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# Recent Measurements of (and Inferences About) Magnetic Fields on K and M Stars

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**Abstract.** I review recent progress in measuring magnetic fields in K and M stars, including new detections (including T Tauri's), new observational and modeling methods, and new insight (from various sources) on the nature and evolution of magnetic regions on cool stars.

## 1. Introduction

In the three years since my last reviews of direct magnetic field measurements in cool stars (Saar 1996ab), there have been some notable advances. These include a few new measurements (including some lovely work on T Tauris), but most of the progress has been in three areas: new and improved measurement and analysis methods, new insight into magnetic field structure and generation, and their role in atmospheric heating. Since an excellent recent review exists (Johns-Krull & Valenti 1999), I only briefly recount (§2) discoveries mentioned there to avoid yawn-inducing repetition. I will also only briefly touch on some of the exciting results from Zeeman Doppler imaging (ZDI), since these are more amply reviewed elsewhere (e.g., Strassmeier 2000). Instead, I broaden the scope of this review to consider more indirect measurements of stellar magnetic properties (§3), and make an (unwise?) attempt to divine future research directions (§4).

## 2. Direct magnetic measurements

In an arena where measurements are often difficult, fraught with systematics, and difficult to interpret, confirmation is especially welcome. Johns-Krull & Valenti (1996) reasoned that if the large field strengths ($B$) and magnetic area filling factors ($f$) detected in M dwarfs were real, Zeeman broadening should be visible in the Fe I 8468Å line (Landé $g_{\rm eff} = 2.5$). Significant line blending (mostly from TiO) led the authors to ratio their magnetically active targets with an inactive star with otherwise similar properties (e.g., Saar 1988). Zeeman $\sigma$ components were clearly seen, confirming previous IR detections of dMe stars (Saar & Linsky 1985; Saar 1996ab). Fitting the ratio with a two component (equal $T_{\rm eff}$) model for the target (a fraction $f$ with field $B$ and 1-$f$ with $B = 0$), a $B = 0$ model for the comparison star, and new M dwarf model atmospheres, yielded strong fields and large $f$ in two M4Ve stars, EV Lac and GJ 729 (Table 1).

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The result is particularly interesting in that it shows quite different $B$ on stars of the same spectral type, demonstrating that $B$ is not limited by photospheric gas pressure in all cases. Apparently when $f$ is sufficiently large, $B$ is no longer restricted by the photospheric gas pressure and begins to dominate the structure. Thereafter, increased rotation and field production probably increases $B$ instead of $f$ (e.g., Solanki 1994; Saar 1996ab).

Table 1. New Magnetic Field Measurements (Stokes I, after 1996).

| Name | Spec. type | B–V | $P^*_{\rm rot}$ [d] | $\tau^+_C$ [d] | $fB$ [kG] | $f$ [%] | $B$ [kG] | $F_X/10^{5\dagger}$ [ergs cm$^{-2}$ s$^{-1}$] | $B$ ref. |
|---|---|---|---|---|---|---|---|---|---|
| 58 Eri | G1V | 0.61 | 10.8 | 15.8 | 0.33 | ... | ... | 11 | 0 |
| 36 Oph B | K1V | 0.85 | 21.1 | 27.8 | 0.06 | ... | ... | 2.8 | 0 |
| $\epsilon$ Eri | K2V | 0.88 | 11.7 | 28.7 | 0.165 | ... | ... | 5.5 | 0 |
| EV Lac | M4Ve | 1.61 | 4.38 | 67 | 3.9$^\ddagger$ | 68 | 3.4 | 120 | 1,2 |
| GJ 729 | M4Ve | 1.72 | ... | 76 | 2.0$^\ddagger$ | 60 | 2.4 | 6.2 | 1,2 |
| AD Leo | M3Ve | 1.54 | 2.7 | 62 | 3.3$^\ddagger$ | ... | ... | 47 | 2 |
| YZ CMi | M4.5Ve | 1.60 | 2.78 | 66 | 3.3$^\ddagger$ | ... | ... | 80 | 2 |
| HII 1100 | K3V | 1.10 | ... | 33 | 1.25 | 50 | 2.5 | 160 | 3 |
| BP Tau | K7 | ... | 7.6 | 205 | 2.6$^\ddagger$,2.1$^\ddagger$ | ... | ... | ... | 4,5 |
| LkCa15 | K5 | ... | ... | ... | 1.1 | ... | ... | ... | 6 |
| T Tau | K0 | ... | 2.8 | 44 | 2.4,2.5$^\ddagger$ | ... | ... | ... | 6,5 |
| TW Hya | K7 | ... | 2.2 | 145 | 2.6$^\ddagger$ | ... | ... | ... | 5 |
| DK Tau | M0 | ... | 8.4 | 190 | 2.7$^\ddagger$ | ... | ... | ... | 5 |
| DF Tau | M2 | ... | 8.5 | 180 | 2.3$^\ddagger$ | ... | ... | ... | 5 |
| Hubble 4 | K7 | ... | ... | ... | 2.4$^\ddagger$ | ... | ... | 30 | 5 |

