TITLE
ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR**
EDITORS

Magnetic Field Measurements for Cool Stars

Jeff A. Valenti

STScI, 3700 San Martin Dr., Baltimore, MD 21218, USA

Christopher Johns–Krull

Space Sciences Lab #7450, UC Berkeley, Berkeley, CA 94720, USA

Abstract. Magnetic field measurements for cool stars provide important constraints on models of stellar dynamos and coronal heating. We describe recent spectropolarimetric measurements for the Sun and cool stars. We show recent Zeeman broadening measurements for an M dwarf, a Pleiad, and a T Tauri star, commenting on the validity of equipartition. Finally, we discuss FeH as a new Zeeman diagnostic for very cool dwarfs.

1. Introduction

Magnetic fields are ubiquitous in astronomy. Indirect signatures can be obvious (e.g. stellar flares), but direct measurement is difficult. Better magnetic field measurements are necessary, however, to obtain a complete physical understanding of many phenomena. Cool stars provide one of the few systems where active generation of magnetic fields can be studied.

Figure 1 shows chromospheric (R'_{HK}) or coronal ($L_{\mathrm{X}}/L_{\mathrm{bol}}$) activity versus reciprocal Rossby number (convective turnover time divided by stellar rotation period). Activity presumably traces magnetic heating of the upper atmosphere. Rotation and convection presumably drive dynamo generation of magnetic fields which buoyantly rise to the surface. Despite this universally accepted premise, the underlying processes are poorly understood. Surface magnetic field measurements allow heating and dynamo problems to be tackled separately. Activity saturates above a Rossby number of $\sim$0.6, where fields perhaps cover the entire stellar surface, though field strength may continue to increase. On the other hand, activity saturation may simply reflect a dynamo limit. Magnetic field measurements would empirically distinguish between these possibilities.

Activity cycles have been observed for the Sun and other stars (Baliunas et al. 1995). Cycle periods span a narrow range compared to rotation periods (Saar, this volume). Maunder minima stars have chromospheres, but no activity cycles, suggesting a non-cyclical dynamo. Solar magnetic flux varies cyclically in active regions, but has little or no cycle dependence in quiet regions (Rabin 1991; K. Harvey, private comm.). Magnetograms at solar minimum often show no large scale structure. Perhaps a small scale dynamo operates in the Sun and other cool stars, dominating field generation in the coolest dwarfs with deep convection zones (e.g. Durney, De Young, & Roxburgh 1993).

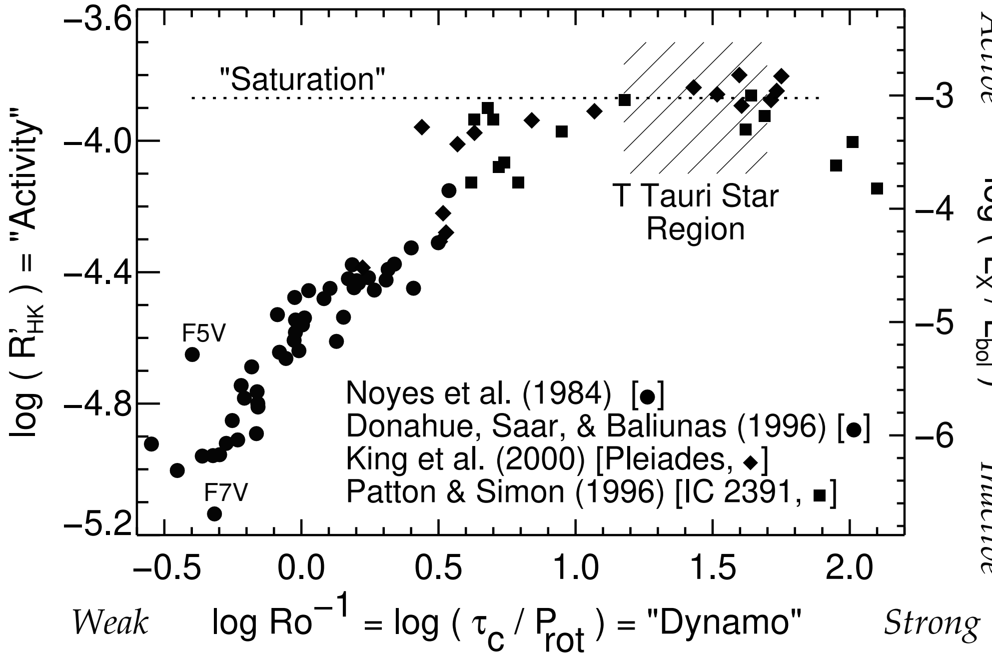

Figure 1. Rotation–activity relationship with saturation for cool stars. $R'_{\rm HK}$ and $L_{\rm X}/L_{\rm bol}$ related using Sterzik & Schmitt (1997).

