M dwarf companions to white dwarfs – I. Relating magnetic activity, rotation and age

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ABSTRACT
We make use of the largest and most homogeneous sample of white dwarf/M dwarf (WD/dM) binaries from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7) to investigate relations between magnetic activity, rotation, magnetic braking and age in M stars. These relations are studied separately for close WD/dM binaries that underwent a common envelope phase and thus contain tidally locked and hence rapidly rotating M dwarfs, and for wide WD/dM binaries that never interacted. For the wide WD/dM binary sample we find that the M dwarf activity fractions are significantly higher than those measured in single M stars of spectral type M0 to M5. We attribute this effect as a consequence of M dwarfs in wide SDSS WD/dM binaries being, on average, significantly younger and hence more active than the field M dwarf population. The measured M dwarf activity fractions in wide WD/dM binaries show as well a significant increase from spectral types M3 to M5, where these low-mass stars become fully convective. This provides additional observational evidence for magnetic braking being less efficient below the fully convective boundary, in agreement with the hypothesis of fully convective stars having considerably longer activity lifetimes than partially convective stars. The M dwarfs in all our close binaries are active, independently of the spectral type, giving robust observational evidence for magnetic activity being enhanced due to fast rotation. The rotational velocities of the M dwarfs in our close binary sample are significantly higher than seen among field M dwarfs, however, the strength of magnetic activity remains saturated at \( \log \frac{L_{\text{H\alpha}}}{L_{\text{bol}}} \sim -3.5 \). This unambiguously confirms the M dwarf saturation-type rotation–activity relation.

Key words: binaries: close – binaries: spectroscopic – stars: low-mass – white dwarfs.

1 INTRODUCTION

The mechanisms that induce magnetic activity in field stars have been intensively studied and discussed over the last decades and this effort is now converging in a fairly consistent scenario that explains both magnetic field generation and angular momentum evolution in both partially and fully convective stars.

Magnetic fields in partially convective (F, G, K and early M) stars are believed to be generated at the transition region between the radiative interior and the differentially rotating outer convective zone (tachocline) through a solar-type \( \alpha/\Omega \) dynamo. In this scenario magnetic fields are generated as a result of a combination of differential rotation (\( \Omega \) effect) and cyclonic convection (\( \alpha \) effect) (Parker 1955; Leighton 1969; Spiegel & Zahn 1992; Charbonneau 2005; Browning 2008). Lower mass M dwarfs of spectral type later than \( \sim \) M3 are fully convective and therefore do not possess a tachocline, however, display clear signs of magnetic activity (e.g. Delfosse et al. 1998). Such stars are suggested to rotate as rigid bodies (Barnes et al. 2005), implying that the \( \alpha/\Omega \) dynamo cannot be responsible for producing magnetic fields. Instead, an \( \alpha^2 \) dynamo has been proposed for magnetic field generation in fully convective stars (Raedler et al. 1990; Chabrier & Kükker 2006).

The efficiency of both the \( \alpha/\Omega \) dynamo and the \( \alpha^2 \) dynamo is expected to be strongly correlated with the Rossby number \( (R_0 = P_{\text{rot}}/\tau_0) \), with \( P_{\text{rot}} \) the rotational period and \( \tau_0 \) the convective overturn time-scale; Noyes et al. 1984). In partially convective stars magnetic activity rises with decreasing Rossby numbers, implying that larger rotational velocities lead to higher levels of magnetic activity (for a given \( \tau_0 \); Hartmann & Noyes 1987). Similarly, a correlation between activity and rotation is also expected in fully convective stars in which magnetic fields may be generated by the...
Several early observational studies have explored the connection between magnetic activity and rotation (Wilson 1966; Kraft 1967). More recently, Pizzolato et al. (2003) showed that the X-ray emission increases with rotation for slowly rotating stars but saturates below a threshold of $R_\alpha \approx 0.1$. The same relation seems to apply for the magnetic field strength (Reiners, Basri & Browning 2009). Unfortunately, the phenomenon of saturation is not fully understood yet, one possible explanation is that saturation occurs due to a change of dynamo configuration (Vilhu 1984; Wright et al. 2011). An additional explanation is that saturation is reached when a certain maximum fraction of the available energy flux (from convection) is converted into magnetic energy (Christensen, Holzwarth & Reiners 2009). For ultracool dwarfs of spectral type M7-9.5 this clear rotation–activity relation, however, seems to be no longer valid (Mohanty et al. 2002; Reiners & Basri 2010). Moreover, it has to be stressed that rotation and magnetic activity in single (late-type) M dwarfs might not always be linked (West & Basri 2009).

