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ZEEMAN ENHANCEMENT OF LINES IN EXTREMELY ACTIVE K DWARFS

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ABSTRACT

We have searched for the predicted enhancement of the equivalent widths of Zeeman-sensitive lines in five chromospherically active K dwarfs, by direct comparison with inactive dwarfs of similar spectral type. In two active stars, EQ Vir and HD 82558, the equivalent widths indeed exhibit enhancements (of up to 30%) which correlate with the Zeeman sensitivity of the individual lines. HD 17925 barely shows the effect, and ϵ Eri does not show it. The amount of the Zeeman effect is related to the enhancement of the emission cores of the Ca II infrared triplet lines. Radiative transfer models including magnetic fields permit estimates of Bf, the product of field strength (B) and surface filling factor (f). Our detections imply $Bf \approx 2kG - 3kG$, in agreement with Saar. Difficulties in predicting line strengths from active stars arise due to surface inhomogeneities. These render the method ineffective in our most active case, Gl 171.2.

Subject headings: line: profiles — stars: activity — stars: atmospheres — stars: late-type — stars: magnetic fields — techniques: spectroscopic

1. INTRODUCTION

During the past decade, detection of Zeeman broadening in the spectra of G, K, and M main-sequence stars has demonstrated that magnetic fields strongly influence the physics of stellar atmospheres. Magnetic coverage on stars correlates with the presence of chromospheres, coronae, "starspots," and flares (e.g., Marcy & Basri 1989; Saar 1991), but detailed descriptions of the relevant MHD processes as a function of stellar type require further work (see proceedings edited by Ulmschneider et al. 1991). Stellar magnetic fields also correlate with rotation, suggesting a dynamo connection, but predictive dynamo models remain elusive (Schrijver 1992).

Those cool stars that are most magnetically active provide the best opportunity to determine empirical relationships that bear on dynamos and magnetic atmospheres because of their easily measured activity diagnostics. Also useful is the variability in these diagnostics which occurs on timescales of minutes to decades, caused by flares, surface inhomogeneities (seen during rotation), and magnetic (spot) cycles (Saar & Baliunas 1992; Saar, Piskunov, & Tuominen 1992). Variability in an individual star potentially yields the dependence of activity diagnostics on magnetic fields directly, and demands only differential analyses. Unfortunately, the rapid rotation of these very active stars produces Doppler line broadening which obscures the Zeeman broadening.

The Zeeman effect is nonetheless detectable in absorption lines because Zeeman splitting lowers the optical depth at line center while raising it in the line wings. This reduces the "saturation" effect at line center, thereby enhancing the equivalent width (Unno 1956; Basri, Marcy, & Valenti 1992, hereafter Paper I). Here we consider several very active field K dwarfs and search for enhancement of equivalent widths caused by the Zeeman effect. Saar (1991), and Saar et al. (1992) have attempted several Zeeman measurements of these stars, mostly using a single optical Zeeman-sensitive line, λ6173. Measured values of Bf lie in the range 1–3 kG for the most active K dwarfs. These magnetic measurements require confirmation because the Zeeman effect is small and analysis of a single line may suffer from blends and modeling errors.

2. OBSERVATIONS

2.1. *Targets and Observations*

A sample of very active K dwarfs was selected from Strassmeier et al. (1990), Rutten et al. (1991) and Saar (1991), with the primary criteria being (1) extreme activity, gleaned from chromospheric or coronal diagnostics, or periodic photometric modulation, (2) single stars or SB1 (no lines from a companion), (3) brighter than $V = 9$ to permit $S/N = 100$ in high-resolution spectra, and accessible to northern latitudes. The final stars, given in Table 1, are representative of the most active K dwarfs known to exist in the field (Rutten et al. 1991).

Also shown in the lower half of Table 1 are four nonactive stars, as determined from low Ca II H and K emission, slow rotation (Noyes et al. 1984) and our observations of the Ca II IR triplet. All active stars show clear emission or filling-in of the Ca II IR triplet lines, as shown in Figure 1, compared to the nonactive stars. The selected active stars have rotation periods less than 7 days, except for ϵ Eri, the least active, which has $P_{\rm rot} = 11.3$ days. The nonactive stars all have rotation periods longer than $\sim$30 days as suggested either by Ca II modulation (Noyes et al. 1984) or by the observed narrowness of the absorption lines.

