Magnetic fields in A stars besides Ap stars

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Abstract I review ongoing efforts to understand the incidence of magnetism in intermediate-mass stars that are different from the magnetic Ap stars. This includes the search for magnetic fields in chemically peculiar stars of the Am and HgMn types as well as in normal A and late-B stars. I discuss different techniques for detecting weak stellar magnetic fields, and present a critical evaluation of recent magnetic detections in non-Ap stars. Special attention is given to the magnetic status of HgMn stars and to the discovery of weak polarization signatures in Sirius and Vega.

1. Introduction

Studies of stellar magnetism, carried out during the six decades since the first discovery [6] of global magnetic fields in peculiar A stars, have firmly established the bimodal character of the incidence of magnetic fields among intermediate-mass main sequence stars. On the one hand, the majority of those stars do not have fields exceeding several hundred Gauss, and are rapid rotators with approximately solar chemical composition. On the other hand, certain sub-groups of chemically peculiar (CP) stars possess globally organized magnetic fields with strengths up to ~ 30 kG [13]. These magnetic CP (or Ap/Bp) stars are characterized by slow rotation, and also exhibit conspicuously non-solar surface chemical abundance patterns. Among the cooler CP stars, magnetic fields are invariably found in objects with SrCrEu spectral peculiarities. As the temperature increases, similar magnetic properties are observed in Si-rich and He-abnormal B-type stars. At the same time, there exists another group of CP stars (Am on the cooler side, and HgMn/PGa on the hotter side) for which no credible evidence of magnetic fields has ever been presented.

Thus there exists a dichotomy in the magnetic properties of intermediate-mass A and B stars: strongly magnetic objects share the H–R diagram with the stars deemed to be completely void of surface magnetic fields. Recent improvements in the observational techniques of stellar magnetometry support that paradigm, demonstrating that every SrCrEu and Si-rich Ap/Bp star has a field of at least 300 G [3]. That limit is physically significant, because for brighter stars it substantially exceeds the sensitivity of modern spectropolarimetric surveys. Furthermore, theoretical simulations [11] suggest a convincing framework for understanding the interior structure and stability of the global magnetic fields in Ap stars, although the questions of how A and B stars acquired their fields in the first place and why only 10% of stars have done so remain unanswered.

At the same time, a number of recent studies have also claimed discoveries of magnetic fields in A and B stars other than Ap stars, thereby challenging the classical division of intermediate-mass stars into “magnetic” and “non-magnetic” groups. Many of those claims were subsequently refuted, but a few were supported by independent analyses. In this paper I attempt to clarify the current observational picture of the incidence of magnetic fields in A and late-B stars other than magnetic Ap stars, by summarizing and critically evaluating the outcomes of relevant recent studies.

2. Methods of detection of weak stellar magnetic fields

2.1. Low-resolution spectropolarimetry

Low-resolution spectropolarimetry with the FORS1/2 instruments at ESO’s VLT [7] is one of the most frequent techniques used during past decade for large-scale searches of stellar magnetic fields. The method estimates the mean longitudinal magnetic field, $\langle B_z \rangle$, by correlating the Stokes I derivative with the Stokes V signal in the wings of hydrogen lines, or in unresolved blends of metal lines. FORS1/2 spectropolarimetry appears to be robust when applied to strongly magnetic Ap stars [8, 26].

However, the FORS instruments cannot be used reliably to study magnetic fields below a few hundred Gauss. A detailed assessment of certain controversial FORS results and a re-analysis of the entire FORS1 archive revealed the presence of several artifacts related to flexures in this Cassegrain-mounted instrument [9, 10]. There are also significant ambiguities in the data reduction that can lead to changes in the resulting field estimates that are well in excess of the formal photon noise error bars, and are triggered by small variations in the reduction parameters. The FORS1/2 results can be summarized by saying that the detections of weak magnetic fields are trustworthy only if a $\langle B_z \rangle$ significance of better than 5–6σ is obtained [9, 10]. But any field measurements may turn out to be spurious below 100–200 G owing to occasional large systematic errors. Such detections require confirmation by other instruments.

