A HEATING MECHANISM FOR THE CHROMOSPHERES OF M DWARF STARS

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INTRODUCTION

The systematic, detailed observational and theoretical investigation of the atmospheric structure of the dwarf M stars is especially important to the general field of stellar chromospheres and coronae. More specifically, the M dwarf stars constitute a class of objects for which the discrepancy between the predictions of the acoustic wave chromospheric/coronal heating hypothesis and the observations is most vivid. Conversely, they must therefore represent a class of stars where alternative atmospheric heating mechanisms, presumably magnetically related, are most clearly manifested. We thus propose to ascertain the validity of a recently advanced hypothesis to account for the origin of the chromospheric and transition region line emission in M dwarf stars.

As a prelude to the discussion of the heating mechanism that may give rise to the chromospheric and transition region line emission in M dwarf stars, we will briefly summarize our recent ultraviolet, optical and X-ray observations of a sample of dMe and dM stars. In particular, we will delineate the similarities and differences in the observed chromospheric line spectra of dMe and dM stars, and discuss the relative importance to chromospheric radiative cooling of various spectral line features. Finally, we will perform a preliminary assessment of the role of coronal X-ray emission in the heating of M dwarf atmospheres.

DISCUSSION

A detailed description of the ultraviolet and optical spectrum of M dwarf stars is given by Linsky et al. (1981). We will briefly discuss a principal result of this investigation and, in conjunction with our X-ray data, demonstrate the importance of these results for theories that seek to describe the heating mechanisms that give rise to stellar chromospheres.

The far ultraviolet line spectra of several dM and dMe stars are shown in Figures 1 and 2. The brightest "high temperature" features tend to be C IV
Fig. 1. Far ultraviolet observations of d^me stars.
Fig. 2. Far ultraviolet spectra of dM and dMe stars.
$\lambda 1550$, C II $\lambda 1335$ and He II $\lambda 1640$, although the He II line may be formed by recombination-cascade following photoionization by coronal X-rays. Hence its temperature of formation is somewhat ambiguous. We also note, parenthetically, that the C II $\lambda 1335$ line arises in more nearly chromospheric ($T \sim 2 \times 10^6$ K) regions while the C IV doublet is purely a transition region diagnostic ($T \sim 10^5$ K). The transition region lines, such as C IV $\lambda 1550$, are brighter than the relatively low temperature chromospheric lines (e.g. C I $\lambda 1657$ and Si II $\lambda 1812$) in the dMe stars while the reverse is true in the dM stars. Furthermore, the surface fluxes of the high temperature lines (N V, C IV, S IV, etc.) in the dMe stars are 10 - 100 times greater than the corresponding line surface fluxes for the quiet Sun. In contrast, the high temperature line surface fluxes for the dM stars are similar to or slightly less than those of the quiet Sun.

A significant new result of our optical and ultraviolet survey of M dwarf stars is the following: the Balmer lines are the most prominent chromospheric emission line features in the dMe stars (see Figure 3 herein and Worden et al. 1981 for examples of hydrogen line profiles in dMe spectra). The Balmer lines are, in total, 3 - 9 times as bright as the Mg II resonance lines and, consequently, emit more energy than all the other chromospheric lines combined. Thus the Balmer lines are the principal contributors to the net radiative cooling of the chromospheres of dMe stars. Utilizing the line surface flux data given by Linsky et al. (1981), we find that the largest integrated cooling rates for the dMe stars in order of decreasing importance are due to the Balmer lines, Fe II, the Mg II resonance lines, and the Ca II resonance lines (although the last 3 cooling rates are within factors of 2 or 3 of each other). Interestingly, this order of importance also follows the order of elemental abundance, with hydrogen the most abundant element and calcium the least abundant among the principal contributors to the chromospheric radiative cooling of dMe stellar atmospheres. This result is likely a consequence of the relative abundance of a particular atom or ion coupled with the collisional control of the source functions of the important line transitions. In contrast, Vernazza, Avrett and Loeser (1980) find for the average quiet Sun that the largest integrated cooling rates in order of decreasing importance are due to the Ca II infrared-triplet and resonance lines, the Mg II resonance lines, H$^-$ and L$\alpha$.

