ANALYSIS OF THE SOLAR O II/O III MULTIPLES AT 834 Å: IMPLICATIONS FOR THE EMISSION MEASURE DISTRIBUTION IN THE VICINITY OF 40,000 K

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ABSTRACT

A previously unpublished very high resolution solar spectrum has been analyzed to determine the relative contributions of O II and O III at 834 Å. The resulting ratio of O II to O III emissions is found to be 0.35, which is lower than derived from lower resolution data or expected from calculations based on standard emission measure theory. In order to reproduce the ratio observed in the high-resolution spectrum, it is proposed to lower the emission measure in the vicinity of 40,000 K by a factor of 2. This would also reconcile differences among apparently discrepant lines of C II and is consistent with the physical interpretation that the emission measure between 10^4 and 10^5 K is comprised of components arising from physically different regimes in the solar atmosphere.

Subject headings: Sun: chromosphere — Sun: spectra

1. INTRODUCTION

Since the early work of Pottasch (1964, 1967), the concept of emission measure has been used to relate observations of solar far- and extreme-ultraviolet (FUV and EUV) emission lines to a systematic, globally averaged model of temperature, electron concentration, and composition of the Sun's chromosphere, transition layer, and corona (e.g., Withbroe 1970, 1975; Dupree 1972; Raymond & Doyle 1981a, b). Values of the emission measure, defined as the integral of the square of the electron concentration along the line of sight through the solar atmosphere, have been derived from ion emission lines formed at different temperatures. When plotted as a function of temperature, the emission measure curve shows a remarkable degree of consistency among the various ions (e.g., see Fig. 1 of Raymond & Doyle 1981a). The emission measure has a minimum at 125,000 K and increases dramatically with decreasing temperature below that minimum. Thus far, the slope of the emission measure curve for temperatures below 40,000 K has been established only by the 1335 Å line of C II. But, as pointed out by Raymond & Doyle (1981b), other lines of C II are not consistent with 1335 Å: C II 904 Å computed from the emission measure is 4 times stronger than observed, and C II 1010 and 1036 Å are also computed to be brighter than observed by factors of 4 and 2, respectively.

Additional information on the emission measure at lower temperatures can be obtained from the O II emission at 834 Å, but data published so far have not had sufficient resolution to separate the blend of O II and O III multiplet components. For example, Vernazza & Reeves (1978) used Skylab measurements at 1.6 Å resolution to estimate that the O II and O III components were of nearly equal brightness. It will be seen from the higher resolution spectra presented in this paper that is not, in fact, the case.

In 1962, the Naval Research Laboratory flew a sounding rocket payload consisting of several instruments, including a solar extreme ultraviolet (EUV) spectrophotograph with 0.07 Å resolving power (Tousey et al. 1963). The 834 Å blend was within the range of the instrument passband, but apparently the only data published were at wavelengths longer than 900 Å (Tousey et al. 1963, 1965). In this paper, we report the analysis of the 834 Å data from the 1962 flight. The resolution was sufficient to separate the O II and O III components, leading to a ratio of O II/O III emission rates of 0.35. This is smaller by a factor of 3 than estimated by Vernazza & Reeves (1978), and smaller by a factor of 1.7 than computed from the emission measure of Raymond & Doyle (1981a). The implications for the emission measure, of the observed O II/O III ratio, are discussed in this paper.

2. OBSERVATIONS

Details of the rocket flight and instrumentation which obtained the high-resolution solar spectrum were reported by Tousey et al. (1963). A brief description is given here. Four spectrographs were flown on an Aerobee-Hi rocket on 1962 August 22 to a height of 233 km above White Sands Missile Range, NM. The solar 10.7 cm flux on the day of flight was 78.2 at the Earth, and the 81 day average was 80.5. Calcium K and Hα spectroheliograms taken on the flight date verify that the period was one of low solar activity—only one bright active region appeared in Hα. One of the instruments was a double-dispersion normal incidence grating spectrograph, having a principal grating with 2400 lines mm^-1 and a 10 μm slit width, leading to a resolving power (defined as the half-width at half-maximum response) of 0.07 Å over the wavelength range from about 800 to 1250 Å. Spectra of different exposure times were recorded on Kodak-Pathe SC-5 film. The longest exposure was 50 s. Examples of spectra above 900 Å from the long exposure are shown in Figure 8 of Tousey et al. (1963) and Figure 2 of Tousey et al. (1965).

A search through the NRL solar spectra archives yielded much of the data from the various instruments flown in 1962, including several exposures from the 800–1250 Å spectrograph. Unfortunately, they were all short exposures, and the 834 Å feature was not evident. Apparently the 50 s exposure plate has been lost. On the other hand, several very high quality prints of the 834 Å multiplets had been made and these were located. Examination of these second-generation prints by R. Tousey (private communication, 1990) verified their high quality and were deemed more than adequate for densitometry. The original calibration curves for converting from film density to
intensity were also located, as well as the flight planning notebook of J. D. Purcell. Our investigation of the old records leads us to believe that the instrumentation performed quite well, and that the data can be used for spectral analysis.

The spectrum around 834 Å was densitometered with a resolution of 2600 pixels parallel to the slit (across the solar disk) and to 700 pixels perpendicular to the slit (covering a 5 Å interval beginning at 832 Å). The data were then summed along the slit (a solar diameter) to improve the signal. The single active region seen in the Hα spectroheliogram mentioned earlier (Tousey et al. 1963) is not thought to be within the projection of the slit on the Sun. The spectra are thus representative of average solar minimum conditions.

The resulting spectrum after conversion to intensity (more appropriately irradiance or radiance integrated along a solar diameter) units is shown as the solid line in Figure 1. The background has been removed from the data in the figure and the estimated uncertainty due to film grain irregularities is shown as an error bar. The wavelength scale was established by using the two bright features, which are due to O iii (see below).

3. SPECTRAL ANALYSIS

To extract the relative proportions of O ii and O iii emissions from the observed solar spectrum, a synthetic spectrum for each of the multiplet transitions is needed. O ii consists of a triplet 2s2p4 3P upper term and a singlet 2s2p3 3S lower state, yielding a triplet transition. Both the upper 2s2p3 3D and lower 2s2p2 3P states of O iii have three levels, leading to a sextuplet. Thus the emission at 834 Å is a blend of nine lines. Table 1 contains the relevant atomic data used in the analysis. Wavelengths are from Kelly (1987) and Moore (1985), and the oscillator strengths (f) from Ho & Henry (1983). If it is assumed that there are no opacity effects and that the upper densities of 1 x 10¹⁰ cm⁻³ the level populations of the O iii 2s² 2p³ 3D term are distributed according to their statistical weights. The same is expected for the levels of the O ii 2s² 2p⁴ 3P term.

To complete the spectral synthesis, the widths of the O ii and O iii features must be known. For O iii, the 1666 Å line width of 0.18 Å (Doschek et al. 1976) was scaled to 834 Å, yielding a FWHM of 0.090 Å, or 0.054 Å width for a Gaussian line. The O ii lines were estimated to be in the range 0.06–0.07 Å FWHM by scaling from C ii lines (Doschek, Feldman, & Cohen 1977), assuming low opacity. A value of 0.065 Å FWHM or 0.039 Å Gaussian width was chosen. Since the

![Figure 1](https://example.com/fig1.png)

**Figure 1.** The solid line is the solar spectral irradiance with background removed, observed from a sounding rocket on 1962 August 22. The spectra were summed along the spectrograph slit (solar diameter), resulting in an approximate quiet Sun average. The error bar indicates the ± 1σ uncertainty in the data, estimated from the grain irregularities in the film. The dotted line is the model of the O ii and O iii emission lines as described in the text. The model spectrum was convoluted with the 0.14 Å instrument FWHM resolution. The best fit to the data resulted in an O ii/O iii radiance ratio of 0.26/0.74 = 0.35. The line positions and relative strengths are shown at the bottom.

### Table 1

**Transition Data for O ii and O iii**

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<tr>
<th>Transition</th>
<th>Wavelength* (Å)</th>
<th>Lower Level</th>
<th>Upper Level</th>
<th>g_i</th>
<th>g_J</th>
<th>A_i</th>
<th>A_J</th>
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<td></td>
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<td>3/2</td>
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<td>6</td>
<td>1/2</td>
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<td>7.6</td>
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<td>7/15</td>
<td>0.0816</td>
<td>5.6</td>
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</table>


* From Ho & Henry 1983.
instrument resolution was 0.14 Å FWHM, the emission widths could not be retrieved from the data. To compare the synthetic spectrum with the observations, it must first be convoluted with the instrument function. The synthetic spectrum thus convoluted was then fitted to the observations using the least-squares method to obtain the best estimates of the relative contributions of the O II and O III emissions to the observed spectral irradiance. The best fit to the observed spectrum is shown as the dotted line in Figure 1. The corresponding ratio of the O II to O III irradiances is 0.35 \pm 0.08, based on the uncertainty in the data. Line positions and relative strengths are indicated in the lower part of Figure 1. The agreement between the observed line widths and those predicted can be seen in Figure 1 to be excellent. Therefore, it is unlikely that the intrinsic solar widths are significantly larger than estimated. Most of the fluctuations seen in the data are caused by grain noise, with a possible exception at 834.2 Å. However, no line of measurable strength has been identified at that wavelength, either in first or second order.

No attempt was made to recover the laboratory calibrations necessary to place the observed irradiances on an absolute scale. Rather, the synthesized spectra were normalized to the quiet Sun spectrum of Hinteregger, Fukui, & Gilson (1981), identified as SC#21REF, which lists a total irradiance of \(6.7 \times 10^8\) photon cm\(^{-2}\) s\(^{-1}\) in the 834 Å band. Based on the above analysis, 26% of that emission can be assigned to O II and 74% to O III.

4. INTERPRETATION

In order to interpret these results, solar emission measure theory can be employed to calculate the ratio of O II to O III emissions. In this paper we adopt the quiet Sun emission measure distribution of Raymond & Doyle (1981a) derived from the averaged quiet Sun line fluxes of Vernazza & