

RECENT MEASUREMENTS OF STELLAR MAGNETIC FIELDS

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1. Introduction

High resolution, high S/N spectra have been successfully modeled to yield information on the magnetic properties of cool stars for some 15 years now. These analyses yield estimates of the intensity weighted surface filling factor of active regions, f , and the mean unsigned field strength in these regions), B . The measurements are difficult, though, hampered by the small magnitude of the Zeeman effect, small f values for most stars, and the unknown spatial and thermodynamic properties of the active regions. Recent data, mostly in the infrared (IR) where the Zeeman effect ($\propto \lambda^2$) is larger, are yielding better measurements than ever before. I summarize the new observations here, and show how they are expanding and modifying our understanding of magnetic fields on cool stars.

2. Recent Observations

The largest group of new observations come from the sensitive new cryogenic echelle (CSHELL; Greene et al. 1993) and InSb array on NASA's Infrared Telescope Facility (IRTF). With at least 100 times more sensitivity than Fourier transform spectrometers (FTS) used in the past (e.g., Saar & Linsky 1985), this instrument (and similar ones under construction) promise to revolutionize measurement of stellar magnetic properties.

One important group of recent observations *does* make use of an FTS. Valenti et al. (1995) have recently made careful measurements of three K dwarfs using the $g_{\text{eff}} = 3$ Fe I line at $1.56\mu\text{m}$. They detect a weak, but clear magnetic signal in their most active target, ϵ Eri, and upper limits for two other stars. The values derived for ϵ Eri, $B = 1440$ G and

$f = 0.088$ are considerably lower than most previous values, and call some older measurements into question (cf. Saar 1988; Marcy & Basri 1989). These f and B data are important constraints on the behavior of magnetic properties in low-to-moderate activity GK stars (see §3).

I now turn to the new CSHELL data, much of which is described here for the first time (see also Saar 1995). Observations were made in January 1995 of four Ti I lines near $2.22\mu\text{m}$ visible in K and M stars (Saar & Linsky 1985) at a spectral resolution of $\lambda/\Delta\lambda \approx 35,000$. Briefly, the spectra were dark and sky subtracted, flat-fielded, and telluric lines were removed by dividing by the scaled spectrum of rapidly rotating A or B star at similar airmass. I stress that the analyses of these data is still in progress and thus the results presented here are preliminary. In particular, only two of the four Ti I lines have been modeled so far, and corrections for residual fringing due to the circular variable filter may be inexact.

We first studied GL 171.2A (= BD +26°730), an active, nearly pole-on K5Ve with previous magnetic measurements (Saar et al. 1990; Basri & Marcy 1994). We modeled the Ti I flux profiles with a simple two component model: $F_{\text{obs}} = fF_{\text{mag}}(B) + (1 - f)F_{\text{quiet}}(B = 0)$ where F_{mag} and F_{quiet} are the disk-integrated fluxes from a completely magnetic and a completely quiet star, respectively. We employed a Milne-Eddington atmosphere, full Zeeman patterns and magneto-optical effects in the line transfer. We adopted $v \sin i = 7.5 \text{ km s}^{-1}$ (Saar et al. 1990), and a radial-tangential macroturbulence model ($v_{\text{mac}} = 2 \text{ km s}^{-1}$). The best fit is found for $B \approx 2800 \text{ G}$ and $f \approx 0.60$ (see Saar 1995), quite consistent with an optical determination of $B \approx 2600 \text{ G}$ and $f \approx 50\%$ (Saar et al. 1990) and a contemporaneous NSO McMath spectrum. While the agreement supports the idea that at least some of the older measurements are accurate, the presence of starspots on Gl 171.2A clouds the interpretation of what *kind(s)* of active region are being measured in each case.