All stars were observed with the "Hamilton" echelle-CCD spectrometer using the Lick Observatory 3 m Shane telescope (Vogt 1987). By using a Ford-Aerospace 2048 × 2048 CCD, we acquired the wavelength region from λ3800–λ9000 Å in a single exposure, at a resolution, $\lambda/\Delta\lambda = 47{,}000$. The signal-to-noise ratio in the spectra is about 150 for the standard stars, ϵ Eri, and HD 17925, just over 100 for Gl 171.2 and EQ Vir, and about 80 for HD 82558. The exposure times were 1–2 hours. The raw CCD data were reduced in the usual way, with a package written in IDL by J. Valenti: all images were dark subtracted, corrected for scattered light by using the inter-order signal, flat-fielded (with special attention to treatment of CCD-induced interference fringes), and spectral orders extracted and converted to one-dimensional spectra. Wavelength calibration was accomplished with an exposure of a

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TABLE 1

PROGRAM K DWARFS

Gliese	Name	Spectral Type	$P_{\rm rot}$(days)	$v \sin i$	This work Bf(kG)	Past Bf(kG)	References
117	HD 17925	K2 Ve	6.6	8	0.67 ± 0.5	0.53	Saar 1991
144	ϵ Eri	K2 V	11.3	0	0.0 ± 0.35	0.30	Marcy & Basri 1989
171.2	BD +26°730	K5 Ve	1.85	7.5	0.0 ± 1.1	1.30	Saar et al. 1990
355	HD 82558	K2 Ve	1.60	25	4.2 ± 4.0	1.02	Saar et al. 1992
517	EQ Vir	K5 Ve	4.0	9	1.73 ± 0.5	2.00	Saar et al. 1987
28.....................	HD 3765	K2 V	46	...	...	...	
570A	HD 131977	K4 V	...	...	...	...	
688	HD 160346	K3 V	34	...	...	...	
689	HD 160964	K5 V	...	...	...	...	

hollow-cathode thorium lamp. The correction for scattered light is not perfect, and contributes an uncertainty of ±1% of the continuum to the final reduced spectra.

2.2. *Line Selection and Equivalent Widths*

We selected Fe I absorption lines that are relatively free of blends as seen in the Arcturus spectral atlas (Griffin 1968). We selected 10 lines in each of three categories: insensitive to Zeeman enhancement, intermediate in sensitivity, and extremely sensitive. Here, "Zeeman sensitivity" refers to the enhancement of equivalent width caused by magnetic fields and is not simply related to the usual Landé "g-factor," as described in § 3.1. The line growth depends on the atomic physics of the transition and on the details of the polarized line transfer (Paper I). From each of the three categories, we discarded several absorption lines that were severely blended due to Doppler broadening in the active program stars. Table 2 lists the final 23 lines, including wavelength, excitation of the lower level, oscillator strength, the Zeeman g-factor, and the enhancement of the equivalent width due to the Zeeman effect for $B = 2$ kG (see § 3.1). The oscillator strengths were initially drawn from laboratory measurements (Fuhr, Martin, & Weiss 1988). Lines not in their list were assigned an oscillator strength based on modeling them in the standard stars, and all were adjusted to work with our model, as in Paper I. This adjustment means that the gf-values are not just atomic parameters, but correct some of the errors inherent to the modeling process.

Equivalent widths were measured for all stars by a method which enhanced the relative consistency of the measurements. The difficulty is that each active K dwarf has substantial rotational broadening that smears its lines, making measurement of equivalent width vulnerable to blends and continuum misplacement. However, the important quantities to measure here