The value of the previously described observations is significantly enhanced with the addition of recently acquired X-ray observations of these stars. Recent Einstein satellite observations have shown that the dMe stars are intense X-ray sources characterized by X-ray luminosities that can be as large as 10% of the visual luminosity of the star (Vaiana et al. 1981). In terms of bolometric luminosity, $L_b$, the fractional quiescent X-ray luminosity, $L_x/L_b$, can still be an order of magnitude greater than that for solar active regions and two orders of magnitude greater than $L_x/L_B$ for the quiet Sun (Haisch and Linsky 1980). As a result, Cram (1981) has suggested that the atmospheric regions (i.e. chromospheres and transition regions) beneath the X-ray emitting coronae of these stars are illuminated by an intense flux of X-rays, and are consequently heated above the temperature that would exist in a pure radiative-convective equilibrium model. In particular, the major
Fig. 3. Balmer line profiles for dMe stars.
portion of the downwardly directed X-ray flux will be absorbed by the underlying atmosphere, subsequently leading to photoionization. The resulting high energy photo-electrons will rapidly thermalize, thus converting the original X-ray radiative flux from the corona to thermal energy. This thermal energy is then emitted as transition region and chromospheric radiation.

If X-ray heating by an overlying corona is an important component in the energy balance of dwarf M chromospheres, then the observed quiescent X-ray flux from a dMe star should be similar to the total observed chromospheric-transition region radiation. We may therefore consider the viability of the hypothesis by comparing our recent optical, IUE and HEAO-B observations of M dwarf stars. The total chromospheric-transition region line luminosities and the X-ray luminosities, as taken from Linsky et al. (1981) and Vaiana et al. (1981), respectively, for a small sample of dwarf M stars are shown in Table 1.

<table>
<thead>
<tr>
<th>Object</th>
<th>Chromosphere $L_C$ (erg s$^{-1}$)</th>
<th>Corona $L_X$ (erg s$^{-1}$)</th>
<th>$L_X/L_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ Vir (dK7e)$^1$</td>
<td>1.1 (29)</td>
<td>2.3 (29)</td>
<td>2.1</td>
</tr>
<tr>
<td>61 Cyg B (dM0)</td>
<td>1.3 (28)</td>
<td>3.2 (27)</td>
<td>0.2</td>
</tr>
<tr>
<td>EQ Peg (dM4.5e+dM3.5e)$^1$</td>
<td>3.8 (27)</td>
<td>6.3 (28)</td>
<td>16.6</td>
</tr>
<tr>
<td>YZ CMi (dM4.5e)</td>
<td>3.0 (28)</td>
<td>2.5 (28)</td>
<td>0.83</td>
</tr>
<tr>
<td>Prox Cen (dM5e)</td>
<td>1.1 (27)</td>
<td>1.2 (27)</td>
<td>1.0</td>
</tr>
<tr>
<td>UV Ceti (dM6e)</td>
<td>4.9 (27)</td>
<td>3.5 (27)</td>
<td>0.71</td>
</tr>
</tbody>
</table>

$^1$ Estimate of chromospheric losses does not include radiative losses attributable to Balmer line emission.

Inspection of Table 1 reveals that the chromospheric-transition region luminosities, $L_C$, are comparable to the X-ray luminosities, $L_X$, in four of the six stars in this small sample. The fact that $L_X/L_C$ is greater than 1 in some cases may be due, in part, to the lack of data for Balmer line emission strengths in the estimate of $L_C$. A further important caveat is that the UV and X-ray observations were not contemporaneous. Thus variability due to flare activity as well as variability intrinsic to stellar surface active regions, as recently demonstrated by Linsky et al. (1981), may also account for differences between $L_C$ and $L_X$. The eventual acquisition of additional IUE data for these stars, as well as other M dwarf stars for which X-ray data are currently available, will enable us to more accurately define the mean quiescent level of chromospheric emission present and thus partially circumvent the problems introduced by variability.
CONCLUSIONS

Our preliminary investigation corroborates the suggestion by Cram (1981) that X-ray heating by an overlying corona is the dominant heating mechanism in dMe stellar chromospheres. Of course this does not entirely resolve the problem of the heating of M dwarf atmospheres since the question concerning the origin of the X-ray emission itself (i.e., coronal heating) still remains. Nevertheless, the identification of a dominant chromospheric heating mechanism for a particular class of stars is a significant advance for the understanding of the origin of stellar chromospheres. The importance of X-ray heating in other stellar types should be assessed by comparing the observed total chromospheric-transition region line luminosities with the observed X-ray luminosities for sets of "active" and "quiet" stars of various spectral types. Interestingly, X-ray heating appears important in that region of the H-R diagram where turbulent velocities are low. We therefore speculate that for earlier stellar types, characterized by higher turbulent velocities, direct heating of the stellar chromosphere by magneto-acoustic mechanisms (e.g., see Ulmschneider and Bohn 1981; Leibacher and Stein, this volume) becomes relatively more important than external heating by coronal X-rays.

REFERENCES