TEMPERATURE GRADIENTS IN THE INNER CORONA

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(Received 17 July, 1978)

Abstract. Emission gradient curves for extreme ultraviolet (EUV) resonance lines of O vi and Mg X have been constructed from spectroheliograms of quiet limb regions observed with the Harvard experiment on Skylab. An analysis of these data suggests that the coronal temperature rises throughout the height range $1.03 R_\odot \leq r \leq 1.3 R_\odot$. This result implies that in quiet regions there is significant coronal heating beyond $r = 1.3 R_\odot$.

1. Introduction

A major problem of solar physics is determining the energy balance in the solar corona. At the present time there remains considerable uncertainty as to the coronal heating mechanism (e.g., Withbroe and Noyes, 1977). Improved empirical information about the temperature-density structure of the inner corona can provide valuable constraints on theoretical models for the coronal energy balance (e.g., Kopp and Orrall, 1976). Most previous studies of the quiet corona were directed toward deriving mean coronal temperatures and ignored the influence of temperature gradients. In the present paper we utilize new measurements of extreme ultraviolet (EUV) emission gradients to obtain information on the magnitudes of the temperature and density gradients in the inner corona.

EUV observations of quiet regions on the disk and above the limb have been interpreted using isothermal coronal models (e.g., Withbroe, 1970; Dupree, 1972; Mariska and Withbroe, 1975). Mariska and Withbroe (1975) examined the limb brightening behavior of O vi $\lambda$ 1032 and Mg X $\lambda$ 625 and concluded that the quiet corona could be represented by a homogeneous model with a temperature of about $10^6$ K in the height range below $1.1 R_\odot$ and a temperature of about $1.1 \times 10^6$ K for $1.1 R_\odot \leq r \leq 1.25 R_\odot$. In the present study we use EUV data from above the limb to examine the temperature-density structure of the inner corona in quiet regions. The objective of this analysis is to place limits on possible temperature gradients in the inner corona.

2. Observations

From observations obtained at the limb with the Harvard instrument on Skylab, eleven regions that appeared to show no obvious signs of activity were selected for

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Solar Physics 60 (1978) 67–82. All Rights Reserved
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further analysis. The date and limb position for each observation are listed in Table I. All of the observations listed in the table consist of spectroheliograms obtained in the lines $\text{O vi } \lambda 1032$ and $\text{Mg x } \lambda 625$. Each spectroheliogram is $5' \times 5'$, was acquired over a period of 5.5 min and has a spatial resolution of $5'' \times 5''$.

**TABLE I**

Quiet region isothermal models

<table>
<thead>
<tr>
<th>Day hr min</th>
<th>Angle$^a$</th>
<th>$\text{Mg x}$</th>
<th>$\text{O vi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\log T_e$</td>
<td>$\log N_0$ $^b$</td>
<td>$\chi^2/\nu$</td>
</tr>
<tr>
<td>154 21</td>
<td>6.16</td>
<td>8.46</td>
<td>2.99</td>
</tr>
<tr>
<td>164 23 06</td>
<td>6.06</td>
<td>8.57</td>
<td>1.91</td>
</tr>
<tr>
<td>164 23 23</td>
<td>6.04</td>
<td>8.64</td>
<td>0.66</td>
</tr>
<tr>
<td>196 16</td>
<td>6.04</td>
<td>8.79</td>
<td>1.78</td>
</tr>
<tr>
<td>225 23</td>
<td>6.12</td>
<td>8.32</td>
<td>1.77</td>
</tr>
<tr>
<td>291 03</td>
<td>6.08</td>
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<tr>
<td>347 16</td>
<td>6.22</td>
<td>8.31</td>
<td>1.99</td>
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</tr>
<tr>
<td>348 19</td>
<td>6.06</td>
<td>8.62</td>
<td>1.61</td>
</tr>
<tr>
<td>370 21</td>
<td>6.06</td>
<td>8.56</td>
<td>4.14</td>
</tr>
<tr>
<td>28 23</td>
<td>6.08</td>
<td>8.43</td>
<td>1.17</td>
</tr>
</tbody>
</table>

$^a$ Angle in degrees from solar north pole eastward.

$^b$ Log of the electron density at $1.01 R_\odot$.

Emission gradient curves were constructed for each spectroheliogram by averaging all points in the spectroheliogram that fell at the same solar radius and plotting the average as a function of distance $\rho$ from Sun center where $\rho$ is measured in units of a solar radius $R_\odot$. The standard deviation of the mean was also computed for each average. The absolute scale of the observations was determined using the calibration of Reeves et al. (1977). This calibration has an assigned uncertainty of $\pm 35\%$. A typical emission gradient curve for $\text{Mg x } \lambda 625$ is displayed in Figure 1. For a typical set of quiet region observations, such as those made on 18 October 1973 and used in Figure 1, the standard deviation of the mean intensity at $\rho = 1.03$ is about 2% for both $\text{Mg x } \lambda 625$ and $\text{O vi } \lambda 1032$. It increases to about 5% for $\text{Mg x}$ and 7% for $\text{O vi}$ at $\rho = 1.20$.

The temperature of maximum concentration of $\text{Mg x}$ is about $1.5 \times 10^6$ K. Unfortunately, few observations were made above the limb in the lines of higher temperature ions such as $\text{Si xii}$. From these observations two sets of data were found that can place some limits on $\text{Si xii}$ emission above the limb. The observations, taken on 27 August 1973 and 6 February 1974, indicate that the $\text{Si xii } \lambda 521$ intensity decreases with height from 80–95 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at $\rho = 1.03$, to 70–76 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at $\rho = 1.05$, to 38–40 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at $\rho = 1.10$. © Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
3. Temperature Estimates

In the transition region the temperature is changing rapidly with height; in the corona it is not. Thus, above the limb one cannot assume that each ion radiates at the temperature of maximum concentration. For example, O vii $\lambda$1032 shows substantial emission at an appreciable distance above the limb where the temperature must certainly be higher than the temperature of maximum concentration of the ion ($T = 300,000$ K). Thus, an emission measure analysis using the standard techniques for transition region lines (cf. Dupree, 1972) will be meaningless. We therefore begin our determination of the temperature-density structure of the inner corona by estimating the coronal temperature and trying to model the data with an isothermal model.

We assume that the corona can, to a first approximation, be represented as homogeneous over a quiet area. Mariska and Withbroe (1975) estimated that on the disk the root-mean-square fluctuations in the coronal electron density, where the Mg x lines are formed, are of the order of 13% of the mean density. Thus a homogeneous model represents a good first approximation. Soft X-ray observations suggest that the quiet corona is a series of large scale structures associated with closed magnetic field configurations (Maxson and Vaiana, 1977). These are frequently
visible at the limb as a series of nested loops. If such a configuration fills a major portion of the inner corona, then an analysis of the energy balance in the inner corona using limb observations is greatly complicated. While an average temperature-density model would provide a useful starting point in modeling the energy balance of loops, one could not go directly from it to a determination of the coronal energy loss due to thermal conduction unless he had knowledge of the magnetic field configuration.

3.1. Line Ratios

The intensity of an optically thin EUV emission line observed above the limb (cf. Withbroe, 1970) is given by

\[ I(\rho) = 1.73 \times 10^{-16} A f \int_{-\infty}^{\infty} G(T) N_e^2 \, ds, \]  

where \( \rho \) is the distance from the center of the solar disk in units of the solar radius \( R_\odot \); \( A \) is the abundance of the element forming the line, measured relative to hydrogen; \( f \) is the oscillator strength; \( G(T) \) is a function that depends on the fraction of atoms in the ionization state producing the line, on the Gaunt factor, and on the excitation potential of the line; and \( ds = r \, dr / \sqrt{r^2 - (\rho R_\odot)^2} \). In this study the \( f \) values are those tabulated by Dupree (1972) and the Gaunt factors used in computing \( G(T) \) are from Bely (1966). The ionization equilibrium calculations used to compute \( G(T) \) are from Allen and Dupree (1969) and Wood and Dupree (1969). The abundances are based on EUV abundance determinations (Withbroe, 1976). On a scale where \( \log A_{\text{H}} = 12.0 \), we use \( \log A_{\text{O}} = 8.63 \), \( \log A_{\text{Mg}} = 7.65 \), and \( \log A_{\text{Si}} = 7.67 \).