The large continuum contrast between spot and photosphere at optical wavelengths insures that most previous fB data reflect conditions in the stellar analogs of plage and active network on the sun. On the sun, for example, the continuum contrast between a $T_{\text{spot}} \approx 4250 \text{ K}$ and the photosphere is $\approx 20\%$ at $0.6\mu\text{m}$, while at $2.2\mu\text{m}$, the contrast is $\approx 70\%$. Umbral contributions to B and f are thus potentially significant if f_{spot}/f is large. Several of our IRTF targets are known to be heavily spotted, and two of these give strong evidence for the measurable presence of starspot fields.

LQ Hya is a rapidly rotating ($P_{\text{rot}} \approx 1.6 \text{ d}$; $v \sin i \approx 25 \text{ km s}^{-1}$) single K2 dwarf; using our simple two component model, we compute $B \approx 3500 \text{ G}$ and $f \approx 0.7$ (Fig. 1, left). Its mean $B - V = 0.91$, suggesting $\langle T_{\text{eff}} \rangle \approx 5000 \text{ K}$. The equivalent width of the $2.2233 \mu\text{m}$ feature, however, is $W_{\lambda} \approx 250 \text{ m}\text{\AA}$, ~ 4 times larger than in $\epsilon \text{ Eri}$ (K2V; $B - V = 0.88$; $T_{\text{eff}} \approx 5050 \text{ K}$). While

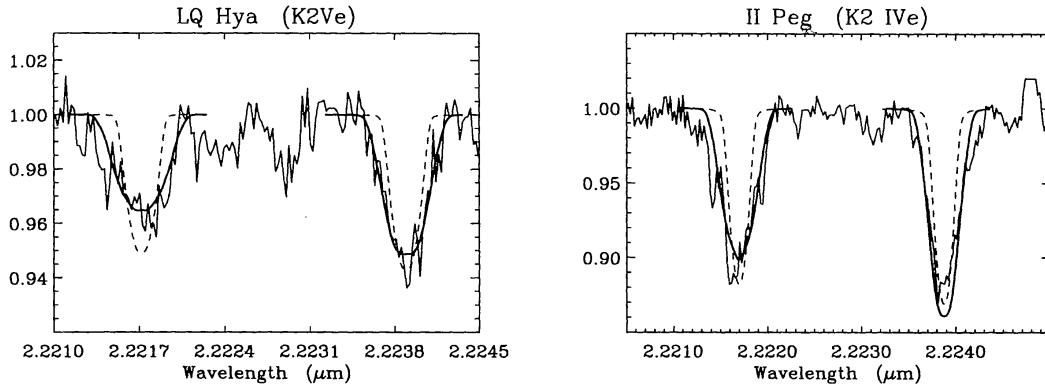


Figure 1. Left: IRTF CHELL spectrum of LQ Hya ($\lambda/\Delta\lambda = 35,000$, thin solid line) showing Ti I lines at $2.2211 \mu\text{m}$ ($g_{\text{eff}} = 2.00$) and $2.2233 \mu\text{m}$ ($g_{\text{eff}} = 1.67$). Line models with $B = 0$ (dashed) and $B = 3500 \text{ G}$ and $f = 0.70$ (heavy solid) are also shown. Right: IRTF spectrum of II Peg, showing the same lines (thin solid) and models with $B = 0$ (dashed) and $B = 3000 \text{ G}$ and $f = 0.60$ (heavy solid). In both cases, cool spots dominate the magnetic parameters.

magnetic intensification (see e.g., Basri & Marcy 1994) can account for some of the W_λ enhancement (indeed, our model has $W_\lambda(B)/W_\lambda(B=0) \approx 1.4$), the increase in W_λ with decreasing T_{eff} is a much more important effect. Thus, the Ti I profiles are dominated by a significant, cool, magnetic component. This represents the first direct measurement of B_{spot} (in contrast to B_{plage} or net flux $\sum_i^n (f_i \vec{B}_i)$) on a non-solar star. The lack of TiO absorption at 8860 \AA implies $T_{\text{spot}} \geq 3700 \text{ K}$ (Saar & Neff 1990). If we take $T_{\text{spot}} = 4000 \text{ K}$ and $T_{\text{quiet}} = 5000 \text{ K}$, and assume B comes only from spots, the actual $f_{\text{spot}} \sim 0.5$. Proper interpretation of f is more complex, though, since there is likely a contribution from plage/network fields as well (Saar, Piskunov, Tuominen 1994). More detailed, three component modeling (quiet, plage, spot) with more realistic atmospheres is clearly needed.

