EFFECTS OF MASS MOTIONS ON SOLAR EMISSION MEASURES INFERRED FROM TRANSITION-REGION EMISSION LINES

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ABSTRACT

Extreme ultraviolet emission line intensities predicted by a numerical model which includes nonequilibrium ionization balance are used as input "observational" intensities to calculate volume emission measures following a standard method which assumes ionization equilibrium. These "observational" emission measures are then compared with the actual emission measure distribution in the atmospheric model. For static equilibrium models, the two sets of emission measures are in good agreement. When mass motions are present, the emission measures calculated from the line intensities differ significantly from the actual values.

Subject headings: Sun: atmospheric motions — Sun: chromosphere — Sun: corona — ultraviolet: spectra

I. INTRODUCTION

Emission line intensities in the ultraviolet and extreme ultraviolet regions of the solar spectrum are an important tool for inferring the atmospheric structure of the upper chromosphere, the transition region, and the inner corona. The optically thin allowed transitions provide estimates of the emission measure $\int N_e^2 dV$ as a function of temperature, while the density-sensitive forbidden lines provide electron density estimates. These two atmospheric parameters then constitute the basic information for constructing empirical models of the temperature-density structure in these layers.

A common assumption in these emission measure-based analyses is that the ions producing the emission lines are in ionization equilibrium. High spectral resolution observations (e.g., Brueckner and Bartoe 1977, 1983; Gebbie et al. 1981) show, however, that over much of the Sun emission lines formed in the transition region are Doppler shifted, indicating that the region in which they are formed is in motion. This then leads to an inconsistency in the analysis. The emission measure-based models indicate steep temperature gradients which would produce departures from ionization equilibrium if mass motions were present, and the observations indicate that mass motions are indeed present.

A number of authors have considered aspects of this problem. The most common approach has been to examine the ionization balance in steady flows through predetermined empirical temperature-density models (e.g., Raymond and Dupree 1978; Dupree, Moore, and Shapiro 1979; Francis 1981; Roussel-Dupre and Beerman 1981). The results are usually presented as a comparison of the nonequilibrium ion distributions with the equilibrium distributions. Athay (1982), on the other hand, considered the effect of flows and changes in the magnetic field geometry on the emission measure calculated directly from the temperature-density distribution. However, he did not examine how the flow would modify the ionization balance and change the emission measures determined from spectral lines formed in his model atmosphere.

We consider this problem in this paper. We use the results of time-dependent numerical simulations of the atmospheric structure to predict spectral line intensities which can be analyzed as if they were data to determine emission measures. These empirical emission measures can then be compared with emission measures determined directly from the actual numerical model. Our analysis is thus similar to Athay's (1982) with the addition of nonequilibrium ionization balance and a fully time-dependent atmospheric model. This approach has the advantage that the two emission measure estimates come from the same well-defined model, which is a realization of a given set of physically reasonable assumptions, rather than the result of an empirical analysis of solar data. The model thus serves as an experimental Sun. Unlike the calculations presented in most previous work, the temperature-density structure of the numerical model presented here is modified in a physically self-consistent manner by the existence of the flow. It is not treated as a perturbation on an existing static background. The goal of this work is to assess the errors that are introduced into empirical models when the assumption of ionization equilibrium is incorrect.

II. THE ATMOSPHERIC MODELS

The atmospheric models used in this study are from a series of simulations performed by Mariska and Boris (1983) to examine the dynamics and spectroscopy of asymmetrically heated coronal loops. The models were calculated using the NRL dynamic flux tube model (Mariska et al. 1982). This model provides a solution to the equations for mass, momentum, and energy conservation for a two-fluid solar plasma as a function of time and position along a magnetic flux tube of variable cross-sectional area. In addition to the two-fluid conservation equations, the model also solves the time-dependent ionization balance equations for all of the ionization stages of oxygen. Thus the material for this analysis consists of the distributions of temperature, density, pressure, velocity, and oxygen ion abundance as a function of time and position along a magnetic flux tube of variable cross-sectional area.

