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Magnetic Fields of Massive Stars, on and after the Main Sequence

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Abstract

The presence of a magnetic field in the outer layers of hot OB-type main sequence stars has clear and immediate impacts on their radiation-driven winds, resulting in obvious physical consequences than directly influence their observational properties and subsequent evolution. Furthermore, those initial magnetic fields are transported and modified during the stars' future histories, and may appear as evolved fossils or they may seed dynamos as the stars cool and grow during their post-main sequence evolution.

In this paper I will review the characteristics and consequences of the magnetic fields observed in hot stars, both on the main sequence and at later stages of stellar evolution.

Keywords: Massive stars, stellar magnetic fields, stellar evolution

1. Magnetic Fields across the Hertzsprung–Russell diagram

The magnetic fields at the surfaces of stars roughly trace their exterior convective structure across the Hertzsprung–Russell diagram (HRD; see Fig. 1). Stars exhibiting vigorous surface convection, like the Sun and other cool ($T_{\rm eff} \lesssim 7000$ K) stars, host dynamos that generate magnetic fields contemporaneously. Those magnetic fields are generally variable on both short and long timescales (think of the evolution of solar active regions versus the 22-year solar cycle), locally strong (typically of order the equipartition field strength), and relatively complex. Those magnetic fields correlate strongly with the current physical properties of the star, especially the rate of rotation and the convective zone properties. These fields are ubiquitous: essentially all convective stars with sufficiently rapid rotation will drive a dynamo and exhibit these characteristics.

In contrast, in about 10% of main sequence (MS) stars with temperatures above ~ 7000 K (again, see Fig. 1), in which the the principal mode of energy transport in the stellar envelope is through radiation, magnetic fields are observed whose properties differ qualitatively from the dynamo-generated fields described above. These strong ($\sim$ kG, often super-equipartition), organized ($\sim$ dipolar), stable (on timescales $\gtrsim$ decades), and oblique (relative to the stellar rotation

