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Stars with a Stable Magnetic Field

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Abstract. In this review I will summarise what we know about magnetic fields in stars and what the origin of these magnetic fields may be. I will address the issue of whether the magnetic flux is conserved from pre-main sequence to the compact star phase (fossil field origin) or whether fields may be dynamo generated during some stages of stellar evolution or perhaps during stellar merging events.

Key words: stars: magnetic field – stars: protostars – stars: chemically peculiar – white dwarfs – pulsars – stars: magnetars

1. Introduction

Babcock (1947) was the first astronomer to detect a magnetic field in a star (78 Vir). He also discovered what is still now the most highly magnetic main sequence star, HD 215441 whose field strength is about 3.4×10^4 G (Babcock, 1960). This became known as "Babcock's star" (see Fig. 1).

The existence of strong magnetic fields in white dwarfs was revealed much later when Kemp et al. (1970) detected strong circular polarisation in the continuum of Grw+70°8247 while in neutron stars came with the discovery of the first pulsar, a fast spinning neutron star (Pacini, 1968), by Jocelyn Bell in 1967 (Hewish et al., 1968).

Since those early years, major progress has been made on stellar magnetism thanks to high quality data coming from surveys covering the full range of stellar masses and spanning all evolutionary phases, including pre-main sequence (e.g. Alecian et al., 2013a,b; Hubrig et al., 2013), main and post main-sequence (e.g. Hubrig et al., 2011; Aurière et al., 2015; Wade et al., 2016; Mathys, 2017), white dwarfs (e.g., Schmidt et al., 2001; Landstreet et al., 2012; Kepler et al., 2013) and neutron stars (the Parkes multibeam pulsar survey; Manchester et al., 2001). The data secured by these surveys have allowed researchers to explore the incidence of magnetism among stars, probe their magnetic field strength and structure, and study their field evolution and origin.

The origin of large scale and stable magnetic fields in stars remains an open question in astrophysics. In this paper I will review what is currently known about stellar magnetism and the hypotheses that have been advanced to explain the origin of magnetic fields in stars. A comprehensive paper on stable magnetic

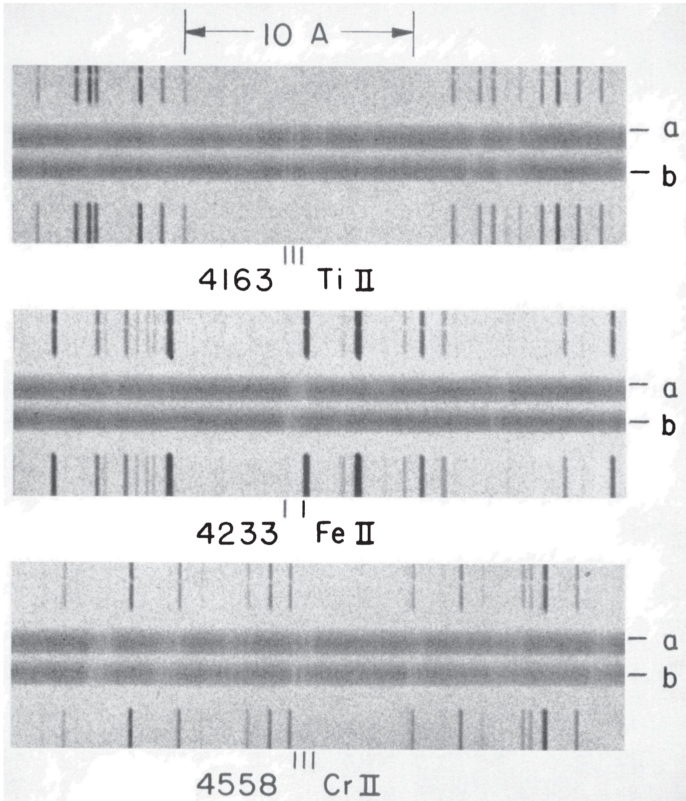

Figure 1. Spectrum of HD 215441 (Babcock, 1947) showing Zeeman split lines in a magnetic field of about 34 000 G. The spectra marked by *a* and *b* were photographed simultaneously through the left-hand and right-hand sections of a double circular analyzer. The original dispersion 4.5 Å mm^{-1}; slit width corresponds to 0.14 Å.

equilibria and their evolution in main-sequence and compact stars can be found in Reisenegger (2009) and an extensive review on the origin of stellar magnetic fields in Ferrario et al. (2015b).

