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OBSERVATIONS OF MAGNETIC FIELDS ON SOLAR-TYPE STARS[1]

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ABSTRACT

Magnetic-field observations have been carried out for 29 G and K main-sequence stars. The area covering-factors of magnetic regions tends to be greater in the K dwarfs than in the G dwarfs. However, no spectral-type dependence is found for the field strengths, contrary to predictions that pressure equilibrium with the ambient photospheric gas pressure would determine the surface field strengths. The dependence of Ca II H and K emission on magnetic fields and effective temperature is consistent with Stein's (1981) theoretical expectations for the generation-rates of magnetically-channeled acoustic waves (so-called, "slow-mode" mhd waves), but inconsistent with the expectations for other mhd modes. Coronal soft X-ray fluxes from the G and K dwarfs correlate well with the fraction of the stellar surface covered by magnetic regions. The dependence of coronal soft X-ray fluxes on photospheric field strengths is consistent with Stein's predicted generation-rates for Alfven waves. For the eight G5 to K5 dwarfs for which reliable rotational velocities are available, the magnetic flux is found to vary as $\phi \propto V_{Rot}^{0.6} T_{eff}^{-2.8}$. These dependences are inconsistent with the one dynamo model for which a specific prediction is offered, suggesting that some important dynamo process is yet to be included. Finally, time variability of magnetic fields is seen on the two active stars that have been extensively monitored. Significant changes in magnetic fields are seen to occur on timescales as short as one day.

I. INTRODUCTION

The notion that magnetic fields are present on the surfaces of stars of spectral types G, K, and M finds support in a variety of indirect evidence including observations of stellar chromospheres, coronae, starspots, and stellar flares, all of which have solar counterparts that are spatially associated with magnetic fields (cf. Linsky 1980, Skumanich and Eddy 1981). Additional evidence of magnetic fields on late-type stars comes from the supposed signatures of dynamo processes, manifest in the correlation of the above magnetic diagnostics with stellar rotation rate, and in the identification of the presumed analogues to the sunspot cycle, seen as long-timescale periodicity in Ca II H and K emission (cf. Vaughan, Preston, and Wilson 1978 ; Pallavicini et al. 1981; Vaughan et al. 1981). The direct detection of magnetic fields on cool stars would serve not only to substantiate these indirect arguments, but also to provide considerable information on two long-standing solar problems: the nature of dynamos and the magnetohydrodynamics of the surface layers.

Efforts to address these problems from existing stellar data have been hampered by the difficulty in interpreting presumed magnetic indicators such as chromospheric emission and coronal soft X-ray fluxes in terms of magnetic field strengths and fluxes. Even for the sun, the nature of the interactions between photospheric magnetic fields and the overlying gas remains virtually unknown. This ignorance is due, in large part, to the as yet unresolved sub-arcsecond-sized magnetic structures of which most solar magnetic regions are composed. Hence, little is known about the dynamics of

these small magnetic structures or about their role in the development of the solar chromosphere and corona.

Direct stellar magnetic-field measurements would, in principle, provide new information about chromospheric and coronal heating as well as about dynamo processes, owing to the various effective temperatures, gravities, and internal structures that provide non-solar environments for the mhd processes. Hopefully, the empirical specification of how chromospheric and coronal heating depend on photospheric gas temperature, local gravity, and magnetic field-strength would provide unique information on the actual mhd processes that are operative. Similarly, a knowledge of how surface magnetic fluxes vary with stellar mass and rotation rate would be valuable in testing dynamo models.

At present, very few detections of magnetic fields on solar- or late-type stars have been reported, and in view of the difficulty and paucity of such measurements, skepticism surrounding those reports remains widespread. Boesgaard (1974), using a conventional Zeeman analyzer, observed eight young stars and reported a positive detection for η Vir N (F0V) and marginal detection for ξ Boo A (G8V) and 70 Oph A (K0V). However, four higher-dispersion Zeeman spectrograms measured by Boesgaard, Chesley, and Preston (1975) showed no evidence for a magnetic field on ξ Boo A. Other attempts made with Zeeman analyzers (e.g., Vogt 1980; Brown and Landstreet 1981; Borra, personal communication) have yielded only upper limits to field strengths on late-type stars. As noted by Robinson, Worden, and Harvey (1980, hereafter RWH), localized bipolar fields on unresolved stellar surfaces are difficult to detect with conventional Zeeman analyzers because

the fields of opposite polarity tend to cancel the expected circular polarization in the Zeeman split line components. However, the linear polarization in the Zeeman components from a star covered with locally bipolar magnetic fields should not cancel out. Tinbergen and Zwaan (1981) have reported evidence of broadband linear polarization on late-type stars that they attribute to surface magnetic fields.

An alternative technique (e.g., Preston 1971) for the detection of magnetic fields involves the observation of line profiles which have been broadened by unresolved Zeeman splitting. Using this method, RWH have reported the first positive field detection for a late-type dwarf star, ξ Boo A, as well as a marginal detection for 70 Oph A. A Fourier deconvolution technique (Robinson 1980) was employed by RWH to infer fields with a strength of 2650 gauss for ξ Boo A, covering 45% (one night) and 20% (the next night) of the stellar surface. Subsequently, five attempts were made to confirm these field detections for ξ Boo A (Marcy, 1981) using a similar technique, but none showed convincing evidence of Zeeman splitting. However, various arguments were presented supporting the possibility of variations in the field on ξ Boo A.

Recently Timothy, Joseph and Linsky (1981) have reported detections of fields on late-type stars using Robinson's (1980) approach and noted, in particular, significant changes in the field on ε Eri over time intervals of one day. M. Smith (personal communication) has also found Zeeman-broadening in ε Eri and his rough interpretation of the line breadths yielded a magnetic field strength of about 1000 gauss.

This paper will describe an attempt to detect and measure magnetic fields, via Zeeman broadening observations, on a number of G and K main sequence stars. Section II contains the details of the observations. Section III provides a review of the line-profile analysis described previously (Marcy 1982), and also includes several details of the analysis not mentioned there. Section IV contains a presentation of the magnetic-field measurements, and Section V offers interpretations of these measurements as they pertain to a variety of somewhat distinct stellar problems.

II. THE OBSERVATIONS

The general approach used to detect magnetic fields is similar to that described by Robinson, Worden, Harvey (1980). Their procedure involves comparing the shapes of two line profiles which have very different sensitivities to the Zeeman effect, but which are identical in the absence of magnetic fields. The aim is to detect the presence of the outer two σ-components of a normal Zeeman triplet, seen as an excess broadening in the Zeeman-sensitive line. The wavelength splitting of the outer σ components from the central component is given by $\Delta\lambda = 4.67 \times 10^{-13}\ g\lambda^2 B$, where g represents the Lande factor, λ the wavelength in Å, and B the field strength in gauss. This implies that even magnetically sensitive lines ($g \sim 2.5$) formed in fields of a few kilogauss will be split by amounts comparable to typical line widths. It is therefore imperative that the comparison be made between

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lines that have nearly identical atomic characteristics but quite different Lande factors.

The magnetically sensitive line chosen here is Fe I λ6173.34 (lower EP = 2.21 eV, g = 2.5), a line used extensively in solar magnetic-field work (von Kluber 1947, Degl'innocenti 1982). The insensitive line chosen is Fe I λ6240.65 (lower EP = 2.21 eV, g = 1.0) (Robinson 1980; Beckers 1969). The Zeeman sensitive line arises in multiplet # 62, the insensitive line from multiplet # 64, but both arise from the same lower $^5P_1$ state of Fe I (Moore 1972). The equivalent widths of the lines are 50 mÅ and 40 mÅ for the sensitive and insensitive lines, respectively, as seen in the solar spectrum. The insensitive line at λ6240.65 has a neighboring line of equivalent width = 13 mÅ located 0.34 Å away, which for most slowly rotating G and K stars does not seriously affect the profile of interest since the FWHM of the lines is about 0.15 Å. However, for stars with $\underline{v}$ sin $\underline{i}$ > 8 km s^{-1} the line is not usable.

The observations were obtained with the double-pass echelle spectrograph (Soderblom 1982) and an image-tube image-dissector scanner (Robinson and Wampler 1972) mounted at the coudé focus of the Shane 3 m telescope at Lick Observatory. (Many observations were actually made using the 0.6 m coudé auxiliary telescope.) The spectrograph set-up yielded a spectral resolution of 65 mÅ (FWHM of a laser line), each resolution element being sampled at 8 points. Since the detector covers only about 8 Å, each observation of a program star consisted of obtaining a spectrum centered at λ6173 followed immediately by one at λ6240. Careful studies have been made of the stability of the instrumental profile and of the polarizing effect of

the spectrograph, with the result that neither poses a problem in obtaining high signal-to-noise spectra.

The raw data were reduced using standard software written by Dr. M. Hartoog. The wavelength scale is determined from an observation of an interference etalon which produces equally spaced fringes separated by a known amount. The stellar continuum, after the formal data reduction, often contains a slope which is corrected by dividing the data by a straight-line fit to the continuum points. No correction is made for scattered light or the instrumental profile.

The stars for this magnetic-field study were chosen from several sources including Vaiana et. al. (1981), Duncan (1981), Walter (1982), Linsky et. al. (1979), and Vaughan (private communication). The sample contains main-sequence stars between G0 and K5 for which the chosen magnetically sensitive and magnetically less-sensitive lines are usable. Stars that had a comparably bright, unresolved companion or that had a $v \sin i$ greater than 8.0 km s^{-1} were excluded from the sample. The observed stars contain a nearly complete sample of G5-K5 dwarfs down to V = 5.5.

Figures 1a and 1b show a fraction of the data set including particular profiles that are representative of various results to be addressed later in the paper. Each panel contains the Zeeman-sensitive profile, λ6173.34 (represented by crosses) and the Zeeman less-sensitive profile, λ6240 (represented by the connected line), laid one over the other. At the bottom of each panel is shown the difference of the profiles multiplied by a factor of two, for visibility. The tick marks and the data points are spaced at intervals of 0.030 Å, and zero intensity for all of the plots is indicated

by the horizontal line with the zero outside the left border. In the upper left of each panel is found a vertical bar (occasionally of unresolved length), the length of which is equal to the average of the standard deviations in the continua of the two profiles. Each point in the displayed profiles represents a bin of four pixels from the image dissector scanner.

In order to more easily detect differences in the shapes of the profiles, the λ6240 profile (weaker by about 15%) has been scaled to the λ6173 profile in the following way. The weaker profile was scaled such that the log of the intensity ratios of the old to new points was equal to a constant at each point in the profile, the constant being set by the condition that the scaled profile has the same depth as the λ6173 profile. This scheme is designed to reproduce the way in which a weak line-profile scales as the oscillator strength is increased slightly, i.e., the flux at each point in the profile is approximately given by $I(\lambda) = I_0 e^{-gf\phi(\lambda)}$, where gf is the oscillator strength and $\phi(\lambda)$ is the line absorption coefficient. (Acknowledgement is due G.H. Herbig for suggesting this approach.) It should be mentioned, however, that a simple arithmetic multiplication of the weaker profile apparently performs the scaling adequately.

Finally, the weak absorption feature located 0.34 Å shortward of the line of interest at λ6240.65 has been removed from these profiles by fitting a smooth gaussian to it and simply adding the gaussian to the data. Although the fit is certainly not perfect, the line is so weak that the small departures of the fit to this feature are evidently insignificant.

Several observational tests have been performed to determine the sensitivity and reliability of λ6173 and λ6240 for magnetic field

measurements. Most important is the verification that the two line-profiles have the same shape in stars of various spectral types and gravities. Of course, no late-type magnetic "null" stars are known and it is premature to assume that chromospherically inactive stars are definitely void of fields. The sun, however, has such a low filling-factor of magnetic regions (1-2%) that no Zeeman-broadening should be detectable. Figure 1a shows the observed profiles for the sun (actually the day sky), and we notice no significant departures between the two profiles. As another possible null-star, Arcturus was chosen because of the low thermal energy density of its photospheric gas. Any detectable magnetic fields, i.e., those of strength greater than 700 gauss, on Arcturus would dominate the vertical gas structure in the photosphere since $B^2/8\pi$ would exceed nkT and $\rho v^2/2$. Since the spectrum of Arcturus is well behaved and void of exotic or time-varying features it may serve as a magnetic null candidate. Figure 1a shows the Zeeman-sensitive and -insensitive profiles of Arcturus, and no significant departures of the two profiles are seen. The similarity of the two line profiles in Arcturus suggests that their collisional broadening coefficients are nearly equal, thus ensuring that gravity cannot effect differential changes in them. These Arcturus data also indicate that curve of growth effects do not produce significant differences between the two profiles.

To demonstrate the sensitivity of the chosen line pair λ6173 and λ6240, to Zeeman broadening, the observed profiles from a sunspot (Mount Wilson Group No. 22952) of strength about 2 kilogauss are shown in Figure 1a. Subtraction of the Zeeman-insensitive from the sensitive profile (see the bottom of the panel) shows the characteristic "double-hump" pattern that is

directly attributable to the unresolved σ-components in the Zeeman-sensitive profile. Notice also that the shortward and longward humps are not identical and that the asymmetry is most evident in the Zeeman-sensitive line. This effect is probably due to the well known downdrafts in solar magnetic regions.

Many of the spectra of G- and K-type main-sequence stars contained no evidence of Zeeman broadening. Typical examples of such non-detections are given in Figure 1a for τ Ceti, ι Persei, and β Com. Examination by eye of the "difference-profile", shown at the bottom of the panel, is particularly effective for spotting the shifted, unresolved σ-components; however, the characteristic double-humps are not visible in these three data sets. The low significance of the small deviations that are visible in the difference-profile may be verified by comparison with the 1-σ error bar in the upper left corner of the panel.

Examples of stars whose spectra do show evidence of Zeeman splitting, are given in Figure 1b. The data shown here have somewhat lower noise than the average in the data set and represent the more dramatic examples of Zeeman-broadening. The left column of Figure 1b shows the profiles for 61 Cyg A, HD166, and 36 Oph A, each of which illustrates the characteristic double-hump pattern in the difference-profile that was seen in the sunspot data. Indeed, as will be discussed later, these three sets of data represent field strengths of the same order as those found in sunspots viz., 2000-3000 gauss.

