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Understanding the fossil magnetic fields of Ap/Bp stars

Conclusions from a volume-limited survey

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Abstract. Various observational properties of Ap/Bp stars have been well-established such as the often-cited 10 % incidence rate of strong, organized magnetic fields amongst all A- and B-type stars. However, these inferences have generally been drawn from surveys biased towards the strongest most easily detectable fields. A volume-limited spectropolarimetric survey of all intermediate-mass stars within 100 pc was initiated in 2007 in order to avoid the biases inherent in previous studies. This work yielded the magnetic properties of a large number of Ap/Bp stars in the sample; however, nearly half of the sample remained either unobserved or had relatively poor constraints on their field strengths and geometries. We have recently completed this survey using measurements obtained by ESPaDOnS and NARVAL. We discuss here some of the recent findings of this survey.

Key words: stars: magnetic – stars: chemically peculiar

1. Introduction

The generation and broader characteristics of magnetic fields of cool stars are reasonably well understood within the framework of stellar dynamo theory (e.g. Charbonneau, 2010). In contrast, the origin of the magnetic fields of main sequence stars (MS) more massive than about $1.5\,\mathrm{M}_\odot$ remains a profound mystery. It is now reasonably well established that all chemically peculiar Ap/Bp stars, corresponding to roughly 10% of MS A- and B-type stars, host organized (primarily dipolar) magnetic fields with strengths $\lesssim 30\,\mathrm{kG}$ (e.g. Wolff, 1968; Landstreet, 1982; Shorlin et al., 2002). However, these results have typically been derived from magnitude-limited surveys or from surveys with relatively high detection thresholds and thus, are inherently biased.

In 2007, Aurière et al. (2007) attempted to explore the weak field regime of Ap/Bp stars by obtaining high-precision longitudinal field measurements of 28 objects with reportedly weak or otherwise poorly constrained field strengths.

All of the observed Ap/Bp stars were found to exhibit dipolar field strengths of $B_\mathrm{d} \gtrsim 300\,\mathrm{G}$ with the two weakest fields found to have $B_\mathrm{d} = 100^{+392}_{-100}\,\mathrm{G}$ and $B_\mathrm{d} = 229^{+248}_{-76}\,\mathrm{G}$. Aurière et al. (2007) hypothesized that there exists a critical field strength ($B_\mathrm{c} \approx 300\,\mathrm{G}$), which corresponds to the minimum field strength that an Ap/Bp star must host in order to be invulnerable to a pinch-instability (Tayler, 1973; Spruit, 2002). More recently, a small number of A- and B-type stars hosting fields having B_d well below the proposed critical field strength have been identified in apparent contradiction to this explanation (e.g. Lignières et al., 2009; Petit et al., 2011; Alecian et al., 2016). While these recent discoveries call into question whether or not the so-called "magnetic desert" truly exists, the question remains why the vast majority of known Ap/Bp stars host fields with $B_\mathrm{d} \gtrsim 300\,\mathrm{G}$.

In the following article, we present several results from a volume-limited spectropolarimetric survey of Ap/Bp stars located within 100 pc. This survey has been carried out in order to constrain various fundamental and magnetic properties of this stellar population while attempting to minimize observational biases. This work was initiated by Power (2007), who obtained a large number of measurements using the now retired MuSiCoS instrument. These observations allowed for the magnetic parameters of approximately 50 % of the Ap/Bp stars in the sample to be derived. More recently, we have completed this survey primarily using Stokes V measurements obtained with ESPaDOnS along with a small number obtained with NARVAL. In Section 2, we briefly describe the sample and present the derived incidence rate of Ap/Bp stars with respect to stellar mass. In Section 3, we present several results from our analysis of the Ap/Bp magnetic properties and, in Section 4, we state our conclusions.

