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Explaining the unusual Stokes V signatures of ultra-weak magnetic A stars

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Abstract. Recently, extremely weak magnetic fields have been found in a small number of A-type stars. These magnetic fields are on the order of a few gauss or less, which is two to three orders of magnitude weaker than those found in magnetic Ap and Bp stars. The Stokes V (circularly polarized) line profiles of three out of five of these stars known (Sirius, beta UMa, and theta Leo) are highly unusual, consisting of a single positive lobe spanning most of the width of the line. While there is evidence that this signal is due to a magnetic field, the shape of the line profile cannot be explained by Zeeman splitting in a static atmosphere. Using synthetic spectra, we investigated introducing radial gradients in velocity and magnetic field strength, which can produce qualitatively similar model spectra. With some simple assumptions of geometry we produced disk integrated spectra that can match the observations. We propose this as a possible explanation for the unusual Stokes V signatures in these ultra-weak magnetic A stars.

Key words: stars: magnetic fields – stars: chemically peculiar

1. Introduction

A small fraction of A- and B-type stars (Ap and Bp stars) have strong magnetic fields, with strengths of hundreds to thousands of gauss. Recently, much weaker magnetic fields, on the order of a few gauss or less, have been detected in a few A stars, using extremely high signal-to-noise spectropolarimetric observations. These very weakly magnetic stars include Vega (Lignières et al., 2009), Sirius A (Petit et al., 2011), β Uma (Blazère et al., 2016b), θ Leo (Blazère et al., 2016b), and Alhena (Blazère et al., 2016a, see also Blazère et al. in these proceedings). These new detections suggest that very weak magnetic fields may be more common among A and B stars than the strong fields of Ap and Bp stars, and raises the question of the origin of these weak magnetic fields.

The spectropolarimetric observations used to detect these very weak magnetic fields exploit the Zeeman effect, as observed through circularly polarized (Stokes V) spectra. While the observations of Vega and Alhena have normal Zeeman signatures in their Stokes V line profiles, Sirius A, β Uma, and, θ Leo

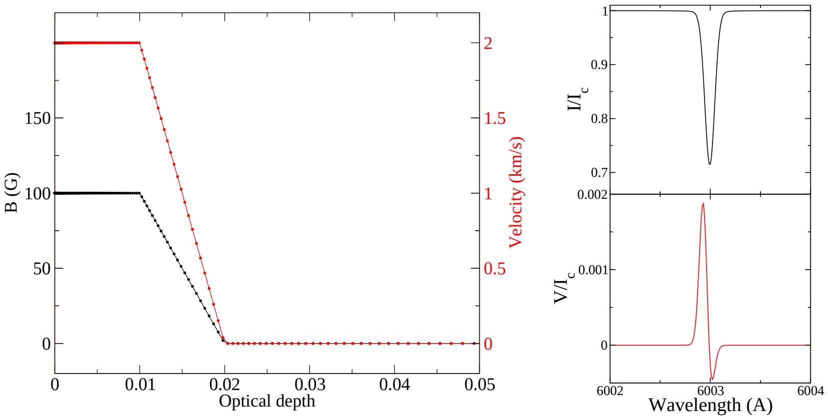

Figure 1. *Left:* magnetic field strength and velocity along the line of sight, as a function of optical depth. *Right:* model Stokes I and V profiles produced using this magnetic field and velocity distribution.

display unusual Stokes V line profiles, with a dominant positive lobe at the line center and little to no negative lobes. If V is integrated across the line, these unusual V profiles do not integrate to zero, and are referred to here as "asymmetric" line profiles (the profiles are approximately symmetric about the line center, but not symmetric in positive and negative V). Such a net circular polarization cannot be produced by the Zeeman effect in a static stellar atmosphere with an uniform magnetic field. This is essentially because the + and − σ components of a Zeeman split line have equal strengths and displacements from the line center.

Tests by Petit et al. (2011) and Blazère et al. (2016b) suggest that these asymmetric V signatures are due to the Zeeman effect, since the signatures are sensitive to the Landé factor and wavelength of the lines. The Zeeman effect can produce asymmetric V signatures if there are gradients in velocity and magnetic field strength in a stellar atmosphere. Here we investigate this possibility and apply it to the peculiar profiles of Sirius A.

2. Model line profiles

In order to investigate asymmetric V profiles numerically we used the ZEEMAN (Landstreet, 1988; Wade et al., 2001) spectrum synthesis code. This code performs polarized radiative transfer through a plane parallel model atmosphere using the "full" semi-analytic solution from Martin & Wickramasinghe (1979). The code was extensively tested against other polarized radiative transfer codes

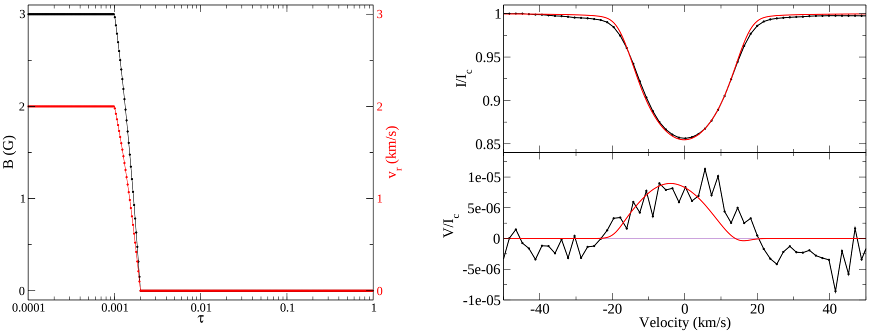

Figure 2. *Left:* Magnetic field and velocity distributions. *Right:* Resulting disk integrated model line profile, compared with an observed LSD profile of Sirius A.

by Wade et al. (2001). As input, an ATLAS9 model atmosphere with $T_{\rm eff} = 7000$ K, and log $g = 4.5$ was used.

