ACTIVE LATE-TYPE STARS AND THE APPLICABILITY
OF CORONAL LOOP MODELS

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ABSTRACT

We combine far ultraviolet IUE observations with existing soft X-ray measurements obtained by Einstein (HEAO-B) satellite observatory for a sample of solar-type stars. We utilize the resulting data-set and a new coronal loop model numerical code developed at the Harvard-Smithsonian Center for Astrophysics to perform a preliminary investigation of the applicability of coronal loop models to solar-type stars. In particular, we find that reasonable agreement between the predictions of single-component, coronal loop model atmospheres and the observational data is achieved for a relatively well defined, plausible range of stellar atmospheric parameters for the sample of solar-type stars considered herein. We thus demonstrate that semi-empirical, coronal loop models can be applied to account for observed stellar transition region and coronal emission. This result is corroborative evidence for the presence of magnetic field structures analogous to solar coronal loops on the surfaces of solar-type stars. Moreover, we suggest that observed stellar transition region emission arises predominantly from the base of quiescent coronal loop configurations.

INTRODUCTION

The atmosphere of the Sun exhibits a variety of structural inhomogeneities that are defined by magnetic field configurations. We now recognize these atmospheric inhomogeneities as a fundamental property of the solar outer atmosphere. In particular, magnetic field configurations that define atmospheric thermal inhomogeneities are especially evident in the solar corona which is characterized by open and closed coronal loop structures (e.g., see Vaiana and Rosner 1978). Previous investigations have delineated the physical structure of open (Rosner and Vaiana 1977) and closed field regions in the solar corona, culminating in the development of scaling laws relating loop size, temperature and pressure for coronal loops in hydrostatic equilibrium (Rosner, Tucker and Vaiana 1978; hereafter RTV). The results of the solar investigations may be applicable to stars given that the occurrence of stellar surface features similar to solar plage and sunspots is now well established. The existence of stellar surface inhomogeneities, analogous to solar surface features, provides compelling circumstantial evidence for the presence of coronal magnetic field structures on stars that are similar to solar coronal loops.

Recently, coronal loop models have been utilized by several investigators to explain the observed soft X-ray emission from active stars (e.g. Golub et al. 1982; and references therein). These investigations reveal that, without additional constraints, coronal loop models deduced solely on the basis of stellar X-ray observations can only yield a locus of

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possible atmospheres in the coronal pressure - filling factor (p-f) plane. Consequently, we have utilized observed far ultraviolet line fluxes of prominent transition region emission lines, as obtained with the International Ultraviolet Explorer (IUE) satellite, combined with measurements of coronal soft X-ray emission, acquired by Einstein Observatory, to construct semi-empirical, single-component loop model atmospheres that best fit the aforementioned observations for a sample mainly composed of solar type stars. In this way, we (1) test the applicability to solar-type stars of solar coronal loop models, (2) obtain estimates of stellar coronal properties such as coronal base pressure and the filling factor of coronal loops, and (3) ascertain the extent to which the addition of UV transition region observations to X-ray measurements can constrain the range of possible loop atmospheres. The observations, detailed model computations and results are given by Giampapa et al. (1984). We summarize the basic results and conclusions herein.

RESULTS

Following Golub et al. (1982a), we envisage a stellar atmosphere consisting of loops of magnetically confined plasma where each loop is subject to the constraint imposed by the RTV scaling law

\[ T = 1.4 \times 10^3 (pL)^{1/3}, \]

or the generalization of this law given by Serio et al. (1981). We adopt the theoretical constraints outlined by Pallavicini et al. (1981) for the static stellar loop models we construct. The observational constraints that a model must satisfy include the value of the coronal temperature, assumed to characterize the maximum loop temperature which, in turn, occurs at the top of the loop (RTV 1978), and the observed ultraviolet line fluxes combined with the soft X-ray flux. The ultraviolet lines used include C IV 1550, N V 1240 and Si IV 1400 (we apply a correction to the observed Si IV-0 IV 1400 blend to account for the contribution from O IV).

The results of the model computations are displayed in Table 1. We show relevant stellar parameters in the first three columns of Table 1. The remaining columns include the coronal temperature, \( T_{\text{max}} \) coronal loop base pressure, \( p \), and the filling factor \( f \) of identical loops characterized by length \( L \) necessary to best fit the observed UV and X-ray emission.

DISCUSSION

Consistent with the results of Golub et al. (1982), we find a locus of allowed values in the \( (p,f) - \) plane which would satisfy the observational constraints provided by measurements of only \( f \) and \( T_{\text{corona}} \). Examination of Table 1, however, reveals that the addition of the transition region emission line fluxes severely constrains the range of permissible values in the \( (p,f) - \) plane that yield acceptable loop model atmosphere that satisfy both the far ultraviolet and X-ray data for the solar-type stars considered in this investigation. We note that the assumed primary emitter in the RS CVn system HD5303 is characterized by high pressure loop structures with loop lengths \( L > R \) and a filling factor \( f > 1 \). Both Swank et al. (1981) and
Walter et al. (1980) find similar results in their investigations of RS CVn systems within the context of loop model atmospheres. The inferred loop length \( L > R \) can be attributed to the high coronal temperature \( T_{\text{corona}} = 2.5 \times 10^7 \) combined with a consideration of the RTV scaling law (equation 1). Thus the inferred filling factor is more representative of a volume, rather than surface, filling factor of emitting loops. Additional evidence for these kinds of loop structures is given by Simon, Linsky and Schiffer (1980) in the specific case of the RS CVn system UX Ari.