Rotation and magnetic activity decrease in time (Skumanich 1972; Mastel 1984; Mastel & Spruit 1987; Kauwaler 1988; Sills, Pinsonneault & Terndrup 2000; West et al. 2008) as a consequence of magnetic braking, i.e. angular momentum is extracted from the convective envelope and lost through a magnetized wind. The braking time-scales strongly depend on the spectral type (or mass) of the star (Barnes 2003; Barnes & Kim 2010), which results in lower mass partially convective stars spinning down slower than their higher mass counterparts. Fully convective stars have even longer rotational braking time-scales (Reiners & Basri 2008; Browning et al. 2010; Schreiber et al. 2010). Unfortunately the reason for magnetic braking being less efficient in fully convective stars is not completely understood. This might be related to a change in the magnetic field topology, which has been observed to switch from less ordered field structures to dipoles at the fully convective boundary going from partially to fully convective stars (Donati et al. 2008; Morin et al. 2008, 2010; Reiners & Basri 2009). However such a switch should lead to increased magnetic braking for fully convective stars, exactly opposite to what is indicated by the observed rotation rates. A new scenario for magnetic braking has been recently developed by Reiners & Mohanty (2012) who suggest that the steep transition of the braking rates at the fully convective boundary arises due to the significant drop in radius, without invoking any change in the dynamo theory.

M dwarf companions to white dwarfs that form part of detached binaries (hereafter WD/dM binaries) offer an ideal test bed for studying magnetic activity, rotation and magnetic braking across the fully convective boundary for three reasons. (1) WD/dM binaries can easily be separated into wide binaries with orbital periods typically exceeding 100 d, and close binaries that evolved through common envelope evolution (Webbink 1984; Zorotovic et al. 2010) with final orbital periods generally below 1 d (Nebot Gomez-Morán et al. 2011). While the M dwarfs in wide binaries should be unaffected by the presence of the white dwarf, those in close post-common envelope binaries (PCEBs) are tidally locked, i.e. they are rapidly rotating. Comparing the two samples can provide clear constraints on the impact of fast rotation on activity. (2) Using PCEBs with measured orbital periods one can furthermore directly relate the strength of activity to the rotational velocity of the M dwarf (the orbital period of the binary equals to the rotational period of the M dwarf which then gives the rotational velocity by adopting a spectral type–radius relation). (3) The age of the M dwarfs in wide WD/dM systems can be estimated relatively accurately using cooling tracks plus an initial-to-final mass relation for their white dwarf companions. This allows us to test activity lifetimes that are presumably related to magnetic braking models.

The first studies of magnetic activity in M dwarfs that form part of WD/dM binaries from the Sloan Digital Sky Survey (SDSS; York et al. 2000; Aihara et al. 2011) were performed by Silvestri et al. (2006) and more recently by Morgan et al. (2012). However, these two studies consider all WD/dM binaries in SDSS to be part of close binaries, which is clearly not the case (Schreiber et al. 2010; Rebassa-Mansergas et al. 2011), and their results should be interpreted with extreme caution. Only our dedicated radial velocity survey of WD/dM binaries from SDSS allows us to accurately separate wide binaries (in which the stellar components have evolved as if they were single) from close binaries that underwent a common envelope evolution and therefore contain tidally locked fast rotating M dwarfs (Schreiber et al. 2010; Rebassa-Mansergas et al. 2011). This is fundamental to explore the relation between activity and rotation. The largest and most homogeneous sample of WD/dM binaries from SDSS including radial velocity information has been presented in Rebassa-Mansergas et al. (2012a). This sample forms the input for the present paper where we analyse the magnetic activity of M dwarf components in WD/dM binaries, thereby testing possible relations between age, activity and rotation.