If we assume that the coronal plasma along the line of sight is isothermal, then Equation (1) can be rewritten as

\[ I(\rho) = 1.73 \times 10^{-16} A f G(T_c) \int_{-\infty}^{\infty} N_e^2 \, ds. \]  

The ratio of the intensities of two spectral lines, here \( \text{Mg} \times \lambda 625 \) and \( \text{O} \ \text{vi} \ \lambda 1032 \), observed at the same height above the limb will then be given by

\[ \frac{I(\rho)_{\text{Mg} \times \lambda 625}}{I(\rho)_{\text{O} \ \text{vi} \ \lambda 1032}} = \frac{A_{\text{Mg}}}{A_{\text{O}}} \frac{[fG(T_c)]_{\lambda 625}}{[fG(T_c)]_{\lambda 1032}}. \]  

Figure 2a illustrates the \( \text{Mg} \times / \text{O} \ \text{vi} \) intensity ratio as a function of temperature. Also plotted on the graph is the average observed ratio at \( \rho = 1.05 \) for the quiet regions listed in Table I.

The observed ratio indicates a temperature of around \( 1.2 \times 10^6 \) K. If we use photospheric abundances (Withbroe, 1976; dashed line) rather than the EUV abundances, then the ratio indicates a temperature of \( 2.8 \times 10^6 \) K. Thus, any small uncertainty in the abundances will be reflected as a large uncertainty in the deduced
coronal temperature. We are thus forced to conclude that the Mg X/O VI ratio will allow any coronal temperature from just over $10^6$ K to almost $3 \times 10^6$ K at $1.05 R_\odot$.

Figure 2b shows the Si XII/Mg X intensity ratio as a function of temperature and the observed ratio at $\rho = 1.05$ from the 6 February 1974 Skylab data. The ratio suggests a temperature of around $2 \times 10^6$ K. Using photospheric abundances rather than EUV values makes little difference in the temperature determination. However, the ratio observed for these lines is close enough to the plateau in the curve that an error in the data or the calibration could put the ratio into the temperature insensitive portion of the curve where $T > 2 \times 10^6$ K.

3.2. Emission measure

Withbroe (1975) has developed a method that, given enough lines in the temperature range of the plasma, will provide an estimate of the emission measure as a function of temperature. Aside from spectra taken very close to the limb, there are very few observations of the inner corona with a sufficient number of lines for such an analysis. Vernazza and Reeves (1978) have compiled an averaged composite spectrum from a number of spectral scans taken just above a quiet solar limb with the Harvard
instrument on Skylab. Using their data for the resonance lines of O vi, Ne viii, Mg x, and Si xii and Withbroe’s emission measure analysis method it is possible to calculate the emission measure and estimate the coronal temperature. Figure 3 displays the results of these calculations of the differential emission measure, \[ Q(T) = N_e^2 \frac{ds}{dT}, \] as a function of temperature. The solid curve, calculated using the lines listed above, indicates that there is a large amount of material at a temperature of around \( 1.4 \times 10^6 \) K. The solid curve also remains quite high at temperatures above the peak. This is because there are no constraints on the emission measure above \( \log T = 6.35 \), the temperature of maximum concentration of Si xii. An emission measure curve such as the one shown here predicts far more Fe xvi \( \lambda 335 \) than is observed even over active regions (e.g., Withbroe, 1975).

To further constrain the emission measure calculation, the differential emission measure was recomputed using the same line intensities that were used for the solid

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Fig. 3. The quantity \( Q(T) \) derived from the averaged above limb spectrum of Vernazza and Reeves (1978). The solid line is the solution obtained using lines of O vi, Ne viii, Mg x, and Si xii. The dashed line is the solution obtained using the lines listed above and an intensity of 120 erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) from Fe xvi \( \lambda 335 \).
curve plus varying intensities in Fe xvi λ 335. Disk center intensities ranging from a few to several hundred erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ have been reported for this line (e.g., Dupree, 1972; Dupree et al., 1973). Coronal lines usually limb brighten by only a factor of two to four, so the range of disk center estimates suggests that the limb intensity is in the range from around ten to a thousand erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Vernazza and Reeves (1978) found a value of 985 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for a quiet limb; however, their value is highly uncertain because it is based on a count rate of only a single count per 0.040 s and the line may be blended with a line of Mg vii. They suggest that most of the emission seen in quiet regions at 335 Å is due to the Mg viii line. We find that converged emission measure solutions are possible for most of this range of intensities. The dashed line in Figure 3 is a typical solution. It was computed using an intensity of 120 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for Fe xvi λ 335. Requiring that the differential emission measure be consistent with the Fe xvi line intensity drastically reduces the amount of material at temperatures above the maximum concentration of Si xii and shifts the peak in the differential emission measure curve to a temperature of 1.8 × 10$^6$ K.