References: [0]Rüedi et al. (1997); [1]Johns-Krull & Valenti (1996); [2]Johns-Krull & Valenti (1999); [3]Valenti & Johns-Krull (1999, private comm.); [4]Johns-Krull et al. (1999a); [5]Johns-Krull et al. (2000); [6]Guenther et al. (1999).
* Saar & Brandenburg (1999) or Johns-Krull et al. (1999a).
+Gilliland (1986).
† Hünsch et al. (1999) except HII 1100 (Micela et al. 1996) and Hubble 4 (Neuhäser et al. 1995).
‡ $fB$ distribution.

Poorly fit line wings in EV Lac and GJ 729 suggested the presence of a significant horizontal or vertical distribution of fields, supporting similar evidence in the IR spectra of dMes (Saar 1992, 1996ab). Further observations fit with multiple (horizontal) magnetic components (Johns-Krull & Valenti 1999) yielded $\Sigma fB = 3.9$ and 2.0 kG for the two stars, plus two more detections. Regions with $B \geq 6$ kG occupied 30% of EV Lac. While some of this may be due to dark starspots (the true $f$ would then be even larger due to the $T = T_{\rm eff}$ assumption for the $B$ atmosphere), a vertical gradient $dB/dz$ is more likely. If so, a model with $dB/dz$ included in the atmosphere is needed, as the physical effects of horizontal and $B(z)$ distributions are quite distinct. This might partly explain the difference between EV Lac and GJ 729; higher activity and larger $fB$ on EV Lac could lead to an altered atmospheric structure where one sees to greater depths (and larger $B$) in the magnetic atmospheres, magnifying the measured $fB$ difference. It is noteworthy that such field distributions are not clearly necessary in more massive stars of similarly high activity and $f$ (e.g., DT Vir, GJ 171.2A; Saar 1996b). Fully convective M stars may evolve a different photospheric fluxtube structure than equally active, higher mass brethren.

Significant progress has been made in detections of $B$ in T Tauri stars. Guenther et al. (1999) used the increase in equivalent widths due to Zeeman de-saturation (ala Basri et al. 1992) to measure $fB$ (the unsigned magnetic flux density or surface average field) on T Tau and LkCa 15. Johns-Krull et al. (1999a) performed detailed line synthesis with the latest model atmospheres to fit IR spectra of BP Tau. They again find a distribution of fields with $\Sigma fB = 2.6$ kG and a total $f$ approaching unity (here a horizontal distribution of $B$ is the most likely culprit; Johns-Krull & Valenti 1999). Circularly polarized spectra of the same star show a clear signal ($\sim$2.5 kG) in the chromospheric He I D3 line (likely formed in the accretion column) but nothing in photospheric lines (Johns-Krull et al. 1999b). These observations combine to suggest small scale bipolar fields carpet most of the surface (producing net Stokes V $\sim$ 0) while accretion occurs along a few large scale loops of similar strength but small $f$ (a few %). Further Stokes I and V observations have yielded photospheric fields for five more T Tauris (Johns-Krull et al. 2000) and polarized measurements for most of these plus a sixth (AA Tau; Johns-Krull & Valenti 1999). Peak longitudinal $B$ (in the D3 line/accretion shock) appear to scale reasonably well with the Shu et al. (1994) models (Johns-Krull et al. 2000).

The "least squares deconvolution" (LSD) method was developed during this period (Donati et al. 1997), allowing ZDI, by virtue of a clever line combination to reduce noise, to be applied to a wider range of targets and data than before. Among the intriguing (and in some cases, even controversial!) results are: prominent regions with primarily azimuthal fields, increasing field complexity with more rapid rotation and deeper convection zones, evidence for $B$ production *in* the convection zone, circumpolar azimuthal magnetic rings in some stars, plus detections of differential rotation on AB Dor, and a possible magnetic cycle on HR 1099 through $P_{\rm rot}$ changes (e.g., Donati 1999; Donati et al. 1999).