## 2 THE SDSS WD/dM Binary Catalogue

The catalogue of Rebassa-Mansergas et al. (2012a) consists of 2530 white dwarf main-sequence binaries from the Data Release 7 (DR 7) of SDSS of which 2019 contain an M dwarf (WD/dM binaries). The SDSS WD/dM binary sample is described in more detail in this section. We begin introducing our radial velocity survey that allows us to separate between close and wide binaries. We then explain how SDSS WD/dM binary spectra can be used for obtaining reliable stellar parameters of both components and finally give indications of how we estimate the ages of our systems.

### 2.1 Close and wide WD/dM binaries

The population of WD/dM binaries contains close binaries (PCEBs) that underwent common envelope evolution (Webbink 1984; Iben & Livio 1993; Zorotovic et al. 2010), and wide binaries that never interacted. The M dwarfs that form part of PCEBs are tidally locked and are therefore fast rotators. The properties of the M dwarfs that are part of wide binaries should resemble those of single M dwarfs as the stellar components in wide WD/dM binaries have evolved as if they were single stars (Willems & Kolb 2004).

To characterize large samples of both close PCEBs and wide WD/dM binaries we are performing a large radial velocity follow-up programme of SDSS WD/dM binaries. Our observing strategy follows a two-step procedure. In a first step we obtain at least two spectra per target, separated by at least one night, and identify systems as PCEBs if the radial velocities we measure from these spectra show more than 3σ radial velocity variation. If we do not detect significant radial velocity variation, we consider the system as a wide WD/dM binary candidate. This technique is obviously less sensitive towards the detection of long orbital period PCEBs and/or low-inclination systems and we predict that, on average, ~16 per cent of the wide WD/dM binary candidates are in fact unrecognized PCEBs (Nebot Gomez-Morán et al. 2011). In a second step, the orbital periods of the PCEBs identified in this way are measured from higher cadence radial velocity follow-up.

So far we have identified 191 PCEBs and 1055 wide WD/dM binary candidates (e.g. Rebassa-Mansergas et al. 2011) and have
measured the orbital periods of 81 PCEBs (e.g. Rebassa-Mansergas et al. 2008, 2012b; Schreiber et al. 2008; Nebot Gómez-Morán et al. 2011). These samples of wide and close WD/dM binaries offer the potential to e.g. directly compare activity fractions of slowly and fast rotating M dwarfs as a function of spectral type. Furthermore, the rotational velocities of the M dwarfs in PCEBs with known orbital periods can also be known (assuming a spectral type–radius relation). These M dwarfs are very fast rotators and should populate the saturated regime, therefore allowing us to test the saturation-type rotation–activity relation.

2.2 Stellar parameters

Reliable stellar parameters of the WD/dM binaries are obtained from the SDSS spectra using our decomposition/fitting routine (Rebassa-Mansergas et al. 2007). The SDSS spectrum is initially fitted with a two-component model using a grid of observed M dwarf templates and a grid of observed white dwarf templates (see Fig. 1), and the spectral type of the M dwarf is determined. Then, the best-fitting M dwarf template, scaled by the appropriate flux scaling factor, is subtracted and the residual white dwarf spectrum is fitted with a model grid of DA white dwarfs (Koester 2010) to determine the white dwarf effective temperature and surface gravity. From an empirical spectral type–radius–mass relation for M dwarfs (Rebassa-Mansergas et al. 2007) and a mass–radius relation for white dwarfs (Bergeron, Wesemael & Beauchamp 1995; Fontaine, Brassard & Bergeron 2001) the masses and radii of the M dwarf and the white dwarf components are calculated.

