

THE FILLING FACTOR OF ACTIVE REGIONS ON THE SURFACES OF THE dM STARS

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Received 1984 November 13; accepted 1985 June 18

ABSTRACT

Results from M dwarf chromospheric models combined with observational considerations suggest that the surfaces of those dM stars that exhibit chromospheric H α absorption can be characterized by a significant area coverage of, presumably, magnetic field-related active (plagelike) regions. Lower limits to the area coverage, or filling factor, of active regions on the surfaces of the non-dMe stars based on the equivalent width of the observed chromospheric H α absorption line are derived. Results inferred from data provided by J. R. Stauffer, in advance of publication, yield a range in lower limits to the active region filling factor of 0.31–0.67 for a sample of dM stars characterized by $(R-I)_K = 0.9$. The upper limit is 1.0. These area constraints can, in turn, be used to infer upper limits to the intrinsic chromospheric Ca II and Mg II resonance line emission in active regions on the dM stars. The implications of the results for dynamo theory and theories of chromospheric heating are discussed. In particular, dynamo theory must now account for the occurrence of a high filling factor of magnetic field regions on the surfaces of the relatively slowly rotating dM stars while theories concerning atmospheric heating must account for the relatively low chromospheric and coronal emission of dM stars despite the fact that their surfaces can have a high filling factor of magnetic field regions. In order to account for the latter phenomenon, a hypothesis involving open magnetic field geometries combined with downwardly directed coronal X-ray emission as the source of chromospheric heating in M dwarfs, as suggested in 1982 by Cram, is discussed. Finally, an extension of the conceptual approach presented herein to more nearly solar-type dwarfs is described. In particular, the triplet He I lines, $\lambda 5876$ and $\lambda 10830$, can potentially be utilized as diagnostics of the filling factor of active regions on solar-type stars.

Subject headings: stars: chromospheres — stars: emission-line — stars: late-type — stars: magnetic

1. INTRODUCTION

The M dwarf stars are subdivided into two classes according to the appearance of the H α line in their spectra. In particular, the dMe stars exhibit H α emission while the non-dMe stars or, simply, the dM stars are characterized by an H α absorption feature. Besides the Balmer lines, the M dwarf stars exhibit chromospheric Ca II and Mg II resonance line emission (Giampapa *et al.* 1981; Linsky *et al.* 1982). These chromospheric emissions are strongly enhanced in the dMe stars relative to the dM stars. Moreover, the dMe stars are characterized by strong transition region line emission while dM stellar spectra show only emission lines of neutral metal species in the far-ultraviolet (Linsky *et al.* 1982; see also Ayres *et al.* 1983). The mean X-ray luminosity of dM stars is reduced somewhat relative to dMe stars (Bookbinder, Golub, and Rosner 1985). Furthermore, dMe stars often exhibit quasi-periodic variability in lines and continua which has been attributed to the probable presence of magnetic surface activity that is similar in character to such solar phenomena as sunspots and plages. By contrast, the dM stars do not generally show evidence for the occurrence of significant surface inhomogeneities as would be detected in broad-band photometry (Bopp *et al.* 1981 and references therein).

The aforementioned observational facts imply that the dissipation of nonradiative energy in the outer atmospheres of the M dwarf stars is enhanced in the dMe stars as compared to the dM stars. Fosbury (1974) found that H α line emission observed in the dMe stars arises from a chromospheric temperature rise

combined with a collisionally controlled H α source function in a region with electron densities of $N_e \approx 10^{11} \text{ cm}^{-3}$. Cram and Mullan (1979) extended this investigation to demonstrate that H α absorption is also indicative of the presence of a chromospheric temperature rise but in a region of relatively lower electron density; an M dwarf atmosphere in pure radiative-convective equilibrium can exhibit only a very weak H α absorption line (Cram and Mullan 1979). Within the context of single-component, homogeneous model chromospheres, both Cram and Mullan (1979) and Giampapa, Worden, and Linsky (1982) find that chromospheric line emission strength is most sensitive to the total amount of chromospheric material within the thermal range in which the particular diagnostic is formed. This general result has been used to distinguish between the so-called active and quiet chromosphere stars, and, by implication, the dMe and dM stars (Kelch 1978; Kelch, Linsky, and Worden 1979). An alternative approach to account for the degree of chromospheric emission in M dwarf stars is to assume that the dM and dMe stars differ fundamentally from each other in terms of the fractional area of their surfaces which is covered by active regions. Such an approach is suggested by the inhomogeneous nature of the solar atmosphere and the aforementioned evidence for the appearance of spots, analogous to sunspots, on the dMe stars.