2. The Dichotomies of Magnetic Non-Degenerate Stars

Herbig Ae/Be (HAeBe) objects are pre-main sequence stars of $2 - 15\,M_\odot$ at the later stages of their formation. These objects are still immersed in their protostellar gas-dust envelope and exhibit emission lines of stellar type A/B. Alecian et al. (2013a,b) and Hubrig et al. (2013) conducted large spectro-polarimetric surveys of HAeBe stars to investigate their magnetic and rotational properties and explore possible evolutionary links between their characteristics to those of the magnetic main sequence Ap/Bp stars. These observations have indeed shown that around 7% of HAeBe objects display large-scale, mainly dipolar magnetic fields with strengths in the range $300-2\,100$ G which are similar to those of magnetic main sequence Ap and Bp stars if conservation of magnetic flux is assumed. The incidence of magnetism among HAeBe is also consistent with that observed on the main-sequence. The surveys have also revealed that while the non-magnetic HAeBe objects exhibit rotations $v \sin i = 0-300\,\mathrm{km\,s^{-1}}$, the magnetic ones are generally much more slowly rotating with $v \sin i \leq 100\,\mathrm{km\,s^{-1}}$. This dichotomy is reminiscent of that observed in magnetic stars on the main sequence (as first reported by Wolff, 1975) that can have spin periods of up to 1 000 years (see Mathys, 2015). This suggests that those physical processes that are responsible for rotational braking in magnetic main-sequence stars are already at play in the late stages of stellar formation. In this context, Netopil et al. (2017) and Netopil et al. (2018, these proceedings) have studied the rotational characteristics of a sample of more than 500 magnetic main-sequence stars. Their results have confirmed the previous results of North (1998) and Stepien (1998) that the angular momentum is conserved during the evolution on the main-sequence and that no further magnetic braking is observed. Furthermore, they showed that while stars with the highest fields tend to be the slowest rotators, the strongest fields are found only in stars with spin periods shorter than about 150 d, thus confirming the earlier findings of Mathys et al. (1997) and more recently of Mathys (2017).

A second dichotomy exists among A and B type stars with masses of $1.5-6\,\mathrm{M_\odot}$, that is, they either exhibit large-scale fields of $300-34\,000$ G or they are not magnetic down to the current detection limit of a few Gauss (see Fig. 2). The lack of stars in the 1-300 G field regime has been called the “Ap/Bp magnetic desert” (Aurière et al., 2007). Below the magnetic desert lies another type of magnetic stars, typified by Vega, whose longitudinal field is at the sub-Gauss level (Lignières et al., 2009). Thus this magnetic desert separates intermediate-mass stars with large-scale stable fields from those with unstable fields suggesting that two different mechanisms may be responsible for the generation of their fields. However, Fossati et al. (2015) have reported that massive stars may not have a magnetic desert, although its absence may be linked to mass-dependent field decay (see below Fossati et al., 2016).

A third dichotomy concerns the dearth of close binaries among main-sequence magnetic stars. The aim of the BinaMIcS (Binarity and Magnetic Interactions in various classes of Stars) programme (Alecian et al., 2015) was initiated to explore the incidence of magnetism in binaries with periods shorter than 20 d. Their studies have shown an incidence of magnetism that is about 3 to 5 times lower than in non-magnetic stars, thus confirming the results of Carrier et al. (2002) who first reported that binary systems hosting an Ap star tend to have periods ≥ 3 d.

The above three dichotomies tell us the following. It appears that large-scale

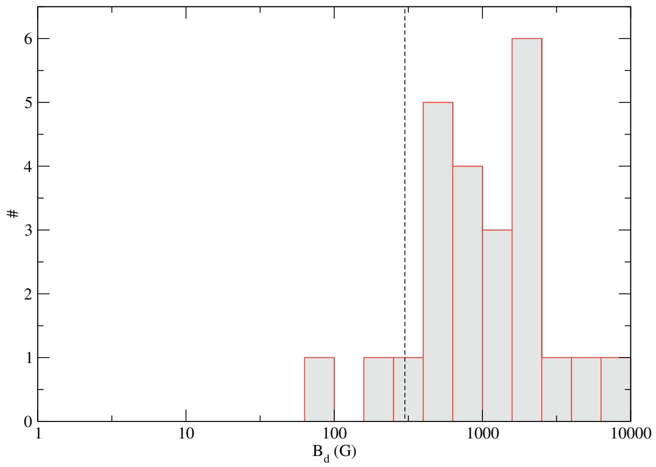

Figure 2. Histogram of the derived dipole strengths B_d of a sample of 28 magnetic Ap/Bp stars from Aurière et al. (2007). Note the dearth of Ap stars with $B_d < 300\,\mathrm{G}$.

magnetic fields in proto-stars and on the main-sequence are present only in a small fraction ($\sim 7\%$) of stars with radiative envelopes and that these magnetic stars are very rarely found in close binaries. The magnetic field strength dichotomy tells us that the origin of stellar magnetism cannot be attributed to some dynamo action taking place in some evolutionary phases, because if this were the case all stars would be magnetic at some level and there would be no Ap/Bp magnetic desert.