Withbroe (1975) performed a similar analysis on several disk center spectra and found the $Q(T)$ peaked at temperatures between 1.5 × 10$^6$ and 2.1 × 10$^6$ K, in agreement with the above the limb results presented here. Thus, although there is quite a large uncertainty in the actual temperature, the differential emission measure analysis suggests that near the solar surface the corona reaches temperatures of between 1.5 × 10$^6$ and 2.0 × 10$^6$ K.

3.3. Hydrostatic temperature

The emission gradients can provide additional constraints on the coronal temperature. We know the emission gradient over a considerable height range in the inner corona and can see whether an isothermal coronal model in hydrostatic equilibrium will fit the observations. For each of the eleven sets of limb data a number of isothermal models were computed and compared with the observations. In each case the density was determined by assuming hydrostatic equilibrium and requiring that the intensity predicted with the model fit the data at $\rho = 1.10$. Figure 1 shows a sample of the emission predicted with the isothermal models compared with the 18 October 1973 data. It is clear from the figure that no isothermal model will fit the data over the range 1.03 ≤ $\rho$ ≤ 1.20. The data do seem to be fit by an isothermal model for $\rho \geq 1.10$. To examine this possibility each set of data was compared with isothermal models in the range 6.00 ≤ log $T_c$ ≤ 6.30. The best fit for $\rho \geq 1.10$ was determined in the least squares sense. Table I presents the results of this fitting. For each line we list the best fit coronal temperature, the density required to match the observed intensity at $\rho = 1.10$, and the reduced chi squared for the fit. A reduced chi squared near 1 indicates that the model provides an acceptable fit to the data. The mean coronal temperatures determined from all of the data are log $T_c = 6.09$ for Mg x and log $T_c = 6.07$ for O vi. The mean densities at a height of 1.01 $R_\odot$ are log $N_c = 8.54$ and 8.45, respectively.

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Thus, the picture presented by the line ratios and emission gradients appears to be somewhat contradictory. The Mg X/O VI ratio, which because of the large uncertainty in the oxygen abundance and the shape of the curve does not appear to be a good temperature indicator, and the emission gradients seem to indicate that the inner corona has a temperature of around $1.2 \times 10^6$ K. The Si XII/Mg X ratio and the emission measure analysis suggest a much higher temperature, around $2 \times 10^6$ K. Additional evidence for the higher temperature is provided by the Si XII $\lambda 521$ intensities listed earlier. For the mean isothermal coronal model determined above from the Mg X and O VI emission gradient data, the calculated Si XII $\lambda 521$ intensities are more than an order of magnitude too small to match the observations.

Other investigators find evidence for high temperatures in the inner corona. Maxson and Vaiana (1977) studied typical large scale structures seen in soft X-ray images obtained from Skylab and found mean line-of-sight temperatures from $2 \times 10^6$ to $2.2 \times 10^6$ K. Nakada et al. (1976) examined brightness gradients in EUV lines measured by the spectroheliograph on OSO-7 and found a temperature of about $2.3 \times 10^6$ K at $\rho = 1.1$. They also found evidence for a negative temperature gradient in the range $1.2 \leq \rho \leq 1.8$.

At first glance it would appear that the isothermal models could be made to fit the Mg X and O VI data inside $\rho = 1.10$ simply by allowing the temperature to decrease slightly, with decreasing height which would result in a steeper emission gradient in the inner corona caused by the decreased density scale height. Examination of the $G(T)$ curve for Mg X (e.g., Withbroe, 1975) shows why this is not the case. The isothermal models are already on the low temperature side of the peak in the Mg X $G(T)$ function. Thus, any further decrease in the temperature will result in a very rapid decrease in $G(T)$ and a decrease in the emission rather than the required increase. Such a solution would also fail to provide sufficient Si XII $\lambda 521$ emission.

4. Temperature Gradients

Comparison of the predicted emission from isothermal models with the emission gradient data suggests that there may be temperature gradients in the inner corona. In this section we investigate the effects of temperature gradients on the predicted EUV emission gradients. First we consider the emission from a conduction dominated inner corona. Then we look at more arbitrary temperature structures.

