I. MAGNETIC FIELDS IN STELLAR PHOTOSPHERES

OBSERVATIONS OF MAGNETIC FIELDS ON LATE-TYPE STARS

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ABSTRACT

The "Robinson" method for measuring magnetic fields on solar- and late-type stars is reviewed. The results of such measurements for a sample of 29 G and K main-sequence stars are presented. The area covering-factors of magnetic regions are greater in the K dwarfs than in the G dwarfs, but no spectral-type dependence is found for the field strengths, contrary to expectations of some flux-tube models. The dependence of Ca II H and K emission on magnetic fields and T_{eff} is consistent with theoretical expectations for "slow-mode" mhd wave-generation rates, but inconsistent with those of other mhd modes. Coronal soft X-ray fluxes correlate well with the magnetic fields, and it is argued that Alfvén waves are the likely energy-transport mechanism. Surface magnetic fluxes vary with rotation as $V_{rot}^{0.5-1.0}$, depending on spectral type.

1. INTRODUCTION

Cool stars are observed to exhibit a variety of phenomena such as chromospheres, coronae, starspots, flares, and activity cycles, that appear qualitatively similar to features associated with the magnetic fields on the sun. (For recent reviews, see Linsky 1980, Golub 1981, Hartmann 1981, Noyes 1981, Skumanich and Eddy 1981, Zwaan 1981.) The correlation of all of these telltale signs of fields with stellar rotation has led to the widespread belief that the Russel-Vogt theorem must be amended to include rotation as another fundamental parameter, with magnetic fields constituting its most visible effect. To further understand the processes by which rotation is coupled to magnetic fields, and in turn determine the influence of those fields on the surfaces of solar-type stars, we must observe how such effects change on stars with different masses and rotation rates.

In this review I will try to provide a summary of the several attempts made to detect and measure magnetic fields on late-type stars directly. The written history of such trials is brief; however, I have

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been told that various exploratory attempts by such farsighted observers as G. E. Hale, H. W. Babcock, G. W. Preston and R. P. Kraft were made, but proved impossible to pursue with existing detectors. More recently, the so-called "Babcock technique," in which one measures the circular polarization induced by the Zeeman effect in absorption-line wings, was used by Boesgaard (1974) and Boesgaard, Chesley, and Preston (1975), resulting in marginal field detections for XI Boo A and 70 Oph A. A similar effort by Vogt (1980) with a Reticon detector yielded upper limits of about 100 gauss for the "effective" field strength on active late-type stars. Recently, Brown and Landstreet (1981) and Borra and Mayor (personal communication) have modified "Griffin-type" radial velocity spectrometers to perform a multi-line Zeeman analysis. These efforts have further reduced the upper limit to about 5 gauss.

These null results are thought to have been due to two effects: (1) small magnetic-field area coverages on the stellar surfaces; (2) the small-scale, bipolar character of the field regions, similar to those on the sun, so that the opposing field polarities result in cancellation of the circular polarization expected from the Zeeman effect (Robinson 1980). Such bipolar regions, however, could produce net transverse fields if, for example, a star is viewed equator-on and has radial field lines located near the limb. The Zeeman-induced linear polarization from such transverse fields is expected to be observable both in absorption-line wings, and with broad-band polarimetry (e.g. Landi Degl'Innocenti 1982). The latter is possible because of the relative saturation of the central π-component in the Zeeman pattern, thereby suppressing its state of polarization. Unfortunately, such broadband polarimetric observations apparently require accuracy of at least 0.01%. Careful polarimetric studies by Pettersen and Hsu (1981) and Clayton and Martin (1981) on selected stars have yielded no positive detections, though the stated errors tend to be somewhat higher than 0.01%. However, Tinbergen and Zwaan (1981) have reported intrinsic linear polarization in a large sample of late-type stars based on the statistically higher polarization in the bandpass containing the greater density of lines. Though the levels of polarization are too low to be interpreted in detail, the results suggest that future measurements of linear polarization in the line wings may prove fruitful in extracting not only field strengths but also geometry information about photospheric magnetic fields. E. Borra has begun such a program.

Perhaps the most promising method for detecting and measuring magnetic fields on late-type stars is the so-called "Robinson technique" (Robinson 1980). This approach was motivated by recent solar line-profile analyses that have proven eminently successful in measuring field strengths in spatially unresolved magnetic structures in the solar photosphere (e.g., Tarbell and Title 1976). The first attempts on stars with Robinson's method were quite encouraging, and this success has led several investigators, including myself, to attempt similar observations and analyses.

2. THE ROBINSON METHOD

Robinson (1980) revived an old idea, exployed successfully on Ap stars as recently as 1971 (Preston 1971), that the Zeeman effect on lines may be detectable by the excess "broadening" of a profile observed in unpolarized light. Robinson suggested this be done on solar-type stars by comparing line profiles that have very different Zeeman sensitivities but which otherwise have similar transition characteristics. Any difference between two such profiles would be attributable to the presence of magnetic fields in the line-forming region.

The analysis of the two profiles is based on the premise that a Zeeman-broadened line formed in a photospheric region with a uniform magnetic field may be represented by the sum of three displaced components (a Zeeman triplet), the shapes of which are, to first order, given by the profile of a Zeeman-insensitive line. We know, from atomic physics, the expected ratio of the strength of the outer "sigma" components to that of the central "pi" components in a given Zeeman triplet. Therefore, any observed enhancement of the central component, over that expected, must have arisen from the nonmagnetic areas where no splitting occurs. This enhancement yields the area-coverage of the nonmagnetic and hence magnetic regions. The splitting of the components is proportional to the field strength: $\Delta\lambda = 4.67 \times 10^{-13} \lambda^2 gB$ (Å), where λ is the wavelength, g the Landé factor, and B the field strength in gauss.