2. Polarization Measurements

Zeeman analyzers are used to study organized magnetic fields on Ap stars, white dwarfs, and the resolved solar surface. For unresolved cool stars, circular polarization has not been unambiguously detected in individual spectral lines, implying significant cancellation due to regions of opposite magnetic polarity.

What is the net circular polarization signal of the Sun as a star? Collapsing solar magnetograms, Plachinda & Tarasova (2000) find a 2 G peak-to-peak amplitude at solar maximum and a 0.3 G amplitude averaged over 30 years. A custom polarimeter to measure the Sun as a star would alleviate any systematic errors in magnetogram data and provide a solar baseline for stellar observations.

Plachinda & Tarasova also claim a 30 G amplitude for ξ Boo A (G8V), based on 17 years of sparse data, including their own measurements using 16 spectral lines. Currently, we do not know how net circular polarization scales with stellar activity. Polarimetry using hundreds of spectral lines may now allow stellar measurements precise enough to yield rotation and cycle periods and to constrain magnetic geometry.

Zeeman Doppler imaging (ZDI) creates magnetic field maps from Stokes spectra obtained at many rotational phases. Rapid stellar rotation spectroscopically resolves surface magnetic structures, reducing polarization cancellation. Even with this advantage, many lines must be combined to detect a net circular polarization signal.