The right column of Figure 1b contains data for 70 Oph A, ξ U Ma B, and ε Eri, which also exhibit double-hump structure in their difference-

profiles; however, the separation of the σ-components is evidently less here than in the previous three examples because the humps do not extend as far from line center. Note that the actual σ-components of the line-absorption coefficient certainly overlap considerably; but the scaling of the depths of the two profiles for purposes of display tends to suppress the heights and increase the separation of the humps in the difference-profile, compared with the characteristics of the true σ components. The low magnetic field strengths implied by the profiles for these latter three stars will be discussed further in light of measurements made with the line-profile analysis.

III. THE REDUCTIONS

The absorption-line profiles will be interpreted by the method described previously (Marcy 1982), viz., by deconvolving the Zeeman-broadened profiles into three components representing the normal Zeeman-triplet. Briefly, the wavelength splitting of these three components yields the characteristic field strength on the stellar surface. Further, the fraction of the stellar surface that is covered by magnetic fields may be inferred from the strength of the central component relative to the outer two components. This is because the central component is always found enhanced, relative to the outer components, owing to the large contribution from non-magnetic regions on the stellar surface, where no Zeeman splitting occurs. The tests of this method and the estimates of systematic and random

errors were reported in an earlier paper (Marcy 1982), and were carried out under conditions nearly identical to those applying to the data presented here. These tests showed that errors in the magnetic flux measurements are roughly 20%, while field strengths and filling factors have errors that depend on the actual values.

However, the application of the profile-fitting method required some attention to details not mentioned previously. Curve of growth effects, owing to the different oscillator strengths of the two line profiles, may tend to enhance the wings of the stronger line. To correct for this, the weaker line, λ6840, was scaled to the stronger line as described in Section II to simulate the logarithmic growth of weak lines. (In this case, the lines were scaled to equal equivalent widths rather than equal depths in order to simulate lines of equal gf value.) However, this applied correction was found to have an insignificant effect on the subsequent profile analysis.

Before application of the profile-fitting routine, each profile was made symmetric by averaging the left and right halves about the centroid of the line. This procedure has no effect on the result, but makes the fit of the triplet of components to the Zeeman-sensitive profile easier owing to the deeper χ^2 minima which result.

As a final note on the line profile analysis, it should be reemphasized that the estimate of the fraction of a stellar surface that contains fields depends both on the assumed magnetic field geometry and on the relative strength of the lines in and out of magnetic regions. Tests using theoretical profiles (Unno 1956) generally yield "deduced" field strengths

and filling factors in close agreement with the input values. However, while field strength measurements are relatively model independent, the deduced filling factors may be incorrect by as much as 50% if physical parameters are considerably different from those assumed. Here it is assumed that the stellar fields are oriented 34° to the line of sight on average, and the line strengths are assumed to be equal in and out of magnetic regions on the star (further discussion of these assumptions is given in Marcy, 1982).

IV. RESULTS

The journal of observations is presented in Table 1 in which the first three columns give the various identifications for each star, the fourth column gives the spectral type as indicated by Gliese (1969), columns (5) and (6) specify the U.T. Date and telescope used (either the 0.6 m Coudé Auxiliary Telescope or the 3 m Shane Telescope). Columns (7) and (8) contain the magnetic-field strengths and area filling factors which come directly from the line-profile analysis. Column (9) contains the surface magnetic flux, computed by:

$$\phi = \int B \, da = f 4\pi R^2 \, B \qquad (1)$$

where it is assumed that the flux lines are predominantly normal to the stellar surface, and f, B, and R represent the filling factor, field strength and stellar radius, respectively. Note that this equation assumes

that the observed filling factor is representative of that over the entire surface. The stellar radii were taken from Allen (1976).

Many of the observations showed no Zeeman-broadening, which can be interpreted either as evidence of low filling factors or as evidence of low field strength. No generalization can be made since many of the measured stars apparently have field strengths near the detectability limit of 500-1000 gauss, while the sun serves as an example of a magnetically undetectable star owing to small filling factor. However, an upper limit to the magnetic flux for a given non-detection is, to first order, independent of the assumed field strength, as may be seen in the detectability curves derived previously (see figure 2 of Marcy, 1982). There it was shown that, for a non-detection with signal-to-noise ratio equal to 100, the star could have B = 1000, f = 0.2 or B = 2000, f = 0.08, but the product of B·f, proportional to the flux, changes little. Therefore in order to provide somewhat meaningful upper limits for the non-detections, it was arbitrarily assumed that the field strength for such stars was 1500 gauss, and the subsequent upper limit for the filling-factor was read from figure 2 of Marcy (1982). Finally, a correction was applied to the magnetic flux upper limits for stars with very broad or very shallow line profiles to account for the lower detectability of fields in such cases. The above procedure was used to estimate upper limits of magnetic fluxes for the non-detections and are included in column (9) of Table 1. It should be noted that these flux upper limits could be too low by as much as a factor of three for stars having extremely low field strengths (B~500 gauss) and filling factors near unity.

The magnetic field measurements given in Table 1 show that field strengths range from about 600 gauss to 3000 gauss and filling factors are seen as high as 0.89. However, it should be recalled that the filling factor represents, of course, only the coverage of fields on the hemisphere facing the observer, and is weighted significantly toward regions directly "below" the observer owing both to foreshortening toward the limb and to limb darkening. Therefore a magnetic region covering perhaps only 30% of the total surface and located directly below the observer would result in a measured filling factor near unity. Table 1 also shows magnetic fluxes ranging from upper limits of 0.5×10^{25} to measured values of 4.1×10^{25} gauss-cm^2.

The above ranges in magnetic field characteristics may be compared with the solar magnetic field properties, in particular those pertaining to the photospheric facular and network regions. It has been demonstrated by a variety of both indirect and direct empirical arguments that most of the solar magnetic flux comes through the surface with field strengths between 1000 and 2000 gauss (Livingston and Harvey 1969, Stenflo 1973, Harvey and Hall 1975, Tarbell and Title 1977). Apparently, the measured characteristic field strengths on stars encompass those found on the sun. The solar filling factor of field regions is poorly known owing both to the fact that the flux tubes are generally unresolved and to the difficulty in measuring magnetic fields at the poles. Based on Ca II spectroheliograms and measured filling factors of flux tubes within plage and network regions, the average solar magnetic filling factor is found to be one to two percent (Marcy 1981), depending on phase of the solar cycle. However, on smaller time

scales, the plage filling factor may vary by a factor of roughly five (Sheeley 1966), suggesting corresponding changes in the magnetic field. It is interesting to note that although the global solar magnetic filling factor falls well below those of the stars for which fields are detected, the filling factor of magnetic flux tubes within solar plage regions is estimated to be 10% to 30% (Tarbell, Title and Schoolman 1979), not unlike some of the measured stellar values.

The observations listed in Table 1 may also be compared with the only other set of magnetic-field detections on late-type stars that have been published to date by Robinson, Worden and Harvey (1980). Their most convincing field detection was for ξ Boo A on which field strengths of 2900 gauss and 2400 gauss were deduced on successive nights while the filling factor measurements were 40-45% and 20-45%. This star was also found to have fields in the present study, though the measured field strengths were consistently lower, averaging about 1100 gauss, and the filling factors were somewhat higher than theirs. Although none of the ξ Boo A observations presented here yielded strengths as high as those of Robinson, Worden and Harvey, the field strengths measured for ε Eri, shown in Table 1, exhibit dramatic changes in field strength, suggesting the possibility that Robinson, Worden and Harvey happened to catch ξ Boo A with temporarily strong fields. Indeed a number of arguments can be given to support the suggestion that the magnetic field on ξ Boo A is variable (Marcy 1981).

The other field detection by Robinson, Worden, and Harvey was for 70 Oph A for which they measured fields of 1800 gauss covering 10% of the surface one night, but were unable to detect fields the following night.

All three 70 Oph A observations presented here yielded detections with field strengths ranging from 750 to 1750 gauss and filling factors ranging from 30% to 73%.

This comparison with the Robinson, Worden, and Harvey data suggests that their field strengths are systematically higher, and their filling factors systematically lower than those reported here. Indeed, their sunspot measurement of 2900 gauss seems to be high, especially for the "small spot" they observed (typical large sunspot field strengths are 1800-2300 gauss). Similarly their deduced magnetic filling factor for the spot was only 40-60%, though scattered photospheric light may account for much of this discrepancy. The sunspot observations made in this study yielded filling factors of 75%.

V. INTERPRETATIONS

While the sample of stars chosen for this study is not complete to a meaningful magnitude limit, it is nonetheless of value to look for correlations between the magnetic-field measurements and other stellar characteristics. Since in most cases simultaneous measurements of both the magnetic field and other, possibly variable, stellar diagnostics are not available, the average magnetic field strength and filling factor were computed for each star.

For self-consistency, the average magnetic flux was computed by

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$$\phi_{avg} = B_{avg} f_{avg} 4\pi R^2 \qquad (2)$$

where B_{avg} and f_{avg} represent the previously calculated average field strength and filling factor, respectively. The two stars HD 101501 and HD 131156A were seen to have sometimes detectable and sometimes undetectable fields on different occasions. In those two cases, the average strength and filling factor were computed using the detections only, but the average flux was computed by taking the mean of the fluxes from each night, and employing half the measured upper limits to the flux for the nondetections. For those two stars, therefore, the averages of the field strength, filling factor, and flux will be somewhat mutually inconsistent. These final average values are given in columns 2, 3, and 4 of Table 2, where the sun has been included as the last entry.

a) Distribution of field strengths and filling factors

The physical processes that determine the internal and surface magnetic-field characteristics of late-type stars, may be investigated by looking for trends in the observed fields with spectral type. Histograms of area filling factors and field strengths for all main-sequence stars in this study are shown in Figure 2 in which the K dwarfs are distinguished from the G dwarfs by the cross-hatching. It should be noted that this sample of main-sequence stars is not complete to a given magnitude or distance. However, the stars in the sample do appear to be representative of all the nearby G and K dwarfs. In particular, there is no difference in mean rotational velocity between those G dwarfs observed and those not observed.

The histogram of magnetic-field area filling factors shown in Figure 2a 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 20-80%. 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 raises the possibility that some model-dependent, systematic error is being made in the interpretation of the line profiles.

Indeed, small intrinsic differences between the two profiles used in a study such as this will translate into significant errors in the deduced filling factors. However, there are several strong arguments supporting the reality of the large filling factors, at least for those stars having higher field strengths. First, the known sources of systematic errors, such as unknown field geometry and velocity fields, are expected to produce uncertainties of no more than about 25% of the measured filling factor (Robinson 1980, Marcy 1981). Second, the independent measurements of the magnetic filling factor for ξ Boo A of 20-45% by Robinson, Worden, and Harvey (1980), and of 40-60% by G. Timothy and C. Joseph (private communication) are consistent with the large filling factors found here for that star. Finally, visual inspection of the enhancement of the wings in the Zeeman-sensitive profile of, say, 61 Cyg A, presented in Figure 1b, or of ξ Boo A presented by Robinson, Worden and Harvey (1980) implies the presence of quite hefty σ-components. Only stars having significant fractions of their surfaces covered by magnetic regions could produce σ-components of sufficient strength to remain visible against the undisplaced, central component produced in both the magnetic and the nonmagnetic regions.

Parenthetically, it is interesting that the observed amplitudes of light variations 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. 1980). In short, the weight of both indirect and direct evidence indicates that large fractions of the surfaces of active main-sequence stars are covered by kilogauss fields.

While the K dwarfs systematically have larger magnetic filling factors than the G dwarfs (to be discussed further in section V.d.), Figure 2b shows no apparent difference in the distribution of field strengths between the G and K dwarfs. This is noteworthy because the characteristic field strength on the sun of about 1500 gauss has been attributed by some as the result of gas-pressure confinement of the thin flux tubes (Galloway and Weiss 1981, Parker 1981). Since the photospheric gas pressure is expected to increase toward later spectral types, roughly as, $P_g \propto T_{eff}^{-3}$ (Stein 1981), the above assumption would predict that field strength would vary as, $B^2/8\pi \propto P_g \propto T_{eff}^{-3}$. We would therefore expect field strengths of about 2400 gauss for all K2 dwarfs, which is not observed.

One alternative point of view is that the flux tubes are confined by the dynamical pressure of turbulence given by $0.5\rho V_{turb}^2$, in the convection zone just below the photosphere (Zwaan 1978 and Penrod, personal communication). Indeed Zwaan anticipated flux tubes to rise to the surface with strengths of 600 gauss, much lower than those observed on the sun, but consistent with the lowest stellar field strengths measured here, for

example that of HD 149661 which was twice observed at about 650 gauss. One may show that for stars in which the entire stellar luminosity is carried by convection just below the photosphere, i.e., $0.5\rho V_{turb}^3 \sim \sigma T_{eff}^4$, the equipartition field strength given by $B^2/8\pi = 0.5\rho V_{turb}^2$ is expected to decrease toward later spectral types, opposite the trend expected if gas pressure confines the fields, as described above.

However, not only do the measured field strengths as a function of spectral type show no convincing trend, but there are indications that effective temperature and surface gravity do not uniquely determine the surface field strengths on G and K dwarfs. For example ε Eri (HD 22049) and 61 Cyg A (HD 201091) have similar spectral types (K2V and K5V, respectively) and yet have dramatically different, well-measured, field strengths of 1170 gauss and 2950 gauss respectively. If effective temperature and gravity do not uniquely determine surface field strength, stellar rotation may play a role (or more directly, differential rotation) by twisting existing field lines into "ropes" of higher field strength (see, for example, Piddington 1976). However, a plot of field strength vs rotation period for the nine available stars shows no correlation.

It should be noted that the concept of surface magnetic fields confined to isolated, stable, thin flux-tubes may not lead to the appropriate model for the morphology of fields on stars which produce and exhibit significantly more magnetic flux than does the sun (Durney, personal communication). Indeed, the exceedingly large filling factors of magnetic regions for the more active K dwarfs lends further skepticism to the notion that field confinement is an important process on such stars.

