MAGNETIC SURFACE IMAGES OF THE BY DRA STAR HD 82558

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ABSTRACT We present preliminary results of a new analysis method applied to spectra of the BY Dra star HD 82558. We invert a time series of unpolarized line profiles with different Landé $g_{\text{eff}}$ values to derive both temperature and magnetic field maps of the star. We find strong fields ($B > 2$ kG) near cool spots and weaker fields elsewhere, with $B \approx 1$ kG.

Keywords: stellar magnetic fields; starspots; stellar atmospheres

1. INTRODUCTION AND OBSERVATIONS

HD 82558 is a single, rapidly rotating ($P_{\text{rot}} = 1.5978$ days; Strassmeier & Hall 1988), spotted K2 dwarf with high magnetic activity levels (Fekel et al. 1986). The star's high $v \sin i$ permits the use of surface mapping techniques, which determine the spatial temperature distribution by modeling the Doppler motions of features through absorption lines (e.g., Vogt et al. 1987). We have developed an extension of these methods, magnetic surface imaging (MSI), which can model the full Stokes vector ($I, Q, U, V$). By studying lines with different Landé $g_{\text{eff}}$, we can simultaneously derive both $T_{\text{eff}}$ and magnetic maps.

Here, we study Stokes $I$ alone. Observations of HD 82558 were made with the NSO McMath stellar echelle spectrograph and a CCD detector, yielding a resolution of $\lambda/\Delta\lambda = 125,000$ and S/N ratios of 100–225. The CCD recorded $\approx 20\text{Å}$ centered near 6173Å. Data were obtained in two epochs: seven spectra in 2/1991 and nine in 4–5/1991. As significant line profile changes (at fixed phase $\phi$) can be seen between the epochs, we focus here on the 2/1991 data only.

2. ANALYSIS AND DISCUSSION

The MSI analysis is based on the surface imaging code of Piskunov et al. (1990) as extended (Hackman et al. 1991) to permit simultaneous modeling of several lines. These inversion routines employ the Tikhonov regularization – minimizing local gradients in the solution – rather than maximum entropy (cf. Vogt et al. 1987). We have further extended the analysis to compute the local line profiles using the full magnetic radiative transfer equations and the DELO method (Rees et al. 1989). Lines are computed for a large set of model atmospheres (Kurucz 1991), with full center-to-limb effects and radial-tangential macroturbulence ($\zeta_{\text{RT}}$) included on a grid size of $3^\circ \times 3^\circ$. We model Stokes $I$ at each point as: $I = I(\text{T}_{\text{eff}}, B)$, where $T_{\text{eff}}$ is the local temperature and $B$ is the magnetic field.
(assumed radial). $B$ can be determined at high $v\sin i$ – despite the “smearing-out” of most line shape clues – from the increase of local equivalent width ($W_{eq}$) of optically thick lines in the presence of a field (e.g. Leroy 1962); roughly, $\Delta W_{eq} \propto f g_{eff}^2 B^2$, where $f$ is the filling factor. As we cannot uniquely determine $f$ for each grid point, the derived $B$ refers to the local average field, $B = fB$.

We studied lines of various excitation potentials ($\chi_L$) to enhance $T_{eff}$ discrimination. First, two low $g_{eff}$ lines (Fe I 6165Å, $g_{eff} = 1, \chi_L = 4.1$ eV and Ca I 6166Å, $g_{eff} = 0.5, \chi_L = 2.5$ eV) were modeled, assuming $B = 0$ and including blends, to generate a rough $T_{eff}$ map and define $v\sin i$ ($= 27$ km s$^{-1}$) and $\zeta_{RT}$ ($= 2.0$ km s$^{-1}$). We set the microturbulence $\xi = 0.5$ km s$^{-1}$, and increased the damping parameter $C_6$ by 0.3 dex. These values produced excellent fits to an inactive, low $v\sin i$ K2V comparison star (HD 166620, $B-V = 0.87$); for HD 82558 they yielded Fe/H = 0.0 and an average $T_{eff} \approx 5000$ K, consistent with the star’s mean $B-V$ ($= 0.91$). We next modeled five lines simultaneously (the above, plus Fe I 6173Å, $g_{eff} = 2.5, \chi_L = 2.2$ eV; Ni I 6175Å, $g_{eff} = 1, \chi_L = 4.1$ eV; Fe I 6180Å, $g_{eff} = 0.6, \chi_L = 2.7$ eV), now allowing $B$ also to vary. The final line models (Fig. 1) were computed assuming $i = 75^\circ$ (Strassmeier & Hall 1988).