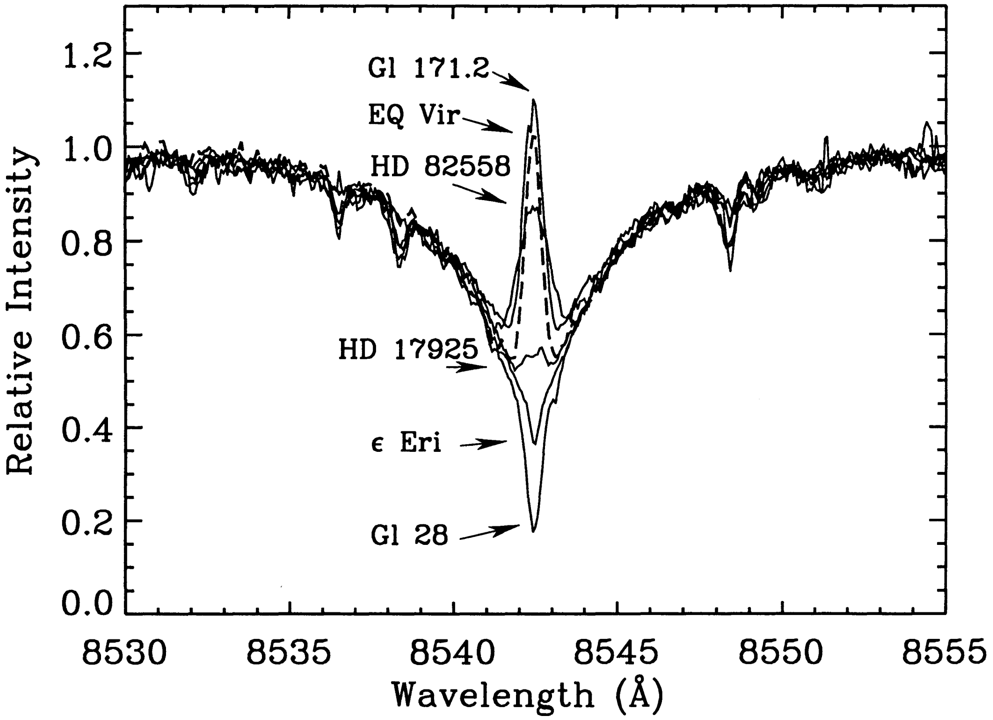

FIG. 1.—Spectra of the chromospheric diagnostic, Ca II λ8542, for the five chromospherically active stars and one quiet star. The flux at line center increases with chromospheric activity, showing that Gl 171.2, EQ Vir, and HD 82558 are most active, and ϵ Eri is the least active program star (though considered an active solar-type star). Gl 28 is a spectral standard (K2 V) quiet star.

TABLE 2

LINES USED IN ZEEMAN ANALYSIS

Wavelength (Å)	χ_{ex} (eV)	log (gf)	Landé (g)	W_{eq}(2 kG)/W_{eq}(0 kG)	ϵ Eri	EQ Vir	HD 82558	Gl 171.2	HD 17925
5322.04.........	2.305	−3.030	0.667	1.105	0.90	1.10	1.07	1.25	0.95
5415.21.........	4.392	+0.500	1.080	1.006	0.93	0.95	0.99	1.04	0.94
5862.37.........	4.550	−0.230	1.100	1.026	0.95	1.02	1.22	1.16	1.05
5987.07.........	4.790	−0.440	1.000	1.026	0.99	1.00	1.23	1.29	0.97
6024.07.........	4.554	−0.120	1.300	1.032	0.96	0.96	0.81	1.15	0.99
6151.62.........	2.179	−3.300	1.800	1.173	0.95	1.12	1.26	1.42	1.07
6173.34.........	2.248	−2.880	2.500	1.191	0.95	1.12	1.19	1.32	1.05
6180.22.........	2.759	−2.780	0.625	1.115	0.97	1.07	1.29	1.28	1.04
6254.26.........	2.305	−2.480	1.500	1.123	1.02	1.04	1.20	1.10	1.00
6270.24.........	2.891	−2.710	0.500	1.024	0.92	1.00	0.16	1.26	0.99
6358.69.........	0.860	−4.470	1.750	1.232	0.93	1.20	0.97	1.14	1.02
6421.36.........	2.281	−2.030	1.500	1.116	0.95	1.02	0.98	1.02	0.99
6710.32.........	1.487	−4.880	1.700	1.125	0.82	1.05	1.11	1.57	0.87
6750.16.........	2.427	−2.620	1.500	1.137	0.97	1.05	1.05	0.90	1.04
6806.85.........	2.731	−3.210	1.150	1.190	0.95	1.30	1.16	1.31	0.99
7491.68.........	4.280	−1.100	1.500	1.213	0.95	1.08	1.40	1.15	1.08
7507.30.........	4.410	−1.100	1.167	1.089	0.91	0.99	1.01	1.28	1.02
7511.03.........	4.180	−0.500	1.400	1.057	0.97	0.93	0.88	0.99	0.99
7568.93.........	4.280	−1.000	1.500	1.117	0.96	1.05	0.60	1.14	1.14
7780.59.........	4.450	−1.300	0.833	1.038	1.04	0.92	0.95	1.00	1.05
7807.92.........	4.9900	−1.000	1.400	1.045	0.96	0.88	0.87	1.18	1.03
8468.40.........	2.2484	−2.072	2.500	1.247	0.96	1.04	1.33	0.99	1.13
8757.19.........	2.8780	−2.026	1.500	1.156	0.97	1.17	1.18	1.30	1.03