Observations indicate that the magnetic flux is conserved during the evolution from the pre-main sequence to the main sequence. However, if magnetism is a relic of the interstellar field from which the stars formed (see, e.g., Mestel, 1966) then we would expect that the incidence of magnetism should vary across diverse stellar populations. Thus the incidence in the Galactic field should differ from that in clusters and also from cluster to cluster. However, this does not seem to be the case (e.g. Paunzen et al., 2005, 2006). It is also curious that all magnetic stars in binaries (with the exception of ϵ Lupi; Shultz et al., 2015) have non-magnetic companions.

In order to explain the above dichotomies, Ferrario et al. (2009) advanced the hypothesis that magnetic fields could form when two proto-stars merge as they approach the main-sequence and when at least one of them has already developed a radiative envelope. These late mergers would produce a brief period of strong differential rotation and give rise to the large-scale fields observed in the radiative envelopes of Ap, Bp, and Of?p stars. They would also explain the scarcity of close binaries among intermediate-mass main-sequence magnetic stars. One of the merging proto-star predictions is that the incidence of mag-

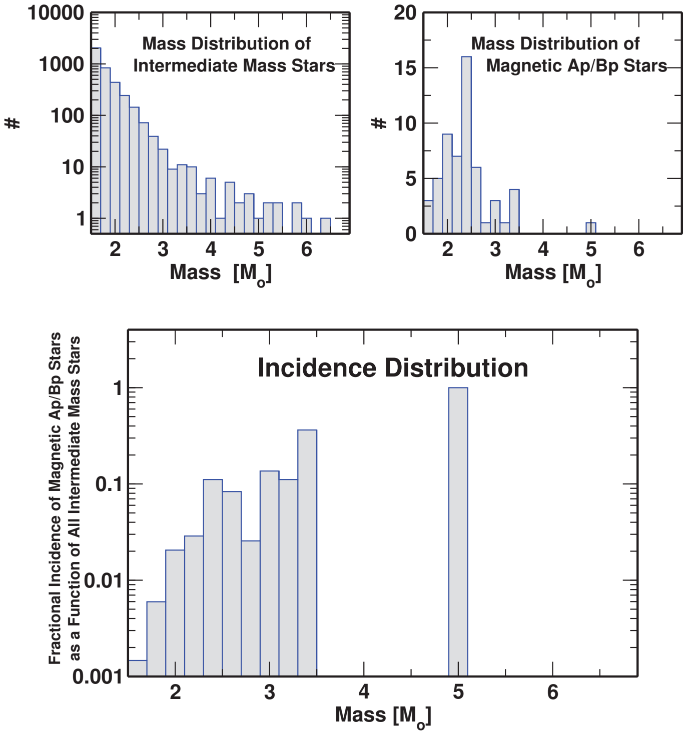

Figure 3. Mass distribution of A/B stars in the solar neighbourhood. *Top left*: mass distribution of all intermediate mass A/B stars. *Top right*: mass distribution of magnetic Ap/Bp stars. *Bottom*: incidence of Ap/Bp stars as a function of mass (Power et al., 2007).

netism should grow with stellar mass, which appears to be validated by the studies of Power et al. (2007) (see Fig. 3) and Sikora et al. (2018, these proceedings) who conducted a volume-limited sample of A/B stars with $M \leq 4\,\mathrm{M}_{\odot}$.

