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Magnetic Fields in Massive Stars, their Winds, and their Nebulae

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Abstract Massive stars are crucial building blocks of galaxies and the universe, as production sites of heavy elements and as stirring agents and energy providers through stellar winds and supernovae. The field of *magnetic* massive stars has seen tremendous progress in recent years. Different perspectives – ranging from direct field measurements over dynamo theory and stellar evolution to colliding winds and the stellar environment – fruitfully combine into a most interesting and still evolving overall picture, which we attempt to review here. Zeeman signatures leave no doubt that at least some O- and early B-type stars have a surface magnetic field. Indirect evidence, especially non-thermal radio emission from colliding winds, suggests many more. The emerging picture for massive stars shows similarities with results from intermediate mass stars, for which much more data are available. Observations are often compatible with a dipole or low order multi-pole field of about 1 kG (O-stars) or 300 G to 30 kG (Ap / Bp stars). Weak and unordered fields have been detected in the O-star ζ Ori A and in Vega, the first normal A-type star with a magnetic field. Theory offers essentially two explanations for the origin of the observed surface fields: fossil fields, particularly for strong and ordered fields, or different dynamo mechanisms, preferentially for less ordered fields.

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Numerical simulations yield the first concrete stable (fossil) field configuration, but give contradictory results as to whether dynamo action in the radiative envelope of massive main sequence stars is possible. Internal magnetic fields, which may not even show up at the stellar surface, affect stellar evolution as they lead to a more uniform rotation, with more slowly rotating cores and faster surface rotation. Surface metallicities may become enhanced, thus affecting the mass-loss rates.

Keywords massive stars · magnetic fields · dynamos · fossil field · stellar evolution · binaries · colliding winds · non-thermal emission

1 Introduction

One may wonder why a review on magnetic fields in massive stars enters a book dealing with large scale magnetic fields in the universe. Several reasons may be given.

A first line of argument may stress the relevance of massive stars as cosmic engines for the chemical and dynamical evolution of galaxies and the universe, their role as production sites of heavy elements and as stirring agents and energy providers in the form of stellar winds, supernova explosions, gamma ray bursts, and galactic super-bubbles. Also, if the stars are magnetic, their wind driven structures will be magnetized as well. One may further argue with the magnetic dipole field observed at the surface of some massive stars, whose large scale ordering not trivial to achieve or maintain. Or with the conditions under which magnetic fields in massive stars exist or form, which represent relative exotic locations of the parameter space. Massive stars may be viewed as laboratories to study and observe magnetic fields under such conditions. Better understanding of the role of magnetic fields in massive stars then will not only help to better understand the role of massive stars in the universe but will also broaden our knowledge on the existence and generation of magnetic fields in the universe. Like the field of magnetism in massive stars has profited from combining different points of view, from direct field measurements to modeling of colliding winds, the reader of this book may profit from the presented largely different perspectives on magnetism in the universe.

The term massive star is typically used for stars with initial masses above 8 $M_\odot$, which will ultimately end their lives as supernovae. Early type massive stars refer to massive stars of spectral type O or B, thus stars on or close to the main sequence but not, for example, massive stars having entered the red super-giant phase. The first definite magnetic field detections in massive stars, by means of spectropolarimetry, date back only about a decade, to around the year 2000. Since then, observational techniques have been further refined and field detections, although still difficult for physical reasons, have multiplied. We stress that all these detections refer only to *surface magnetic fields*, and that any *magnetic fields in the interior* of stars need not even show up at the surface. A 'snapshot' overview of the rapidly evolving observational results is given within the frame of this review, Sect. 2.

Crucial and interesting with regard to magnetic fields in massive stars is the radiative envelope of these stars, which prevents the existence of a solar type dynamo. Any magnetic field thus must be due to another cause. Theories on the origin of magnetic fields in early type massive stars may be roughly divided into two categories: dynamos working differently than the solar dynamo or fossil fields of debated origin that are present before the star reaches the main sequence. The dynamo aspects may link to another review in this book on turbulent dynamos. Similarly, the fossil fields may link to the review by Beck et al., which touches on magnetic fields in the ISM. Part of this review, Sect. 3, is devoted to a more detailed presentation of these theories, their analytical argumentation as well as numerical simulations which allow to access the non-linear and time-dependent regime.

Equally important as the cause of magnetic fields in massive stars are the consequences of such fields. The issue may again be roughly subdivided into two parts, consequences for the stellar evolution and consequences for the ambient medium. Even weak magnetic fields in the stellar interior, which may not even show up as surface fields, are expected to affect the stellar evolution from 'cradle to graveyard', by modifying the internal transport of angular momentum. Subsequent changes in the transport of chemical yields, surface abundances, or mass loss, may even influence the ultimate fate of the star as a neutron star, gamma-ray burst, or black hole. Sufficiently strong surface fields can, by contrast, convincingly explain a number of observational signatures originating at the surface of or at some distance from the star. Termination shocks of magnetized winds or wind collision in binaries or open clusters can contain indirect evidence on the presence of a stellar magnetic field. Moreover, such structures could potentially serve as a laboratory to test non-thermal shock models, super-enhancement of magnetic fields in shocks, or particle acceleration, aspects which may link to two other contributions in this volume, one on supernova remnants and pulsar nebulae, the other on particle acceleration. The consequences of stellar magnetic fields add another two parts to this review, Sect. 4 and 5.

The presented material and the rapid speed at which this knowledge, observational and theoretical, currently grows leads us to believe that some of the above questions will have a more definite answer in the not too far future. Some more room to these considerations will be given in the closing section of this review, Sect. 6.

2 Observations of Surface Fields in Intermediate and High Mass Stars

Stellar magnetism is ubiquitous in most parts of the HR diagram, along the main sequence as well as during pre- and post-main-sequence evolution (Berdyugina 2009; Donati and Landstreet 2009). With the possible exception of a narrow mass range between 1.5 and 1.6 $M_\odot$ (Donati and Landstreet 2009) stellar magnetism has been found throughout the main sequence. Widely different are, however, the concrete manifestations of stellar magnetism, such as the strength of the field, the field topology, or just the percentage of stars of a given spectral type which have a detectable magnetic field. Our knowledge on these aspects has been rapidly evolving in recent years, as better instruments became available and data analysis techniques were refined. This development is still ongoing and, consequently, some of the current conclusions may need revision in the future, when both the quality and quantity of the observational data will have increased even further. We include a brief overview of current observational techniques in Sect. 2.1 in the hope that this will help the reader to better rate the reviewed observational results.

Current observational data suggests the following rules of thumb, which may be subject to change as new data becomes available. Magnetic fields are common among low-mass stars ($M < 1.5\ M_\odot$), but only a minority of intermediate- and high-mass stars ($M > 1.5\ M_\odot$) show a magnetic field. The field topology in intermediate- and high-mass stars is frequently dominated by a simple dipole, while low-mass stars typically display a much richer topology. For intermediate- and high-mass stars, the presence of a magnetic field often goes hand in hand with a comparatively slow rotation of the star and with a chemically peculiar photosphere.

These rules of thumb demand for physical explanation, thus inspiring a lively and ongoing debate on the detailed physical origins and consequences of magnetic fields in intermediate- and high-mass stars. Some aspects of this debate deserve mentioning here as they directly feed back in new observational campaigns. Fossil fields (see Sect. 3.3), for example, are the currently favored explanation for the dipole magnetic fields in intermediate- and high-mass stars, in contrast to convection in low-mass stars. This explanation promoted recent observational surveys to search for magnetic fields in intermediate and high-mass pre-main-sequence stars. Magnetic braking as the proposed agent to explain the on average slower rotation of magnetic stars inspired observational efforts to find a possible age - magnetic field strength relation ship. The argument that magnetic dipole fields are stable only above a certain threshold field strength led to an intense search for stars with field strengths below this threshold value (see Section 2.2).

2.1 Measuring Stellar Magnetic Fields

Babcock (1947) showed that the circular polarization observed in some absorption lines of the spectrum of 78 Vir can be interpreted in terms of the Zeeman effect and thus give access to the measurement of magnetic fields in stars. Since then, observational techniques have been greatly refined (Mathys 1989; Kochukhov 2006b; Donati and Landstreet 2009). A recent review on current instruments and techniques, given at the IAU symposium 272 on active OB stars, can be found in Petit (2010).

The basic idea behind Zeeman-measurements is simple. The component of a magnetic field parallel to the line of sight of an observer, B_l, manifests itself in a split of spectral lines into two components of opposite circular polarization (Landstreet 2009). For relatively weak magnetic fields the resulting Zeeman shift $\Delta\lambda$ between the two components is proportional to B_l, the magnetic splitting sensitivity or effective Landé factor g_{eff}, and the wave length squared,

$$\Delta\lambda \propto B_l g_{eff} \lambda^2. \tag{1}$$

The Zeeman shift thus is particularly pronounced for strong fields (large B_l) and large wave lengths (infra red).

In real observations, complications of this simple picture arise from mainly two sides. First, thermal and stellar rotation broadening are superimposed on the the $\Delta\lambda$ of the Zeeman shift. The Zeeman effect thus may only result in some additional line broadening and not in any clear line splitting. Second, the observed spectral signal is an average signal from the entire stellar disk, thus not due to one particular value of B_l but rather due to a composite of magnetic field strengths and orientations. If polarity of the field changes over the stellar disk, significant cancellation of the observable signal results. Taken together these effects demand for a measurement accuracy on the order of 10^{-3} to 10^{-4} if stellar magnetic fields are to be detected (Donati and Landstreet 2009; Berdyugina 2009). Only for strong dipole fields of slowly rotating stars (as in some Ap stars) the Zeeman-effect may be directly visible as a splitting of spectral lines in intensity spectra (Stokes I). In these cases, or if at least a substantial line broadening exists, one may determine the mean value of the field strength averaged

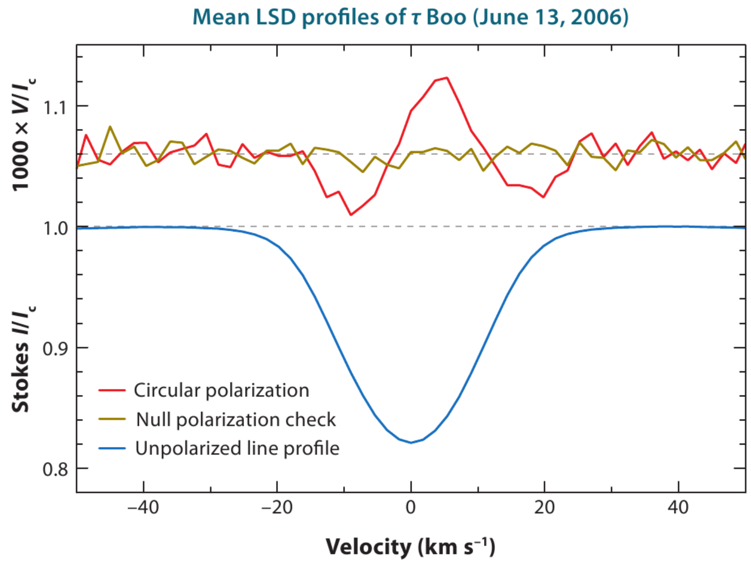

Fig. 1 LSD circular polarization (Stokes V) Zeeman signature (red line), null polarization check (dark yellow line, both expanded by 1000 and shifted vertically by 1.06 for graphical purposes) and unpolarized (Stokes I) profile (blue line) from the photospheric lines of τ Boo, as derived from ESPaDOnS data. A clear Zeeman signature is detected. The Figure is taken from Donati and Landstreet (2009), their Figure 1.

over the stellar disk, $< |B| >$, also known as the mean field modulus or mean surface field $< B >$ without detailed line profile modeling (Mathys 1995; Mathys and Hubrig 2006; Landstreet 2009).

The magnetic field observations reviewed in this article address these difficulties in mainly two ways. First, on the 'hardware' side, by measuring circular polarization profiles (Stokes V) with high frequency resolution. Second, on the 'software' side, by combining Zeeman signatures from several spectral lines to increase the signal to noise ratio and by combining observations taken at different times, thus different rotational phases of the star, to learn more about the 3D field topology.

The currently most advanced instruments for magnetic field observations in massive stars are two high-resolution spectropolarimeters. One of them is ESPaDOnS (Donati 2003), installed in 2004 on the Canada-France-Hawaii Telescope on Mauna Kea, Hawaii. The other is, NARVAL (Aurière 2003), a clone of ESPaDOnS, installed at the Télescope Bernard Lyot on Pic du Midi, France. Both instruments are regularly used by the MiMeS (Magnetism in Massive Stars) project (Wade et al. 2009b; Wade and the MiMeS Collaboration 2010). Two other instruments that were frequently used in recent years for magnetic field observations in massive stars are the low-resolution spectropolarimeter FORS1 on the ESO Very Large Telescope (VLT) on Cerro Paranal, Chile, and MUSICOS (Donati et al. 1999), also on Pic du Midi, France.