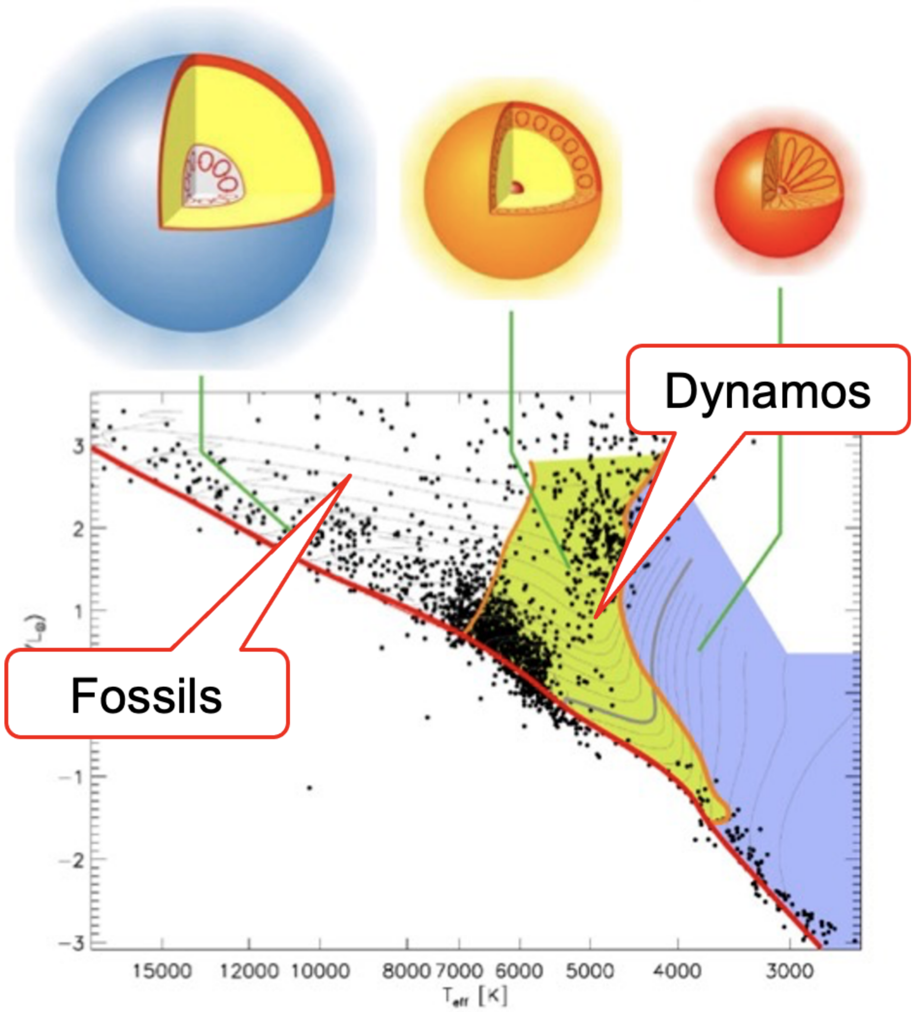

Figure 1: The magnetic fields of stars trace their external convective structure. Cooler stars with external convection zones (green and blue regions) generate dynamos that yield magnetic fields that are largely (but not entirely!) globally quite weak and variable. These fields correlate strongly with the characteristics of the exterior convection zone and with the rate of rotation. In contrast, hotter stars with radiative envelopes (white region) generally show no evidence for significant surface magnetism, apart from a small fraction (about 10%) that clearly host strong, stable magnetic fields. These *fossil fields* are independent of rotation or (main sequence) evolutionary properties. Through their interaction with the stellar wind, they are capable of strongly influencing the observational properties and evolution of hot OB-type stars. Figure courtesy of J. Morin, adapted from Reiners (2008).

axis) magnetic fields are widely believed to be "fossil" magnetic fields: slowly-evolving remnants generated as a consequence of prior stellar evolution through amplification of a primordial seed field (see Wade et al., 2016, and references therein).

2. (Magnetic) OB Stars

Massive stars begin their (hydrogen-burning) lives as hot, luminous O- and B-type stars on the main sequence. With initial masses from 8 to upwards of $100 M_{\odot}$, effective temperatures from roughly 25–50 kK, and luminosities of approximately 10^4–$10^6 L_{\odot}$, these stars drive powerful supersonic winds that strongly imprint on their observational properties and influence their evolution by modifying their mass and rotation. They are also generally rapid rotators, sufficiently so that modern evolutionary models must include the effects of rotation (and mass loss) in order to reasonably explain their positions on the HRD.

The presence of a magnetic field at the surface of an OB star can strongly modify its mass loss and angular momentum loss, leading to important consequences for its evolution. While these effects are (likely) strongest on the main sequence, they (likely) remain an important consideration for much of a stars' pre-supernova lifetime.

3. On the Main Sequence

We consider the example of a B0 main sequence star with a dipolar surface magnetic field of 3 kG at the magnetic pole. The axis of the magnetic field is oblique, i.e. inclined relative to the axis of stellar rotation. As the star drives accelerating mass loss via its radiatively-driven wind, wind ions interact with the magnetic field lines via the Lorentz force, leading to channelling of the wind flow. Near the magnetic poles, where field lines are open and leave the stellar surface more-or-less radially, the wind flow is relatively unimpeded. However, in the region surrounding the magnetic equator closed magnetic field lines confine the wind and direct flows from opposite hemispheres toward the equatorial plane, generating a supersonic wind shock. The resulting magnetosphere is a complex and dynamic structure composed of (relatively) unimpeded wind flow, hot post-shock plasma, and cooled gas (Fig. 2, left). For more detail regarding the theoretical and observational underpinnings of this picture, see e. g., ud-Doula and Owocki (2002) and Petit et al. (2013).

The obliquity of the magnetic field relative to the stellar rotation axis - typical amongst stars hosting fossil fields - results in the rotational modulation of many observables as the magnetosphere is presented to the observer from varying aspects as the star rotates. In the example of the magnetic O-type star HD 191612 shown in Fig. 2 (right), the line-of-sight component of the magnetic field (top), the Hα equivalent width (middle), and the Hipparcos magnitude (bottom) all vary coherently with the star's inferred rotation period of 538 d.

The very slow rotation of HD 191612 (also confirmed by independent photometric and polarimetric measurements (Munoz et al., 2022)) is not unusual amongst magnetic OB stars.