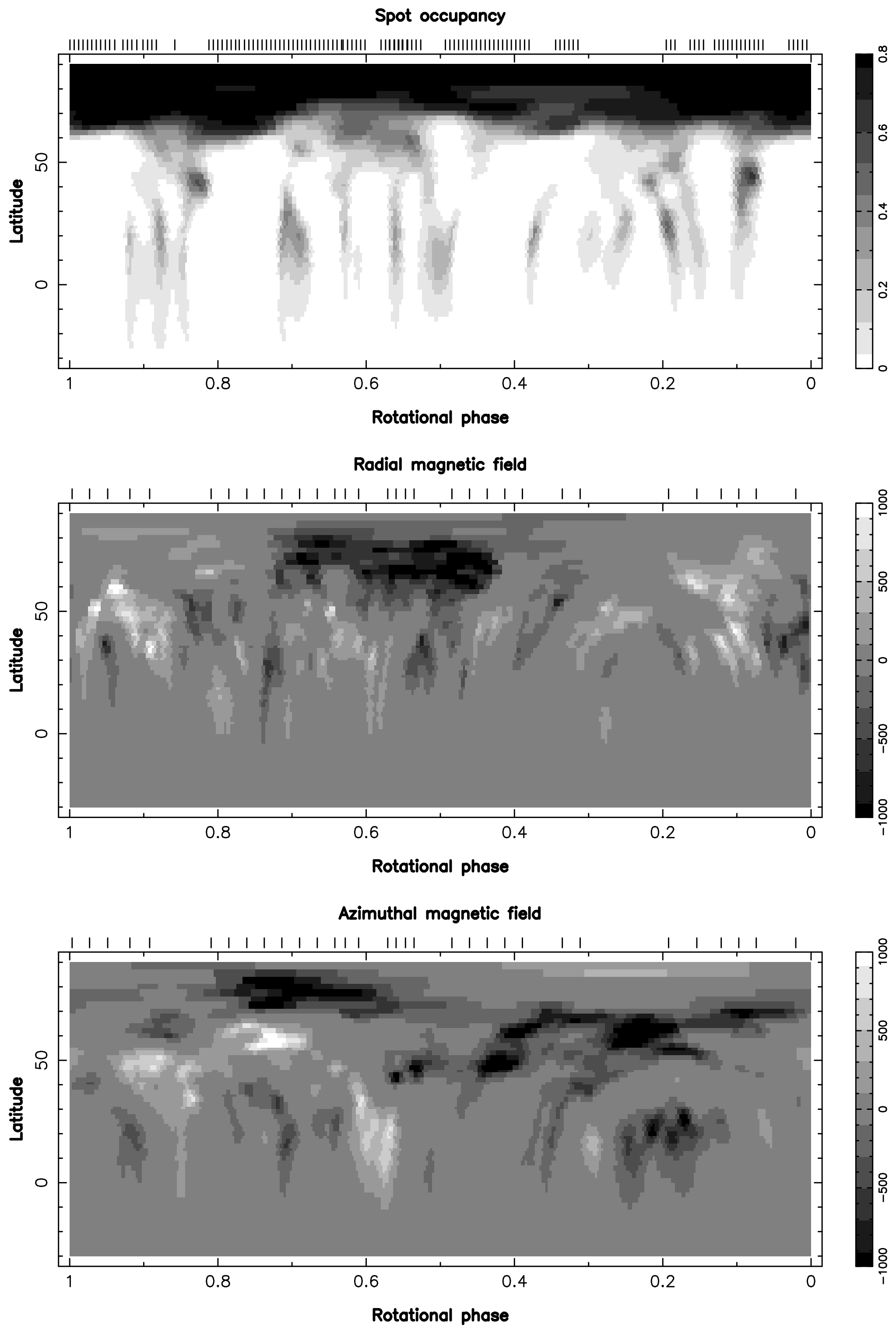

Figure 2. ZDI maps of AB Dor courtesy of Donati et al. (in prep.).

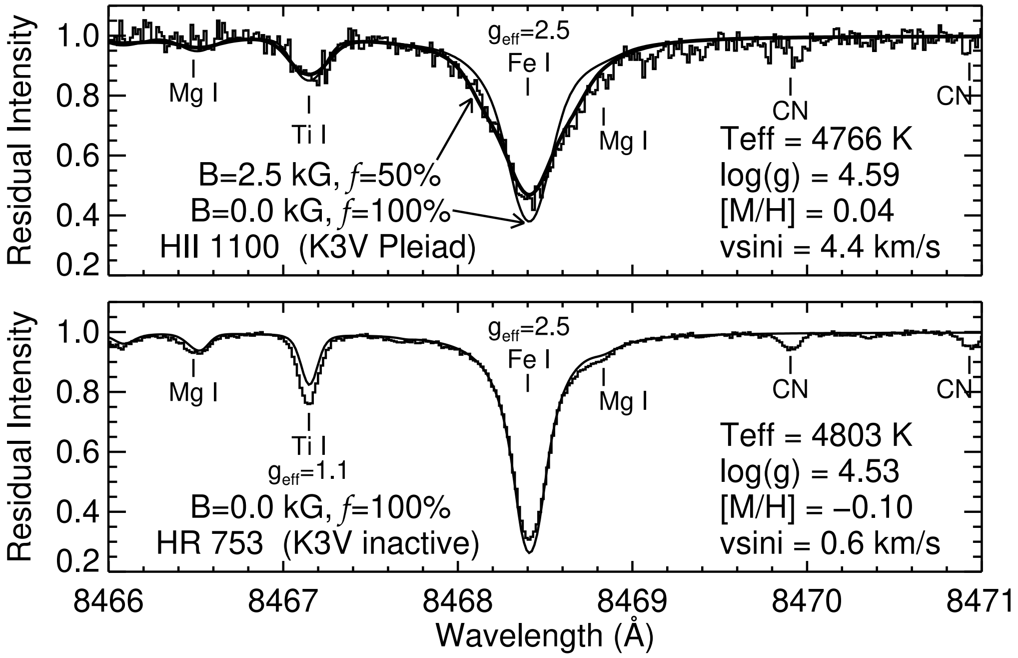

Figure 3. Zeeman broadening in an R=120,000 McDonald spectrum of an active Pleiad. No excess broadening is seen in an inactive analog.

Donati et al. (1997) combine lines using a technique dubbed least squares deconvolution (LSD, see Stenflo poem). LSD obtains a mean Stokes V profile vs. velocity offset (v) from the least squares solution of $V(v) = g_i\lambda_i d_i Z(v)$. This follows heuristically from the weak field approximation, $V_i(v) \propto g_i\lambda_i I_i'(v)$, and an assumption that the derivative of Stokes I with respect to v is self-similar, $I_i'(v) = d_i Z(v)$. Blends and splitting patterns should be treated explicitly for each line, but ZDI provides an important step towards this ultimate goal.

Donati et al. (1999) combine Stokes V for >1000 lines. The time sequence of mean V for AB Dor shows clear rotational modulation, as organized magnetic structures are carried across the visible hemisphere. Figure 2 shows reconstructed spot fraction, radial field, and azimuthal field maps. A giant polar spot is present, as in many analyses of rapidly rotating cool stars, perhaps due to the Coriolis force acting on anchored flux tubes (Schüssler & Solanki 1992). Longitudinal reversals in circular polarization verify a complicated magnetic structure. Latitudinal smearing is due in part to poor constraints. The presence of an azimuthal ring of magnetic flux has important dynamo implications, if true.