Even for lines with Landé factors as large as 2.5, the Zeeman triplet is spectroscopically unresolved for solar field strengths of 1 to 3 kilogauss, necessitating some deconvolution procedure. Robinson (1980) has advocated a general Fourier approach in which a continuum of field strengths is permitted, and the area coverage for each field strength is deduced. The method I have employed is a numerical chi-square fit to the Zeeman-sensitive profile, to solve for the strength and separation of the underlying Zeeman-triplet components. This approach yields some ill-defined average of the surface field strength and area coverage, which is also the ultimate result of the Fourier technique. This is because currently available spectral resolution and signal-to-noise ratios, as well as ubiquitous weak blends, permit at most three or four degrees of freedom to characterize a profile. A direct comparison of Robinson's Fourier technique with my chi-square profile-fitting approach yielded the same result to within 10%, for the one data set (generously supplied by R. Robinson) to which both were applied.

A third approach is possible, viz., to interpret the Fourier transform of the Zeeman-broadened profile in terms of a two-component stellar surface -- a nonmagnetic component and a magnetic component of some characteristic field strength (M. Smith, personal communication). Such a technique might allow the user to more readily acquire an understanding of the analysis, as with the profile-fitting approach, while retaining the advantages of Fourier methods in handling noise in the data.

Unfortunately, all of the versions of the Robinson technique require two significant assumptions. First, the implicit assumption is made that both the energy removed from the continuum in the line and the shape of the line are the same in and out of magnetic regions. The assumption of similar profile shapes has been used successfully in solar profile analyses (e.g., Stenflo 1973). However, it is well known that continuum brightness increases and line strength decreases in the small-scale magnetic elements of which solar faculae and network regions are comprised (Stenflo 1975, Chapman and Sheeley 1968). Second, the field geometry modulates the expected relative strengths of the sigma and pi components from the magnetic regions (Seares 1913, Beckers 1969). I have chosen to assume that the field lines lie predominantly normal to the surface and that they are uniformly distributed over a spherical surface, which implies an average field-line to line-of-sight angle of 34° for a (solar) limb-darkened hemisphere.

Both the assumption of constant line strength and the field-geometry assumption will affect only the deduced area-coverage of the fields since the interpretation of the splitting of the Zeeman-components remains model-independent. Tests with theoretical profiles (Unno 1956) indicate that errors of about 20% in magnetic area-coverage may accrue from either of the above assumptions, and larger errors are possible if active regions on other stars are dramatically different in character than solar. Note also that starspot umbrae, if similar to their solar counterparts, will have surface brightnesses roughly 20% of the surrounding photosphere and hence will contribute little to the observed integrated line profiles. Starspot penumbrae, however, would contribute to the deduced magnetic field measurements (both strength and area-coverage) because the locally enhanced strength of the neutral metal lines would compensate for the slightly reduced continuum brightness.

In addition to the model-dependent errors discussed above, random errors from noise in the data demand that spectra be obtained with high signal-to-noise ratio (S/N > 100), owing to the small effect of Zeeman broadening compared with other sources. A good estimate of the magnitude of the Zeeman-induced broadening may be gained from the theoretical line profiles shown in fig. 1, derived from Unno's (1956) relations. The small vertical discrepancy between the Zeeman-sensitive line (assumed to have Landé g = 2.5) and the insensitive line (g = 1.0) shows the necessity of low-noise data. Tests of the random errors in the field measurements have been made by myself and Robinson (1980) by introducing random fluctuations in the theoretical profiles. Such measurement errors in field strength and area-coverage are neither gaussian nor independent, and they depend on the strength and coverage themselves. For fields of solar strength, about 1500 gauss, covering 30% of a stellar surface, spectra with a signal-to-noise ratio of 100 will result in random errors of about 25% in strength and flux (strength multiplied by area) and about 35% in area-coverage.

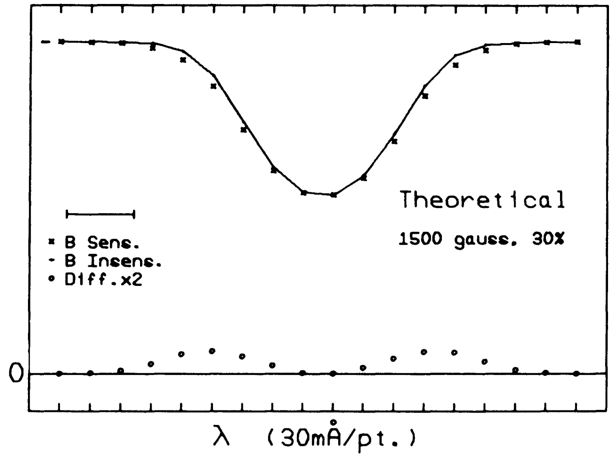

Figure 1. Comparison of a theoretical, Zeeman-sensitive profile (upper points) with that of a Zeeman-insensitive line (continuous line), for a star with magnetic fields of 1500 gauss, covering 30% of its surface. The points at the bottom show the difference of the profiles multiplied by 2. The bar indicates the assumed resolution of 60 mÅ.

Finally, tests similar to those above indicate that the Robinson method, applied in its pure form, can detect fields of solar strength only if the area coverage is greater than about 5%. The magnetic flux tubes on the sun cover only about 1% of the solar photosphere. Therefore, we can successfully detect fields only on stars which have 5 times the magnetic flux of the sun. One ray of hope for significant future improvements is to obtain high-resolution spectra of hundreds of line profiles simultaneously, thereby minimizing the effect of ubiquitous weak blends in late-type stellar spectra.

3. RESULTS OF MAGNETIC-FIELD MEASUREMENTS

The first measurements of magnetic fields with the Robinson technique were made of XI Boo A (G8V) and 70 Oph A (KOV) by Robinson, Worden and Harvey (1980). Their deduced field strength of 2500 gauss covering 20-45% of XI Boo A implies a magnetic flux 50 times greater than that of the sun! Later failures to measure the field of XI Boo A (Marcy 1981), followed by positive detections by myself and G. Timothy, C. Joseph and J. Linsky at Boulder, Colorado, have confirmed the validity of the original detection and suggested that the fields on active stars may be quite variable. In addition, Timothy, Joseph and Linsky (1981) have reported detections of fields on several other late-type stars, and I am aware to date, via personal communications, of similar detections by M. Smith at Sacramento Peak Observatory, and by J. Harvey at Kitt Peak National Observatory.