### TABLE 1

<table>
<thead>
<tr>
<th>Object</th>
<th>( d ) (cm s(^{-2}))</th>
<th>( T_{\text{max}} ) (K)</th>
<th>( p ) (dyne cm(^{-2}))</th>
<th>( f ) (K)</th>
<th>( R / R_\odot )</th>
<th>( L ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha ) Cen B (K1 V)</td>
<td>3.23(4)</td>
<td>1.34</td>
<td>0.87</td>
<td>2.4(6)</td>
<td>0.56</td>
<td>1.68</td>
</tr>
<tr>
<td>( \iota ) Per (G4 V)</td>
<td>2.91(4)</td>
<td>11.6</td>
<td>0.95</td>
<td>2.6(6)</td>
<td>0.65-0.85</td>
<td>1.25-1.69</td>
</tr>
<tr>
<td>( \upsilon ) Her (G5 IV)</td>
<td>5.08(3)</td>
<td>8.06</td>
<td>3.10</td>
<td>2.6(6)</td>
<td>0.35</td>
<td>0.27</td>
</tr>
<tr>
<td>( \delta ) Dra (K0 V)</td>
<td>2.95(4)</td>
<td>5.68</td>
<td>0.85</td>
<td>2.3(6)</td>
<td>4.0-16.0</td>
<td>0.04-0.16</td>
</tr>
<tr>
<td>HR 3538 (G3 V)</td>
<td>2.88(4)</td>
<td>11.8</td>
<td>0.98</td>
<td>3.2(6)</td>
<td>5.0-10.0</td>
<td>0.085-0.17</td>
</tr>
<tr>
<td>( \epsilon ) Eri (K2 V)</td>
<td>3.08(4)</td>
<td>3.31</td>
<td>0.82</td>
<td>3.5(6)</td>
<td>5.0-20.0</td>
<td>0.54-0.22</td>
</tr>
<tr>
<td>HD 206860 (G0 V)</td>
<td>2.75(4)</td>
<td>17.5</td>
<td>1.05</td>
<td>4.4(6)</td>
<td>6.0-8.0</td>
<td>0.35-0.47</td>
</tr>
<tr>
<td>HD 206860-( \ast ) (G0 V)</td>
<td>2.75(4)</td>
<td>17.5</td>
<td>1.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HD 5303 (G2 V+F)</td>
<td>2.75(4)</td>
<td>66</td>
<td>1.0</td>
<td>24(6)</td>
<td>25.0</td>
<td>3.64</td>
</tr>
</tbody>
</table>

\*Multiple ultraviolet observations available for this object.

In brief summary, inspection of Table 1 reveals that, in general, reasonable agreement between the predictions of coronal loop model atmospheres and the observational data is achieved for plausible stellar atmospheric parameters (i.e., \( T_{\text{max}}, p, f, L \)) for the sample of solar-type stars considered herein. Hence the results of this preliminary investigation demonstrate that semi-empirical coronal loop models can be applied to account for the observed transition region and coronal emission from solar-type stars. This conclusion represents corroborative evidence for the existence of magnetic field configurations analogous to solar coronal loops on the surfaces of solar-type stars.

The aforementioned results are particularly intriguing in view of the (1) occurrence of variability in stellar transition region and coronal emission, and (2) the lack of simultaneous UV and X-ray observations for this study. Consequently, we suggest that the amplitude of UV and X-ray variability in solar-type stars must rarely exceed factors of 2-3. This low-amplitude variability is a characteristic of static, quiescent (\( L < s_p \)) loop structures which have evolved from originally compact (\( L < s_p \)) high pressure, newly-emerged flux loops. Hence the implication of this suggestion is that the observed far UV stellar transition region line emission predominately arises from the footpoints of quiescent coronal loop structures. Furthermore, we have examined the applicability of high pressure, compact loops. We find that these kinds of loops can correctly predict the observed X-ray emission but they completely fail to account for the far UV emission due to the low filling factor (\( f \ll 1 \)) of these loops (e.g., see Swank et al. 1981). This fact constitutes additional evidence for our claim that stellar UV emission is principally diagnostic of the transition regions at the base of quiescent loop structures.

Finally, we note that intrinsic stellar variability may account for
some of the discrepancies between the model predictions and the observations. In particular, we obtained models that satisfactorily predicted the observed X-ray emission and the initial UV observations for HD 206860 (designated HD 206860-1 in Table 1). However, no acceptable model could account for both the X-ray emission and the second set of UV observations acquired for this star (designated HD 206860-2 in Table 1). More specifically, all models that correctly predicted the X-ray emission consistently overpredicted the UV emission in all lines. Low pressure loops correctly predicted the UV emission of HD 206860-2 but they underpredicted the X-ray emission by at least an order of magnitude. Moreover, these low pressure models were characterized by physically unrealistic filling factors of f $>>$ 1. The transition region UV emission of the initial observation of HD 206860 (HD 206860-1) was enhanced relative to the later observation (HD 206860-2). Thus the single measurement of the X-ray emission from the star must be more compatible with the relatively enhanced transition region of HD 206860-1 than that of the later observation of this object. A similar result was obtained for models of the dMe flare star AD Leo. These models were based on recent (non-flaring) IUE observations and an earlier X-ray measurement that likely contained a flare contribution. We therefore suggest on the basis of these results that intrinsic stellar variability can contribute to the discrepancies between the observations and the model predictions for the stars considered in this investigation.

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REFERENCES