CSHELL spectra of the RS CVn variable II Peg also show both Zeeman broadening and evidence for spot fields. Very few RS CVns have reliable measurements of B and f . Early data on λ And were low S/N and inconclusive (e.g., Gondoin, Giampapa, & Bookbinder 1985), and while HD 17433 was detected (Bopp et al. 1989), Zeeman Doppler imaging of HR 1099 (Donati et al. 1990) measured only the *net* flux within spatial resolution elements; interpretation in terms of B and f values is not straightforward. Thus, our measurement of $B \approx 3000 \text{ G}$ and $f \approx 0.60$ on II Peg (using $v \sin i = 21 \text{ km s}^{-1}$ and $v_{\text{mac}} = 3 \text{ km s}^{-1}$; Fig. 1, right) represents one of the first such measurements for an active, evolved star. Once again, though, the Ti I W_λ values are too large to arise from the stellar photosphere (e.g., $W_\lambda(2.2233 \mu\text{m}) \approx 450 \text{ m\AA}$). The IR measurement must, then, come primarily from dark starspots. O'Neal, Saar, & Neff (1995) fit TiO bands plus

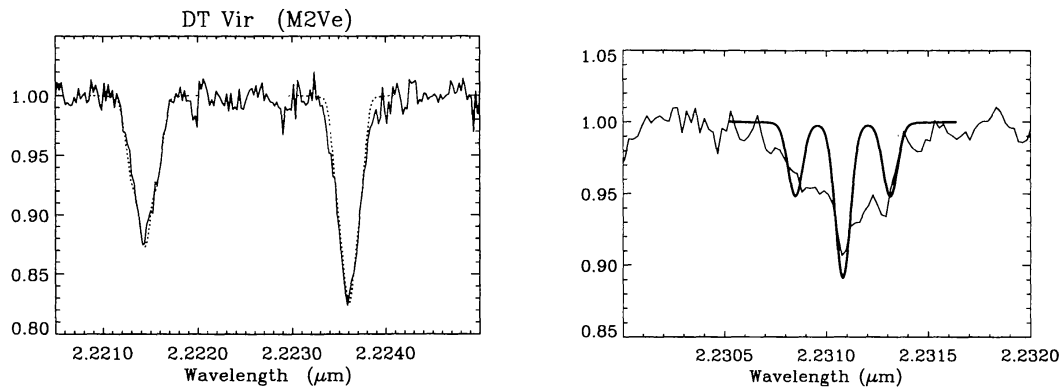


Figure 2. Left: IRTF CSHELL spectrum of DT Vir (thin solid line), showing the same lines as Fig. 1 and a line model $B=3000$ G and $f=0.50$ (dashed), using $v \sin i = 11$ km s⁻¹ based on optical NSO data. Right: CSHELL spectrum of AD Leo showing the Ti I line at 2.2310 μm ($g_{\text{eff}} = 2.50$) and a line model with $B=4000$ G and $f=0.60$ (heavy solid). It is clear from this and other lines that a single component model is inadequate; a distribution of B values, either across the surface or vertically or both, is needed.

photometry and find that $T_{\text{quiet}} = 4800$ K and $T_{\text{spot}} = 3500$ K, with f_{spot} ranging from 40% to 55% during 1989 to 1992.