In constructing an empirical model of the corona with a nonisothermal temperature structure, we are faced with the problem of where to begin and end the models. Since for a spherically symmetric, homogeneous atmosphere the temperature-density structure above any height will lie along the line of sight to that height, it appears to be best to locate the upper boundary of the models at a distance at least one scale height above the last line of sight for which we have observations. The models will then be insensitive to any variations above that height because the density will have fallen sufficiently to produce a negligible contribution to the integral of the emission along the line of sight. Since the density scale height in the inner
corona is about $0.1 R_\odot$ and the EUV measurements extend to $\rho \approx 1.2$, we have located the upper boundary of the model at a height of $1.40 R_\odot$. As the height increases beyond the height of the line of sight to the last data point, the local emission from each volume element will contribute a smaller fraction of the total emission observed in the range of impact parameters covered by the data. Thus, any empirical model will become increasingly uncertain in the height range above the last data point ($\rho \approx 1.20$).

Examination of typical limb spectroheliograms in transition region lines (e.g., Mariska and Withbroe, 1975) shows that inhomogeneous structures visible in these lines at the limb can extend quite high into the corona. To avoid the complications introduced by these structures we take $1.03 R_\odot$ as the lower height limit for the coronal models. Any model that fits the coronal observations will, of course, have to have a temperature and density at its base that will allow it to be joined with a transition region model that accounts for the network-cell structure seen in the EUV data.

Since all of the emission gradient curves are very nearly the same, we will concentrate on one set of data. The spectroheliograms obtained on 18 October 1973 extend the furthest in $\rho$ and have therefore been selected. We will also concentrate our attention on the Mg $\lambda 625$ data, since the temperatures we expect are closer to the peak of the Mg $\times G(T)$ function than the maximum of the O $\nu 1 G(T)$ function and we expect no additional emission from resonance scattering in Mg $\times$.

4.1. Constant conductive flux

Low resolution EUV observations suggest that the conductive flux is constant in the transition region (e.g., Dupree, 1972). If mechanical energy is deposited well above the inner corona, then, for a static inner corona, conduction should dominate the temperature structure if the conductive flux is as large as is found in the transition region. To check on this idea we computed a series of models for the inner corona, with the assumption that the temperature structure is controlled by conduction according to the relation (Ulmschneider, 1970)

$$F_0 \left( \frac{r_0}{r} \right)^2 = 1.1 \times 10^{-6} T^{5/2} \frac{dT}{dr}, \quad (4)$$

where $F_0$ is the conductive flux at radius $r_0$. A reference height, $r_0$, of $1.30 R_\odot$ was selected and models were computed for a range of conductive fluxes and initial temperatures. For each initial temperature, the conductive flux was varied by more than an order of magnitude from that value that, if the model were continued inward, would reach a temperature of $10^5$ K at 2000 km, the assumed location of the base of the transition region (cf. Burton et al., 1973; Doschek et al., 1976; Vernazza et al., 1973, 1976). The density structure was determined by using the equation of hydrostatic equilibrium and adjusting the density so that the predicted Mg $\times \lambda 625$ intensity agreed with the observations at $\rho = 1.10$. 

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In no case was a model found that provided a reasonable fit to the \( \text{Mg} \times \lambda 625 \) and \( \text{O} \ \text{vi} \ \lambda 1032 \) emission gradient data and the constraints imposed by the \( \text{Si} \ \text{xii} \ \lambda 521 \) observations. Figure 4 shows the 18 October 1973 \( \text{Mg} \times \lambda 625 \) data and three typical models. These models have a temperature of \( 2.2 \times 10^6 \) K at \( 1.30R_\odot \). The value of \( F_0 \) used for each model is shown on the figure. The model characterized by a conductive flux of \( 3.3 \times 10^5 \) erg cm\(^{-2}\) s\(^{-1}\) comes close to fitting the observations above \( \rho = 1.10 \), however it fails to match the data closer to the limb. It is appealing to think that if radiative losses were included in the model, the conductive flux would be sufficiently reduced that the model would fit all of the data. The radiative losses in the inner corona are only of the order of \( 1 \times 10^4 \) to \( 5 \times 10^4 \) erg cm\(^{-2}\) s\(^{-1}\) (Chiuderi and Kuperus, 1977; Kopp, 1972), so they would do little to alter the conductive flux. Thus, if the inner corona is homogeneous and static, it is not conduction dominated.

