Magnetic Fields throughout Stellar Evolution
Proceedings IAU Symposium No. 302, 2013
P. Petit, M. Jardine & H. Spruit, eds.

doi:10.1017/S1743921314001756

Magnetic higher-mass stars in the early stages of their evolution

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Abstract. Over the past decade, significant investigations have been made through the use of high-resolution spectropolarimetry to probe the surface magnetic field characteristics of young higher-mass ($M \gtrsim 1.5\,\mathrm{M}_\odot$) stars from pre-main sequence to zero-age main sequence evolutionary phases. The results of these observational campaigns suggest that these young higher-mass stars host similar magnetic properties to their main sequence descendants - strong, stable, globally-ordered fields that are detected in approximately 10 percent of all stars. This strongly contrasts with lower-mass stars, where it is generally accepted that a solar-like dynamo is in operation that generates more complex, globally-weak fields that are ubiquitous. The consensus is magnetic fields in higher-mass stars are fossil remnants of a magnetic field present in the molecular cloud, or generated very early during stellar formation. This review discusses the spectropolarimetric observations of higher-mass stars and how these observations have guided our current understanding of the magnetic characteristics of young higher-mass stars.

Keywords. stars: magnetic fields, stars: ealry-type, stars: pre–main-sequence, stars: statistics, techniques: polarimetric

1. Introduction

1.1. *Magnetism in low-mass, main sequence stars*

Many articles can be found in these proceedings alone that discuss the magnetic properties of cool, low-mass stars (e.g. Gregory *et al.*), but a brief summary is provided here nonetheless. Magnetism in cool, low-mass stars is ubiquitous. Besides indirect proxies of magnetism (e.g. emission in Balmer lines, Ca H&K lines, or UV, X-ray or radio emission; e.g. Donati & Landstreet 2009), magnetometry of the Sun and other solar analogues reveal these stars to host topologically complex fields. It is also well-established that these same observations indicated the fields to show intrinsic variability on timescales of days, weeks and even years, some of which may be cyclical (analogous to the solar cycle; e.g. Berdyugina 2005).

It is generally well-accepted now that the observed fields in these stars are a result of contemporaneous dynamo processes that convert mechanical energy driven by convection into magnetic energy (Parker (1955)). While the details of dynamo mechanisms are not fully understood, its basic principles are well established over a large range of masses from planets to stars (e.g. Charbonneau 2005; Christensen *et al.* 2009). As a consequence of dynamo processes, a clear correlation between the rotation period of the star and the strength of the magnetic activity is observed (e.g. Donati & Landstreet 2009). Furthermore, as the size of the convective envelope increases, we see significant changes in the characteristics of magnetic field properties that vary from being topologically complex with globally weak magnetic fields (as observed in solar analogues) to being more organized with globally stronger fields (as observed in the fully convective M-dwarfs (e.g. Morin *et al.* 2010)). Therefore, in addition to a clear correlation between rotation and magnetic activity, there is also a clear correlation between stellar mass/internal structure and the magnetic properties (e.g. Donati & Landstreet 2009).

1.2. *Magnetism in intermediate-mass main sequence stars*

In contrast to cool, low-mass stars, more massive stars ($M \gtrsim 1.5\,\mathrm{M}_\odot$) have a significantly different internal structure. Instead of an outer convective envelope (as found in stars with $M \lesssim 1.5\,\mathrm{M}_\odot$), higher-mass stars host an outer radiative envelope. Without the necessary convective motion in their outer envelopes, higher-mass stars are therefore not expected to drive a dynamo. Indeed, classical observational tracers of dynamo activity fade and disappear among stars of spectral type F, at roughly the conditions predicting the disappearance of energetically-important envelope convection. Despite this fact, magnetic fields have been detected in a small population of (over 400) A- and B-type stars (e.g. Bychkov *et al.* 2009) dating back over 60 years to the first discovery by Babcock (1947). These stars are easily identifiable as they present distinctive photospheric chemical peculiarities compared to non-magnetic A- and B-type stars, presumably a result of the magnetic field (e.g. Folsom *et al.* 2007).