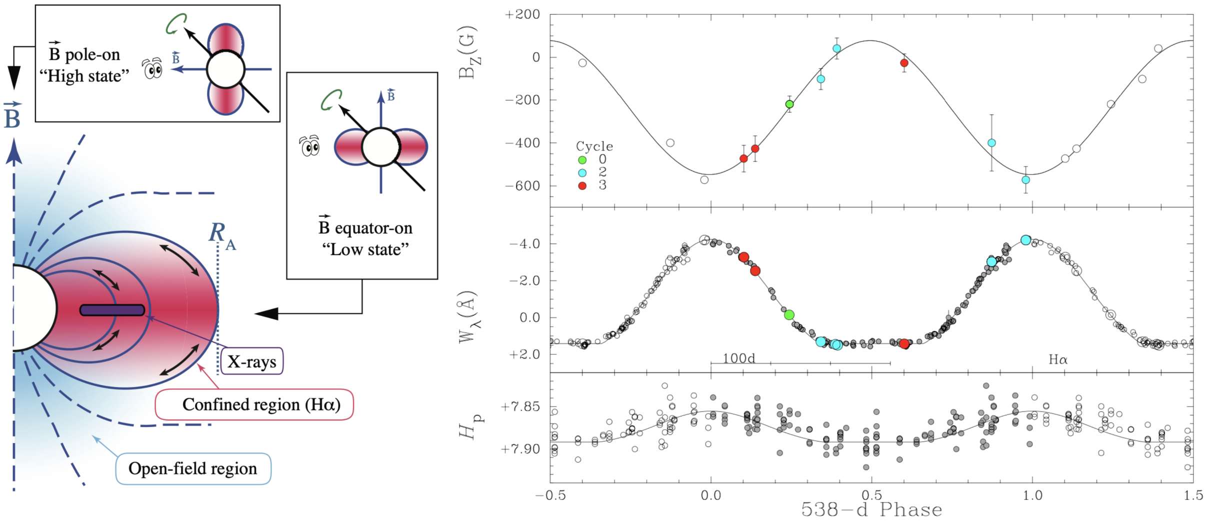

Figure 2: (*Left*) Schematic of the magnetosphere of a magnetic OB star. Solid blue lines indicate regions below the last closed magnetic loop that confine the wind. Dashed lines indicate regions where the momentum of the wind results in open field lines. Reproduced from Petit et al. (2015). (*Right*) Longitudinal magnetic field, Hα equivalent width, and Hipparcos magnitude of the magnetic Of?p star HD 191612. The observations are phased, and are observed to be modulated, according to the star's inferred rotation period of 538 d. Adapted from Wade et al. (2011, Fig. 3).

Magnetic braking (e. g., Ud-Doula et al., 2009) due to the coupling of their powerful winds and magnetic fields results in efficient shedding of rotational angular momentum.

The magnetic characteristics of main sequence B and O stars have been extensively studied. Shultz et al. (2018, 2019a,b, 2020) investigated all then-known magnetic B stars as a population, characterizing their physical and atmospheric properties, evolutionary state, rotation, magnetic geometry, and magnetospheric properties. The population of magnetic O-type stars is much smaller (only about a dozen confirmed examples); their properties were summarized by Wade and MiMeS Collaboration (2015).

4. After the Main Sequence

Following the exhaustion of hydrogen core burning, classical stellar evolution sees massive stars evolving across the HRD in a series of blue loops, alternating between blue and yellow/red supergiant phases as they proceed through subsequent nuclear burning phases. Ultimately, they are predicted to end their lives in type II, Ib, or Ic supernova explosions, yielding a neutron star or black hole remnant (see Petit et al., 2017). However, the details of the evolution of magnetic (single) OB stars, influenced by modified mass loss and rotational properties, is not well understood and is currently being investigated (Keszthelyi et al., 2019).

Our ability to measure the magnetic fields of massive stars during their post-MS evolution remains limited. Their fields are predicted (and observed) to weaken considerably, and uncertainties in stellar structure predictions leave the origins of observed fields uncertain.

4.1. Cool supergiants

To our knowledge, Aurière et al. (2010) were the first to present a direct detection of a magnetic field in a clearly post-MS massive-star descendent, in the M supergiant Betelgeuse, measuring its 0.5–1.5 G field a half-dozen times and speculating that it had its origin in a local dynamo associated with giant convection cells. Grunhut et al. (2010) presented the first survey of weak magnetic fields in a sample of over 30 intermediate-mass and high-mass cool supergiants ranging in spectral type from late M to early A. They detected Zeeman signatures in the line profiles of about one-third of their sample, and also concluded that the magnetic fields were likely of dynamo origin.