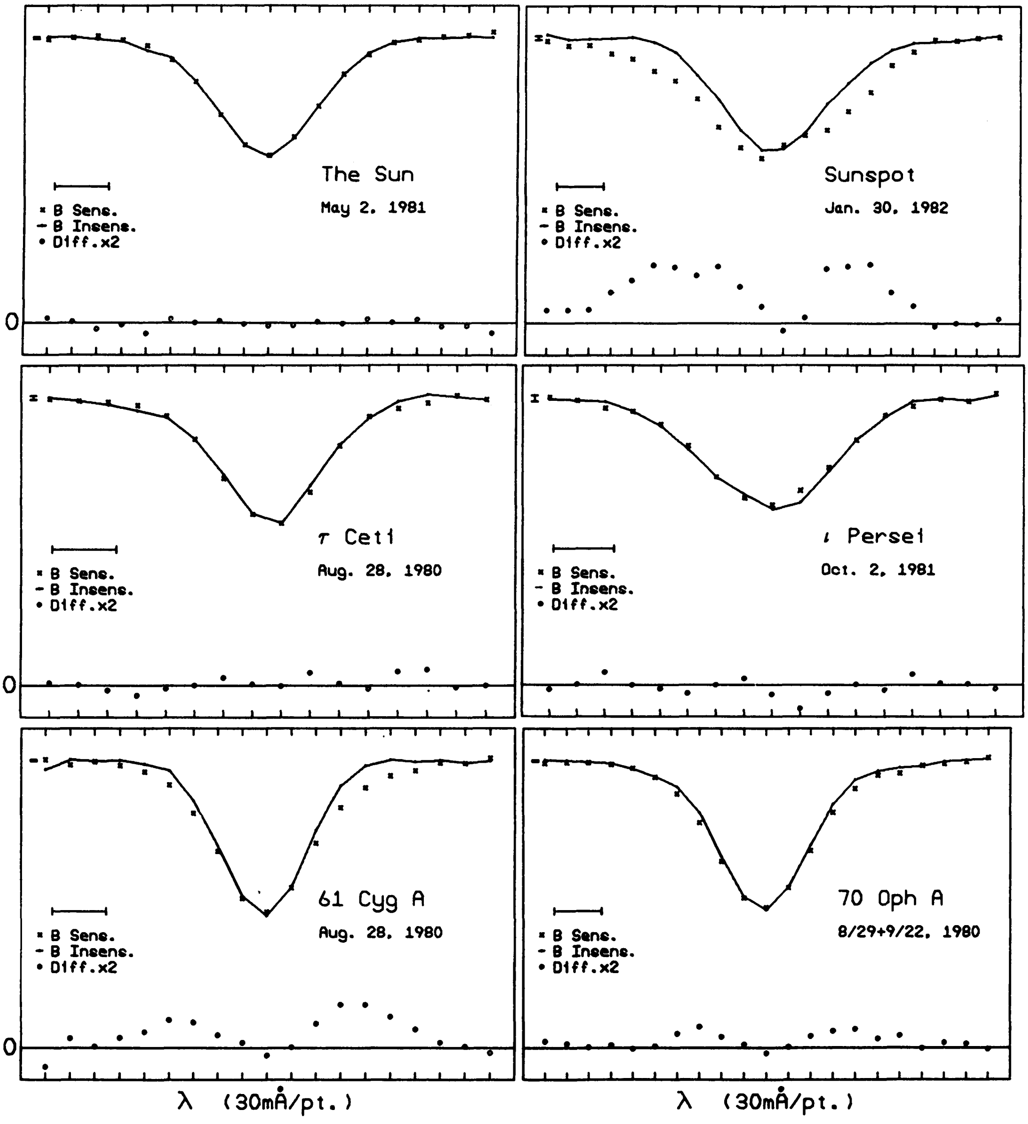

Figure 2. Examples of observed line profile pairs for the daytime sky, a sunspot, and four stars, as in figure 1. The difference in the Zeeman-sensitive and insensitive profiles is shown multiplied by 2 at the bottom. Tau Ceti and iota Per do not show evidence of split Zeeman components in their difference profiles, but the sigma components are visible in 61 Cyg A and 70 Oph A.

During the past two years I have been engaged in a program of measuring and monitoring fields on 29 G and K main-sequence stars, and the remainder of this review paper will contain a description of the results obtained thus far. The observations have been made with the coudé double-pass echelle spectrograph (Soderblom et al. 1978) and the image-dissector scanner (Robinson and Wampler 1972) at Lick Observatory. The Zeeman-sensitive line employed was $\lambda6173.34$ (lower EP = 2.21 eV, g = 2.5) and the insensitive line was $\lambda6240.65$ (lower EP = 2.21 eV, g = 1.0), both arising from the same lower state of Fe I.

Examples of some of the data are shown in figure 2. Profiles from the daytime sky (labeled "sun") show no evidence of Zeeman broadening because of its low area-coverage of fields (1%). However, the sunspot data show clear evidence of fields and the deduced field strength of 2000 gauss is comparable with the value obtained at Mt. Wilson Observatory (kindly provided by Dr. Robert Howard) of 2300 gauss. Examination of the "difference profile" shown at the bottom of the panels reveals no sigma components on either tau Ceti (G8V) or iota Per (G4V), but prominent Zeeman components are seen for 61 Cyg A (K5V) and 70 Oph A (K0V). To date, 19 of the 29 surveyed stars have shown fields. The sample, though not complete to a given magnitude, is not biased in rotational velocity. However, most of the stars on which fields have not yet been detected are G dwarfs.

Indeed, the histogram of area-coverage (or "filling factor") shown in figure 3 shows that many of the G dwarfs have less than 10% of their surfaces covered by fields while the K dwarfs have filling factors ranging from 20% to 80%. In order to show an unbiased histogram, the nondetections have been included at half of their upper-limit values. The very large area-coverages seen on some stars may indicate that a model-dependent systematic error is being made in our interpretation of the line profiles; however, a year of searching for such an error source has uncovered nothing save the possible 20% errors, mentioned previously, from field geometry and line-strength changes. Further, the independent measurements of area-coverages for XI Boo A of 20-45% by Robinson, Worden and Harvey (1980), and of 40-60% by G. Timothy and C. Joseph (private communciation) confirm the large area-coverages found here for many active stars. Possibly related are the reports that the observed amplitudes of light variation on some spotted stars demand that the spots cover up to 40% of the stellar surface (e.g., Vogt 1981). Similarly, analyses of chromospheric lines from active stars suggest the need for much more extensive active regions than are found on the sun (Kelch, Linsky and Worden 1979; Giampapa et al. 1982. The apparently larger median value of the magnetic covering-factors (indicated by the arrows in figure 3) for the K dwarfs, compared with that of the G dwarfs, will be addressed in section 6 in conjunction with stellar rotation effects.

The accompanying histogram in figure 3 for the magnetic field strengths shows no difference in field strength between the G and K dwarfs. This is remarkable because the characteristic field strength

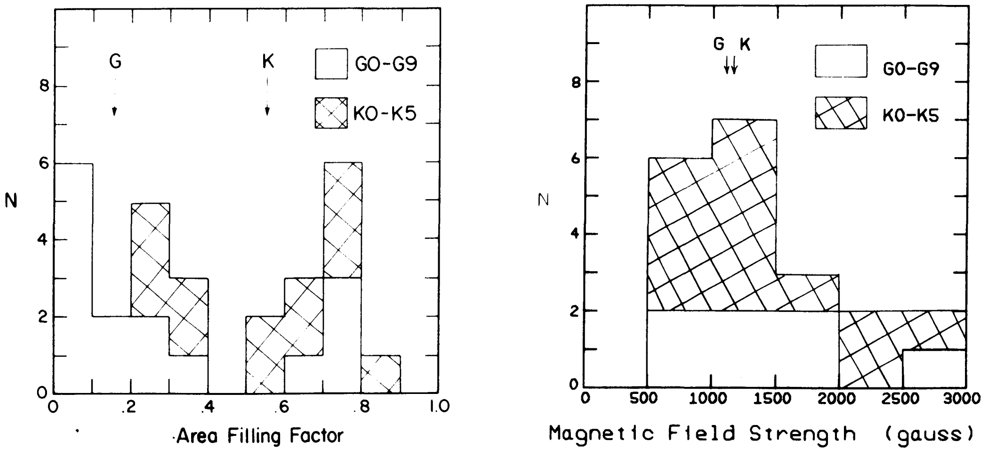

Figure 3. Left: a histogram of magnetic area-coverage for all observed dwarfs with nondetections included as 1/2 their upper limits to minimize bias between G and K stars. Right: a histogram of field strength. Nondetections are left out because no upper-limit estimates are possible. Both panels display G dwarfs as open rectangles and K dwarfs as cross-hatched. The arrows represent the median values.

on the sun of about 1500 gauss has been attributed by some as the result of gas-pressure confinement of the thin flux tubes ($B^2/8\pi = P_g$), i.e., tubes with stronger fields would disperse owing to high internal magnetic pressure (Galloway and Weiss 1981; Parker 1981). Since photospheric gas pressure is expected to increase toward later spectral types approximately as, $P_g \propto T_{eff}^{-3}$, the thin flux-tube models would predict fields of about 2400 gauss on all K2 dwarfs. This expectation is in disagreement with, for example, the well-observed stars epsilon Eridani (K2V) and 70 Oph A (K0V) that usually show field strengths under 1500 gauss. (Robinson, Worden and Harvey found 1880 gauss for 70 Oph A for their single observation.) It may be that the concept of isolated, stable, thin flux-tubes, confined by gas pressure, will not be useful in describing either the nature or the dynamics of the fields on the more active stars.

An alternative possibility, that magnetic-field strength is determined by confinement from turbulent pressure, ρV_{turb}^2, has led some to suggest that flux ropes of lower field strengths (600 gauss) might rise to the surface (Zwaan 1978). Though this might explain the 1 kilogauss fields observed on some stars, a further refinement is necessary to account for the wide variation in field stregths observed at a given spectral type. In view of the short time scale variations of magnetic fields (1 day) seen by Timothy, Joseph, and Linsky (1981), and also found in the Lick data, a more dynamic and stochastic model of rising and dissipating flux ropes may be needed to describe the surface fields on active stars.

4. MAGNETIC FIELDS AND CHROMOSPHERES

A longstanding problem in stellar astronomy has been the unknown source of heating in solar- and late-type stellar chromospheres. Until recently, pure acoustic waves generated by convective turbulence at the base of the photosphere was perceived as the most likely energy-transport mechanism (e.g., Renzini et al. 1977; Ulmschneider and Bohn 1981). Observations of velocity fluctuations in solar optical lines by Deubner (1976) seemed to support their existence. However, a variety of solar and stellar observations are in conflict with the notion that pure acoustic waves supply much of the chromospheric energy. These arguments have been summarized elsewhere (e.g. Linsky 1980), but the most complelling are: (1) spatial coincidence on the sun of chromospheric and transition-region emission with photospheric magnetic fields; (2) the dependences of stellar chromospheric emission on effective temperature and gravity contradict those expected theoretically for pure acoustic-wave heating; and (3) the wide range of chromospheric emission at a given spectral type conflicts with expectations that acoustic-wave generation depend only on T_{eff} and gravity.

Alternatively, mhd waves have been proposed as the dominant energy transport mechanism (for a review, see Stein and Leibacher 1980), and three modes can satisfy the mhd equations: Alfvén waves, "slow"-mode, and "fast"-mode. Alfvén waves involve bending and twisting of the field lines, slow-mode waves are simply acoustic waves channeled by vertical field lines, and fast-mode waves involve fluid compression but depend on magnetic tension for the restoring force, and need not travel along field lines as is required for the former two wave types. The wave-flux generated by turbulent motions at the top of the convection zones of cool stars has been given by Stein (1981) and Ulmschneider and Stein (1982):

$$F(\mathrm{Acoust})/T_{eff}^4 \propto g^{-1}\, T_{eff}^{10.6} \quad (1a)$$

$$F(\mathrm{Alfvén})/T_{eff}^4 \propto g^{0.1}\, T_{eff}^{0.7}\, B^{-1} \quad (1b)$$

$$F(\mathrm{Slow})/T_{eff}^4 \propto g^{-0.2}\, T_{eff}^{2.1} \quad (1c)$$

$$F(\mathrm{Fast})/T_{eff}^4 \propto g^{0.5}\, T_{eff}^{3.4}\, B^{-5} \quad (1d)$$

where g is gravity and B is magnetic field strength.

We may use the Mt. Wilson measurements of Ca II H and K emission, as indicators of radiative loss rates in the lower chromosphere, by converting them to surface fluxes as done by Duncan (1981) and

Middelkoop (1982), and subtracting the contribution from the "photosphere" (Linsky et al. 1979). A three-parameter least-squares fit was made to these chromospheric Ca II H and K fluxes, $F'(H + K)$, to determine the observed dependence on T_{eff}, B and magnetic area-coverage. The result of the fit was:

$$F'(H + K)/\sigma\ T^4_{eff} = 6.14 \times 10^{-14} B^{0.5}\ T^{2.0}_{eff}\ f^{0.6} \qquad (2)$$

where f is the area-coverage. The errors in the above exponents are about 1/2 the stated value in all three cases. A plot showing the relationship between $F'(H + K)$ and the above-determined dependences is given in the left panel of figure 4.

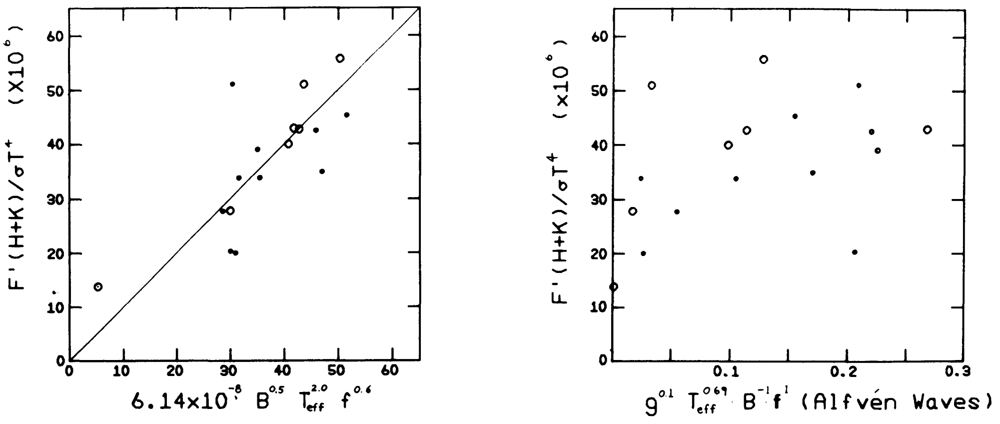

Figure 4. Left: The fraction of total stellar luminosity that is emitted in Ca II H and K from the chromosphere vs. the best-fit power-law dependences on field strength, B, effective temperature, and magnetic area-coverage. These exponents correspond closely with those expected for slow-mode mhd waves. Right: Same plot for the expected dependences assuming Alfvén waves heat lower chromospheres.

The power-law dependences on B and T_{eff} given above are in clear disagreement with those expected for pure acoustic waves and for fast-mode waves (eq. 1), and are many standard deviations away from those dependences expected for Alfvén waves. Indeed the right panel of figure 4 shows a plot of observed Ca II H and K emission vs. the function of B and T_{eff} expected if Alfvén waves provide the heating (eq. 1b). No correlation is apparent. However, the observed dependences of Ca II flux on T_{eff} and B are quite close to those expected if slow-mode waves (eq. 1c) heat stellar chromospheres. Indeed, magnetically channeled acoustic waves have been previously suspected as the energy transport mechanism to lower chromospheres on the basis of the variation of Mg II emission-line fluxes with effective temperature and gravity (Ulmschneider and Stein 1982; Basri and Linsky 1979).

A remaining uncertainty in the identification of slow-mode waves as the dominant mechanism derives from the poorly known variation in the radiative damping rate of such waves with changing T_{eff} and gravity, over the relevant range of G0V to K5V. Further theoretical work in this regard would certainly be most useful.

5. MAGNETIC FIELDS AND CORONAE

The detailed observations by Skylab of arch-like coronal structures having feet planted on bipolar active regions suggest that both coronal structure and heating are related to photospheric magnetic fields (e.g., Billings 1966; Vaiana et al. 1973; Rosner, Tucker and Vaiana 1978; and a recent review by Golub 1981). The measurements of soft X-ray fluxes from other G, K and M dwarfs have led a number of investigators (e.g., Rosner and Vaiana 1979; Ayres and Linsky 1980; Pallavicini et al. 1981; Walter 1982) to suspect that magnetic fields control stellar coronae as well. Though we do not know a priori how coronal development will depend on field strength, the above suspicion implies that stellar soft X-ray fluxes will be related in some fashion to the photospheric area-coverage of magnetic fields.

To test this, soft X-ray measurements from the Einstein Observatory have been taken from Johnson (1981), Pallavicini et al. (1981), Ayres et al. (1981), Walter (1982), Vaiana et al. (1981) and from Vogt, Walter and Marcy (unpublished, for XI Boo A, XI Boo B, and HR 5553). Figure 5 shows a plot of photospheric, magnetic area-coverage against $\log(f_x/l_{bol})$, the ratio of soft X-ray flux to bolometric flux. The correlation seen in Figure 5 provides strong confirmation of the notion that the coronae around all G and K main-sequence stars depend sensitively on the underlying, photospheric magnetic fields.

Additional information regarding the actual mechanism by which coronae are heated may be gained from determining how the soft X-ray fluxes depend on photospheric magnetic field strength. A least-squares fit to the meager data (there are only 7 points besides the sun) showed that

$$f_x/l_{bol} \propto B^{-1.5 \pm 1.0} \cdot f, \qquad (3)$$

where B is field strength and f is magnetic area-coverage. (Including T_{eff} in the fit results in a dependence of T_{eff}^{11} but this exponent is

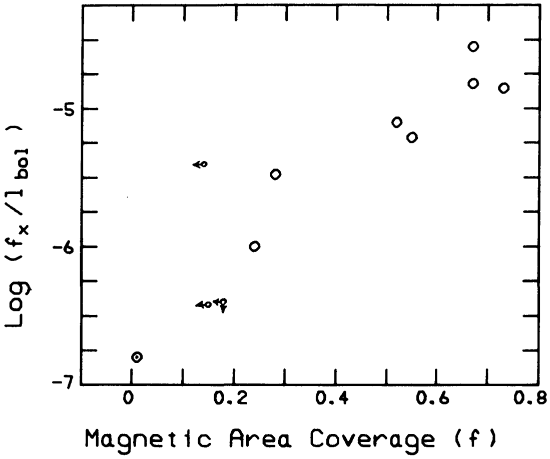

Figure 5. The ratio of soft X-ray flux to bolometric flux vs. photospheric magnetic area-coverage for G and K dwarfs.

uncertain by ±5, i.e., meaningless, because of the extremely narrow range of spectral types available, G0-K5, and the few stars.)

According to Stein (1981) and Ulmschneider and Stein (1982), we may apply equations 1a-1d, given here previously, to describe the generation rate of mhd waves which may eventually propagate to the coronae. Here again, we know little about the variation of deposition efficiency with spectral type for any of the waves. The expected generation rate for fast-mode waves (eq. 1d) disagrees, in field-strength dependence, with the $B^{-1.5}$ dependence observed here. And, of course, the good correlation between soft X-ray flux and magnetic area-coverage in figure 5 suggests that pure acoustic waves are not responsible for coronal heating. Unfortunately, the expected generation rates for both slow-mode and Alfvén waves given in equation 1 are consistent, within two standard deviations, with the observed dependence on B. However, the well known high radiative damping rate (Schmitz and Ulmschneider 1980) of all compression waves, such as slow-mode, in the photosphere and lower chromosphere has led some to choose Alfvén waves as the only surviving mhd wave in the corona (Leibacher and Stein 1981; Hartmann and MacGregor 1980).

Indeed it seems that in order to get Alfvén waves to dissipate at all, they must first couple to either the compressive slow or fast waves after traversing the lower chromosphere (Leibacher and Stein 1981). Certainly, further theoretical study of the dissipation mechanisms available for Alfvén waves are needed to clarify this process, and may lead to better understandings of the winds from cool giants and, perhaps, T Tauri stars (Ayres et al. 1981; Hartmann and MacGregor 1980).

6. MAGNETIC FIELDS AND STELLAR ROTATION

The observed correlations between stellar rotation and such characteristics as chromospheric and coronal emission, age, and the presence of starspots, flares and activity cycles have led many investigators to suggest that magnetic fields provide the missing link via dynamo generation (Skumanich 1972; Hartmann 1981; Pallavicini et al. 1981; Vaughan et al. 1981). Independently, most theoretical descriptions of the dynamo process require rotation and differential rotation for the production (by coriolis-affected convection) and enhancement (by longitudinal stretching of field lines) of magnetic fields (for a recent review, see Gilman 1981).

To investigate the dependence of stellar magnetic fields on rotation, equatorial velocities have been determined from Vaughan et al. (1981) and, when not available there, from Soderblom (1980) and Smith (1979). Unfortunately, few stars have both a measured field and rotation velocity. Those available are shown in the left panel of figure 6, where magnetic flux is plotted against equatorial velocity. The 3 data points representing G dwarfs (circles) are consistent with the

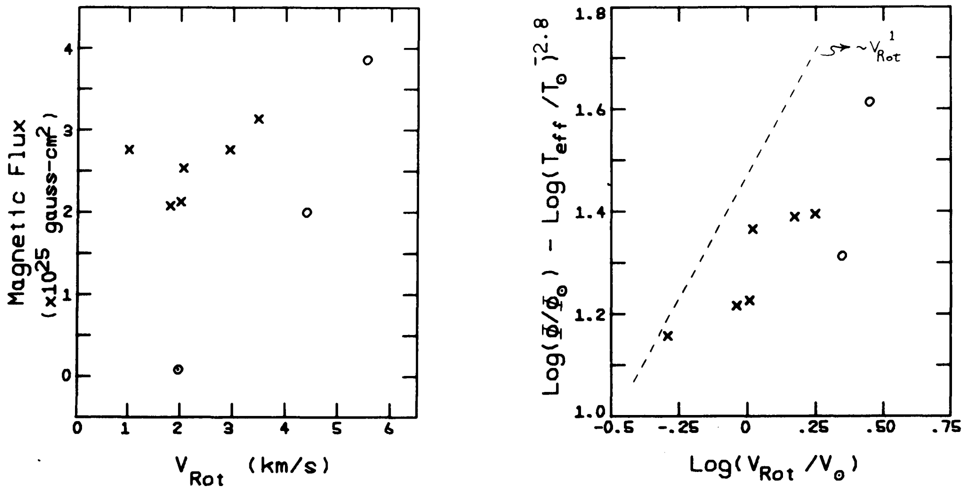

Figure 6. Left: Magnetic flux vs. equatorial velocity. Crosses are K dwarfs, circles are G dwarfs. Right: Same as left panel, but on a log scale and the magnetic flux, Φ, has been corrected for the T_{eff} dependence in observed flux. The dashed line indicates the slope for a linear dependence on V_{rot}.

possibility that magnetic flux increases with rotation. The K stars would show a similar relationship, except for the far left point in the diagram. This is 61 Cyg A and, at K5, has the lowest T_{eff} of the plotted stars.

This suggests (as does the visible difference between the K and G dwarfs in the plot) that magnetic field flux increases toward later spectral types. To quantify this, a least-squares fit to the data yields:

$$\Phi = 4.1 \times 10^{10}\, V_{rot}^{0.55 \pm 0.2}\, T_{eff}^{-2.8 \pm 1.1} , \qquad (4)$$

where Φ is magnetic flux in gauss-cm^2 and V_{rot} is equatorial velocity in km/s. The relationship between magnetic flux and rotation may be more graphically displayed by correcting the magnetic fluxes for the T_{eff} dependence, as has been done in the right panel of figure 6. There, the logarithm of the magnetic flux minus -2.8 log $(T_{eff}/T_\odot)$ is correlated with rotational velocity at the 1% confidence level. This deduced dependence of magnetic flux on $V_{rot}^{0.55}$ can be shown to be completely consistent with the rotational dependence of Ca II H and K emission found by Vaughan et al. 1981, for their sample of stars near K0 (B-V = 0.86 - 0.89, see their figure 4). However, their data indicate that at G0, Ca II H and K flux depends nearly linearly on rotation, suggesting that the same will be found true for magnetic flux when enough G dwarfs are measured. Skumanich and Eddy (1981) found corroborating evidence in the Ca II H and K emission from spectroscopic binaries that varies as $V_{rot}^{2/3}$.

Finally, it is difficult at this time to interpret the observed dependence of magnetic flux on V_{rot} and T_{eff} (equation 4) in terms of available dynamo models. Durney and Robinson (1981) have computed dynamo models in which the field generation at the bottom of the convection zone is determined by the rise time of a magnetic flux tube due to buoyancy. Their results suggest that observed magnetic flux should vary as $V_{rot}^{2.3}\, T_{eff}^{-15}$. These dependences are in the right direction, but are so discrepant both with those found here and with those implied by Vaughan et al. (1981), that some crucial physical process must have been overlooked.

A different approach is taken by Stix (1972) who argues that the critical field attained in the convection zone is that which suppresses the helicity of convection, i.e., $B_c \propto \Omega^{1/2}$, where Ω is angular velocity. It can be shown that the observed surface toroidal field will also vary as $\Omega^{1/2}$, assuming that the turbulent and magnetic Reynolds numbers depend only on spectral type (see Skumanich and Eddy 1981). The agreement between Stix's predicted square-root dependence on rotation and that observed suggests that the suppression of convective helicity by the fields may constitute an important process in late-type stellar dynamos.

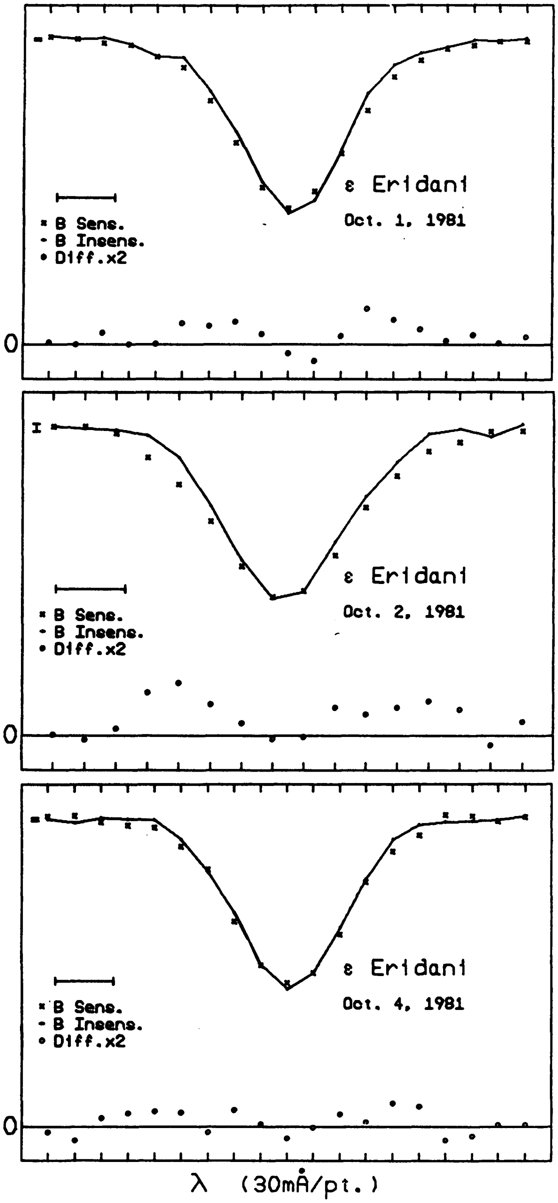

Figure 7. Magnetic field data for epsilon Eridani as in figure 2. Changes seen in the difference profile suggest that the magnetic fields are variable on time scales of one day.

7. MAGNETIC FIELD VARIABILITY

As first reported by Timothy, Joseph and Linsky (1981), the magnetic fields on epsilon Eridani seem to vary significantly on time scales as short as one day. The data taken at Lick have also suggested short time-scale variations for both epsilon Eridani and XI Boo A. Figure 7 shows data for epsilon Eridani from three closely-spaced nights. The difference profiles shown at the bottom of each panel suggest that the magnetic fields became somewhat more widespread from Oct. 1 to Oct. 2, 1981, and then nearly disappeared by Oct. 4. Since the rotation period of epsilon Eridani is 11 days (Vaughan et al. 1981), these magnetic field variations cannot be due to active regions rotating across the stellar disk. One possibility is that we are seeing large magnetic flux bundles, comparable in size to solar complexes, that are gently rising to the surface and then sinking below the photoshhere. Such processes normally take weeks on the solar surface.

In any case, these variations in magnetic flux must be more convincingly demonstrated and correlated with simultaneously obtained chromospheric diagnostics to better understand the dynamics and effects of magnetic fields on the more active stars.

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DISCUSSION

HARTMANN: Are you not surprised that 61 Cyg A, which is not a very active star and is a slow rotator, has such a large measured magnetic field?

MARCY: The field *strength* is large (3000 G), but the area covering factor is about 20% , so the total surface magnetic flux is moderate. Also, 61 Cyg A, at K5, is the coolest star among the dwarfs in the survey, so it is consistent with the suspicion that magnetic fields increase towards later spectral types, for a given rotational velocity.

ZWAAN: Did you find a relation between covering factor and field strength?

MARCY: It seems that stars with exceptionally small field strengths have the larger covering factors. This may, however, be a selection effect since low strengths are not observable unless the fields cover a significant fraction of the surface.

IONSON: When you speak of "covering factor" it appears that you are referring to the percentage of the star covered by the maximum field. I would expect that the covering factor is a function of the B-field, which we know from solar studies can vary over quite a large range. Can you comment on this?

MARCY: The present data suggest that stars with the larger filling factors have smaller relative field strengths. Should a distribution of field strengths exist on a given star, the analysis of the Zeeman broadening given here will yield some ill-defined average of both the field strength and the covering factor.

SCHÜSSLER: The weak dependence of field strength on spectral type is no evidence against fluxtube models because the peak fields do not only depend on surface pressure but also on the efficiency of lateral heat influx and the depth of the Wilson depression, which determines the geometrical height where the observed lines are formed. Of course, thin fluxtube models may be irrelevant for a surface flux coverage $> 70\%$.

MARCY: I agree. Furthermore, both the Ca II H and K data and the magnetic-field data suggest that significant changes in the surface magnetic flux occur on time scales as short as one day. If so, the observed field strengths may be less related to surface conditions such as photospheric pressure, but more to the conditions and confinement processes at the top of the convection zone.

GIOVANELLI: We observe in magnetic regions on the sun two types of waves, propagating outwards from the feet of the tubes of force. One of these two types is a longitudinal wave. If you look at the center of the disk, for example, it is a wave that oscillates up and down. Call it an acoustic wave or a slow-mode wave, but at any rate it is one of these waves that is propagating along a flux tube. It is later in phase at greater heights. Therefore the wave is propagating outwards. We do not find any evidence of waves propagating inwards. If, however, 25% of the wave energy were propagating inwards, we probably would not see it. So you could have 25% reflection, but you would have 75% going out. And there is enough energy in these waves to cook up the corona. I am talking about periods of 3–5 min. These are the things that we see in Hα and in lines at lower levels.

The second type of wave is Alfvén waves propagating upwards along fibrils. (I am going to show a movie about this later during the Symposium.) Every fibril that you see on the sun in Hα carries these waves, which I at least interpret as Alfvén waves. They carry a sufficient amount of energy to cook up the corona. You never see them propagating backwards.

CRAM: Presumably, the $F(H+K)/T^4_{eff}$ ratio for a set of stars depends almost completely on the area covered by calcium emission. How was the area effect removed from the quoted relations between $F(H+K)/T^4_{eff}$ and $T^n_{eff}B^m$? After the area effect is removed, how much residual correlation remains to determine the indices n and m?

MARCY: The magnetic area covering-factor was in fact included in the least-squares solution to the dependence of $F'(H+K)/\sigma T^4_{eff}$ on T_{eff} and B, and the result was that $F'(H+K)/\sigma T^4_{eff}$ varies as covering factor to the 0.6 power. The somewhat weaker than linear dependence may be interpreted in terms of the overlapping of diverging, dense fluxtubes in the more active stars.

GRAY: I would like to ask you about the effects of line saturation. As I understand your analysis, no radiation transfer is taken into account. Saturation of the lines will systematically affect the values of the filling factor. Could you comment specifically on this?

MARCY: The lines used, λ6173 and λ6240, are weak, having equivalent widths of about 50 mÅ on the sun. However, "equivalent width broadening" is not negligible. Tests with theoretical profiles indicate that the effect of such saturation is significantly smaller than the Zeeman-broadening effect; however, I agree that future magnetic-field measurements should include line-transfer effects.

GRAY: Can you tell us (qualitatively) whether you expect your filling factors to be too large or too small if saturation is significant?

MARCY: The filling factors would be overestimated. This effect becomes important for later-type stars like K5, but should be essentially non-existent for K2.

LINSKY: There are two additional problems in the interpretation of the magnetic data using the Robinson technique. (1) Line blends can lead to false magnetic field strengths and filling factors. This may not be a severe problem for the G stars, but it becomes worse for the K and M stars. (2) The continuum in the magnetic regions could be darker (star spots) or brighter (stellar faculae) than in non-magnetic regions in late-type stars. In either case the derived magnetic-field filling factor would be in error. Since some of the derived filling factors are as large as 80% for the most active stars, I suspect that the continuum brightness in the most active stars is enhanced (stellar faculae), in which case the derived filling factors are upper limits. Could you comment on these two problems?

MARCY: The absorption lines were specifically chosen to be free of blends. But for stars later than K5, blends do become a problem, so we have observed no stars later than that. Regarding the second point, I have emphasized that indeed the derived filling factors are model dependent. Both the facular brightness and the field-geometry will affect the covering factors, while the derived field strengths are much less dependent on such assumptions.