Compared to the magnetic fields found in low-mass stars, the incidence and characteristics of magnetic fields found in intermediate-mass stars ($1.5 \lesssim M \lesssim 8\,\mathrm{M}_\odot$) are significantly different. While magnetism in low-mass stars is essentially ubiquitous, magnetic fields are only detected in 5-10% of the population of intermediate-mass stars (e.g. Bagnulo *et al.* 2006). Observations suggest that the majority of intermediate-mass stars present globally-ordered, topologically simple magnetic fields, often characterized by a dipole or a low-order multipole (e.g. Aurière *et al.* 2007), although a few stars show evidence for additional small-scale structure (e.g. Kochukhov *et al.* 2004; Kochukhov & Wade 2010). Furthermore, the magnetic axis is typically found to be oblique to the rotation axis.

In strong contrast to the topologically variable fields found in low-mass stars, observations of intermediate-mass stars suggest the fields to be stable over timescales of at least decades (e.g. Silvester *et al.* 2012). The interpretation is that the magnetic field is *frozen* into the star and any observed variations result from rotational modulation. Additionally, unlike low-mass stars, there appears to be no strong correlation between the fundamental physical and magnetic properties (e.g. Donati & Landstreet 2009). Curiously, there appears to be a puzzling magnetic dichotomy among intermediate-mass stars (Aurière *et al.* 2007) - these stars are either found to be highly magnetic (polar field strengths $> 300\,\mathrm{G}$) or non-magnetic. However, this picture has changed slightly over the last few years with the discovery of very weak magnetic fields in a few bright stars (longitudinal field strengths $< 1\,\mathrm{G}$; e.g. Lignières *et al.* 2009; Petit *et al.* 2011; see also Lignières *et al.* in these proceedings).

The surface polar field strengths of the highly-magnetic stars are generally strong, ranging from several hundred to tens of thousands of gauss (e.g. Donati & Landstreet 2009). The strongest fields among the intermediate-mass stars detected to date are in the range of $\sim 30-35\,\mathrm{kG}$ (e.g. HD 215411 (Babcock 1960); HD 75049 (Freyhammer *et al.* 2008; Elkin *et al.* 2010)). While the overwhelming majority of magnetic intermediate-mass stars host dipolar magnetic fields, there are a few exceptions that host more complex fields (e.g. HD 32633 (Leone *et al.* 2000), HD 133880 (Landstreet 1990; Bailey *et al.* 2012), HD 137509 (Kochukhov 2006)).

The magnetic properties of intermediate-mass stars suggest a fundamentally different origin for the field - the observed fields cannot be generated by a contemporaneous dynamo. Despite our greatly improved understanding of the characteristics and statistical properties of magnetism among intermediate-mass main sequence stars, the fundamental question regarding the origin of the magnetic field is still debated.

2. The origin of magnetism in higher-mass stars

The reader is also encouraged to read the discussion of the origin of magnetism in higher-mass stars from Braithwaite *et al.* (these proceedings).

2.1. *Dynamos*

2.1.1. *Core-dynamo*

As already discussed, it is well established that dynamo processes are responsible for contemporaneously driving the magnetic fields observed in low-mass stars, so it is not surprising to imagine similar processes being responsible for the fields observed in higher-mass stars. Since higher-mass stars lack a significant convective envelope, it has been proposed that dynamo fields could instead be generated deep in the stellar cores (Charbonneau & MacGregor 2001; MacGregor & Cassinelli 2003; Brun *et al.* 2005). While it has been shown that a dynamo generated field is capable of being generated in the core, it is unlikely that those fields can be transported to the stellar surface where they can be observed and detected e.g. Walder *et al.* 2012. The two suggested mechanisms for transporting magnetic flux from the core to the surface are through buoyancy/diffusion and/or meridional circulations. However, MacGregor & Cassinelli (2003) point out that the timescales for buoyancy/diffusion are longer than the typical main sequence lifetime of intermediate-mass stars and therefore should not be observable at the surface. Furthermore, strong meridional currents are necessary to transport magnetic flux to the surface (Charbonneau & MacGregor 2001, but MacGregor & Cassinelli (2003) show that these required strong currents inhibit the dynamo process. Therefore, core-dynamo generated fields are unexpected to account for the observed magnetic fields.