Unfortunately, the fractional surface coverage of active regions cannot be ascertained on the basis of chromospheric emission lines alone (such as the Ca II H and K lines) since the quantitative level of chromospheric emission that is intrinsic to stellar active regions is unknown. If the structure of active regions on dM and dMe stars is identical, then observed Ca II chromospheric emission line fluxes yield estimates of active

¹ Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

region surface coverages on the dM stars that are of order a few percent while the surface coverages implied for the dMe stars are at least several times larger (Giampapa 1980). However, I present arguments herein, based on the unique properties of H α line formation in the M dwarf stars, to demonstrate that the surfaces of the dM stars must, in fact, be characterized by a significant areal coverage (or "filling factor") of presumably magnetic field-related active regions. Furthermore, I estimate the lower limit to the filling factor of chromospheric regions on dM stars, and I present an empirical relation for the upper limit to the intrinsic Ca II (and Mg II) emission in these stellar surface regions. In so doing, I rely on the general model results obtained by Cram and Mullan (1979) and Giampapa, Worden, and Linsky (1982) for H α and Ca II line formation, respectively, in the atmospheres of the M dwarf stars.

II. RESULTS

An atlas of high resolution Balmer line profiles for dM and dMe stars has been presented by Worden, Schneeberger, and Giampapa (1981). Inspection of the H α region in the dM spectra shown by Worden *et al.* reveals the presence of H α absorption in a heavily line-blanketed region. Moreover, the equivalent widths of the observed H α absorption lines are several times greater than that computed by Cram and Mullan (1979) for a dM model atmosphere with no chromosphere. Since the H α spectral region is severely affected by line blanketing in the cool dM stars, a chromospheric region which is characterized by zero flux in the core of the H α absorption line and which covers only a few percent of the stellar surface would likely not be detected. Hence the detection of H α absorption that has an equivalent width significantly greater than that which would be expected for an M dwarf atmosphere in pure radiative-convective equilibrium is clearly indicative of an extensive surface coverage of active regions on the dM stars that, in turn, gives rise to a detectable chromospheric H α absorption feature. These active regions are presumably related to areas of magnetic flux since classical acoustic wave energy dissipation fails to account for the observed chromospheric line fluxes; the convective velocities in the cool M dwarf stars are simply too low to generate sufficient acoustic energy (Mullan 1975).

In order to obtain constraints on the filling factor of active (plagelike) regions, I can describe an observed chromospheric line flux with a two-component representation or (Giampapa 1980; see also Cook, Brueckner, and VanHoosier 1980)

$$F = (1 - A)F_q + AF_a, \quad (1)$$

where A is the dimensionless ratio of the area of the active region to the area of the visible stellar surface. The symbols F_q and F_a represent the line surface fluxes in the quiet stellar photosphere and active region, respectively. I have implicitly assumed in equation (1) that the background photosphere of the stellar active (plagelike) region is identical to that of the quiet stellar photosphere, as it is on the Sun.

The active region filling factor A cannot be obtained from equation (1) unless F_a and F_q are known. The value of F_q can be obtained from model photospheres (e.g., Mould 1976). Unfortunately, chromospheric emission lines are, by themselves, virtually useless as diagnostics of the filling factor A of active regions since their intrinsic active region emission (F_a) characteristics are unknown. However, in the case of the dM stars, the unique formation characteristics of the H α absorp-

TABLE 1
FRACTIONAL ACTIVE REGION FILLING FACTORS FOR dM STARS

Star	Spectral Type ^a	W^a (Å)	$\Delta\lambda^b$ (Å)	A^c
SZ UMa (GL 424)	dM1.5	-0.39	1.8	$\geq 0.17^d$
SZ UMa ^e	dM1.5	-0.29	2.1	$\geq 0.10^d$
DM +36°2147 (GL 411)	dM2	-0.35	1.2	$\geq 0.24^d$
DM +5°1668 (GL 273)	dM4	-0.16	1.6	≥ 0.10
Ross 248 (GL 905)	dM5.5	-0.24	0.9	≥ 0.26

^a Spectral type and observed H α equivalent width from Worden *et al.* 1981.