are the ratios of the equivalent widths of the active program star to those of quiet reference stars. For each active star, two quiet stars were chosen that were closest in spectral type, as given in Table 1. In particular, the K2 V active stars were assigned reference quiet stars, Gl 28 and Gl 688, and the K5 V active stars were assigned Gl 570A and Gl 689.

The W_{eq} ratio measurements were done with an algorithm intended to provide as much consistency as possible between program and standard star. We first artificially rotationally broadened to two reference quiet stars to the $v \sin i$ of the active star (using the equations of Gray 1976). Next we fit a continuum in the 10 Å segment centered on the line of interest. The three spectra were aligned horizontally and normalized vertically so that the lines coincided in wavelength and the continuum heights were unity. We overplotted the spectra of the three stars, then chose by eye the left and right limits under which to compute the equivalent width. In this way, the equivalent widths used to determine each ratio were determined with identical wavelength limits, making the effect of blends the same in each case. The final continuum used was determined separately for each line by the three pixels nearest the wavelength limits on either side of each line. Based on the S/N of the spectra, the formal errors in equivalent width should be 2–6 mÅ, but this is typically less than a 4% fractional error (as much as 10% in weak lines in the fainter rapid rotator HD 82558). We thought it useful for future workers to tabulate the average values of the equivalent widths themselves for the standard stars in Table 3.

The measured equivalent widths are approximate because of the pervasive blends, especially for the rapidly rotating program stars. Indeed, the standard stars yield different values for each program star measurement, since they were processed separately in each case. The ratios of equivalent widths are less sensitive to the presence of weak blends, however, since both program and standard star suffer a similar contamination. We estimate the errors in the resulting ratios of equivalent widths to be ~5%, as determined by trying different placements of the wavelength limits around the measured line. A similar estimate is found by comparing the equivalent-width ratios for ϵ Eri to its quiet reference stars, as seen in the sixth column of Table 2, or Figure 2. We also returned to the spectra after some time and remeasured them, finding consistency to about 3%. Finally, we had further observations for several stars and measured the new spectra. The errors were less than 6% for EQ Vir and HD 17925, but as high as 10% for HD 82558. The latter is known to have spots and a varying light curve.

TABLE 3

STANDARD STAR LINE STRENGTHS

Wavelength (Å)	Gliese 28 (mÅ)	Gliese 570 (mÅ)	Gliese 688 (mÅ)	Gliese 689 (mÅ)
5322.04.........	83	102	81	87
5415.21.........	298	328	291	284
5862.37.........	126	141	129	119
5987.07.........	98	104	102	82
6024.07.........	170	182	164	169
6151.62.........	77	82	71	75
6173.34.........	99	105	98	104
6180.22.........	103	125	94	96
6254.26.........	168	197	162	159
6270.24.........	75	83	67	68
6358.69.........	122	129	119	119
6421.36.........	182	201	175	181
6710.32.........	46	55	44	39
6750.16.........	106	116	101	113
6806.85.........	63	83	60	69
7491.68.........	96	123	99	101
7507.30.........	89	102	82	82
7511.03.........	292	305	279	267
7568.93.........	85	138	86	108
7780.59.........	207	227	192	187
7807.92.........	80	73	77	59
8468.40.........	228	291	223	248
8757.19.........	138	165	128	132

