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THE MAGNETIC FIELD ON THE RS CANUM VENATICORUM STAR LAMBDA ANDROMEDAE

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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 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 observations of the RS CVn star λ And. At the epoch of observation, 1981 April 26, we find a field strength of 1290 ± 320 gauss covering 48% ± 7% of this star's surface. This measurement compares with an estimate of coronal magnetic flux in the cooler component of the stellar corona of 1110 gauss with a coronal volume filling factor of 75%, based on X-ray data for λ And.

Subject headings: magnetic fields — stars: chromospheres — stars: coronae

I. INTRODUCTION

Quantitative stellar magnetic flux measurements provide essential inputs for theories which describe the origin of stellar magnetic fields and associated atmospheric structure, such as chromospheres and coronae. It is believed that magnetic fields arise from an interaction between existing magnetic fields, convection, and differential rotation as embodied in the "dynamo" process. In order to provide more stringent observational constraints on 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 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. Recent results have shown that magnetic fields could be deduced 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 derive both estimates of the actual field strengths and the fraction of the visible stellar surface covered by the fields. This method was initially applied by Robinson, Worden, and Harvey (1980). Similar results have been shown by Marcy (1981). In this *Letter* we illustrate applications of this method by presenting flux measurements on the RS CVn star λ And.

RS Canum Venaticorum stars are late-type binary systems with relatively short periods. The standard models for these systems have been reviewed by Hall (1976). These stars are considered to be somewhat evolved, consisting of a F-G main-sequence or subgiant star and a cooler G-K subgiant. The latter star appears to have a single complex of starspots extending over a large fraction of one hemisphere. This activity, presumably magnetic in origin, is empirically related to the observed, extensive chromospheric activity, X-ray emission, and radio and optical flaring (e.g., see Baliunas and Dupree 1982). The RS CVn stars have periods of about 10–20 days as defined by the rotational modulation of the spot seen in the system light curve. The phases of the rotational light curves remain fairly constant, or drift slowly, suggesting that the spot complexes are long lived.

X-ray observations of the RS CVn stars have revealed the presence of coronal emission (Swank *et al.* 1981; Walter *et al.* 1980) at a level of 10^{30}–10^{31} ergs s^{-1}, or

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10^3 times the solar value. Models require that a two-component corona be present in these systems in order to account for the observed X-ray emission. A cooler component, representing line emission characteristic of plasma at approximately 10^7 K, is superposed on a hotter bremsstrahlung continuum chacteristic of a thermal plasma at about 10^8 K. The variability of the X-ray components has not been well studied, but the hotter component appears to be more variable (Swank *et al.* 1981).

The RS CVn star λ Andromedae is an interesting target for several reasons. The visible component of the system is a G8 IV-III star 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). It has a slightly longer period than most RS CVn stars, at 54 days, as deduced from rotational modulation of the Ca II emission lines (Vaughan *et al.* 1981). The observed X-ray luminosity of λ And is $2.5 \pm 0.7 \times 10^{30}$ ergs s^{-1} for the cooler component, and $1.6 \pm 0.6 \times 10^{30}$ ergs s^{-1} for the hotter component (Swank *et al.* 1981). Periodic broad-band 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). The infrared magnitude of λ And is $H = 2.0$.

II. OBSERVATIONS AND RESULTS

We use infrared spectral data in our analysis for two reasons: first, the interesting cool K-M stars have their energy maxima near 1 μm; second, magnetic sensitivity, and therefore detectability, is greater in the infrared as seen from the Zeeman splitting relation:

$$\Delta_H = 4.7 \times 10^{-13}\, gH\lambda^2\ \text{Å}, \qquad (1)$$

where H is the field strength in gauss, g is the Landé g-factor which is a measure of magnetic sensitivity, 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 (KPNO) 4 m Mayall reflector and Fourier Transform Spectrometer (FTS; see Hall *et al.* 1979 for a detailed description of the KPNO 4 m telescope FTS). We record a bandpass of 0.32 μm centered at 1.65 μm (6178 cm^{-1}). A large number of suitable spectral lines have been identified with effective g-factors between 0 and 3. The spectral resolution of these data is 0.1 cm^{-1}.