One of the targets detected by Grunhut et al. (2010) was η Aql, the first classical Cepheid variable suggested to exhibit a detectable field. Barron et al. (2022) followed this breadcrumb to conduct the first significant survey of the magnetic fields of these important objects, reporting the detection of a strong and complex field in Polaris Aa (F7Ib-F8Ib) and three other stars: η Aql (again), ζ Gem (F7Ib-G3Ib), and the eponymous δ Cep (F5Ib-G1Ib). A remarkable characteristic of the Zeeman signatures of classical Cepheids reported by Barron et al. (2022) are their unusual, approximately unipolar, positive circular polarization lobes. Those authors also demonstrated that the magnetic field of η Aql was detectable during the entire pulsation cycle of that star, and that the character of the Zeeman signature did not change appreciably on that timescale (Fig. 3).

4.2. Tepid supergiants

Neiner et al. (2017) were the first to present detections of magnetic fields in warmer A-type supergiants, reporting detections for ι Car (A7Ib) and υ Car (HR 3890; A7Ib). It should be noted that the longitudinal field uncertainties required to achieve these detections were of order 0.1 G – these are *tiny* magnetic fields! These detections were soon followed by the detection of a magnetic field in the A5Ib-II supergiant 19 Aur by Martin et al. (2018). In the context of the LIFE (Large Impact of Magnetic Fields on Stellar Evolution) project, Martin et al. (2018) reported ESPaDOnS (Echelle Spectro-Polarimetric Device for the Observation of Stars) observations of 15 evolved OBA giant and supergiant stars, detecting two: the aforementioned 19 Aur, and HR 3042 (likely a main sequence or early post-main sequence late Bp star). Additional detections of the supergiants η Leo (A0Ib) and 13 Mon (A1Ib) were reported by Neiner et al. (2018) (see Fig. 4).

Unlike the magnetic fields detected in cool supergiants by Aurière et al. (2010) and Grunhut et al. (2010), which exhibit all of the hallmarks of dynamo-powered fields, the magnetic fields of many of these warmer supergiants appear to be more fossil in nature (see Wade et al., in prep.). In particular, they exhibit Zeeman signatures that are simple and bipolar. Those signatures