The basic idea for increasing the signal to noise ratio is to combine the information from numerous spectral lines instead of analyzing only a single line. Different approaches exist to achieve this combination of multiple lines and Semel et al. (2009) recently suggested to summarize all these different methods under the term

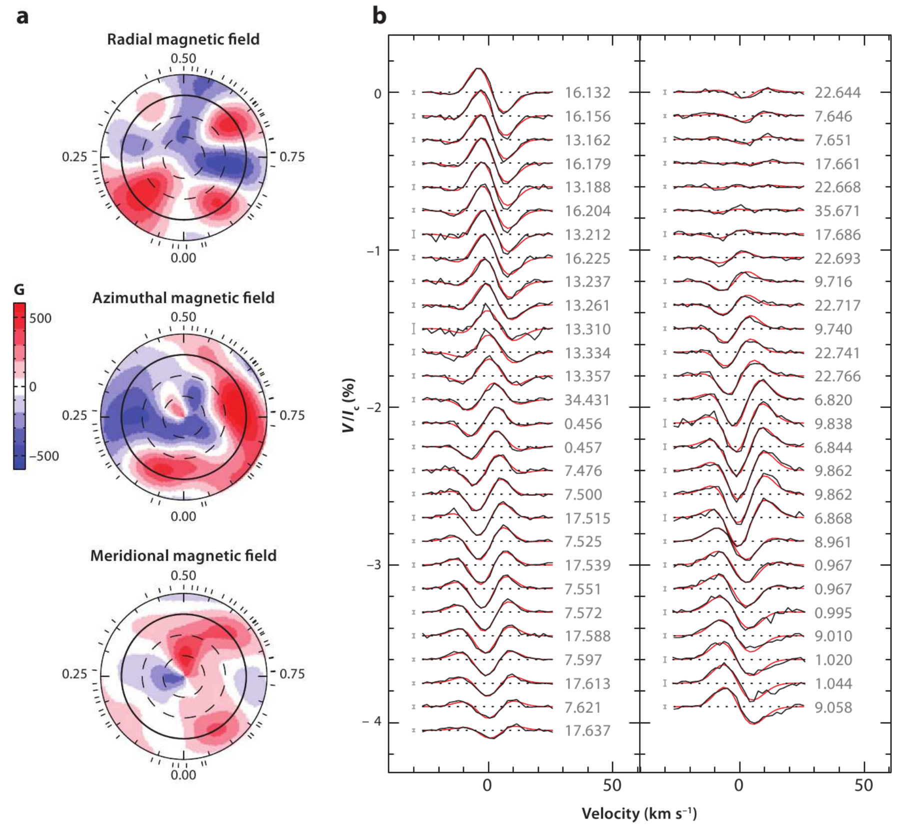

Fig. 2 Large-scale magnetic topology of the young early B-star τ Sco (**right**) derived with ZDI from a time series of circular polarization (Stokes V) Zeeman signatures covering the whole rotation cycle (**left**). The Figure is taken from Donati and Landstreet (2009), their Figure 5.

multi-line Zeeman signature (MZS). One very basic approach is known as line addition technique (Semel 1989; Semel and Li 1996). Here, several observed lines are just added up. Another technique is the Least Squares Deconvolution (LSD) introduced by Donati et al. (1997) and illustrated in Figure 1. Comparing the two techniques by applying them to a synthetic test, case Semel et al. (2009) obtain very similar results. A detailed investigation of the capabilities and limitations of LSD can be found in Kochukhov et al. (2010). More recently, yet another technique was proposed for de-noising the Zeeman signatures, based on principle component analysis (PCA) (Semel et al. 2006; Martínez González et al. 2008).

To obtain information not only on the line of sight magnetic field component but on its 3D structure it would be necessary to measure also Stokes Q and U, in addition to Stokes V. However, these components carry an even weaker signature than Stokes V. Therefore, they are hardly explored so far in the context of massive stars. An alternative approach is followed instead, by exploring the time dependence of the Zeeman signatures. To illustrate the basic idea, assume a star with a bipolar magnetic field, the dipole not being aligned with the rotation axis of the star. A distant observer will see the Zeeman signature to vary with time as the dipole axis processes about the rotation

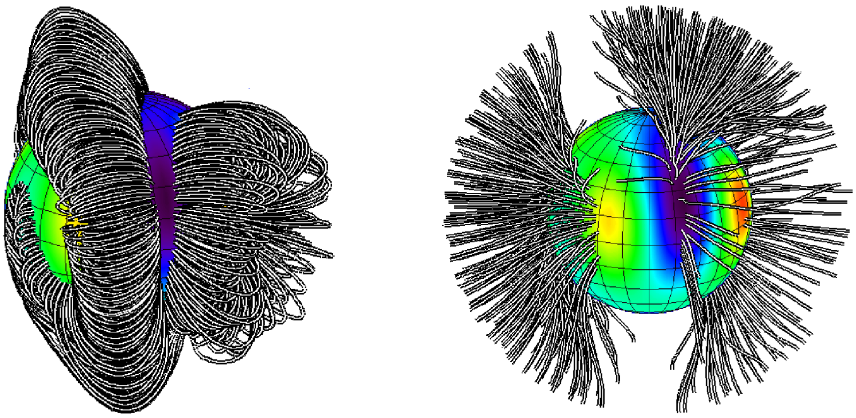

Fig. 3 Closed (**left**) and open (**right**) magnetic-field lines of the extended magnetic field configuration of τ Sco, extrapolated from photospheric maps using the technique by Jardine et al. (1999). The star is shown at phase 0.83. The Figure is taken from Donati et al. (2006b), their Figures 11 and 12.

axis of the star. Note that the interpretation of such a signal requires the inclination i of the rotation axis of the star to be known. The time dependent Zeeman signature carries the imprint of the magnetic dipole field. Information on the dipole (or higher moments) can be retrieved again from this signal by decomposing the observational data in terms of spherical harmonics. This technique today is known under the name Zeeman Doppler imaging (ZDI). An example of ZDI is shown in Figure 2, derived field lines using the field-extrapolation technique by Jardine et al. (1999) are shown in Figure 3.

Note that the term ZDI originally stood for the detection of a Zeeman signature thanks to the Doppler effect (Semel 1989; Semel et al. 2009). In fast rotating stars, the later can help to disentangle the contributions from opposite magnetic polarities and their respective opposite polarization which otherwise may cancel. The combination of Zeeman and Doppler effects is one of the reasons why the detection of the Zeeman effect in fast rotating active solar type stars became possible.

2.2 A and late B stars

A and B stars account for around 0.6 % and 0.1 %, respectively, of all main sequence stars in the HR diagram. Their masses range between 1.4 - 2.1 $M_\odot$ (A stars) and 2.1 - 16 $M_\odot$ (B stars). A small fraction of these stars distinguishes themselves from normal A- and B-type stars by chemically peculiar atmospheric compositions, for example high abundances of Si, Cr, Sr, or Eu (Preston 1974; Landstreet et al. 2007). These stars are commonly referred to as CP stars. A subset of these stars are the Ap/Bp stars. In the following, *we will collectively refer to these stars as Ap stars.*

Typically, Ap stars display periodic variability on time scales that range from about half a day up to several decades and that are inversely correlated with $v \cdot \sin i$, where i denotes the inclination of the rotational axis of the star and v the rotation velocity. The variability is commonly attributed to a magnetic dipole field, whose axis is not aligned with the rotation axis of the star. In fact, the strongest magnetic fields observed to date in non-degenerated stars belong Ap stars: HD 215441 (34 kG) (Babcock 1960), HD 75049 (30 kG) (Freyhammer et al. 2008; Elkin et al. 2010), HD 137509 (29 kG) (Mathys 1995; Kochukhov 2006a), HD 154708 (24.5 kG) (Hubrig et al. 2005).

Assuming the field topology to be bipolar generally gives reasonable agreement with the observational data (Preston 1967; Landstreet 1992; Mestel and Landstreet 2005; Aurière et al. 2007). Evidence for additional higher-order multi-polar contributions is, however, found in most cases when searched for (Preston 1969; Landstreet 1988; Landstreet and Mathys 2000; Aurière et al. 2007). Nevertheless, magnetic fields of Ap stars are often specified in terms of the surface strength of the dipole field. The relative frequency of magnetic Ap stars compared to the number of A- and B-type stars of similar mass is below 10% and may be decreasing with mass from about 10% at 3 $M_\odot$ to around 0% at about 1.6 $M_\odot$ (Power et al. 2008; Donati and Landstreet 2009).

Whether all Ap stars are magnetic remains controversial in the sense that no direct field measurements are available for the majority of the known Ap stars. A recently published catalog by Renson and Manfroid (2009) lists 3652 Ap stars. By contrast, an equally recent catalog by Bychkov et al. (2009) of direct line of sight magnetic field measurements contains 1223 stars of spectral type O to M, 610 of which are chemically peculiar and only 410 belong to the classical Ap class as defined by Preston (1974). To clarify the question, Bagnulo et al. (2006) used the low-resolution FORS1 instrument to monitor 97 Ap stars for magnetic fields. A clear detection was obtained for only 41 stars. Meanwhile, it seems reasonable to assume that the many non-detections in this study were due to the low-resolution.

Aurière et al. (2007) employed the high-resolution spectropolarimeter ESPaDOnS to monitor 28 firmly established Ap stars. They found magnetic fields well above the detection limit in all of them. The result is all the more remarkable as the 28 stars were deliberately selected to have a weak magnetic field, if one at all. Nevertheless, for all but two stars the inferred surface dipole field is larger than 300 G. The authors conclude that not only all Ap stars have a detectable magnetic field but also that this field is always larger than some magnetic threshold value of about 300 G. For a possible explanation for the existence of such a threshold value they refer to Spruit (1999). The basic argument is that a too weak magnetic field will be wound up due to differential rotation, a pinch-type instability will set in, and the magnetic field will be destroyed. In more formal terms, the order of magnitude estimate for the critical field B_c given by the authors is

$$\frac{B_\mathrm{c}}{B_\mathrm{eq}} \simeq 2 \left(\frac{P_{rot}}{5_\mathrm{day}}\right)^{-1} \left(\frac{r}{3R_\odot}\right) \left(\frac{T}{10^4\mathrm{K}}\right)^{-1/2} \tag{2}$$

with B_eq the equipartition field ($B_\mathrm{eq}^2 = 8\pi P$, P the gas pressure) at the surface ($\tau_{5000} = 2/3$), and P_{rot}, r, and T the stellar rotation period, radius, and temperature, respectively. For a typical Ap star, $B_\mathrm{eq} = 170$ G and $B_\mathrm{c} \approx 300$ G.

The authors stress that such a mechanism would not only explain the apparent lower bound in the strength of magnetic fields in Ap stars. If a large enough field strength is required in order that the magnetic field does not decay within a short time, this may explain why only a small fraction of A- and B-type stars have a magnetic field. Moreover, that the critical field strength increases with initial stellar mass (thus increasing temperature T and stellar radius r) would naturally explain the even greater scarcity of magnetic field detections in more massive stars.

Additional high-resolution observations have further refined the picture of magnetic Ap stars. Power et al. (2008) identified 57 Ap stars within 100 pc from the Sun, by means of the Hypparcos Catalog and additional sources. They find for the distribution of surface dipole field strengths a plateau at 2.5 $\pm$ 0.5 kG, dropping off to higher and lower field strengths. The mass distribution of these stars peaks around 2.1 to 2.3 $M_\odot$ with a strong decrease towards lower and higher masses. The lowest mass stars in the sample are 1.6 $\pm$0.1 $M_\odot$. The findings for the magnetic fields are consistent with the weak field results obtained by Aurière et al. (2007). The picture is further supported by Kholtygin et al. (2010), who carried out detailed statistical analysis of the stars catalogued by Bychkov et al. (2009).

To detect a potential dependence of the magnetic field strength on the main sequence age of the star, a number of observations of Ap stars in open clusters where performed by Bagnulo et al. (2006) and Landstreet et al. (2007, 2008). The observational data suggests that the magnetic field of an Ap star indeed decays with time, but that the time scale for the decay depends strongly on the mass of the star. The time over which an initially strong (about 1 kG) magnetic field essentially disappears ranges from about 250 Myr for stars of 2 - 3 $M_\odot$ over 40 Myr for stars of 3 - 4 $M_\odot$ to 15 Myr for stars of 4 - 5 $M_\odot$.

Further peculiarities of magnetic Ap stars may or may not be related to their magnetic field. Probably related is their comparatively slow rotation, with periods on the order of a few days instead of a few hours to one day. Landstreet and Mathys (2000) find that most slow rotators (periods longer than 25 days) have small inclination angles of less than 20 degrees between the rotation axis and the axis of the magnetic field, whereas stars with short rotation periods have larger inclination angles. Maybe also related to the presence of magnetic fields are chemical abundance variations in the observed spectra. Their period is mostly identical to the rotation period, implying that the variations stem from chemical inhomogeneities on the surface. Not clear is the reason for the lack of short period binaries among magnetic Ap stars. Based on a sample of 95 Ap stars, North et al. (1998) find 27% to be spectroscopic binaries, as compared to (47 $\pm$ 5) % for normal A- and B-type stars, particularly apparent is the lack of tight orbits as compared to normal stars. Renson and Manfroid (2009) report 5 definite detections of binary Ap stars with orbital periods below 3 days. Tutukov and Fedorova (2010) ascribe this lack of close binaries to mergers. Effective temperatures of Ap stars are reported to lie in a range between 7000 K and 23000 K (North and Debernardi 2004). The authors argue that for temperatures outside this range all chemical peculiarities will be erased by either strong radiatively driven winds (higher temperatures) or convection (lower temperatures).