In the context of the present paper the spectral types of the M dwarfs are of fundamental importance. We therefore compared the spectral types of our template fitting routine with those obtained by West et al. (2011). Fitting several hundred M dwarfs from the list of West et al. (2011), equally distributed in spectral type, with our M dwarf templates and adopting an uncertainty of half a spectral subclass, we find that 98 per cent of our spectral classifications agree with those of West et al. (2011) within one spectral subclass.

2.3 Ages

For a given mass, the magnetic activity of M dwarfs is closely related to their rotational velocity (see e.g. Cardini & Cassatella 2007). If other effects, such as a close companion, do not affect the star, magnetic braking is slowing down the rotation with time. The magnetic activity in our sample of M dwarfs that form part of wide SDSS WD/dM binaries should therefore primarily depend on the age of the system. Fortunately, for a given wide WD/dM binary one can estimate the age of the system, and consequently the age of the M dwarf companion, by summing the white dwarf cooling age to its main-sequence progenitor lifetime.1 SDSS WD/dM binary ages were previously calculated by Rebassa-Mansergas et al. (2012a) for a subsample of SDSS WD/dM binaries. We estimate the ages for the wide SDSS WD/dM binary sample studied in this work (Section 3) following the same strategy.

The white dwarf cooling ages were calculated using the evolutionary tracks of Bergeron et al. (1995).2 The initial main-sequence progenitor masses were calculated using the initial-to-final mass relation by Catalán et al. (2008) and we used the equations of Tuffs et al. (2004, see their appendix) to calculate their main-sequence lifetime. In this exercise we excluded wide WD/dM binaries containing white dwarfs cooler than 12 000 K, as the white dwarf spectral fitting overestimates the mass in such systems (e.g. Koester et al. 2009; Tremblay et al. 2011), which affects the resulting cooling age. For the same reason we only determined the age of wide WD/dM binaries if the error of the mass of the white dwarf is smaller than 0.2 M⊙, and given that the initial-to-final mass relation is only well defined for systems with white dwarfs masses >0.55 M⊙, we only considered wide WD/dM binaries containing white dwarfs with masses above this value.

3 IDENTIFICATION OF ACTIVE M DWARFS

In the context of this paper it is necessary to unambiguously identify both active and inactive M dwarfs among the SDSS WD/dM binary catalogue described in Section 2. Two features have been predominantly used as activity indicators in optical spectroscopy, namely the Ca II H&K resonance lines and Hα emission. Hα emission is more accessible in WD/dM binaries because the Ca II H&K lines fall at wavelengths generally dominated by the flux of the white dwarf. We therefore consider a given M dwarf component as active if Hα emission is detected in its SDSS spectrum. We developed an automatic routine for this purpose that is described below.

In a first step the best white dwarf model fit (see Section 2.2, Fig. 1) is subtracted from the SDSS WD/dM binary spectrum. In order to avoid our results being dominated by low-quality data, only residual M dwarf spectra with a signal-to-noise ratio (S/N) of at least >10 are used,3 which results in a sample of 739 objects. For these 739 systems the continuum flux of the residual M dwarf around Hα (6420 < λ < 6700 Å) is fitted with a parabola (excluding the range Ha-7 < λ < Ha+7 Å, where Ha = 6562.76 Å). The parabolic fit is then used to normalize the spectrum. Examples are shown in Fig. 2. Once the spectrum is normalized, the equivalent width of Hα (EW(Hα)) is calculated within the range Ha-7 < λ < Ha+7 Å (emission in our case is indicated by a negative

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1 Note that only reliable ages can be estimated for wide WD/dM binaries as PCEBs have undergone a common envelope phase and an initial-to-final mass relation for the white dwarf is not valid in these cases.