2.1.2. *Sub-surface convection*

In recent years another theory has emerged suggesting that a thin, sub-surface iron convection zone may be responsible for generating magnetic fields (Cantiello *et al.* 2009; Cantiello & Braithwaite 2011). The sub-surface convection theory shares many parallels with the dynamos acting in solar-like stars. Because of this, one expectation is that there should be a strong correlation between stellar mass (which correlates with the size of the iron convection zone) and the field strength. Unfortunately, the known intermediate-mass magnetic stars don't span a large enough range of mass to test this hypothesis. However, as with other dynamo generated fields, the produced fields should be intrinsically variable, which would highly suggest that sub-surface convective dynamos cannot be responsible for the stable, large-scale fields observed in intermediate-mass stars.

2.2. *Fossil origin*

The leading hypothesis suggests that the observed strong and stable magnetic fields are *fossil* fields - the frozen remnants of the Galactic field accumulated and possibly enhanced by a dynamo field generated in an earlier phase of evolution (e.g. Cowling 1945; Mestel 2001; Moss 2001). Numerical and analytical studies show that the surviving fields can relax into configurations exhibiting long-term stability (Braithwaite 2009; Duez & Mathis 2010) and can approximately explain the field topology and other general characteristics of magnetism in intermediate-mass stars. The presence of instabilities (e.g. Tayler 1973; Spruit 1999 during the relaxation process can potentially account for the observed magnetic dichotomy, since only strong fields are expected to survive (Aurière *et al.* 2007). This may potentially explain why all higher-mass stars are not magnetic, but it does not naturally explain why only about 10% host strong magnetic fields.

2.3. *Stellar mergers*

A competing hypothesis that has been gaining significant traction in recent years suggests that the strongly magnetic higher-mass stars are the result of either a stellar merger or mass-transfer event (e.g. Tutukov & Fedorova 2010. Largely motivated by the dearth of magnetic higher-mass stars observed in close binary systems (Abt & Snowden 1973; Carrier *et al.* 2002), the merger hypothesis (e.g. Ferrario *et al.* 2009) suggests that the strong differential rotation or other velocity flows induced during the merger/mass-transfer episode drive a strong but short-lived dynamo field (e.g. Lacaze *et al.* 2006; Donati *et al.* 2008), which ultimately relaxes into a stable configuration. The dynamo action eventually ceases and the resulting field establishes a stable configuration as predicted by Braithwaite (2009) and Duez & Mathis (2010), similar to the fossil field hypothesis. A similar hypothesis is also proposed to account for the highly-magnetic white dwarfs (Tout *et al.* 2008). The attractiveness of this hypothesis is that it more naturally explains why only 10% of higher-mass stars (the mergers) host strong magnetic fields.

2.4. *Understanding magnetism in intermediate-mass main sequence stars*

While the currently favoured hypothesis is that the observed magnetic fields in intermediate-mass main sequence stars are of fossil origin, there are still some outstanding questions that need to be addressed. One particular question is at what stage of the PMS evolution these fields first appear. Furthermore, even though arguments against dynamo fields were already presented, further observational constraints are ideal. To this end, if dynamos are responsible for the observed fields then one would expect a correlation between mass and field properties, similar to what is observed in low-mass stars (or as predicted by Cantiello & Braithwaite (2011)). To address these and other issues we discuss the results of ongoing investigations to study the magnetic properties of a pre-main sequence stars and massive stars.

3. Magnetism in pre-main seqeunce intermediate-mass stars

3.1. *Pre-main sequence evolution*

The pre-main sequence phase of evolution is defined as the period of stellar formation after the proto-stellar phase, but before the main sequence phase where a star is undergoing core-hydrogen burning. At the beginning of the PMS phase the star is on the birthline - the locus of points in the HR diagram where the star is, for the first time, observable at optical wavelengths after shedding the majority of its proto-stellar envelope and is no longer undergoing significant accretion (Stahler 1983). At this point, nuclear-burning has not yet started in the star's core and slow gravitational collapse is the main source of energy. Just before the end of the PMS phase, nuclear reactions begin, contributing more and more energy to the luminosity of the star. As the star evolves closer to the Zero-Age-Main-Sequence (ZAMS), gravitational contraction slows, eventually coming to a stop (see Fig. 1).

Typically, the theoretical birthline computed by Palla (1990) for PMS intermediate-mass stars (the so-called Herbig Ae/Be (HAeBe) stars), using a single proto-stellar mass-accretion rate of $10^{-5}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, is adopted as it well-reproduces the upper envelope of observed distribution of intermediate-mass stars in an HR diagram. However, above $8\,\mathrm{M}_\odot$ this birthline intersects the ZAMS, suggesting that no pre-main sequence stars more