^b Estimated from data given by Worden *et al.* 1981 and not corrected for instrumental broadening.

^c Lower limits calculated using inequality (3) which assumes zero flux in the core of the chromospheric H α absorption line in the active region. See text for a discussion.

^d A small radiative equilibrium correction to the observed H α equivalent width was applied prior to the calculation of this lower limit. See text for a discussion.

^e Multiple observations listed by Worden *et al.* 1981 for this star.

tion feature can be exploited to derive lower bounds on A . More specifically, I can formulate equation (1) in terms of the observed quantity of equivalent width, W , of the H α line or

$$W_{H\alpha} = (1 - A)W_q + AW_a, \quad (2)$$

where the subscripts have the same meaning as in equation (1). Given that a late M dwarf star without a chromosphere exhibits only a very weak H α absorption line, I have that $W_q \approx 0$. Thus, for a minimum flux of zero in the core of the chromospheric H α absorption line in an active region, thus corresponding to $W_a = -\Delta\lambda_a \approx -\Delta\lambda_{H\alpha}$, equation (2) yields

$$A \geq -W_{H\alpha}/\Delta\lambda_{H\alpha}, \quad (3)$$

where the minus sign is an artifact of the definition of W that I adopted. That is, I defined W such that absorption lines have negative equivalent widths.

As an example, Worden *et al.* report a value of $W_{H\alpha} = -0.24$ Å for the dM5.5 star Ross 248 (GL 905). From their Figure 3, I estimate $\Delta\lambda_{H\alpha} \approx 0.9$ Å; hence $A \geq 0.26$, or at least 26% of the visible surface of Ross 248 was covered by active regions at the time of observation.² I list in Table 1 the lower limits for A as deduced from inequality (3) and data given by Worden *et al.* for a small sample of dM stars. In Table 1, I applied an approximate radiative equilibrium correction of 0.1 Å to the observed H α equivalent width of SZ UMa as interpolated from models computed by Giampapa, Worden, and Linsky (1982) near the spectral type of this dM star. In the case of DM +36°2147 (GL 411), a correction of 0.08 Å was applied, following the value given by Cram and Mullan (1979) in their nonspecific model for an M dwarf corresponding to $(R - I)_K = 0.9$. In particular, $(R - I)_K = 0.93$ for GL 411, following Veeder (1974). The remaining dM stars in Table 1 are sufficiently late so that the radiative equilibrium correction to the observed H α equivalent widths is negligible. The upper limit for the filling factors given in Table 1 is $A = 1$.

Of course, the chromospheric H α absorption is not at the zero flux level in active regions; Cram and Mullan (1979) find a maximum value of $W_{H\alpha} = -0.69$ Å before the H α line begins to

² In general, a radiative equilibrium correction should be applied to the observed value of $W_{H\alpha}$ before using inequality (3) to estimate A . However, this correction is small and only declines further with later dM spectral type.

be driven into emission in their nonspecific model chromospheres for an M dwarf star characterized by $T_{\text{eff}} = 3500$ K or $(R-I)_{\text{K}} = 0.9$. In view of the results of Cram and Mullan (1979), a more stringent lower limit for A can be derived by setting $W_a = W_{\text{max}}$ in equation (2). Hence

$$A \geq \frac{W_{\text{H}\alpha} - W_q}{W_{\text{max}} - W_q}. \quad (4)$$

Stauffer (1985) observes H α absorption equivalent widths in the range of -0.27 to -0.49 Å for dM stars characterized by $(R-I)_{\text{K}} = 0.9$. Inequality (4) therefore implies a range in the lower limits to the active region filling factor A of 0.31 – 0.67 for these stars. I note the caveat that W_q may be different for old, metal-poor stars. Of course, this can be investigated through model photospheres computations. In any event, W_q will approach zero with later dM spectral type regardless of metallicity. I further note the caveat that if there are H α emitting regions as well as the less dense absorbing regions on the surface of a dM star, then the observed chromospheric H α absorption will be “diluted” (e.g., see Young, Skumanich, and Harlan 1984). Nevertheless, inequalities (3) and (4) will still apply although they will yield less stringent lower limits for the active region filling factor A .