3. Zeeman Broadening Measurements

Zeeman broadening measurements complement polarization studies, yielding the distribution of magnetic field strengths with little dependence on unknown field geometry. Zeeman broadening is best measured for low $v \sin i$ stars, in contrast to ZDI. Almost all Zeeman broadening analyses to date assume: (1) field is

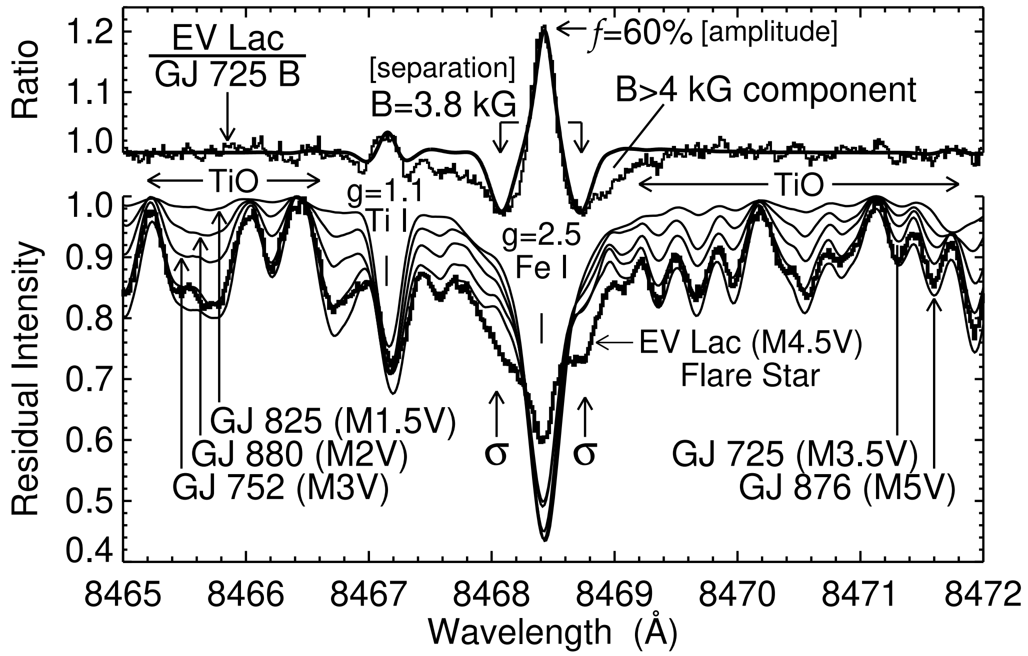

Figure 4. Zeeman broadening in EV Lac, relative to a temperature sequence of inactive dwarfs. TiO cancels in the ratio, which we fit.

concentrated into flux tubes surrounded by field free regions, (2) buoyancy forces orient flux tubes radially in the photosphere, (3) magnetic regions are distributed uniformly over the surface, and (4) magnetic regions are characterized by a single field strength. Observed spectra are fit by the sum of synthetic spectra for magnetic and nonmagnetic regions to derive magnetic field strength (B) and filling factor (f).

Zeeman splitting of π and σ components is proportional to $\lambda^2 gB$, where λ is wavelength and g is Landé factor. Global line broadening is characterized by $g_{\rm eff}$, a weighted sum of g values for all components. Field orientation determines the relative strength of π and σ components, but not their splitting. Reliable measurements require splitting at least comparable to line widths in the absence of a field. For this reason, successful measurements use red or IR lines with large $g_{\rm eff}$ to study stars with large B and f. Many early attempts to measure magnetic fields examined relatively inactive (though bright) stars in visible light.

Figure 3 shows the first magnetic field measurement for a Pleiad. We empirically adjusted atomic data to match the solar spectrum and determined stellar parameters by fitting atomic lines in 13 echelle orders. Figure 3 shows the Zeeman sensitive 8468.4 Å Fe I line. A nonmagnetic model reproduces line widths for an inactive star, but excess broadening is visible (only in Zeeman sensitive lines) in the very active ($L_{\rm X}/L_{\rm bol} = -3.14$) Pleiad. We infer $B = 2.50 \pm 0.09$ kG covering $\sim$50% of surface, assuming similar magnetic and nonmagnetic atmospheres. Field strength is well constrained, but filling factor depends on the unknown temperature structure of magnetic regions.

