FRACTIONAL STELLAR CONVECTION ZONE DEPTH AND THE GENERATION OF MAGNETIC FLUX: AN EMPIRICAL APPROACH

Mark S. Giampapa
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138, U.S.A.

ABSTRACT

I present preliminary results from an observational investigation of very late M dwarf stars utilizing the Multiple Mirror Telescope facility. I find that dwarf stars later than spectral type M5 do not necessarily exhibit Hα line emission, contrary to the assertion by Joy and Abt (1974). The preliminary results I discuss herein tentatively suggest, but do not prove, that the generation of significant magnetic fields and magnetic flux is severely inhibited in fully convective stars.

INTRODUCTION

The chromospheres and coronae of the M dwarf stars are especially interesting since it is this region of the H-R diagram where the discrepancy between acoustic wave heating theories and the observations is most vivid. Also, to the extent that the chromospheric physical conditions in these cool dwarfs differ from those existing in the solar chromosphere, the M dwarfs can provide a unique laboratory to test theories of non-radiative heating of stellar atmospheres. For example, the importance of convection to the origin and structure of stellar chromospheres is not well understood, either empirically or theoretically. Hence, it is crucial to determine the degree of magnetic field-related nonradiative heating present in the atmospheres of a sample of stars which represent a range of fractional convection zone depths (i.e., convection zone depth / stellar radius). The very late M dwarf stars may be entirely convective. Thus these objects provide a sensitive test of the importance of the fractional convection zone depth to the generation of magnetic fields and the associated nonradiative heating in the atmospheres of late-type main sequence stars.

The main sequence M dwarf stars are subdivided into two classes, namely, the dMe stars and the non-dMe or, simply, the dM stars. The dMe stars exhibit Hα emission in their spectra while the spectra of dM stars

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reveal either Hα in absorption or no apparent Hα feature. Both Hα emission and Hα absorption are indicative of the presence of a chromosphere in a M dwarf star (Fosbury, 1974; Cram and Mullan, 1979). A variety of empirical evidence suggests that magnetic heating processes control the energy balance in stellar chromospheres. The compelling circumstantial evidence has been extensively reviewed by Giampapa (1980; see also Giampapa, Worden, and Linsky, 1982) in the case of the M dwarf stars. In basic summary, the strength of Hα line emission (or absorption) essentially constitutes a measurement of the degree of magnetic field-related, nonradiative heating present in an M dwarf chromosphere.

According to Joy and Abt (1974), all dwarf stars later than M5.5 are dMe stars. However, recent investigations by Liebert et al. (1979) disclosed the possible existence of very late (later than Mt. Wilson type dM5) M dwarf stars with no indication of Balmer line emission. Unfortunately, the observations by Liebert et al. (1979) were at low spectral resolutions (8 - 10 Å). I have therefore undertaken a program to obtain significantly higher resolution spectra in order to confirm the existence (or non-existence) of Hα line emission in the spectra of very late M dwarf stars.

OBSERVATIONS AND RESULTS

The observations were obtained with the Multiple Mirror Telescope (MMT) in conjunction with the Agassiz echelle spectrograph, a 100 μm slit and a photon counting Reticon detector. The spectral resolution of the configuration, as deduced from the FWHMs of unblended comparison lines is approximately 0.20 Å. The resulting spectra have been smoothed by successive applications of a triangular smoothing function. The final spectral resolution is typically 0.25 Å. The dark current has been subtracted from each spectrum. Finally, I found that the sky background with 1 arc-sec entrance apertures in the image stacker was negligible compared to the dark counts.

I display in Figure 1 a histogram of the results thus far obtained in this investigation. The program objects are segregated according to those M dwarfs that exhibit Hα emission and those that do not show an Hα emission feature. The abscissa is photographic $(m_{pg} - m_R)$ color deduced from data listed by Luyten (1979). The value of m_{pg} can be considered the "blue" apparent magnitude while m_R is the stellar apparent magnitude in the neighborhood of Hα. Many of the program stars have not been assigned exact M spectral types. I have therefore inferred the range of spectral types represented in Figure 1 in the following manner: I randomly selected 10 - 15 stars of each spectral type listed in the proper motion catalog of Luyten (1979) and computed their $(m_{pg} - m_R)$ colors. I then adopted the mean value of the photographic color as corresponding to the particular spectral type. This procedure yielded the calibration of spectral type versus photographic color shown in Figure 1. Although the calibration is