We observed λ And four times during 1981 and selected the spectrum which most clearly showed magnetic splitting, assuming that it represented the phase when the (presumably) single spot was most in the line of sight to the Earth. Figure 1 shows this selected observation. In this figure we display the profiles of the magnetically sensitive ($g = 3.0$) Fe I line at 6388.65 cm^{-1} for λ And observed on 1981 April 26 and also for a quiet-chromosphere comparison star, α Tau (K III), observed on 1981 January 20. The remaining λ And observations were not reduced for this *Letter*, but they are part of a forthcoming paper on magnetic and chromospheric variability on λ And utilizing both these data and *International Ultraviolet Explorer* (*IUE*) satellite ultraviolet spectra. However, even the raw profiles showed that the magnetic splitting on λ And is time variable. The α Tau profile was artificially broadened by convolution with a Gaussian in order to account for differences in *nonmagnetic* broadening between the two stars. We estimated the amount of artificial broadening necessary by comparing the FWHM of absorption-line profiles with $g \leqslant 1.0$ in the spectra of the two stars. The degree of actual broadening used was small, having a Gaussian broadening parameter of $\sigma = 0.18$ cm^{-1}. The procedure used to derive this value was to compute the value of Gaussian broadening for six low-g lines so that the two stars had each line of identical FWHM. The value quoted above was the average of those six values. The dispersion in the individual values suggests an error in σ of ± 0.04. The six lines used were: Ni I 5882.03 cm^{-1} ($g = 1.0$), Fe I 6052.62 cm^{-1} ($g = 1.0$), Fe I 6063.87 cm^{-1} ($g = 0.86$), Fe I 6127.12 cm^{-1} ($g = 0.43$), Si I 6412.01 cm^{-1} ($g = 1.0$), and Fe I 6436.65 cm^{-1} ($g = 0.75$). The main source of error in this broadening parameter derivation was the uncertainty in setting the continuum level, which was done by a linear least squares fit to what we chose to be the nearby continuum. The FTS data provide a direct estimate of the signal-to-noise ratio since the spectrum is recorded simultaneously by two detectors. From the differences between the two signals, we deduce that the λ And data have a normalized rms noise of 0.023, and the α Tau data, a noise of 0.005. 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.

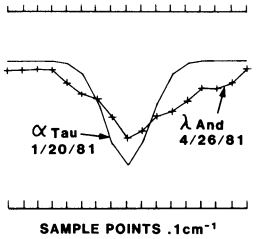

FIG. 1.—Plot of α Tau and λ And 6388.65 cm^{-1} line profiles. The α Tau profile has been artificially broadened so that the mean broadening of absorption lines in that star are the same as those in λ And.

III. 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)

$$I(\lambda) = A\left[Z(\lambda - \Delta_H) + Z(\lambda + \Delta_H)\right] + BZ(\lambda), \tag{2}$$

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

$$A = \tfrac{1}{4}(1 + \cos^2 \gamma); \qquad B = \tfrac{1}{2}\sin^2 \gamma, \tag{3}$$

with γ the angle between the line of sight and the field orientation. Equation (2) is the result of the convolution of the unsplit profile, $Z(\lambda)$, with a triple impulse function that parameterizes the splitting. The magnetically sensitive stellar line profile is the combination of the profiles from nonmagnetic (quiet) and magnetic (active) regions. The flux profile of such a two-component model is:

$$\begin{aligned} M(\lambda) = {} & (1 - f)Q(\lambda) \\ & + Af\left[Z(\lambda - \Delta_H) + Z(\lambda + \Delta_H)\right] + BfZ(\lambda), \end{aligned} \tag{4}$$

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:

$$g(k) = (1 - f) + \frac{M}{Q}f\left[B + 2A\cos(\Delta_H k)\right], \tag{5}$$

where M/Q is the ratio of the relative depths of the central components of the unsplit profiles. For complex multicomponent atmospheres, the observed profile is a summation of profiles arrising from each magnetic region and the nonmagnetic area. In this analysis we have characterized λ And by a two-component atmosphere. Averaging equation (5) over all possible line-of-sight angles yields:

$$g(k) = (1 - f) + \frac{1}{4}\frac{M}{Q}f\left[1 + 3\cos(\Delta_H k)\right]. \tag{6}$$

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 (6). From this fit we find a field strength of 1290 ± 50 gauss covering 48% ± 2% of the visible hemisphere of λ And. The error estimates are the formal fitting uncertainty in the fitting routine, taking into account the error of the input data, for the parameters of interest.