\[\text{Fig. 4. Emission gradient data for Mg x \lambda 625. The points are the observed values. The solid lines are the predicted emission gradients for coronal models with log } T = 6.35 \text{ at a height of } 1.30R_\odot \text{ and the conductive fluxes (in erg cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \text{) shown.}\]

4.2. Arbitrary temperature gradients

To investigate whether models with temperatures that increase or decrease with increasing height will fit the observations, we constructed a series of models beginning with an assumed temperature at \( 1.40R_\odot \). For each temperature, models
were constructed with varying temperature gradients. The models were assumed to be in hydrostatic equilibrium. As with the isothermal models, the density was fixed by matching the observed Mg X \( \lambda 625 \) absolute intensity at \( \rho = 1.10 \).

For a negative temperature gradient (temperature decreasing with increasing height), no model was found that would fit all of the data.

For a positive temperature gradient a range of acceptable models was found for \( \rho > 1.10 \), but, as with the isothermal models, some of the models could not be continued inward to \( 1.03 R_\odot \). The range of models examined is shown in Figure 5. Each model temperature distribution in the figure ends at the height to which the emission it predicts can be made to fit the data. The three uppermost models fit the data throughout the entire range of heights. For reference the short dash line shows the temperature distribution for a transition region model with a constant conductive

![Graph of temperature as a function of height](image)

**Fig. 5.** Log temperature as a function of height for the models that satisfy the Mg X \( \lambda 625 \) data in Figure 1. The solid curves are models in hydrostatic equilibrium; the long dash curve is the temperature distribution that fits the Saito (1970) density distribution. The short dash curve is the temperature distribution for a constant conductive flux transition region model.
flux of $6.9 \times 10^5$ erg cm$^{-2}$ s$^{-1}$ and a boundary temperature of $10^5$ K at a height of 2000 km (Mariska and Withbroe, 1975).

As the figure indicates, the temperatures in the acceptable models are much higher throughout the inner corona than the temperature of the isothermal model. All three of the acceptable coronal models predict greater Si XII $\lambda 521$ emission than the isothermal model, which gives a calculated intensity an order of magnitude smaller than is observed. For the log $T(1.40) = 6.40$ model the Si XII $\lambda 521$ emission is about a factor of two smaller than the observed Si XII $\lambda 521$ emission discussed earlier, while for the log $T(1.40) = 6.50$ model it is within 30% of the observed emission. The upper limit model shown in Figure 5 (log $T(1.40) = 6.60$) predicts a factor of two more Si XII $\lambda 521$ emission than is observed.

In Figure 6 we plot the density distributions found for the log $T(1.40) = 6.40$ and 6.50 models. Also plotted is the mean equatorial solar minimum model determined.

Fig. 6. Log electron density as a function of height. The solid curve is the Saito (1970) model, the long dash curve is the log $T(1.40) = 6.50$ model, and the short dash curve is the log $T(1.40) = 6.40$ model.
by Saito (1970). This model was derived from a large body of eclipse and K-coronameter observations and has been found to be a good representation of quiet coronal conditions during the period of the Skylab observations (Munro, 1977). As the figure indicates, both model density distributions determined using hydrostatic equilibrium are well within a factor of two of the Saito model.

Using the Saito density distribution we can find a temperature distribution that will also fit the observed Mg x emission. With the density constrained, only a limited set of temperature models will fit both the slope and the absolute intensity distribution of the Mg x λ625 data. One such model is shown in Figure 5 by the long dash line. The temperature distribution is very similar to the log $T$ (1.40) = 6.40 model, with only a slightly smaller logarithmic temperature gradient. Because of the slightly smaller logarithmic temperature gradient, the model comes within 30% of fitting the Si xii λ521 data at all heights.

Since virtually all of the Si xii λ521 emission produced on the disk comes from the temperature ranges of the models discussed here, we can predict the disk center emission from the models without extrapolating them downward. The log $T$ (1.40) = 6.40, 6.50, 6.60 models predict disk center Si xii λ521 emission of 6, 14, and 22 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$, respectively, while the Saito model predicts a value of 9.5 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Vernazza and Reeves (1978) find an average sun center Si xii λ521 emission of 15 to 20 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$, Dupree (1972) found a value of 18.8 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$, and Dupree et al. (1973) found a value of 46 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

None of the empirical models described above provides a perfect fit to all of the data available. The log $T$ (1.40) = 6.50 model appears to offer the best compromise. It is as good as or a little better than the Saito model at predicting the Si xii λ521 emission above the limb, comes closer to predicting the observed disk center intensity, and has a density distribution that is reasonably close to the Saito mean density model.