2 We used Bergeron’s updated grids available at http://www.astro.umontreal.ca/~bergeron/CoolingModels/

3 Originally a S/N of at least >3 was used, however, the activity fractions (see details in Section 4) we obtained for late-type M dwarfs where very much affected by low-quality data, and we therefore decided to increase the S/N threshold to a least >10.

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Figure 1. SDSS spectrum of SDSS J042200.51+073358.9, together with the best-fitting white dwarf model (blue dashed line) and best-fitting M dwarf template (red solid dotted line).
M dwarf magnetic activity

Figure 2. Left: the residual M dwarf spectrum of SDSS J042200.51+073358 (the complete spectrum can be seen in Fig. 1) after the subtraction of the best-fitting white dwarf model (top left), the parabolic fit to the continuum around Hα (red solid line, top right) and the normalized spectrum (bottom). The vertical dashed lines indicate, from left to right, Hα-7 Å, Hα and Hα+7 Å, where Hα = 6562.76 Å and Hα-7 < λ < Hα+7 Å is the wavelength range in which the equivalent width of Hα is calculated. In this case, Hα emission is clearly detected, and we catalogue the system as active. Right: the same but for SDSS J091333.06+124429.7, an inactive system in our sample.

4 ACTIVITY FRACTIONS

SDSS single M dwarf activity fractions have been published by West et al. (2004, 2008, 2011) for different SDSS data releases (DR 4, DR 5 and DR 7, respectively), as well for independent (non-SDSS) M dwarf samples (e.g. Hawley, Gizis & Reid 1996; Reiners, Joshi & Goldman 2012). All show the same general trend, i.e. a significant increase of the fraction of active systems going from partially to fully convective stars.

The M dwarf activity fractions of our 739 SDSS WD/dM binaries as a function of spectral type are shown on the left-hand panel of Fig. 3 (black dots) together with the activity fractions obtained by West et al. (2011) for single M dwarfs from the SDSS. The two distributions differ significantly at early-to-mid (M0-4) spectral types. At first glance this difference may not seem entirely surprising, as a significant fraction of WD/dM binaries are in fact close PCEBs containing rapidly rotating M dwarfs and, as outlined in the Introduction, fast rotation induces magnetic activity. One might therefore speculate, as e.g. Silvestri et al. (2006) and Morgan et al. (2012), that the increased activity fraction of WD/dM binaries containing early-to-mid spectral type M dwarfs is caused by a fraction of short orbital period PCEBs. However, we have shown that very few WD/dM binaries containing early-type M dwarfs (<M3) are PCEBs (Schreiber et al. 2010), i.e. the majority of these PCEBs have evolved towards shorter orbital periods due to angular momentum loss via magnetic braking and entered a semidetached configuration becoming cataclysmic variables (Politano & Weiler 2006). Therefore the fraction of PCEBs misclassified as wide systems in our radial velocity survey should be low in this spectral type range too.

Clearly, the observed activity fraction does not only depend on the rotational velocities but also on the intrinsic ages of the M dwarfs. Therefore, to understand the measured activity fractions requires to separately investigate close PCEBs and wide WD/dM binaries, and to take into account the ages of the latter population.

4.1 PCEBs

The SDSS PCEB orbital period distribution peaks at ~8 h (Nebot Gómez-Morán et al. 2011), and the longest SDSS PCEB orbital
period is slightly below 10 d (Rebassa-Mansergas et al. 2012b). Consequently M dwarfs in SDSS PCEBs are tidally locked (Gladman et al. 1996) and are expected to be magnetically active.