We have considered the error sources in our analysis. As discussed above, we computed a formal fitting error for the parameters noted. Based on the sum and difference signals of the two separate detectors, we computed the error of each point in Fourier space following Gray (1976) for both stellar spectra. From this analysis and using 17 input points from the line profile, we deduce an input error for each point of 8.3%. This value was used as input into the χ^2 error analysis. The small apparent errors derived in this manner require some additional elaboration. Marcy (1983) reports a threshhold value of 500 gauss and 10% surface coverage using a magnetic field analysis related to ours, which suggests that our errors are inappropriately small. However, Marcy's values are thresholds for the method and not formal errors. For stronger fields and larger surface coverages, our method might be expected to provide far more accurate results. This aspect of the detection method is based on the fact that the detectability of magnetic split line components increases dramatically as the relative strength of the split σ components increases over the intrinsic noise in the wings of the line profile. To check our analysis, we examined the effects of changing our input parameters. A change in the broadening applied to the α Tau comparison profile of 10% produced no change in our results. This shows that the prebroadening of comparison lines is not a significant driver to our results. However, when we changed the value of our Landé g-factor by 5%, we found a 25% change in the estimated field strength and a 14% change in estimated filling factor. The g-factor we used in this analysis for the 6388.65 cm^{-1} line was calculated based on standard atomic coupling theory. Recent work (Harvey 1983) suggests that this may not yield valid effective g-values for lines such as 6388.65 cm^{-1} in the near-infrared. To check our assumption of $g = 3.0$ for this line, we examined a sunspot spectrum with known magnetic field strength. Based on measures of splitting in lines with lower g-values, we would have deduced a g of 2.7 for the 6388.65 line. We consequently feel that an error of ±5% in the g-value is plausible and adopt the error estimates discussed above as our resultant values. We are therefore perfecting methods, to be reported in future papers, which use multiple lines with differing g-factors.

By employing scaling laws derived from solar coronal studies which relate magnetic field strength and topology to the X-ray emission properties of the corona, we are able to interpret stellar X-ray observations in terms of the underlying magnetic field structure of a star. We assume that the stellar coronal magnetic fields are organized into closed three-dimensional loops with footpoints in the stellar photosphere as in the case of solar coronal structures. The quantitative relation between

X-ray emission and magnetic field has been discussed by Golub *et al.* (1980, 1982) who derived a scaling law between observable quantities:

$$p \propto H_z^{3/2} L^{-1/4} v_\phi^{3/2}, \tag{7}$$

where p is the coronal plasma temperature, H_z is the average longitudinal magnetic field at the base of the loop of length L, and v_ϕ is the effective twisting velocity of the velocity shear at the footpoint of the loop in the stellar photosphere.

We may combine equation (7) with Rosner, Tucker, and Vaiana's (1978) scaling law for coronal temperature, $T_{\rm cor}$, to eliminate the coronal pressure, or

$$T_{\rm cor} = 1.4 \times 10^3 \left(pL\right)^{1/3}, \tag{8}$$

which yields

$$T_{\rm cor} = 1.2 \times 10^3 H_z^{1/2} L^{1/4} \left(v_t/v_{\rm sol}\right)^{1/2}, \tag{9}$$

where we have normalized the stellar twisting velocity, v_t, to the solar value, $v_{\rm sol}$, in order to account for the variation in surface turbulent velocities for different stars.