The only types of Ap / Bp stars for which no large scale magnetic fields have been detected yet are the helium weak Bp stars of type PGaS, and the Bp HgMn stars (North and Debernardi 2004). More recent observations of the HgMn star in AR Aur, the only eclipsing binary known to contain a HgMn star, place an upper limit of 100 G and 400 G on any longitudinal or dipole field, respectively (Folsom et al. 2010). For the same star, Savanov et al. (2009) report the detection of patchy chemical inhomogeneities at the surface. As an explanation they suggest a weak magnetic field, caused by differential rotation in the wake of a depth dependent tidal torque. For another HgMn star, α And, Wade et al. (2006) find an upper limit on the order of 100 G as well, depending on the assumed field geometry. Studying a larger sample of 12 Am and 3 HgMn stars with NARVAL, Auriere et al. (2010) confirm these upper limits. Together, these observations support the existence of a dichotomy between spectroscopically defined Ap stars and any other A-type stars, with only the former harboring substantial magnetic fields.

Turning finally back to normal A- and B-type stars it is interesting to note that Bagnulo et al. (2006) examined 138 normal A- and B-type stars but found no evidence for any magnetic field. It has to be stressed, however, that this does not necessarily imply that normal A- and B-stars do not have a magnetic field. The field may just be too weak to be measured or its topology may be too complicated, leading to cancellation effects. In fact, Lignières et al. (2009) recently reported the detection of a weak magnetic field for the young (a few hundred Myr) normal A-type star Vega. Petit et al. (2010) meanwhile confirmed the detection using the NARVAL and ESPaDOnS instruments. The field distinguishes itself, however, in several aspects from the field of Ap stars. Averaged over the visible part of the stellar surface the field strength does not exceed 1 G. The field topology is comparatively complex, putting it at odds with the fossil field hypothesis for which more simple, bipolar like geometries are expected.

2.3 Herbig Ae / Be Stars

Herbig Ae / Be stars (HAeBe) are the progenitors of main sequence A / B stars. A fraction of 5 - 10% of the later are known to have a magnetic field, the magnetic Ap stars. Their field typically is well organized with a dominant dipole component of around 300 G or more at the surface. As the envelope of Ap stars is not convective but radiative, two hypothesis have been brought forward to explain the presence of the observed magnetic fields. One idea is that the field is generated below the stellar surface, in the stellar core or envelope, from where it is transported to the surface of the star (see Sect. 3.2). The other suggestion is that the magnetic field is of fossil origin, that it existed already during the formation of the Ap star (see Sect. 3.3). This second hypothesis lead to intense measurement campaigns in recent years to search for magnetic fields in HAeBe stars, the progenitors of Ap / Bp stars (Hubrig et al. 2004; Wade et al. 2007; Hubrig et al. 2007; Alecian et al. 2008a,2008b; Power et al. 2008; Hubrig et al. 2009; Wade et al. 2009a).

A synthesis of the results from the above campaigns can be found in Wade et al. (2009a). Based on observational data obtained with the ESPaDOnS instrument on the Canada-France-Hawaii Telescope, this survey is the largest and most sensitive published survey for magnetic fields in HAeBe stars we are aware of. The survey covers about 130 HAeBe stars with masses from about 2 to 13 $M_\odot$. Those stars in which magnetic fields are observed correspond to about 7% of the observed stars. The detected magnetic fields all show organization on large scales. Those three stars which so far have been studied in greater detail, namely V380 Ori, HD 72106A, and HD 200775, display an important dipole component with characteristic polar strength on the order of 1 kG, have ages between 0.1 and 10 Myr, and rotation periods between half a day and a few days (see Table 1 in Alecian et al. (2007) for details).

The 7% are remarkably similar to the 5 - 10% of magnetized A / B stars. Concerning the field strength, Wade et al. (2009a) argue that the dipole intensity derived by Alecian et al. (2008a,2008b) and Folsom et al. (2008) for the detected magnetic HAeBe stars is compatible with the typical field strengths of Ap stars (few kG) if flux conservation as described in Alecian et al. (2008b) applies when the HAeBe stars evolve towards the main sequence.

One may wonder whether the fraction of 7% is detection limited or physical in origin. Using Monte Carlo simulations to study synthetic populations of HAeBe stars and their observational signatures in FORS1 data, Wade et al. (2007) place the following limits on the non-detections of magnetic fields in HAeBe stars: within statistical uncertainty, the observational data is consistent with a distribution of non-magnetic stars; the observations are inconsistent with a *uniform* population of magnetic stars with dipole intensities above 300 G or 500 G in case the dipole axis is aligned or perpendicular to the rotational axis of the star, respectively.

While the above Monte Carlo study was carried out for the FORS1 instrument, Wade et al. (2009a) point out that the results essentially apply to ESPaDOnS as well, where they have a 90% chance of detecting even weak fields of only 300 G. The authors conclude that, on the one hand, it is likely that some magnetic HAeBe stars still went undetected in their survey, because of a too weak or too unorganized magnetic field. On the other hand, it is highly probable that they captured the majority of magnetic HAeBe stars in their sample. Consequently, they do not expect the fraction of 7% magnetic stars among all HAeBe stars to change substantially with future surveys.

Somewhat a by product of the above surveys is the finding that only two of the detected magnetic HAeBe stars, HD 72106A and NGC 6611-601, display chemical peculiarities similar to those of Ap stars (Wade et al. 2009a). According to the authors, this aspect of the data has, however, not yet been investigated in detail.

The above results seem compatible with the idea of the fossil origin of the magnetic fields observed in Ap stars. Arguments in favor of this point of view are, in particular, the definite detection of magnetic fields in the HAeBe stars, the progenitors of Ap stars, and the observation that magnetic fields of Ap stars on the main sequence apparently weaken with the age of the star. Whether the surface field observed in HAeBe stars are directly related to the surface fields of Ap stars remains, however, debated. Hubrig et al. (2009) observe 21 HAeBe stars and detect a magnetic field in 6 of them, for which they further find indications of a decline of surface field strength with age. The age range spanned by the sample is 2 - 14 Myr. On this basis, the authors speculate that the surface fields of HAeBe may ultimately vanish and thus need not be direct progenitors of surface fields in Ap stars. Instead, they suggest that the surface fields in both Ap stars and HAeBe stars are due to emergence of interior fields in the wake of slow stellar rotation and that, consequently, the fields observed in Ap and HAeBe stars need not be directly related.

Also enigmatic remains the origin of the field in the HAeBe stars. At least three hypothesis have been brought forward. One idea is that the magnetic fields of HAeBe stars are generated by a convective dynamo during the formation process of the star. A second suggestion is that the magnetic field results in the course of the merger of two stars during pre-main-sequence or early main-sequence evolution. Yet another idea is that the magnetic fields stem from the molecular cloud in which the stars are born. All ideas will have to explain the fact that probably only a small number of HAeBe stars have a (detectable) magnetic field. A possible mechanism might again be the critical field strength introduced earlier on, below which the magnetic field is wound up and destroyed by instabilities.

2.4 O and early B Stars

Up to now, less than 20 O-type and early B-type stars have definite detections of surface magnetic fields. Analysis thus is mostly restricted to case studies, unlike for intermediate mass magnetic stars where several hundred detections (Bychkov et al. 2009) enable statistical data analysis. Much more magnetic OB-stars might be expected, based on indirect indicators. For example, cyclic wind variability in OB stars has long been related to the potential presence of magnetic fields, in particular dipole fields (Moffat and Michaud 1981; Kaper et al. 1997; Rauw et al. 2001; Fullerton 2003). Searching the IUE archive for corresponding signatures, Henrichs et al. (2005) identify 100 O-stars with statistically significant variability, 60 of which show periodic variability. This large fraction of stars showing periodic variability contrasts with the fraction of stars with clear magnetic field detections. On the other hand, a systematic search by Petit et al. (2009) for a direct link between field strength and X-ray emission, as suggested by Stelzer et al. (2005), yielded no confirmation of this hypothesis. Another indication for a large number of magnetic OB stars comes from non-thermal radio emission of colliding wind binaries (see Section 5.3).

A potential explanation for the comparatively few detections lies certainly in the difficulty of direct field measurements in O-type stars as they have rather few suitable spectral lines in spectral ranges amenable by today's instruments. Schnerr et al. (2008) use cyclic wind variability to select 25 OB candidate stars, for which they then carried out observations with the MUSICOS instrument. No clear field detection was obtained for any of these stars.

Definite field detection in early B-type stars (estimated field in parentheses) exist for β Cep (360 G), ζ Cas (335 G), τ Sco (500 G), ξ^1 CMa (300 G, line of sight), Par 1772 (1150 G), and ν Ori (620 G) (Henrichs et al. 2000; Neiner et al. 2003; Donati et al. 2006b; Hubrig et al. 2006; Petit et al. 2008).

For O-type stars, five reliable detections of a magnetic field are known: θ^1 Ori C (Donati et al. 2002), HD 191612 (Donati et al. 2006a), ζ Ori A (Bouret et al. 2008), HD 57682 (Grunhut et al. 2009), and HD 108 (Martins et al. 2010). Additional detections that are generally regarded as tentative, as they are based on FORS1 observations only, exist for HD 36879, HD 148937, HD 152408, and HD 164794 (Hubrig et al. 2008). See Silvester et al. (2009) for a more detailed discussion.

θ^1 Ori C is a very young star, upper age limits ranging between 0.2 and 0.6 Myr (Donati et al. 2002, 2006a). Observed Stokes V signatures are consistent with a dipole field of 1.1 $\pm$ 0.1 kG (Donati et al. 2002). The magnetic wind confinement parameter η_* (see Section 5.1) is about 20. The star has a rotational period of 15.4 days, a mass of about 40 $M_\odot$, and its spectral type varies between O4 and O6. θ^1 Ori C is a binary with a period of 11 - 26 yr (Nazé et al. 2008).

The Of?p star HD 191612 varies between spectral types O6 and O8 (Walborn et al. 2004). The dipole strength inferred from ESPaDOnS data is 1.5 kG, the magnetic confinement parameter is $\eta_* \sim 10$ (Donati et al. 2006a). The star has a rotation period of 538 days. The estimated age is between 3 and 4 Myr. Its mass is similar to that of θ^1 Ori C, about 40 $M_\odot$. Like θ^1 Ori C, HD 191612 is a binary with a period of 1542 days (Nazé et al. 2008).

ζ Ori A, an O9.7 super-giant, has by far the weakest magnetic field detected so far in a hot massive star. Observations were done by Bouret et al. (2008) using NARVAL. Their data analysis indicates a much more intricate field topology than a simple dipole field. Local surface magnetic fluxes are estimated at only a few tens of Gauss, certainly not exceeding 100 G. Values for the magnetic confinement parameter η_* are between 0.03 and 0.07. A rotation period of 7 days is found, as well as a mass of 40 $M_\odot$ and an age of 5 - 6 Myr.

HD 57682 is an O9 sub-giant. Based on ESPaDOnS data, Grunhut et al. (2009) inferred a magnetic dipole field of about 1680 G. The authors point out that a single inclined dipole field is equally consistent with the observational data as individual dipole configurations. The rotational period is estimated at about 31.5 days, the mass at about 17 $M_\odot$. The wind confinement parameter η_* is estimated to lie in a range 4×10^3 to 2×10^4.

For HD 108, the second Of?p star with a clear field detection, Martins et al. (2010) infer a bipolar large-scale field of at least 0.5 kG and most likely on the order of 1 - 2 kG, based on longitudinal field measurements of 100 - 150 G obtained with ESPaDOnS and NARVAL. For the magnetic confinement parameter $\eta_* \geq 100$ is obtained. The rotation period is several decades, probably between 50 - 60 years, the age is about 4 Myr. Estimates for the stellar mass range of 35 - 43$M_\odot$ (Nazé et al. 2008; Martins et al. 2010).

Some properties of the above five O-type stars fit nicely with theoretical expectations. For example, older stars are expected to rotate more slowly as magnetic braking has had more time to act. The young and fast rotating star θ^1 Ori C, as well as the older and more slowly rotating stars HD 191612 and HD 108 seem to confirm this idea (Martins et al. 2010). Why ζ Ori A does not fit into this scheme one can only speculate (Bouret et al. 2008). Support for theoretical models of rotational braking due to a magnetized line-driven wind came recently from Mikulášek et al. (2008). Analyzing 31 years of observational data of the helium-strong star HD 37776, they found a lengthening of the 1.5387 d period by 17.7±0.7 s. Similarly, Townsend et al. (2010) find for the Bp star σ Ori E a linear decrease of the rotational period of 77 ms per year, based on 30 years of observational data. The corresponding spin-down time of 1.34 Myr corresponds to theoretical expectations.

Yet another star, HD 148937, deserves mentioning here although field detection is only tentative so far: -276 ± 88 G, based on FORS1 data (Hubrig et al. 2008). Spectropolarimetric observations are not yet available. HD 148937 is interesting as it is the third of only three known galactic Of?p stars, the other two stars having definitive field detections (HD 191612 and HD 108). The Of?p class was originally introduced by Walborn (1972) and recently slightly refined (Nazé et al. 2008; Walborn et al. 2010). A particularity of HD 148937 is the bipolar circumstellar nebula around it, NGC 6164-6165. As the nebula displays similar chemical anomalies as HD 148937 (nitrogen 4 times overabundant as compared to solar) it was suggested to have been formed by an eruption of the Of?p central star (Leitherer and Chavarria-K. 1987; Dufour et al. 1988). All three galactic Of?p stars show nitrogen over-abundances as compared to solar which, together with other spectral features, lead Walborn et al. (2003) to suggest that there may exist a similarity between Of?p stars and WN9 objects.