To begin with we looked at the spectrum emerging from just one point on the stellar surface. We assumed a linear transition of velocity and magnetic field strength with optical depth. Thus there was a region of constant magnetic field and velocity deeper in the atmosphere, a linear transition, and an region of constant magnetic field and velocity higher in the atmosphere. An illustration of one such configuration, which produces a strongly asymmetric profile, is shown in Fig. 1.

The general behavior of asymmetric V profiles with different magnetic and velocity distributions is complex. However, Sanchez Almeida et al. (1989) derived a convenient approximation for some of this behavior:

$$\int_0^\infty V(\lambda) d\lambda \propto \frac{dv}{d\tau}\frac{dB}{d\tau}. \qquad (1)$$

The net V polarization, integrated over wavelength λ, is proportional to the gradients in magnetic field (B) and velocity (v) with optical depth (τ), when the velocities and Zeeman splitting are both small relative to the line width. Testing this behavior with the ZEEMAN code, we reproduce this linear relationship up to magnetic fields approaching ~1 kG and velocities approaching ~1 $\mathrm{km\,s^{-1}}$. Beyond this point the increase net V polarization becomes slower than linear and eventually starts decreasing. This provides evidence that the ZEEMAN code is behaving as expected.

From these tests we can draw some guidelines for optimizing the asymmetry of the model line profiles. In order to have steep gradients in our model, having the transition over a small range of τ is helpful. In velocity, a maximum asymmetry is produced for a transition of around 2 $\mathrm{km\,s^{-1}}$. In magnetic field, larger strengths produce a larger asymmetry, but also larger normal Zeeman signature

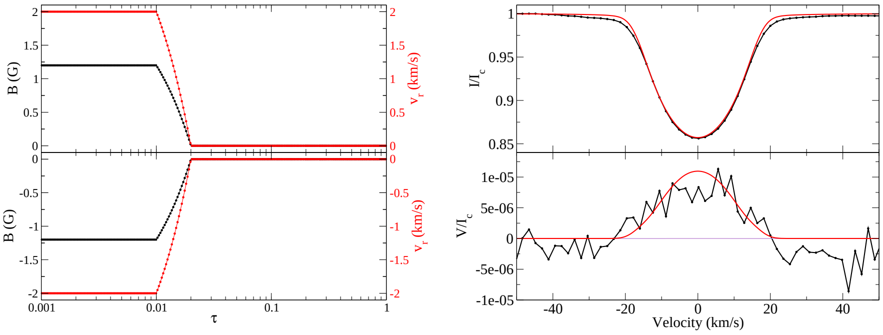

Figure 3. Same as for Fig. 2, but for a model evenly tiled with two regions across the surface of the star.

as well. Thus for a dominantly single lobed V profile, most of the line forming region of the atmosphere should have no or a very weak magnetic field. In our simple transition model, this favors sharp transitions very high or very low in the model atmosphere.

Moving to a disk integrated line profile introduces more potential model parameters and ambiguity. We first consider an uniform horizontal distribution of magnetic field and velocity, both oriented radially in the stellar coordinates. In this case the same general trends above still hold. However, if the line width is dominated by rotational broadening, this horizontal magnetic field distribution has an important impact on the shape of the line in V. For a horizontally uniform distribution, this produces a V profile that is nearly symmetric about the line center. For a dipolar magnetic field, the orientation of the dipole strongly impacts the rotationally broadened line profile. As the sign of the magnetic field changes, the sign of the gradient changes, and the sign of the asymmetry changes, as can be seen from Eq. 1.

The horizontally uniform model is almost certainly an oversimplification, however it is still instructive. We also consider a model where the surface is tiled with regions that have two different radial velocity and magnetic field distributions. In this case, if the regions have equal area, and opposite sign of only the magnetic field or the velocity, then the disk integrated profile has no asymmetry. However, if both velocity and magnetic field have opposite signs, a strongly asymmetric profile can be produced, centered on the line center.

In order to test whether these models can reasonably reproduce observed asymmetries, we attempted to fit the Least Squares Deconvolution (LSD) profile of Sirius A. For this model, we use the line parameters from the LSD profile, and the stellar $v \sin i$, $T_{\rm eff}$, and $\log g$. The fitting was only approximate and performed by hand. First we used a model that is horizontally uniform. The magnetic and velocity distributions, and resulting line profiles, are shown in

Fig. 2. This comes very close to matching the observed profiles, requiring only a very weak magnetic field, and the velocity transition of 2 km s^{-1} is within the microturbulence of the star. However the model V profile is marginally offset from the center of the observed profile. As a second case, we consider a model tiled with regions of positive and negative velocity and magnetic field. The two velocity and magnetic field distributions used are shown in Fig. 3, together with the resulting line profiles. This model reproduces the observed profiles well, although it includes more free parameters.

3. Conclusions

Gradients in velocity and magnetic field in a stellar atmosphere provide a plausible explanation for the unusual asymmetric V profiles of Sirius A, β Uma, θ Leo. The magnetic fields involved can be quite weak, and the velocity changes needed are compatible with the observed microturbulence in these Am stars. The right conditions can produce dominantly asymmetric V profiles from this mechanism, and some conditions can produce these asymmetric profiles centered on the line.

There are substantial degeneracies in these models, the observations do not seem to provide a unique constraint on the magnetic and velocity distributions needed for this mechanism. Further, while these tests show that this mechanism can explain the observations, it does not prove that this is the cause of the observed asymmetries. Nevertheless this provides an exciting avenue for exploring the perplexing Stokes V profiles of these stars.

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