The new IR data also confirm and extend previous results for M dwarfs. One of the main discoveries of older IR studies was that B values on dMe stars were considerably larger than those seen in active G and K stars (Saar & Linsky 1985; Saar 1994a, b). The new IRTF data confirm this: DT Vir (M2Ve), AD Leo (M4Ve), and YZ CMi (M4.5Ve) all show clear magnetic broadening with $B \geq 3000$ G and large filling factors (Fig. 2, left). Further support for these results come from the recent work of Johns-Krull & Valenti (1995), who report large B and f values for two late M dwarfs.

The later M dwarfs (AD Leo and YZ CMi) show another unusual characteristic: they cannot be fit with a simple two component model. This is most clearly seen in the 2.2310 μm $g_{\text{eff}} = 2.5$ simple triplet line, which shows a sharp central component consistent with the star's low $v \sin i$ (5.6 km s⁻¹; Marcy & Chen 1992), but has very broad Zeeman σ components (Fig. 2, right). This implies that there is either a distribution of B across the stellar surface (perhaps spots and plage with differing B values), or dB/dz is significant over the line forming region, or a combination of both. FTS data of AD Leo suggested a similar result (Saar 1992); the new IRTF spectra both confirm this and show it is also present in YZ CMi (M4.5Ve). Johns-Krull & Valenti (1995) see hints of the same effect in optical data of two M4.5Ve stars (EV Lac and GL 729).

3. Analysis and Discussion

It is clearly of interest to explore correlations between B , f and stellar parameters such as T_{eff} and rotation. The new, “low fB ” result for ϵ Eri (Valenti et al. 1995), however, argues for considerable caution in using older measurements. Following Saar (1995), we set aside results which do not employ radiative transfer or disk-integration (which are important for proper line modeling; Landolfi et al. 1989), 8648 Å results for GK dwarfs (due to disagreement with IR data), Zeeman/magnetic Doppler imaging results (due to problems detecting all the flux), curve-of-growth analyses (which can only measure fB to low accuracy), and some low S/N IR results. The resulting, highly pruned sample consists of the new CSHELL results given here and in Saar (1995), plus measurements by Valenti et al. (1995), Saar (1991), Saar & Baliunas (1992), Saar et al. (1994), and Johns–Krull & Valenti (1995). The final list is tabulated in Saar (1995); in the following we consider only dwarf stars.

We have computed a equipartition field strength $B_{\text{eq}} = (8\pi P_{\text{gas}})^{0.5}$ (where P_{gas} is the gas pressure at the height where $T = T_{\text{eff}}$) by using models of Kurucz (1991) and interpolating for the changes in mean $\log g$ along the main sequence and extrapolating for $T_{\text{eff}} < 3500$ K. (We note that the new model atmospheres predict somewhat lower B_{eq} in M dwarfs than previous models; cf. Saar 1990). When we plot B and B_{eq} against color (Fig. 3, left), we find general agreement for G and early K stars, with perhaps a small systematic shift to higher B values in late K and M stars. There are two main exceptions: Gl 729 ($B - V = 1.71$), which, while a flare star, is less active than the other K5V – M5V stars in the sample (Johns–Krull & Valenti 1995), and the very active, heavily spotted LQ Hya ($B - V = 0.91$). Thus we can say, in general, that B is controlled by photospheric pressure balance, with the possible exception of very active stars.

It is well known that stellar activity “saturates” for angular velocities $\Omega > \Omega_{\text{sat}}$ (e.g., Vilhu 1984). The photometric variability (e.g., ΔV) due to spots increases with Ω (Radick et al. 1989) – there is a significant rise in ΔV due to spots above a critical rotation rate (Hall 1991). However, ΔV continues to increase even beyond Ω_{sat} (O’Dell et al. 1995), implying dynamo-induced spottedness (and hence magnetic flux) does *not* saturate there. Thus, one possible explanation for the behavior in Fig. 3 is that f also reaches a maximum value at $\Omega \sim \Omega_{\text{sat}}$, and further increases in Ω increase B and not f . This increased B may well be in the form of starspots, so that f_{spot}/f increases while f remains constant (Saar 1994). Perhaps we are merely detecting enhanced f_{spot} and $B_{\text{spot}} > B_{\text{eq}}$ (Solanki 1994) in the IR spectra of these very active stars. We can test this idea by investigating the relationship between B and rotation. Figure 3 (right) shows some evidence