With improvements in magnetic spectral modeling on several fronts (multiple $B$ components, new model atmospheres), the most physically realistic models are still arguably those of Rüedi et al. (1997), who include depth dependent fields via radiative transfer (RT) calculations (1.5-D) along rays piercing a realistic flux tube "forest". Using such models, they detected fields on $\epsilon$ Eri ($fB = 0.165$ kG), confirming the detection by Valenti et al. (1995), and found marginal evidence for fields on a few other moderately active G and K stars.

Indirect support for these models comes from the first detailed attempts to link $fB$ measurements with outer atmospheric heating (Cuntz et al. 1999). The authors use the Rüedi et al. results to estimate $f$ and thereby constrain simple surface models of K2 dwarfs, made of flux tubes arranged either uniformly or in linear network-like structures. Acoustic (where $B = 0$) and magneto-acoustic waves are then propagated through the structures, and the formation of Ca II HK emission caused by wave energy deposition is computed with 1.5-D RT and compared with observations. Cuntz et al. can reproduce the HK emission flux at cycle minima in inactive K0-K3 stars with acoustic wave heating. They find network geometries provide the best match to data for less active stars ($P_{\rm rot} \gtrsim 30$ d); uniform tube "forests" (with narrower tube opening angles enhancing heating) are better for moderately active K stars (20 d $\lesssim P_{\rm rot} \lesssim$ 30 d). While fluxes for more active K stars ($P_{\rm rot} \sim 10$ d) are somewhat underestimated (flare heating was neglected), overall agreement is encouraging.

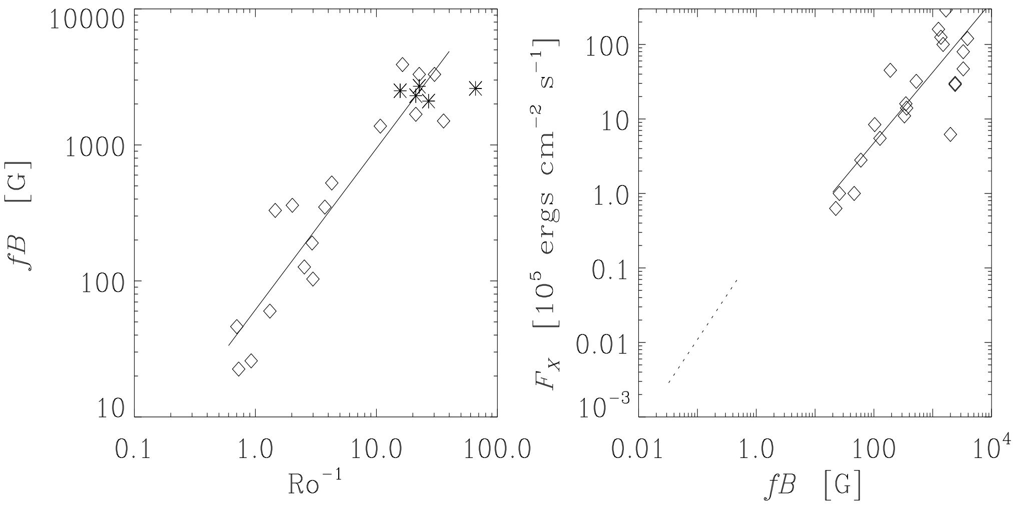


Figure 1. *Left:* Mean (unsigned) magnetic field $fB$ vs. inverse Rossby number $\mathrm{Ro}^{-1}$ (dwarfs=$\diamond$, T Tauris=$*$); the best power law fit (excluding TW Hya) $fB \approx 60\mathrm{Ro}^{-1.2}$ is shown (solid; $\sigma_{\mathrm{fit}} = 0.26$ dex). *Right:* X-ray surface flux vs. $fB$; the best power law fit (excluding GJ 729) is $F_X \propto (fB)^{0.95}$ (solid; $\sigma_{\mathrm{fit}} = 0.36$ dex). Data for solar active regions (dotted) yield the similar $F_X \propto (fB)^{1.19}$ (Fischer et al. 1998).