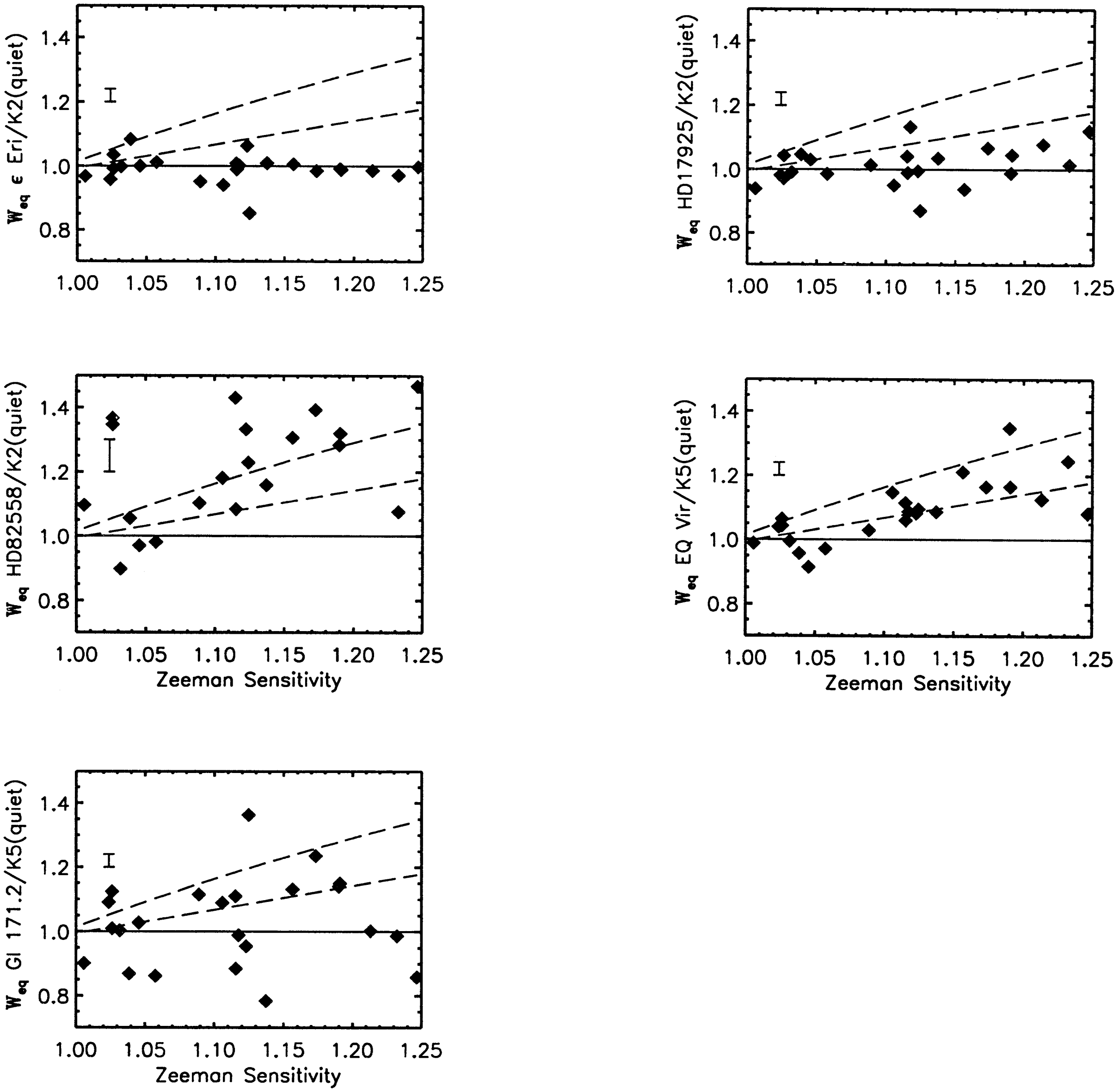

FIG. 2.—Ratio of equivalent width in the active star to that in quiet stars vs. sensitivity to line strength enhancement due to the Zeeman effect. The observations have been renormalized to remove metallicity effects to first order. The dashed lines show the expected enhancement assuming $B = 1.5$ kG and 3.0 kG. The trend apparent for EQ Vir indicates that $Bf \sim 1.7$ kG. The large scatter for HD 82558 and Gl 171.2 indicates the presence of multiple surface temperature components of comparable brightness. An approximate error bar in the equivalent widths for each program star is shown on the left.

The last five columns of Table 2, list, for each active star, the equivalent-width ratio between active star and the average of its two quiet reference stars of similar spectral type:

$$W_{\rm eq}\ {\rm Ratio} = \frac{W_{\rm eq}({\rm active})}{1/2[W_{\rm eq}({\rm ref}_1) + W_{\rm eq}({\rm ref}_2)]}\ . \qquad (1)$$

The $W_{\rm eq}$ ratios given in Table 2 for lines that are not too magnetically sensitive lie within ~20% of unity, indicating that the iron abundances and spectral types of the active stars and reference stars are similar. In some cases the average ratio differs from unity, indicating mild differences in the iron abundance between the active and reference stars. This can be taken into account by modeling, or (as done below) by renormalizing the ratios.

3. ANALYSIS

3.1. *The Zeeman Measurement*

The method for extracting a magnetic field measurement has been discussed in detail in Paper I. One establishes the Zeeman sensitivity of each line at a given field strength by computing the theoretical ratio of the magnetically enhanced equivalent width to that for the null field case. We used a single K4 model (scaled HSRA), adjusted to the metallicity of EQ Vir, to compute the Zeeman sensitivities used in this work (listed in Table 2). Our hottest stars are about 350 K hotter, but atmospheric differences are a second-order effect on the Zeeman enhancement ratios (we see no systematic effect with excitation potential). In principle one should compute different models for each metallicity and spectral type. One should also compute models for both standard and program stars individually, but here we prefer to remain as model-independent as possible by comparing the observational ratios directly. Our purpose is to show that the method works in active main-sequence stars with a minimum of modeling (and confirm their high fields). Paper I dealt only with pre–main-sequence stars and was more model-dependent.

