EVIDENCE FOR A COMPLEX DISTRIBUTION OF MAGNETIC FIELD STRENGTHS ON THE FLARE STAR AD LEO

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ABSTRACT I present a preliminary analysis of four Ti I lines from a high S/N IR spectrum of the flare star AD Leo. The lines show consistent evidence for a complex magnetic field distribution, and may be fit with either (a) fields arising from a single atmospheric component but having a large vertical gradient, or (b) a two component field with $B_1 \approx 2 \times B_2$.

Keywords: stellar magnetic fields; stellar atmospheres; flare stars

1. INTRODUCTION AND OBSERVATIONS

The Sun exhibits two types of magnetic regions (MR): warm (plage, network) and cool (umbrae, penumbræ and pores). These regions differ in continuum brightness, field strengths ($B$), and in typical filling factors ($f$). A large range of $B$ are present in cool MR, but hot MR show only a small dispersion in $B$ at fixed height $z$ (Zayer et al. 1990). In contrast, bright MR show significant vertical gradients in $B$, while cool MR do not. The existence of plage and spots on stars suggests these $B$ distributions may also be present. I present here, the first direct evidence for such distributions – on the flare star AD Leo (M3.5Ve).

Three observations of AD Leo were made over several days with the NOAO 4m Fourier Transform Spectrometer (FTS) with an interference filter passing 4400–4600 cm$^{-1}$ at a apodized resolution of $\lambda/\Delta \lambda = 45,000$ (0.1 cm$^{-1}$). The spectra were reduced following Saar and Linsky (1985), coaligned and coadded, yielding a final spectrum ($S/N \approx 100$) with contributions from most of the surface. The spectrum of an inactive star of similar spectral type (GL 273; M4V; Saar et al. 1987) was also obtained, to help in distinguishing weak blends.

2. ANALYSIS AND DISCUSSION

Comparison of AD Leo with Gl 273 and sunspot (Hall 1973) spectra near a multiplet of magnetically sensitive Ti I lines (Fig. 1) reveals a complex situation. The 4481 cm$^{-1}$ (simple triplet) line shows a sharp central component, whose width consistent with $v \sin i$, embedded in a broad, shallow background. The other Ti I lines (only a factor of 2–3 more optically thick) are much too wide to be explained by opacity or rotational broadening. Strong magnetic broadening is the best explanation, implying the 4481 cm$^{-1}$ “background” is due to Zeeman split $\sigma$ components. To explain their anomalously large width, several scenarios are possible: (1) greatly enhanced microturbulence ($\xi$) in the MR; (2) multicomponent MR with different $B$ in each component; (3) single component MR with a substantial vertical gradient; or (4) some combination
of the above. As (1) required an unreasonably large $\xi \approx 10 \text{ km s}^{-1}$, I focused on the other scenarios, fitting the data $(F)$ with three models: 

(A) A three spatial component model of the form: $F = f_1 F(B_1) + f_2 F(B_2) + (1 - f_1 - f_2) F(0)$;

(B) A two component model + gaussian $B$ distribution with height $(\Phi(B, \sigma_B))$: $F = f F(\Phi(B, \sigma_B)) + (1 - f) F(0)$; and

(C), a model like (B), but with a half-gaussian, truncated for $B < B_{\text{cut}}$. Model (C) attempts to simulate the merging of flux tubes quite low in the atmosphere when $f$ is large (Solanki & Steiner 1990), so that part of the line formation occurs in a “pseudo-canopy” with a low, constant $B$ value (I thank S. Solanki for suggesting this).

The models were calculated with a 15 $\mu$m angle disk–integration (including radial–tangential macroturbulence, $\zeta_{RT}$) of local line profiles computed using the Unno–Rachkovsky radiative transfer solution, including magneto–optical effects (see Saar et al. 1990). I used $v \sin i = 5$ km s$^{-1}$ and $\zeta_{RT} = 3$ km s$^{-1}$ (Vogt et al. 1983). Line opacities were constrained to have their predicted (Kurucz & Peytremann 1975) ratios, and areas affected by blends (as determined from the Gl 273 spectrum) were given less weight. Results are shown in Fig. 1.

Figure 1: Ti I line profiles from AD Leo (+) and a sunspot/quiet Sun ratio (heavy solid; Hall 1973) near 2.25 $\mu$m; blends (as judged from a Gl 273 spectrum) are marked (B). Curves through the AD Leo data show the best fits with model (A) (top; a two spatial component model with $f_1 = 45\%$, $B_1 = 2.4$ kG, $f_2 = 30\%$, and $B_2 = 5.0$ kG) and with model (C) (middle; a truncated $dB/dz$ model with $f = 45\%, \overline{B} = 3.0$ kG, $\sigma_B = 1.6$ kG).
Model (B) produced unacceptable fits, yielding too much absorption near line center. Model (A) fit the Ti I multiplet well for $f_1 = 45\%$, $B_1 = 2.4$ kG, $f_2 = 30\%$, $B_2 = 5.0$ kG. This result could be interpreted as the detection of the analog of plage/network ($B_1$) and spot/pore ($B_2$) fields on AD Leo (note that $B_2/B_1 \approx (B_2/B_1)_0$; Zwaan 1987). If this hypothesis is correct, it signifies the first detection of spot fields on a cool star. $B_2$ is smaller than the > 10 kG fields predicted by Mullan (1975). $B_1$ is smaller than a simple estimate a gas pressure equipartition field: $B_{eq} \propto P_{gas,7500}^{0.5} \approx 3.8$ kG (e.g. Saar 1991), but this may merely reflect the need to compute $P_{gas}$ at $\tau_{line}$. The average of $B_1$ and $B_2$ (3.7 kG) is close $B_{eq}$ and is similar to previous measurements (3.8 kG, Saar & Linsky 1985; 4.0 kG, Saar et al. 1987). Note however, that if $B_2$ arises from spots like those on BY Dra, $f_2$ is underestimated by a factor of at least 0.7 (see Saar & Linsky 1985), implying MR cover nearly the entire star ($f_1 + f_2/0.7 = 88\%$).

Model (C) produced good fits for $f = 45\%$, $B_{cut} = 1.9$ kG and $\sigma_B = 1.6$ kG (Fig. 1). Here, the mean $\overline{B}$ (averaged over the distribution) is 3.0 kG – smaller than previous measurements – but the half-maximum of $\Phi(B_{cut}, \sigma_B)$ is at 3.8 kG, again similar to $B_{eq}$. If this model is correct, it represents the first direct detection of a field gradient on a non-solar star (see however Grossmann–Doerth & Solanki 1990). Since $\Phi$ is introduced directly into the magnetic radiative transfer, line equivalent widths are increased (as expected when $dB/dz \neq 0$) and (C) requires considerably lower $f$ values than (A) to fit the data. (Note however, the model is only approximate: $dB/dz \neq 0$ violates the Milne–Eddington atmosphere used.) Of course, some combination of (A) and (C) is also possible. While better data and/or more sophisticated modeling will be needed to distinguish which scenario is more likely, the lower $f$ needed if $dB/dz \neq 0$ makes model (C) quite attractive. Both (A) and (C) show some measure of $B$ similar to previous results, suggesting the lower $S/N$ of the older data may have prevented the detection of the $B$ distributions seen here.

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