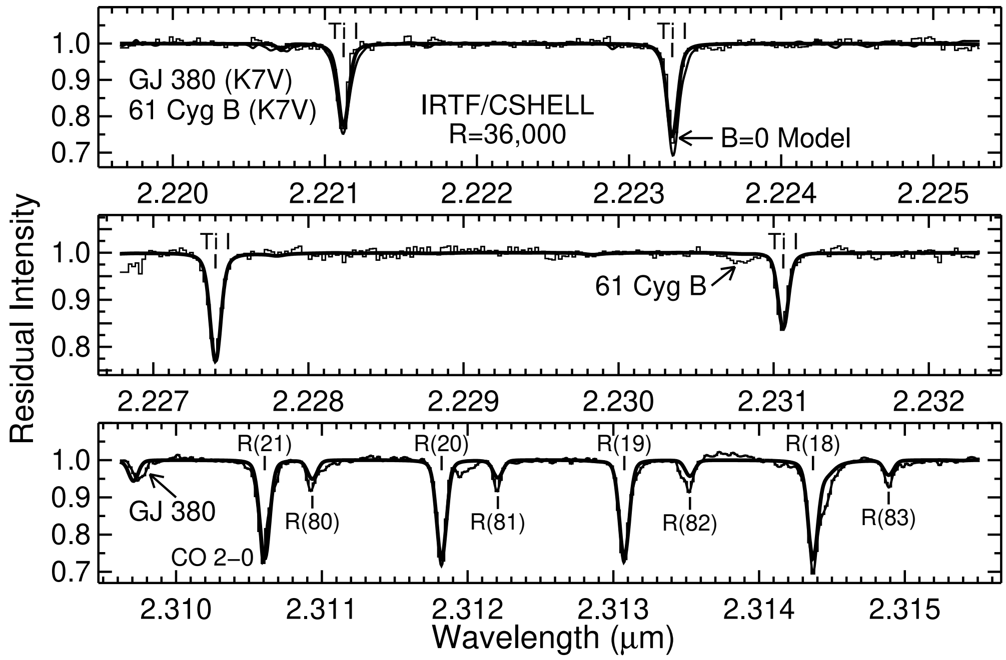

Figure 5. IRTF spectra of two inactive K7 dwarfs with model fit.

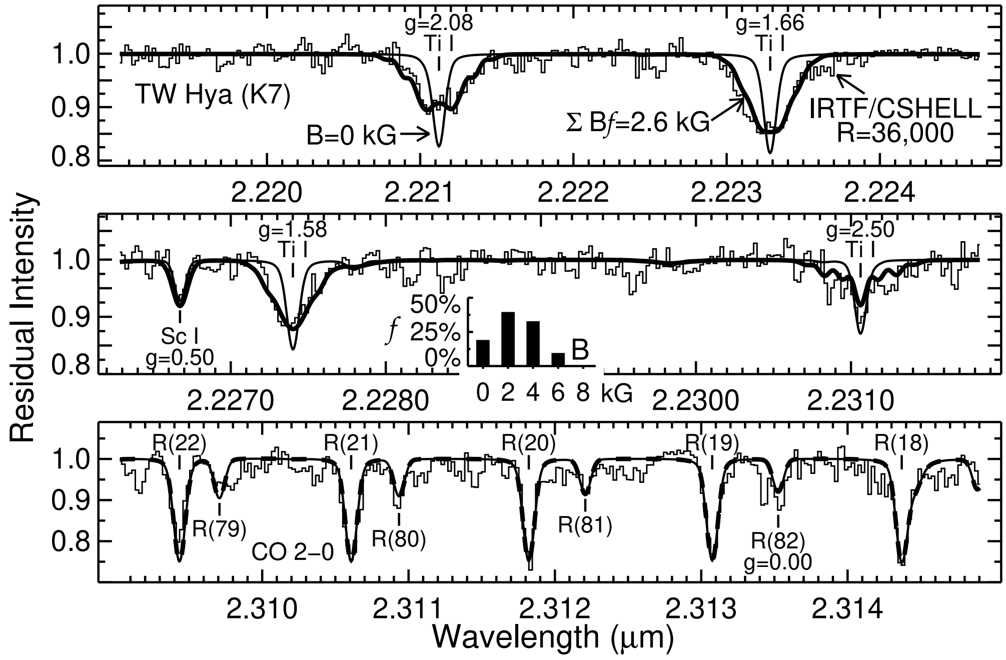

Figure 6. Zeeman broadening on the accreting T Tauri star TW Hya.

