THE APPEARANCE OF MAGNETIC FLUX ON THE SURFACES OF THE EARLY MAIN-SEQUENCE F STARS

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Received 1984 April 30; accepted 1984 July 23

ABSTRACT

We examine available chromospheric, transition region, and coronal observations of the early main-sequence F stars to find that while these objects exhibit enhanced levels of magnetic-field-related radiative emissions, significant inhomogeneities in surface activity are not present. We discuss this phenomenon within the context of the calculations published by Schmitt and Rosner in 1983 for the production of flux ropes of various spatial scales at a given rotation rate at the bottom of a stellar convection zone. We find that the spatial scales and area contrast of emergent magnetic flux in these stars that, as a class, are characterized by rapid rotation and thin convection zones are substantially reduced relative to that of the Sun.

Subject headings: magnetic fields — stars: atmospheres — stars: magnetic

I. INTRODUCTION

Determination of the magnetic field configurations that appear on stellar surfaces can ultimately provide valuable constraints for theories of magnetic field generation and magnetic flux tube formation in stars. In the case of the Sun, much work has recently been done in this regard (cf. Galloway, Proctor, and Weiss 1978; Golub \textit{et al.} 1981; Rosner 1983; Parker 1983; Schüssler 1983; and references therein); and recent observational studies have revealed the presence of magnetic field structures analogous to sunspots, solar plages, and solar coronal loops on the surfaces of late-type stars. In this Letter, we focus on recent observational studies of dwarf F stars and discuss the implication of these studies for magnetic field activity in these stars.

The long-term pioneering study by Wilson (1978) of chromospheric Ca II resonance line variability, combined with the results attained through seasonal monitoring of these same spectral features by Vaughn \textit{et al.} (1981; see also Baliunas \textit{et al.} 1983) at Mount Wilson, have disclosed the typical occurrence of asymmetrically distributed, localized "centers of activity" extending over significant fractions of the visible surfaces of late-type, main-sequence stars. In addition, Radick \textit{et al.} (1982, 1983a, b) have discovered that solar-type stars exhibit luminosity variability associated with the disk passage of spots that is analogous to the solar luminosity variability discovered with the \textit{Solar Maximum Mission} ACRIM experiment (Willson \textit{et al.} 1981). Of course, the occurrence of large spots on dMe stars (the so-called BY Draconis syndrome) and on the active component of RS CVn systems (viz. Catalano 1983; Vogt and Penrod 1983) is well known.

We extend these previous studies in the present investigation through the deduction of the likely appearance of magnetic field configurations on the surfaces of the early main-sequence F stars; these stars are of particular interest because theory predicts that they have shallow outer convection zones, and hence rather different dynamo properties than more solar-like stars. Furthermore, dF stars are, as a class, characterized by relatively rapid rotation rates. It is therefore clear that knowledge of the surface magnetic field morphology of these stars can provide useful constraints on models of stellar magnetic flux generation, emergence, and surface distribution.

In the following section, we briefly summarize the surface distribution and spatial scales of emergent magnetic flux on the early dF stars, as inferred from available data extending from the soft X-ray to the optical. We then discuss the implications of these observations for the magnetic field configurations that occur on the surfaces of early dF stars and consider a variety of hypotheses that may account for the inferred localized magnetic surface structures. We summarize our results and present suggestions for future research in § III.

II. DISCUSSION

Inspection of the Ca II H and K line observations presented by Wilson (1978) reveals that either the early dF stars do not exhibit cycles, analogous to the solar cycle and the cycles of later type stars, or that such periodic fluctuations which may be present are of sufficiently low amplitude as to be undetectable at present. Furthermore, the Ca II resonance line spectrophotometry reported by Vaughan \textit{et al.} (1981) and Baliunas \textit{et al.} (1983) indicate that rotational modulation of stellar active regions is again either not present, or occurs only at very low amplitudes, in the early dF stars. Moreover, Radick \textit{et al.} (1982, 1983a, b) find that continuum variability at their detection limit of 0.5% is not present among main-sequence stars earlier than F7.

These results would seem to indicate a relatively low level of magnetic-field-related chromospheric, and by implication, coronal activity on the early dF stars. However, the surface fluxes of the chromospheric Ca II H and K emission cores of a

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limited sample of early dF stars are ~5–10 times greater than that of the quiet Sun (Linsky et al. 1979). Furthermore, Saxner (1981) reports the observation of transition region surface fluxes among early dF stars that are comparable to those of active binaries, such as RS CVn systems. Finally, the soft X-ray luminosities of main-sequence F stars are, as a class, enhanced by factors of 10–100 times that of the quiet Sun (Vaiana et al. 1981; Topka 1980; Walter 1983; Schmitt et al. 1984). We therefore conclude that the early dF stars are, in fact, characterized by enhanced levels of magnetic-field-related atmospheric activity, at least relative to dwarf stars of the spectral type of the Sun.

