METHODS AND RESULTS FOR DETECTING MAGNETIC FIELDS ON LATE-TYPE STARS

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ABSTRACT

We discuss our program to detect and measure magnetic flux on the surfaces of late-type stars. We adopt a novel technique to deconvolve magnetically insensitive lines from similar, magnetically sensitive lines to infer the degree of Zeeman splitting in the latter lines. These measurements yield values for the magnetic field strength and filling factor (flux). To illustrate our approach we present multiple observations of the RS CVn star λ And. At the epoch of observation 26 April 1981 we find a field strength of 1290 ± 50 gauss covering 48 ± 2 percent of this star's surface. Observations at other epochs clearly demonstrate magnetic flux variability on λ And.

1. INTRODUCTION

Quantitative stellar magnetic flux measurements provide essential inputs for theories which describe the origin of stellar magnetic fields and associated chromospheres and coronae. It is believed that magnetic fields arise from an interaction between existing magnetic fields, convection, and differential rotation, the "dynamo" process. To refine accutately nonlinear solar dynamo models, we require detailed comparisons with stellar dynamos. Stellar magnetic field strengths and extents (filling factors) are essential observational delineators of the dynamo process. Direct measures of stellar magnetic fields may also be compared with measures of chromospheric and coronal emission to study the mechanisms involved in the heating and evolution of these stellar atmospheric regions. Magnetic field detection methods, based on detailed analysis of line profiles, enable us to measure directly field strengths and filling factors for active chromosphere stars.

Standard polarization methods for measuring stellar magnetic fields are inappropriate for solar-type field topologies where the field polarities are tangled, and where polarization effects cancel.

J. O. Stenflo (ed.), Solar and Magnetic Fields: Origins and Coronal Effects, 29–34.

Recent results by our group and others have successfully deduced magnetic fields from the shapes of magnetically sensitive line profiles (Robinson, 1980). The Zeeman line splitting pattern is deconvolved from the line profiles by comparing magnetically sensitive lines with similar, but magnetically insensitive, lines. From this procedure we get both estimates of the actual field strengths and the fraction of visible stellar surface covered by the fields. This method has been verified by Robinson, Worden, and Harvey (1980). Recent work in this area is reviewed by Marcy in this volume. In this paper we illustrate applications of this method by presenting one of our results, flux measurements on the RS CVn star λ And.

2. OBSERVATIONS AND RESULTS

We use infrared spectral data in our analyses for two reasons. First, the interesting cool K-M stars have their energy maxima near 2μ. Second, magnetic sensitivity and therefore detectability is greater in the infrared based on the Zeeman splitting relation

$$\Delta_H = 4.7 \cdot 10^{-13}\ g \cdot H \cdot \lambda^2\ Å\ , \tag{2.1}$$

where H is the field strength in gauss, g is the Landé g factor, and Δ_H is the separation of each σ component from the cental π component. Although the splitting is proportional to λ^2, the intrinsic absorption line width is proportional to λ, so magnetic detectability is only proportional to λ.

Our data were obtained with the Kitt Peak National Observatory 4-m Mayall reflector and Fourier Transform Spectrometer (FTS). We record a bandpass of 0.32μ centered at 1.65μ (6178cm^{-1}). A large number of suitable spectral lines has been identified with effective g factors between 0 and 3. The spectral resolution of this data is 0.1 cm^{-1}.

We observed 19 late-type stars during 1981, many of them several times. Complete analysis for these objects is not yet complete, thus we provide here only our results for λ Andromedae to demonstrate our approach. This star is especially interesting since it is a G8 IV-III RS CVn-type system with variable chromospheric emission lines enhanced by factors of 10-100 over corresponding lines in the sun (Linsky et al., 1979; Baliunas and Dupree, 1982). This star's X-ray luminosity is $L_x \sim 10^{30}$ ergs^{-1} or 10^3 times the solar value (Walter et al., 1980; Swank et al. 1981). Periodic broadband optical fluctuations have been observed on λ And which are attributed to starspots covering 30% or more of the stellar surface (Eaton and Hall, 1979). λ And is bright in the infrared with an H magnitude of 2.0.

Figure 1 shows profiles of the magnetically sensitive (g=3.0) FeI line at 6388.65 cm^{-1} for λ And and for a quiet chromosphere star, α Tau (K III). The profile for the latter star was artificially broadened by convolution with a gaussian to account for differences in nonmagnetic broadening between the two stars. We estimated the necessary broadening by comparing absorption line profiles for the two stars which had $g < 1.0$. The FTS data provide a direct estimate of S/N since the spectrum is recorded simultaneously by two detectors. From the differences between the two signals we deduce that the λ And data has a normalized RMS noise of 0.023, and α Tau a RMS noise of 0.005.

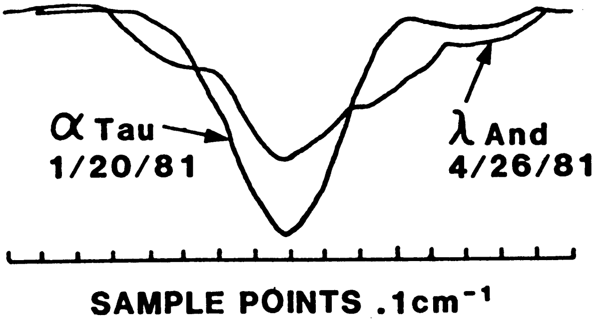

Figure 1. Plot of α Tau and λ And 6388.65 cm^{-1} line profiles. α Tau has been artificially broadened to a mean λ And value.

