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MAGNETISM IN MASSIVE STARS

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Abstract. Stars with mass more than 8 solar masses end their lives as neutron stars, which we mostly observe as highly magnetized objects. Where does this magnetic field come from? Such a field could be formed during the collapse, or is a (modified) remnant of a fossil field since the birth of the star, or otherwise generated by a dynamo during its lifetime in the pre-collapse stages. The answer is unknown, but traditionally magnetic massive stars should not exist since they do not have a convective layer such as the Sun. In the last decade, however, a number of magnetic massive stars have been found, which likely possess a stable field from their birth, and indirect evidence is accumulating that localized fields can indeed be generated during the main-sequence lifetime and beyond. These observational facts opened a new field of research, which is the topic of this review.

Among the indirect evidence is a large range of observational phenomena among O and B stars that cannot be explained without the presence of surface magnetic fields. These phenomena include photospheric turbulence, wind clumping, cyclic wind variability observed in UV lines, other types of wind variability in optical lines, anomalous X-ray emission, and non-thermal emission in the radio region. A summary of the properties of observed magnetic massive OB stars is given and the role of magnetic fields in massive stars will be discussed, including how to identify new magnetic candidates.

1. INTRODUCTION

Why would we study massive stars? Among the hydrogen-burning stars, the most massive ones have the highest central pressure and temperature, and hence the most powerful thermonuclear processes operating in their cores, in particular the CNO cycle, which causes them to be the most luminous stars. Their energy output is so high that their life times are relatively short (<100 million yrs), being proportional to to the mass-luminosity ratio. At the end of their life they return the processed material, including heavy elements, into the interstellar medium, out of which new generations of stars form. The high luminosity of these stars drives a strong stellar wind, which is ejected into the interstellar medium. The emitted ultraviolet radiation is the main source of ionization in the interstellar radiation field. This rapid recycling and chemical enrichment is why massive stars dominate the chemical evolution in the Galaxy. Due to their brightness, massive stars also serve as extragalactic standard candles, one of the tools to set the cosmic distance scale.

Stars more massive than 8 $M_{\odot}$ end their lives as black holes or neutron stars. Neutron stars, and the even more strongly magnetic magnetars, can have magnetic fields up to 10^{10} Tesla or more, and the unanswered question is where this field comes from. In contrast to their low-mass counterparts, massive stars have no well-developed convective outer layer, the region where the magnetic field is formed by a dynamo mechanism, as in the Sun, A fossil field, acquired at birth, is a possibility, but such a field should then be maintained through the whole evolutionary path of the star: along the main sequence, through the expansion of the supergiant stage, and survive the collapse to the neutron star. Flux conservation of a small initial stellar surface field, say 100 G, during its evolution is not incompatible with such a scenario ending up in a highly magnetic compact object. Another option is that the strong neutron-star magnetic field is formed during the final collapse, independent of the field strength at the pre-collapse phase. A leading, unanswered, question is whether magnetars need a magnetic progenitor (see Hu & Lou 2009). The situation with magnetic white dwarfs, who descend from A-type stars, is different. Statistically the fraction of magnetic white dwarfs and magnetic A stars is similar (about 10 %), and since white dwarfs have no convection, fossil fields are likely the only option for their progenitors (Ferrario & Wickramasinghe 2005).

Due to the advent of advanced spectrapolarimeters (FORS1, Sempol, Musicos, Espadons, Narval, Harpspol) in the last decade a number of massive stars have been found with stable dipolar fields ($\simeq$ 1000 G), which were likely present from their birth. In addition, indirect evidence is accumulating that a large range of observational phenomena in massive stars cannot be explained without the presence of surface magnetic fields, for example photospheric turbulence, wind clumping, cyclic wind variability observed in UV lines (see below), other types of wind variability in optical lines (Hα, He II 4686, Moffat & Michaud 1981; Stahl et al. 1996; Rauw et al. 2001), specific pulsation behavior, anomalous X-ray emission (Cohen et al. 2003, Gagné et al. 2005), and non-thermal emission in the radio region (Bieging et al. 1989, Schnerr et al. 2007). Their magnetic origin is however not established. From the theoretical side, indirect evidence is accumulating that localized fields can indeed be generated during the main-sequence lifetime and beyond (Cantiello & Braithwaite 2011). Magnetic fields can now be incorporated in 3D MHD calculations, which allows numerical studies of these phenomena (ud-Doula 2012).

In this review we consider the evidence of magnetic fields in massive stars and its relation to stellar winds.