2.2. Moment technique

The moment technique [38, 40] was originally introduced in the context of analyzing moderate-quality circular polarization spectra of Ap stars. In this method, different magnetic field moments (mean longitudinal field, quadratic field, etc.) are inferred from the moments of Stokes I and V profiles of individual metal lines. While successfully applied to strongly magnetic Ap stars, the moment method has not been verified against other techniques or synthetic spectrum calculations for fields weaker than ~ 100 G. Some spurious field detections obtained with this method (see discussion in [30], and below) suggest that it may suffer from hitherto unrecognized biases when applied to noisy circular polarization data.

2.3. *Least-squares deconvolution*

Least-squares deconvolution (LSD [12, 28]) relies on combining intensity and polarization profiles of a large number of metal lines into mean Stokes profiles that are characterized by a very high signal-to-noise ratio. The primary field detection diagnostic is the presence of a statistically significant signature in the LSD Stokes V profile. The field strength can be quantified by computing $\langle B_z \rangle$ and other field moments from the LSD profiles. Its ability to recover a high-quality mean polarization signature represents a major advantage of LSD compared to methods that only estimate the mean longitudinal field. In particular, LSD is sensitive to complex fields [31], and to magnetic-field geometries with a negligible mean longitudinal field, such as toroidal fields or equator-on oblique dipoles.

The LSD technique has been applied successfully to strongly-magnetic Ap stars [3], and to a wide range of late-type stars that have different activity levels [43], some having sub-G magnetic fields [4]. The performance and limitations of LSD were explored thoroughly using synthetic Stokes spectra [28]. In comparison to the low-resolution spectropolarimetry of FORS1/2 and the moment technique, LSD is much better understood and is consequently a far more reliable approach for finding weak stellar magnetic fields.

3. Recent observational results

3.1. *Am and normal A/B stars*

Several magnetic field surveys have addressed the question of the incidence of magnetism in Am and normal A/B-type stars. High-resolution observations with the MuSiCoS [47] and NARVAL [5] spectropolarimeters probed the presence of magnetic fields in about 40 normal A and Am stars. No field detections were reported, the typical $\langle B_z \rangle$ uncertainties being 10–50 G for most targets but down to 1–3 G for several bright, narrow-lined Am stars. The FORS1 cluster survey [8] included over 100 relatively faint A and B stars that did not exhibit noticeable spectral peculiarities, finding no field above 100–200 G. The FORS investigation of a sample of RR Lyr pulsators [32] also yielded null results, at the level of ≈ 30 G.

On the other hand, a magnetic field with $|\langle B_z \rangle|$ of up to 380 G was reported for the A0 supergiant HD 92207 from FORS2 observations [23]. A subsequent study [10] demonstrated that those FORS2 spectra were affected by erratic wavelength variations happening on short timescales and that the detection in HD 92207 was spurious. High-precision HARPSpol measurements of the star [10] have established an upper limit of only 10 Gauss for the mean line-of-sight magnetic field component.

3.2. β Cep, SPB and Be stars

Observations with FORS1 [21] initially suggested an unusually high incidence of weak magnetic fields in spectroscopically normal pulsating β Cep and SPB late-B stars. However, follow-up high-resolution studies [49] and the re-analysis of the FORS1 data [9] could confirm only a couple of those detections. Moreover, the "magnetic field models" of six β Cep and SPB stars published by [22] were shown to be invalid for all but one star [48], as the predicted Stokes V profiles turned out to be many times stronger than the actual upper limit of the circular polarization signals observed. There is no doubt that a few β Cep and SPB stars do possess global dipolar-like fields [42, 49], but the fraction of magnetic stars among late-B pulsators is not anomalously high and is generally consistent with the overall $\sim$10% incidence of magnetism for the entire group of mid- to late-B main sequence stars.

A re-assessment of the FORS1 archive [9] also did not confirm any of the field detections reported for classical Be stars [18, 20], and it was concluded that magnetic fields above 100 G rarely, if ever, occur in these objects. Remarkably, the MiMeS high-resolution spectropolarimetric survey [52] did not detect a field in any of 58 Be stars studied. It therefore appears that the Be phenomenon and that of surface magnetism are mutually exclusive.