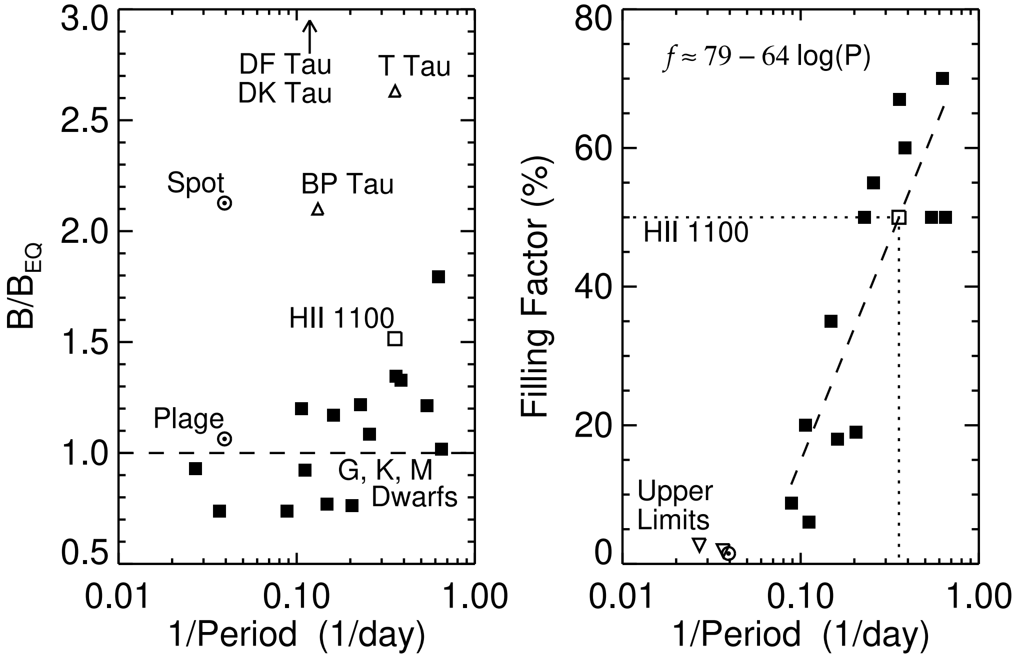

Figure 7. Magnetic field strength and filling factor vs. $1/P$

Figure 4 (lower) shows the same wavelength interval for a temperature sequence of inactive M dwarfs, numerically broadened by 4.5 km/s to mimic rotation of the flare star EV Lac (heavy histogram). Note that TiO lines in EV Lac are bracketed by inactive M dwarf spectra, but the Zeeman sensitive 8468.4 Å line is much broader. Line blends and instrumental artifacts would be visible in the inactive stars, so the excess line width in EV Lac must be magnetic field (see Kochukhov, this volume).

Figure 4 (upper) shows the ratio of active over inactive spectra. Zeeman insensitive TiO lines disappear (1% residuals), while a magnetic signature remains in Zeeman sensitive atomic lines. Separation of minima in the ratio yields field strength, while amplitude constrains filling factor. We fitted the observed ratio with the ratio of synthetic spectra, inferring $B = 3.8$ kG covering $\sim$60% of surface (Johns-Krull & Valenti 1996). Line cores are fit by the model, but the extended wings of 8468.4 Å imply a distribution of field strengths with depth and/or across the stellar surface.

Magnetic fields are obvious in cool T Tauri stars (TTS). Figure 5 shows IR spectra of inactive K7 dwarfs. Figure 6 shows the same wavelength interval for TW Hya, an accreting TTS. Inactive spectra are well matched by a $B = 0$ synthetic spectrum, as are Zeeman insensitive CO lines in TW Hya, but Zeeman sensitive Ti I lines are much broader than the $B = 0$ model. We fitted the Ti I lines with a distribution of field strengths (inset), inferring a mean B of 2.6 kG over the entire surface. Realistic magnetic atmospheres may change the field strength distribution. We measure comparable fields for a dozen TTS, including a TTS with no disk (see Johns-Krull, this volume).