2. MAGNETIC-FIELD MEASUREMENTS

Measurement of the Zeeman splitting of polarized spectral lines due to the presence of a magnetic feld is the base of all techniques to measure the field strength. The splitting of the circularly polarized components of the lines is used because it exceeds the splitting of the linearly polarized components. Even then, in practice, for stellar objects with small field strengths, the splitting is so small that it can only be detected with extremely high signal to noise ratios. A common technique (Donati et al. 1997), called the Least-Squares Deconvolution (LSD) method, is to multiplex all suitable stellar lines in the spectrum, weighted by the proper Landé factor, and corrected for the wavelength dependency and central depth, in order to increase the S/N of the resulting composed Stokes I and V line profiles. The first moment of the polarized Stokes V LSD profile gives the field strength of the integrated longitudinal component of the magnetic field over the visible hemisphere of the star. For late-type stars more

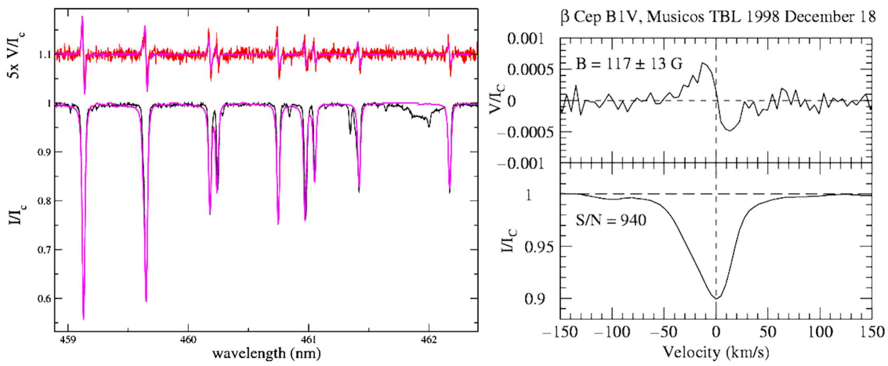

Figure 1: Left panel: portion of the unpolarized I (bottom) and circularly polarized Stokes V (top) spectrum of a strongly magnetic star. The typical Stokes V profiles show up in all stellar lines. Superposed is the modeled spectrum which includes the magnetic field signatures. Right panel: LSD Stokes unpolarized I (bottom) and circularly polarized Stokes V profile (top), composed out of more than 200 selected spectral lines for a weakly magnetic star. The field strength follows from the first moment, which is the surface subtended by the profile.

than 5000 lines may contribute, allowing for a very small detection treshold (<1 G), but for O stars less than 20 lines are available, which gives a much larger error bar (typically 100 G). In rotationally broadened lines the magnetic signal is diluted, so that for a given spectral type the error bar depends on the $v\sin i$ of the star as well. As an example Fig. 1 shows a Stokes V spectrum of a strongly magnetic star where the magnetism is readily visible and the LSD Stokes V profile of a weakly magnetic star which shows the magnetic signature only after deconvolution of many lines. Other techniques are applied as well, in particular with low-resolution polarized spectra obtained with FORS1 at the VLT, see for instance Hubrig et al. (2004) and references therein for the method.

3. MAGNETIC-FIELD DISCOVERIES

All stars of the well-known class of early B-type helium-strong and late B-type helium-weak stars are known for a long time to be magnetic. Other magnetic OB stars were only much later discovered with the new advanced instrumentation. Table 1 lists the earliest found magnetic OB stars, in order of discovery until 2009. Since then many more magnetic OB stars are found, partly due the the international MiMes collaboration which studies magnetism in massive stars (Wade et al. 2009).

These initial discoveries were made after a careful selection of potential magnetic stars by considering indirect evidence. The most reliable evidence is by looking at wind variability in the form of strictly periodic variations in wind lines, symmetric around the rest wavelength (see below). In this way the period (identified with the rotation) was determined from UV wind line variability beforehand, which greatly facilitates the analyis. The first three stars have been discovered this way. Other indirect evidence came from considering the N abundance of magnetic candidate stars, which were known to be enriched beforehand and put on the target list. This was later confirmed by Morel et al. (2006). Some of these magnetic stars appeared to be He enriched. It also emerged that τ Sco with its odd wind behavior, had similar magnetic counterparts, called the τ Sco clones. All Of?p stars appear to be magnetic, another clear morphological signature. For a recent critical compilation of all magnetic OB stars known as of medio 2012, see Petit et al. (2012).