An alternative possibility for active stars is that after some flux buoyantly rises to the surface, it proceeds via turbulent and magnetic diffusion to simply disperse until dissipated by any of a variety of mechanisms (turbulent diffusivity, magnetic reconnection, Alfven waves, etc.). Such a scenario would lead us to expect short time-scale enhancements in the observed, characteristic field-strength from a star when a flux rope first appears, followed by a decay in field strength. Short time-scale (1 day) field variations have indeed been observed (Timothy, Joseph and Linsky 1982, and Section V.e., this paper), but better time-resolved observations are required to explore this further.

b) The Heating Mechanism for Stellar Chromospheres

It is of considerable interest to determine whether the chromospheric emission in Ca II H and K correlates at all with the magnetic field fluxes measured here. Column 5 of Table 2 contains the average values of the Mount Wilson "S" parameter (Vaughan, Preston, and Wilson 1978) which were kindly provided by Dr. A. Vaughan. This parameter is a measure of the flux in the Ca II H and K emission cores divided by the local continuum flux. However, the S values are not pure measurements of chromospheric emission but rather they depend on the nearby continuum flux and on the underlying photospheric contribution to the H and K cores.

The conversion from Mount Wilson S values to chromospheric surface fluxes in Ca II H and K requires accounting for both of these effects. A calibration of the continuum near H and K as a function of V - R has been

constructed by Linsky et al. (1979) and was based on the narrow-band photometry of Willstrop (1964). Multiplying the S values by this continuum flux yields a quantity that is proportional to the surface flux in the Ca II H and K emission cores. Conversion to an absolute surface-flux measurement can now be made by fitting a straight line to these unnormalized surface fluxes plotted against actual measurements of H and K surface fluxes made by Linsky et al. (1979) for the 12 dwarfs between G0 and K5 that have Mount Wilson S measurements.

To isolate the portion of these absolute surface fluxes in Ca II H and K that originates in mechanically heated regions, the radiative-equilibrium models (no chromosphere) of Kelch, Linsky, and Worden (1979) and Linsky et al. (1979) may be employed. Using their four "chromospherically quiet" dwarfs for which models have been constructed (the sun, α Cen A, α Cen B, and 61 Cyg B), a relationship was determined between the radiative-equilibrium, Ca II H and K fluxes and V − R. As was done for the total H and K surface fluxes above, a small linear correction was applied to the values of the radiative-equilibrium H and K fluxes so that the measures all refer to passbands of size 1.0 Å, centered on H and K. The resulting relationship between radiative-equilibrium contribution to H and K and V − R is nearly identical to the similarly derived function given by Duncan (1981) in his figure 2 for chromospherically quiet stars (multiplied by a factor of 2, since his relationship is for K-line only). Subtracting this radiative-equilibrium contribution from the total H and K surface flux results in the following expression for the mechanically-heated contribution to the Ca II H and K surface fluxes:

$$F'(H+K) = 4.22\times10^{5}+S\ 10^{[8.635-3.076(V-R)]} - 10^{[7.127-2.578(V-R)]} \quad (3)$$

in which F'(H+K) is expressed in erg/cm^2/s/2Å. As a final check of this relationship, Figure 3 shows a graph of measured values for F'(H+K) taken from Linsky et al. (1979) and from Duncan (1981) plotted against the predicted value of F'(H+K) based on S and V-R in equation (3). Evidently the correspondence is satisfactory, considering that much of the scatter certainly comes from the intrinsic variability of each star. As a result of this variability, equation (3) will be used to compute the mechanically-heated H-K flux for all the dwarfs in this study (including those for which direct measurements exist), since the Mount Wilson S values represent averages taken over several years. However, the solar value of F'(H+K) will be taken directly from Linsky et al. (1979) both because the solar H and K line profiles are well-studied, and because use of the solar value of S and (V-R) places it substantially below the 45° line in Figure 3. Column (6) of Table 2 contains values of V - R taken from Johnson et al. (1966) or, when not available, from the relationship (V-R) = 0.881(B-V)-0.035. Column (7) contains the values of F'(H+K) computed as described above.

The parameter F'(H+K) represents a measure of the radiative cooling rate in the lower chromosphere and upper photosphere. Therefore, assuming steady state, F'(H+K) provides a measure of the heating rate in that region. Note that HI, H^-, and the Mg II h and k lines also provide significant cooling in chromospheres; but Linsky and Ayres (1978) have argued that the relative contributions from these cooling agents will not vary substantially among dwarfs.

We now have an opportunity to address the question of the source of the mechanical heating in stellar atmospheres. A number of energy transport mechanisms have been proposed, among the most prominent are acoustic waves, gravity waves, and various mhd waves (for an overview, see Stein and Leibacher, 1980). Magnetic field reconnection or current dissipation may be important for flares or coronae (e.g., Vaiana and Rosner 1978), but is unlikely as a source of steady energy input over time scales greater than a few hours (Ayers, Marstad, and Linsky 1981; Stein and Leibacher 1980). Gravity waves are also unpromising as an energy-transport mechanism because the oscillatory motions are so slow that radiative damping is severe, and in any case the direction of propagation is mostly horizontal (Athay and Waite 1979; Stein and Leibacher 1980).

Acoustic wave heating of the upper atmospheres of stars, especially the sun, is perhaps the most carefully explored mechanism for heating chromospheres and coronae (see for example, Renzini _et al_. 1977). This mechanism has been appealing primarily because of the obvious driving source, viz., the turbulence in the sub-photospheric convection zone. However, serious difficulties with pure acoustic waves are apparent. The solar chromosphere is not spherically symmetric as would be expected if due to acoustic waves, and indeed the bright regions seen on spectroheliograms are highly localized and strongly spatially correlated with the underlying photospheric magnetic fields. Furthermore, the possibility that pure acoustic flux might account for chromospheres on other cool stars is rebutted by several arguments, including spectral-type dependencies that are inconsistent with theory and insufficient predicted heating rates (cf.

Linsky 1980; Basri and Linsky 1979; Schmitz and Ulmschneider 1980b).

The most promising class of energy-transport mechanisms depends upon the presence of magnetic fields to efficiently convert subphotospheric convection motions into waves. Three mhd waves are thought to be possible: Alfven waves, fast-mode, and slow-mode. Briefly, Alfven waves involve transverse distortions in the background field lines, and propagate at the Alfven speed along the direction of the magnetic field. Fast-mode waves are compressive, travel at either the sound or Alfven speed (whichever is greater), and are emitted isotropically. The slow-mode waves constitute acoustic waves in which the fluid motions and direction of propagation are channeled along field lines. Presumably the OSO8 observations of Athay and White (1979) and Brueer (1981) should have detected such waves. However, only upper-chromospheric lines were analyzed by OSO8 so that slow-mode waves may still be depositing the bulk of their energy in the lower chromosphere and upper photosphere, as indeed is expected from theoretically-determined damping rates (Stein and Leibacher 1974). If so, Ulmschneider and Bohn (1981) argue that a factor of 30 may be gained with slow-mode mhd waves over previous estimates of pure acoustic heating rates.

A recent comparison of the characteristics of all three mhd-modes along with the pure acoustic waves has been carried out by Stein (1981) and Ulmschneider and Stein (1982) in which scaling arguments are presented to predict the wave-generation rates at the base of the photosphere. Their approach assumes that some fraction of the available turbulent kinetic energy is converted to waves. The conversion efficiency depends both on the ratio of the eddy size to the wavelength of the mhd wave, and on the

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multipole order of the emission. For isotropic waves such as fast-mode, quadrapole emission dominates, while for waves moving one-dimensionally along field lines, such as the case for Alfven and slow-mode waves, monopole emission is possible (Parker 1964; Stein 1981). Simple scaling laws have been employed by Stein (1981) to determine the dependences of subphotospheric turbulent velocity, gas density, and the ratio of eddy size to wavelength on the basic atmospheric parameters of effective temperature, gravity, and magnetic-field strength. A summary of the results from Ulmschneider and Stein (1982) are as follows:

$$F(\text{acoust})/\sigma T_{eff}^4 \propto g^{-0.96}\ T_{eff}^{10.6} \tag{4a}$$

$$F(\text{fast})/\sigma T_{eff}^4 \propto g^{+0.48}\ T_{eff}^{3.4}\ B^{-5} \tag{4b}$$

$$F(\text{slow})/\sigma T_{eff}^4 \propto g^{-0.19}\ T_{eff}^{2.1} \tag{4c}$$

$$F(\text{Alfven})/\sigma T_{eff}^4 \propto g^{0.1}\ T_{eff}^{0.7}\ B^{-1} \tag{4d}$$

where the expressions represent the surface energy flux in the various wave modes divided by total stellar surface flux, g is surface gravity, and B is field strength.

The quantity of interest, for comparison with the expressions for mechanical energy flux, given in equations (4a-4d), is $F'(H+K)/T_{eff}^4$. Values of T_{eff} for all but a few of the stars in this study were found in Perrin et al. (1977). For the remaining stars the relationship $\log T_{eff} = 3.895 - 0.213\ (B-V)$ was used which was determined from twenty stars in the study which had T_{eff} determined by Perrin et al. The rms scatter about the relationship is 0.006 in $\log T_{eff}$ or about 70 K. The values of $\log T_{eff}$ for

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the observed stars are given in Table 2, column eight.

With the values of $F'(H+K)/T_{eff}^4$ determined as above, a four parameter least-squares fit was performed to determine the best values of the power-law exponents in the following expression:

$$F'(H+K)/\sigma T_{eff}^4 = k\ T_{eff}^a\ B^b\ f^c \qquad (5)$$

where B is field strength, f is filling-factor, and k is some constant. A numerical χ^2 minimization procedure was carried out by varying k, a, b, and c in small increments, and thereby mapping out the χ^2-statistic hypersurface until its minimum was located.

The values of the parameters in equation (5) determined from the χ^2 -fit were as follows:

$$a=2.0\pm1.2 \qquad b=+0.5\pm0.3 \qquad c=0.6\pm0.2 \qquad k=6.14\times10^{-14}$$

The determination of the parameters was made by using only those stars with measured magnetic fields, i.e., none of the non-detections were used in the fit. Further, neither ξ UMa A nor ξ UMa B were included because they are both spectroscopic binaries. The values of the exponents are not significantly affected by including the sun in the determination. The errors in the parameters a, b, and c were determined from the hypersurface of the χ^2-square statistic by using the method advocated by Avni (1976), for the case of three "interesting" parameters.

A comparison of these power-law dependencies with those predicted theoretically (equations 4a through 4d) shows that the observed dependencies on both temperature and field strength are independently consistent with the

slow-mode mhd wave heating mechanism. Clearly, pure acoustic waves may be ruled out because of the theoretically expected high sensitivity to effective temperature that was not observed. Both the fast-mode and Alfven waves may also be ruled out because the theoretically expected T_{eff} and B dependences fall outside the uncertainties found for the exponents. This exclusion of the Alfven waves over the slow-mode may be verified graphically in Figures 4 and 5. Figure 4 shows the plot of $F'(H+K)/\sigma T_{eff}^4$ against the expression in equation (10) for the "best fit" exponents. The scatter in the correlation is consistent with a unique relationship along the drawn 45° line, given the errors of roughly 25% in both B and f, and the errors of at least 10% in $F'(H+K)/\sigma T_{eff}^4$. The most discrepant point located at the top, center of the panel, is that of ξ Boo B for which only a poor magnetic field measurement was possible owing to its faintness. For comparison, Figure 5 shows the analogous plot, assuming that Alfven waves (the next best possibility to slow-mode) provide the heating in the lower chromosphere. No correlation is evident.

Recently, a number of indirect arguments presented by Ulmschneider and Stein (1980) have also pointed toward slow-mode mhd waves as the main contributor to the heating of solar and stellar lower chromospheres. They point out that semi-empirical chromospheric models, particularly the locations of the temperature minima, are consistent with the expected dissipation characteristics of slow-mode or acoustic shock waves. Further, the slow-mode waves are generated much more efficiently than pure acoustic waves owing to magnetic channeling. Also the small gravity-dependence of chromospheric emission, as deduced from observations of giants (Linsky and

Ayres 1978; Basri and Linsky 1979), is consistent with the theoretically-expected weak dependence of slow-mode wave-generation on gravity. And finally, the variation in chromospheric flux among stars of similar spectral type may be explained as a result of different filling factors of magnetic regions over the stellar surfaces.

The empirically-determined dependence on filling factor, viz., $f^{0.6}$ is perhaps surprising since the total mechanical energy deposited should be proportional to the area of the chromosphere. However, the chromospheric area of a star is not equal to the photospheric magnetic-field area, owing to the force-free spreading of the field lines in a flux-tube upon entering the chromosphere. For example, only about 1% of the solar photosphere contains fields while spectroheliograms show 20 to 40% of the solar surface covered by chromospheric plage and network regions (e.g. Skumanich, Smythe and Frazier 1975). Therefore, we would expect that stars with significantly greater photospheric filling factors than the sun's would not be able to accommodate proportionately larger chromospheric areas. Hence the power-law dependence of heating rate on magnetic filling factor is anticipated to be less than one. Indeed, this "saturation" of the chromospheres may also be inferred from the large variability of fields on active stars compared with the significantly less variation of Ca II H and K emission (Marcy 1981). The actual relationship between stellar photospheric and chromospheric filling factors probably depends on the spatial distribution of photospheric flux-tubes, i.e., their clumpiness and latitudinal extent.

Finally, some further explanation is needed for the observed dependence of chromospheric losses on the square root of field strength, since no field

strength dependence is expected theoretically for slow-mode mhd-wave heating (Stein 1981). Of course, the error in the observed power-law dependence on field strength is consistent, at the 2-σ level, with no dependence at all. However it should also be mentioned that equations (4a-4d) cannot be accurate as B approaches zero, since the mhd wave fluxes do not go to zero. This problem occurs because in Stein's approach if the field is too weak to control the fluid motions, no monopole radiation occurs. But if the field is strong enough to control the motions, monopole radiation occurs, but is independent of field strength. Clearly, a more detailed calculation might yield a small correction term which expresses this weak dependence on field strength in the 1 to 2 kilogauss regime of interest.

c) Heating of Coronae

The most useful diagnostic available to estimate the heating rate in the coronae of G and K main-sequence stars is the emitted soft X-ray flux, which represents a measure of the rate of radiative cooling. To ensure a consistent set of soft X-ray flux measurements, only those made with the Einstein Observatory will be used here. Column nine of Table 2 contains such measurements, given as the ratio of soft X-ray flux between 0.2 and 4.0 keV, f_x, to bolometric flux, l_{bol}.