HD 148937 has a rotational period of 7 days (Nazé et al. 2008; Naze et al. 2010). Based on its position in the HR diagram, its mass and age are estimated at 55 $M_\odot$ and 2 – 4 Myr, respectively (Nazé et al. 2008). With these properties - magnetic field, old age, yet short rotation period - HD 148937 would be much more similar to ζ Ori A than to the other two galactic Of?p stars HD 191612 and HD 108.

2.5 Late Stages of Massive Star Evolution

Late-type super giants (spectral type F and later) represent the late evolutionary stages of most massive stars. Characteristics of these stars are extended radii, helium-burning core, a convective hydrogen-burning envelope, and slow rotation. A recent systematic survey of more than 30 late-type super-giants using ESPaDOns revealed clear detection of magnetic fields in one third of all stars (Grunhut et al. 2010). Clear detections were obtained for the following stars (Grunhut et al. (2010), Table 1): α Lep, α Per, η Aql, β Dra, ξ Pup, ϵ Gem, c Pup, 32 Cyg, λ Vel. The most massive and also the hottest star among this sample is α Lep (15 $M_\odot$, $T_{\rm eff} \approx 7200$ K). The lowest mass star is β Dra (5 $M_\odot$), the coolest c Pup ($T_{\rm eff} \approx 3700$ K). The observations suggest topologically complex fields, longitudinal magnetic fields are generally below 1 G. The authors speculate that probably even a larger fraction of late-type super-giants or even all of them may have a magnetic field, but that the signal to noise ratio of their measurements is insufficient to detect these fields. They see their point confirmed by the detection of a magnetic field in Betelgeuse (Aurière et al. 2010) where a signal to noise (S/N) about twice as high as in their study was crucial.

The case of Betelgeuse and other late-type super-giants is of interest as these stars occupy an extreme position in parameter space. Their rotation is too slow that a solar like dynamo could be at work. An alternative idea for the origin of the observed magnetic fields are large convection cells (Schwarzschild 1975). The idea obtains further support from 3D convection simulations (Freytag et al. 2002; Dorch 2004).

Very high mass stars with initial masses between 25 $M_\odot$ and 40 $M_\odot$ evolve into Wolf-Rayet (WR) stars towards the end of their life (Hirschi et al. 2010). To date, no direct magnetic field detection for any WR exists. However, WR 142 recently gained attention because of the detection of weak ($L_{\rm X} \approx 7 \cdot 10^{30}$ ergs s^{-1} or $L_{\rm X}/L_{\rm bol} \leq 10^{-8}$) but hard X-rays with XMM-Newton (Oskinova et al. 2009) and Chandra (Sokal et al. 2010). The inferred plasma temperature is on the order of 10^8 K (Oskinova et al. 2009), which is difficult to explain in terms of internal shocks in the WR wind. The authors suggest that the X-rays may be due to the presence of a stellar magnetic field that deviates the stellar wind and creates magnetically confined wind shocks (MCWS, see Section 5.1). The authors estimate that a surface field strength of some 10 kG would be required, a value they consider compatible with the order 1 kG measured magnetic fields in the much larger O-type stars. Alternative explanations have been suggested as well, most notably inverse Compton scattering in colliding winds in a (yet unresolved) binary (Sokal et al. 2010). In fact, the 'colliding winds community' has been assembling indirect evidence for the existence of magnetic fields in WR+OB and O+OB binaries for several decades already, mostly in the form of non-thermal radio emission (see Section 5.3).

2.6 Summary

Measurements of Zeeman signatures clearly demonstrate the presence of dipole fields of about 1 kG strength in four O-type stars. One more O-type star, ζ Ori A, has a clear field detection as well, but the field is much weaker (tens of Gauss) and less ordered. A clear field detection also exists for the late-type supergiant Betelgeuse. For WR stars only indirect evidence for a magnetic field exists, in the form of hard X-ray emission and non-thermal radio emission from WR+O binaries.

Much more data is available for intermediate mass Ap / Bp stars. Evidence is growing that probably all Ap / Bp stars have a magnetic field. The field of these stars often is dipole like with strength between about 300 G and 30 kG. The lower limit of 300 G is probably not detection limited but constitutes a physical lower limit instead. Only one normal A-type star, Vega, is currently known to have a magnetic field. The field is weak and unordered, resembling in this sense the field of ζ Ori A.

Observations from open clusters suggest the field strength in Ap / Bp stars to decrease with the age of the stars. Apart from field detections in main sequence Ap / Bp stars, there exist a few field detections in pre-main-sequence Herbig Ae / Be stars. Measured field strenghts are compatible with those of Ap / Bp stars if stellar evolution is taken into account.

3 Theoretical models for magnetic fields in massive stars

3.1 Introduction

even strong – magnetic fields on their surfaces demands for explanation in terms of analytical and numerical models. Beyond the interpretation of observational data, a better physical understanding of magnetic fields in massive stars will allow a more consistent inclusion of such fields in stellar evolution models[1]. For the potentially far reaching consequences of magnetic fields for stellar evolution we refer to Sect. 4. Here we only stress that magnetic fields relevant for stellar evolution need not necessarily emerge on the stellar surface. It is sufficient that they dynamically link the (convective) core and (radiative) envelope of the star. This poses some difficulty as current observations of magnetic fields in massive stars (see Section 2) deal for the most part with surface fields only.

The basic challenge associated with magnetic fields in early type massive stars is that the envelope of such stars is for the most part radiative. This excludes a solar type dynamo as the origin of the magnetic field. Two groups of alternative explanations are favored instead: some other kind of dynamo, the precise nature of which is under debate, or fossil fields, which have been preserved since the formation time of the star and whose precise origin is under debate as well. Both groups of mechanisms may be required to explain observed surface magnetism in the upper main sequence: fossil fields for the kG dipole fields typical of Ap-stars, dynamos for weak (1G) and unordered fields as in the normal A-type star Vega (Lignières et al. 2009; Petit et al. 2010).

A common issue in both explanations, dynamo or fossil field, is the stability or instability of the involved magnetic field. Some dynamo theories rely on instabilities for closing the dynamo loop, while fossil field theories rely on a sufficiently stable field configuration for the field to last over the lifetime of the star. The relevance of the question is reflected in a quite exhaustive literature. We sketch here only the basic picture. Further details will be given later on as needed.

A first point to note is that Ohmic dissipation alone is not efficient in destroying a stellar magnetic field. The corresponding destruction time scale is on the order of the life time of the star. Turning to instabilities instead, it has long been known that the field topology plays a decisive role. Only mixed poloidal-toroidal topologies

[1] A very good presentation of the physics of rotating stars, including an elusive chapter on the role of magnetism, can be found in the book by Maeder (2009). We also refer to the book by Mestel (1999), which is perhaps the most complete compilation of stellar magnetism.

may be sufficiently stable. This hypothesis got recent support from 3D simulations by Braithwaite and Spruit (2004) and Braithwaite and Nordlund (2006) which show that initially unordered fields often relax to a long-lasting mixed topology. Several decades earlier, Prendergast (1956, 1958) showed already that an exact solution of the hydromagnetic equilibrium exists if the field is of mixed topology, has a toroidal and a poloidal component. Probably one of the earliest results in this direction is the Ferraro-law (Ferraro 1937):*"The magnetic field of a star can only remain steady if it is symmetrical about the axis of rotation and each line of force lies wholly in a surface which is symmetrical about the axis and rotates with uniform angular velocity"*.

By contrast, purely poloidal fields were shown to be unstable if some (Markey and Tayler 1973; Wright 1973; Markey and Tayler 1974) or all (Flowers and Ruderman 1977) field lines are closed outside of the star. A purely toroidal field is unstable to non-axisymmetric perturbations of low azimuthal order, with a strong dominance of the $m = 1$ mode (Tayler 1973; Wright 1973; Goossens et al. 1981). Rotation (Pitts and Tayler 1985) or the addition of thermal and Ohmic diffusion (Acheson 1978) help to stabilize such a situation, but cannot suppress the $m = 1$ instability. Note that the above considerations refer to the full field, inside and outside the star. A bipolar field outside of the star can still exist, provided that some toroidal component exists within the star.

In the rest of this Section, we review dynamo models proposed for the different layers of massive stars (in Sect. 3.2). This includes the question whether such fields can raise to the surface, for example by buoyancy or due to meridional circulation. In Sect. 3.3 we review fossil field models, which propose that the field observed in massive stars was enclosed during the process of their formation. A summary concludes the section (Sect. 3.4).

3.2 Dynamo generated fields and their appearance at the surface

3.2.1 Convective core

An obvious candidate for a place in a massive star where magnetic fields may be created is its convective core. By mean field dynamo theory, Charbonneau and MacGregor (2001) found that $\alpha 2$-, $\alpha 2\Omega$- and $\alpha\Omega$ dynamos can operate in such cores. In addition, the authors investigate whether meridional circulation could bring the field to the surface. They conclude, however, that this is not the case. The main argument is: *In all models with strong core-to-envelope magnetic diffusivity contrast (presumably closest to reality) whenever circulation is strong enough to carry a significant magnetic flux, it is also strong enough to prevent dynamo action.*

In a follow-up paper, MacGregor and Cassinelli (2003) looked at alternative transport mechanisms – buoyant, centrifugal, Coriolis, magnetic tension, and aerodynamic drag forces – whether they may be able to bring the field generated in the convective core to the surface. They found that thin, axisymmetric, toroidal flux tubes can be advected from the outer boundary of the convective core to the atmosphere within a life-time of a 9 solar mass star. The trajectories of the raising ring are more or less parallel to the rotation axis of the star. They also found that the rise-time for smaller rings is faster. Mullan and MacDonald (2005) argue, however, that correct inclusion of yield gradients may suppress the buoyancy.

The idea of substantial field generation in the convective cores of A-type stars is further supported by more recent 3D simulations by Browning et al. (2004) and Brun et al.

(2005). Mega-Gauss fields are found in the core, at its boundary layer to the radiative envelope. Featherstone et al. (2009) find, by means of 3D simulations of the innermost 30% of a 2 $M_{\odot}$ A-type star, that the presence of a fossil field in the radiative envelope which threads into the convective core can considerably augment the field generated by a core dynamo. Apart from pointing out that stronger fields generally have a better chance of reaching the surface, the authors do not comment on whether or not the core dynamo generated fields may emerge at the stellar surface.

Taken together, the above papers demonstrate that dynamo action in the convective cores of upper main sequence stars is likely to exist, but that it is unclear whether the generated fields can reach the stellar surface.

3.2.2 Radiative envelope

Dynamos that can operate without a convection-related α-mechanism have been known for several years. An example is the dynamo generated by differential rotation and the magneto-rotational instability in accretion-disks (Hawley et al. 1996). The recognition that a similar dynamo mechanism, one without a convection-related α-mechanism, may also take place in the stably stratified radiative regions of stars had far reaching consequences. The two corresponding papers (Spruit 1999, 2002) are seminal for two reasons. Firstly, because they re-shape the theory on stably stratified radiative regions and, secondly, because of their impact on stellar evolution models, the topic of Sect. 4. Whether such a dynamo can indeed operate in real stars of the upper main sequence has been questioned (Zahn et al. 2007) and is the topic of a still ongoing debate.

One starting point of the above developments were results of helioseismology, which found that the radiative solar core is uniformly rotating. At the tachocline, this uniform rotation switches rather abruptly, in only 0.05 $R_{\odot}$, to the differential rotation of the envelope, which itself shows a 30 percent contrast in its rotation between equator and poles. The observed uniform rotation of the solar core was puzzling. A potential agent for the necessary efficient transport of angular momentum could be magnetic fields, but under the prevailing radiative conditions a conventional 'convective dynamo' – and thus magnetic fields – would not exist. The connection of this problem with the radiative envelopes of upper main sequence stars is obvious.

Spruit (1999) re-investigated the stability of magnetic fields in stably stratified, but differentially rotating stars. He reviews the processes which contribute to the evolution of an initially weak magnetic field in a differentially rotating star: rotational smoothing and five instabilities, among them magnetorotational instability, buoyancy instability, and pinch-type instabilities. The Pitts-Taylor instability, a pinch-instability driven by the free energy of the field itself, is found to set in first. It generically occurs in a region near the pole, in the form of an m = 1 displacement of the field lines along horizontal surfaces (see Fig. 4). The analysis is complemented by an investigation of the relevance of thermal and magnetic diffusion on these instabilities. Based on heuristic arguments, concrete numbers are provided that characterize the behavior of the instabilities.