The line profile seen in the spectrum of λ And is broadened with respect to the comparison (α Tau) profile. The σ components are evident and partially blended with the central component, which is composed of the π component and a component profile from the nonmagnetic regions of the stellar surface.

3. ANALYSIS AND DISCUSSION

The intensity profile of a line produced in a region of uniform magnetic field may be represented by (Title and Tarbell, 1975)

$$I(\lambda) = A\cdot[Z(\lambda-\Delta_H) + Z(\lambda+\Delta_H)] + B\cdot Z(\lambda) \;, \qquad (3.1)$$

where $Z(\lambda)$ is the intensity profile of the unsplit line and A and B are constants given by Babcock (1949)

$$A = {}^1/_4\ (1 + \cos^2\gamma\ ) \quad ; \qquad B = {}^1/_2\ \sin^2\gamma \;, \qquad (3.2)$$

with γ the angle between the line of sight and the field orientation. Equation 3.1 is the convolution of the unsplit profile, $Z(\lambda)$, with a triple impulse function which parametizes the splitting. The magnetically sensitive stellar line profile is the combination the profiles from nonmagnetic (quiet) and magnetic (active) regions. The flux profile of such a two-component model is

$$M(\lambda) = (1-f)\cdot Q(\lambda) + A\cdot f\cdot[Z(\lambda-\Delta_H) + Z(\lambda+\Delta_H)] + B\cdot f\cdot Z(\lambda) \;, \qquad (3.3)$$

where $Q(\lambda)$ is the flux profile of the unsplit line and f is the fraction of stellar surface covered by fields (filling factor). Upon

Fourier transforming with k as the transform variable, and applying the Fourier shift theorem

$$g(k) = (1-f) + {}^{M}/_{Q} \cdot f \cdot [B + 2A \cdot \cos(\Delta_H \cdot k)] \ , \qquad (3.4)$$

where M/Q is the ratio of the relative depths of the central components of the unsplit profiles. For complex multi-component atmospheres, the profile is a summation of each component's profile, but we have characterized λ And by a two-component atmosphere. Averaging equation (3.4) over all possible line-of-sight angles yields the following:

$$g(k) = (1-f) + {}^{1}/_{4} \cdot {}^{M}/_{Q} \cdot f \cdot [1 + 3 \cdot \cos(\Delta_H \cdot k)] \ , \qquad (3.5)$$

We performed the indicated Fourier deconvolution with the profiles shown in Figure 1, assuming the broadened α Tau profile to be a suitable comparison line. We used a χ^2 fitting routine to find best fit values of f, M/Q, and Δ_H in equation (3.5). From this fit we find a field strength of 1290 ± 50 G covering 48 ± 2 % of the visible hemisphere of λ And. We obtained multiple observations of λ And during 1981 and show the 6388 cm^{-1} line from these spectra along with the comparison α Tau data in Figure 2. We were able to derive magnetic field values for only the 26 Apr 1981 data. This result clearly suggests that the magnetic flux on λ And is variable.

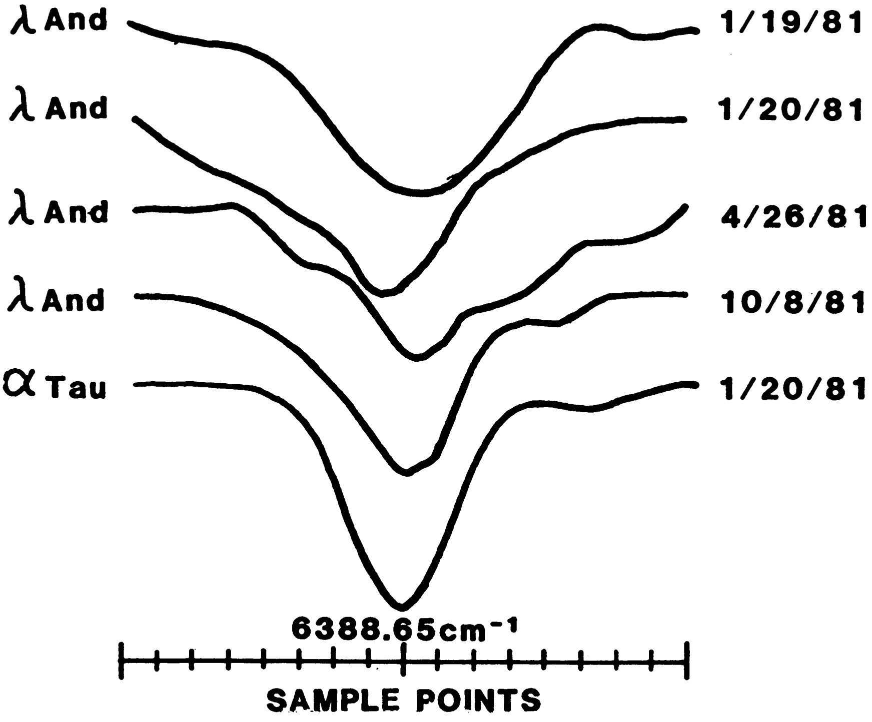

Figure 2. λ And and α Tau FeI 6388.65 cm^{-1} line profiles for 1981, the α Tau profile has been broadened to match λ And.