The middle panel of Fig. 3 shows that all M dwarfs within SDSS PCEBs are active independently of the spectral type. One might be inclined to interpret this result as an obvious consequence of rotation causing activity, nevertheless it is important to keep in mind that Hα emission in PCEBs may arise from irradiation effects if the white dwarf is relatively hot and/or the PCEB orbital period is relatively short (e.g. Tappert et al. 2011a,b). Therefore, we investigate below the effect of irradiation present among the 63 PCEBs in our sample. For 47 of these PCEBs the orbital periods are well known and the stellar parameters relatively well constrained (Nebot Gómez-Morán et al. 2011). With this information at hand we can easily estimate the influence of irradiation by calculating the ratio between the intrinsic flux of the M dwarf ($F_{\text{int}}$) and the irradiating flux from the white dwarf on the M dwarf’s surface ($F_{\text{irr}}$):

$$\frac{F_{\text{int}}}{F_{\text{irr}}} = \left( \frac{T_{\text{M}}}{T_{\text{WD}}} \right)^4 \left( \frac{a}{R_{\text{WD}}} \right)^2,$$

where $T_{\text{M}}$ and $T_{\text{WD}}$ are the M dwarf and white dwarf effective temperatures, respectively, $R_{\text{WD}}$ is the white dwarf radius and $a$ is the orbital separation.

The resulting $F_{\text{int}}/F_{\text{irr}}$ ratios are shown in Fig. 4 as a function of white dwarf effective temperature (top panel) and orbital period (bottom panel). Among the 47 PCEBs, eight were followed-up photometrically as part of our survey (Section 2.1) and inspection of their light curves reveals clear irradiation effects in only two objects (red solid triangles in Fig. 4, cyan dots represent the remaining six systems). Based on the evidence drawn from these eight PCEBs we define $F_{\text{int}}/F_{\text{irr}} = 3$ as the threshold separating systems dominated by irradiation from those that are dominated by the intrinsic emission of the M dwarf (horizontal grey dashed line in Fig. 4). 93 per cent of our systems lie above this limit and are presumably unaffected by irradiation. Although the limit defined in that way just represents an empirically motivated estimate, we conclude that irradiation induced Hα plays a minor role for our sample of PCEBs and that all M dwarfs in PCEBs are magnetically active.

4.2 Wide WD/dM binaries

It is generally accepted that the stellar components in wide WD/dM binaries have evolved in the same way as if they were single stars (Willems & Kolb 2004). Consequently the properties of the M dwarf companions in such binaries should be fairly similar to those of single M dwarfs, and naively one would expect similar activity fractions in both populations. This is clearly not the case (see the right-hand panel of Fig. 3).

The larger activity fractions detected in our sample must be caused by the fact that these M dwarfs are part of binary systems, but as these binaries are fairly wide ($P_{\text{orb}} > 100$ d; Willems & Kolb 2004), interactions between the two stars can be excluded to be the cause of the increased activity fractions. As mentioned in Section 2.1, our radial velocity survey suffers from observational biases and we expect a small percentage of the wide WD/dM binaries to be in emission. Red solid triangles represent confirmed activity fractions in both populations. This is clearly not the case (see the right-hand panel of Fig. 3).
binary sample to be formed by unrecognized PCEBs. It is therefore important to evaluate whether this effect can explain the increase of the activity fractions seen in M dwarfs that are part of wide WD/dM binaries as compared to those of single M dwarfs. For this purpose we calculate in what follows the PCEB contamination in our wide WD/dM binary sample at a given spectral type. The exact number of unrecognized PCEBs depends on the spectral type of the M dwarf components. Schreiber et al. (2010) demonstrated that the observed fraction of PCEBs containing early-type M dwarfs is $\sim 10$ per cent at M0–1 spectral types, and increases to only $\sim 20$ per cent at M2. Combining these fractions with the PCEB detection probability of our radial velocity survey of $\sim 0.8$ (Schreiber et al. 2010; Rebassa-Mansergas et al. 2011) we calculate a PCEB contamination of less than 5 per cent in the M0–2 range (where the activity fractions most differ). Therefore this effect can certainly not explain the difference between the activity fractions in the single and wide WD/dM binary samples (right-hand panel of Fig. 3).

Identifying both components in a SDSS WD/dM binary spectrum requires that neither the white dwarf nor the M dwarf completely outshines the other component. Cold white dwarfs are too faint to be detected in binaries with early-type M dwarfs. This implies the white dwarf to have an effective temperature $\geq 10 000$ K thus excluding the coolest (i.e. oldest) white dwarfs (Rebassa-Mansergas et al. 2007, 2010).\(^4\) The mass distribution of white dwarfs in wide WD/dM binaries is similar to the mass distribution of single white dwarfs (Rebassa-Mansergas et al. 2011) implying that the progenitors of such white dwarfs were mainly F stars that spent a rather short time on the main sequence. In other words, the simple requirement that we need to be able to detect the white dwarf in the SDSS spectrum to classify a system as WD/dM binary introduces a significant bias towards young systems that is not present in the samples of single M dwarfs.

In order to investigate this hypothesis further we show in Fig. 5 the activity fractions as a function of age for 118 wide WD/dM binaries with available estimated ages (Section 2.3). Two important results are extracted from inspecting this figure. (1) As expected, M dwarfs in wide WD/dM binaries are in general significantly younger than the average age of field M dwarfs of $\sim 5$ Gyr (West et al. 2008). On average, younger stars rotate faster and therefore a considerably higher fraction of M dwarfs in WD/dM binaries are active. (2) There is a clear decrease of the activity fractions for older systems. Even though the errors in the activity fractions are fairly broad, this is in very good agreement with magnetic braking slowing down the rotation of the M dwarfs that are part of wide WD/dM binaries with time.

It is worth mentioning that the activity fractions measured for the systems with available ages seem to be higher than those obtained for the complete wide WD/dM binary sample (see Fig. 5 and right-hand panel of Fig. 3). This is simply because we can only obtain reliable ages if the white dwarfs are hot enough to dominate the SDSS WD/dM binary spectra, which reflects in an effective temperature of $\geq 15 000$–$20 000$ K, depending on the spectral type of the M dwarf. Thus an older population containing inactive systems exists in our wide WD/dM binary sample for which we are not able to estimate the ages, making the activity fractions lower for the complete wide WD/dM binary sample but still considerably higher than those measured for field M dwarfs.

We conclude that the age effect described above can explain the observed difference between the activity fractions measured by West et al. (2011) for single M dwarfs and those obtained here for the M dwarfs in wide WD/dM binaries.

5 THE ROTATION–ACTIVITY RELATION

As outlined in the Introduction, rotation and magnetic activity are strongly correlated. The strength of activity increases with rotation and saturates around $R_0 \approx 0.1$, the exact value of the saturation threshold velocity depending on the mass of the star (Pizzolato et al. 2003). Such a saturation-type rotation–activity relation has been observed for the entire spectral type range of M dwarfs (Mohanty & Basri 2003; Reiners & Basri 2010; Reiners et al. 2012).

In this section we investigate the saturation-type relation in our sample of 47 PCEBs for which we know the orbital periods (Section 4.1). For this purpose, the strength of magnetic activity of the 47 systems is quantified by the ratio between the $H\alpha$ and bolometric luminosities, $\frac{L_{H\alpha}}{L_{\text{bol}}}$. This luminosity ratio is obtained from the measured $E_{\lambda H\alpha}$ values (see Section 5) following the equations of West & Hawley (2008), who obtained conversion factors between the two considered quantities. Compared to single field stars, M dwarf companions in PCEBs are tidally locked and are therefore expected to be very fast rotators that should populate the saturated regime.