We consider the two separate loop geometries shown in Figure 1. Each loop is $1.2 \times 10^4$ km long and is bent into a semicircle with a radius $3.8 \times 10^3$ km. For case A the loop has a constant cross section with a radius of 300 km, while for case B the radius is held constant at 300 km for the first 670 km of distance in each chromosphere. The radius then expands to 900 km over the next 970 km. It then remains constant in the upper portion of the loop.

In each of these loop geometries an initial atmospheric
model in hydrostatic equilibrium was constructed. At each end of the loop is a base chromospheric region of plasma approximately 1000 km in length with a temperature of $10^4$ K. Above these base regions are transition regions initially in hydrostatic equilibrium whose properties are found by solving the static force and energy balance equations. The pressure at the base of each transition region is initially taken to be 0.2 dyn cm$^{-2}$, a typical pressure for the quiet Sun (see, e.g., Withbroe and Noyes 1977). A spatially uniform energy deposition of $6-8 \times 10^{-4}$ ergs cm$^{-3}$ s$^{-1}$ maintains each initial model. The overall initial conditions are symmetric about the top of the loop. Figure 2 shows the initial temperature, electron density, and pressure structure for the atmosphere in case A. The initial model for case B is nearly identical.

The loop length used in these calculations is relatively small and is meant to be typical of the small-scale structure that may comprise the quiet solar network at transition region temperatures. The case A geometry represents the simplest possible loop configuration, while the case B geometry is an attempt to simulate the effects that might be introduced by an expanding magnetic field. Of course many other configurations are possible. Although the peak temperatures in the loops are lower than those encountered in the large-scale structure, they are high enough relative to the temperatures of formation of the transition region ions that all of the effects noted here should also be present in larger loops.

To induce the steady flow, the heating was changed from uniform in space to asymmetric. At the beginning of the calculation the total energy was reduced to 50% of the initial equilibrium value, and the excess was deposited in the regions indicated in Figure 1. Note that the total energy input remains constant, only the deposition profile has been changed. This change of the energy deposition profile was accomplished over a time interval of 200 s in order to reduce any transient disturbances that might be produced. The models were then evolved for several sonic transit times to reach a new steady state. A detailed discussion of the hydrodynamic response of the atmosphere to the heating location change can be found in Mariska and Boris (1983). The change in location of the heating may appear somewhat arbitrary. Boris and Mariska (1982) found, however, that once the degree of asymmetry in the heating becomes large, the flow saturates at the velocity that will allow the enthalpy flux to effectively resymmetrize the energy deposition asymmetry. That is the case for the calculations presented here. They thus represent the largest steady flow velocities achievable with this method of producing a flow.

Figure 3 summarizes the most important new characteristic of the final steady states for the two cases, the flow velocity as a function of distance along the flux tube. Also plotted in each panel is the variation of the flux tube radius with distance along the flux tube. The final temperature and density distributions are only slightly changed from the initial model shown in Figure 2, so that the transition regions continue to be located a little more than 1000 km in from each end of the loop. Thus it

Fig. 1.—Flux tube geometries for the two cases examined in this study. The shaded areas indicate the regions of excess energy deposition.

Fig. 2.—The initial distribution of temperature, pressure, and electron density with distance along the flux tube for case A. The temperature is in units of K, the pressure is in units of $10^{-2}$ dyn cm$^{-2}$, and the electron density is in units of $10^{5}$ cm$^{-3}$.

Fig. 3.—Velocities as a function of position along the flux tube at the end of the two simulations. Also plotted are the flux tube radii as a function of position. The horizontal lines mark the locations where the excess heating is taking place.
is clear from Figures 2 and 3 that significant velocities are present throughout the transition regions of the models and hence we expect departures from ionization equilibrium.