![Fig. 1: Line profiles of HD 82558 in 2/91 (thin line) and inverse solutions (thick) as a function of $\phi$ (the Fe I 6165Å–Ca I 6166Å blend, Fe I 6173Å, Ni I 6175Å).](image)

The resulting $T_{eff}$ map (Fig. 2) is dominated by a large cool region at $\phi \approx 0.20$, latitude $\theta \approx 40^\circ$, and $\Delta T_{eff} \approx -300$ K. Other, more extended cool regions are also present. The general pattern differs from surface images of RS CVn and FK Comae stars (e.g. Vogt 1988; Strassmeier et al. 1991), which generally show larger $\Delta T_{eff}$ and more spots at higher latitudes. The spot parameters are consistent with values derived from TiO absorption (Saar & Neff 1990; $\Delta T_{eff} \leq 1200$ K, $f_{spot} \geq 0.22$), and we note that $\Delta T_{eff} < \Delta T_{eff,\odot} \approx 0.75 \times T_{eff,\odot}$.

The average field on the visible surface of HD 82558 is $\overline{B} = fB = 1.02$ kG (Fig. 3). If the plage $B$ is governed by gas pressure balance (as in slower
rotators; Saar 1991), \( B \propto P^{0.5}_{\text{gas}} \approx 2.2 \text{ kG} \), implying \( f \approx 46\% \), which is similar to the “saturation” levels of other spotted K dwarfs (e.g., BD +26°730). The greatest concentrations of magnetic flux (\( fB \geq 2.5 \text{ kG} \)) seem to be near, but somewhat displaced from the centers of the cool regions (compare Figs. 2 & 3).

Fig. 2: Temperature maps of HD 82558 in Feb. 1991 at four phases; the \( T_{\text{eff}} \) scale runs from 4700 K (black) to 5260 K (lightest grey) in steps of 40 K.

Fig. 3: Magnetic field maps of HD 82558 in Feb. 1991 at four phases; the \( T_{\text{eff}} \) scale runs from 104 G (black) to 2544 G (white) in steps of 175 G.
Donati et al. (1991; these proceedings) also find the main (unipolar!) flux concentrations near cool spots in their studies of circular polarization (Stokes \( V \)) from the RS CVn HR 1099 using the “Zeeman Doppler Imaging” (ZDI) technique. In contrast with the warm magnetic region they detected earlier (Donati et al. 1990), warm areas on HD 82558 have some of the lowest \( fB \) values.

Based on the above, we propose the following tentative scenario: Warm areas on HD 82558 are mostly quiet photosphere. Darker regions are areas with more magnetic flux, but with larger \( R_{\text{spot}} \equiv f_{\text{spot}} / f_{\text{plage}} \) than the Sun (consistent with the much higher activity levels on HD 82558 – see Radick et al. 1989). Thus, plage brightness is overwhelmed by dark spots. \( R_{\text{spot}} \) is generally \( \ll 1 \), though, and so the measured \( fB \) is dominated by plage/network. Darker regions have progressively larger \( R_{\text{spot}} \) ratios, but only in the darkest areas is \( R_{\text{spot}} \) large enough that the low continuum contrast in the spots begins to depress the magnetic signal with it, the measured \( fB \).

We caution that our results are still rather preliminary; further study is needed to explore the degree of cross-talk between \( \xi \), \( T_{\text{eff}} \) and \( fB \) in the solution. Since \( \sin \theta \) is large, there is also some ambiguity near the equator. Nevertheless, the MSI technique, even using Stokes \( I \) alone, promises to be a useful tool for obtaining \( fB \) data from rapid rotators. MSI in Stokes \( I \) actually has some advantages, as it derives the actual \( fB \) at each point, unaffected by cancellation of unresolved polarities (cf. ZDI). Still, simultaneous imaging in Stokes \( I \) and \( V \) (or in all four Stokes parameters, as our MSI code is capable of doing) is clearly ideal, yielding information on \( T_{\text{eff}} \), \( fB \), and polarity organization. This, however, requires higher \( S/N \): the maximum Stokes \( V \) for the \( fB \) distribution presented here is only 2.5%, for example. Simultaneous photometry will also be useful for better calibration of \( T_{\text{eff}} \) (e.g., Hackman et al. 1991).

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