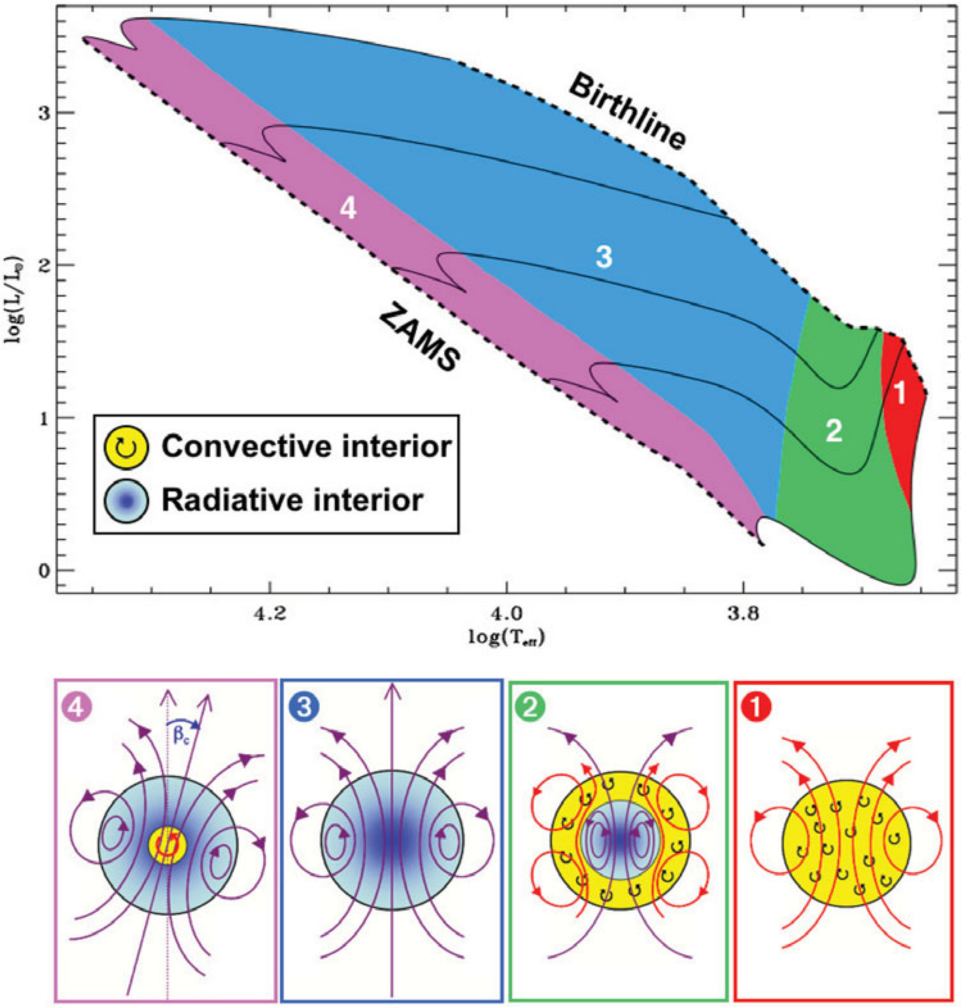

Figure 1. Top: Pre-main sequence evolutionary tracks (full lines) for 1.2, 2, 3, 5, and 8 $M_\odot$, computed with CESAM (Morel 1997). The birthline is from Behrend & Maeder (2001). The shaded area separate regions with different internal stellar structures: phase 1 (red) - fully convective interior, phase 2 (green) - radiative core + convective envelope, phase 3 (blue) - fully radiative interior, phase 4 (purple) - convective core + radiative envelope. **Bottom:** Schematic view of the possible structure of the magnetic field for the four different phases. Regions drawn in yellow with circular arrows represent convection where dynamo fields are generated (represented with red field lines). Blue regions represent radiative interiors containing large-scale fossil fields (represented with purple field lines).

massive than 8 $M_\odot$ should be visible in the optical domain. Therefore, a single mass-accretion rate for all masses might not be fully correct, as argued by Alecian *et al.* (2013), and instead an alternate birthline, such as that computed by Behrend & Maeder (2001) could be used. In computing their birthline, Behrend & Maeder (2001) assume that all stars, independent of their final mass, evolve along the birthline, increasing in mass (from the lower right to the upper left), during the proto-stellar phase during which accretion is the dominant source of energy. Since the star is still embedded in its parental cloud it accretes a large amount of material with an accretion rate that depends on the mass (luminosity) of the embedded star. Once the star has accreted most of its close, surrounding material, it leaves the birthline and evolves along the usual PMS track. In this simple view, all stars, independent of their mass, have been formed from a unique core of a certain mass, and the final mass of the star is determined from the mass of the original cloud from which the star forms.

Within this view of star formation, the energy transport within all higher-mass stars undergo significant variations. The usual PMS evolution of an intermediate-mass star begins with the star containing a fully convective interior and therefore the star initially evolves along the Hayashi track, almost vertically in the HR diagram. As the star continues to contract its core reaches a critical temperature at which point energy is more efficiently transported by radiation. From this point on the radiative core continues to grow until it reaches the surface. Eventually, nuclear reactions are ignited in the core and convection becomes the most efficient means of energy transport, right before the star reaches the ZAMS (Fig. 1). For higher mass stars, the evolution is very similar, but most of the internal structural changes occur as the star evolves along the brithline, and therefore begin their PMS life with either a partially or totally radiative interior.

It should be emphasized here that, according to this scenario of star formation, all stars, independent of their final mass, go through a fully convective phase. Therefore, the passage of all higher-mass stars through a fully convective phase needs to be seriously considered in any theory for the origin of magnetic fields in higher-mass stars, as convective motion can have a significant impact on the generation or enhancement of magnetic fields. To this end, the following section will review an ongoing project that has been undertaken over the last decade to determine the magnetic properties of PMS intermediate-mass stars during the four major phases of the PMS evolution (the fully convective phase, the core-radiative phase, the fully radiative phase, and the core-convective phase, respectively red, green, blue and purple in Fig. 1).