For sources in which only the total stellar soft X-ray luminosity L_x is reported, the ratio f_x/l_{bol} was computed as follows. The bolometric luminosity of the star was determined with the equation,

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$$\log L_{bol} = \log(3.83\times10^{33}) + (4.75-M_{bol})/2.5.$$

The absolute bolometric magnitudes, M_{bol}, were obtained by adding the appropriate bolometric corrections (Allen 1976) to the absolute visual magnitudes given by Gliese (1969). Since all the stars in this study suffer insignificant extinction in both the visual and soft X-ray passbands, owing to their proximity, the ratio L_x/L_{bol}, as computed above, is equal to the desired quantity f_x/l_{bol}, the ratio of fluxes at earth.

For the stars HD 131156A, HD 131156B, and HD 131511, the Einstein measurements were made on 1981 January 24, by guest investigators Drs. S. Vogt, F. Walter, and G. Marcy. The soft X-ray fluxes were determined from the standard conversion of 2×10^{-11} erg $cm^{-2}s^{-1}$ per IPC count/s (Vaiana et al. 1981). The image of HD 131511 was near the edge of the IPC field, but no correction has yet been applied for vignetting, so this measurement constitutes a lower limit to its soft X-ray flux. The soft X-ray fluxes of ξ Boo A and B were determined from an HRI observation in which A and B were partially resolved. Application of the Weiner filter deconvolution option at the Harvard-Smithsonian Center for Astrophysics permitted complete resolution of the flux contours of the two components, with the result that component A was emitting 10 times the flux of B.

The soft X-ray observations for the stars 70 Oph A and 61 Cyg A are also contaminated by an unresolved late-type companion. Since no high-spatial-resolution X-ray observations of these two pairs are available, it will be assumed that both components in each system contribute equally to the observed flux. Therefore, in those cases, f_x/l_{bol} was computed by taking half the total soft X-ray flux, and dividing by the bolometric flux

of the one component of interest. It should be noted in this connection that the unresolved soft X-ray observation of ξ UMa A and B (Walter 1981) will not be included in the following discussions or analyses because both visual components are themselves spectroscopic binaries so that the one Einstein observation represents the flux from at least four stars.

If photospheric magnetic-field regions play a role in confining and/or heating coronal gas, as argued by numerous authors (for example, Rosner and Vaiana 1979), then a correlation must exist between observed soft X-ray flux and the measured photospheric magnetic-field filling factor. In Figure 6, the ratio of X-ray to bolometric flux, log (f_x/l_{bol}), is plotted against the fraction of the stellar photosphere which contains fields, f, for the dwarfs in the sample. Included in the plot are the three stars for which only upper limits are available for one or both of the quantities. For τ Ceti and ι Per, upper limits to the magnetic filling factor were computed by dividing the magnetic flux upper limits, given in column (4) of Table 2, by an assumed field strength of 1500 gauss and also by the total surface area appropriate for the spectral type, i.e., $f = \phi/(4\pi R^2 B)$. The correlation seen in Figure 6 between magnetic filling factor and log f_x/l_{bol} strongly suggests that late-type stellar corona are indeed related to the underlying photospheric magnetic fields.

The magnetic-related nature of stellar coronae had been suspected previously by several lines of reasoning. First, X-ray images of the sun indicate that most of the coronal gas is confined to arch-like structures, the feet of which are planted on photospheric, magnetic active regions (e.g. Golub 1981). Second, the magnitude, spectral dependence and variation at a

given spectral type of soft X-ray emission from late type dwarfs are inconsistent with the predicted characteristics of pure acoustic waves [Vaiana et al. 1981, but see also Ulmschneider and Bohn (1981) for revisions to acoustic heating theory]. Third, for stars later than G0, soft X-ray emisson correlates well with stellar rotation, suggesting that dynamo-generated magnetic fields serve as the link between the two (Pallavicini et al. 1981, Stern et al. 1981; Walter 1982).

The precise mechanism by which stellar coronae are heated may involve a chain of events beginning with the generation of an mhd wave, its successful propagation through highly stratified plasma, possible coupling to other mhd wave modes, and finally dissipation (e.g. Leibacher and Stein 1981). Though none of these processes are well understood, the scaling arguments developed by Stein (1981) for the production of various mhd waves (presented here in equations 4a, b, c, d) apply equally well to waves destined for the chromosphere or the corona. Unfortunately, the paucity of soft X-ray measurements, as well as the expected variability of coronal flux, do not permit accurate determination of the relationship between f_x/l_{bol} and such quantities as effective temperature, gravity, magnetic field strength and surface filling factor. In any event, an attempt to fit by least squares the observed f_x/l_{bol} ratios with a product of power-law dependencies was made by assuming that coronal emission was linearly proportional to the photospheric, magnetic filling factor, and by ignoring gravity differences among the G and K dwarfs (small, in any case). For the eight stars with measured fields and soft X-ray fluxes (including the sun) the fit to the equation,

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$$\log\frac{f_x}{l_{bol}} = k + a \log B + b \log T_{eff}$$

yielded a = -1.5 ± 1.0 and b = 11.0 ± 5. The field strength dependence of $B^{-1.5\pm1.0}$ is 3 σ from the predicted dependence of B^{-5} for mhd fast-mode generation (equation 4b). However, the observed dependence is consistent with both the slow-mode and Alfven waves (equations 4c and 4d). Because of the extremely limited range in T_{eff} of the few stars in this X-ray sample, the dependence of X-ray luminosity on T_{eff} is essentially undetermined, as is evident by the large formal error in parameter b.

To get a handle on the effective temperature dependence, note the fact that many M dwarfs are seen with $L_x/L_{bol} = 10^{-3}$ to 10^{-4} (Haisch et al. 1980; Vaiana et al. 1981) while the sun has $L_x/L_{bol} = 10^{-6}$ to 10^{-7}. Therefore, if mhd-wave-heating is responsible for coronae, some late-type stars must have photospheric magnetic filling factors that approach unity, to account for the large coronal fluxes. Since at most a factor of 100 may be gained from increasing the filling factor over the solar value of 0.01, the low field strengths seen on some stars may play a supplementary role, consistent with Stein's (1981) theoretical Alfven-wave generation rate that is inversely proportional to field strength (equation 4d). Indeed, Alfven waves are to be favored over slow-mode waves for coronal heating because of the expected high damping rate of all compression waves (as are slow-mode) in the photosphere and lower chromospheres (Schmitz and Ulmschneider 1980a; Leibacher and Stein 1981).

d) Stellar Rotation and Magnetic Fields

To investigate the prediction of most dynamo theories (see Gilman 1982, for a review) that flux generation increases with rotation, the available measurements of equatorial rotation rate for the stars in the present sample are listed in column 10 of Table 2. These rotational velocities were derived from the Ca II H and K periodicities (Vaughan *et al*. 1981), if available, and if not, from measurements of $v \sin i$ reported by Smith (1979) and Soderblom (1982). As Soderblom's measurements are systematically lower than Smith's (for $v \sin i < 5$ km s^{-1}), the bias was removed by multiplying Smith's measurements by 0.70, though the source of their discrepancy is presently unknown. For stars measured by both Smith and Soderblom, the average $v \sin i$ was used, after applying the above-mentioned correction. Finally, the $v \sin i$ measurements were multiplied by $4/\pi$ to correct statistically for inclination angle, so that those measurements would be consistent with the equatorial velocities derived from Vaughan *et al*.

Figure 7a shows a plot of observed magnetic flux against rotational velocity for all nine available stars that have positive field detections and measured rotation rates. We see that the 3 G dwarfs (indicated by circles) are consistent with the notion that rotation enhances magnetic production. The six K dwarfs (indicated by the crosses) seem to exhibit more magnetic flux at a given rotation velocity than the G stars, consistent with the histogram of magnetic area coverage (Fig. 2a) which showed greater coverage, on average, for the K stars.

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Closer examination of the K dwarfs in Figure 7a shows that the far left point, 61 Cyg A, represents spectral type K5, while the others are all K0 to K2. Thus, if a correction is made for spectral type, the magnetic fluxes on the K dwarfs may correlate with rotation as was apparently the case with the G dwarfs. Such a spectral type correction is expected in the framework of dynamo theory, in which the larger convection zones in later type stars would provide a greater volume, longer amplification times, and different convection characteristics for the production of the magnetic fields. Similarly, both chromospheric and coronal emission is seen to increase with later spectral types at a given rotation period (Vaughan et al. 1981; Walter 1981).

This spectral type dependence can be determined, and corrected out of Figure 7a, by performing a two-parameter least-squares fit to the magnetic-flux measurements of the form,

$$\phi = k\, T_{eff}^{a}\, V_{Rot}^{b}$$

The resulting values of the parameters are:

$$a = -2.8 \pm 1.1, \qquad b = 0.55 \pm 0.2 \qquad k = 4.1 \times 10^{10}$$

where ϕ is expressed in 10^{25} gauss-cm^2, T_{eff} in ^{o}K and V_{Rot} in km s^{-1}. The fit was performed without using the data for the sun because its surface magnetic flux is a factor of ten below that of the stars measured here, indicating that it must be considered separately from the magnetically-detectable stars.

The dependence of the surface magnetic flux on effective temperature may now be corrected out of the flux measurements, leaving only the dependence on rotational velocity. Such a correction is shown in Figure 7b, where the temperature dependent term, $-2.8 \log (T_{eff}/T_{\odot})$, is subtracted from the log of the observed magnetic flux (normalized to the solar value), and the resulting quantity is plotted against rotation velocity. For clarity, only the magnetic field detections are shown. Figure 7b shows that the surface magnetic fluxes, corrected for spectral type, indeed increase with increasing stellar rotation rates. The correlation coefficient is 0.84 implying that a random distribution of points would yield such a high correlation less than 1% of the time. The least-squares fit described above indicates that the observed magnetic flux increases with rotation as $V_{Rot}^{0.55}$ as can be roughly verified by the dashed line in Figure 7b that was drawn with a slope of unity.

This deduced dependence of magnetic flux on $V_{Rot}^{0.55}$ is based on eight stars of spectral types G5 to K5, and is 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 early-type G dwarfs are measured.

Finally, it is difficult at this time to interpret the observed dependence of magnetic flux on V_{Rot} and T_{eff} in terms of available dynamo models. Durney and Robinson (1982) 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 subject to magnetic 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, yielding, $B_c \propto \Omega^{1/2}$, where Ω is the angular velocity of the star (See also Skumanich and Eddy 1981). More recently, Gilman (1982) has found that a j x B force acting to suppress differential rotation may play a more significant role as a negative feedback on magnetic-field production. Hopefully, future dynamo calculations will address the above-mentioned effects and will yield predictions of magnetic-field production as a function of rotation rate and stellar mass.

As a final comment, it is puzzling that the sun has a surface magnetic flux that is at least a factor of ten below that expected by the trend in Figure 7b, based mostly on active K dwarfs. It is extremely unlikely that the stellar magnetic field measurements are systematically too high by more than about a factor of two. Furthermore, the magnetic flux measurements of ξ Boo A by both Robinson, Worden, and Harvey (1980) and by Timothy, Joseph and Linsky (private communication) are consistent with those given here, i.e., a factor of about twenty above the sun. Clearly magnetic-field measurements are needed for a greater number of early G stars before we can explain the sun's magnetic field in the context of those on other stars.

e) Magnetic-Field Variability

The disk-integrated magnetic properties of the sun change rather slowly (with the exception, perhaps, of infrequent flares). Such global quiescence clearly is not representative of the surfaces of all "normal", cool main-sequence stars. Variations of order 5 percent in the equivalent width of Ca II H and K emission from ε Eridani (K2V) are apparently common over timescales of 15 min. (Baliunas et al. 1981). Significant changes in the surface magnetic fields on ε Eri from night to night were reported by Timothy, Joseph, and Linsky (1981), and similar variations are suspected in the present magnetic-field data for ε Eri and ξ Boo A. Figure 8 shows magnetic-field data for ε Eri 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 1981 October 1 to 1981 October 2, and then nearly disappeared by October 4. (No data were available for October 3 owing to poor weather.) Since the rotation period of ε Eri is 11 days (Vaughan et al. 1981), these field variations cannot result from active regions rotating across the stellar disk.

Although some magnetic phenomena on the sun evolve on timescales shorter than one day, such as flares and so-called ephemeral active regions, it would be premature to attempt to identify these short timescale stellar changes with some solar process. Baliunas et al. (1981) concluded that the temporal behavior of the Ca II H and K lines was often unlike that seen in solar flares. And the solar ephemeral active regions are too small to provide a direct analogue for the large magnetic-field variations inferred on active stars.

It would be useful to follow both the Ca II H and K lines and the magnetic field continuously for many hours on a given star to determine the temporal relationship between the two. It is not clear, for example, whether a sudden increase in chromospheric emission would be accompanied by increased magnetic fields (owing to recently-surfaced magnetic flux) or by decreased magnetic fields (if the extra chromospheric heating results from field-line reconnection and destruction).

One attempt has been completed thus far to monitor both the magnetic field and the Ca II H and K flux from a late-type star. From 1982 January 28 through 1982 February 1, measurements of the Ca II H and K emission from ε Eri were made at Mount Wilson Observatory while simultaneous observations of its magnetic field were carried out at Lick Observatory. This project was made possible with the cooperation of Dr. Douglas Duncan and the staff of observers devoted to the Ca II H and K monitoring program at Mount Wilson Observatory. The values of the "S" parameter, a measure of the equivalent width of the H and K emission lines, for ε Eri on the 4 dates were as follows: 1/28, 0.483; 1/30, 0.492; 1/31, 0.480; 2/1, 0.516, with no observation on 1/29 owing to bad weather. These H and K measurements represent the mean of several observations made during the night, and the uncertainty in the the mean was never more than 0.004. The coarse interpretation of these Ca II H and K data is that the chromospheric emission was roughly constant until the last night on which a significant increase occurred. The magnetic-field observations (given in Table 1) show a large increase in the field strength on the second-to-last night, to 2850 gauss, from the 700 gauss level on all other nights.