In a follow up paper, Spruit (2002) argues that on the basis of the Pitts-Taylor instability a dynamo can operate in the stably stratified radiative regions of stars. He states *'the generation of a magnetic field in a star requires only one essential ingredient: a sufficiently powerful differential rotation. The recreation of poloidal field components which is needed to close the dynamo loop can be achieved by an instability in the toroidal field.'*. The paper gives concrete formulas for the field strength in radial and azimuthal

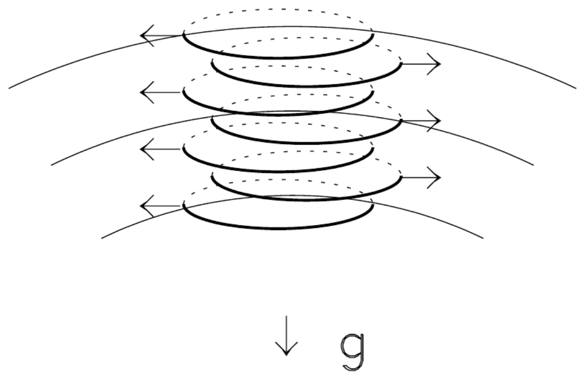

Fig. 4 Unstable displacements in an azimuthal field near the pole. Shown is the $m = 1$ mode, which occurs under the widest range of conditions. The displacements are along horizontal surfaces (indicated by arcs). The Figure is taken from Spruit (1999), his Figure 1.

direction produced by a dynamo of this type. The crucial parameter is the differential rotation, which of course will be affected by the presence of a field.

Numerical confirmation of the dominance of the Pitts-Taylor instability and the associated growth rate predicted by Spruit (2002) is reported by Braithwaite (2006b). The $m = 1$ kink-mode is indeed found to be the dominant instability in a toroidal field, where the field strength is proportional to the distance from the axis, such as the field formed by the winding up of a weak field by differential rotation. The growth rate of the instability for initially weak fields is found to agree with the analytic predictions.

Braithwaite (2006a) further report that he finds the dynamo mechanism to work: an initial small poloidal field is wound up. The resulting toroidal field is subject to the Pitts-Taylor instability, thus producing a poloidal field again, which is then wound up again. This process continues up to a certain saturation level, at which *'the field is being wound up by differential rotation at the same rate as it is decaying through its inherent magneto-hydrodynamic instability.'*

Doubts on the above results were raised by Zahn et al. (2007). While numerically investigating the solar tachocline they found inconsistencies between their results and results reported by Spruit (1999, 2002) and Braithwaite (2006a). In their paper, Zahn et al. (2007) first provide a more rigorous analysis than the more heuristic argumentation by Spruit (1999). They confirmed the scaling of Spruit but give better bounds and factors (differences are of order 1). Comparing their analytical results with numerical results from the ASH code Zahn et al. (2007) find excellent agreement. In strong contrast to Braithwaite (2006a) they observe: *'Although the instability generated field reaches an energy comparable to that of the mean poloidal field, that field seems unaffected by the instability: it undergoes Ohmic decline, and is neither eroded nor regenerated by the instability.'* They conclude that *'In our simulations we observe no sign of dynamo action, of either mean field or fluctuation type, up to a magnetic Reynolds number of* 10^5*.'* The authors also doubt that a large scale dynamo-loop can be closed in the way suggested by Spruit (2002) and Braithwaite (2006b), but suggest an alternative instead.

The contradictory numerical results demand for some details, given the importance of the question. The two simulation codes employed differ in several respects, including magnetic boundary conditions and the way differential rotation is enforced (see Zahn et al. (2007) for details). Maybe the most important difference is the way the equations are solved. The ASH code used by Zahn et al. (2007) is of pseudo-spectral type and should allow to reach a magnetic Reynolds number of 10^5 in the simulations under debate, which the authors consider enough to detect any dynamo action if existent. Braithwaite (2006b) use a 6^{th} order finite difference code on a Cartesian domain. Whether or not dynamo action sets in in the model by Braithwaite (2006b) crucially depends on the artificially enforced differential rotation. Adding a uniform rotation does not suppress the dynamo but the field strength shows an oscillatory behavior. Further investigations are clearly needed to disentangle the issue.

Apart from generating a magnetic field by dynamo in the radiative envelope - if possible at all - there is again the question of whether such a field may eventually become visible at the surface. Two possibilities come to mind: the field is generated near the surface or the field is generated further below and transported to the surface. As to the first possibility, Zahn et al. (2007) agree with Maeder and Meynet (2005) who pointed out that there is too little differential rotation in the layers immediately below the surface to operate the Taylor-Spruit-dynamo (see Sect. 4). The second possibility is rejected as well, as meridional circulation very likely does not reach the surface layers and as the field generated would be too weak for the magnetic buoyancy instability. The raising fields reported in numerical simulations by Mullan and MacDonald (2005) rely on field strengths on the order of 1 MG. These field strengths, in turn stem from their stellar structure model (MacDonald and Mullan 2004), which neglects the back-coupling of the magnetic field on the rotation rate, thus resulting in a very high differential rotation. In fact, as will be discussed in Sect. 4, even a weak field will suppress differential rotation to a high degree and the consistent rotation rate is nearly flat. Since the performance of the dynamo depends on the root of $d\Omega/dr$, this makes a huge difference.

3.2.3 Giant Convection Cells and Surface Dynamos

Yet another form of dynamo action has been proposed to explain observed magnetic fields in red super giants (see Sect. 2.5), the late stages of stellar evolution of massive stars. Freytag et al. (2002) performed detailed 3D radiation hydrodynamic simulations of the late-type super-giant Betelgeuse. The simulations, in comparison with observations, convincingly demonstrated the existence of giant convection cells. In a subsequent paper, Dorch (2004) presented magneto-hydrodynamical simulations of non-linear dynamo action in Betelgeuse and found that the giant convection cells can indeed result in the formation of surface magnetic fields of up to 500 G. More recent simulation results further support the existence of giant convection cells (Chiavassa et al. 2010, 2009).

3.3 Fossil fields

An alternative to dynamo generated fields are field configurations which – once formed – are stable over an essential part of the life-time of the star. Such fields are generally called *fossil fields*. They are particularly attractive to explain the existence of magnetic fields in Ap-stars and the like: stars with a static, strong, large-scale magnetic field. Although, as discussed in the last section, there are competing ideas which ascribe such

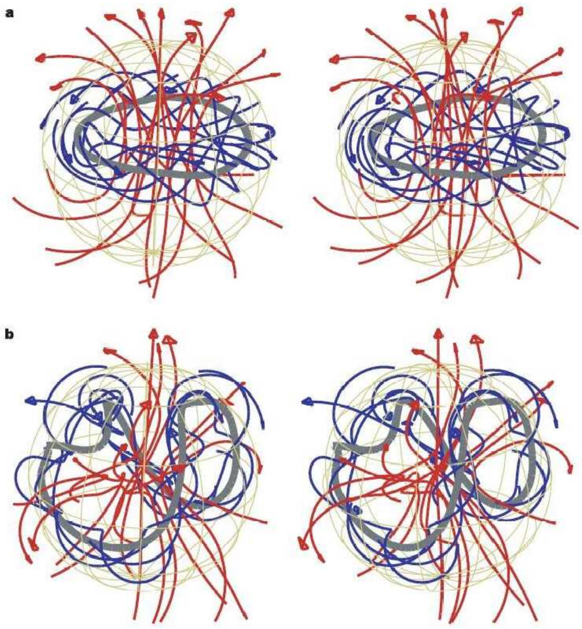

Fig. 5 Structure of stable magnetic fields, as found with three-dimensional numerical simulations. **a:** Stereographic view of the long-lived magnetic field configuration as it evolves from a random initial condition. The stable core of the configuration is formed by a torus of twisted field lines inside the star (blue, with axis of torus shown in grey). Field lines that pass through the stellar surface (red) are stabilized by the torus. The configuration slowly evolves outwards by magnetic diffusion. When the torus reaches the surface it becomes unstable (stereographic view **b**). From Braithwaite and Spruit (2004), their Figure 1.

fields to dynamo action in the convective core with subsequent raise to the surface (Charbonneau and MacGregor 2001; MacGregor and Cassinelli 2003), a fossil origin of these fields seems more attractive. One main reason in favor of a fossil origin are that no correlation is observed between field strength and stellar rotation, as would be expected for a dynamo dragging its force from the differential rotation of the star. Also, the field strengths are so large that dynamo action is suppressed (Spruit 1999). The two main questions associated with fossil fields are their origin and their stability.

We already briefly touched the question of the stability of a magnetic field over essentially the life time of a star at the beginning of Sect. 3. There we pointed out that a mixed poloidal-toroidal topology is a necessary prerequisite. The results quoted there have been further refined in recent years. For an overview see for example Mestel and Landstreet (2005).

More recently, Braithwaite and Spruit (2004) and Braithwaite and Nordlund (2006) identified by means of numerical simulations a first concrete field topology that is stable over long time, illustrated in Fig. 5. They follow the evolution of a random field initially concentrated in a sphere of radius $r_m < R^*$ within a star of radius R^* and using a polytrope with index $n = 3$. For $r_m \lesssim 0.5R^*$, the initial configuration rapidly changes, within a few Alvén times the field strength decays strongly before stabilizing into a configuration which is always similar, independent of the concrete initialization: *'the poloidal field component is very similar to that which would be produced by* *an azimuthal current loop near the equator of the star. The toroidal component then threads along this loop.'* The field subsequently diffuses outwards, on a much longer time scale. While roughly preserving the overall configuration, the poloidal component gets stronger compared to the toroidal component. Once the imaginary current associated with the toroidal field component reaches the surface, the entire field rapidly decays. For initial field realizations of $r_m \gtrsim 0.5$, the field directly enters this final distorted state and decays rapidly.

The authors predict that the first appearance of the field on the surface is after about 1/3 of the life-time of the star, that the field strength subsequently should increase, and that contributions from lower order modes should gradually add to the initially bipolar surface field. Comparison of these predictions with observations shows a mixed picture. Hubrig et al. (2000) find that magnetic Ap stars are typically older than 30% of their total main sequence life span. By contrast, Landstreet et al. (2008) find no such age barrier. In addition, these authors find a decrease of magnetic field strength with the main sequence age of the star. As possible explanations for the discrepancy they suggest the non-consideration of both, rotation and the changing stellar radius and structure with age, in the simulations by Braithwaite and Spruit (2004).

The above picture essentially still holds today, although it has been refined in details since (Braithwaite et al. 2010). Using numerical simulations, Braithwaite (2009) found that for a stable field topology the poloidal component must not be significantly stronger than the toroidal component, while the toroidal may well be much stronger than the poloidal component. Reisenegger (2009) investigated the effect of a non-barotropic stratification. Mestel and Moss (2010) constructed a simple analytical model of tori as those found in numerical models and show that radiative heat transfer, Archimedes' principle, Lorentz force, and Ohmic decay all play a significant role. Duez and Mathis (2010) largely generalized the Prendergast models (Prendergast 1956, 1958) to barotropic magneto-hydrostatic equilibrium states of realistic stellar interiors. The analytic solutions they obtain strongly resemble the numerical results by Braithwaite and Spruit (2004) and Braithwaite and Nordlund (2006). Although stability has not yet been proofed for the analytical model, this combined effort between numerical and analytical work is exemplary and has already proofed to be seminal. Note, however, that Duez et al. (2010) tested the model numerically and found no significant change of the configuration over 10 Alfvénic times.

Turning now to the second corner stone of the fossil field hypothesis, namely the physical origin of these fields, we find a much less settled debate. At least three ideas have been put forward and are being investigated today: field generation during the convective pre-main sequence evolution, field generation in the wake of early binary mergers (Ferrario et al. 2009), and fields inherited from the molecular cloud in which the stars are born (Tout et al. 2004; Ferrario and Wickramasinghe 2006). Not surprisingly, each idea has its pros and cons.

So far, only the most simple model, the flux-conservation model put forward by Tout et al. (2004) and Ferrario and Wickramasinghe (2006), is worked out to a stage which allows confrontation with observations. The model relies on flux conservation and assumes that the field of a star is built by the magnetic flux trapped in the collapsing pre-stellar cloud. It then assumes that the magnetic flux is given as the sum of two Gaussians in the logarithm with dispersions σ_i with appropriate weightings. The model builds up on the remarkable fact that Ap and Bp-stars as well as magnetic white dwarfs have magnetic fluxes of the same order. Moreover, when fields of magnetic white dwarfs are appropriately rescaled, the distribution of their strengths matches to a good degree the distribution of the same quantity of neutron stars. They also point out that the flux of θ Orion C (1.110^{27} G cm^2) and HD191612 (7.51027 G cm^2) is remarkably similar to the flux of the highest-field magnetar SGR 180620 (5.710^{27} G cm^2).

For massive main sequence stars, this model predicts a distribution which peaks at 46 G with 5 percent of the stars having a field in excess of 1 kG (originally 8 percent, but see the footnote in Petit et al. (2008)). The still very small sample of massive stars in the Orion Nebular Cluster (ONC) allows a first test of this prediction. As reported by Petit et al. (2008), the ONC contains nine massive OB stars, ranging from B3 V ($\sim$ 8 $M_\odot$) to O7 V ($\sim$ 40 $M_\odot$), three of them showing a very strong field. These authors find that, according to the multinomial distribution of Ferrario and Wickramasinghe (2006), the probability of obtaining the distribution of magnetic field strengths observed in the ONC is about 1 per cent. As pointed out by Petit et al. (2008), the sample is much too small to be representative. Also, the ONC may just be particularly magnetized, thus biasing the sample. Nevertheless, this demonstrates that observations now are at a level which starts to allow discrimination between different models.

3.4 Summary

Theory basically offers two hypothesis for the origin of magnetic fields in intermediate mass and massive stars: fossil fields, which existed already before the star reached the main sequence, and several kinds of dynamo generated fields. Fossil fields are the preferred explanation for strong and ordered (dipole) fields, whereas dynamo generated fields are believed to be less ordered and weaker. In fact, dynamo generated fields may not even emerge on the surface.