3.3. HgMn stars

Since the first reports of magnetic fields in Ap stars, it was recognized that the presence of a field is often accompanied by surface inhomogeneities in chemical abundance distribution – starspots – and that magnetic and line strength variations occur with the same period. These observations inspired the oblique rotator model [50], according to which both the field geometry and the spot topologies are stable and the prominent periodic spectrophotometric and magnetic variability of Ap stars is attributed entirely to the changing aspect angle brought about by the star's rotation. The stability of the surface inhomogeneities in Ap stars is confirmed by the repeatability of their photometric light curves. Apart from occasional slowing down and precession, the patterns of photometric variability in these stars do not change on a timescale of at least several decades [1, 41].

The straightforward and conceptually attractive picture of the one-to-one correlation between starspots and magnetic fields had to be revised with the discovery of chemical inhomogeneities in HgMn stars [2, 18, 25, 29]. Contrary to the widespread belief that non-magnetic stars should have homogeneous atmospheres, it was ascertained that some HgMn stars exhibit low-level spectrum variability, typically in the lines of strongly overabundant elements such as Hg, Pt, Sr and Y. Moreover, the temporal behaviour of those chemical spots turned out to be noticeably different from that in magnetic Ap stars; several studies demonstrated that spots in HgMn stars change their configurations on a timescale of one year or less [27, 33].

However, attempts to find magnetic fields that might be associated with those chemical inhomogeneities failed to yield a single undisputed magnetic field detection. For example, a comprehensive HARPSpol survey of nearly 50 HgMn stars [35] and previous high-resolution spectropolarimetric studies [5, 47] inferred upper limits of 1–10 G for $\langle B_z \rangle$ using LSD analysis. The best precision was obtained for HgMn stars with the sharpest spectral lines, which show no detectable spectral variability. But even intense dedicated observations targeting individual HgMn stars with clear spot signatures did not reveal any magnetic fields [14, 29, 36, 37, 51], the highest precision of 2–3 G being obtained for μ Lep [29].

Despite these results, sporadic reports of magnetic-field detections of a few tens to a few hundred G have appeared in the literature [18, 19, 24]. These reports were based on moment analyses of archived HARPSpol circular polarization spectra and on observations with low-resolution (FORS1/2 at VLT) and intermediate-resolution (SOFIN at NOT) Cassegrain mounted instruments. None of these analyses presented a direct detection of the spectral line polarization signatures for HgMn stars. Instead, the existence of the field was inferred only through non-zero $\langle B_z \rangle$ measurements. The results have not withstood independent scrutiny [9, 14, 30], and in every case more precise high-resolution spectropolarimetric observations of the same stars and re-analysis of the archival data have found no evidence for the reported field. As mentioned above, careful examination of the publicly available FORS1/2 data revealed instrumental artifacts and uncertainties in the reduction, rendering questionable the claims of detections of fields $\leq$ 100–200 G made with this instrument. Similar instabilities may plague the low-resolution mode of the SOFIN spectropolarimeter.

In summary, there is currently no reliable evidence of globally organized magnetic fields in any of the *bona fide* HgMn stars, including objects with chemical spots. The upper limits to possible surface fields that could still remain undetected is $\sim$ 10–30 G, although 2–3 times weaker fields have been excluded in the case of several sharp-line stars.

The absence of circular polarization in line profiles does not rule out much more complex "tangled" magnetic fields. Although LSD analysis of the Stokes V spectra can reveal fields structured on scales down to a few degrees [31], one can in principle envisage even more complex turbulent fields, which contribute to the line broadening but are invisible in polarization owing to a complete cancellation of opposite field polarities. Leaving aside the question of the physical origin of such hypothetical magnetic fields, several studies tried to diagnose them in HgMn stars from high-resolution intensity spectra, using the relative intensification of the spectral lines with different Zeeman splitting patterns [16, 17] or analyzing magnetic broadening by the quadratic field diagnostic method [15, 24, 39]. Somewhat surprisingly, these analyses indicated fields of the order of 2–4 kG for a number of HgMn stars. The results appear to be in strong contradiction of numerous detailed model atmosphere and spectrum synthesis studies of the same targets, which never required such strong fields to reproduce their Stokes I spectra. The discrepancy was addressed in our recent study [30] based on detailed radiative transfer modelling of HgMn star observations at a spectral resolution $> 10^5$. It was found that turbulent fields stronger than 200–500 G are inconsistent with spectroscopic observations of slowly rotating HgMn stars, and that relative intensification and quadratic field measurements are not trustworthy as field detection techniques owing to unrealistic assumptions about magnetic line formation.

3.4. Vega and Sirius

An application of the LSD processing to high-resolution spectropolarimetric data recorded over a wide wavelength region enables a major gain in sensitivity to weak stellar magnetic fields. Several studies have achieved a precision better than 1 G for $\langle B_z \rangle$, corresponding to a polarimetric sensitivity of 10^{-5} and better, for bright late-type stars [4]. Rapid rotation and sparse metal line spectra prevent that level of precision from being reached for all but the brightest A stars such as Vega and Sirius. For those objects a sub-G field precision can be attained by co-adding spectropolarimetric observations obtained over several nights, provided the spectrometer has adequate stability. This observing methodology was exploited for Vega [34, 44] and Sirius [45] using ESPaDOnS and NARVAL.

Analyses of the circularly polarized LSD profiles of both stars revealed signatures with an amplitude of 10^{-5} of the continuum intensity and a longitudinal field below 1 G. Detection of a magnetic field in Vega was accomplished using both the aforementioned instruments, and was further supported by Zeeman Doppler imaging inversions [44]. Consistent with a narrow Stokes *V* profile, the inversions showed a relatively complex surface field structure that was dominated by a polar field concentration where the field reached 3 G locally. The short-term variation of the polarized signatures corresponded well to the rotation period expected for Vega.

On the other hand, the Stokes *V* signature reported for Sirius [45] defies an explanation in terms of the Zeeman effect. The mean Stokes *V* profile of this star shows a strong asymmetry between the positive and negative lobes, yielding a significant zero-order moment. Such Stokes *V* profiles are known for active regions on the Sun that are characterized by strong vertical magnetic and velocity gradients [46]. It is unknown how such exotic polarization profiles can appear in the disk-integrated flux spectrum of a star that has a quiescent and relatively well understood atmosphere. The possibility of a persistent instrument artifact cannot be neglected, but appears unlikely given that this Stokes *V* signature was confirmed for Sirius using another spectropolarimeter with a different design (HARPSpol, Kochukhov et al. in preparation).

In any case, these observations of Vega and Sirius point to an entirely new manifestation of magnetism among A and B stars (if a reasonable explanation for the peculiar Stokes *V* profile in Sirius could be found). These fields probably exist in all intermediate-mass stars, and are weaker by about two orders of magnitude with respect to the lower limit to the Ap star magnetic field of 300 Gauss. More observational work is clearly required in order to probe the presence of such fields in other normal bright A stars and to investigate their magnetic field topologies and evolution.

4. Conclusions

Numerous magnetic field surveys conducted with spectropolarimeters at large and intermediate-size telescopes have increased significantly the sample of A and B stars which have been examined for the presence of magnetic fields. At the same time, the literature has become contaminated with spurious field detections, originating primarily in unrecognized instrumental artifacts affecting Cassegrain-mounted spectropolarimeters and from unfortunate application of the moment technique to low S/N circular polarization spectra. One should therefore be extremely careful when interpreting these results. Recent studies showed that the LSD analyses of Stokes *V* spectra recorded with stabilized fibre-fed spectrometers yield the least number of spurious detections, and are more trustworthy.

With those cautionary notes in mind, we can draw up the following major conclusions from the recent magnetic field studies of peculiar and normal A/B stars:

1. All Ap stars are magnetic, with a minimum dipolar strength of 300 G.

2. Weak global magnetic fields below that limit and down to 10–50 G can be excluded for all Am, HgMn, and Be stars. Tangled magnetic fields stronger than 0.2–0.5 kG are also ruled out for HgMn stars.

3. A few β Cep and SPB stars are magnetic, but the incidence of magnetism among these B-type pulsators is not abnormally high.

4. There is a "magnetic desert" between 300 and ~ 10 G for A stars. Below that range, Vega-like fields can exist in the majority of stars.

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