2. The Sample

The full sample of intermediate-mass stars (magnetic and non-magnetic early-F, A-, and B-type stars) was compiled by identifying all objects within the Hipparcos catalogue having parallax angles $> 10\,\mathrm{mas}$ ($d < 100\,\mathrm{pc}$) (van Leeuwen, 2007). This list was then cross-referenced with the Catalogue of Ap, HgMn and Am Stars (Renson & Manfroid, 2009) in order to identify both known and candidate Ap/Bp stars. This yielded a total of 139 stars, which were classified as being unlikely, probably, or definitely Ap/Bp stars based on whether they had reported (1) photometric variability, (2) chemical peculiarities consistent with Ap/Bp stars (identified either spectroscopically or through the use of photometric indices; i.e. Paunzen & Maitzen, 2005), or (3) magnetic detections. We obtained 327 Stokes V observations of 65 stars using MuSiCoS (185 measurements), ESPaDOnS (114 measurements), and NARVAL (28 measurements). Based on our magnetic measurements, archived magentic measurements, and on published magnetic measurements, we conclude that the sample of early-F, A-,

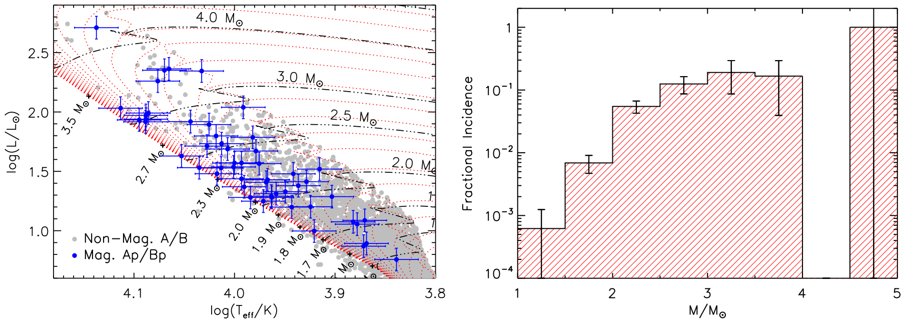

Figure 1. *Left*: The Hertzsprung-Russell diagram for the volume-limited sample. Grey points correspond to the presumably non-magnetic MS stars while the blue points correspond to the known magnetic (Ap/Bp) MS stars. *Right*: Incidence rate of Ap/Bp stars with respect to stellar mass. The large uncertainty and 100 % incidence rate associated with the highest mass bin ($4.5 \leq M/\mathrm{M}_\odot < 5$) is due to the fact that it contains only one star.

and B-type stars within a 100 pc volume contains 52 confirmed Ap/Bp stars and $\sim$ 3 700 non-magnetic stars.

We derived each of the (presumably) non-magnetic stars' effective temperatures and luminosities by applying various photometric calibrations to a wide range of archived photometric measurements (e.g. Mermilliod et al., 1997). A more detailed analysis of the fundamental parameters was performed on the 52 Ap/Bp stars. This involved fitting both the available photometry and spectroscopy (including Balmer lines, which are relatively sensitive to $\log g$, and multiple $25 - 100$ Å width spectral regions containing He and metallic lines) to synthetic models. The synthetic SEDs were generated using the LLMODELS code (Shulyak et al., 2004) while accounting for flux abnormalities caused by chemical peculiarities and, in the case of strongly magnetic stars ($B_{\rm d} \geq 5\,{\rm kG}$), the anomalous Zeeman effect. All of the stars' stellar masses and ages were then estimated through comparisons with the evolutionary models of Ekström et al. (2012). The total sample of MS stars is shown plotted on the Hertzsprung-Russell diagram in Fig. 1 (left). The incidence rate of Ap/Bp stars as a function of stellar mass is shown in Fig. 1 (right); it is evident that the incidence rate increases from $\lesssim 1\,\%$ at $M \lesssim 2\,\mathrm{M}_\odot$ and plateaus at $\approx 10\,\%$ for $M > 2\,\mathrm{M}_\odot$.

3. Magnetic Properties

Both the dipole magnetic field strength and the obliquity angle β (i.e. the angle between the dipole field's axis of symmetry and the star's rotational axis) can be derived if the inclination angle i and the extrema of the longitudinal field ($B_{\rm z}$) are known (Stibbs, 1950). We attempted to derive these properties by obtaining