We can make a simple comparison of our result to magnetic flux estimates expected from equipartition arguments, which suggest that magnetic pressure ($H^2/8\pi$) should roughly equal the ambient gas pressure. If we adopt the photospheric model of Bell et al. (1976) with T_{eff} = 4500°K, log g = 3.0, and metallicity of − 0.5, we derive a gas pressure of Pg = 4.58 • 10^4 dynes cm^{-2} at a Rosseland mean optical depth τ_{ross} = 1. This gas pressure implies H = 1073G, in good agreement with our measurement.

An alternate estimate of magnetic flux for λ And may be based on scaling laws found in solar coronal studies (Golub et al., 1980) which relate magnetic field strength to coronal base pressures and loop lengths. By combining this information with scaling laws given by Rosner et al. (1978), we can predict magnetic field strengths if the X-ray luminosity and coronal temperature are known. Based on information supplied to us by Golub (1982) we estimate a mean coronal field of 650 G with a filling factor of unity, although the actual filling factor is probably larger than unity due to the large surface area of the loop structures. This estimate for the mean field does not include the effects of different turbulent velocities for λ And as compared to the sun, which would tend to increase the field strength estimate for λ And. Nonetheless, this estimate for coronal field strength is consistent with a photospheric field of 1290 G covering about 50% of the stellar surface.

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DISCUSSION

SCHÜSSLER: Could you comment on your determination of an equipartition field, and did you take into account the Wilson depression of a fluxtube?

WORDEN: When we spoke of "equipartition" we were comparing magnetic energy density ($H^2/8\pi$) with thermal energy density (nkT) rather than with a kinetic energy density based on turbulent motions within the fluxtubes ($\frac{1}{2}\rho v^2$). We did not take into account any peculiarities with the physics within the fluxtube. Once again, we used the pressure (or thermal energy density) at Rosseland mean optical depth unity in a representative photospheric model for λ And.

VOGT: (1) It seems that magnetic-field measures in the visible can go to much fainter objects, faster than your IR technique, even though your telescope aperture is much larger (4 meter vs. 24" for Marcy's work). Can you comment on this large discrepancy in detection efficiency? (2) Have you observed any of the stars for which Marcy measures fields, and are you in agreement with these results? (3) What are your blending problems with the lines selected?

WORDEN: (1) The IR Fourier Transform Spectrometer is a single channel device as well as a relatively wide spectral bandpass instrument. Thus, the efficiency on a single line is low. Moreover, the quantum efficiency of IR detectors is being improved to that of visible detectors. Our methods are greatly enhanced by using many lines, thus the broad spectral bandpass is required. But perhaps the best reason for suffering the lower efficiency in the infrared spectral region is that these spectra represent the energy maxima of the cooler K and M stars. For this reason the IR is much more efficient and indeed the only way to obtain adequate spectral resolution for the interesting dMe stars. Furthermore, due to increased magnetic sensitivity, lower spectral resolution is needed for the IR. Thus with improvements in IR detection, and keeping in mind the broad spectral bandpass we need, the IR is potentially more efficient than the visible for studying magnetic fields on later-type stars. (2) We have some stars in common with Marcy, e.g. the star for which results are presented here, λ And. I believe that Marcy's results for this star are similar within the limits of the errors. It is also important to make sure that the levels in the stellar atmosphere which the observations represent are comparable. Marcy's results, based on visible spectra, probably represent higher levels, especially for the cooler stars. This may explain why Marcy's results for the later-type stars tend to show lower field strengths than equipartition arguments suggest, because the field lines have spread with height. Clearly further intercomparison of IR and visible results are needed. (3) Blending problems in the IR are due primarily to terrestrial atmospheric lines. We have carefully avoided these for our line choices. The IR is considerably better than the visible for the later-type stars in avoiding blends. We have obtained extremely high resolution and high S/N solar data for quiet sun and sunspot to verify that our lines are unblended. In addition to proving that our lines are unblended, the Fourier reduction method is highly insensitive to blends except in the unlikely event that line blends are exactly evenly spaced in opposite wings of the absorption line being used.

SODERBLOM: In examining your profiles of λ And, I notice that the profiles are sampled at fairly wide intervals — maybe 5 or 6 points for the FWHM. This is a very broad-lined star; can one sample at much more closely spaced intervals needed for the slowly rotating late-type dwarfs?

WORDEN: Our resolution is 0.1 cm^{-1}, which is sufficient to oversample all but the narrowest stellar lines in the 5000–7000 cm^{-1} region. The 4-meter telescope Fourier Transform Spectrometer can be used to obtain resolutions of up to about 0.02 cm^{-1}, but at a corresponding penalty in integration time.