The question of how fields evolve with stellar age was addressed by Landstreet et al. (2008) who performed surveys of magnetism in A and B type stars in clusters. These observations allowed them to link field strength and structure to stellar mass, fractional ages, and metallicity. Their work revealed that fluxes clearly decrease with age indicating field decay. They also reported that such a decline is faster in stars with a mass larger than about $3\,\mathrm{M}_{\odot}$. Fossati et al. (2016) conducted a similar study on the field evolution in massive (5-100 $\mathrm{M}_{\odot}$) main-sequence stars and found an obvious deficiency of evolved magnetic stars which is more prominent at higher masses. So they propose that the absence of a magnetic desert in massive magnetic stars may be caused by the mass-dependent timescales over which field decay occurs. That is, if all magnetic stars are born with a field above a certain cutoff, the lowest mass stars would retain it as they evolve on the main-sequence. This is because the field decay times in these stars is comparable to or longer than their main-sequence lifetime. However, if field decay acts faster as mass increases (and thus on timescales that are progressively shorter than their main-sequence lifetime), then massive magnetic stars will display, as a class, a smooth magnetic field distribution that extends to very low fields.

Fossati et al. (2016) also noted that field decay may explain the intriguing mismatch between the percentage of massive magnetic stars and that of slowly rotating massive stars. That is, many massive stars that used to be strongly magnetic (and therefore slowly rotating) are no longer magnetic at any measurable level (see also Fossati et al., 2015).

Despite this decay, fields have been observed in some post-main-sequence stars. The first field discovered in an evolved star was that in EK Eridani (Aurière et al., 2011). This is a very slowly rotating red giant ($P = 308.9$ d) with a convective envelope and a large scale poloidal field of about 270 G. Neiner et al. (2017) detected magnetic fields in another two hot evolved stars: ι Car (either on its first crossing of the HR diagram or on a blue loop) and HR 3890 (on its first and only crossing of the HR diagram) and confirmed the field in ϵ CMa (near the end of the main-sequence) first reported by Fossati et al. (2015). Their field strengths are compatible with magnetic flux conservation during stellar evolution indicating that at least in a fraction of stars magnetic fields can persist when a star evolves off the main-sequence.

The magnetic Ap/Bp stars show periodic variabilities caused by the non-uniform distribution of chemical elements on their surface. It is still not clear what causes these inhomogeneities and the viability of theoretical models is mostly restricted to observations of Galactic objects. However, stellar magnetism data obtained in extragalactic systems with different environmental properties would give us additional information that would allow us to better constrain theoretical models. This is what motivated Paunzen et al. (2013) to conduct photometric observations of a sample of magnetic Ap/Bp candidates in the Large Magellanic Cloud (LMC). They discovered that their LMC sample exhibits a low variability amplitude and explained it as due to the absence of regions of the stellar surface that have an overabundance of optically active elements. Paunzen et al. (2005, 2006) also found that while the percentage of chemically peculiar stars in Galactic open clusters is almost identical to that of the Galactic field, in the LMC the incidence is only about 2.2% – less than half of that estimated in the Galaxy. On the other hand, stellar masses and ages do not seem to be dissimilar from Galactic objects. These authors note that the LMC metallicity is about 0.5 dex compared to the Sun thus yielding important insights into the origin of chemical peculiarities and on the origin of magnetic fields in stars.

There are currently no calculations that include fossil fields and follow their evolution as the star ages and all the results highlighted in this section provide us with valuable constraints for the construction of evolutionary models.

A very comprehensive review of magnetic fields in non-degenerate stars is given by Donati & Landstreet (2009).

3. Magnetic White Dwarfs

Magnetic fields of isolated magnetic white dwarfs lie in the range $10^3 - 10^9$ G. The upper limit cutoff near 10^9 G may be real but the incidence of magnetism below a few 10^3 G still needs to be established (see Landstreet et al., 2012, 2017). Since the discovery of the first magnetic white dwarf (Grw+70°8247; Kemp et al., 1970) the number of objects has been steadily increasing. We now have about 300 isolated and 170 magnetic white dwarfs in interacting binaries (the magnetic cataclysmic variables, MCVs). Extensive reviews on magnetism in white dwarfs can be found in Ferrario et al. (2015a), Wickramasinghe & Ferrario (2000) and also Kawka (2018, these proceedings).