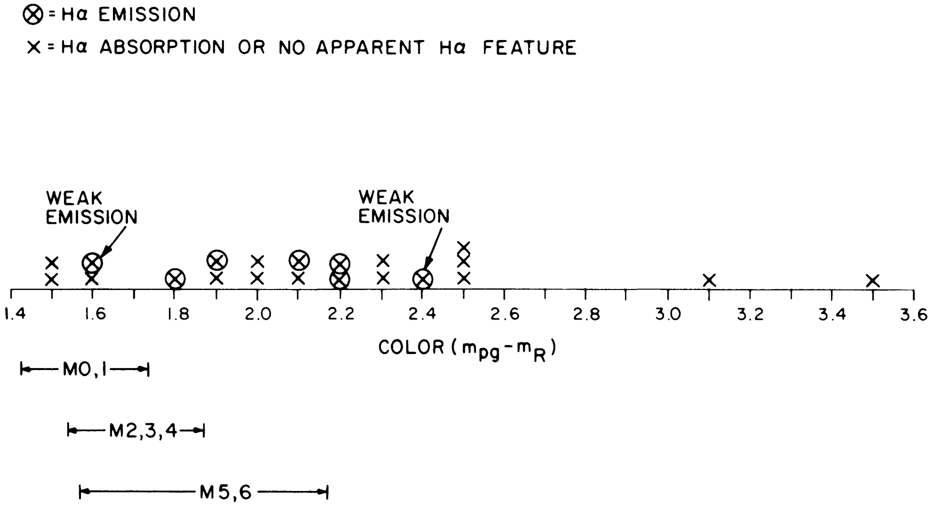

Figure 1. Histogram of the program M dwarf stars. The appearance of Hα is indicated. Note that nearly all the M dwarfs later than M6 are non-dMe stars.

crude, there are several program objects that are clearly later than M6. Furthermore, I demonstrate via Figure 1 that there exist dM stars later than M6 that are not dMe stars. I can therefore refute the claim by Joy and Abt (1974) that all M dwarfs later than dM5.5 are dMe stars.

Unfortunately the sample of very late-type dM stellar spectra thus far obtained is not statistically significant. I therefore cannot claim that all M dwarf stars later than $(m_{pg} - m_R) = 2.4$ are non-dMe stars. The test of such a hypothesis will require a larger sample of stars. Moreover, multiple observations should be obtained in order to investigate the possibility of variability. Nevertheless, the preliminary results displayed in Figure 1 tentatively suggest that there is a decline in chromospheric activity, and by implication, a decline in the generation of significant magnetic flux, toward the very late M dwarf stars.

DISCUSSION

The results given in Figure 1 invite a preliminary empirical exploration of the consequences for the importance of the fractional stellar convection zone depth to the generation of magnetic flux in late-type stars. I show in Table 1 the fraction of M dwarf stars that are dMe stars within a given spectral type. These data are taken from Joy and Abt (1974, their Table 2). I also list the fractional convection zone depth, $1 - r_c/R_*$, where r_c is the radius to the base of the convection zone and R_* is the stellar radius, following the stellar interior computations of Copeland, Jensen, and Jorgensen (1970).

Table 1. M Dwarf Emission and Convection Zone Depths

Sp. Type	% of dMe	$1 - r_c/R_*$
M0	3	0.343
M0.5	3	
M1	7	0.376
M1.5	8	
M2	9	0.451
M2.5	16	
M3	41	1.0
M3.5	35	
M4	33	1.0
M4.5	50	
M5	80	
M5.5	100	

The precise location in spectral type for the onset of complete convection is uncertain because the mass-luminosity law for the very late main sequence is ill-defined. Nevertheless, we can confidently presume that all stars later than dM6 must be wholly convective. The results of Table 1 appear to indicate an increase in the frequency of occurrence of chromospheric activity with increasing depth of the stellar convection zone. However, the histogram in Figure 1 tentatively suggests that those M dwarf stars which are surely wholly convective (even in view of the uncertainties in current model computations) suffer a decline in chromospheric activity. Thus, the generation of significant magnetic fields and magnetic flux may be severely inhibited in completely convective stars.