For stars like the Sun, with fairly steady quiescent coronal emission, we may calculate an atmospheric model which allows us to specify completely all necessary parameters in an atmosphere consisting of only a single loop type. In that case we do not attempt to model a mixture of different atmospheric components. If we are modeling quiescent coronal emission, we assume that it comes from large-scale, evolved loop structures. This is because loops on the Sun tend to be very active and variable during their emergence (see, e.g., Wolfson *et al.* 1977). Furthermore, emerging magnetic flux evolves in only one direction, namely, that of initial rapid emergence followed by gradual and sustained field line spreading. We expect that quiet emission involves larger, diffused magnetic loops which may, depending on coronal temperature and surface gravity, be larger than the pressure scale height of the coronal plasma, s_p.

The coronal X-ray luminosity can be represented by

$$L_x = 4\pi R_*^2 h_e n_e^2 P(T) f, \tag{10}$$

where R_* is the stellar radius, h_e is the emission scale height of the corona, n_e is the coronal electron density, $P(T)$ is the plasma emissivity, and f is the filling factor at the base of the corona. For a very hot corona and low surface gravity, such as that of λ And, the atmospheric scale height is not small compared with the stellar radius. Therefore, we redefine the coronal filling factor to be a *volume* rather than a surface filling factor. We use the function $q(\xi)$, defined by Rosner, Golub, and Vaiana (1983) as

$$q(\xi) = (1/3)(0.5 + 2\xi + \xi^2) \times \left[1 + \xi^{-1} - \xi^{-1}(1 + \xi)^{-2}\right], \tag{11}$$

$$\xi = h_e/R_*. \tag{12}$$

The revised volume filling factor is then $f' = f/q(\xi)$.

We take $h_e = s_p = 5 \times 10^3$ T $(g/g_{\rm sol})^{-1}$, and $n_e = p/2kT$; we then solve for f. By letting $F_x = L_x/4\pi R_*^2$, we can also solve equation (7) for the magnetic field B.

$$f = \left[3.4 \times 10^{-9}/P(T)\right] F_x \left[T^3/(g/g_{\rm sol})\right]^{-1}, \tag{13}$$

$$H_{\rm em} = 1.2 \times 10^{-8} (v_t/v_{\rm sol})^{-1} \left[T^3/(g/g_{\rm sol})\right]^{1/2}, \tag{14}$$

where the subscript em indicates that it is the average field in the emitting regions; the average stellar field is thus $\langle H \rangle = f H_{\rm em}$.

We have calculated coronal magnetic field values for λ And based on the published X-ray measurements by Swank *et al.* (1981). Assuming that the magnetic fields of interest reside in the cooler X-ray component, the results are:

$$f' = 0.75,$$

$$H_{\rm em} = 1110 \text{ gauss}. \tag{15}$$

Thus, we predict on the basis of the X-ray data that λ And is covered over most of its surface with a kilogauss magnetic field. The coronal field value and filling factor agree well with the photospheric values we report herein, even though the two data sets are not simultaneous. However, we selected the infrared spectrum for analysis which showed the largest flux. Thus we believe the photospheric values represent a time when the stellar spot complex was most directly visible. Since the coronal values are based on volume emission rather than on surface emission, they should be less subject to geometrical effects. It may therefore not be as important that the X-ray observations were not simultaneous with the photospheric magnetic field measurements.

We note that this calculation was performed using the lower temperature, presumably quiescent X-ray emission component. Lambda And, as commonly found in RS CVn stars, also has a more variable, high-temperature X-ray emission component. If we use values of L_x and T appropriate to that component, we calculate in addition to the quiescent values above:

$$f' = 0.1,$$

$$H_{\rm em} = 10^4 \text{ gauss}.$$

This high-temperature, active component may be equated with active-region–type emission, representing compact (i.e., smaller than the pressure scale height) and relatively short-lived emerging flux areas with elevated field strength, higher coronal temperatures, and increased activity. The (unobserved) photospheric magnetic field for this component may also be strong, perhaps representing fields such as those found in solar sunspot umbrae.

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

We conclude that the situation on λ And may be analogous to the Sun, but with the amount of magnetic flux higher by several orders of magnitude.

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