The origin of magnetic fields in white dwarfs has been vigorously debated since their discovery. The proposal that the magnetic Ap/Bp stars are the progenitors of the High Field Magnetic White Dwarfs (HFMWDs; Tout et al., 2004; Wickramasinghe & Ferrario, 2005), as first suggested by Woltjer (1960), has recently been questioned (Liebert et al., 2005, 2015). The point is that there should be the same fraction of HFMWDs in binaries as in single stars. The Sloan Digital Sky Survey has identified thousands of detached white dwarf – M dwarf spectroscopic binaries (e.g., Rebassa-Mansergas et al., 2013, 2016; Ferrario, 2012) but none of these has a field above a few 10^6 G (the detectable limit in the SDSS spectra) even if there are hundreds of HFMWDs known to have fields greater than this detection limit (Liebert et al., 2005, 2015). The sample of white dwarfs within 20 pc (Holberg et al., 2008) has shown that $19.6 \pm 4.5\%$ of white dwarfs have main-sequence companions. Thus, $14 - 24\%$ of the ~ 300 HFMWDs should also have such companions, but none has been identified. The magnitude-limited Palomar-Green survey has shown that $23 - 29\%$ of hot white dwarfs have cool companions. Thus, we expect 7090 of the ~ 300 HFMWDs to have a companion. However, none has been found. The logical conclusion is that the origin of high magnetic fields in white dwarfs is intimately related to their binarity, as first proposed by Tout et al. (2008). We know that some HFMWDs are the result of merging events (EUVE 0317-855 is probably the best example, Vennes et al., 2003). Thus, if magnetic fields in white dwarfs arise as a result of either double degenerate or common envelope mergers, then the complete absence of main sequence (generally M-dwarf) companions to HFMWDs can easily be explained. Despite the total absence of detached binaries composed by a HFMWD and a non-degenerate companion, there are quite a few examples of binaries comprising two white dwarfs, one of which is highly magnetic (see Kawka et al., 2017, and references therein). Close post-common envelope magnetic binaries could have developed their fields during the common envelope phase (Kawka et al., 2017, e.g., the fast spinning super-Chandrasekhar system NLTT 12758), while distant binaries could have been initially triple systems with two of the three stars merging at some point (e.g., EUVE 0317-855). Following Tout et al. (2008), the stellar merging hypothesis has been explored by Bogomazov & Tutukov (2009), Nordhaus et al. (2011), García-Berro et al. (2012) and Wickramasinghe et al. (2014).

One feature that characterises the HFMWDs is that their mean mass is around $0.78\,M_\odot$, considerably larger than that of non-magnetic white dwarfs ($0.66\,M_\odot$, Tremblay et al., 2013). The population synthesis calculations of Briggs et al. (2015) used the incidence of magnetism among white dwarfs and their mass distribution to constrain their models computed for different values of the common envelope efficiency parameter α. They found that the best agreement with observations is obtained for $\alpha < 0.3$ with the major contribution coming from the merging of a late asymptotic giant branch star with a main-sequence star.

A field distribution similar to that of the isolated HFMWDs is observed in the MCVs. In these interacting systems the mass flowing from the M-dwarf to the magnetic white dwarf is funnelled by the strong fields (a few $10^6 - 10^8$ G, as revealed by photospheric Zeeman lines and/or cyclotron emission features in their UV to IR spectra, e.g., Ferrario et al., 1992, 1993a, 1996, 2003; Schwope et al., 2003; Hoard et al., 2004) to form accretion shocks near the magnetic poles. Truncated accretion discs may or may not be present depending on the accretion rate and field strength (e.g., Ferrario et al., 1993b; Ferrario & Wehrse, 1999). The birth properties of MCVs have been analysed in the context of the common envelope origin of magnetic fields by Briggs et al. (2018, these proceedings). According to this scenario, those systems that emerge from common envelopes as close binaries and about to exchange mass will evolve into MCVs. They found that the best agreement with observations is obtained again for $\alpha < 0.3$. The study by Zorotovic et al. (2010) of the possible evolutionary histories of a sample of SDSS post-common-envelope binaries is in good agreement with the Briggs et al. (2018) results.

I note that there is an interesting parallel between the rarity of close binaries among magnetic main-sequence stars and HFMWDs, supporting a similar (merging) hypothesis for the origin of their fields.

Magnetic white dwarfs are also becoming important tools to investigate the formation and composition of exoplanets. For instance, the suggestion that GD 356 may have an Earth-type planetary companion (Li et al., 1998) is still a tantalising possibility to explain its unique emission line spectrum (Ferrario et al., 1997). Furthermore Kawka & Vennes (2014) have shown that the incidence of magnetism among cool and polluted white dwarfs is much greater than among their non-magnetic counterparts, and proposed a link between crowded planetary systems and the generation of magnetic fields in white dwarfs (see also Kawka, 2018, these proceedings).

4. Neutron Stars

The vast majority of neutron stars is made up by the classical radio pulsars (see the review by Beskin et al., 2015). Pulsars are powered by the loss of rotational energy caused by magnetic braking (remarkably, Pacini, 1967, suggested that a rotating pulsar might emit radio waves just before their discovery). If a pulsar has a spin period P, typically $0.3 - 2\,\mathrm{s}$, and a period derivative $\dot{P}$ (the rate at which the pulsar spins down), typically $10^{-17} - 10^{-13}\,\mathrm{s\,s^{-1}}$, then the dipole radiation formula $B = 3.2 \times 10^{19}\sqrt{P\dot{P}}\,\mathrm{G}$ (Manchester & Taylor, 1977) gives an estimate of a few $10^{11} - 10^{13}\,\mathrm{G}$ for the magnetic field strength. Thus, in the vast majority of cases the magnetic field strength of neutron stars can only be measured indirectly. The only exception arises in those rare cases when the X-ray spectrum of accreting neutron stars shows cyclotron harmonic features, such as those observed in the accreting neutron stars in X0115+63 (Santangelo et al., 1999), Vela X-1 (Kreykenbohm et al., 2002) and 1E1207.4-5209 (Bignami et al., 2003). These fields have been estimated to be a few $10^{10} - 10^{12}\,\mathrm{G}$, thus consistent with the fields inferred in classical pulsars. I show in the left panel of Fig. 4 the X-ray spectrum of X0115+63 and in the right panel, for comparison, the infrared spectrum of the accreting magnetic white dwarf in the MCV VV Puppis showing cyclotron emission features (Visvanathan & Wickramasinghe, 1979).

The millisecond pulsars (MSPs) are very rapidly spinning neutron stars with rotational periods $\gtrsim 30\,\mathrm{ms}$ and magnetic fields typically $\lesssim 10^9\,\mathrm{G}$. The most widely accepted theory regarding the origin of MSPs (mostly found in binary systems with white dwarfs or substellar mass companions) is that they are old neutron stars that have been spun up (recycled) via mass accretion (as first suggested by Backus et al., 1982). However, Ferrario & Wickramasinghe (2007) and Hurley et al. (2010) have demonstrated through population synthesis calculations that the birthrates of binary MSPs via accretion-induced collapse (AIC) of white dwarfs can be as large as, and possibly greater than, those for core collapse. In addition, AIC pulsars can better reproduce the orbital period distributions of some classes of binary MSPs.

At the very high end of the field distribution we find the soft gamma repeaters (SGRs) and the anomalous x-ray pulsars (AXPs), commonly referred to as the magnetars. They are generally characterised by very high fields of a few $10^{13} - 10^{15}\,\mathrm{G}$ (but not always, see below) and spin periods between 2-12 s which are much longer than those of radio-pulsars. The lifetime of magnetars is only a few 10,000 years and they are often found still embedded in their supernova remnants. It is still not clear whether these objects were born rotating very slowly or have spun down rapidly. The persistent and strong X-ray emission of magnetars ($\sim 10^{35}\,\mathrm{erg\,s^{-1}}$) is too large to be powered by their rotational energy. In addition they suffer from violent bursts lasting $0.1 - 40\,\mathrm{s}$ with peak luminosities of up to $\sim 10^{43}\,\mathrm{erg\,s^{-1}}$. SGRs also exhibit giant flares with an energy output of up to $\sim 10^{47}\,\mathrm{erg\,s^{-1}}$ lasting about one second. These activities have been