Since emission measures usually can only provide information on the amount of emitting material as a function of temperature and the transition region covers only a short distance relative to the total loop length, it is useful to examine the final steady state velocities as a function of temperature. Figure 4 displays this information. For each of the cases we have divided the loop into an upflowing side (solid line) and a downflowing side (dashed line). The flow in case A increases gradually throughout the transition region on the upflowing side, but never becomes larger than about 6 km s$^{-1}$. The downflowing side has equally small velocities, with the region above about $3 \times 10^5$ K being roughly symmetric about the top of the loop. This is the expected result; since radiative losses are relatively unimportant in the upper portion of the loop, the flow is both mass and energy conserving. The flow velocity as a function of temperature is markedly different in case B. The expanding geometry and larger heat flux to the lower transition region result in a velocity peak near $3 \times 10^5$ K, with a rapid drop at greater temperatures. The peak velocity is near 12 km s$^{-1}$, twice the peak in case A. Because the cross-sectional area of the loop in the corona is significantly larger, radiation losses are significant in the coronal portions of the loop and the flow is not symmetric about the top. The flow velocities in both cases are in qualitative agreement with those seen in the quiet transition region network (see, e.g., Gebbie et al. 1981).

Figures 5 and 6 and Table 1 summarize the results of the
ionization balance calculations. The figures show for each of the two cases the relative fractional ion abundances for O\textsc{iii}, O\textsc{iv}, O\textsc{v}, and O\textsc{vi} as a function of temperature for the initial static model, for the upflowing side, and for the downflowing side. Note that the two sides are defined in terms of the spatial middle of the full loop. In the case B calculations, the final steady state has a temperature maximum one computational cell to the left of the middle of the loop. Thus there are small "hooks" in the ion abundance curves for the upflowing side of the loop. Below $10^5$ K the transition region becomes very steep and is contained in just a few computational cells. This results in the "stairsteps" that are noticeable in some of the plots. This lack of resolution at low temperatures somewhat compromises the usefulness of the O\textsc{iii} ion abundance determinations. We will be primarily concerned with the O\textsc{iv}, O\textsc{v}, and O\textsc{vi} ions.

Table 1 summarizes the emission line luminosities for the initial and final models for both cases. Here we list the power in ergs s\(^{-1}\) from a number of spectral lines of O\textsc{iii}, O\textsc{iv}, O\textsc{v}, and O\textsc{vi}. As with the figures, the final model for both cases has been divided into an intensity from the upflowing side and from the downflowing side. Note that the luminosities from the initial model are for a full loop.

III. EMISSION MEASURES

Using the calculated power in each emission line listed in Table 1 and standard analysis techniques, it is possible to calculate the volume emission measure from each of the atmospheric models. The power (ergs s\(^{-1}\)) in an optically thin emission line is given by

$$P = \frac{hc}{\lambda_{\text{ul}}} \times 0.8 A_{\text{ul}} A_{\text{el}} \int \frac{N_{\text{ul}}}{N_{\text{ion}} N_{\text{el}}} N_{\text{e}} dV,$$

where $\lambda_{\text{ul}}$ is the wavelength of the line, 0.8 is the hydrogen-to-electron number density ratio for a fully ionized plasma of solar composition, $A_{\text{ul}}$ is the spontaneous transition probability, $A_{\text{el}}$ is the elemental abundance relative to hydrogen, $N_{\text{ul}}/N_{\text{ion}}$ is the fractional population of the upper level, $N_{\text{ion}}/N_{\text{el}}$ is the fractional ion abundance, $N_{\text{e}}$ is the electron number density, and the integral is carried out over the emitting volume of the loop.

For all of the lines in Table 1, we use a modified form of the standard emission measure analysis that is correct for both allowed lines and for intersystem lines where ground state depletion may be significant. We rewrite equation (1) as

$$P = \frac{hc}{\lambda_{\text{ul}}} A_{\text{ul}} A_{\text{el}} \left< F(T) \right> \int N_{\text{e}}^2 dV,$$

where

$$F(T) = N_{\text{ul}} N_{\text{ion}} \frac{1}{N_{\text{el}} N_{\text{e}}}.$$  

The value of $\left< F(T) \right>$, the average value of the contribution function over a constant logarithmic temperature width of 0.3 dex, for each line is computed using the technique outlined in Mariska (1980). Both the equilibrium ion abundances and the upper level populations required in the calculations use the same atomic physics data that the numerical model uses. References for all of these data are in Mariska et al. (1982). Thus for each spectral line for which we list a power in Table 1, we can apply equation (2) and compute an "observational" emission measure. Note that it is the assumption of equilibrium values for the quantities defined in equation (3) that leads to the differences between the actual emission measure distribution and the "observational" emission measure distribution calculated using standard analysis techniques. The "observational" volume emission measures derived using the calculated line luminosities and the atomic data are listed as the second entry for each emission line in Table 1.