The relation between the ratio of program to standard star equivalent widths and magnetic sensitivity is shown for each star in Figure 2. We see an apparent magnetic signal for EQ Vir, a clear null result for ϵ Eri, a marginal detection for HD 17925, and excessive scatter for the other two targets. The ordinates are entirely observational ratios (eq. [1]), and the abscissas have been computed as described above. The vertical scatter therefore reflects real observational errors or differences in the line strengths of the active and inactive stars, and not errors in our modeling of their atmospheres. We examined the behavior of low and high excitation lines separately, and found no systematic difference between them.

The ratio of magnetic to null equivalent width for each line changes with field strength as discussed in Paper I. To make Figure 2 we have fit a curve through the theoretical ratios for each line assuming fields of 1500 and 3000 G, and using the sensitivity for each line at 2000 G as the abscissa. In what follows, "sensitivity" refers to the Zeeman enhancement factors computed at 2000 G (see Table 2). These curves provide a fiducial in each plot against which to assess the observed ratios. Even if the model provided a perfect match to the observations, the individual points would scatter a little ($\lesssim 5\%$) about these fits because the adopted Zeeman sensitivity applies precisely only at $B = 2000$ G. Furthermore, the metallicity of each star is different than assumed in the model, which introduces an offset (and scatter) in the ratios even in the null field case. We have removed this to first-order by forcing the median of the observed ratios to unity for lines with sensitivity less than 1.08 for each star.

In order to quantify the measurements, we fit a quadratic to the points for each star. To interpret the ratios as magnetic fields, we use a very approximate method. We find the value of each fit at a sensitivity of 1.25, and linearly interpolate them between their values in the theoretical fits at 1500 and 3000 G. The result is given in Table 1. The error listed in Table 1 is the standard deviation of the difference between the fit and the observations (interpreted as a deviation from a ratio of unity). We also examined the correlation coefficients in each case; these confirm the impression by eye and give high confidence of a detection only for EQ Vir.