Fig. 6 (top panel) shows the activity strength as a function of rotational velocity $V_{\text{rot}}$ for the 47 M dwarf companions in PCEBs with well known orbital periods (black solid dots) and the single M dwarfs from the catalogue of Reiners et al. (2012, red triangles). Note that the latter sample is divided into systems with accurately measured rotational velocities (solid red triangles) and systems with upper limits to the rotational velocities (open red triangles), and that these values, contrary to ours, represent projected rotational velocities ($V_{\text{rot}}$ sin $i$). Inspection of the top panel of Fig. 6 clearly reveals that the M dwarfs in PCEBs populate the regime of the fastest rotators in which the strength of magnetic activity saturates at $\log \frac{L_{H\alpha}}{L_{\text{bol}}} \sim -3.5$. This result represents a crucial and very robust confirmation of the proposed rotation–activity relations in M dwarfs. To further illustrate this point, we show in the bottom
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Figure 6. Top panel: the strength of magnetic activity (evaluated through the \( L_{\alpha}/L_{bol} \) luminosity ratio) as a function of rotational velocity (\( \nu_{rot} \)) of 47 M dwarfs in close PCEBs. Our data (black solid dots) extend the work by Reiners et al. (2012, red triangles) to faster rotators and unambiguously confirm the saturation limit of the strength of magnetic activity at \( \log L_{\alpha}/L_{bol} \sim -3.5 \). Bottom panel: the strength of magnetic activity as a function of the Rossby number. The increased scatter of \( \log L_{\alpha}/L_{bol} \) at \( \log (R_0) \lesssim -1.8 \) may indicate chromospheric supersaturation.

6 SUMMARY AND CONCLUSIONS

Angular momentum evolution, rotation and age are closely related in low-mass stars. Magnetic field generation strongly depends on the Rossby number, therefore the rotation, of a given star (Hartmann & Noyes 1987; Chabrier & Küker 2006). Thus, magnetic activity increases with rotation until its strength saturates for fast rotation rates (Pizzolato et al. 2003; Reiners et al. 2009). Magnetic braking slows down the rotation of the star and consequently magnetic activity and rotation decrease in time (Skumanich 1972; Browning et al. 2010). The time-scale of magnetic braking depends on the mass of the star, i.e. in fully convective stars magnetic braking becomes inefficient (Reiners & Basri 2008; Schreiber et al. 2010) and the activity lifetimes increase (West et al. 2008).

WD/dM binaries offer an excellent opportunity to independently investigate the relations among magnetic activity, rotation and age in M dwarfs. This is because WD/dM binaries can be separated into wide binaries that never interacted, and in which the properties of the M dwarf components should be fairly similar to those of single stars, as well as close binaries that underwent common envelope evolution (PCEBs) in which the M dwarf is tidally locked and rotates very rapidly (Schreiber et al. 2010; Nebot Gómez-Morán et al. 2011; Rebassa-Mansergas et al. 2011). To test the activity–rotation–age connection with the largest and most homogeneous sample of SDSS WD/dM dwarf binaries currently known (Rebassa-Mansergas et al. 2010, 2012a) has been the main goal of this paper. Our main results can be summarized as follows.

(i) We have demonstrated that for M dwarfs in PCEBs fast rotation implies activity independently of the spectral type. This supports the connection between rotation and activity as a necessary ingredient for dynamo models responsible for magnetic field generation in both partially and fully convective stars (Chabrier & Küker 2006; Browning 2008).

(ii) We have shown that M dwarfs in close WD/dM binaries populate the saturated regime (\( R_0 < 0.1 \)) and that the strength of magnetic activity saturates at \( \log L_{\alpha}/L_{bol} \sim -3.5 \). This represents a crucial confirmation of the saturation-type rotation–activity relation for M dwarfs that are very fast rotators, in perfect agreement with the results by Reiners & Basri (2010) and Reiners et al. (2012) for single M dwarfs.

(iii) We have provided additional observational evidence for magnetic braking becoming inefficient in fully convective stars, i.e. the activity fractions of M dwarfs in wide WD/dM binaries show a significant increase at the fully convective boundary. We have also shown that the activity fractions of M dwarfs in wide WD/dM binaries decrease in time, which proves the spin-down of these M dwarfs due to magnetic braking.

We conclude the observational findings from the SDSS WD/dM binary sample are consistent with the current picture of angular momentum evolution and dynamo generation of magnetic fields in low-mass stars, and add important information to our understanding of the relations between magnetic activity, rotation, age and magnetic braking in M stars.

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