In Figure 7 we show the emission predicted by that model in O vi λ1032. As the figure indicates, the model provides an acceptable fit to the O vi data out to $\rho = 1.10$ and is only 0.20 dex low at $\rho = 1.20$. The entire temperature range encompassed by the model is much higher than the temperature $T_p = 300,000$ K where the O vi $G(T)$ peaks. At temperatures $T \gg T_p$ the values of $G(T)$ are very uncertain. In addition the effects of radiative excitation, which are included in the calculated line emission, add more uncertainty (Mariska, 1978). Given these uncertainties, agreement of the calculated and observed O vi intensities to within 0.2 dex is satisfactory.

5. Discussion

We have found that the only type of empirical homogeneous, spherically symmetric temperature-density model for the inner corona that will reproduce the observed Mg x λ625 intensities for $1.03 \leq \rho \leq 1.23$ is one in which the temperature increases with height throughout the inner corona. Several models of this type will fit the Mg x data, but satisfying the constraint of reproducing the observed Si xii λ521 emission
on the disk and above the limb restricts the choice severely. The observed mean density structure of the inner corona as determined by Saito (1970) further limits the selection of possible models. With all of these constraints in mind, the best selection appears to be the model in Figure 5 with log $T$ (1.40) = 6.50.

The large positive coronal temperature gradient found for this quiet region, if interpreted with the assumption of a radial magnetic field, results in a conductive flux that increases with increasing height in the model. The increase is from $2.3 \times 10^5 \ erg \ cm^{-2} \ s^{-1}$ at $1.06 R_\odot$ to $5.0 \times 10^5 \ erg \ cm^{-2} \ s^{-1}$ at $1.20 R_\odot$. A similar increase, from $1.3 \times 10^5$ to $2.2 \times 10^5 \ erg \ cm^{-2} \ s^{-1}$ is predicted by the model based on the Saito density distribution. These increases are much larger than that necessary to balance the $2 \times 10^4 \ erg \ cm^{-2} \ s^{-1}$ radiative flux emitted by the volume between 1.06 and $1.20 R_\odot$. The radiative flux was calculated with Raymond's (1978) radiative loss rates. Thus, if this region of the solar atmosphere can be interpreted using a homogeneous, static, spherically symmetric model with radial magnetic fields, the temperature gradient inferred here indicates that additional energy sinks are required in the inner corona. Examination of the energy equation shows that the only energy loss terms available are the losses due to mass motions, i.e. the fluxes of kinetic energy, enthalpy, and gravitational energy. A crude calculation of the energy balance in the quiet region model suggests that an outflow of material at a velocity of
around 20 km s\(^{-1}\) would provide the necessary energy sink. Outflows with velocities near this value have been observed in the corona by Cushman and Rense (1976). There is some question, however, about whether they were observing a quiet region or a coronal hole (Doschek and Feldman, 1977).

A more likely possibility is that the assumption of a homogeneous, spherically symmetric model with radial magnetic fields is inadequate and is the cause of the apparent need for energy sinks. As we noted earlier, soft X-ray observations show the presence of large scale loop structures in the inner corona. It is therefore unlikely that the energy balance in these structures can be interpreted with a simple radial field geometry. Without a detailed knowledge of the magnetic field structure the only firm conclusion we can draw is that the EUV emission gradients indicate a large positive coronal temperature gradient in quiet regions for \(\rho \approx 1.3\). They also suggest that the temperature maximum in quiet coronal regions is located beyond a radius of \(1.3R_\odot\). These conclusions are of fundamental importance because they imply that in quiet regions there is significant coronal heating beyond this radius.

Acknowledgements

We thank R. Noyes, R. Rosner, and J. Vernazza for their comments on the manuscript. This work was supported in part by NASA contract NAS 5-3949 and Air Force Geophysics Laboratory contract F19628-76-C-0281. This work was completed while J.T.M. held an NRC Resident Research Associateship at the Naval Research Laboratory.

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