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DETECTION OF STRONG MAGNETIC FIELDS ON M DWARFS[1]

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ABSTRACT

We have detected Zeeman splitting of the Fe I line ($g_{\rm eff} = 2.5$) at 8468.40 Å in the very active M4.5 Ve stars Gliese 729 and Gliese 873 (EV Lac). High-resolution ($R = 120{,}000$), low-noise (∼0.5%) spectra show clear Zeeman-shifted σ components from which we infer field strengths of 2–4 kG, independent of uncertainties in model atmospheres. Similar observations of a sequence (M0 V–M5 V) of low-activity M dwarfs demonstrate that the wing components in the 8468.40 Å line are not due to the ubiquitous TiO lines in the vicinity. This strongly suggests that discrepancies in the shape of the magnetically sensitive iron line are due to magnetic fields rather than differences in photospheric temperature. By fitting the ratio of active to inactive line profiles with simple one-component models, we estimate that 50 ± 13% of the photosphere of EV Lac is covered by 3.8 ± 0.5 kG magnetic fields, while 50 ± 13% of Gliese 729 is covered by 2.6 ± 0.3 kG fields. This confirms earlier reports of large magnetic fields on M dwarf flare stars. We see evidence for a distribution of magnetic field strength, spatially across the surface and/or with depth. The twofold increase in field strength relative to G and K dwarfs is predicted by flux tube equilibrium arguments, but the 1 kG difference in the measured field strengths for these two stars suggests that field strengths may also grow with activity as the photospheric filling factor approaches unity.

Subject headings: line: profiles — stars: individual (EV Lacertae, Gliese 729) — stars: magnetic fields

1. INTRODUCTION

Magnetic fields almost certainly play a fundamental role in the physics of late-type stellar atmospheres. For example, there is a good correlation between rotation period (or better yet, Rossby number) and emission from chromospheres, transition regions, and coronae (Noyes et al. 1984; Simon & Fekel 1987; Basri 1987; Rutten & Schrivjer 1987). Together with observations of the solar magnetic cycle, this suggests that heating in the upper atmosphere is related in part to magnetic fields generated by a dynamo. Details of both the dynamo and heating mechanisms are poorly understood, in part because stellar magnetic fields are difficult to measure. Because the Sun is a relatively inactive star, extrapolating solar results to other spectral types and/or to more active stars is speculative. At the same time, studies of stellar magnetic fields provide an important context for interpreting solar data. Below, we demonstrate a valuable technique for measuring magnetic fields on active M dwarfs.

Magnetic fields on late-type stars have typically been measured by comparing two or more line profiles that cover a range in magnetic sensitivity (Robinson 1980; Marcy 1984; Gray 1984; Saar 1988; Basri & Marcy 1988; Mathys & Solanki 1989; Marcy & Basri 1989; Basri & Marcy 1994). For G and K dwarfs, field strengths of 1–2 kG covering 10%–50% of the photosphere have been reported. Large measurement errors are common because the splitting of the Zeeman σ components in the optical is less than the intrinsic line width due to thermal, turbulent, collisional, and rotational broadening. For the $g_{\rm eff} = 2.5$ Fe I line at 8468.40 Å, the σ components split by an amount

$$\Delta\lambda = \frac{e}{4\pi mc^2}\,\lambda^2 g_{\rm eff}|\boldsymbol{B}| = \pm 83.7\,|\boldsymbol{B}|\ {\rm m\AA\ kG^{-1}}, \qquad (1)$$

where $|\boldsymbol{B}|$ is the strength of the magnetic field at the characteristic depth of line formation. Because the 1–2 kG fields on G and K dwarfs are not large enough to fully split optical lines, careful spectrum synthesis is needed to recover magnetic parameters. The accuracy of this technique is limited by uncertainties regarding the thermodynamic structure of magnetic (and even nonmagnetic) regions on active stars.

When σ components actually separate out of the line core, derived magnetic parameters are substantially improved because there is no longer any confusion with other broadening mechanisms. For late-type stars, σ components have been resolved using spectral lines in the infrared, where the Zeeman effect is enhanced. On the other hand, IR spectrographs are not yet as efficient as optical spectrographs, so instrumental limitations have been a problem. Nonetheless, significant progress has been made using IR diagnostics to measure stellar magnetic fields (Saar 1988, 1994a, b; Valenti, Marcy, & Basri 1995).