It should be emphasized that the tabulated polar values of the magnetic field follows from modeling the field geometry, which requires an estimate of the inclination angle of the rotational axis and the obliquity of the magnetic axis. The reported values are on average about 3 times the maxmimum of the measured longitudinal field. Exceptions are τ Sco and ζ Ori, where deviations of a dipole are apparent.

Table 1: Early history of discovery of magnetic OB stars. The well known magnetic helium-peculiar B stars are excluded.

Year	Star	Spectral Type	Mass ($M_\odot$)	B_p (G)	Instrument	Reference
1998	β Cep	B1IV	12	360	TBL, Musicos	Henrichs et al. (2000)
2002	V2052 Oph	B1IV	10	250	TBL, Musicos	Neiner et al. (2003a)
	ζ Cas	B2IV	9	340	TBL, Musicos	Neiner et al. (2003b)
	θ^1 Ori C	O7Vp	45	1100	TBL, Musicos	Donati et al. (2002)
2006	ξ^1 CMa	B1III	14	500	VLT, FORS1	Hubrig et al. (2006)
	HD 191612	Of?p	37	1500	TBL, Musicos	Donati et al. (2006)
	τ Sco	B0.2V	15	500	CFHT, Espadons	Donati et al. (2006)
2008	NU Ori	B0.5V	14	600	CFHT, Espadons	Petit et al. (2008)
	ζ Ori	O9.7Ib	40	100	TBL, Narval	Bouret et al. (2008)
	σ Lup	B1-2V	9	460	AAT, SemPol	Henrichs et al. (2012)*
2009	HD 57682	O9V	17	1700	CFHT, Espadons	Grunhut et al. (2009)*
	HD 108	Of?p	17	1700	TBL, Narval	Martins et al. (2010)*
	HD 148937	Of?p	17	1700	VLT, FORS1	Hubrig et al. (2008)

*and the MiMeS collaboration, an international consortium to study magnetism in massive stars (see Wade et al. 2009).

4. WIND VARIABILITY

Stellar winds of early-type stars are observed in UV resonance lines, like C IV λ 1548, 1550, Si IV λ 1393, 1403 and N V λ 1239, 1243. O-type stars have generally dense winds, and the line profiles show a characteristic P-Cygni shape with red-shifted emission and blue-shifted absorption. The blue edge of the of the absorption is taken as the terminal velocity of the wind. The strength of the wind contribution in these lines decreases towards lower temperature. B-type stars (non supergiants) show the same trend, but with much less emission.

There are two types of wind variability. The first is the one described above, where the profiles change from emission to absorption symmetrically around the rest wavelength. All magnetic oblique rotators show this behavior, including the He-peculiar stars, see Fig. 2. This behavior directly lead to the discovery of 4 of the stars