Therefore, the preliminary implication is that the lower chromosphere took no more than 24 hours to fully respond to the appearance of new magnetic flux from the interior. Both the Alfven- and sound-crossing time through the stellar photosphere is less than one hour. However, the timescale over which a section of the lower chromosphere could heat up will depend on the actual rate at which mechanical energy is deposited in the region and on the heat capacity of the local plasma. It is probably premature to interpret in more detail this single observation of chromospheric response to magnetic field change, and further coordinated Ca H and K and magnetic field measurements are planned.

f) Speculations on the Morphology of Magnetic Fields on Active Main-Sequence Stars

There seems to be little doubt that the ways in which magnetic fields manifest themselves on so-called "chromospherically-active" stars, such as ε Eri and ξ Boo A, must be significantly different from the magnetic structures commonly found on the solar surface. Indications of such morphological differences may be inferred from the chromospheric and coronal loss rates that are, on some stars, as much as a factor of 10 greater than those on the sun (see, for example, Linsky 1980). The first-order interpretation of these large non-thermal fluxes suggested by Linsky (1980), Vaiana et al. (1981), Zolcinski et al. (1982), and Gary and Linsky (1981) is that large fractions of the stellar surface must be covered by magnetic regions on the more active stars. Certainly the magnetic filling factors

presented here (albeit model-dependent) also imply that large fractions of the photospheres on active stars are embedded in magnetic fields. Therefore, the morphology of solar magnetic fields, viz., a light peppering of isolated, unresolvable magnetic elements, cannot serve to characterize the surfaces of all G and K dwarfs.

Large-scale structure must exist in the surface distribution of magnetic regions on the active stars to account for the rotational modulation in both broad-band photometry and in the Ca II H and K lines (i.e., Rucinski 1980; Vaughan et al. 1981). This magnetic structure must have a spatial scale that is a significant fraction of a stellar radius (10-50%), because smaller structures placed uniformly over the surface would not produce such visible Ca II H and K modulations.

These larger structures must however have smaller structures within them in order to account for the lack of circular polarization in Zeeman-sensitive lines reported by Vogt 1980, Brown and Landstreet 1981, and Borra and Mayor, personal communication. This apparent cancellation of circular polarization is almost certainly caused by small-scale bipolar magnetic regions which produce equal contributions of opposite polarization to a given displaced σ-component in a Zeeman triplet. Evidently, the large structures that produce the Ca II H and K rotational modulation must be comprised of at least several locally bipolar magnetic regions.

This picture of large magnetic structures made up of bipolar regions is not unlike that found on the solar surface where we see the so-called "activity complexes", described by Bumba and Howard (1965). These are collections of distinct bipolar regions which appear at about the same time

and at the same general longitude and latitude. Some evidence suggests that the solar activity complexes, sometimes refered to as "active longitudes", persist for several years (e.g., Dodson and Hedeman 1975; Svalgaard and Wilcox 1975).

Noyes (1981b) and Baliunas (1982) have reported possibly analogous persistence, of duration at least one year, in the phase of the periodicity of Ca II H and K emission from some active dwarfs. If the large-scale magnetic structures on other stars are the counterparts of solar activity complexes, they must be much more densely packed with bipolar magnetic units to account for the large magnetic filling factors and large chromospheric fluxes on active stars. Further, such large filling factors may not be consistent with the constraint that stellar active regions be confined to narrow bands in latitude centered about the star's equator, as on the sun.

Indeed, there is growing evidence of considerable magnetic flux at high latitudes on late-type stars. The spectrum of ε Eri shows very narrow absorption lines, implying a V sin i of less than 1.5 km s^{-1} (M. Smith, personal communication). Yet its rotation period of 12 days measured from H and K line-periodicity (Vaughan et al. 1981) dictates an equatorial velocity of about 3.5 km s^{-1}, implying an inclination of about 25°. Therefore, the large filling factor of active regions seen on this nearly pole-on star suggests that significant amounts of magnetic flux reside at high latitudes. A similar case exists for the narrow-lined star ξ Boo A which has a reported photometric periodicity of 11 days (Rucinski 1980), and a Ca II H and K periodicity of 6 days (Vaughan, personal communication). In this connection, it is interesting that a growing body of observations of spotted

stars, the BY Dra and RS CVn members, suggests that the dark regions are commonly located at high latitudes and drift poleward (Vogt 1982). This apparent existence of considerable magnetic flux at high latitudes on active dwarfs contrasts with the sun on which less than 10% of its flux emerges at latitudes greater than 50°.

Considering the evidence cited in this section, along with the short timescale variability in magnetic activity stressed by Baliunas et al. (1981), it is increasingly difficult to interpret the active main-sequence stars as simply stars having more solar-type, quiescent faculae on the surface. This apparent gap in the solar-stellar connection may be bridged by studies of solar phenomena that are reminiscent of phenomena found on active stars. In particular, further study is needed of the birth and evolution of activity complexes on the sun. Also, the mechanism by which large amounts of solar flux vanish on timescales as short as one day (Wallenhorst and Howard 1982) must be determined. Finally, the "transport" of active regions poleward on the sun (Howard and LaBonte, 1981) may be related to the apparent presence of magnetic flux at the poles of active stars.

VI. SUMMARY

An attempt has been made here to detect and measure magnetic fields on G and K stars by searching for excess broadening in an absorption line that is very sensitive to Zeeman splitting. Among the 29 main-sequence stars observed, 19 showed Zeeman broadening, and a simple line-profile analysis has been applied which yields the characteristic magnetic-field strength and the fraction of the stellar surface that contains fields. The main results of this study are as follows:

1. Magnetic-field strengths on G and K main-sequence stars range from below 1 kilogauss to 3 kilogauss, compared with the solar value of about 2 kilogauss. No systematic difference is found between the field strengths of the G and K dwarfs. Thus the higher photospheric gas pressures on the K dwarfs has not resulted in higher magnetic-field pressures, as might be expected on the basis of some models of magnetic flux tubes on the sun.

2. Chromospheric emission in the Ca II H and K lines varies as the square root of the magnetic field strength and as the square of the effective temperature. These dependences are consistent, within the errors, with the predicted dependences derived by Stein (1981) for mhd-wave heating of the lower chromosphere only if slow-mode waves (magnetically-channeled acoustic waves) provide most of the heating.

3. Coronal soft X-ray fluxes correlate well with the measured fraction of the stellar surface covered by fields, and vary with field strength as $B^{-1.5}$, for the few available stars. This dependence is consistent with that predicted by Stein (1981) for Alfven-wave generation rates, though details

of transmission and dissipation of the waves have not been considered.

4. Surface magnetic fluxes vary as the square-root of rotational velocity and as $T_{eff}^{-2.8}$ for the eight G5 to K5 dwarfs having available magnetic and rotational measurements. Measurements of chromospheric emission in the Ca II H and K lines suggest that magnetic fluxes for G0 dwarfs vary roughly linearly with rotation rate. These dependences are not consistent with the one dynamo model which offers a specific prediction.

5. The stellar magnetic fields are found to be variable on timescales as short as one day for the two well-monitored, chromospherically-active stars.

6. Speculation on the morphology of the magnetic fields on the more active stars is made based on the rotational modulation of magnetic diagnostics, the lack of Zeeman-induced circular polarization, and the large magnetic fluxes found on nearly pole-on stars. Such considerations imply the presence of large magnetic structures composed of smaller, bipolar regions. These surface fields are apparently not confined to equatorial bands, as on the sun.

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Table 1

Journal of Observations

HD	HR	Name	sp.	U.T. Date	CAT 3 m	B (gauss)	Fill Factor	Flux (10^{25}Mx)	Note
166	8	--	K0Ve	8/29/80	3m	2250	0.41	4.06	*
"				1/9/81	CAT	2000	0.27	2.38	
4614	219	η Cas A	G0V	10/1/81	CAT	N	N	< 2.0	
10700	509	τ Ceti	G8Vp	8/28/80	3m	N	N	< 1.2	
"				8/19/81	3m	N	N	< 1.3	
19373	937	ι Per	G4V	10/2/81	CAT	N	N	< 1.4	
20630	996	κ Ceti	G5Ve	2/5,6/81	CAT	-	-	-	*
"				1/31/82	CAT	1000	0.73	3.86	
22049	1084	ε Eri	K2Ve	9/22/80	CAT	780	0.87	2.60	
"				1/8/81	CAT	750	0.86	2.47	
"				10/1/81	CAT	1910	0.30	2.20	
"				10/2/81	CAT	2000	0.32	2.45	
"				10/4/81	CAT	670	0.89	2.29	*
"				10/5/81	CAT	750	0.76	2.18	
"				1/28/82	CAT	620	0.88	2.09	
"				1/30/82	CAT	700	0.88	2.36	*
"				1/31/82	CAT	2850	0.20	2.18	*
"				2/1/82	CAT	670	0.78	2.00	*
26965	1325	40 Eri A	K1Ve	8/28/80	3m	1850	0.24	1.81	
75732	3522	55 Cnc	G8V	4/12/81	CAT	N	N	< 0.76	
76151	3538	--	dG3	1/8/81	CAT	750	0.77	3.37	*
78366	3625	--	dG0e	4/10/81	CAT	-	-	-	*

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Table 1 (cont.)

HD	HR	Name	sp.	U.T. Date	CAT 3 m	B (gauss)	Fill Factor	Flux (10^{25}Mx)	Note
97334	4345	—	G0V	3/6/81	CAT	N	N	<5.2	*
98230	4374	ξ UMa B	G0Ve	2/16/81	3m	1660	0.37	4.09	
98231	4375	ξ UMa A	G0Ve	2/16/81	3m	2990	0.16	3.19	
101501	4496	61 UMa	G8Ve	4/11/81	CAT	915	0.75	3.31	
"				5/8/82	3m	N	N	<0.90	*
114710	4983	β Com	G0V	2/1/82	CAT	N	N	<1.4	
115383	5011	59 Vir	G0V	5/3/81	CAT	N	N	<4.5	
131156A	5544A	ξ Boo A	G8V	5/7/80	3m	N	N	<0.94	
"				5/27/80	3m	N	N	<0.51	
"				6/24/80	3m	N	N	<1.3	
"				6/25/80	3m	1000	0.69	3.33	
"				6/26/80	3m	N	N	<0.72	
"				1/8/81	CAT	750	0.86	3.11	
"				1/9/81	CAT	880	0.85	3.61	*
"				2/5/81	CAT	1250	0.63	3.80	
"				2/6/81	CAT	1500	0.55	3.98	
"				4/10/81	CAT	N	N	<2.1	
"				4/12/81	CAT	N	N	<1.7	
"				10/4-5 1981	CAT	1250	0.41	2.47	
131156B	5544B	ξ Boo B	K4Ve	6/4/81	CAT	670	0.73	1.67	
131511	5553	—	K1V	6/5/81	CAT	1000	0.52	2.13	
131977	5568	—	K5Ve	6/3/81	CAT	1000	0.66	2.20	
149661	6171	12 Oph	K0Ve	7/6/81	CAT	580	0.87	2.22	*
"				7/14/81	CAT	750	0.87	2.87	*

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Table 1 (cont.)

HD	HR	Name	sp.	U.T. Date	CAT 3m	B (gauss)	Fill Factor	Flux (10^{25}Mx)	Note
155885	6401	36 Oph B	K1Ve	7/15/81	CAT	670	0.76	2.08	
155886	6402	36 Oph A	K1Ve	7/16/81	CAT	2080	0.25	2.13	
165341	6752	70 Oph A	K0Ve	8/29/80	3m	750	0.73	2.41	
"				9/22/80	CAT	920	0.63	2.55	
"				6/3/81	CAT	1750	0.30	2.31	
185144	7462	σ Dra	K0V	8/19/81	3m	1160	0.32	1.63	
190406	7672	15 Sge	G1V	10/5/81	CAT	N	N	<2.5	
201091	8085	61 Cyg A	K5Ve	8/28/80	3m	2660	0.30	2.66	
"				7/16/81	CAT	3240	0.25	2.70	
206860	8314	--------	dG0e	8/19/81	3m	N	N	----	*
219134	8832	--------	K3V	10/4/81	CAT	670	0.72	1.78	

Notes to Table 1

HR	Comment
8	The chi-square statistic has a weak minimum at B=1100 gauss on 8/29/80
996	The Zeeman-sensitive line, λ6173, has an enhanced red wing prohibiting analysis.
1084	The chi-square statistic for the profile analysis has a weak local minimum at B=2300 gauss on 10/4/81. Similar weak chi-square minima occur at strengths 2000, 800, and 1800 gauss on 1/30/82, 1/31/82 and 2/1/82, respectively.
3538	A weak local minimum in chi-squared was found at B=1800 gauss.
3625	λ6173 was slightly narrower than λ6240.6. The star is not a spectroscopic binary to my knowledge.
4345	Only poor quality line profiles obtained (S/N=40). The lines look shallow.
4496	The observation on 5/8/82 was made using λ6842.6 and λ6843.6 as Zeeman-sensitive and -insensitive profiles.
5544A	A weak local minimum in chi-squared found at b=1700 gauss.
5544B	A weak local minimum in chi-squared found at B=2800 gauss.
6171	The observations on both 7/6/81 and 7/14/81 show enhanced red wings on the Zeeman-sensitive line, λ6173.
8085	Astrometric Binary, a=0".010, P=4.8 yrs. (Strand, 1957).
8314	No meaningful upper limit to magnetic flux was possible owing to a combination of low quality data (S/N=50), and broad, shallow lines.

Table 2

Average Magnetic-Field Values and Related Parameters

HD	avg. B (gauss)	avg. fill factor	avg. Flux (10^{25} Mx)	avg. S_{HK}	V-R	F'(H+K) (10^{+5} erg/s/cm^2)	log T_{eff}	f_x/l_{bol} ($\times 10^{-7}$)	V_{Rot} (km s^{-1})
166	2125	0.34	3.18	0.486	0.63	25.2	3.735	---	---
4614	N	N	<2.0	0.159	0.50	17.2	3.753	---	2.87[g,h]
10700	N	N	<1.2	0.170	0.62	9.93	3.729	<4.0[a]	2.51[g,h]
19373	N	N	<1.4	0.152	0.53	13.8	3.773	3.8[b]	4.46[g]
20630	1000	0.73	3.86	0.351	0.57	26.4	3.753	---	5.54[i]
22049	1170	0.67	3.14	0.529	0.72	16.3	3.707	150.[a]	3.48[i]
26965	1850	0.24	1.81	0.203	0.69	8.60	3.720	10.1[e]	---
75732	N	N	<0.76	0.186	0.73	7.02	3.716	---	---
76151	750	0.77	3.37	0.258	0.53	24.54	3.752	---	---
78366	---	---	---	0.245	0.47	33.9	3.773	---	---
97334	N	N	<5.2	0.322	0.49	40.1	3.767	---	5.73[g]
98230	1660	0.37	4.09	0.445	0.54	40.7	3.763	200.[d]	---
98231	2990	0.16	3.19	0.175	0.54	15.3	3.783	---	---
101501	915	0.75	1.88	0.301	0.61	17.9	3.739	---	---

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Table 2 (cont.)