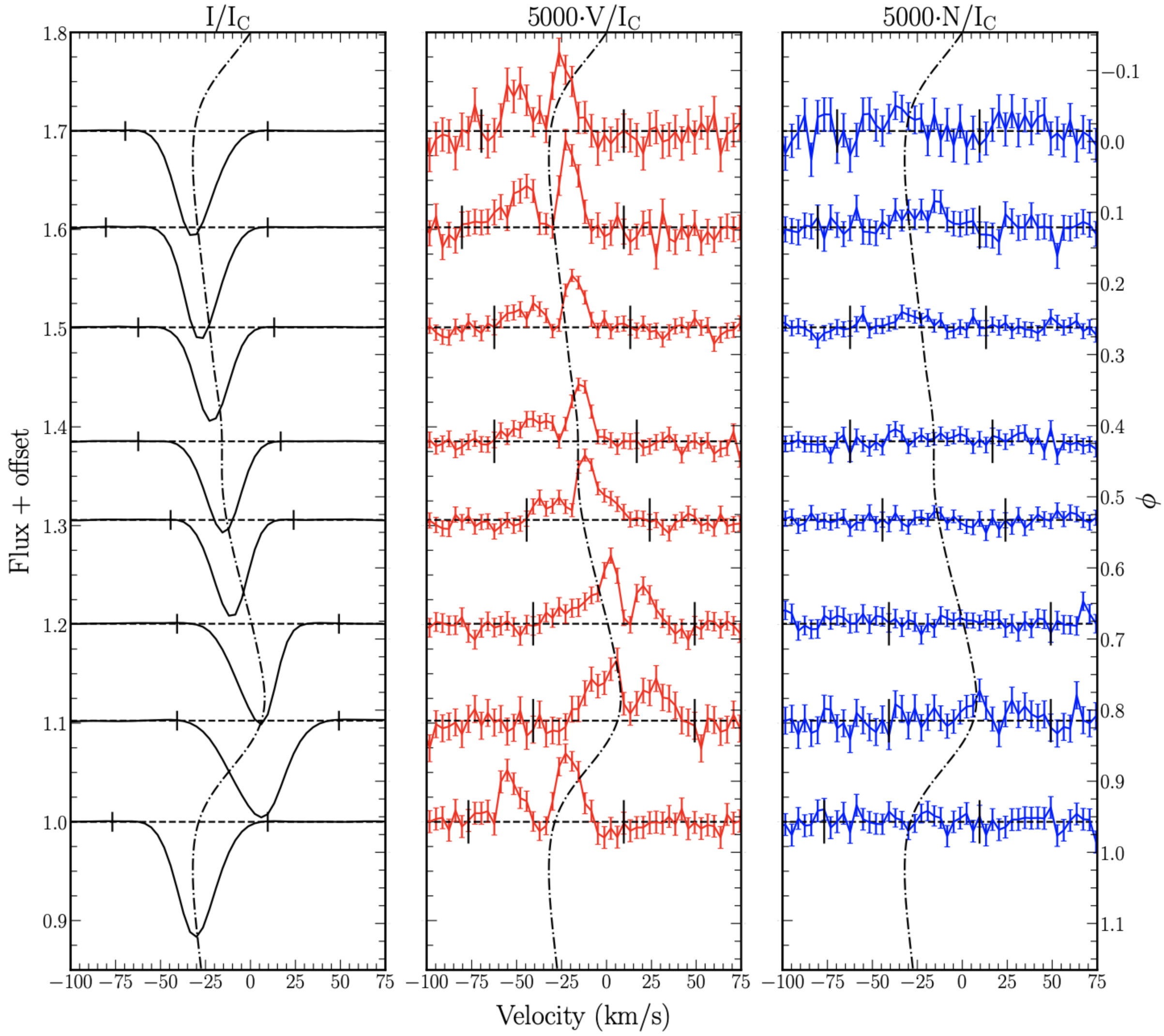

Figure 3: Least-Squared Deconvolved profiles (*left:* Stokes I; *middle:* Stokes V; *right:* null N profiles) of η Aql phased according to its pulsation ephemeris $\mathrm{JD} = 2448069.8905 + 7.176841(12) \cdot E$. Observations were obtained on consecutive nights from top to bottom. Black dash-dotted lines show η Aql's radial velocity variation. Reproduced from Barron et al. (2022, Fig. 2).