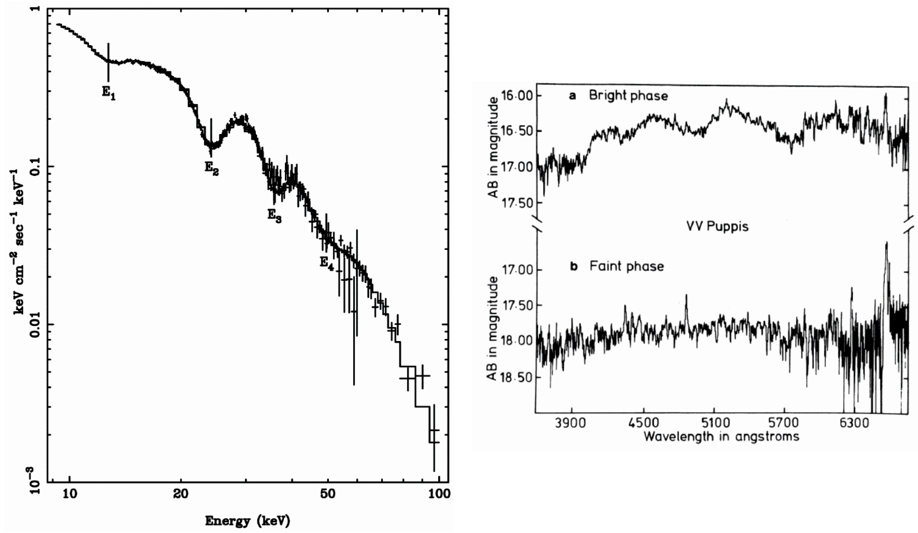

Figure 4. *Left*: Spectrum of X0115+63 showing cyclotron resonant scattering features suggestive that the accreting neutron star has a field of about 10^{12} G (Santangelo et al., 1999). *Right*: The discovery spectrum of VV Puppis exhibiting cyclotron harmonic lines from the accretion shock on the surface of the magnetic white dwarf (Visvanathan & Wickramasinghe, 1979) indicating a field strength of 3.2×10^7 G.

attributed to the decay and instabilities of their magnetic fields (Thompson & Duncan, 1996). Two very comprehensive reviews on the properties of magnetars can be found in Turolla et al. (2015a) and Mereghetti et al. (2015).

We show in Fig. 5 the $P-$ diagram of neutron stars (Manchester et al., 2005).

Another class of neutron stars is that formed by the very quiet and (probably) weakly magnetic ($\leq 10^{10}$ G) central compact objects (CCOs), found in young supernova remnants ($< 10^4$ yr). These are characterised by: (i) thermal X-ray emission (0.4 keV blackbody with dimensions of less than 1 km); (ii) absence of optical or radio emission; and (iii) lack of a pulsar wind nebula. Of the known supernova remnants within 5 kpc, 14 harbour normal radio pulsars, 6 harbour CCOs, and 1 hosts an AXP giving an incidence of CCOs of about 30% (de Luca, 2008). Thus, the birthrate of CCOs may be similar to that of normal radio pulsars. It is still not clear whether these objects were born with a low field (the proposal of Gotthelf & Halpern, 2008, that CCO pulsars anti-magnetars) or whether the field is submerged due to fallback matter from an accretion disc. Viganò & Pons (2012) have shown that some rather moderate accretion of $<< 0.1\,M_\odot$ can bury fields of a few $10^{12} - 10^{14}$ G that may re-emerge on a time-scale of $10^4 - 10^5$ yrs and convert a CCO into a normal radio pulsar (or even a magnetar). Popov & Turolla (2012) suggested that these pulsars would

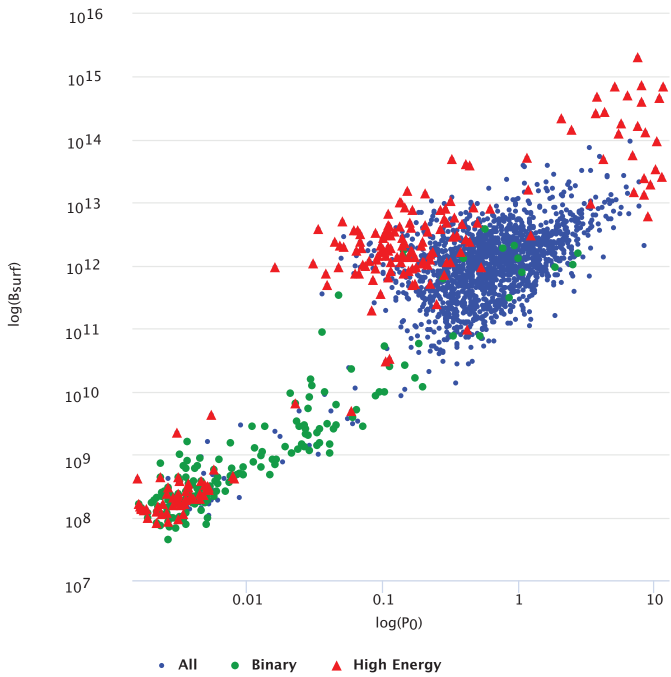

Figure 5. Plot of the surface magnetic field strength $B_{\rm surf}$ against spin period P_0 for pulsars obtained from the ATNF catalogue (Manchester et al., 2005).

be injected into the general population at periods of $0.1 - 0.5\,$s and would be expected to have a negative braking index because their magnetic fields would be increasing. They note that this is indeed the case for $20 - 40$ known pulsars.