Using Kitt Peak FTS spectra with a resolution of 64,000 and 2% noise, Saar & Linsky (1985) found that 4 kG magnetic fields cover much of the surface of the very active M dwarf, AD Leo. Magnetic fields have now been reported (Saar 1994b) for a total of three M dwarfs: EV Lac ($|\boldsymbol{B}| = 4.3$ kG, $f = 85\%$), AD Leo ($|\boldsymbol{B}| = 4.0$ kG, $f = 65\%$), and AU Mic ($|\boldsymbol{B}| = 4.2$ kG, $f = 55\%$). These consistently high field strengths are remarkable when compared to results for G and K stars, but models

[1] Based on observations obtained at the McDonald Observatory operated by the University of Texas at Austin.

TABLE 1

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Gliese Number	Spectral Type	log (L_X/L_{bol})	Exposure (hr)	S/N
825.....	M0 V	−5.38	0.6	280
880.....	M2 V	−5.17	1.5	220
752A...	M3 V	−5.40	1.6	220
725B...	M3.5 V	−5.20	1.9	270
729.....	M4.5 Ve	−3.50	2.1	170
873.....	M4.5 Ve	−3.07	3.0	240
876.....	M5 V	−5.24	3.0	170

of flux tube equilibrium predict that higher surface pressures on M dwarfs should result in higher magnetic field strengths (Spruit & Zweibel 1979). Furthermore, a large fraction (~0.1%) of the bolometric luminosity of active M dwarfs is in the form of X-rays (Fleming 1993), indicating extremely active coronae and by inference, large magnetic filling factors.

The field strengths on active M dwarfs are so large that the σ components are split out of the core of the Fe I line at 8468.40 Å. This means we can use efficient optical spectrographs to measure accurate magnetic field parameters for M dwarfs, while circumventing the difficulties currently associated with high-resolution infrared spectroscopy. Using the Fe I line at 8468.40 Å together with other spectral diagnostics, we have begun to measure magnetic field parameters for several nearby M dwarfs. We report initial results here, which demonstrate the value of the line at 8468.40 Å as a magnetic probe for this important class of stars.

2. OBSERVATIONS AND DATA REDUCTION

Spectra were obtained with a double-pass, cross-dispersed, echelle spectrometer (Tull et al. 1995) on the Harlan J. Smith 2.7 m telescope at the McDonald Observatory. A Tektronix 2048 × 2048 CCD was used at the F1 focus with a 0.″59 slit to achieve a spectral resolving power of 121,000 with 4.65 pixels per resolution element. Total observing time for each star was a few hours, split into subexposures of ~1 hr. Spectra were reduced using an automated echelle reduction package written in IDL (Valenti 1994). Wavelengths were determined by fitting a two-dimensional polynomial to $n\lambda$ as function of pixel and order number, n, for a total of 97 thorium lines. Table 1 summarizes the observations.

3. ANALYSIS

Figure 1 (Plate L13) shows segments of our echelle spectra in the vicinity of the magnetically sensitive Fe I line at 8468.40 Å. Numerous weaker features are also present, complicating a straightforward identification of resolved σ components. There are two atomic lines located at 8467.13 and 8468.47 Å, both due to Ti I. They have g_{eff} of 1.125 and 1.100 with 21 and 27 Zeeman components, respectively. The Ti I line at 8468.47 Å provides additional opacity near the core of the Fe I line, but the resulting change in the Fe I line profile is only a few percent. Nonetheless, the blends should be included in any detailed model. The Ti I line at 8467.13 Å can be used to constrain the abundance, ionization, and excitation of Ti, allowing the effects of the 8468.47 Å line to be predicted. Most, if not all, of the other spectral features in Figure 1 are due to TiO.

To empirically characterize spectral behavior as a function of temperature, we observed inactive M dwarfs ranging in