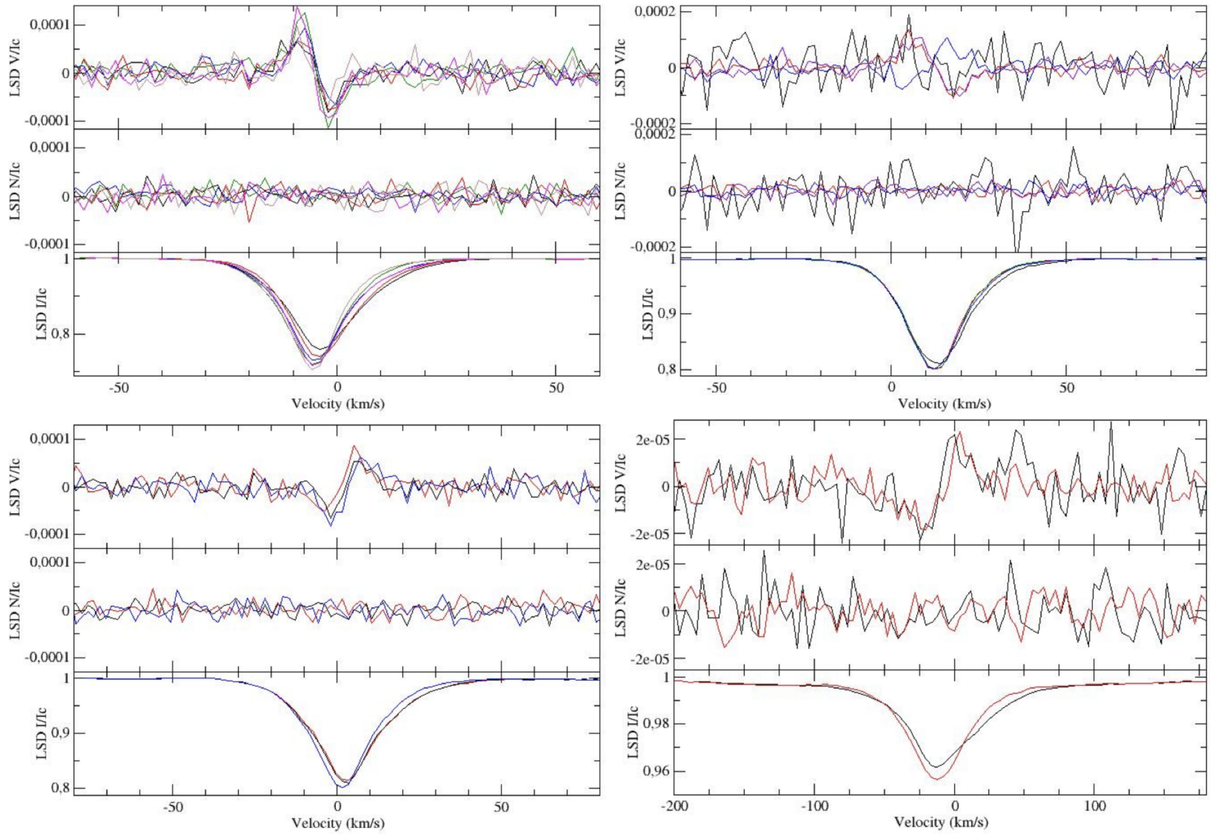

Figure 4: Least-Squares Deconvolved Stokes *V* (*top*), Null polarization (*middle*), and Stokes *I (bottom*) profiles of the blue supergiants 19 Aur (*top left*), 13 Mon (*top right*), η Leo (*bottom left*) and d Car (*bottom right*). Adapted from Neiner et al. (2018).

change slowly with time (as is expected from rotational modulation according to a long period) and sometimes change polarity (e.g. 13 Mon, Fig. 4, upper right).

5. Binarity and Magnetism of Massive Stars

Alecian et al. (2015) reported that the incidence of magnetic OBA stars in shorter-period binary systems is anomalously low. Of 151 multi-lined spectroscopic binary systems observed by them (i. e. at least 302 stars), only one magnetic field was detected, and that in a rather cool F4V+F5V binary. This low incidence rate should be contrasted to the canonical $\sim 10\%$ incidence rate of fields in effectively single stars (e. g., Grunhut et al., 2017). As a consequence, those close binary systems containing a magnetic star (or stars) are of particularly interest as evolutionary tracers of the origins of fossil magnetism. Moreover, because of the high incidence of mass transfer and mergers in massive binaries, magnetic stars in such systems represent novel laboratories for investigating stellar evolution under the combined influence of magnetism and binarity. Here we provide three examples of short-period binary systems in which magnetic fields are likely implicated in their long-term evolution.

ε Lupi is a double-lined spectroscopic binary consisting of components of spectral types