As it is for the magnetic white dwarfs, the origin of magnetic fields in neutron stars is still unclear. The convection-driven dynamo of Thompson & Duncan (1993), which was inspired by solar dynamo calculations scaled to neutron stars' physical conditions, predicted fields of up to $10^{16}\,$G and it is still the most widely accepted theory for the origin of neutron stars' magnetic fields. Another avenue for field generation is given by the differential-rotation driven dynamo mechanism where toroidal and poloidal fields grow together until they reach equilibrium values (Braithwaite, 2006). Differential rotation can also be the outcome of stellar merging events, as suggested by Tout et al. (2008) and Wickramasinghe et al. (2014) in the context of magnetism in white dwarfs. Magnetic fields in neutron stars could also be explained according to the fossil field hypothesis (Ferrario & Wickramasinghe, 2006, 2008) which invokes magnetic flux conservation from the main-sequence (or earlier phases) to the compact star stage.

It is curious that neutron stars with similar dipolar field strengths (as inferred from their P and $\dot{P}$) can exhibit a very different array of emission behaviour. For instance, X-ray observations of SGR 0418+5729 by Rea et al. (2010) have revealed a dipolar magnetic field of only 7.5×10^{12} G which is typical of classical radio-pulsars. This indicates that a strong dipolar magnetic field is not necessary for a neutron star to display the violent emission characteristics of a magnetar. Instead, these could be caused by the decay of a large internal toroidal field that does not take part in the spin-down of the star (Thompson & Duncan, 1996; Ferrario & Wickramasinghe, 2008; Rea et al., 2010). It is this toroidal field that could be the differentiating factor among neutron stars of similar P and $\dot{P}$. Interestingly, SGR 0418+5729 is located at a rather high Galactic latitude and its P and $\dot{P}$ indicate that it is close to the death line for radio pulsars. Thus, as suggested by Rea et al. (2010), this SGR is much older than the other magnetars, further supporting the hypothesis that its emission and bursting characteristics (occurring when magnetic stresses overpower the rigid elastic crust causing crust-quakes Lander et al., 2015) may be due to the reservoir of energy amassed in its super-strong toroidal field that is slowly dissipating.

The population synthesis calculations of Ferrario & Wickramasinghe (2008) suggested that massive Of?p stars could be the progenitors of the magnetars because many of them have been associated with young clusters of massive stars. On the other hand, it may even be possible that the stellar merging hypothesis proposed for the explanation of magnetism on the upper main sequence and in the HFMWDs may also be applicable to the magnetars. This would give a unified origin for the fields in most magnetic stars (Wickramasinghe et al., 2014).

An interesting suggestion is that magnetars could also be responsible for short and long gamma-ray bursts (GRBs; Turolla et al., 2015b). For instance, Tout et al. (2011) propounded that the merging of an oxygen-neon white dwarf with the carbon-oxygen core of a naked helium star during a common envelope phase would produce a rapidly spinning magnetar giving rise to long GRBs. However, because the birth rate of magnetars is much higher than that of LGRBs, not all magnetars can be linked to LGRBs and thus the majority of magnetars is expected to originate from single-star evolution.

5. Conclusions

A 5-10% incidence of magnetism in stars is observed at all evolutionary phases, from pre-main-sequence to the compact star stage. Are these magnetic fields of fossil origin? Taken at face value, the observational results seem to support this hypothesis. However, the total absence of HFMWDs paired with non-degenerate companions in detached binaries has shed some serious doubts on this theory. The alternative scenario that would allow us to overcome the problem presented by this lack of duplicity is that HFMWDs could originate from stars that merge during the common envelope phase or from two merging white dwarfs (double degenerate mergers). Those systems that survive the common envelope evolution and emerge as close binaries just before the onset of accretion will evolve into MCVs. A similar merging scenario could apply to magnetic pre-main-sequence stars, thus explaining the dearth of short-period binaries among Ap/Bp stars.

The origin of fields in neutron stars is more difficult to ascertain, partly because of our incomplete knowledge of their magnetic field strength, structure and evolution. Furthermore, many neutron stars seem to share the same location in the $P - \dot{P}$ diagram, thus suggesting that magnetic field strength alone cannot determine the observed emission behaviour of neutron stars. One proposal is that a hidden (internal) ultra-strong toroidal field that is slowly dissipating could be responsible for most magnetar-like activities observed in neutron stars.

An interesting possibility that has not been fully explored yet is that the fields of magnetars could also have originated through binary interaction, like the mechanism proposed to explain the origin of fields in the progenitors of the Ap/Bp stars and in the HFMWDs. The beauty of this scenario is that it leaves a unified picture for the origin of the highest magnetic fields in all types of stars.

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