The actual volume emission measures from the model atmospheres were determined by calculating the product of $N_{\text{e}}^2$ and the volume in each of the finite difference cells used in the calculation. These quantities were then binned over a logarithmic temperature array, with each bin containing the sum of all the volume emission measures from cells within the temperature interval $\Delta \log T = \pm 0.15$ dex around the central temperature of the bin. This results in emission measures that are defined in

### Table 1

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda$ (Å)</th>
<th>$\log T_e$</th>
<th>Initial</th>
<th>Upflow</th>
<th>Downflow</th>
<th>Case A</th>
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<tr>
<td>O\textsc{iii}</td>
<td>1666</td>
<td>4.95</td>
<td>4.19 (+18)</td>
<td>1.45 (+18)</td>
<td>1.40 (+18)</td>
<td>1.04 (+19)</td>
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<td></td>
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<td>2.21 (+42)</td>
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<td></td>
<td></td>
<td></td>
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<td>4.95</td>
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<td>8.44 (+19)</td>
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<tr>
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<td></td>
<td></td>
<td>600</td>
<td>4.95</td>
<td>9.86 (+41)</td>
<td>3.41 (+41)</td>
</tr>
<tr>
<td>O\textsc{iv}</td>
<td>1401</td>
<td>5.25</td>
<td>4.96 (+18)</td>
<td>2.01 (+18)</td>
<td>1.62 (+18)</td>
<td>1.82 (+19)</td>
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<tr>
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<td></td>
<td></td>
<td>1.06 (+42)</td>
<td>4.31 (+41)</td>
<td>3.47 (+41)</td>
<td>3.96 (+42)</td>
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<td>554</td>
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<td>2.69 (+19)</td>
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<td></td>
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<td>1.10 (+42)</td>
<td>4.76 (+41)</td>
<td>3.30 (+41)</td>
<td>4.54 (+42)</td>
</tr>
<tr>
<td>O\textsc{v}</td>
<td>1218</td>
<td>5.40</td>
<td>1.29 (+19)</td>
<td>7.34 (+18)</td>
<td>4.07 (+18)</td>
<td>8.76 (+19)</td>
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<td></td>
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<td>3.58 (+19)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1.40 (+42)</td>
<td>1.33 (+42)</td>
<td>8.43 (+41)</td>
<td>1.82 (+43)</td>
</tr>
</tbody>
</table>

Note: The first entry for each ion is the total power in ergs s\(^{-1}\) in the emission line; the second entry is the volume emission measure derived from the first entry.
EFFECTS OF MASS MOTIONS

Fig. 7.—The actual and derived emission measures for case A. The filled circles show the actual emission measures determined from the simulation, while the crosses show the emission measures derived from the emission lines.

The final emission measure distributions for case B reflect the effects of the flow in the expanding geometry. On the upflowing side of the loop, the model emission measure distribution has steepened considerably near $4 \times 10^5$ K. This is the result of the somewhat larger temperature gradient change produced by the heating asymmetry in the expanding geometry. Since the coronal volume is large relative to the transition region volume below it, more energy is being conducted downward to the left transition region than in case A. This results in a steeper transition region temperature gradient and the larger velocities. In the lower portions of the transition region, $5.2 < \log T_e < 5.5$, the slope in emission measure is also altered somewhat by the temperature and density change produced by the presence of larger flow velocities than those in case A. On the downflowing side the changes in the model emission measures are relatively small, since the velocities are small.

The emission measures calculated from the spectral lines in case A depart somewhat from the model values. For the upflowing side of the loop they tend to fall above the actual emission measure, while for the downflowing side they tend to fall below the actual values. If one were to derive the slope of the emission measure distribution using the O iv and O v data alone, it would be a little low for the downflowing side and a little high for the upflowing side, but roughly the same as the model values. The slope determined using the O v and O vi points would be too great by a factor of 5 on the downflowing side and more than a factor of 6 on the upflowing side. When the loop as a whole is considered, the differences in the two sides partially cancel, and the overall agreement is good in the value of the emission measure, although the slopes still disagree by more than a factor of 5.