The details of both hypothesis are not well known so far. The origin of the fossil fields – from the parent molecular cloud, an early merger, or pre-main-sequence convection – are debated. Simulation results disagree on whether or not a dynamo can operate in the radiative envelope of a massive star. Similarly, it is unclear whether fields from the convective core can reach the surface of the star.

A particular case are surface fields in late-type supergiants like Betelgeuze, which numerical simulations indicate to be due to a surface dynamo operating in the outer convection layers of the star.

4 Magnetic fields in massive stars: implications for stellar evolution

The role of magnetic fields in stellar evolution is an area of research which largely remains to be explored and represents a top priority challenge in astrophysics. This is illustrated by the fact that the topic of magnetic field has been identified with rotation as one of the areas of discovery potential in the report “New Worlds, New Horizons in Astronomy and Astrophysics” written by the Committee for a Decadal Survey of Astronomy and Astrophysics (2010).

Magnetic fields have probably a very crucial impact at the two extreme points of the lifetime of a star, namely during their formation and when they disappear in a supernova explosion. But the magnetic field has also likely an important impact, at least when strong enough, during the hydrostatic phases of stellar evolution.

At the moment, stellar evolution computations taking into account the effects of magnetic fields remain rare. The available models have focused on exploring the consequences of the Tayler-Spruit dynamo mentioned in Sect. 3.2.2 above. In the present Section we shall briefly describe the main results of these computations.

Let us recall that in the Tayler-Spruit dynamo (Spruit 1999, 2002), a pristine poloidal magnetic field is amplified through a dynamo effect. In a first step, the poloidal field is sheared by differential rotation. This produces a toroidal component which is sensitive to a pinch-type instability (the Pitts & Tayler instability). This generates an amplified poloidal component. The process can then begin again and the dynamo loop is closed. The energy needed for this amplification is obtained from the excess energy contained in differentially rotating layers.

The amplification will of course not be pursued indefinitely. The regulating mechanism is due to two counteracting effects: on one hand the source of the instability, which is differential rotation, will be progressively eroded by the strong radial coupling exerted by the increasing poloidal magnetic field, on the other hand meridional currents, which become stronger when the angular velocity gradient flattens, will rebuild the differential rotation. As a result of these two counteracting effects an "equilibrium profile" of the angular velocity in the star is reached. This angular profile presents the right degree of shear to sustain both the dynamo that continually erodes the shear and the meridional currents which continually rebuild it. Such a dynamo will produce internal magnetic fields of the the order of 10^4 G in massive stars with an initial rotation of 300 km s^{-1} (Maeder and Meynet 2005).

The theory and the equations describing these effects are presented in (Spruit 1999, 2002) . In this theoretical frame, two modifications of the equations have been brought by further works: 1) using the condition that the energy of the magnetic field created by the Tayler-Spruit dynamo cannot be larger than the energy excess present in the differential rotation, Maeder and Meynet (2003) propose a criterion for the existence of the magnetic field in stellar interior; 2) Maeder and Meynet (2004) avoid the simplifying assumptions that either the mean molecular weight- or the temperature-gradient dominates, but they treat the general case and also account for the nonadiabatic effects, which favor the growth of the magnetic field.

An interesting property of the Tayler-Spruit dynamo is that it can explain the internal near solid body rotation of the Sun (Eggenberger et al. 2005). However some critics of the theory have been presented: Zahn et al. (2007), using the 3-dimensional ASH code conclude that, although the Pitts & Tayler instability is present in their simulations, the mean poloidal field remains unaffected by it and thus that the dynamo loop is not closed. Denissenkov and Pinsonneault (2007) critic the fact that an important approximation used in the derivation of the equations is only valid for small length scales while, for obtaining the equations presented in Spruit (2002), it is applied for scales of the order of the radius of the star.

Despite these difficulties, the effects of the Spruit-Tayler dynamo are still explored in stellar models. A justification for using this theory is that, as discussed in Maeder et al. (2009), except for the expression of the growth rate of the instability, the equations presented in Spruit (2002) are quite general and can be derived by simply imposing that the rate of dissipation of the excess energy of the shear is equal to the production rate of magnetic energy. Said in other words, everything can be computed once the growth rate is known. As long as this growth rate is short enough, magnetic field will produce solid body rotation during the Main-Sequence phase.

So, to first order, we can say that models accounting for the Tayler-Spruit dynamo will differ from models with rotation only by the fact they have a solid body rotation all along the MS phase while the models with rotation only (and no magnetic fields)

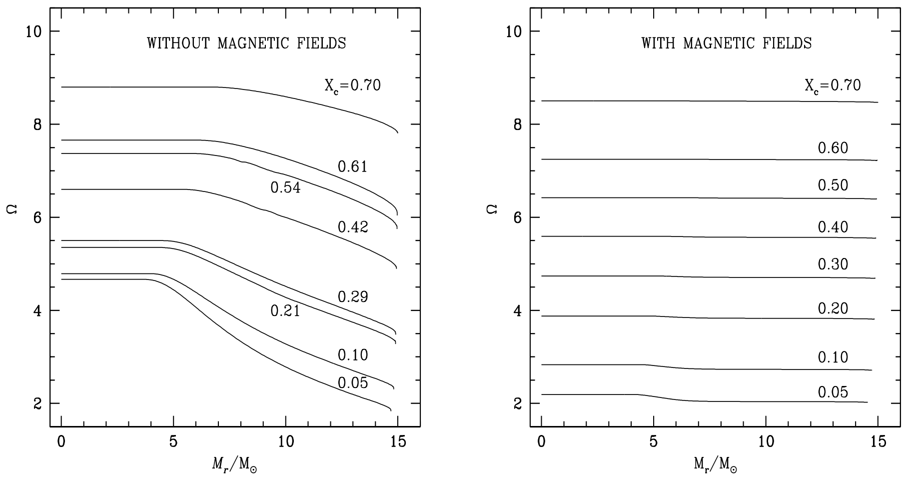

Fig. 6 *Left panel*: Internal distribution of the angular velocity $\Omega(r)$ as a function of the Lagrangian mass in solar units in a 15 $M_\odot$ model, without magnetic fields, at various stages of the model evolution indicated by the central H-content X_c during the Main-Sequence phase. The initial velocity is 300 km s^{-1}. *Right panel*: Same a left panel but with magnetic fields. Figures taken from Maeder and Meynet (2005).

show a moderate contrast (by a factor of a few) between the rotation rate of the core and that of the surface (see Fig. 6).

An immediate consequence of the Tayler-Spruit dynamo is that mixing of the chemical species by the shear is no longer efficient. However, as shown by Maeder and Meynet (2005), meridional currents are more rapid in the rigid rotating models than in those with differential rotation. As a result, the deficit of mixing from the shear mechanism is more than compensated by the increasing efficiency of the mixing due to the meridional currents. These authors thus obtain more important surface enrichment (at equivalent age) in magnetic models with respect to non-magnetic ones.

Another important consequence of the magnetic models is that they predict for a given value of the initial rotation, higher surface velocities during the MS phase. This is because the magnetic field imposes a strong coupling between the core and the envelope. It allows to extract angular momentum from the contracting still faster rotating convective core and to bring it to the expanding and slower rotating radiative envelope.

So from what has been said above, magnetic fields will produce, for given initial conditions and a given age, faster rotating and more surface enriched stars. Also, the angular momentum of the core will be decreased in magnetic models. Heger et al. (2005) find that magnetic torques decrease the final rotation rate of the collapsing iron core by about a factor of 30-50 when compared with the nonmagnetic models. From their 15 $M_\odot$ model, they predict pulsar periods at birth near 15 ms which is in agreement with the observed periods of the most rapidly rotating pulsars (see detailed discussion in the above reference). Thus we see that magnetic models can reasonably well account for the observed rotation rate of young pulsars, while models with rotation only would predict much too fast rotating pulsars. Let us however mention that such arguments in favor of magnetic models should be taken with some caution because extraction of angular momentum from the core can also occur at the time of the explosion and/or during the early life of the pulsars.

For very massive stars (above 40 $M_\odot$ at solar metallicity), strong stellar winds during the Main-Sequence phase remove the outer layers and thus angular momentum from the star. Since magnetic field, by tightly coupling the core to the envelope increases the angular momentum content of the outer layers, models with magnetic fields lose more angular momentum by mass loss than their non-magnetic counterparts (everything else being kept the same). This feature of magnetic models makes the production of a very fast spinning core more difficult. As just seen above, this is a nice feature in the frame of explaining the rotation rate of young pulsars, but it becomes a difficulty when one wants to explain the progenitors of collapsars proposed by Woosley (1993) to be at the origin of the long soft Gamma Ray Bursts (GRB). Let us briefly recall here that collapsars are core collapsing stars producing a fast rotating black hole. The fast rotation allows the formation of an accretion disk around the black hole. Gravitational energy extracted from the accretion disk is used (at least in part) to power polar jets. The gamma ray burst comes from shocks in these jets characterized by very high Lorentz factors. In order for the gamma ray burst to be observable, the star must have shed away its H-rich envelope. Thus models producing collapsars should present two properties which at first sight do appear very difficult to reconcile: on the one hand, a core with a high angular momentum content[2], and at the same time no H-rich envelope, which means that the model had to suffer strong mass loss and hence strong angular momentum loss.

Non-magnetic models for high mass stars at low metallicity can easily reach the needed conditions as discussed by Hirschi et al. (2005). However such models would predict a rate of long soft gamma ray burst which is at the upper level of the observed range. Magnetic models can reproduce the required condition for having a collapsar but for a more restrained range of initial velocities. Only stars initially very rapidly rotating have a chance to give birth to a collapsar and then to a long soft gamma ray burst. Magnetic fileds thus reduce the predicted rate of GRBs.

The initial velocity needed to produce a collapsar is such that the star will follow a homogeneous evolution during the Main-Sequence phase, i.e. the stellar composition of the star will be nearly equal from the core to the surface at every time. Such an evolution has many advantages for producing a collapsar: quasi homogeneity during the MS phase allows the star to remove its H-rich envelope by nuclear processing rather than by mass loss, moreover the tracks of such homogeneous evolution in the Hertzsprung-Russel diagram remain in the blue, reducing the mass loss rates during the pre-WR phases. Evolution of these very fast rotating stars has been computed by Hirschi et al. (2005). These authors estimate that such stars might comprise roughly 1% of all stars above 10 $M_\odot$ and that they can, under certain circumstances, retain enough angular momentum to make GRBs. They underline the fact that the possibility to make GRBs is very sensitive to mass loss and is favored in regions of low metallicity. A similar scenario has been explored by Yoon and Langer (2005).

The rapid rotation needed in such scenario may be obtained either as a result of the initial very rapid rotation of the star or acquired by mass transfer in a close binary system (Petrovic et al. 2005; Detmers et al. 2008; Cantiello et al. 2007).

[2] Typically, the massive stars that give rise to gamma-ray bursts must have an amount of angular momentum in their inner regions, 1-2 orders of magnitude greater than the ones that make common pulsars (Woosley and Heger 2006).

Let us end this section by saying a few words about the possibility for massive stars to suffer magnetic braking. At the moment of writing this review, there are no evolutionary computations accounting for this effect in the range of massive stars[3]. We expect that such computations will soon appear. Recently Ud-Doula et al. (2009) have proposed a numerical recipe for accounting for the angular momentum loss and associated rotational spin-down for magnetic hot stars with a line-driven stellar wind and a rotation-aligned dipole magnetic field. The numerical scaling relation that they obtain gives typical spin-down times of the order of 1 Myr for several known magnetic massive stars. This is quite in line with the recent spin down time scale for σ Ori E estimated to be 1.34 Myr by Townsend et al. (2010). These authors thus conclude that the observations are consistent with σ Ori E undergoing rotational braking due to its magnetized line-driven wind. Other stars present wind and surface magnetic field characteristics which are compatible with the existence of a magnetized line-driven wind. This is the case for instance of the Of?p star HD108 (Martins et al. 2010) which has also a slow rotation rate (lower than 50 km s^{-1}). How the surface chemical enrichments are affected by such a magnetic braking remains to be seen and will probably constitute an interesting line of research for the near future.

5 Magnetic massive stars in their environment

Despite the comparatively strong wind of massive stars in all stages of their evolution, the dynamics of the mass-loss in the vicinity of the star will be affected by the magnetic field of the star if such a field is present at all and if it is sufficiently strong. This likely also affects photospheric emission and probably also leads to X-ray emission (Sect. 5.1). If observed and if properly understood, such effects may in turn be used to confine properties of the stellar magnetic fields.

Going to larger scales, due to the faster decrease of the magnetic energy density as compared to the kinetic energy density, the kinetic energy of the stellar wind will dominate again. Owocki (2009) estimates that for the star with the largest ratio of magnetic to kinetic energy density detected so far, σ Ori E, this transition from magnetically to kinetically dominated flow takes place within less than 100 stellar radii, assuming a dipole field. The transition radius is approximately the radius where the first open field lines appear. Note that although the magnetic field no longer dominates the flow, the flow remains magnetized as the magnetic field is advected with the flow.

Observing consequences of the magnetic field at these larger scales, like particle acceleration at shocks and non-thermal emission, could again give a clue on the magnetism of the star. The general situation is potentially similar to strong supernova-remnant shocks (see the contributions in this volume: 'Magnetic Fields in Supernova Remnants and Pulsar Wind Nebulae' and 'Magnetic Fields in Cosmic Particle Acceleration Sources'). Although we are not aware of many definitive results using this approach, we nevertheless will discuss some points in this respect. The discussion is split into two parts, which may roughly be described as single stars interacting with the interstellar medium (Sect. 5.2) and multiple stars interacting among themselves, in binaries, or open clusters (Sect. 5.3).

[3] This effect is taken into account in solar models on a standard basis.

5.1 Magnetic wind structure and associated emission

An excellent review on stellar magnetospheres, their theoretical and observational aspects especially also in early-type stars, has recently been given by Owocki (2009). Much of the following is adopted from this source.

Typical wind speeds and mass losses in O-stars are on the order of 1000 km/s and 10^{-6} $M_\odot$/yr. The winds are driven by the radiation field of the stars, by photon scattering in metal lines. Analytical considerations and numerical simulations show this acceleration mechanism to be subject to an instability, leading to the formation of internal shocks in the O-star wind (Owocki and Rybicki 1984; Owocki et al. 1988; Feldmeier et al. 1997). The emission from these shocks is the generally accepted explanation for the observed soft (10^7 K), thermal, broad-lined X-ray emission (L_X/L_{Bol} 10^{-7}) from O-type stars.

Magnetic fields affecting the stellar winds of early-type stars have been suggested as a possible explanation for a number of additional observational peculiarities of these stars. Among these are strong X-ray emission in combination with narrow spectral lines of some stars (Babel and Montmerle 1997a; Favata et al. 2009), occasional flares of very hard X-rays (Townsend and Owocki 2005; Mullan 2009), or the rotation modulated Balmer line emission of Be stars (Townsend and Owocki 2005; Oksala et al. 2010). The concrete theoretical and numerical models invoked to explain these observational data have become more and more elaborate over the years.

As a simple measure to estimate the relative importance of a magnetic field for the wind of an early type star, ud-Doula and Owocki (2002) introduced the wind magnetic confinement parameter

$$\eta_* = \frac{B_*^2 R_*^2}{\dot{M} v_\infty}. \tag{3}$$

Here, B_* denotes the surface magnetic field of the star, R_* the stellar radius, $\dot{M}$ the mass loss, and v_∞ the terminal wind speed. Basically, η_* measures the ratio of the magnetic to the kinetic energy densities (ud-Doula and Owocki 2002; Owocki 2009). Values of $\eta_* << 1$ indicate that the stellar wind dominates the magnetic field, and as the magnetic field is carried with the wind a roughly radial field configuration results. By contrast, if $\eta_* >> 1$ the magnetic field dominates, an extreme example here being σ Ori E with $\eta_* \sim 10^7$. Closed magnetic field lines occur, at least in the vicinity of the star, guiding the stellar wind. With increasing distance from the star the stellar wind will generally dominate again, as the magnetic field energy decreases faster than the kinetic energy of the wind.

The basic effect of a strong enough dipole field on the wind structure is to deflect the stellar wind towards the equatorial plane separating the two magnetic hemispheres. There, collision flows results in strong shocks and associated X-ray emission. This magnetically confined wind shock model (MCWS) was first brought forward by Babel and Montmerle (1997b). In its semi-analytical formulation, the model provided a natural explanation of the periodic X-ray emission of θ^1 Ori C (Babel and Montmerle 1997a). Subsequent numerical simulations demonstrated that the X-ray emitting collision zone is not stable (ud-Doula and Owocki 2002; Ud-Doula et al. 2008). Shocked matter, once cooled, falls down along magnetic field lines, unless supported by rapid rotation of the star and associated centrifugal forces, as illustrated in Figure 7. The simulations also demonstrated, however, that despite the much more complicated, un-

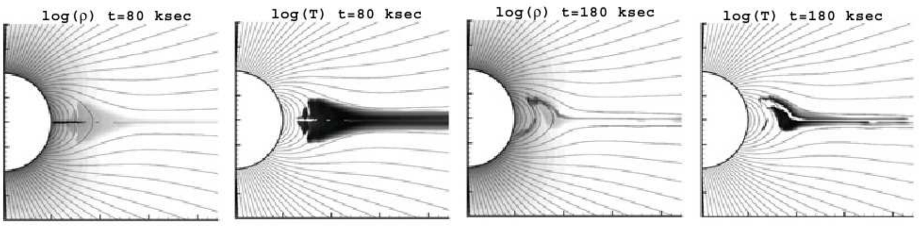

Fig. 7 MHD simulations of the MCWS for θ^1 Ori C, compiled by Owocki (2009) on the basis of ideas developed in Ud-Doula et al. (2008), his Figure 5. Shown is the logarithmic density ρ and the temperature T in a meridional plane at 80 ksec (**left**) and 180 ksec (**right**) after initialization. At the earlier time, the magnetic field has channeled wind material into a compressed, hot disk at the magnetic equator. At the later time, the cooled equatorial material is falling back toward the star, along field lines. The darkest areas in temperature correspond to about 10^7K.

stable flow structure the X-ray emission predicted by Babel and Montmerle (1997a) is approximately recovered if time-averages are considered.

Considering the effect of a strong dipole field in rapidly rotating stars, Cassinelli et al. (2002) suggested that the coupling of matter and field could result in a spin-up of the stellar wind and the formation of a quasi-Keplerian magnetically torqued disk (MTD) at the magnetic equator. The idea was not supported by subsequent numerical simulations (Owocki and Ud-Doula 2003). For the field strengths required to spin up material to Keplerian velocities, the numerical models showed a tendency for centrifugal mass ejection instead of disk formation. Alternatively, a situation where material rotates at about Keplerian velocities can be obtained if much stronger fields ($\eta_* \to \infty$) are invoked, as assumed in the rigidly rotating magnetosphere (RRM) model (Townsend and Owocki 2005). Although the disk rotation in the RRM model is rigid body rather than Keplerian, approximate Keplerian velocities result as the material accumulates at the right distance from the star in the form of a thin disk or of clouds. Applying the RRM model to σ Ori E, Townsend et al. (2005) could well reproduce the periodic modulations observed in the light curve, Hα emission-line profile, and longitudinal field strength.

Numerical simulations confirm the general working mechanism of RRM but also reveal that the accumulation of matter cannot continue for infinite time. Eventually, the centrifugal force will overcome the magnetic tension forces and plasma ejection will result. During such a centrifugal break-out (Townsend et al. 2004; ud-Doula et al. 2006), magnetic field lines will first be drawn away from the star before they snap and reconnect again. The energy release associated with this reconnection may explain the occasional observed hard X-ray flares in some early-type stars.

5.2 Single stars and their wind blown bubbles

We restrict ourselves to three kinds of wind blown bubbles and the potential effect stellar magnetic fields may have on their shape and emission: the case of an O-star wind blowing against the interstellar medium, a Wolf Rayet (WR) wind blowing into the remnant flow structures from earlier evolutionary phases, and planetary nebulae as a phase in the life of an intermediate-mass A-type or late B-type star.

As the wind of an O-type star runs highly supersonically against the interstellar medium, a strong wind-termination shock forms. There, particles will be accelerated and non-thermal emission is likely to take place. In principal, the observation of this shock and in particular of the associated non-thermal emission should give access to the field strength and topology in the wind. Unfortunately, if the O-star wind runs against the low-density ISM ($\sim$1 cm^{-3}) the termination shock is found at distances from the star, where wind densities are well below 1/100 cm^{-3}. This makes detection of non-thermal emission extremely difficult and we are actually not aware of any detection of such emission so far. One should add perhaps that – from an astronomical point of view – the observation of such a shock has hardly been of interest at all so far. However, with the increasing interest in the magnetism of massive stars this may change now.

For the roughly 300 galactic WR stars, van der Hucht (2001, 2006) estimates that only about one quarter have a ring nebula. These nebulae are commonly attributed to the fast WR wind ploughing its way through the slow wind shed by the star when being in its super-giant phase. The WR wind compresses the material from the super-giant phase into a high density shell. Not all WR stars evolve, however, through a super-giant phase and about 40% of them live in binaries (van der Hucht 2001, 2006) with different evolutionary features. If the above wind collision scenario applies, theoretical considerations by Chevalier and Luo (1994) suggest that the field might even be able to affect the shape of the resulting ring nebula.

The work by Chevalier and Luo (1994) is, however, not particularly designed for WR ring nebulae but looks instead at the general situation where a fast, powerful wind catches up with a slow, massive wind. A thin interaction zone is produced, bounded by two shocks. The inner shock is the termination shock of the magnetic wind from the central star. As they point out, the field in the wind gets increasingly toroidal as this component drops in the free wind only linearly with the distance r, in contrast to the radial component of the field, which drops quadratically in r. Also in contrast to the radial field, the toroidal field is compressed at the termination shock. Thus, even if the magnetic field is not dynamically important in the free wind, it can become dynamically very important in the shocked wind bubble. A bipolar or elliptical nebula is a natural consequence of the fact that magnetic tension exists in the equatorial direction and the lack of such effects in the polar direction. As derived in this paper, the shape of the nebula depends on two parameters, namely, on λ, the ratio between the expansion velocity of the nebula and the velocity of the slow wind, and $\sigma = \eta_*(v_{rot}/v_\infty)^2$. The paper provides the shaping of the nebulae for different combination of these parameters.

García-Segura et al. (1999) performed a numerical study of this effect for the case of planetary nebulae and also provided a series of different shapes of nebulae depending on two parameters: rotation and magnetic field strength. The authors point out that magnetic hook-stresses can collimate the flow along the rotation axis and even produce jet-like features and ansae which are indeed observed in planetary nebulae of low-mass stars. Zhekov and Myasnikov (2000) point out that heat-conduction by thermal electrons further contributes to the shape of such structures. Heat conduction, in turn, is largely influenced by the presence of magnetic fields, suppressing to a great deal conduction normal to the field.

To test the magnetization of the outflow from a massive star, and thus the presence of a stellar magnetic field, wind collision regions in binary star systems and open clusters offer much better conditions than the wind blown bubbles of Sect. 5.2. While both scenarios, wind collisions and wind blown bubbles, are accompanied by strong shocks, densities are much higher in the wind collision case and accompanying emissions thus are stronger. In fact, Eichler and Usov (1993) predicted by analytical means that the wind collision zone in early type binaries may be a strong source of synchrotron generated, non-thermal radio emission. Key ingredients of the model are the strong shocks confining the interaction zone, where electrons can undergo Fermi acceleration and reach relativistic speeds, and the availability of a magnetic field, which causes the electrons to spin and emit synchrotron radiation.

A number of WR- and O-stars are indeed known to show non-thermal radio emission due to synchrotron radiation, indicating the presence of a magnetic field. Based on observational data, van der Hucht et al. (1992) noted that many WR-stars with non-thermal emission were long-period binaries. The hypothesis that binarity is even a prerequisite for non-thermal emission of WR stars was put forward by Dougherty and Williams (2000), based on observations of 9 non-thermal WR emitters, 7 of which known binaries. In a recent review, De Becker (2007) lists 17 WR stars that show non-thermal radio-emission. Of these, 13 live in binaries, for one binarity is strongly suspected (as of November 2005), while for the remaining three stars no companion has been detected to date. Binarity remains, however, a possible explanation also for those non-thermal emitters without a detected companion, as excluding binarity is very difficult, especially if the companion is substantially less luminous. The situation is similar for O-stars. De Becker (2007) lists 16 O-stars with non-thermal emission, 14 of them are confirmed binaries or multiple systems.

That the inverse is not true, that binarity does not imply observable non-thermal emission, was already pointed out by Dougherty and Williams (2000). Of the 11 WR+OB binary star systems they observed, only those 7 systems with binary periods longer than about one year showed non-thermal emissions, while the 4 short period systems showed thermal emissions only. The authors argue that such short periods result in densities that are so high as to be opaque to radio emissions. Qualitatively the same conclusion is reached by Eichler and Usov (1993) on analytical grounds and by Pittard and Dougherty (2006) and Blomme (2010) using numerical simulations.

With binarity (or multiplicity in general) observationally established to accompany most if not all non-thermal radio emission in WR- and O-stars, the wind collision zone becomes the prime suspect for the source of the observed emission, as suggested by Usov (1991) and Eichler and Usov (1993). That the interaction zone of the two stellar winds indeed coincides with the source of the non-thermal emission was demonstrated by Williams et al. (1997) for the system WR147 (WN8 + B0.5V) by means of spatially resolved radio observations. From the radio flux they further derive a field strength between 1 and 9 mG in the WR wind, corresponding to a field on the stellar surface in the range of 30-300 G.