By combining the new measurements (Table 1) with the old (Saar 1996ab), relations between magnetic parameters, rotation, and activity can be updated. To treat both dwarfs and T Tauris consistently, I take convective turnover times $\tau_C$ from Gilliland (1986). I use X-ray fluxes from ROSAT throughout. I neglect $\tau_C$ when $P_{\mathrm{rot}}$ is unknown, and neglect $F_X$ for T Tauris (except the "weak-lined" Hubble 4) due to uncertain accretion-related contributions. In dwarfs stars, both $\Omega$ and the inverse Rossby number $\mathrm{Ro}^{-1} = \tau_C/P_{\mathrm{rot}}$ are well correlated with $fB$. $\mathrm{Ro}^{-1}$ is clearly preferred if T Tauris are included (Fig. 1, left). The combined data show $fB \approx 60\mathrm{Ro}^{-1.2}$; I have neglected TW Hya, which seems to have a low $fB$ for its large $\mathrm{Ro}^{-1}$ ($\approx 70$). This is a rather shallower power-law than previously determined (Saar 1996ab); one could also possibly terminate the fit at $\mathrm{Ro}^{-1} \sim 20$, yielding a steeper slope, and introduce a saturated state thereafter. Is TW Hya indicating saturation at $fB \sim 3$ kG for large $\mathrm{Ro}^{-1}$ (at least in plage fields which probably dominate in the observed Zeeman lines)? More data are needed! Theory (e.g., Solanki et al. 1997) and photometry (e.g., Krishnamurthi et al. 1998) suggest that saturation, if present, may well be restricted to the plage component alone.

X-rays also correlate fairly well with $fB$ (Fig. 1, right). Setting aside one star (GJ 729) which falls well below the main relation, the data show a linear relationship $F_X \approx 6100(fB)^{0.95}$. Scatter seems to increase with $F_X$, perhaps due to flares. This is similar to the relation between $L_X$ and magnetic flux for solar active regions (Fischer et al. 1998), which converts to $F_X \approx 16900(fB)^{1.19}$ ergs

$\mathrm{cm}^{-2}$ $\mathrm{s}^{-1}$. The linear relation is consistent with several recent heating models (e.g., Fischer et al. 1998; Sturrock et al. 1999).

## 3. Indirect inferences about magnetic structure and generation

Several groups have studied stellar magnetic cycle periods, $P_{\rm cyc}$, in an effort to better understand the underlying dynamo mechanism. Saar & Brandenburg (1999; building on Brandenburg et al. 1998), have gathered cycle data from Ca II HK, photometry and other sources and found that non-dimensional parameterization of the cycle period as $P_{\rm rot}/P_{\rm cyc}$, shows complex behavior as a function of $\mathrm{Ro}^{-1}$ ($\propto D_{\alpha\omega}^{0.5}$ the $\alpha\omega$ dynamo number). Three branches were found, each showing $P_{\rm rot}/P_{\rm cyc} \propto \mathrm{Ro}^{-\delta}$. Most stars lie on two roughly parallel branches with $\delta \sim 0.5$, with less active stars on the branch with larger $P_{\rm rot}/P_{\rm cyc}$ (cf. Ossendrijver's 1997 result $P_{\rm cyc} \propto \mathrm{Ro}^2$ for inactive stars). A third branch with $\delta \sim -0.4$ contains the most rapid rotators. Many stars can have secondary $P_{\rm cyc}$ on another branch (the solar ~100 yr Gleissberg cycle is consistent with this). Older stars with two $P_{\rm cyc}$ have cycles appearing on two branches. The authors sketch out the evolution of $P_{\rm cyc}$ with time and suggest the $\alpha$ effect may actually be enhanced rather than quenched by $B$ in some regimes. Lanza & Rodonò (1999) have revived an idea by Applegate (1992) whereby orbital period modulations seen in many close binaries (Algols, W UMas, RS CVns) may be due to magnetic cycle-driven changes in the stellar quadrupole moment. They find $P_{\rm cyc} \propto P_{\rm rot}^{0.36}$, similar to "fastest rotators" branch in Saar & Brandenburg (1999).

Turbulent dynamos have received renewed attention as well. Such dynamos are clearly needed to explain activity in completely convective M and brown dwarf stars (where a boundary layer dynamo is impossible), but are increasingly considered important in a wide variety of settings. Starting close to home, the ubiquitous "magnetic carpet" on the Sun, likely responsible for much of the weak diffuse X-ray emission, is probably of turbulent origin (Schrijver et al. 1997). So-called "flat activity" stars (which show minimal long-term Ca II HK variation, e.g., Baliunas et al. 1995) are also likely candidates for turbulent dynamos (Saar 1998); they have weak coronae (Schmitt 1997), but no clear dependence of X-ray or transition region (TR) activity on rotation (Saar 1998). Late M and brown dwarfs show a similar lack of a rotation-activity relation; if anything, available data suggests an *inverse* relationship, with the fastest rotators being *least* active (Basri 2000). Very active stars may need a turbulent-generated component to explain their complex surface structures (Donati 1999); for example, despite modeling advances for evolved stars (Granzer et al. 2000) it is still difficult to explain near-equatorial spots on rapidly rotating dwarfs, given their shallower convective zones (Deluca et al. 1997). Weak TR and weak (or absent) coronae in late K-M giants may also be due to fields a generated by a turbulent process (e.g., Ayres et al. 1997). A large subset of the "flat activity" stars also show a $\mathrm{Ro}^{-1}$ (and dynamo number) distribution consistent with cyclic stars of age >2 Gyr (Saar 1998; Saar et al. 2000), strongly suggesting many "flat" stars are only temporarily quiescent – in the stellar analog of magnetic grand minima. This brings us full circle to the Sun, implicating a turbulent dynamo for much of the residual activity in the Maunder minimum.