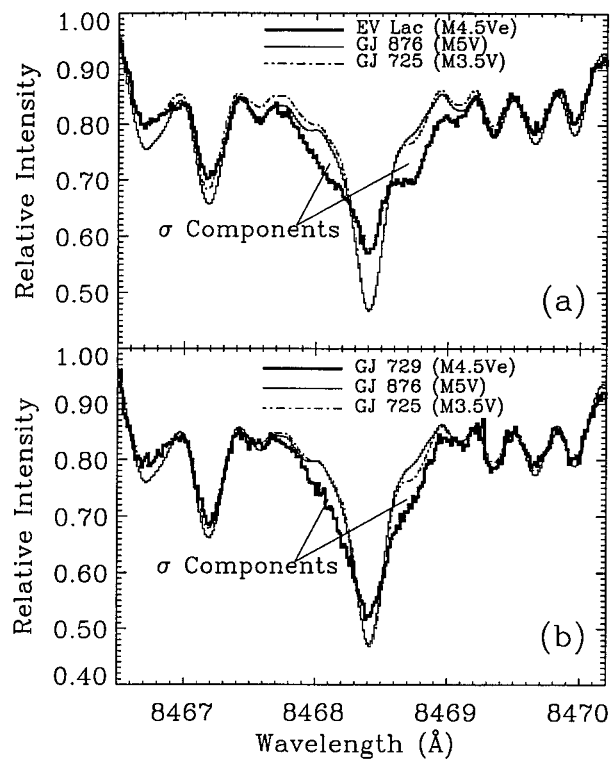

FIG. 2.—(a) Spectra of EV Lac and two inactive M dwarfs of similar spectral type in the wavelength interval around the Zeeman-sensitive Fe I line at 8468.4 Å. (b) Similar plot for Gliese 729. For both stars, the Zeeman split σ components are indicated.

spectral type from M0 V to M5 V. The rotational broadening experienced by EV Lac was simulated by numerically broadening the inactive spectra, using a standard limb-darkening law (Gray 1992) with $\varepsilon = 0.35$, determined from a preliminary $T_{eff} = 3100$ K model (Allard & Hauschildt 1995). The results are shown in Figure 1. Using the TiO lines near 8468 Å and the TiO bandhead near 7087 Å, we estimate that $v \sin i$ is 4.5 ± 0.5 km s^{-1} for EV Lac and 3.5 ± 0.5 km s^{-1} for Gliese 729. More accurate values will follow from a detailed analysis of the entire spectrum. The low activity M dwarfs require similar broadening to match the active stars, so their $v \sin i$ are probably all below 1 km s^{-1}. This agrees with the results of Marcy & Chen (1992), who found 0.8 ± 1.0, 2.8 ± 2.2, and 1.1 ± 1.1 km s^{-1} for Gliese 729, 876, and 880. Our $v \sin i$ of 4.5 km s^{-1} for EV Lac is consistent with the equatorial velocity of 4.2 ± 0.5 km s^{-1} reported by Pettersen (1980) on the basis of a 4.378 day photometric period, if the inclination is more than about 60°. On the other hand, Pettersen (1980) argues that the sinusoidal form of his light curve suggests a low inclination.

Figure 1 shows that the TiO lines all strengthen toward later spectral types, providing a valuable temperature diagnostic. Except for the Fe I line at 8468.40 Å, the EV Lac (M4.5 Ve) spectrum is well bracketed by spectra of Gliese 752A (M3.5 V) and Gliese 876 (M5 V). An equivalently good correspondence holds for the flare star Gliese 729 (M4.5 Ve). *This strongly suggests that the discrepancies in the shape of the magnetically sensitive iron line are not due to simple differences in photospheric temperature.* We believe the extra components seen in the wings of the Fe I line in EV Lac and Gliese 729 (Fig. 2) are σ components that have separated out of the line core due to the presence of strong magnetic fields. The line core is also substantially weaker in the flare stars, as expected if magnetic fields are shifting opacity into the line wings.

Spectral changes due to the magnetic field are seen more clearly in the ratio of active to inactive line profiles. Figure 1 demonstrates that Gliese 725B (M3.5 V) best matches the various TiO features in the spectrum of EV Lac (and also Gliese 729), so we construct line ratios using Gliese 725B as an inactive reference. Figure 3 shows that the molecular features divide out well, leaving a characteristic magnetic signature (Valenti et al. 1995), which we then model. Choosing Gliese 752A or the average of Gliese 725B and 752A as the inactive reference yields slightly different magnetic parameters, contributing to the uncertainties quoted below. By modeling the line ratio, we may (to first order) ignore molecular and atomic blends as well as systematic errors in the grid of model atmospheres, which is reasonable for this preliminary analysis.

We synthesized line profiles with and without magnetic fields, using in both cases a model (Allard & Hauschildt 1995) with $T_{\rm eff} = 3100$ K (see Table 1 of Neff, O'Neal, & Saar 1995) and log $g = 5.0$. Changes in the Fe I profile because of the magnetic field were modeled using a Stokes transfer code (Basri & Marcy 1988; Valenti et al. 1995), ignoring the effects of the Ti I 8468.47 Å blend (see below). We will treat blends and molecular opacity in more detail in a later paper.

