $\alpha_{ss} = 0.1$ (*dotted line*) and assuming an accretion efficiency $\eta_{acc} = 0.1$. The white dwarf mass and radius are $M_{WD} = 0.6M_\odot$ and $r_{WD} = 10^9$ cm, respectively. The vertical lines show the companion mass above which photons are trapped in the accretion flow (i.e., $r_{tr} > r_s$; eq. [2]), such that super-Eddington accretion occurs.

cause the disk to expand outwards to the point that radiation pressure may again become dynamically significant [47]. In particular, unlike in the case of neutron star accretion, the WD potential well is not sufficiently deep that neutrino cooling is able to carry away the accretion energy – a necessary requirement for truly steady flow. Indeed, it is well known that radiatively-inefficient accretion flows are prone to powerful outflows that may carry away a significant fraction of the accreting material [49, 50, 51, 52]. Although the precise amount of mass loss remains uncertain, in extreme cases, only a fraction $\eta_{acc} \sim r_{WD}/r_s \sim 0.1$ of the initial disk may ultimately reach the central WD of radius r_{WD}[5]. Nevertheless, as we now discuss, the WD may be significantly magnetized even if only a small fraction of the companion accretes.

Due to the presence of shear in the disk,[6] the MRI is a likely source of turbulence, which in turn amplifies magnetic field. Large-scale fields produced by the MRI have been modeled via $\alpha - \Omega$ dynamos at various levels of sophistication (see [54] for the most recent example). However, for the purposes of estimating orders of magnitude of the fields, approximate values from less sophisticated treatments can be employed. Although this situation is qualitatively similar to that described in the previous subsection, the dynamo we envision here operates in the accretion disk and not the envelope. The Alfvén velocity in the disk obeys $v_a^2 = \alpha_{ss} c_s^2$ [55], such that the mean toroidal field at radius R is given by [55]

$$\begin{aligned}\overline{B}_\phi &\sim \left(\frac{\dot{M}\Omega}{R}\frac{R}{H}\right)^{1/2} \qquad [3]\\ &\approx 160\text{MG}\left(\frac{\eta_{acc}}{0.1}\right)^{1/2}\left(\frac{\alpha_{ss}}{10^{-2}}\right)^{1/2}\left(\frac{\text{M}_c}{30\text{M}_\text{J}}\right)^{3/4}\times\\ &\left(\frac{M_{WD}}{0.6M_\odot}\right)^{1/4}\left(\frac{r_c}{r_\text{J}}\right)^{-1/4}\left(\frac{H/R}{0.5}\right)^{1/2}\left(\frac{R}{10^9\text{cm}}\right)^{-3/4},\end{aligned}$$

where in the second equality we have subsituted equation (1) for $\dot{M}$, and multiplied by the factor $0.1 \lesssim \eta_{acc} \leq 1$ to account for the possibility of outflows as described above. If an $\alpha - \Omega$ dynamo operates, the mean poloidal field $\overline{B}_p$ is related to the toroidal field via $\overline{B}_p = \alpha_{ss}^{1/2}\overline{B}_\phi$ [55]. However, regardless of whether a large scale field is generated, a turbulent field of magnitude $\overline{B}_\phi$ is likely to be present and contributing significantly to the Maxwell stresses responsible for disk accretion.

Figure 1 shows the toroidal field evaluated near the WD surface $R \approx R_{WD} \approx 10^9$ cm as a function of companion mass M_c, calculated for two different values of the viscosity ($\alpha_{ss} = 0.01$ and 0.1). In both cases, we make the conservative assumption that $\eta_{acc} = 0.1$. Note that for the range of relevant companion masses $M_c \sim 0.1 - 500\ M_J$, $\overline{B}_\phi \sim 10 - 1000$ MG, in precisely the correct range to explain the inferred surface field strengths of HFMWDs. Although our results suggest that HFMWDs could result from companion accretion, it is non-trivial to assess what fraction of the accreted material will ultimately be incorporated into the surface layers of the final WD and not decay once the disk turbulence dies away. On the other hand, if the mean field is compressed into flux tubes, this could result in even stronger local concentrations of high field strength. In fact, in WD 1953-011, circular polarization and Hα spectral line observations suggest the presence of a high-field component (possibly a flux tube) in addition to the weaker, global field [56].

