4 METER FTS OBSERVATIONS OF PHOTOSPHERIC MAGNETIC FIELDS ON M DWARFS

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I. INTRODUCTION

Much of the observed activity on M dwarfs (e.g., spots, flares, chromospheric and coronal emission) has been attributed to the interaction of magnetic fields with the stellar atmosphere. Since data on the magnetic field parameters of M dwarfs can potentially reveal much about the physical mechanisms behind these phenomena and, additionally, about stellar dynamos and the evolution of stellar angular momentum, we have begun a program to measure the mean magnetic field strength (B) in stellar active regions, and the surface filling factor (f) of these regions for a sample of M dwarfs. In this paper we discuss some preliminary results of this survey.

II. OBSERVATIONS AND ANALYSIS

We used the National Optical Astronomical Observatory's Fourier Transform Spectrometer at the Mayall 4 meter telescope (4mFTS; Hall et al. 1979) to observe M dwarfs at high resolution (λ/Δλ = 40,000) in the K band. The 4m FTS proved particularly useful for observing M dwarfs, whose optical spectra are unsuitable because of line blends from molecular bands (e.g., Pettersen and Hawley 1987). We typically observed near the Ti I multiplet at 2.2 μm with R = 40,000 and S/N ≥ 30.

We began the analysis of the optical lines by modeling a collection of low Lande g (low magnetic sensitivity) profiles for rotational, macro- and microturbulent broadening. In particular, there is a g = 0.000 Fe I line at 4464.5 cm⁻¹ which can be used for determination of the velocity broadening in many stars. The simple LTE, Milne - Eddington line model of Saar (1987; see also Saar, Linsky, and Beckers 1986) was used with the modifications of Saar and Linsky (1987) to include full-disk integration of the line profiles. A depth-independant microturbulence of 1 km s⁻¹ and a limb-darkening coefficient of 0.4 was assumed. The average v sin i values derived from low g lines is given in Table 1. These values for the velocity broadening were then used in modeling magnetically sensitive line profiles (g > 1.0). Typical data and models are shown in Figures 1 and 2.

In this initial work, we have modeled the line profiles directly, with no attempt to compensate for line blends. The derived B and f values should therefore be regarded as preliminary due to the incomplete nature of the analysis.

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III. IMPLICATIONS FOR DYNAMO AND ACTIVITY THEORIES

There is a definite trend of increasing B towards the cooler dwarf stars. We interpret this result to be due to a functional relationship between B and $B_{eq}$, the equipartition value of the magnetic field strength (Fig. 3). $B_{eq}$ was calculated by setting the magnetic pressure equal to the photospheric gas pressure ($P_{gas}$) at continuum optical depth unity in models (Mould 1976, Kurucz 1985), so that $B_{eq} = (8\pi P_{gas})^{0.5}$. We then scaled $B_{eq}$ slightly by normalizing to the observed solar network magnetic field strength of 1500 G. The M dwarfs continue the tight linear correlation between B and $B_{eq}$ seen in G and K stars, strongly suggesting that the external photospheric gas pressure confines magnetic flux tubes on late-type stars and determines their photospheric magnetic field strengths (e.g., Galloway and Weiss 1981). The field strengths on the three M dwarfs with detected fields are smaller than Mullan’s (1975) estimates by a factor of about 2.

The filling factor, unlike B, shows no obvious dependence on $T_{eff}$ for G, K, and M dwarfs. Instead, f shows a correlation with angular velocity. The correlation is improved when $fB$ is plotted against $\Omega$. Gray (1985) has proposed that the magnetic flux ($\propto fB$) is a constant in late-type dwarfs. This is clearly not the case for our sample of M dwarfs. There is also no $f \propto B^2$ dependence, as would occur if errors in the separation of B and f dominated the results (Gray 1984). The present M dwarf data seem to indicate that the $f - \Omega$ relation may be fit with two power laws: $f \propto \Omega$ for $\Omega < 0.25$ days$^{-1}$, and a saturated level of $f \approx 0.80$ for larger $\Omega$ (Fig. 4). The two power law model is consistent with the saturation of magnetic activity indicators at high angular velocities noted by many investigators (e.g., Walter 1982; Vilhu 1984a). More data at large $\Omega$ is needed, however, to confirm this idea, since at present it depends critically on the magnetic parameters of only one star: AD Leo with $f = 0.73$ and $\Omega = 0.4$. If further data bear out this apparent initial trend, once the surface of a star becomes nearly covered with magnetic activity, B begins to depend on $\Omega$.

Many dynamo theories predict $B \propto \Omega$, e.g., Stix 1972). The linear correlation of $fB$ with $\Omega$ (or inverse Rossby parameter) is consistent with these theories if the theoretical B is identified with the surface-averaged field, $fB$. The only predictive dynamo theory that separately considers both f and B (Durney and Robinson 1982; hereafter DR), assumes equipartition B values and computes the filling factor to scale as $f \propto B^{-1.5} \Omega^{2.5}$, in disagreement with our results. We note that all flare stars (excluding the very low amplitude flare star GL 229) are observed to have large filling factors, consistent with the idea that magnetic reconnection events are stronger and more frequent on these stars. The inclusion of a magnetic flux reconnection timescale in the DR theory might therefore improve (reduce) the filling factor estimates of their model. It is also clear that even stars which are nearly fully convective (AD Leo and EV Lac) can generate enormous amounts of magnetic flux. Perhaps a distributed dynamo operates throughout the convection zone in these stars (Giampapa and Liebert 1986), in contrast with the shell dynamos believed to operate just below the convection zone in warmer objects (Gilman and DeLuca 1986). Inclusion of this possibility would also require changes in the DR theory.