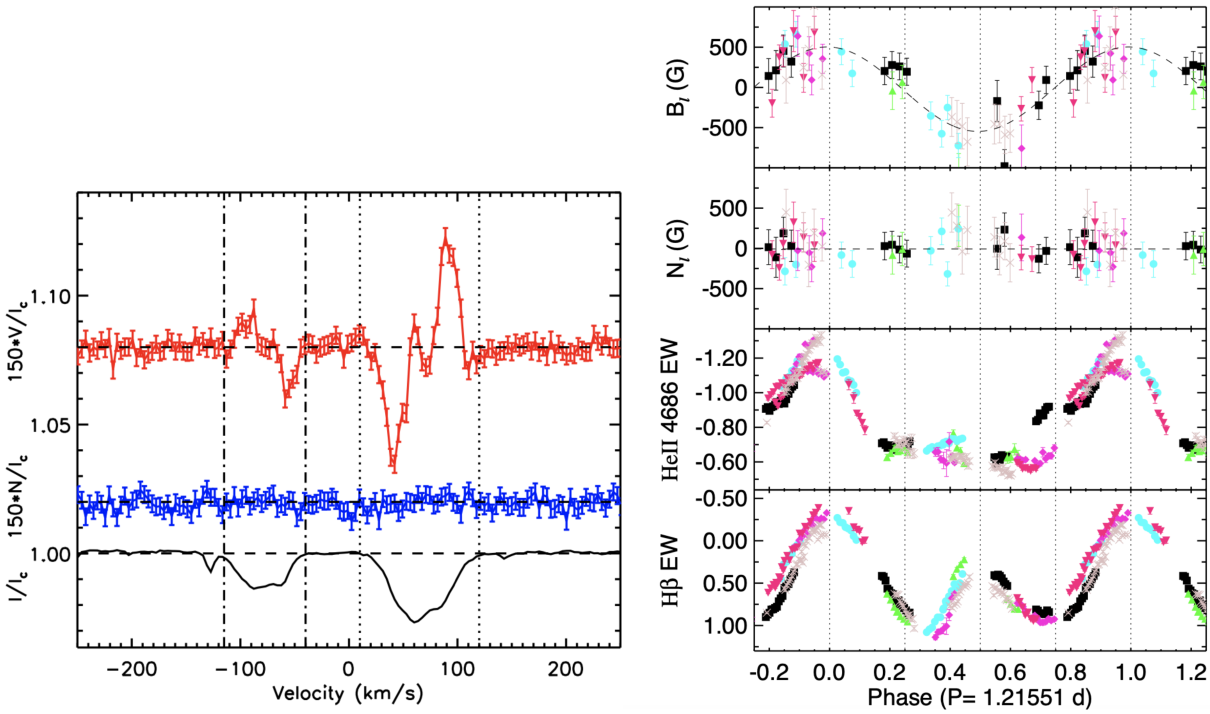

Figure 5: (*Left*) Least-Squared Deconvolved profiles of ε Lupi showing mean spectral lines of both components (black) and the detection of their associated Zeeman signatures in circular polarization (red). Reproduced from Shultz et al. (2015, Fig. 1). (*Right*) Phased magnetic field and magnetospheric spectral line equivalent width variations of the broad-line component of Plaskett's star. Reproduced from Grunhut et al. (2022, Fig. 4).

B2V+B3V (see Pablo et al., 2019) in a moderately eccentric, 4.56 d orbit. The detection of magnetic fields in both components by Shultz et al. (2015) established it as the only known short-period binary containing two magnetized hot stars. The inferred geometries of the stars' magnetic fields are remarkable: they appear to be roughly aligned with their rotation axes, which are themselves likely aligned with the axis perpendicular to the orbital plane. The magnetic polarities of the two stars are opposite: one star shows a consistently positive Stokes V signature, while the other shows a consistently negative signature (Fig. 5, left panel). As was explained by Pablo et al. (2019), the lowest-energy stable magnetic configuration due to the magnetic dipole-dipole interaction force is vertical anti-aligned magnetic fields, as is observed in ε Lupi.

Shultz et al. (2015) also pointed out that the magnetic, wind, and orbital parameters of the two stars imply that their magnetospheres are likely continuously interacting. Moreover, because the orbital eccentricity is non-negligible (~ 0.28), the extent of magnetospheric overlap varies considerably during the orbit. This interaction was clearly revealed by Biswas et al. (2023) who detected pulsed radio emission from the system, with the strongest pulses repeated at the phase of periastron (when the magnetospheric interaction is expected to be most energetic). Simultaneously, Das et al. (2023) detected X-ray emission from the system that was, once again, most intense at periastron.

Plaskett's star (Plaskett, 1922; Linder et al., 2008; Grunhut et al., 2022) has been known for over a century to be a double-lined spectroscopic binary consisting of two O-type components, one with relatively narrow ($v \sin i \sim 75$ km/s) spectral lines and one with rather broad ($v \sin i \sim 350$ km/s) lines. Plaskett (1922), and again most recently Linder et al. (2008), modeled the system as consisting of two $\sim 50 M_{\odot}$ components in a circular, 14.4 d orbit. Linder et al. (2008) considered the emission-line variability of the spectrum in the context of post-Roche Lobe Overflow (RLOF) mass transfer. Grunhut et al. (2013), in the context of the MiMeS survey (Wade et al., 2016), discovered that the broad-line component of Plaskett's star hosts a strong fossil magnetic field. Grunhut et al. (2022) modeled the magnetic field and studied the magnetosphere of the system (Fig. 5, right panel) and discovered that the historical binary model was incompatible with their new circular polarization measurements; in particular, they claimed that the mass ratio of the components is very different from the $\sim 1:1$ value reported in the literature. Recent careful investigation of the radial velocities of the system supports this view, and leads to the conclusion that the narrow-lined component is in fact an intermediate-mass stripped star resulting from a system that has undergone conservative mass transfer (Wade et al., in prep).

Finally, HD 41566 (Willis and Stickland, 1983; Shenar et al., 2023) has been widely referred to in the literature as a Wolf–Rayet (WR) star due to its strong, ubiquitous emission lines, but with incompatible characteristics that have earned it the designation "quasi-WR" (qWR). The star is associated with a main sequence B-type component with narrow spectral lines. Recently, Shenar et al. (2023) observed a very strong (43 kG) magnetic field in the qWR component (see Fig. 6), identifying it as a potential magnetar progenitor resulting from the merger of two intermediate-mass stars.