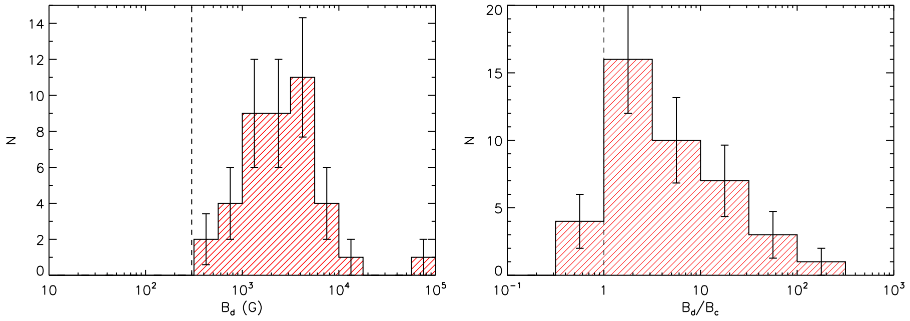

Figure 2. *Left*: The distribution of the derived dipole magnetic field strengths. The vertical dashed line indicates the critical field strength ($B_c = 300$ G) derived by Aurière et al. (2007) for a typical Ap star. *Right*: The ratio of each Ap/Bp star's dipole field strength to its critical field strength where B_c is calculated using Eqn. 8 of Aurière et al. (2007).

approximately five B_z measurements per star such that the rotational periods could be roughly sampled. We adopted a target precision of $15 \lesssim \delta B_z \lesssim 25$ G, which allowed for the detection of surface magnetic fields with $B_d \gtrsim 150$ G. The resulting distribution of B_d values is shown in Fig. 2 (left). The distribution peaks at approximately 2.5 kG and contains a minimum field strength of 340 G – slightly above the estimated critical field limit of $B_c = 300$ G calculated using Eqn. 8 of Aurière et al. (2007). B_c depends on each stars' T_{eff}, rotational period, and radius; therefore, we derived the ratio, B_d/B_c, for each star yielding the distribution shown in Fig. 2 (right). We find that all but four of the Ap/Bp stars in our sample exhibit $B_d/B_c > 1$.

Our analysis also yielded the obliquity angles associated with the dipolar field component of each Ap/Bp stars' magnetic field; this distribution is shown in Fig. 3 (left) while the cumulative distribution functions for both the derived β and i values are shown in Fig. 3 (right). We find that, while the i distribution is consistent with a distribution of randomly oriented axes, the β distribution exhibits a slight excess of instances in which $\beta \lesssim 30°$. Given the relatively small sample size and the difficulty of accurately constraining β, this result may be considered to be insignificant. This is supported by the derived 3 sigma uncertainty in the Kolmogrov-Smirnoff test statistic of 0.16 obtained by employing bootstrap resampling.

4. Conclusions

We have completed a volume-limited spectropolarimetric survey of Ap/Bp stars located within a distance of 100 pc. We do not find any stars in our sample

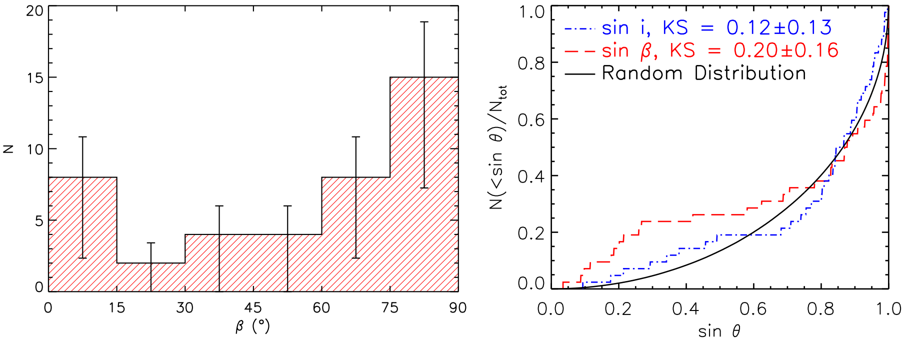

Figure 3. *Left*: Distribution of derived obliquity angles. *Right*: Cumulative distribution functions associated with the inclination angle (blue, dash-dotted) and obliquity angle (red, dashed). The solid black curve is generated from a distribution of randomly oriented axes. The $\sin i$ and $\sin \beta$ distributions are compared to the random distribution yielding Kolmogrov-Smirnov statistics of 0.12 ± 0.13 and 0.20 ± 0.16, respectively.

hosting magnetic fields with dipolar components less than 300 G, which supports the existence of the so-called "magnetic desert" first reported by Aurière et al. (2007). In the preceding article, we have summarized several results from this survey; additional findings, including those obtained from a chemical abundance analysis of the sample of Ap/Bp stars, will be presented in a forthcoming publication.

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Audience in the lecture room