Using a solar iron abundance yields 8468.40 Å synthetic profiles that are 50% *deeper* than the observed lines in Gliese 725B and 876. Although these stars have galactic disk (rather than halo) kinematics, their low activity levels suggest considerable age (Stauffer & Hartmann 1986) coupled with low abundances. In fact, for $T_{\rm eff} = 3100$ K, we find that models with [Fe/H] $= -0.85 \pm 0.15$ match the inactive template fairly well. This estimate does not include iron locked up in FeO and FeH, although the effects of these molecules are included in the models of Allard & Hauschildt (1995), which we use. Since the activity of our flare stars indicates youth, we use solar abundances to calculate profiles for the active stars. After dividing by inactive profiles constructed from the lower metallicity models, the magnetic parameters of the active models are adjusted to match the observed ratio (Fig. 3).

The dash-dotted lines in Figure 3 show model line profile ratios determined by minimizing χ^2 for the bold pixels shown in the two panels. The dashed lines in Figure 3 show the result when fitting to the line core in addition to the bold pixels. No simple model fits the entire observed line ratio. In our fits, we emphasize wing points because they provide a more definitive magnetic signature and they are less likely to be affected by global heating of the upper atmosphere. More realistic models with a temperature rise in the upper atmosphere of the magnetic regions should give shallower active profiles, reduce the contrast in the core of the line ratio, and yield better agreement with the observations. By varying which points we include in the fit and experimenting with warmer models ($T_{\rm eff} = 3500$ K), we obtain an estimate of possible systematic errors. We find $|\boldsymbol{B}| = 3.8 \pm 0.5$ kG with $f = 50 \pm 13\%$ for EV Lac and $|\boldsymbol{B}| = 2.6 \pm 0.3$ kG with $f = 50 \pm 13\%$ for Gliese 729. In all tests, $|\boldsymbol{B}|$ on EV Lac is nearly 1 kG stronger than the fields on Gliese 729 for a similar treatment of both stars, implying that the difference is significant.

For simplicity, we have assumed that the magnetic and quiet regions on active stars have identical atmospheric structure, ignoring any flux weighting that might bias the measured filling factor. In reality, magnetic regions probably consist of both plagelike and spotlike structures. With the large filling factors

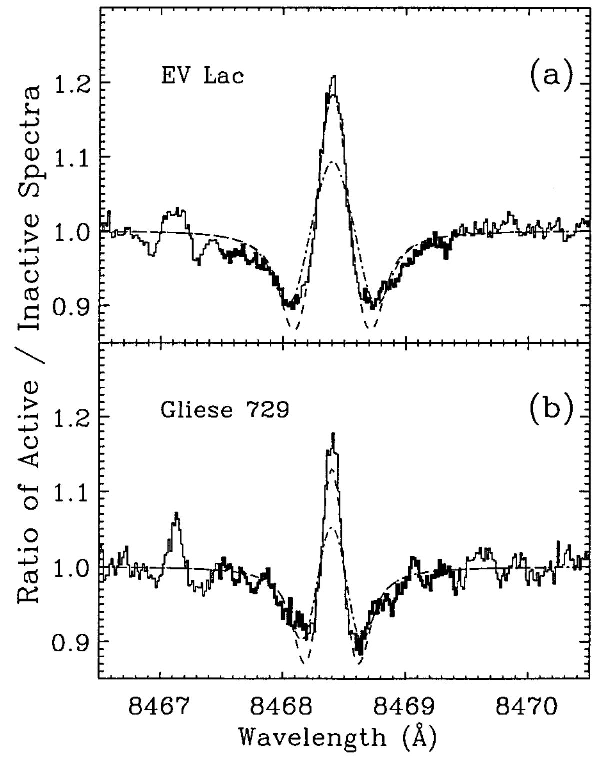

FIG. 3.—(*a*) Histogram shows a line profile ratio, constructed by dividing the observed spectrum of EV Lac by that of Gliese 725B. The darker segments in the line wings were used to fit a model ratio ($|\boldsymbol{B}| = 4.2$ kG, $f = 40\%$) indicated by the dash-dotted curve. Including the line core in fit as well gives the model fit ($|\boldsymbol{B}| = 3.4$ kG, $f = 60\%$) indicated by the dashed curve. (*b*) Similar plot for Gliese 729 and Gliese 725B. The dash-dotted model is ($|\boldsymbol{B}| = 2.8$ kG, $f = 40\%$), and the dashed model is ($|\boldsymbol{B}| = 2.4$ kG, $f = 60\%$). The additional feature at 8467.1 Å is a Ti I blend that also appears to show a Zeeman signature.

implied by the observations, it is plausible that the field is organized into large spots that dominate the flux from magnetic regions, despite their cooler temperatures. Such behavior would be consistent with the inverse correlation between chromospheric emission and bolometric luminosity seen in stars as active as EV Lac (Radick, Lockwood, & Baliunas 1990). Spots would have lower continuum flux, implying true filling factors somewhat larger than we have estimated. Simultaneous photometry and magnetic field measurements will help to clarify this issue.

Ti I blends have been ignored in this preliminary analysis, and it is difficult to predict what systematic effects this might have on derived parameters. The Ti I line at 8467.13 Å does not completely divide out in Figure 3, but instead has a ratio signature similar in character to the magnetic signal of the 8468.40 Å Fe I line. This suggests that the Ti I blend at 8468.47 Å line may also be similarly affected (contrary to our implicit assumption that it divides out in the line ratio). However, this should not greatly affect our magnetic field determinations because the Ti I line has a $g_{\rm eff}$ that is 2.3 times smaller than that of the Fe I line and the equivalent width of the Ti I line is expected to be less than 25% that of the Fe I line. Also, our measured field strengths depend primarily on the wings of the Fe I line, where there should be little contamination from the Ti I blend. In fact, Zeeman broadening of the 8468.47 Å Ti I line would remove opacity from the core of the Fe I line, boosting the core of the line ratio and possibly improving the fit.

Stellar magnetic fields apparently have a characteristic strength set by the confining pressure of the surrounding nonmagnetic atmosphere (Saar 1990). Nonetheless, variations in field strength are expected with depth due to changing external pressure (Grossmann-Doerth & Solanki 1990) and spatially across the surface (due to variations in cross-sectional size, which affects the coupling to the external thermal structure). Both effects are seen in the Sun (see, e.g., Solanki 1993), and some combination of the two has been reported for AD Leo (Saar 1992). We note that the far wings of the line ratios shown in Figure 3 (especially EV Lac) cannot be reproduced with any single magnetic field value. This provides direct observational evidence for a distribution of magnetic field strengths, either spatially across the star or with depth in the line formation region.

4. DISCUSSION

Theoretical models of flux tube equilibrium predict that magnetic field strength should scale with external gas pressure (Spruit & Zweibel 1979), but the $\sim$1 kG difference in the field strength for these two stars with similar surface pressures indicates that future refinements of these ideas may be needed. One possibility is that at high photospheric filling factors, it is the magnetic (rather than the nonmagnetic) component that transports a majority of the energy and therefore determines the global pressure structure. Our initial results suggest that increased activity in the most active M dwarfs manifests itself as a stronger magnetic field, rather than a higher filling factor, in contrast to the behavior seen for less active stars with earlier spectral types. $|\boldsymbol{B}|f$ is slightly higher on EV Lac than on Gliese 729, which is as expected, since EV Lac rotates more rapidly than Gliese 729, and has a larger X-ray flux (Fleming et al. 1995) and Hα equivalent width (seen in our data). We have used the Zeeman-sensitive Fe I line at 8468.40 Å to measure magnetic fields on the active M dwarfs EV Lac and Gliese 729. We find fields in the 2–4 kG range, which are about twice as strong as the fields measured on G and K stars. This confirms existing results, based on infrared spectroscopy (Saar & Linsky 1985; Saar 1994b).

These stars are part of a larger survey of nearby M dwarfs. Once the survey is complete, we hope to quantify the relationship between rotation rate, magnetic field strength, filling factor, and nonradiative heating. Spectra obtained for this project contain other magnetically sensitive lines, such as Fe I lines at 8688.60 Å ($g_{\rm eff}$ = 1.7) and 6430.80 Å ($g_{\rm eff}$ = 1.2), as well as the Ti I lines mentioned above. Simultaneous analysis of all these lines will eventually allow us to set limits on both $|\boldsymbol{B}|$ and f for a sample of $\sim$20 active M dwarfs. Combined with the accurate $v \sin i$-values, these echelle spectra will provide better constraints for stellar dynamo theory.

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FIG. 1.—Spectra of EV Lac and a sequence of five low activity M dwarfs (M0 V to M5 V). Most of the features are TiO lines that systematically strengthen with increasing spectral type, providing a sensitive temperature diagnostic. TiO features in the spectra of Gliese 725B and Gliese 876 nicely bracket the spectrum of EV Lac, but there is a large discrepency in the Zeeman-sensitive Fe I line at 8468.40 Å. Zeeman split σ components are visibly shifted out of the line core and into the wings, allowing a fairly direct determination of the magnetic field strength.

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