The simple dynamo model of DR predicts that even inactive M dwarfs (with $\Omega \approx \Omega_0$) should have large filling factors (> 50%) and equipartition field strengths. Their model predicts that more rapid rotation (such as in dMe stars) will produce complete coverage of the stellar surface with magnetic regions. The 4m FTS data appear to clearly contradict the first of these predictions. With the exception of GL 229, a weak flare star, none of the dM stars we observed have measurable magnetic splitting or broadening in their line profiles (Fig. 2, Table 1). Upper limits to the magnetic filling factors derived assuming equipartition field strengths are typically less than 0.20. It is possible that magnetic fields on dM stars are much smaller than the photospheric pressure balance value (Chou 1986), but this seems unlikely since active stars of the same spectral types (GL 229, AD Leo and EV Lac) follow the $B \propto B_{eq}$ relation along with the G and K stars. This would require activity-dependent magnetic field strengths that are not seen in any other regime of late-type stars.

In this context, the predictions of Giampapa (1985) concerning the filling factors of M dwarfs
must also be reexamined. Using models developed by Cram and Mullan (1979), Giampapa (1985) demonstrated that there should be almost no radiative equilibrium contribution to the Hα line in M dwarfs. The appearance of Hα in either absorption (in excess of some minimal amount) or in emission is thus an indicator of a substantial level of chromospheric activity and nonradiative heating. He derives lower limits to filling factors of the Hα emitting regions, and assumes that they are magnetic field related. For stars with color indexes of (R-I) ≈ 0.9 (about spectral type M3 or M4) from an extensive survey by Stauffer and Hartmann (1986), Giampapa infers f > 0.3 - 0.6, which conflicts with our lower limits of f < 0.2. On the other hand, our limits agree for one of the four stars where he lists a prediction: we find f < 0.25 for GL 273 and Giampapa obtains f > 0.10. In general, however, Giampapa’s filling factors seem high in comparison with the trends observed here.

We can think of three possible explanations for this disagreement. First, filling factors for dM stars are in fact typically ≈ 50%, and their magnetic fields are small enough (B < 500 G) that the spectral resolution of the 4m FTS data is inadequate to clearly resolve them. As stated above, however, this seems unlikely because B ∝ B_{eq} for dMe stars. Second, Giampapa’s filling factors are determined from the Hα line and thus do not refer to the same level in the atmosphere as the magnetic observations. A substantial divergence of the magnetic field lines between the photosphere to the level of Hα formation could then explain the disagreement between the filling factors. A third possibility is that non-magnetic heating is responsible for much of the Hα absorption seen in dM stars. Recent observational (Schrijver 1987) and theoretical (Bohn 1984) evidence indicates that acoustic wave heating could be much more important to the formation of M dwarf chromospheres than previously suspected. Further observations of dM magnetic fields and activity indicators are needed to resolve which of these suggestions is correct.

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REFERENCES


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Table 1: Preliminary Magnetic Parameters of M Dwarfs

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<th>Gliese Number</th>
<th>Spec. type</th>
<th>R-I</th>
<th>log (L_\odot)</th>
<th>S/N</th>
<th>(v\sin i) (km s(^{-1}))</th>
<th>f</th>
<th>B (kG)</th>
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<td>15A</td>
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<td>0.88</td>
<td>27.1</td>
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<td>&lt;3</td>
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*fs = flare star, BY = spotted BY Draconis variable

Figure 1. 4m FTS data (crosses) for 3 M dwarfs of similar spectral type. The inactive dM4 star GL 273 and the sunspot umbra line profiles (Hall 1973) are shown for comparison with the Na I lines from GL 873 (EV Lac) and GL 388 (AD Leo), which show evidence for strong, widespread magnetic fields. Radiative transfer models (solid) and the derived magnetic parameters are given.
Figure 2. FTS data for 3 coronally inactive dM stars. Note that none of the line profiles in this Ti I multiplet shows significant evidence of Zeeman splitting or broadening.

Figure 3. $B$ versus $B_{eq} = (8\pi P_{\odot})^{0.5}$. The M dwarfs (starred points) extend and confirm the trend $B \propto B_{eq}$ indicated by the G and K dwarfs (crosses).
Figure 4. $f$ versus $\Omega$. The most active of the M dwarfs (starred points) in the sample appear to define a saturated level at $f \approx 0.80$. 
DISCUSSION (Paper II.1.)

VOGT : Do you see any evidence for time variability of surface fields ?

SAAR : So far, we have not had enough FTS time to see magnetic variability on M dwarfs. In the optical, where measurements are rather more difficult, we believe we see significant variations, particularly in the filling factor on active G and K stars such as Xi Boo A.

MATHYS : With other techniques of magnetic field diagnosis in late-type stars, such as those employed by Robinson and Marey, one does not derive the filling factor of itself but rather the product \( f \delta_c \delta_1 \), where \( \delta_c \) (resp. \( \delta_1 \)) is the brightness contrast in the continuum (resp. in the lines) between the magnetic and non-magnetic regions of the stellar surface. Does your modelling approach account for this and thus permit you to determine \( f \), or do you actually obtain the product \( f \delta_c \delta_1 \) too ?

SAAR : We assume that the magnetic and non-magnetic regions are identical, apart from the presence of magnetic field. Our filling factors, therefore, are weighted by the thermodynamic properties of the magnetic region. Your statistical multiline technique, which is more sensitive to the thermodynamic properties of the quiet and active regions, is very complementary in this way to our detailed profile modelling.