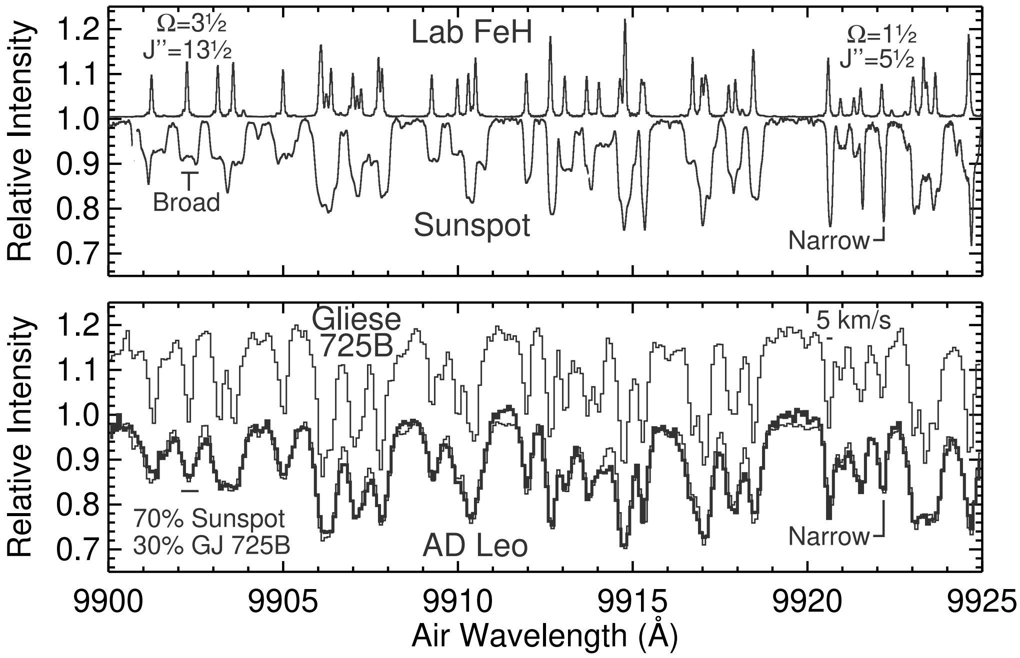

Figure 8. FeH in the lab, a sunspot, and active and inactive M dwarfs

Magnetic pressure commonly exceeds gas pressure in TTS photospheres, as in the solar corona. Typical Rossby numbers for TTS imply saturated activity (Figure 1), so the entire surface of TTS may be covered by magnetic fields and pressure equilibrium need not apply. Many TTS have fully convective envelopes and therefore lack a radiative zone in which to nurture a solar-like dynamo. A turbulent dynamo seems more applicable, as in late M dwarfs and perhaps the noncyclical component of solar activity.

Existing Zeeman broadening measurements, while imperfect, give rise to a useful equipartition hypothesis (e.g. Saar 1996) in which: (1) flux tube field strength depends only on gas pressure in nonmagnetic regions, (2) activity increases with fraction of the surface covered by flux tubes, (3) ratio of gas to magnetic pressure has a typical value empirically calibrated using the Sun, and (4) pressure balance inside and outside flux tube sets field strength. Equipartition is certainly violated for TTS, but may still hold for stars with incomplete surface coverage.

For G and K dwarfs, Fe I lines at 1.56 μm are more sensitive than the 8468.4 Å line. Using IR lines, Valenti et al. (1995) measured $B = 1.44{\pm}0.15$ kG covering $\sim$9% of ϵ Eri (K2V, $R'_{\rm HK}$=-4.4). HII 1100 (K3V) has $B = 2.50 \pm 0.09$ kG and $f \sim 50\%$. Does this significant difference in B violate equipartition? Figure 7 (adapted from Saar 1996) compares observed and equipartition B for main sequence stars, also showing that f scales with reciprocal rotation period, $1/P$. The latter correlation is surprisingly good, even without plotting vs. Rossby number. In fact, we boldly used a fit (valid only for periods yielding $0 < f <$ 100%) of f vs. $1/P$ to estimate P=2.8 days for HII 1100.

In Figure 7, $B_{\rm eq}$ is based on model gas pressure at $T = T_{\rm eff}$. Note that $B < B_{\rm eq}$ for stars with $P > 10$ days, while $B > B_{\rm eq}$ for $P < 5$ days. This rise in $B/B_{\rm eq}$ with activity may reflect a transition from plage to spot dominated surfaces, especially since sunspots exceed equipartition. Flux tube size may increase with filling factor, changing the temperature structure of magnetic regions and hence gas pressure where lines form. Equipartition may only be valid with an improved definition of $B_{\rm eq}$, based on realistic spot models for cool stars. Spot models would also reduce uncertainties in filling factor.

Existing Zeeman diagnostics are all atomic, but there is growing evidence of activity on very cool dwarfs. Molecular Zeeman diagnostics would be useful (see Berdyugina, this volume). Wallace et al. (1998) noted that Zeeman broadening of FeH lines grows with increasing J and Ω. Figure 8 (top) compares lab and sunspot spectra of FeH. Figure 8 (bottom) compares spectra of inactive and active M dwarfs. Lines that are broad in the sunspot spectrum are also broad in AD Leo. For example, lines at 9903.1 and 9903.6 Å are resolved in GJ 725B, but not in AD Leo. AD Leo is well matched by a mixture of rotationally broadened GJ 725B (30%) and sunspot (70%). 8468.4 Å yields a similar result, but FeH can be used to much cooler temperatures. Further progress awaits empirical, theoretical, or lab Landé factors for FeH.