The results I discuss in this investigation may constitute corroborative evidence for the presence of $\alpha-\omega$ "shell" dynamos, as opposed to the so-called "distributed" dynamos, as the principal mechanism for the generation of significant magnetic flux in partially convective stars (e.g., see Parker, 1975; Rosner, 1980; Spiegel and Weiss, 1980; Golub et al., 1981). For those stars that are completely convective, the shell dynamo is no longer meaningful since there is, of course, no shear layer between a radiative core and the base of the stellar convection zone. In these cases, the rise time of toroidal buoyant magnetic flux through the convective interior may be much less than the amplification time (the ω-effect) to produce significant magnetic flux (Parker, 1975; Rosner, 1980; Spiegel and Weiss, 1980; Schmitt and Rosner, 1982; Durney and Robinson, 1982). Consequently, a low level of chromospheric and coronal activity is observed in the very late, fully convective M dwarf stars.

Interestingly, the T Tauri stars could constitute a contradiction to the view I present in this investigation. In particular, the T Tauri stars are pre-main sequence objects that are fully convective <u>and</u> exhibit intense chromospheric line emission (Giampapa et al., 1981, and references therein). If the speculative scenario I discuss in this paper is eventually verified, then the implication would be that the chromospheric (and coronal) activity observed in the T Tauri stars is associated with remnant <u>primordial</u> fields rather than dynamo generated magnetic fields, or that some T Tauri stars have radiative cores.

Finally, I recognize that the current sample of stars later than dM6 must be enlarged and carefully selected so as to avoid possible biases toward very old stars that may be introduced by samples selected from the Luyten proper motion survey.

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DISCUSSION

SODERBLOM: In regard to the very cool stars that show no Hα emission: Do you know the space motions for those stars? Are they kinematically old? If they turn out to be, how would that affect your conclusions about magnetic fields and chromospheric emission for these very low masses? I suspect that these stars may be kinematically old, because they are intrinsically so faint that the only way to find them is because of their large proper motions.

GIAMPAPA: I will soon measure the radial velocities for these stars and obtain their space motions. However, even if the stars are kinematically old, the conclusion that magnetic flux generation is inhibited in fully convective stars would remain. For example, current dynamo models predict very efficient field generation in the M dwarfs at solar rotation periods or longer resulting in high filling factors ($> 50\%$) of kG fields. Perhaps the spin-down mechanism is unusually efficient, but it is difficult to understand why there should be an apparently sharp drop in the frequency of dMe stars just after dM6. I remind you that dMe stars are found among the kinematically old disk as well as young disk populations.

GOLUB: The X-ray survey of M dwarf emission may provide an indication of the point at which M-S stars become fully convective, perhaps with greater sensitivity than the chromospheric indicators. The results show a very abrupt drop in the luminosity function of M dwarfs at a B-V of about + 1.6, corresponding roughly to dM5. Of course, we need some good theoretical work to tell us if this is really a workable hypothesis.

GIAMPAPA: I am happy to see corroborative X-ray evidence for my hypothesis that magnetic flux generation is inefficient in the fully convective dM stars. Additional theoretical work should include more sophisticated M dwarf interior calculations that utilize an improved equation of state and better opacity tables in order to accurately identify the critical mass for the onset of complete convection. Supporting observational work must include the determination of a considerably better mass-luminosity law than exists at present, combined with a more consistent spectral classification scheme for the M dwarf stars.

STIX: The magnetic time scale of a fully convective star is the time of turbulent mixing, which is very short even in comparison with the age of a T Tauri star. It is difficult, therefore, for these stars to keep their primordial fields.

GIAMPAPA: I am aware of this. However, I do not see how to reconcile the apparent contradiction that there is a low level of chromospheric activity in fully convective M dwarf stars while there is a greatly enhanced level of activity in the T Tauri stars. Perhaps radiative cores are present in T Tauri stars or the relatively more rapidly rotating T Tauri stars operate efficiently as "distributed" dynamos.

WALTER: T Tauri stars which are X-ray sources with "normal" K star coronae (Walter and Kuhi: 1981, *Astrophys.J.* **250**, p. 245), do not necessarily have high masses ($\gtrsim 2M_\odot$). If put on Cohen and Kuhi's (1979) H-R diagram, many are $\sim 1M_\odot$ or less. In fact, 5 "post-T Tauri" stars (Mundt et al.: 1982, *Astrophys. J.*, submitted) have $M \approx 0.6M_\odot$, ages of $\sim 2 \times 10^6$ yr (like the T Tauris), and apparently normal coronae, including surface spots.

ROSNER: In response to the previous question regarding activity of dF stars, Vaiana et al. (1981) and Topka et al. (1982) have shown that the X-ray luminosity function of dF stars is "shifted" to higher luminosities when compared to the luminosity functions of later-type dwarf stars. Hence the "activity" of dF stars is, on average, somewhat *higher* than that of later-type dwarfs.