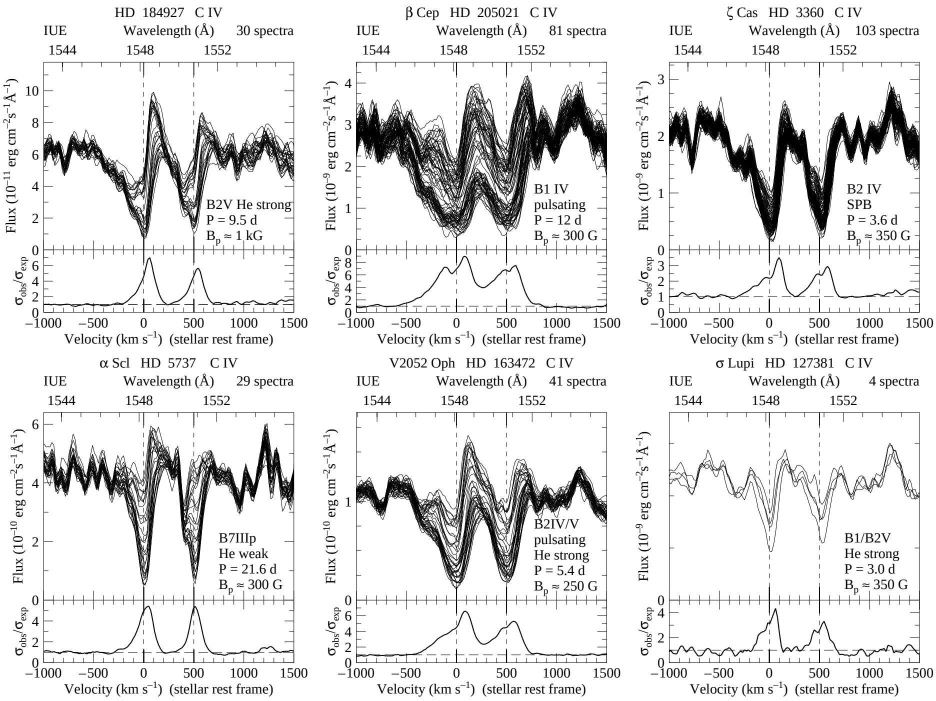

Figure 2: Gallery of signatures of magnetically confined stellar winds in the UV C IV line in magnetic B stars (from Henrichs et al. 2012). The typical modulation in the known magnetic He-strong star (top left) and the magnetic He-weak star (bottom left) is very similar to that observed in the four early B-type stars (see Table 1), which led to the discoveries of their magnetic fields. Note that rotation period, pulsation properties and helium peculiarity differ. In each figure the upper panel shows an overplot of all available IUE spectra, taken over many rotational cycles. The lower panel displays the ratio of the observed variation to the expected variation (due to the noise), showing the velocity range in the stellar rest frame within which significant variations occur. The whole profile moves up and down, nearly symmetrically around zero velocity. This phenomenon is uniquely observed in magnetic oblique rotators.

from Table 1. These stars have magnetically confined corotating winds with maximum wind absorption occurring when the magnetic equatorial plane crosses the line of sight. Combining the magnetic and wind phase dependency yields the inclination and magnetic obliquity angles (e.g. Neiner et al. 2003a).

The second type of wind variability occurs in the well developed UV P Cygni wind profiles, mainly in the form of the so-called discrete absorption components (DACs), which march through the profile from low to high (negative) velocity uuntil the terminal velocity at the blue edge. A close comparison of the time behavior of saturated profiles with unsaturated profiles with DACs show that the observed blue-edge variability is actually the same phenomenon as the DACs, which does therefore not reflect a change in terminal velocity. Fig. 3 shows examples of DACs in stars with different values of $v\sin i$. Other examples are given by Howarth et al. (1995),