4. DISCUSSION

On the basis of HD 17925 and ϵ Eri we conclude that the Zeeman strengthening method cannot detect magnetic flux (Bf) less than half a kilogauss. The method seems to work some of the time for more active stars; the detection of EQ Vir yields a result consistent with the value reported by Saar et al. (1990) using a line-broadening method. This success supports the measurement of a field on a pre–main-sequence star reported in Paper I, and also serves to confirm the high flux values reported by Saar for very active stars. Our nondetection of ϵ Eri is consistent with the theoretical expectation for a star of its activity level (and with Zeeman broadening measurements for it). Our inability to measure the Zeeman strengthening in HD 82558 and Gl 171.2 indicates a limitation of the method: the atmosphere of the target cannot be too perturbed by the magnetic activity or the simple approach used here will not be able to separate Zeeman effects from other perturbations of the line strengths. Both these stars have large photometric periodicity indicative of strong spotting. They have about the same strength emission in the Ca II triplet (Fig. 1 is a little misleading because of the high $v \sin i$ of HD 82558). On the other hand, Saar et al. (1992) have reported preliminary success using equivalent width enhancement combined with Doppler imaging to make magnetic maps of HD 82558 in one Zeeman sensitive line. They compare the same line in the same star at different times; it would be interesting to test whether the same results were obtained from our full set of lines in such a differential comparison.

Gl 171.2 has the largest photometric amplitude known for a BY Dra star (Hartmann et al. 1981). We see lines in its spectrum which do not appear at all in the standards; these seem in some cases to be molecular features indicative of much cooler temperatures. Through it is a near-contact spectroscopic binary with a period 1.9 days (Griffin et al. 1985), the companion is probably around dM4 and therefore unlikely to contribute to the spectrum. A recent analysis of Gl 171.2 by Naftilan & Fairchild (1993) reports that the star "looks very normal." We have examined many of the same lines used by them, with our higher resolution. After accounting for a number of blends and telluric features, we conclude that the scatter in their line ratios (measured by us employing our standards) is consistent with the scatter in the ratios used in our Zeeman analysis. This is not necessarily incompatible with their statement, since they report abundance errors of ±0.2 dex. We consider departures in equivalent width of 30% to be large in our context, while they may not for theirs. One might wonder what the effect of several atmospheric components is on the Zeeman analysis itself; work on this question has been done by Basri, Marcy, & Valenti (1990) and Saar & Solanki (1992).

In conclusion, the use of Zeeman strengthening to detect very strong fields on cool stars has been confirmed for main-sequence K stars. In its simplest incarnation (as here) one can directly divide line equivalent widths by their values in spectral standards, eliminating the need for any modeling beyond that needed to assign a field to a given line enhancement. This simple approach can work when the magnetic flux is above 0.5 kG, so long as the star is not too spotted. Both stars detected are quite young and active and both have strong lithium lines. Our most active stars look very much like the weak-lined T Tauri stars; indeed if they were in star forming regions they would undoubtedly be classified as such (but on the ZAMS). The case for kilogauss fields covering large fractions of very young stars is therefore bolstered by this work. The relation between the emission in the Ca II triplet and magnetic flux is also confirmed. It is apparent from Figure 1 and the measurements in Table 2 that once the triplet core emission approaches or exceeds the continuum level in K stars, they must be mostly covered by kilogauss fields.

It is clear that the technique will only work for extremely active stars, and even for them more work to overcome the effects of atmospheric inhomogeneities is needed to make it more general. For many cases a multicomponent modeling effort may be required, and a set of lines which are Zeeman-sensitive in cooler atmospheres must be developed. The method is complementary to Zeeman broadening measurements in that it can be extended to much fainter stars, and is not rendered ineffective by the high rotation rates that come with high activity levels. Our purpose in this paper was to confirm that Zeeman enhancement is exhibited in objects for which there is independent evidence for very high magnetic flux. It can now be used with increased confidence to study the T Tauri stars, and extended to RS CVn and dMe stars.

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