The final emission measure distributions show significant differences between the two methods of calculation. The case A results in Figure 7 reflect only the effects of the flow. The model emission measures show how the actual atmosphere has changed. The emission measure in the main portion of the transition region, $5.1 < \log T_e < 5.5$, has retained the same slope in both the upflowing and downflowing cases. This is a reflection of the fact that the flow has done little to alter the basic character of the transition regions at each end. The temperature gradient has become a little steeper on the upflowing side and a little shallower on the downflowing side, but not by a large enough amount to be reflected in the emission measures until temperatures above $3 \times 10^5$ K.

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The departures of the emission measures determined from the spectral lines from those determined from the model are easily understood by examining Figures 5 and 6. On the upflowing side of each loop the relative abundance of \( \text{O} \text{vi} \) has increased substantially, due to increased ionization of \( \text{O} \text{v} \) to \( \text{O} \text{vi} \) caused by the upflow of the \( \text{O} \text{v} \) into higher temperature regions. The ionization time from \( \text{O} \text{v} \) to \( \text{O} \text{vi} \) is longer, however, than that from \( \text{O} \text{v} \) to \( \text{O} \text{vi} \) by about a factor of 7. A similar effect takes place for \( \text{O} \text{v} \), leading to a small enhancement of it over the value in the initial model. Thus the enhanced \( \text{O} \text{vi} \) abundance leads to enhanced \( \text{O} \text{vi} \) emission and an overestimate of the emission measures relative to the model value.

On the downflowing side \( \text{O} \text{iv} \), \( \text{O} \text{v} \), and \( \text{O} \text{vi} \) are all underabundant compared with their equilibrium values. This is because the recombination time from \( \text{O} \text{vii} \) to \( \text{O} \text{v} \) is long (about 800 s) in the upper regions of the model. Thus, over much of the transition region, most of the oxygen is in \( \text{O} \text{vii} \) ions and the abundances of the lower stages of ionization are reduced, leading to reduced emission and hence an underestimate of the emission measure.

For case B the larger velocities on the upflowing side increase the magnitude of the \( \text{O} \text{vi} \) abundance enhancement. The relatively smaller velocities in the corona and on the downflowing side, however, provide more time for recombination to operate and thus result in smaller differences in the emission measures calculated from the spectral lines and those calculated from the model.

The flows also change the temperature of the peak abundance for each ion. In the upflowing plasma, ions are formed at a higher temperature than their equilibrium value, and in the downflowing plasma ions are formed at a lower temperature than their equilibrium value. For example, in case A the temperatures of peak abundance for \( \text{O} \text{iv} \), \( \text{O} \text{v} \), and \( \text{O} \text{vi} \) are about 1.65 \( \times 10^5 \), 2.67 \( \times 10^5 \), and 3.53 \( \times 10^5 \) K, respectively, on the upflowing side of the loop. On the downflowing side the corresponding temperatures are 1.43 \( \times 10^5 \), 2.18 \( \times 10^5 \), and 2.87 \( \times 10^5 \) K. The equilibrium values, calculated using the same atomic data, are 1.60 \( \times 10^5 \), 2.41 \( \times 10^5 \), and 2.92 \( \times 10^5 \) K, respectively. These changes in temperature of formation result in some changes in the line emission through the Boltzmann factors in the excitation rate coefficients for the lines. The effect, however, is small. For example, the ratio of the \( \text{O} \text{v} \) 1218 Å line to the \( \text{O} \text{v} \) 629 Å line, which is a measure of effects due to changes in the Boltzmann factor, is 0.080 in the case A equilibrium atmosphere. On the upflowing side where the temperature of the formation has increased, the ratio is only reduced to 0.076, and on the downflowing side the increase is only to 0.082.