3.2. *Magnetism in intermediate-mass pre-main sequence stars*

A high-resolution ($R \sim 68000$) circular polarization (Stokes V) spectropolarimetric survey of 128 HAeBe stars was carried out using ESPaDOnS at the Canada-France-Hawaii Telescope and Narval and the Télescope Bernad Lyot. A sample of field HAeBe stars were selected from the catalogue of Thé *et al.* (1994) and Vieira *et al.* (2003), while an additional sample were selected from members of the following young clusters: NGC 2244 (Park & Sung 2002), NGC 2264 (Sung *et al.* 1997), and NGC 6611 (de Winter *et al.* 1997). It should be noted that the global magnetic properties of HAeBe stars were unknown before this survey. In order to increase the S/N and enhance our sensitivity to weak magnetic Zeeman signatures (used to diagnose and characterize the presence of magnetic fields), we employed the Least-Squares Deconvolution (LSD) multi-line technique of Donati *et al.* (1997) in our analysis. This survey obtained magnetic detections in 8 stars (e.g. Wade *et al.* 2005; Alecian *et al.* 2008b), some of which are fully radiative, and finds a magnetic incidence fraction of ∼6%, similar to the incidence that is found for intermediate-mass main sequence stars. Spectropolarimetric monitoring of many of the detected stars was also carried out in order to characterize the strength and structure of their surface fields. Our results indicate that the magnetic properties of HAeBe star are similar to what is found on the main sequence - the fields are mainly dipolar, are strong (surface field strengths of 300 G to 4 kG), and stable over many years (e.g. Alecian *et al.* 2008a, 2009). This survey has therefore established a direct link between the magnetic properties of stars found on the PMS and on the main sequence. We can therefore conclude that the magnetic properties of A/B stars must have been shaped before the HAeBe phase of the stellar evolution (Alecian *et al.* 2013).

3.3. *Magnetism in young massive stars*

While the magnetic properties of main sequence intermediate-mass stars are well studied, there is a distinct lack of information about magnetism in main sequence massive stars ($M > 8\,\mathrm{M}_\odot$). This largely reflects the fact that unlike intermediate-mass magnetic stars that show strong and distinctive photospheric chemical peculiarities compared to non-magnetic A- and B-type stars (and therefore can be used as a proxy for magnetism), the strong, radiatively-driven outflows of more massive stars generally inhibit these chemical peculiarities, making them difficult to identify. Furthermore, the relatively weak fields of these stars coupled with relatively few spectral lines from which to directly diagnose the presence of magnetism in the optical spectra of massive stars meant that these fields remained undetected by previous generations of instrumentation. Magnetic fields were detected in a small number of massive stars, the majority of these being He-peculiar B-type stars that are high-mass extensions of the chemically-peculiar intermediate-mass stars (e.g. Bohlender *et al.* 1987). Among the massive O-type stars, only 3 were known to be magnetic prior to 2009: θ^1 Ori C, HD 191612 and ζ Ori A† (Donati *et al.* 2002, 2006; Bouret *et al.* 2008).

Thanks to the new generation of spectropolarimeters and large international initiatives like the Magnetism in Massive Stars (MiMeS) project, the magnetic properties of young massive stars are now being thoroughly investigated (see Wade *et al.* (these proceedings) for more information about the MiMeS project and results). In particular, a large survey of ~550 Galactic B9-O4 stars were observed as part of the MiMeS project. A magnetic incidence fraction of $7 \pm 1\%$ is inferred from this sample of stars, which is fully consistent with the incidence fraction among intermediate-mass stars. Furthermore, an incidence fraction of $8 \pm 2\%$ is derived from sample of B-type stars, which is fully consistent with the $6 \pm 3\%$ that is found from the O-type stars.

Of particular interest to this article are the results for O-type stars, as these stars are much more massive than the intermediate-mass stars and are also very young. The MiMeS project has more than tripled the number of known magnetic O-type stars. Magnetic fields have now been firmly detected in 9 O-type stars: θ^1 Ori C, HD 191612, HD 108 (Martins *et al.* 2010), HD 57682 (Grunhut *et al.* 2009, 2012), HD 148937 (Wade *et al.* 2012a), Tr16-22 (Nazé *et al.* 2012), CPD -28 2561 (Wade *et al.* 2012c), NGC 1624-2 (Wade *et al.* 2012b), and Plaskett's star (Grunhut *et al.* 2013). Detailed investigations of these stars (e.g. Grunhut *et al.* 2012) have revealed that these stars host mainly dipolar, strong (surface polar field strengths from 300 G to ~22 kG), and stable fields, similar to the properties found for main sequence and PMS intermediate-mass stars.