Internal shocks embedded in the stellar wind have been discussed as an alternative origin of the shocks needed for the Fermi acceleration of the electrons. However, recent numerical simulations indicate that the shocks are too weak when they reach the outer layers of the stellar wind, from where radio emission would be observable at all (van Loo et al. 2006; van Loo 2010; Blomme et al. 2010). This makes the collid-

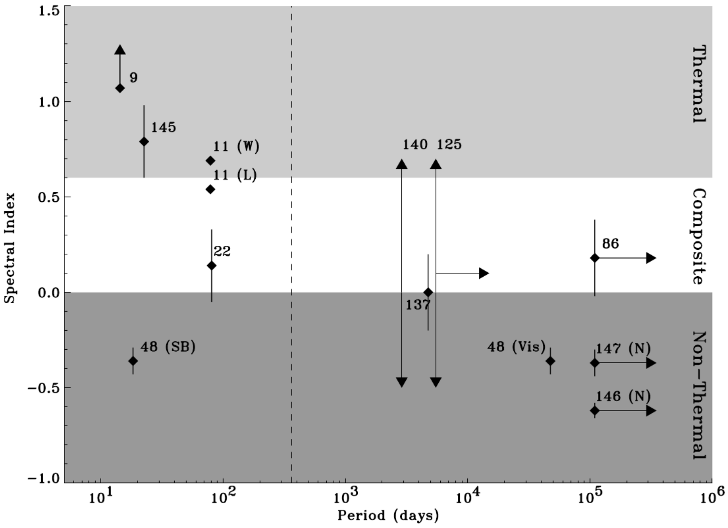

Fig. 8 Radio spectral index of WR+O binary systems against their binary period, taken from Dougherty and Williams (2000), their Figure 1. While all long period binaries show some non-thermal emission, no such emission is found in short period binaries. WR 48 is a particular case, for details see the original work.

ing wind interaction zone not only one but possibly the source of non-thermal radio emission.

With regard to magnetism in massive stars, the above observational results are interesting in at least two ways. First, the detection of 33 non-thermal emitters as listed by De Becker (2007) indicates the presence of a stellar magnetic surface field in at least 33 and maybe up to 66 WR and O stars, thus outnumbering by far the direct detection of fields in such stars (Sects. 2.4, 2.5). From the point of view that the observation of non-thermal radio emission requires a long enough binary period, the number of 33 stars even constitutes a lower limit.

Second, and more speculatively, one might argue that Dougherty and Williams (2000) found indications for the presence of a magnetic field (non-thermal radio emission) in all those WR stars which fulfilled the two necessary conditions for such a field to leave an observable signature: binarity to have a wind collision zone with strong shocks, and a long enough binary period to avoid complete absorption of the non-thermal emission within the system (see Figure 8). Simply speaking, the limiting factor may have been detectability and not the presence of a field as such. One may then further speculate whether all WR+OB and O+OB star binaries have a magnetic field. Or, if the existence of a stellar magnetic field does not depend on the star living in a binary system or not, whether all WR- and O-stars have a magnetic field. While it is unlikely that these speculations hold true in this rigid form, they indicate that it would be most interesting to search for non-thermal emission in additional WR+O star binaries. This would allow to see to what degree the above findings, based on 11 WR+O binaries only, carry over to a larger sample of the around 300 known galactic WR-stars, about 40% of which are binaries (van der Hucht 2001, 2006).

Equally desirable is a better theoretical understanding of the wind collision zone. The physics of the this zone is very complex, in particular if the conditions allow

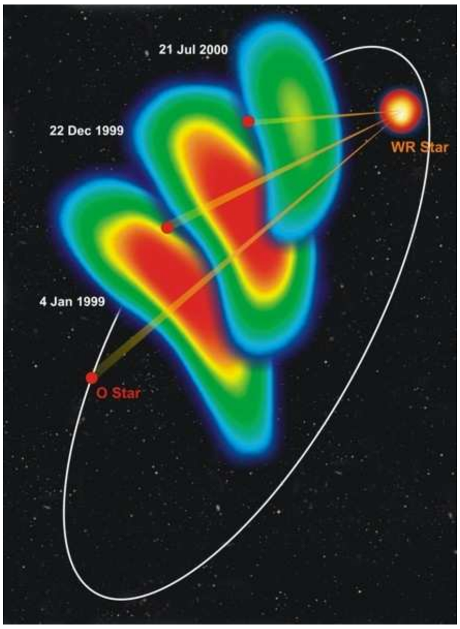

Fig. 9 A montage of 8.4-GHz VLBA observations of WR 140 at three orbital phases showing the rotation of the wind collision region as the orbit progresses. The deduced orbit is superimposed. From Dougherty and Pittard (2006), their Figure 4.

for radiative cooling, and has been studied extensively by analytical and numerical means (Usov 1991; Stevens et al. 1992; Nussbaumer and Walder 1993; Stevens and Pollock 1994; Owocki and Gayley 1995; Walder 1995; Walder and Folini 1996; Gayley et al. 1997; Walder and Folini 1998; Folini and Walder 2000a,2000b; Zhekov and Myasnikov 2000; Folini and Walder 2002; Walder and Folini 2003; Folini and Walder 2006; Pittard 2009, 2010a; Pittard and Parkin 2010). Positively speaking, shocks in colliding wind binaries are an ideal laboratory to test the physics of particle acceleration and other kinetic processes related to collisionless shock waves. With comparatively high densities and large magnetic fields as well as a very intense UV-photon field from the involved stars, the parameter space of colliding winds in massive binaries complements the region covered by shocks in supernova remnants (see the contributions in this volume: 'Magnetic Fields in Supernova Remnants and Pulsar Wind Nebulae' and 'Magnetic Fields in Cosmic Particle Acceleration Sources').

The currently most detailed numerical studies of colliding winds in WR binaries and associated non-thermal emission in radio, X-rays ,and γ-rays are the series of papers by Dougherty et al. (2003), Pittard et al. (2006), and Pittard and Dougherty (2006). Apart from hydrodynamical modeling of the collision zone, the authors developed numerical tools to fit synthetic spectra in radio, X-ray, and γ-rays to observed ones and applied these mainly to the two systems WR147 and WR140. A composite of radio observations of the latter is shown in Fig. 9. The model assumes diffuse shock acceleration of particles at the confining shocks of the wind collision zone. Corresponding particle aspects are described in terms of bulk properties, like the total energy and the energy distribution of the particles. Details on the models may be taken from a recent review of one of the authors (Pittard 2010b) or from corresponding, more recent work on O+O star binaries (Pittard 2009, 2010a; Pittard and Parkin 2010).

Noteworthy in the context of the present review, the results by Pittard and Dougherty (2006) underline again that any non-thermal emission in short-period binaries is unlikely to be observed. It is absorbed already in the stellar winds, by inverse Compton cooling, free-free absorption, and the Razin effect. Due to the strong radiation field, inverse Compton cooling is found to be the by far most effective cooling mechanism. Consequently, the authors expect non-thermal X-ray and γ-ray emission to outpower the synchrotron radio emission by orders of magnitude. The numerical results even predict the emission of TeV photons due to π^0-decay, the π^0 being produced by the collision of shock-accelerated non-thermal hadrons (see also Eichler and Usov (1993)).

Related to the 'classical' colliding wind scenario are processes taking place in dense open clusters, where massive stars often live. Such clusters blow strong galactic wind bubbles. Presumably, such bubbles play a significant role in the chemical enrichment of galaxies. By their energy impact, they furnish the turbulence of the interstellar medium and they can induce secondary star formation. Large bubbles cover a significant part of the galaxy and reach far out of the galactic plane. This huge space is magnetized by the massive star winds, which drive the bubble. As massive stars live very close to each other (roughly 1000 AU), such a bubble is created by some combined effect of single star nebulae and colliding winds. A network of strong, magnetic shocks is established. Very likely, galactic super bubbles are also a strong source of cosmic rays and another field to study particle acceleration. We are not aware of a comprehensive study of the role of magnetic fields in such bubbles. Pittard and Dougherty (2006) and Butt (2009) discuss some points, however.

5.4 Summary

In the immediate vicinity of a magnetic massive star, a magnetic dipole field has a strong effect on the stellar wind, if the ratio of the magnetic to the kinetic energy density, the wind magnetic confinement parameter η_*, is much larger than one. A shock compressed disk forms at the magnetic equator. Apart from periodic variabilities of different kind, a prominent observational signature expected from such a disk are hard X-rays.

For larger scales, further away from the star, much less is known on the effect of a magnetic field on the stellar environment. The only notable exception is the case of colliding winds in massive binary star systems. Non-thermal radio emission from the wind collision zone has been predicted and observed. The emission is considered to be indicative of a magnetic field, which must be the advected, in the wind frozen, magnetic field of the star (unless a dynamo is operating in the wind-collision zone). While the numerical models so far do not explicitly account for the stellar magnetic field, its strength and geometry, the available numerical and observational results suggest that many more massive stars (perhaps even a significant fraction) have a magnetic field than is known from direct field detections through Zeeman signatures. Performing further radio observations of massive binaries thus seems worthwhile.

6 Conclusion

The research on magnetic fields in massive and intermediate mass stars has seen tremendous progress in recent years. Reviewing corresponding developments and results is an intimidating task, all the more so as the author's backgrounds in modeling of astrophysical flows or stellar evolution touch only partly on the subject. Impressing also the range of perspectives taken on the issue: direct surface field measurements by means of the Zeeman effect, from pre-main sequence to post-main sequence stars; indirect indications of surface magnetic fields from observation and numerical modeling of colliding winds and other circumstellar phenomena; stellar evolution models exploring the effects of internal magnetic fields; dynamo theories and considerations on the stability of fossil fields to explain the origin of magnetic fields. Concluding this review by trying to sketch a general, emerging picture in this rapidly developing field is notoriously difficult and prone to misjudgments.

Starting on firm grounds, current Zeeman observations leave no doubt that at least some massive main-sequence stars poses a magnetic field. Indirect evidence, especially the observed non-thermal radio emission from a number of WR+OB and O+OB star binaries, hints at an even much larger number of magnetic massive stars. More speculatively, the only five direct field observations in main sequence O-stars may suggest a dichotomy: relatively strong ($\sim$ 1 kG) dipole fields on the one hand, as for θ^1 Ori C, and rather weak (few tens of Gauss) and unordered fields on the other hand, as for ζ Ori A.

Observational data from intermediate mass main sequence stars seem to support and enlarge this general picture. The 100% detection rate in a sample of 28 Ap / Bp stars suggests that maybe all Ap / Bp stars have a relatively strong (up to 30 kG) magnetic dipole field and that there exists, in addition, a lower limit to the magnetic dipole field of about 300 G. The recent – and first – Zeeman detection of a weak ($\sim$ 1 G) and unordered magnetic field in the normal A-type star Vega may suggest a similar dichotomy as for the massive stars. Observations of Ap / Bp stars in open clusters further suggest that the strengths of their surface fields decrease with the age of the star.

Theory offers essentially two hypothesis on the origin of the observed magnetic fields, but few firm conclusions. Compared to observations, much fewer publications are available.

The fossil field hypothesis assumes that the field was present already before the star reached the main sequence. It requires a field configuration that is stable enough for the field survive for long enough without being replenished by a dynamo. Analytical results showed long ago that such a configuration may exist in the form of a mixed poloidal-toroidal field configuration. But it was only recently that numerical simulations provided the first concrete realization of such a stable field configuration. The origin of fossil fields generally is still speculative. Suggestions range from the field being a relict of the parent molecular cloud, being generated by convection in the forming star, or being due to the merger of a pre-main-sequence binary. Whether the recently detected magnetic fields in some pre-main sequence Herbig Ae / Be stars constitute fossil fields that will eventually evolve into the field of the main-sequence Ap / Bp stars is debated.

The other explanation for the origin of observed surface magnetic fields is some sort of dynamo mechanism. There exists a lively debate on whether the radiative envelope of massive and intermediate mass stars can host a dynamo and how this would work. The only two numerical simulations addressing the topic give contradictory answers.

Equally undecided is the debate on whether fields generated in the convective core can reach the surface. For late stages of massive star evolution, during the super giant phase, surface dynamos may explain the observed magnetic field. One may speculate whether the observed dichotomy between a 'strong and ordered field' and a 'weak and unordered field', if such a dichotomy exists at all, is due to two different origins, fossil or dynamo, of the field.

Rather detailed numerical models exist for the consequences of magnetic fields on the stellar evolution and environment. These models are of particular interest as they often link the magnetism in massive stars with a wider range of phenomena and, obviously, observation with theory. Stellar evolution models link magnetism in massive stars with the rotation rates of pulsars or the origin of gamma ray bursts. Simulations of how stellar winds are affected by a stellar magnetic field lead to the identification of indirect observational evidence of the later. Colliding wind models fulfill a similar task and, in addition, allow to gain insight into the physics of particle acceleration at collision-less magnetic shocks. The dependencies are often mutual and illustrate that advances in the field of magnetism in massive stars go hand in hand with advances in some other fields. In the future, one may want to exploit these perspectives and mutual dependence's even further.

To improve, for example, the statistics on what fraction of massive stars have a magnetic field, it would be interesting to have an observation based estimate of the fraction of WR+O star binaries showing non-thermal emission. The interpretation of such data would greatly benefit from improved colliding wind models that relate the magnetic fields in the interaction zone and at the surface of the star. Such a program would offer a complementary view on the certainly anyway growing observational data base of direct magnetic surface field detections in intermediate and high mass stars.

Given that stellar evolution is probably particularly sensitive to the presence of a magnetic field when a star is formed or dies, another interesting combination could be the observation of early stages of stellar evolution or even molecular clouds with more elaborate models of star formation in the presence of a magnetic field. Also most promising in combination with stellar evolution models is the emerging field of astroseismology of intermediate and high mass stars. First data and proof of concept studies have been published, which use gravity modes that provide information on the stellar interior down to the convective core (Aerts 2008; Degroote et al. 2010b,2010a; Balona et al. 2010).

The above considerations make clear the necessity of combined efforts of observation, analytical theory, and numerical simulations to unravel the mysteries of magnetic fields in upper main sequence stars.

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