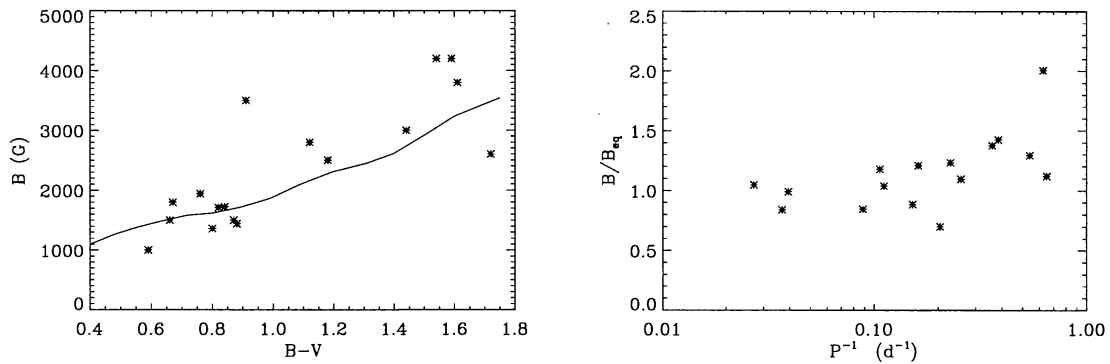


Figure 3. Left: Measured B vs. $B - V$ color; the pressure equipartition field strength B_{eq} is also shown (solid line). Right: B/B_{eq} vs. inverse rotation period. An increase is suggested for $P < 3$ days.

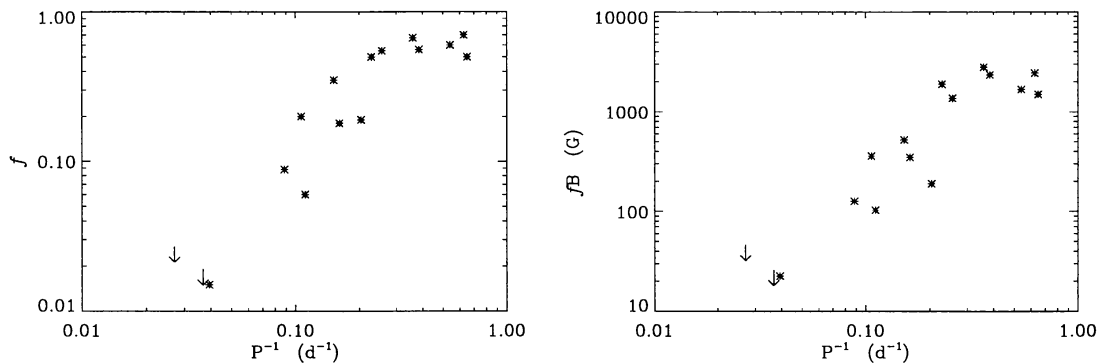


Figure 4. Left: Measured f vs. inverse rotation period, showing a non-linear increase ($f \propto P_{rot}^{-1.8}$) and saturation for $P_{rot} < 3$ days. Right: Measured fB vs. inverse rotation period, which can be fit with a similar relationship without a saturated state.

for an increase in B/B_{eq} above unity for $P_{rot} < 3$ days.