4. Discussion

The results reported here establish that the statistical and magnetic properties of stars with outer radiative envelopes remain unchanged across 1.5 decades of mass and over a large range of ages from the pre-main sequence onwards. Systematic surveys and detailed observations reveal that between 5-10% of these stars host strong ($\gtrsim 300$ G), stable, globally-ordered (mainly dipolar) magnetic fields.

With this information we can now seriously address the question of the origin of magnetism in these stars. Based on the presence of magnetic fields in fully radiative stars, and the lack of correlations between the field properties (such as strength or complexity) with stellar properties, we can all but rule out dynamos as the origin of the large-scale

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† New observations do not confirm the original claim by Bouret *et al.* (Bouret *et al.* (2008)) (Neiner *et al.* in prep)

fields that are observed. Unfortunately, at this point in time there are no real constraints regarding stellar mergers as the origin of the observed fields; however, further interest into this hypothesis is gathering with the discovery of a magnetic field in the secondary companion of the massive, close binary system known as Plaskett's star (Grunhut *et al.* 2013) and from the suggestion that the bipolar nebula around HD 148937 is remnant ejecta from a merging event (Langer 2012). Since the incidence fraction of magnetism amongst PMS stars is fully consistent with that of main sequence stars, strong constraints are placed on the time-frame for these events - the majority of these interactions must occur prior to the PMS phase, and are possibly the result of orbital decay (Korntreff *et al.* 2012). If the majority of these stellar interactions occur very early in the star's evolution then the observed fields (at a later stage of evolution) are essentially indistinguishable from fossil fields.

The fossil field hypothesis naively implies that all high-mass stars should display magnetic fields at their surface. This clearly disagrees with observations that find a magnetic incidence fraction of 5-10%. A natural explanation would be the existence of fundamental differences in the initial conditions of star forming regions (e.g. local density, local magnetic field strength, etc.). An efficient way to test this hypothesis is to study the magnetic properties of a large number ($\sim$150) of close binary systems, containing two stars formed at the same time and from the same environment. This is one of the aims of the recently initiated BinaMIcS project (Binarity and Magnetic Interaction in various classes of Stars; see Mathis *et al.* (these proceedings) for further details). Among other objectives, this project will acquire about 300 high-resolution spectropolarimetric spectra of 150 close binary systems, thanks to large programs obtained at CFHT (PI: Alecian/Wade) and TBL (PI: Neiner). These data will allow us to determine the incidence and to characterize the magnetic fields of both components of these binaries. Since close binaries are expected to be coeval, BinaMIcS will therefore help us to disentangle the effects of initial conditions from other effects (such as early evolution or rotation). This project provides one further step towards understanding the origin of magnetic fields and the magnetic properties of close binaries (Alecian, Wade, Mathis, Neiner *et al.*, in prep.).

In light of of this discussion our current view of the evolution of magnetic fields in PMS intermediate-mass stars is schematically described in Fig. 1. During phase 1 the star is expected to be fully convective, and just like main sequence fully-convective stars (M-dwarfs) that present globally-ordered magnetic fields at their surfaces, we propose that the PMS stars found at this stage should also generate similarly simple and strong large-scale fields. In phase 2, when the radiative core appears, we expect a solar-type dynamo to be driven by the convective envelope and therefore produce a complex surface field. At the same time, the field originally created in phase 1 relaxes in the radiative core. Once the star reaches phase 3 and becomes fully radiative, a dynamo no longer operates and the relaxed fossil field is now observable at the stellar surface. In the final stage when the convective core appears (phase 4), an interaction of the dynamo generated in the core and the relaxed fossil field in the radiative envelope could occur. To this end, Featherstone *et al.* (2009) performed simulations to study such an interaction. They find that an interaction could occur that could result in the change of the obliquity of the fossil field. This likely accounts for the various observed magnetic obliquities.

Acknowledgements

Some of the work described in this contribution was undertaken in collaboration with many other scientists. The authors would like to thank these collaborations and especially C. Catala, C. P. Folsom, G. Hussain, J. Landstreet, N. Langer, S. Mathis, J. Morin, C. Neiner, and G. A. Wade.

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Discussion