HD	avg. B (gauss)	avg. fill factor	avg. Flux (10^{25}Mx)	avg. S_{HK}	V-R	F'(H+K) (10^{+5}erg/s/cm^2)	log T_{eff}	f_x/l_{bol} ($\times10^{-7}$)	V_{Rot} (km s^{-1})
114710	N	N	<1.40	0.202	0.49	24.0	3.778	40.0[c]	5.32[g,h]
115383	N	N	<4.5	0.312	0.47	44.2	3.773	---	7.20[g,h]
131156A	1105	0.67	2.00	0.602	0.63	31.0	3.748	280.[f]	4.40[j]
131156B	670	0.73	1.67	1.160	0.85	15.5	3.682	140.[f]	---
131511	1000	0.52	2.13	0.368	0.69	14.0	3.716	79.[f]	---
131977	1000	0.66	2.20	---	0.99	---	3.665	---	---
149661	665	0.87	2.54	0.339	0.61	20.1	3.729	---	2.06[i]
155885	670	0.76	2.08	0.408	0.70	14.5	3.707	---	1.80[i]
155886	2080	0.25	2.13	0.356	0.70	12.9	3.707	---	2.01[i]
165341	1140	0.55	2.76	0.384	0.65	18.0	3.725	61.[a]	2.94[h]
185144	1160	0.32	1.63	0.233	0.65	11.5	3.716	---	---
190406	N	N	<2.5	0.188	0.50	20.8	3.765	---	3.66[i]
201091	2950	0.28	2.76	0.647	1.03	5.82	3.642	33[a]	1.01[i]
206860	N	N	---	0.318	0.48	42.3	3.772	---	---
219134	670	0.72	1.78	0.235	0.83	6.09	3.681	---	---
Sun	1500	0.01	0.09	0.223	0.53	9.26	3.761	1.6[b]	1.97[k]

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Notes to Table 2

a) Johnson (1981)

b) Pallavacini *et al.* (1981)

c) Ayres *et al.* (1981a)

d) Walter (1982)

e) Vaiana *et al.* (1981)

f) Guest observer Einstein measurements of Vogt, Walter, and Marcy, unpublished. See text for details.

g) Soderblom (1980)

h) Smith (1979)

i) Vaughan *et al.* (1981)

j) Rucinski (1980)

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Figure 4. The fraction of the total stellar luminosity that is carried by chromospheric Ca II H and K emission versus the "best fit" function of field strength, B, effective temperature, T_{eff}, and magnetic filling-factor, f. The larger circles represent stars with more than one magnetic-field measurement. The 45° line represents the best-fit relationship.

Figure 5. Same as Figure 4, (with surface gravity included), except that the abscissa is proportional to the theoretically expected Alfven-wave heating rate as a function of B, T_{eff}, and gravity, g (Ulmschneider and Stein 1982). The poor correlation of this function with Ca II H and K flux suggests that Alfven-waves are not the primary source of energy for the lower chromosphere.

Figure 6. Log of the ratio of soft X-ray flux to bolometric flux versus the fraction of the stellar surface covered by magnetic fields.

Figure 7. a) Magnetic flux vs. equatorial velocity. Crosses represent K dwarfs, circles represent G dwarfs. b) Log magnetic flux, normalized to the sun, and corrected for the T_{eff} dependence in observed flux plotted versus log of the equatorial velocity. The dashed line indicates the slope for a strictly linear dependence on V_{Rot}.

Figure 8. Magnetic-field data for ε Eri as in Figure 1. Changes seen in the difference profile suggest that the magnetic fields are variable on time scales of one day.

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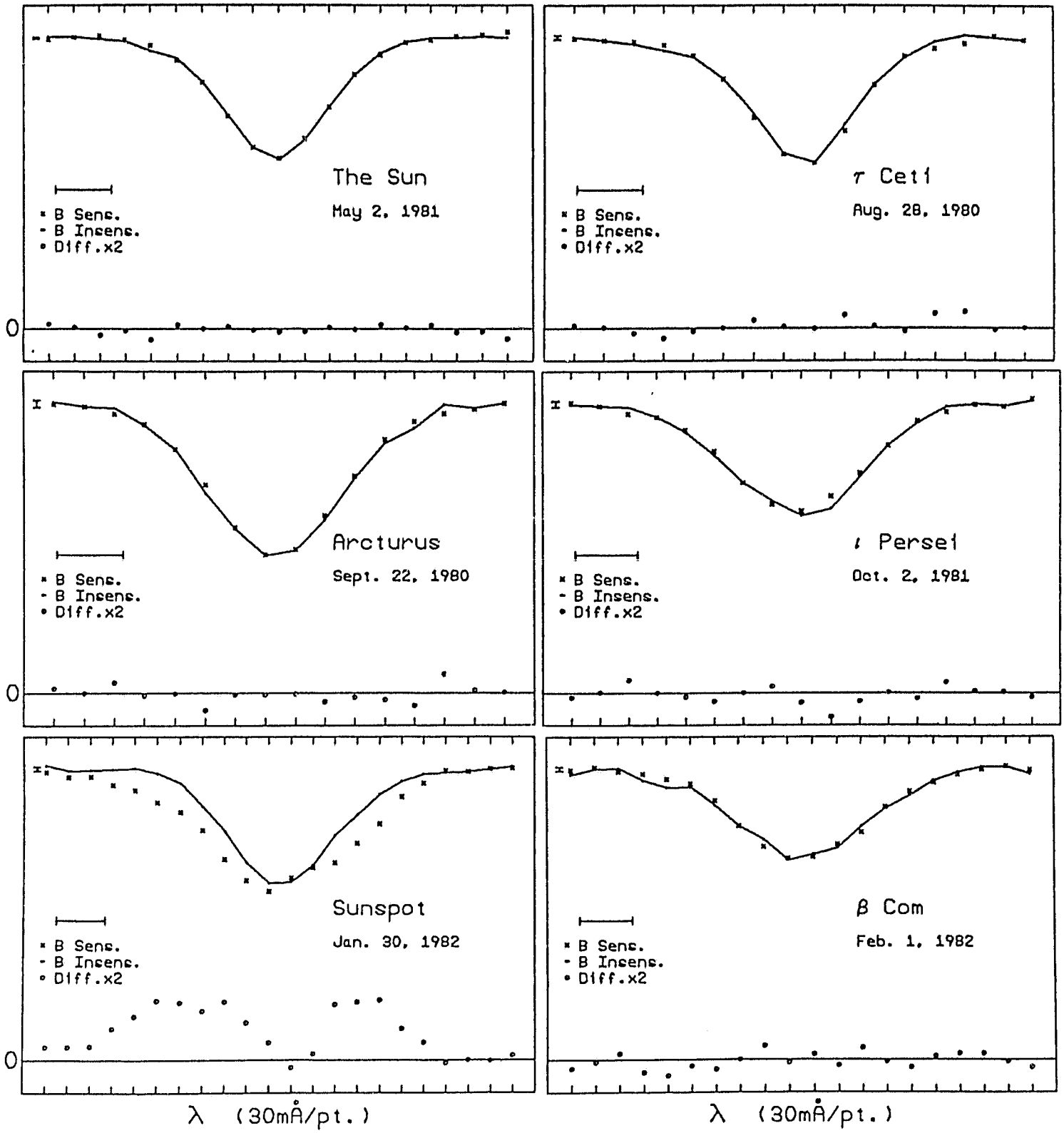

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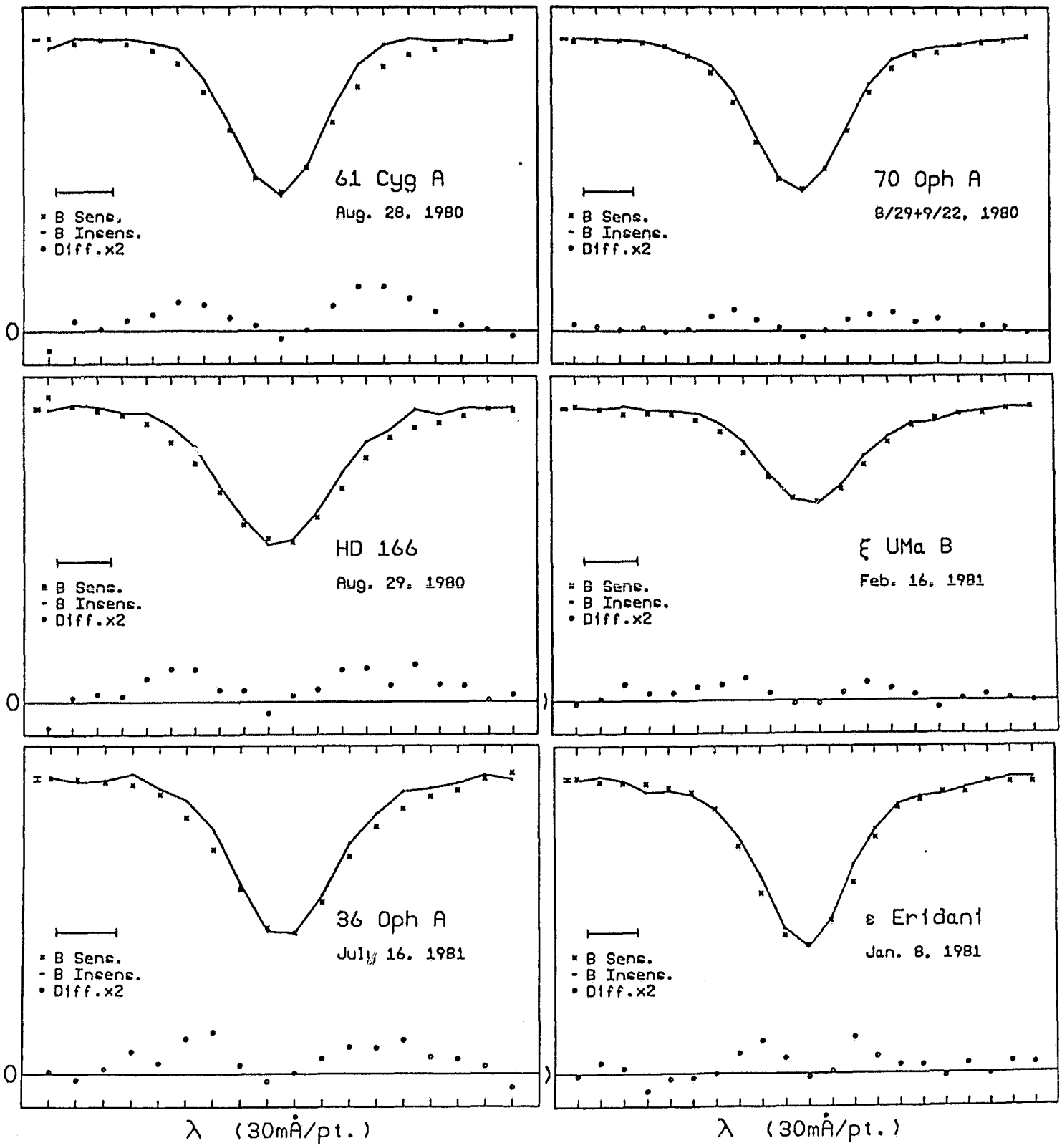