Acknowledgments. We thank Steve Saar for laying the groundwork of our current understanding of magnetic fields on cool stars, and we thank Nikolai Piskunov for the radiative transfer tools we use to measure magnetic fields.

References

Baliunas, S. L. et al. 1995, ApJ, 438, 269

Donahue, R. A., Saar, S. H., & Baliunas, S. L. 1996, ApJ, 466, 384

Donati, J.-F. et al. 1997, MNRAS, 291, 658

Donati, J.-F. et al. 1999, MNRAS, 302, 437

Durney, B. R., De Young, D. S., & Roxburgh, I. W. 1993, SoPh, 145, 207

Johns-Krull, C. M. & Valenti, J. A. 1996, ApJL, 459, 95

King, J. R., Soderblom, D. R., Fischer, D., & Jones, B. F. 2000, ApJ, 533, 944

Noyes, R. W. et al., ApJ, 279. 763

Patton, B. M. & Simon, T. 1996, ApJS, 106, 489

Plachinda, S. I. & Tarasova, T. N. 2000, ApJ, 533, 1016

Rabin, D. M., Devore, C. R., Sheeley, N. R., Jr., Harvey, K. L., & Hoeksema, J. T. 1991, in Solar Interior and Atmosphere, (Arizona: UA Press), 781

Saar, S. H. 1996, in IAU Coll. 153, Magnetohydrodynamic Phenomena in the Solar Atmosphere – Prototypes of Stellar Magnetic Activity, eds. Y. Uchida, T. Kosugi, & H. S. Hudson (Dordrecht: Kluwer), 367

Schüssler, M. & Solanki, S. K. 1992, A&A, 264, 13

Sterzik, M. F. & Schmitt, J. H. M. M. 1997, AJ, 114, 1673

Valenti, J. A., Marcy, G. W., & Basri, G. 1995, ApJ, 439, 939

Wallace, L. et al. 1998, in NSO Technical Report #98–002, An Atlas of the Sunspot Umbral Spectrum in the Red and IR from 8900 to 15,050 cm^{-1}

Discussion

THOMAS: You began your talk by showing the close correlation between Ca II K emission and Rossby number for the F, G, and K stars. From dynamo theory, one expects activity to scale with dynamo number. For a dynamo in which the α effect and differential rotation are distributed throughout the convection zone, dynamo number scales with Rossby number alone. However, for an interface dynamo in which the α effect and differential rotation take place in different, adjacent layers, the scaling is not so simple. There is an additional dimensionless parameter involved, which measures the relative differential rotation in these stars. B. Montesinos and I have been looking at the implications of this using appropriate models and the observed activity-rotation relationship for these stars.

RÜDIGER: If a dynamo is embedded in vacuum, it cannot show toroidal field components at its surface. If observations reveal the existence of such fields, then the traditionally used vacuum boundary condition must not hold.

LINSKY: (1) Zeeman broadening measurements are very important because they provide approximate magnetic field strengths, which are energetically relevant. Polarization measurements tell us about the amount of cancellation of oppositely directed fields. The net field is not important energetically. (2) The filling factors are uncertain because we do not know whether the magnetic regions on stars are bright (like solar faculae) or dark.

VALENTI: Zeeman broadening and polarization measurements complement eachother, probing field strength and geometry respectively. Filling factors are indeed uncertain. If we can get model atmospheres for stellar flux tubes, observational constraints are adequate to determine the temperatures and filling factors of stellar magnetic regions.

ROSNER: For the Sun, one can construct a probability distribution function for surface magnetic field, which can be used to construct the fraction of the surface covered by fields of a given strength. These distribution functions are continuous. The "conventional wisdom" regarding active region (plage and spot) and quiet Sun field strengths is based on applying simple 2 or 3 component models to describe these distribution functions. How then do you interpret your B and f measurements? Have you applied the technique you describe to a high S/N solar spectrum?

VALENTI: For HII 1100, the 8468.4 Å line cannot constrain more than a single field strength and filling factor. For TW Hya, we use the 2.22 μm lines to fit a distribution of field strengths, but we still cannot probe below $\sim$2 kG for this moderate $v \sin i$ star. Beyond these limits, our only recourse is to use models to guide us as to the expected filed strength distribution functions. On the Sun, plage with flux above some threshold all have field strengths of about 1.6 kG, probably due to convective collapse. Perhaps convective collapse on very active stars also produces a preferred field strength. We use the Sun as a star as a null reference. It would be interesting to apply our technique to resolved solar plage or spot spectra, but we have not done this yet.