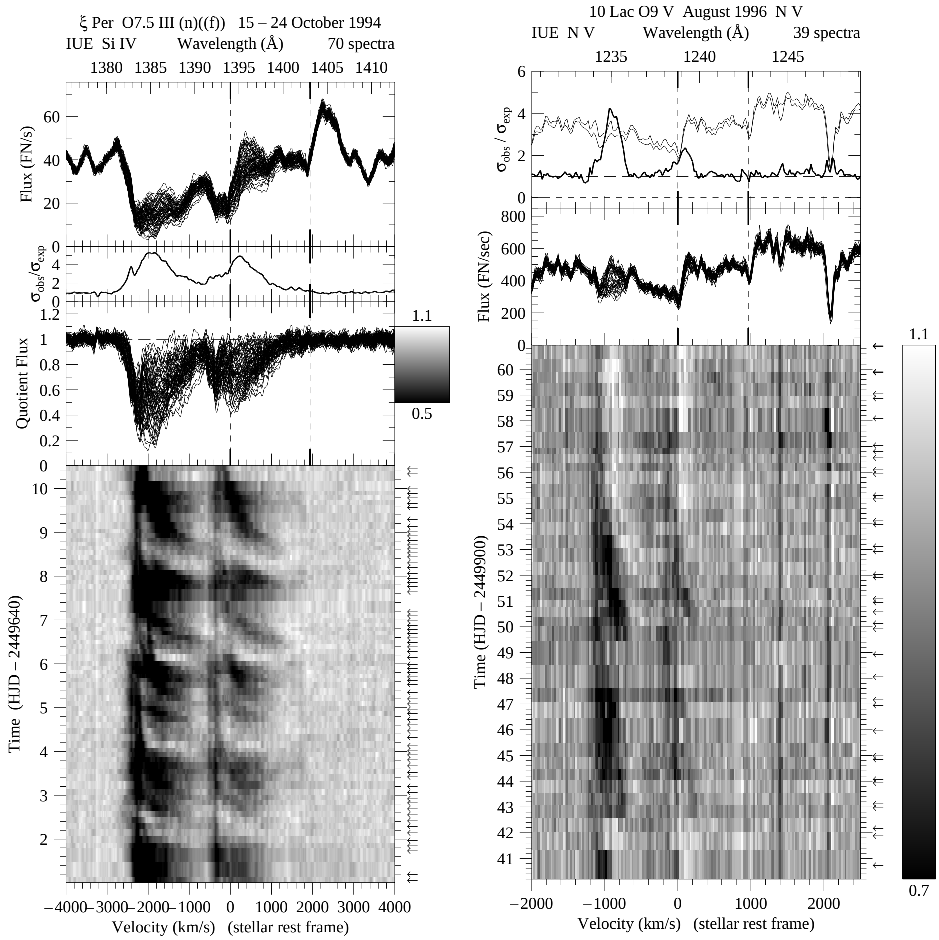

Figure 3: Left: Typical cyclical variability in the UV Si IV doublet wind lines, here shown in the O7.5 III star ξ Per as observed during 9 days with the IUE satellite. The top panel shows an overplot of the profiles with the significance of the variability below. Third panel: residual spectra with respect to a fixed template, with the corresponding greyscale plot below, showing the cyclic behavior of the DACs. The recurrence timescale of about 2 days is comparable with the estimated rotation timescale. Right: Similar plot of the UV N V doublet wind lines of the slow rotator 10 Lac O9V during 20 days. The top panel shows the average, template spectrum, and significance (thick line). The timescale is much slower than for the raprid rotator ξ Per.

Massa et al. (1995) and Kaper et al. (1996, 1999). From all case studies (about twenty) it appears that the DAC reoccurrences are cyclic (like sunspots), as opposed to strictly periodic like in the oblique rotators. The characteristic period of the DACs is approximately the same for a given star, but the pattern differs from year to year, or probably over shorter timescales (see Kaper et al. (1996) for a number of examples).

The minimum velocity at which DACs occur corresponds to $v\sin i$, and Hα or He II λ4686 (which are formed close to the star) variations are clearly correlated with the DACs, which implies that the source of DACs must be at or very close to the stellar surface. A clear example is given by de Jong et et al. (2001).

Mullan (1984, 1986) proposed that DACs are caused by corotating interacting regions (CIRs) as observed in the solar wind. The emergent wind flow is perturbed by some structure at the surface of the star which causes a local change in the radial flow properties. Such a stream will be curved due to the stellar rotation. Further-out in the wind, slow and fast moving streams collide and form a shock-front, corotating with the star. The CIR model was worked out in detail and simulated with hydrodynamical computations by Cranmer & Owocki (1996), which show very similar behavior to what is observed. The unspecified structure on the surface could be due for instance to non-radial pulsations (NRP) or magnetic spots. Not many NRP studies of O stars exist (for instance see Henrichs 1999), but they all show periods which are in the order of hours up to a day, rather than the typical recurrence timescale of DACS which is days to weeks.

Corotating surface features in the form of localized magnetic fields make a valid working hypothesis, but only circumstantial evidence has been found so far. The required field strength can be estimated by considering the wind confinement parameter as defined by ud-Doula & Owocki (2002) as the ratio of the magnetic to wind pressure: $\eta = B_{\rm eq}^2 R_*^2/\dot{M} v_{\rm inf}^2$, with symbols having their usual meanings. For field strengths of order 100 G and for typical O star wind parameters η is as low as of the order of unity, which implies that the dynamics of the wind is already altered. In such a model each magnetic spot would be a footpoint of a DAC. Such low values for the magnetic field have not been detected for the notoriously difficult O stars (but perhaps for ζ Ori, see Table 1), but cancelling effects come into play when more magnetic spots are simultaneously present at the visible hemisphere, and detection may hardly possible with the present instrumentation. From the theoretical side, Cantiello & Braithwaite (2011) calculated maximum magnetic field values for massive stars, assuming that the convective energy in the well-known subsurface convective layers (caused by a peak in opacity of the iron-group elements, Cantiello 2009) is converted into magnetic energy via magnetic buoyancy. They also calculated the turn-over timescale of these layers, which is in the order of years. These authors argue that subsurface magnetism could be responsible for photometric variability and play a role in X-ray emission and wind clumping as well.

5. DISCUSSION AND CONCLUSION

Magnetism in massive stars is a wide-spread phenomenon, but remains difficult to detect. Detection methods have become more and more sensitive, and current surveys point at a maximum of a 10% fraction or less of magnetic OB stars as oblique rotators (see for instance Petit et al. 2012). Whether the progenitors of magnetic neutron stars need to be magnetic is still not solved, neither whether magnetars could be descendents of oblique rotators. Understanding the interaction of a magnetic field with the stellar wind is most critical, and is the most important tool for further progress, along with X-ray studies. The search for magnetic spots as responsible for the DAC stellar wind variability is continuing.

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