Conclusions

Recent observational evidence from the Sloan Digital Sky Survey strongly suggests that high-field magnetic white dwarfs originate from binary interactions. In particular, it was proposed that the progenitors of HFMWDs are binary systems that evolve through a common envelope phase [15]. In this scenario, companions that survive CE evolution (leaving tight binaries) may produce magnetic cataclysmic variables, while those that do not survive (i.e. that merge) may produce isolated HFMWDs.

To investigate this hypothesis, we have estimated the magnetic fields resulting from a low-mass companion embedded in a CE phase with a post-MS giant. During in-spiral, the companion transfers energy and angular momentum to the envelope. The resulting shearing profile, coupled with the presence of convection, can amplify large-scale magnetic fields via dynamo action in the envelope. We incorporate the back-reaction of the magnetic field growth on the shear, which results in a transient dynamo. The fields generated at the interface between the convective and radiative zones are weak ($\sim 2\times10^4$ G) and would have to diffuse to the WD surface and anchor there if they are to explain the HFMWDs. A successful envelope dynamo scenario must also survive to the end of the AGB phase, which probably means only if the companion ejects the turbulent envelope; the dynamo is transient as long as there is a source of turbulent diffusion. The bulk of the systems formed this way might be post-CE, tight binaries – potentially magnetic CVs.

To explain isolated HFMWDs, an alternative to a dynamo operating in the envelope is a dynamo operating in an accretion disk. During the CE phase, if the companion is of sufficiently low mass, it avoids prematurely ejecting the envelope. Instead, in-spiral proceeds until the companion is tidally shredded by the gravitational field of the proto-WD. The subsequent formation of an accretion disk, which also posesess turbulence and shear, can amplify magnetic fields via dynamo action. For the range of disrupted companions

[5] This is approximately the minimum mass that must be lowered into the WD potential well to release sufficient energy to unbind the remaining mass from the outer disk radius r_s.

[6] For black hole disks, differential rotation near the disk midplane is preserved even in a thick-disk, super-Eddington context [53]. However, for white dwarf disks, photons are not advected into, and lost to, the black hole.

considered here, the disk initially accretes at super-Eddington values. In this hyper-critical regime, the timescale for photon diffusion out of the disk is longer than the viscous timescale. For a range of disrupted-companion disks, we find that the saturated toroidal mean-field attains values between a few and a few thousand megagauss. Amplification of the magnetic field in a super-Eddington accretion disk is attractive as it reproduces the observed range of HFMWDs and naturally transports magnetic flux to the WD surface.

High-mass stars may also undergo common envelope interactions in the presence of close companions. If the common envelope field mechanisms described here operate in high-mass stars, then the result could be strong field neutron stars or magnetars (neutron stars with magnetic fields in excess of $\sim 10^{14} - 10^{15}$ G). In particular, formation of an accretion disk from an engulfed companion during a red supergiant phase could produce a magnetized WD core. In the eventual core-collapse and stellar supernova explosion (possibly driven by the neutrino mechanism; [57]), the magnetized WD core collapses to a neutron star. If simple flux freezing operates (itself an open question) and the initial magnetized core is on the order of ∼100-1000 MG, homologous collapse to a neutron star would generate $\sim 10^{14} - 10^{15}$ G fields. Typical neutron stars that possess modest field strengths may originate from core-collapse supernova of single stars or stars without having incurred a CE phase. Note that what we are proposing here is an alternative to the neutrino-driven convection dynamo described in [58, 59]. In our model, the engulfment of a companion and the formation of an accretion disk naturally provides fast rotation, magnetized turbulence and differential rotation. We emphasize that the viability of this mechanism depends on the length scale of the magnetic field deposited in the pre-collapse core, which must be sufficiently large to produce, upon collapse, the dipole-scale, volume-encompassing fields necessary to account for the spin-down behavior of magnetars and the energy budget of their giant flares [60].

In summary, common envelope evolution as the origin of strongly-magnetized, compact objects seems plausible. Whether this hypothesis is ultimately found to be viable will depend on the statistics of low-mass stellar and substellar companions to stars of similar masses to (or somewhat higher masses than) the Sun. The numerous radial velocity searches of the last 20 years have revealed a number of such companions [61, 62, 63]. The precise occurrence rate of companions in orbits that could lead to the kind of disk-dynamo mechanism described above remains unclear (though if such companions turn out to be rarer than the HFMWD fraction, then the SDSS data indicating a binary origin would be puzzling). Further theoretical work into the binary origin of HFMWDs and magnetars requires the development of multi-dimensional, magnetohydrodynamic simulations of the CE phase. Such an approach has already had initial success for purely hydrodynamic adaptive mesh refinement simulations [64].

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