The previous results obtained by considering the properties of H α line formation in the dM stars have interesting implications for the intrinsic chromospheric Ca II line emission in the active regions that give rise to chromospheric H α absorption. In particular, Giampapa, Worden, and Linsky (1982; their Fig. 1) find that $F_q \approx 0$ for the Ca II K line in the M dwarf stars (in other words, the chromospheric Ca II K line flux in an M dwarf star is essentially all the flux above the zero flux level). Equation (1) thus yields

$$F_a(\text{Ca II K}) = A_K^{-1} F_K, \quad (5)$$

where F_K is the observed average chromospheric surface flux in the K line. All other symbols are defined as before but now apply to the Ca II K line. According to Giampapa *et al.* (1982), the region of chromospheric Ca II K line formation is below that of chromospheric H α line formation in the M dwarfs. Unless there is significant spreading of the magnetic field lines with height, or if the chromospheric components of H I and Ca⁺ are not confined to the same areas on the stellar surface, it is reasonable to expect that for a compact chromospheric region $A_K \approx A_{\text{H}\alpha}$. The combination of inequality (4) and equation (5) thus imply that

$$F_a(\text{Ca II K}) \leq F_K \left(\frac{W_{\text{H}\alpha} - W_q}{W_{\text{max}} - W_q} \right)^{-1}. \quad (6)$$

I emphasize that inequality (6) is an empirical rather than a theoretical relation. The application of inequality (6) combined with simultaneous Ca II and H α observations of dM stars will enable the establishment of upper limits to the intrinsic active region emission in the chromospheric Ca II resonance lines. Furthermore, inequality (6) should be equally applicable to the Mg II resonance lines as seen in the dM stars. Of course, the lower limit to the intrinsic active region emission in the Ca II or Mg II resonance lines is given by the total observed flux above the zero flux level averaged over the entire stellar surface. Unfortunately, simultaneous H α and flux-calibrated Ca II K line observations for non-dMe stars are not yet available in the literature. However, a Ca II K line flux measurement is reported by Giampapa *et al.* (1981) for GL 411. Combining this

measurement with the nonsimultaneously recorded H α data given in Table 1 and applying inequality (6) yields an upper limit of $F_a \leq 1.3 \times 10^4$ ergs cm⁻² s⁻¹, where the values of W_{max} and W_q as given by Cram and Mullan (1979) have been adopted for GL 411. This upper limit to the intrinsic plagiellike region K line flux is approximately a factor of 20 below that of the quiet Sun.

III. DISCUSSION

I derived lower limits to the surface area coverage or, filling factor, of magnetic field-related active regions on the dM stars on the basis of the unique properties of H α line formation in M dwarf atmospheres. In particular, the resulting estimates of the filling factors based on equivalent width measures of the chromospheric H α absorption feature (Worden *et al.*; Stauffer 1985) suggest that the surfaces of the dM stars can be extensively covered by active regions. These filling factor estimates imply, in turn, upper limits to the intrinsic Ca II (or Mg II) resonance line surface flux in the active regions on dM stars. Hence, the dMe and non-dMe stars cannot be distinguished from each other simply on the basis of the areal coverage of magnetic field-related activity despite the markedly lower chromospheric and coronal emission exhibited by the non-dMe stars. Moreover, a comparison of the estimates of active region filling factors based on chromospheric H α absorption with those given previously by Giampapa (1980) solely on the basis of relative Ca II emission strengths indicates that the structures of the active regions that are the dominant contributors to chromospheric line emission on the dM versus the dMe stars are not identical.

Interestingly, Bopp *et al.* (1981) suggest that the onset of spot formation and/or H α emission occurs in dMe stars at an equatorial rotational velocity of ~ 5 km s⁻¹ while none of the more slowly rotating dM (i.e., H α absorption) stars in their sample exhibited variability as seen in broad-band photometry. Hence, concentrations of magnetic flux in the form of cool spots either do not occur on the dM stars or any such spots are small and/or uniformly distributed in longitude. Given the results I present herein it would be interesting to determine the distribution of the active regions that extend over a significant fraction of the surfaces of dM stars. I note that Baliunas *et al.* (1983) detect rotational modulation of the Ca II H and K lines in the only M dwarf in their sample, GL 685 (dM0), thus indicating an asymmetry in the surface distribution of active regions for this specific non-dMe star. Clearly, it is vital to pursue a monitoring program of chromospheric line diagnostics in a sample of dM and dMe stars.