### IV. DISCUSSION AND CONCLUSIONS

Recently Jordan (1980) has discussed the use of observed emission measures to place limits on the nature of the energy deposition function. Her analysis is limited to the static case, so we limit our comparison with her work to the initial model for case A. Throughout much of the transition region, the slope of the model emission measure for this case is less than the value of 1.5 required by a constant conductive flux. This is not surprising when one considers the relative importance of the various terms in the energy balance equation. At the top of the model, just below the turnover caused by the temperature maximum, the slope of the emission measure is much greater than 1.5. In this region of the atmosphere radiation is relatively unimportant. Energy deposition is the dominant source term and conduction is the dominant sink term. At a temperature of about 3.9 \( \times 10^5 \) K the radiation rate and the energy deposition rate are equal. Thus here the divergence of the conductive flux is zero and, as expected, the slope of the emission measure decreases to a value of 1.5. Only a short distance further down into the atmosphere, however, the radiation rate becomes much larger than the energy deposition rate. Here conduction becomes a source term to supply the radiative losses and the slope decreases to less than 1.5. Thus in a model atmosphere constructed using hydrostatic equilibrium and energy balance with a constant volumetric energy deposition rate, all three cases discussed by Jordan (1980) are present. The loops modeled in this work are relatively short and thus have low peak temperatures. Because of this, the range over which one would expect the slope to be 1.5 is small. In a larger loop, the region would be larger, but the same overall result would be true; all three cases discussed by Jordan (1980) would be present in one model atmosphere.

Raymond and Doyle (1981) have discussed the changes required in Jordan's (1980) analysis in order to include low-velocity flows. They find that relatively small upflow velocities, on the order of a few km s\(^{-1}\), will easily account for a slope in the emission measure of less than 1.5. There are some small changes in the slope of the emission measure at low temperatures between the initial model and upflowing side of the final model in case A. These changes are quite small, however, suggesting that in practice it would be difficult to deduce the presence of a low-velocity flow from a small deviation in the slope of the emission measure. The effects of the nonequilibrium ionization balance would in practice make the analysis even more difficult. The change in slope at higher temperatures (log \( T \) > 5.5) is toward a larger value of the slope rather than a smaller one.

The results presented in Figures 7 and 8 present something of a dilemma. It is clear from the emission measure distributions for the initial models that the standard techniques for performing emission measure analyses work well when all the assumptions upon which they are based are correct. Chief among these is the assumption that the structure being studied is static. Unfortunately, much of the solar transition region exhibits significant mass motions, and these clearly lead to major departures between the actual emission measure and the emission measure determined using spectral line data. These differences often cancel when one examines complete structures, such as the loop studied here at low spatial resolution. Thus one might be led to predict an average temperature and density structure for a loop which would suggest the overall structure is in static equilibrium, when in fact a steady flow is present.

One solution to this dilemma is to abandon the practice of using derived emission measures to produce empirical temperature and density models. A better approach is to construct reasonable physical models of the structure that is being analyzed and then to use the correct nonequilibrium ionization
balance to predict emission line intensities for comparison with observation. Such an approach requires not only better physical modeling techniques, which are just becoming available, but also sufficient spatial and spectral resolution to make full use of the more complex models.

The calculations presented in this paper are the result of a numerical simulation which attempts to include all of the important physical processes that are believed to be operating in the outer layers of the solar atmosphere. The relationship between these calculations and the real Sun must, however, be viewed with some caution. First, the calculations are still not fully self-consistent. The atomic physics calculations are not used to produce updated radiation rates for the hydrodynamics. Instead equilibrium radiative losses are used. Most of the radiative loss in the model takes place near the base of the transition region and the largest departures in the ionization balance are high in the transition region. Thus, the overall radiative loss from the model is probably reasonable. The detailed interplay between the radiative losses and conduction, heating, and flows is however only a first approximation in this treatment. We defer a more consistent treatment to a later work. Second, examination of the emission measure distributions in Figures 7 and 8 shows a steadily declining emission measure with decreasing temperature. Empirically determined emission measures, on the other hand, generally show an increase below about $2 \times 10^5$ K (e.g., Jordan 1976). Athay (1982) has also noted this disagreement. Our calculations suggest that time-dependent ionization balance effects are not likely to resolve this disagreement between theory and observation. It is more likely that the resolution lies in a fuller understanding of the geometry of the transition region.

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REFERENCES


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