6. Conclusion

While magnetic fields of OB stars on the main sequence have been systematically studied for over 20 years, the magnetic properties of these stars at post-MS phases and in binary systems are in their infancy, revealing new phenomena and physics as sensitive new observations are acquired. Recent observations have revealed weak ($\lesssim 1$ G) magnetic fields in the photospheres of blue supergiants and Cepheid variables. Magnetic fields in stars in binary systems are rare, and therefore poorly studied. However, the detection of fields in systems such as the close binary ε Lupi reveals new radiative phenomena illuminating the interaction of magnetism and binarity. The detection of magnetic fields in HD 45166 and HD 47129 - both examples of binary evolution likely involving mass transfer or mergers - suggests that binary evolution can lead to the generation of magnetic fields with characteristics identical to those of "fossil" magnetic fields in single stars.

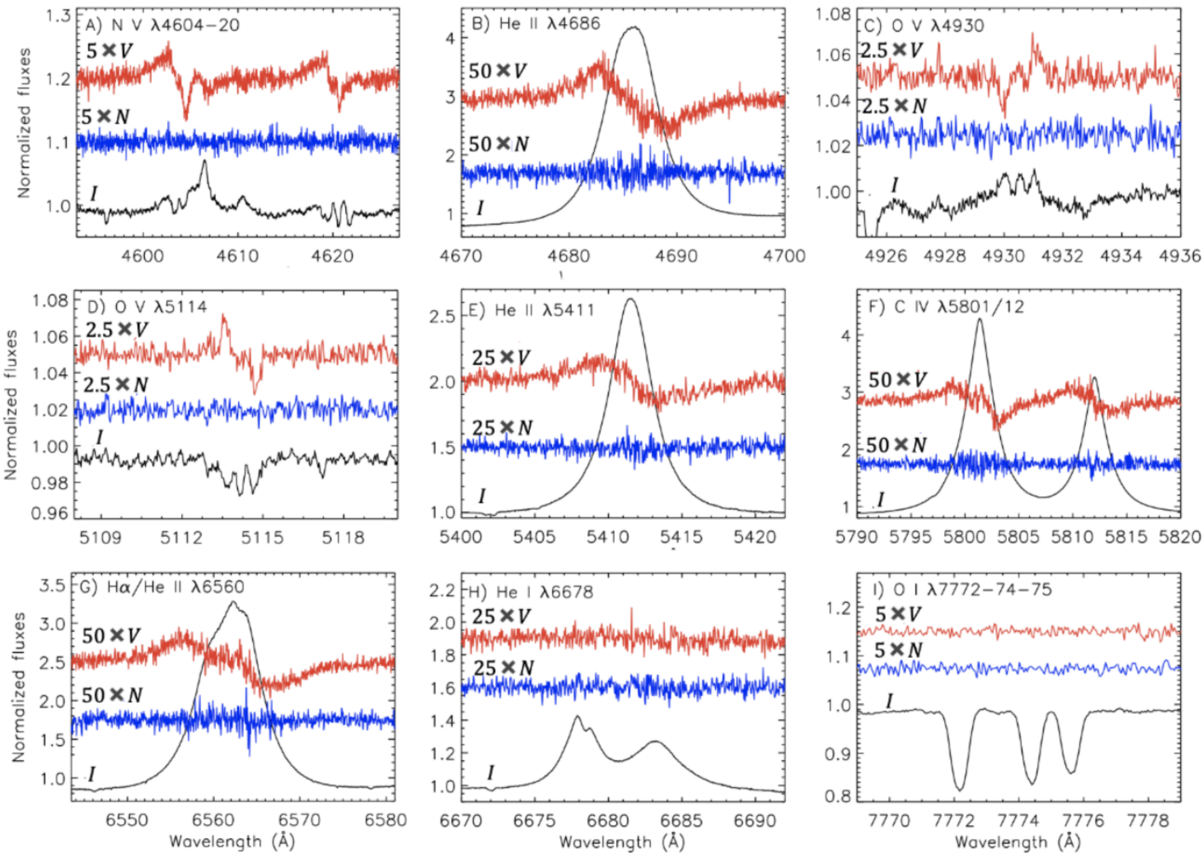

Figure 6: Polarized line profiles of HD 45166. The panels show the intensity spectrum (I, black lines), diagnostic null spectrum (*N* ; blue lines), and Stokes *V* spectrum (upper curves, red lines). (A)–(H): Several diagnostic lines of the qWR component. (I) The O I triplet associated with the B7 V star. Zeeman splitting is visible in the O V λ4930 and O V λ5114 lines (C, D). There is no Stokes *V* signature visible for lines associated with the B7 V star (panel I). Reproduced from Shenar et al. (2023, Fig. 2).

Further Information

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Conflicts of interest

The author declares no conflict of interest.

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