How do we explain the absence of variability that is usually associated with the presumed appearance of plage and spots on active stars (e.g., see Giampapa 1983a, b)? As just discussed, the key observational fact is that the stars in question are presumably extremely active magnetically: if the levels of surface X-ray and Ca II fluxes are correlated with solar magnetic field activity, then the aforementioned data imply that the stellar surface is well covered by magnetic structures. What theory must then account for is the absence of significant modulation in the observed large radiative fluxes due to rotational modulation of the expected inhomogeneous surface.

Such a lack of modulation implies directly that significant inhomogeneities in the surface activity level cannot be present. In the solar case, such inhomogeneities are of course referred to as “active regions”; these regions mark the major sites of large-scale magnetic flux emergence. There are two distinct reasons that such regions might not be observed in the present case:

1. They do exist, but persist only for time scales significantly shorter than the rotation period. This might occur either because the turbulent diffusion rate is significantly higher than in the solar case or because systematic surface shear flows (such as latitudinal differential rotation, as proposed by Shore and Hall 1980 for RS CVn stars, a rather different type of star than we are considering here) redistribute the emerged flux in longitude on time scales short with respect to the rotation period. In either case, one might never see significant inhomogeneity because during the short period (“birth”) in which a given region of activity emerges and is not distorted by surface flows, the contrast levels are still sufficiently low so as to be unobservable. Thus, in this picture, magnetic flux emergence is indeed enhanced, but the persistent spatial structuring seen in the case of the Sun is consistently destroyed by the hypothesized surface flows.

We regard such models as implausible. In the first case, classical scaling of surface diffusion coefficients consistent with observations implies that, in order to enhance diffusion rates sufficiently, the dominant spatial scale of turbulent advection be very large (~four orders of magnitude larger than the typical solar diffusion scale length associated with granules); besides the fact that such dominant scales are unrealistic in and of themselves, such flows would then occur on spatial scales comparable to, or larger than, that of the flux to be advected, and so the process cannot be regarded as turbulent diffusion.

In the second case, the necessary latitudinal differential rotation rates [ΔΩ/Ω = O(1) over distances comparable to the dimension of the emerging active regions] also implies that comparably large differential rotation rates in radius must be sustained in a well-mixed, very thin outer convection zone of dwarf F stars; this is again implausible.

2. The flux tube scale size at formation is determined by the local pressure scale height by some, as yet, unspecified process. We discard this hypothesis in view of the following considerations: The ratio of pressure scale heights at the base of the convection zones for an early F V star and the Sun is near unity, or $H_p(F0)/H_p(Sun) = 1$ (where $T_{ce}$ and $g_{ce}$ are the temperature and effective gravity, respectively, at the base of the stellar convection zone. We used the results of Copeland, Jensen, and Jorgensen (1970) to evaluate $T_{ce}$ and $g_{ce}$. It is evident from this result that in order to produce a significant change in the size scale of surface inhomogeneities, the flux tube formation mechanism would have to be extremely sensitive to $H_p$, even though the flux tube dimension near the convection zone base is much less than $H_p$. We regard such a mechanism as physically implausible. In particular, we are not aware of any extant process which has the requisite sensitivity to the local pressure scale height.

3. Large active regions do not exist because the formation of large flux bundles is inhibited. If, as is commonly supposed, active regions are formed in the deeper layers of a convection zone (cf. Golub et al. 1981), then this kind of explanation must demonstrate why such large flux ensembles are not formed. One possible model is based on the calculations of Schmitt and Rosner (1983), who argue on the basis of linear theory that doubly diffusive magnetic buoyancy instabilities of diffuse magnetic flux at the base of a convection zone can lead to the formation of magnetic structures; for fixed thermal stratification, the dominant scales of unstable structures are largely determined by the stellar rotation rate $Ω$; the eventual spatial scales of the emerged structures then also depend upon their expansion as they rise through the convection zone to the stellar surface.

We first consider the formation process at the convection zone base; to be definite, assume a subadiabatic gradient of $α = 1 - 10^{-4}$ and $β = 10^4$ gauss. The implied magnetic field energy density is of order the kinetic energy density which is, in turn, many orders of magnitude weaker than the thermal energy density (e.g., see Schmitt and Rosner 1983). The maximum growth rates of unstable modes then occurs for $\kappa s^2/Ω = 1 - 10^3$, where $\kappa$ is the thermal diffusion coefficient and $s$ is the meridional spatial wavenumber of the mode. In any case, the spatial scale of the most rapidly growing modes scales as $Ω^{-1/2}$ in the linear regime, that is, large rotation rates lead to smaller scales at which maximum growth occurs. We note that the observed mean values of $v \sin i$ range from 22 km s$^{-1}$ to 78 km s$^{-1}$ for dF5 to dF0 stars, respectively (Allen 1976).