## 4. Some future directions

In the spirit of this last Cool Stars workshop of the century (and inspired by it!), it is perhaps appropriate to try to peer dimly ahead into the murky future. What are some likely directions stellar magnetic research in the next several years? Here are a few ideas ...

The newly discovered Zeeman sensitivity of the FeH molecule (Valenti & Johns-Krull 2000), which is strong at very cool temperatures ($T < 3500$ K), can be used to study magnetic field properties of very cool M dwarfs ($\geq$M5) and brown dwarfs, and detect $B$ in cool starspots. This opens up exploration of magnetic properties at the "fully convective" and "H burning" boundaries, and probing the dark hearts of stellar umbrae.

Further polarized and unpolarized observations of T Tauris should help unravel the complex interactions between the star and accretion disk. Recent detection of mm continuum polarization from a T Tauri (Tamura et al. 1999) disk opens the way for $B$ information in the disk itself, and tests of disk dynamo models. More information in these areas will greatly aid the understanding of stellar, planetary system, and early rotational evolution. Magnetic data on stars in young clusters will also be helpful in this regard (note the first $fB$ detection in the Pleiades cluster of HII 1100!).

In the area of modeling unpolarized spectra, realistic field geometries and $dB/dz$ should be more generally employed (e.g., Rüedi et al. 1997), and expanded to consider spot fields, different magnetic atmospheres, and the effects of flows *around* fluxtubes (e.g., Frutiger & Solanki 2000). Distributions of tubes, perhaps starting from a solar model (e.g., Solanki 1999) could be explored. These improvements should yield more reliable $f$ values, better understanding of the stellar surfaces, and ability to distinguish horizontal and vertical $B$ distributions.

ZDI (with and without a dose of LSD!) holds great potential, but can also be improved. Piskunov (1998) noted that the surface $B$ vector maps produced can be dependent on initial assumptions; all four Stokes parameters were needed for a robust solution. Current forms of LSD ZDI use the "weak line" approximation Stokes V $\propto B dI/d\lambda$, which is accurate only for Zeeman splittings $v_B \lesssim v_D/2$ the *local* Doppler half-width (e.g., Bray & Loughhead 1964). In most late-type stars, $v_D \lesssim 2$ km s$^{-1}$, so the approximation only holds for $B < 1$ kG for an average $g_{\rm eff} = 1.2$ line at 600 nm. If the profile used to compute $dI/d\lambda$ is broader than the true local line profile, systematic mapping errors can arise (Donati & Brown 1997). Ultimately, an RT solution (removing the "weak-line" assumption) combined with a more detailed treatment of the Zeeman patterns (perhaps using moment expansions; Landi Degl'Innocenti 1982) and observations (and simultaneous inversions) in all four Stokes parameters should help make the inferred magnetic maps more robust. Some work in this direction (potential field solutions to ZDI) is already underway (Hussain et al. 2000).

Improvements of heating models, and extension to transition and corona, perhaps including flares in some simple way could expand on Cuntz et al. (1999) and better tie $B$ to non-radiative heating. Stars may soon be able to help test the multitude of coronal heating models (e.g., Mandrini et al. 2000).

Improved dynamo models are needed to explain the observed patterns in cyclic stars (multiple branches and $P_{\rm cyc}$ - $P_{\rm rot}$ relations, the frequency of

Maunder-like minima). Combined with further flux emergence models (e.g., Granzer et al. 2000), we can hope to start to explain the spatial distribution of active regions and their changes in in time. Turbulent dynamo models are also needed to explore how their interact with a cyclic dynamo, and better define their expected dependence on stellar properties. How do fully convective stars make spots? Can they have cycles? And what (if any) is the connection between fields in cool stars and those in magnetic A and B stars? An upcoming workshop in Chile will probe some of these issues; maybe see you there!

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