In brief summary, the results discussed herein imply that stellar dynamo theory must now account for (1) the occurrence of a high filling factor of magnetic field regions on the surfaces of the relatively slowly rotating dM stars as well as on the more rapidly rotating dMe stars and (2) the apparent lack of concentration of magnetic flux to produce large, cool spots on the dM stars while spots are detected on the surfaces of the dMe stars. Theories that address atmospheric heating mechanisms must now account for the relatively low chromospheric and coronal emission of dM stars despite the fact that their surfaces can have a high filling factor of plagiellike regions. I suggest that the dM and dMe stars are fundamentally similar in terms of the filling factor of active regions on their surfaces. However, the dMe stars must have sites of especially strong “activity” that give rise to intense chromospheric and coronal emission. These sites of enhanced activity are likely associated with

closed magnetic field configurations while the predominant magnetic field region on a dM star is likely characterized by an open field configuration.

Phenomenological evidence exists in support of the hypothesis that open field configurations, analogous to solar coronal holes, are the predominant kinds of magnetic field regions on dM stars. In particular, Cram (1982) has suggested that chromospheric emission in dMe stars arises as a result of atmospheric heating by downwardly directed X-rays emanating from the overlying corona. Giampapa *et al.* (1982) have presented some corroborative observational evidence for this hypothesis. If the solar analogy of open coronal hole-like regions which are, in turn, sites of severely reduced levels of X-ray emission, is applicable then, within the context of the X-ray heating hypothesis for the origin of M dwarf chromospheres, the relatively low level of chromospheric and coronal emission observed in dM stars naturally follows as a consequence of the predominant occurrence of open-field geometries. Hence, a lower level of atmospheric emission in the dM stars would be expected despite the fact that a high filling factor of magnetic field regions can occur on the surfaces of these dwarfs.

Future investigations should include the computation of the photospheric H α line for a grid in spectral type and metallicity of M dwarf model photospheres. The results can then be used to correct the observed equivalent widths of dM chromospheric H α absorption features for the radiative equilibrium contribution. In this way, more accurate lower limits for active region filling factors can be inferred. However, I note that this correction is more important for the early M dwarfs than for the later M spectral types. Furthermore, the model determination of the maximum chromospheric H α absorption equivalent width that can be attained at each dM spectral type before

the line begins to fill in as a result of chromospheric emission would further constrain the lower limit for dM active region filling factors. In addition, simultaneous H α and Ca II (and Mg II) resonance line observations will allow the establishment of upper limits for the intrinsic Ca II (Mg II) emission in active regions on dM stars. A monitoring program for a sample of dM and dMe stars would yield data sets from which the surface distribution of magnetic flux can be inferred.

Finally, the following observational question arises: Is there a useful spectroscopic counterpart of the dM-H α chromospheric absorption line in the more nearly solar-type stars? In this regard, the He I triplet lines at 5876 Å and 10830 Å, respectively, merit examination. For example, the λ 5876 line appears in *absorption* in solar plages and is, in fact, an excellent tracer of Ca II plages. The line is extremely weak in the quiet Sun. I can therefore derive lower limits for the plage filling factor on solar-type stars by applying inequality (3) combined with data given by Wolff and Heasley (1984) for the λ 5876 line. On the basis of these data, I find values of $A \geq 0.05$ and $A \geq 0.02$ for ξ Boo A and 70 Oph A, respectively. Obviously, the results are neither surprising nor especially useful. A grid of nonspecific model chromospheres for solar-type stars should be computed in order to determine the values of $W_{\max}$ for the He I triplet lines. If these values are within factors of 2 or 3 of the observed absorption equivalent widths in active solar-type stars, then inequality (4) can be applied to deduce both meaningful lower limits on the plage area coverage in these stars as well as to infer upper limits to the intrinsic Ca II emission in the surface active regions.

I thank Dr. J. Stauffer for providing data in advance of publication and for his constructive comments on an earlier version of the manuscript.

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