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Hence, assuming roughly similar values for the subadiabatic gradient in the dynamo layers, the spatial scales of flux ropes at the base of the convection zone ought to be reduced typically by factors of ~ 3–6 in the early DF stars relative to that of the Sun. If, as is likely, energy transport by convection is less efficient in DF stars than for the Sun, the subadiabatic gradient in the undershoot layer will be larger, and therefore the threshold for instability will be higher (Schmitt and Rosner 1983); hence, our model would predict more magnetic flux amplification for DF stars (because in the "shell" dynamo, buoyancy is one of the principal mechanisms for limiting flux amplification; Knobloch, Rosner, and Weiss 1981). Furthermore, because of the steep reduction of the convection zone depth in mid and early dwarf F stars, the extent of flux rope expansion will also decrease; that is, for a flux rope of given spatial scale at the bottom of the convection zone, the spatial scale of the emerged structure at the stellar surface will be smaller in the case of dwarf F stars than for the Sun. For example, if we assume that both magnetic flux and mass are conserved within a flux tube during its rise through the convection zone, then (for identical flux tube dimensions at the convection zone base) the area size contrast at the stellar surface would scale as \[ \left[ \frac{\rho_b(F)\rho_b(O)}{\rho_b(F)\rho_b(O)} \right]^{1/2}, \] where \( \rho \) is the plasma density, and subscripts "b" and "t" denote the bottom and top of the DF (F) and solar (O) convection zones, respectively. For typical values of \( \rho \) (taken from models by R. Kurucz for the Sun and a star with \( T_\odot = 6500 \) K), we find that the emergence process itself leads to a geometrical reduction in contrast of \( \sim 1.7 \times 10^{-3} \). This severe reduction in size contrast, combined with a shift of the scales of initially formed flux ropes to smaller dimensions and an increase in the total magnetic flux production, leads to a far more uniform surface distribution of enhanced emergent magnetic flux; this would account for the absence of rotational modulation in these stars, while still permitting the observed enhanced level of magnetic-field-related activity. We note that this model makes a definite prediction: Since the properties of the outer convection zone change extremely rapidly in the effective temperature range \( T_\odot = 6000–7000 \) K (with relatively small change in stellar mass), one can test our model by considering matched pairs of stars with comparable rotation rates but lying on either side of this temperature range: we would then predict a distinctly lower variability level for the hotter star.

III. SUMMARY

On the basis of available optical, ultraviolet, and X-ray observations of early main-sequence F stars we infer that the surfaces of these stars are characterized by a uniform distribution of emerging magnetic flux. In particular, the high level of activity combined with the absence of observed rotational modulation in both lines and continua directly imply that the surfaces are well covered by magnetic structures, but that significant inhomogeneities in the surface activity level cannot be present. Moreover, significant concentrations of magnetic flux in the form of spots either do not appear, or are small and uniformly distributed on the surfaces of the early DF stars.

We explain this behavior exhibited by dwarf stars characterized, as a class, by rapid rotation and thin convection zones, by considering the spatial scales of generated and emergent flux ropes: The calculations of Schmitt and Rosner (1983) demonstrate that the spatial scales of the most rapidly growing modes scale (in the linear regime) as \( \Omega^{-1/2} \), so that large rotation rates lead to smaller flux ropes generated at the bottom of the stellar convection zone. Furthermore, a thin convection zone allows only a small (relative to the Sun) expansion of emergent flux ropes; and the increased subadiabatic gradient in the "shell" dynamo layer argues for enhanced magnetic flux amplification. Consequently, large-scale spatial inhomogeneities in observed magnetic-field-related activity would not be expected to occur, but one would expect enhanced magnetic activity levels. Given these results, we suggest that pairs of stars of similar \( \Omega \) but on opposite sides of the boundary separating "thin" and "thick" convection zones, would exhibit contrasting behaviors in Ca II: the "thick" convection zone star ought to display rotational modulation, while the star with a "thin" convection zone ought to show little modulation. We tentatively identify the location of this boundary at \( \sim F7 V \) because it is at this spectral type that Radick et al. first noted the onset of spot-related continuum variability in their sample of solar-type stars. Finally, we caution the reader that the argument presented here is based on linear instability analysis, although plausible arguments can be adduced to suggest that the gross scaling which we rely upon here will not be significantly compromised by nonlinear effects (Schmitt and Rosner 1983).

We acknowledge partial support by NASA grants NAG 8-445 and NAGW-112 to the Harvard-Smithsonian Center for Astrophysics (R. R.) M. S. G. gratefully acknowledges partial support from the visitor program of the Smithsonian Institution.

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