FIGURE 1b

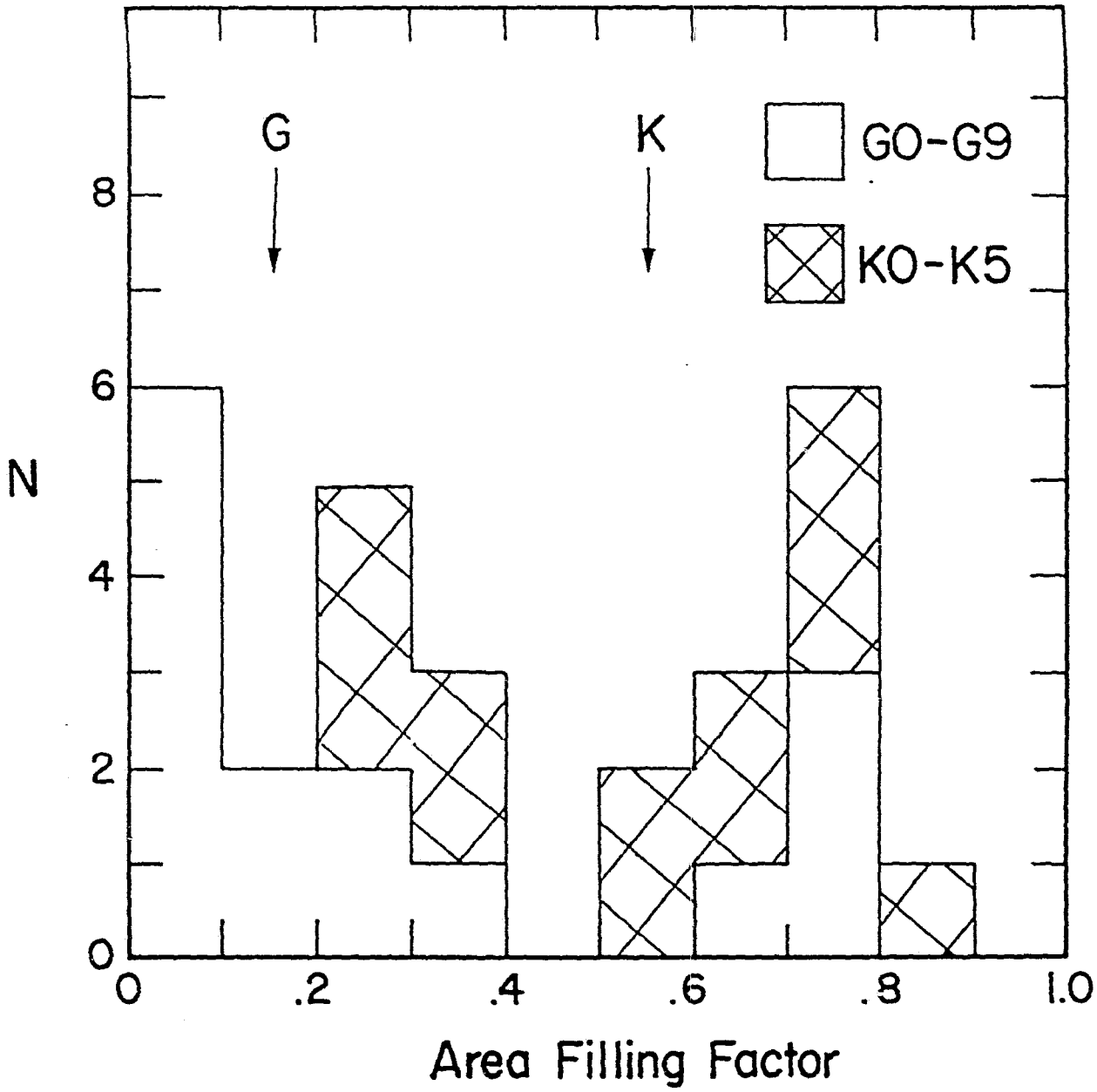

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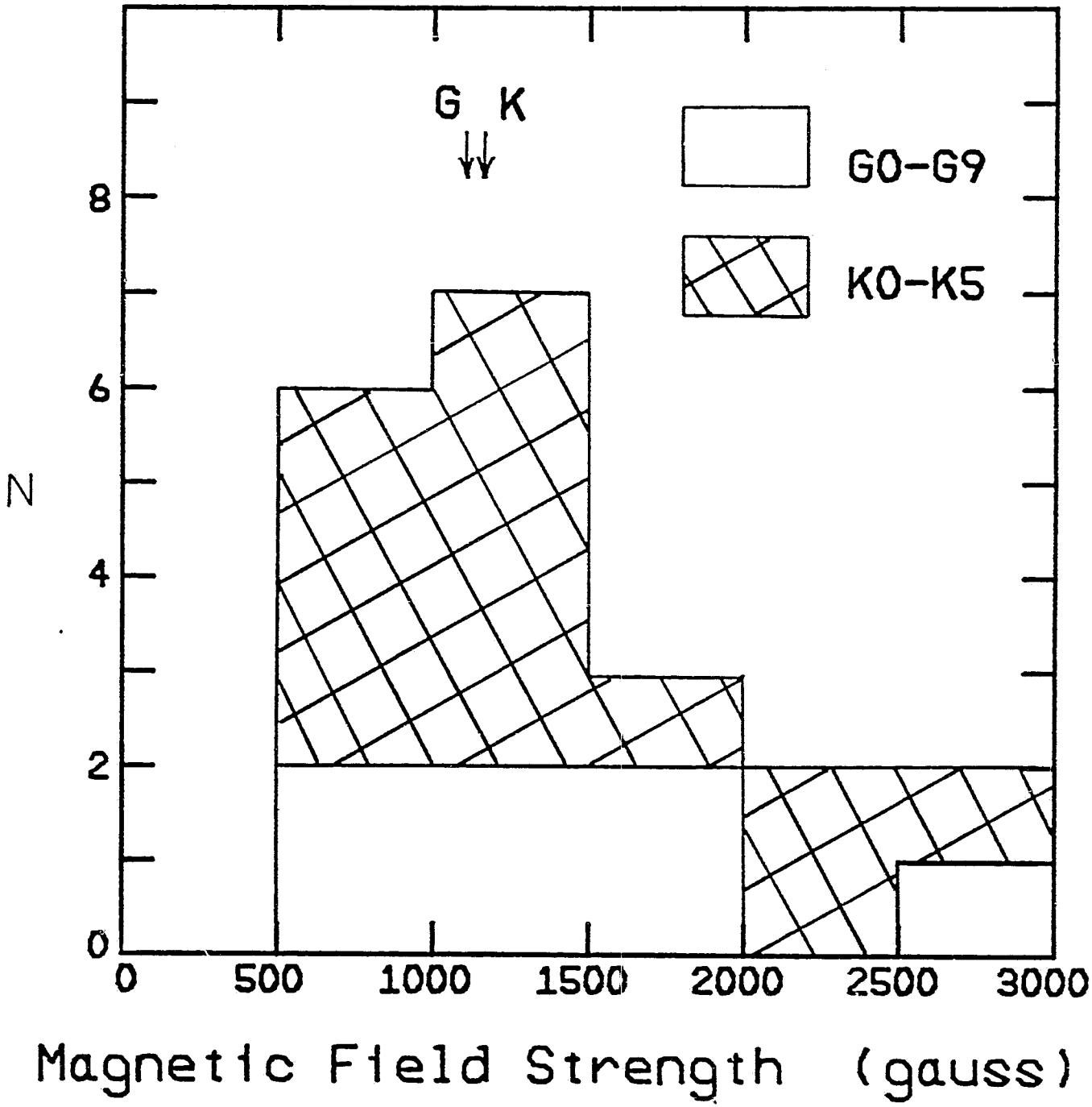
FIGURE 2a



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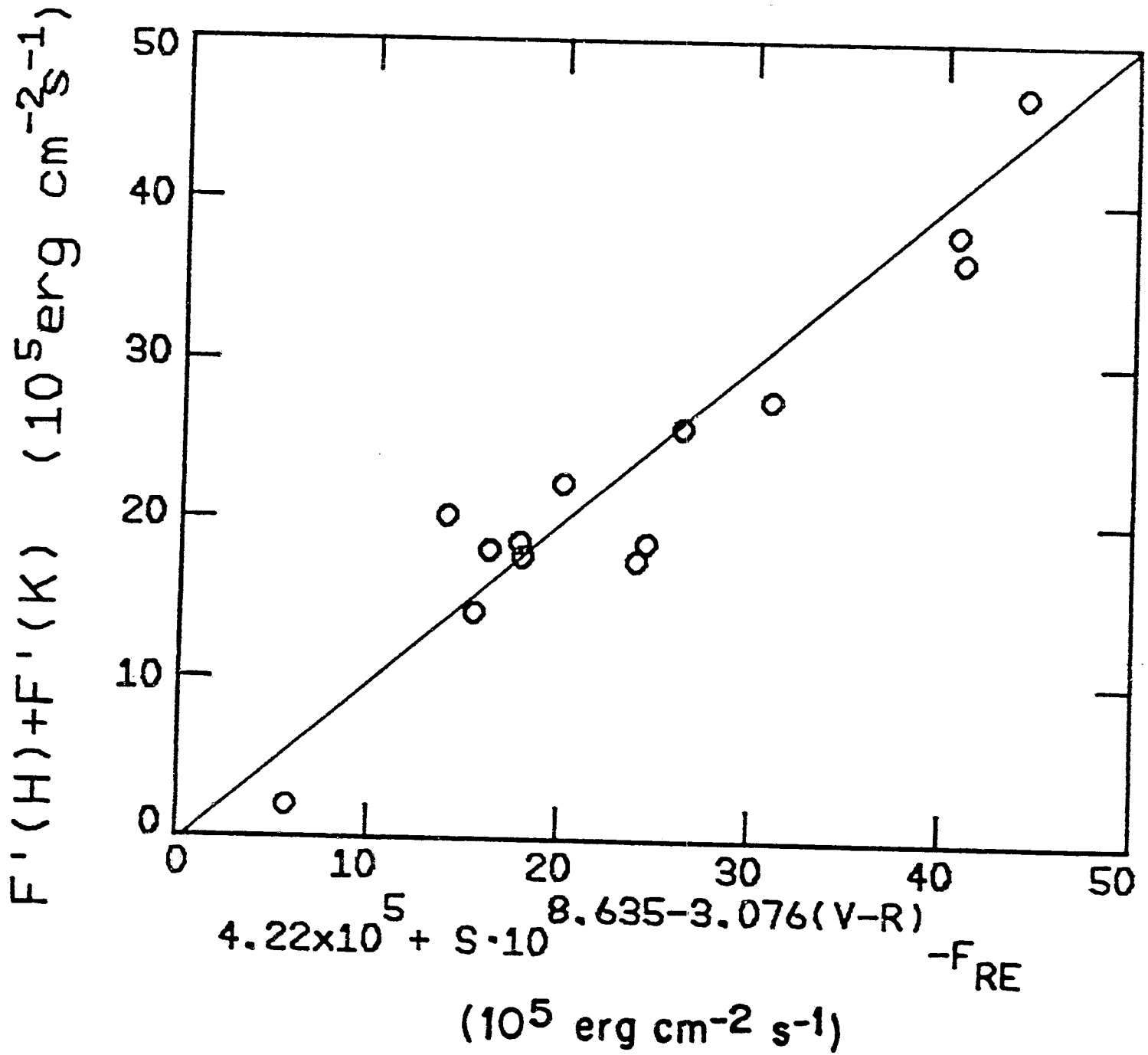

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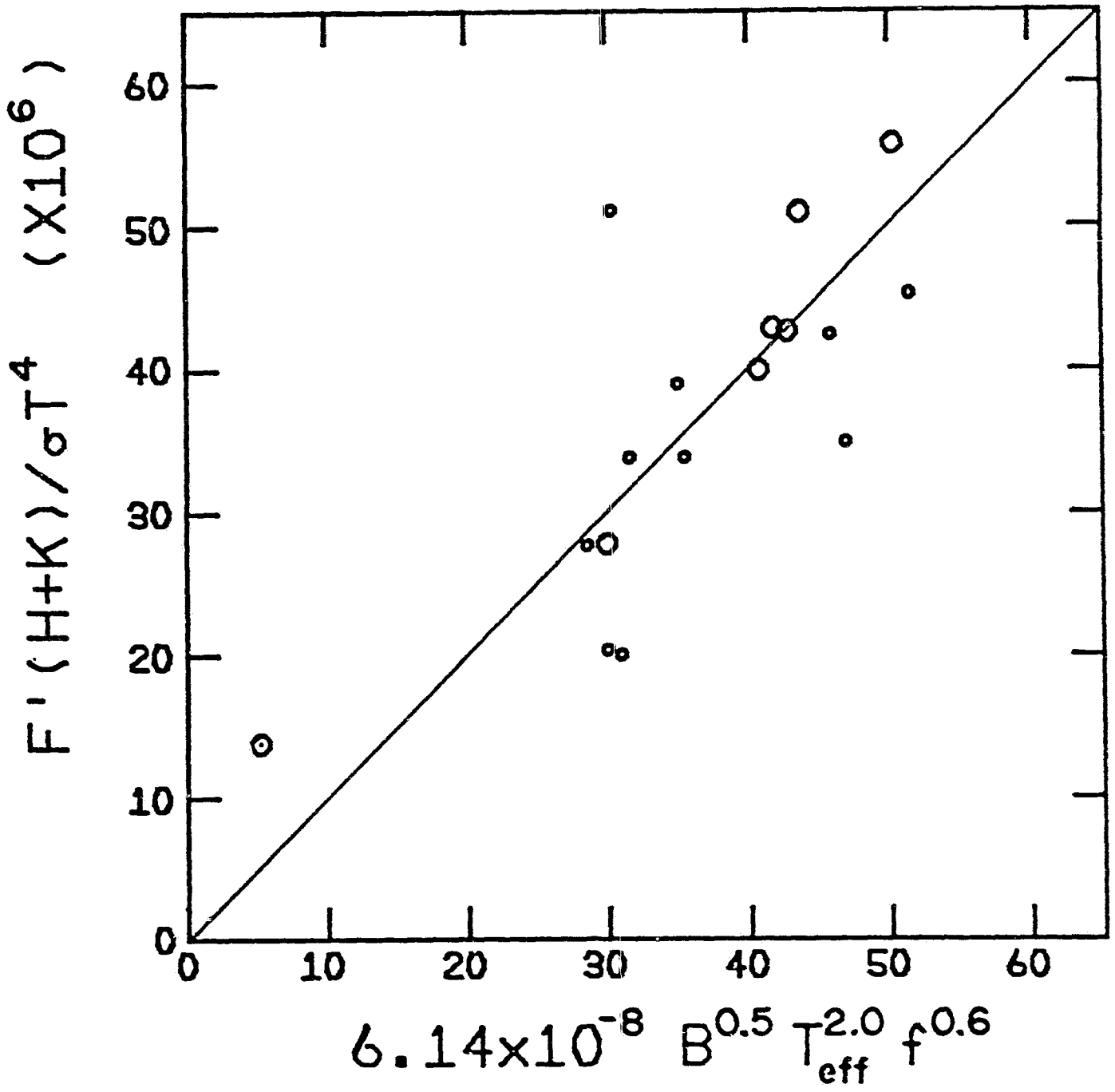

FIGURE 4

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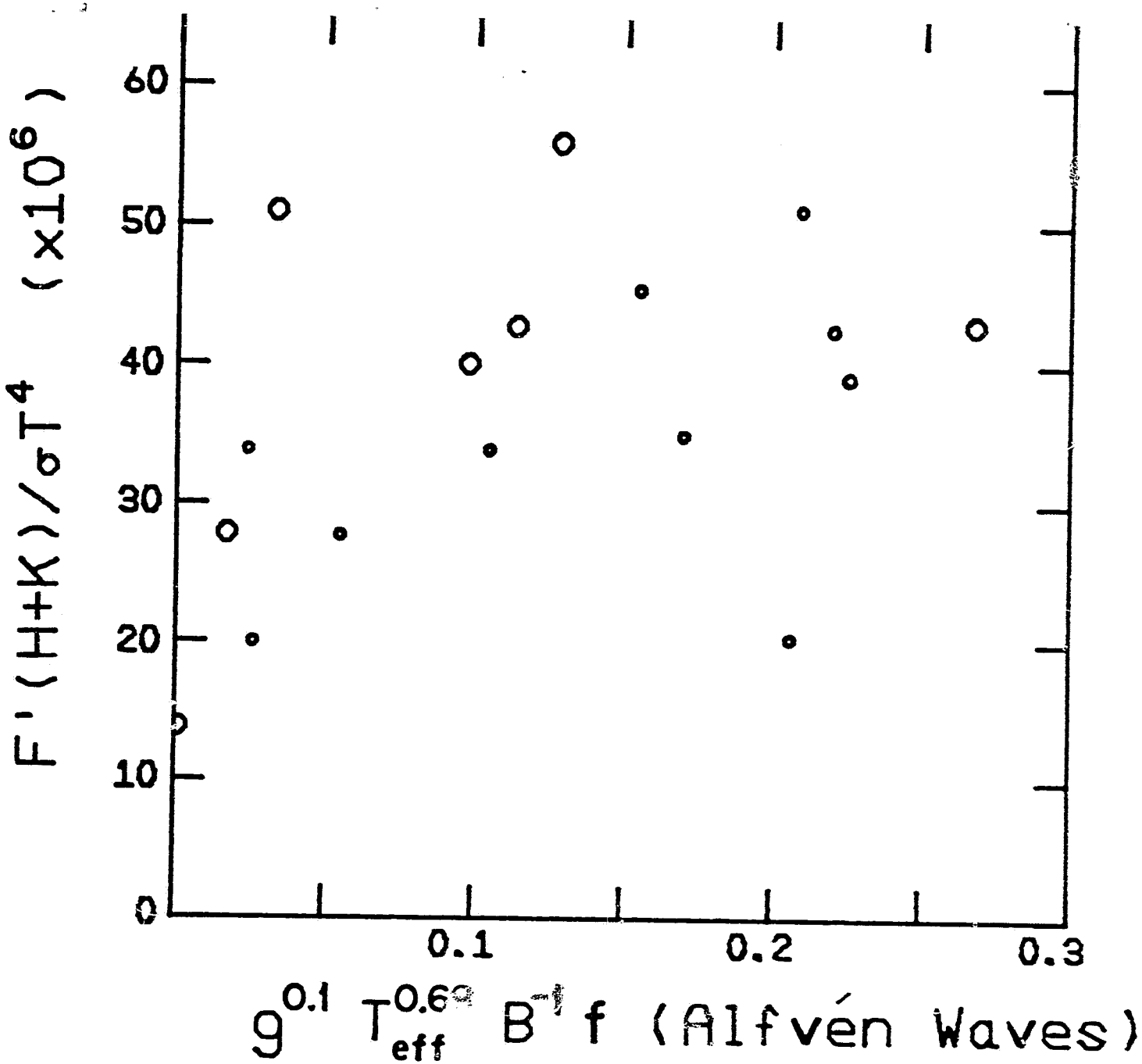
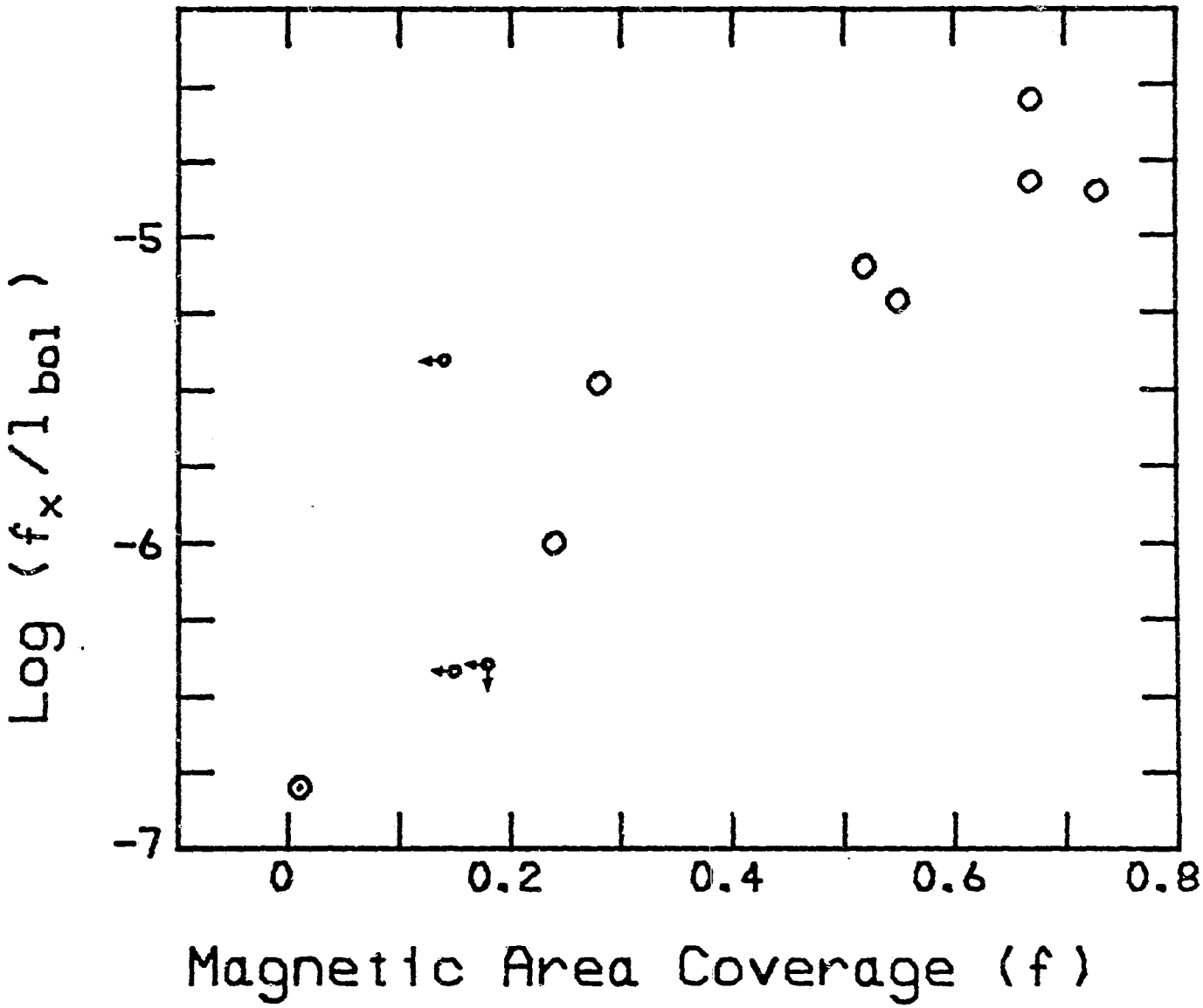


FIGURE 5



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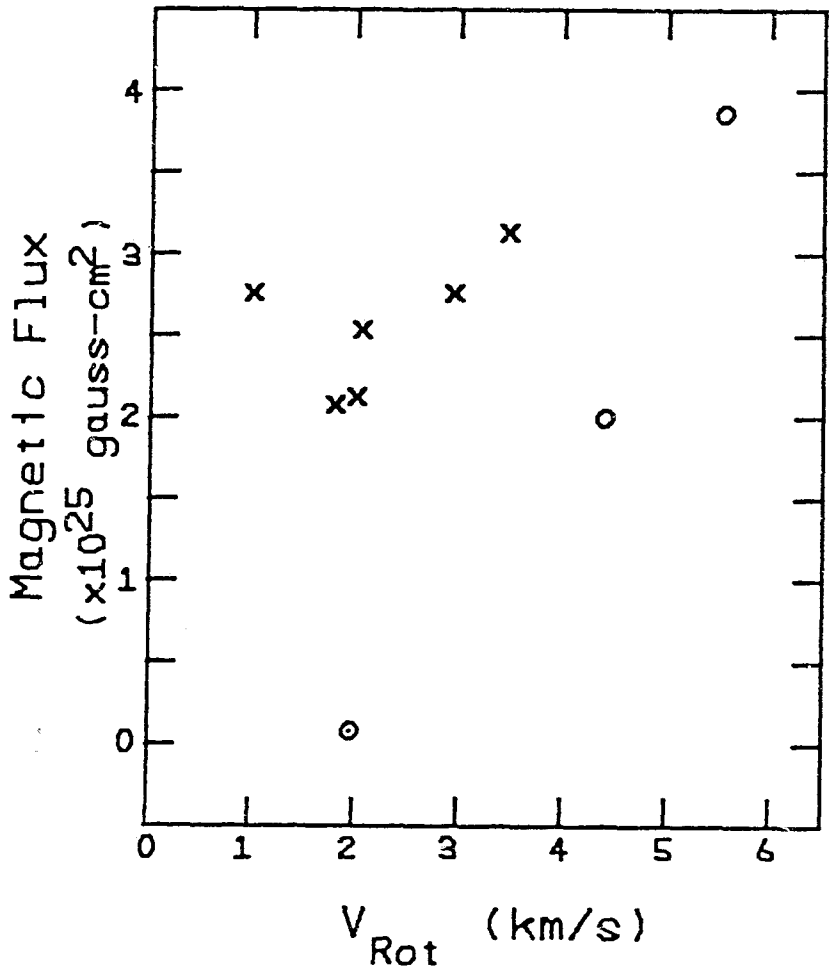

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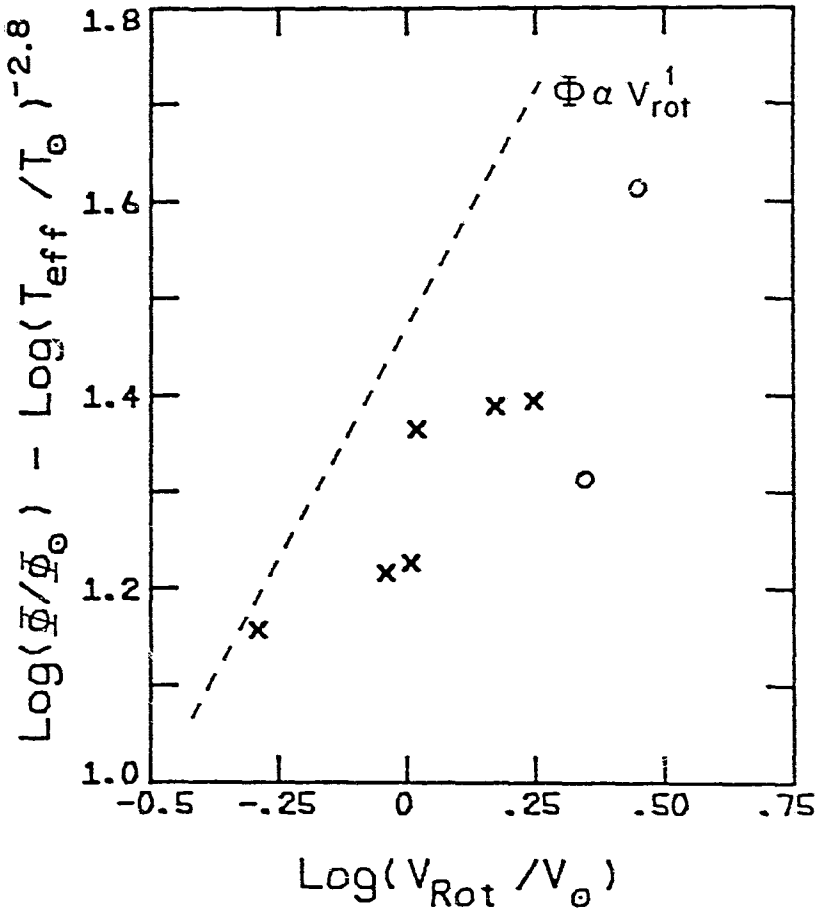

(b)

FIGURE 7

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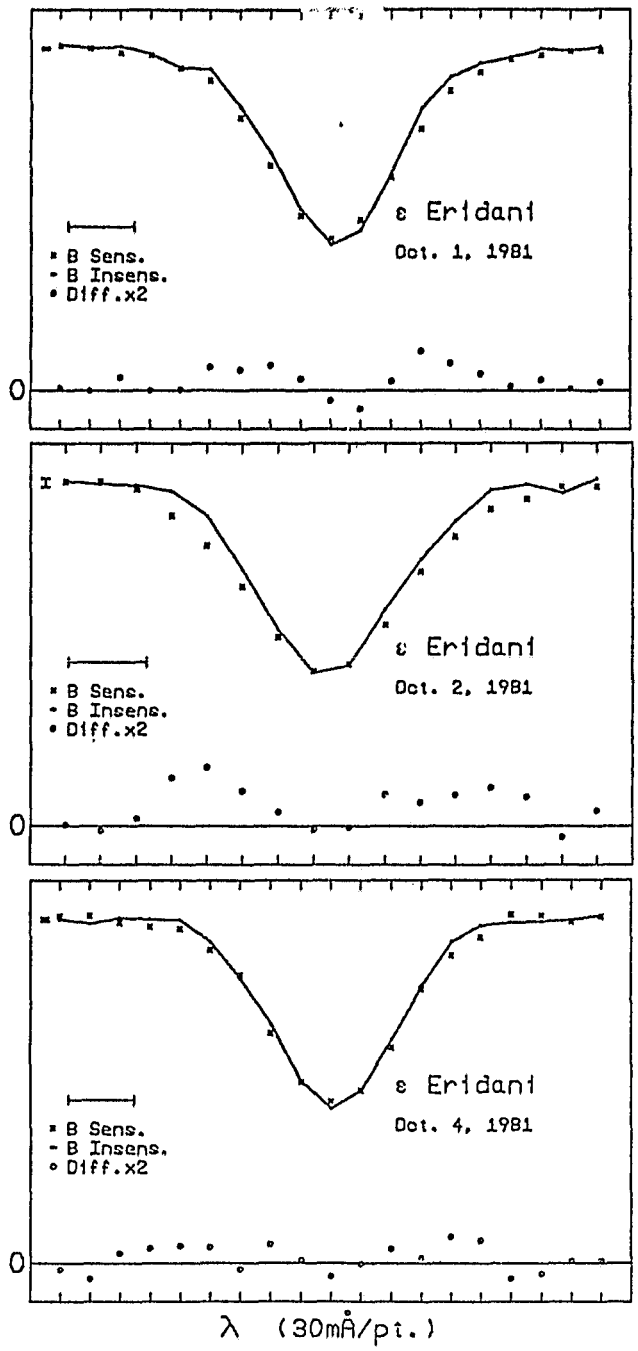

FIGURE 8