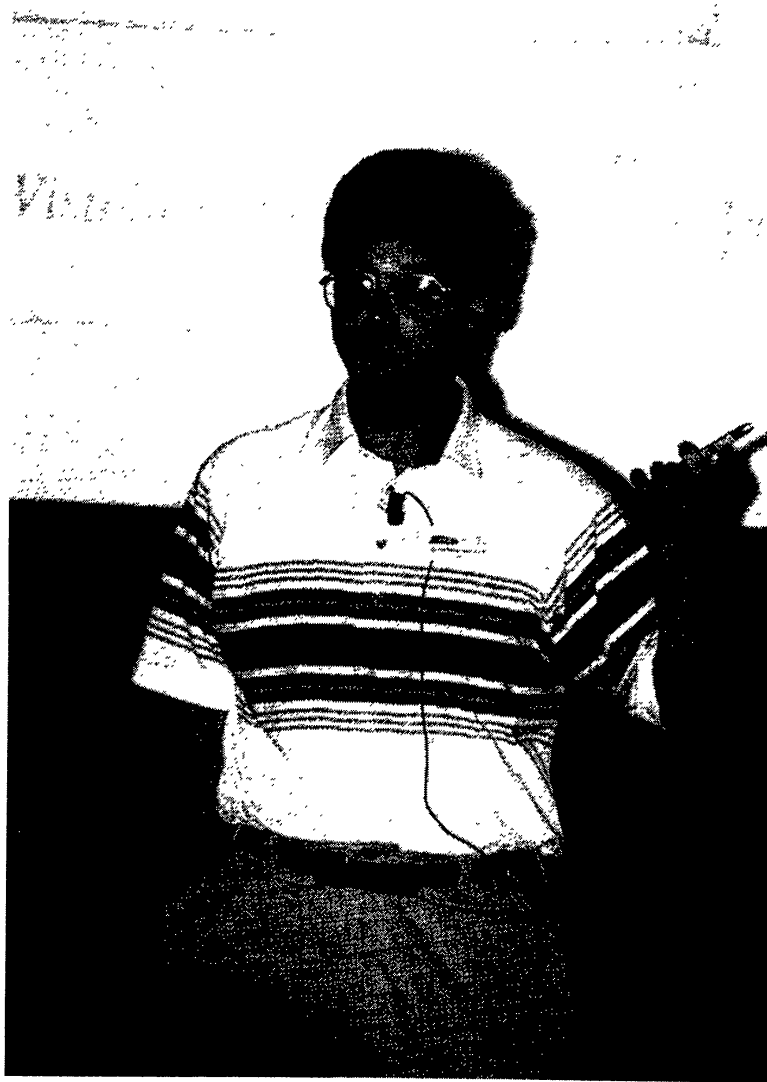
If the above hypothesis is correct, f should be a strong function of Ω below Ω_{sat} and reach an upper bound $\Omega > \Omega_{sat}$. This has been previously shown (e.g., Saar 1990); the new data set here confirms this and shows less scatter (Fig. 4, left). If divided into two sections, $f \propto P_{rot}^{-1.8}$ for $P_{rot} > 3$ days (the exact value of the exponent depends on the choice of f_{\odot}), and $f \approx 0.60$ for $P_{rot} < 3$ days. This value is in good agreement with the observationally determined Ω_{sat} . Furthermore, the product fB shows a similar relation, $fB \propto P_{rot}^{-1.7}$ with *no* saturation, suggesting that B continues to increase once f and activity saturates (Fig. 4, right).

Acknowledgements: This paper made use of data obtained at the NASA IRTF, operated by the Univ. of Hawaii under contract with NASA, and the NSO McMath–Pierce telescope. The NSO is operated by AURA under con-

tract with the NSF. I would like to thank J. Bookbinder for help observing at the IRTF, T. Greene and J. Rayner for deft technical support, and D. Jaksha, M. Giampapa and all involved with the late, great McMath–Pierce Solar–Stellar program for all their help. This work was supported by a Smithsonian ROF grant, and NASA grant NAG5-1975.

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David Mozurkewich on interferometric imaging of stellar surfaces.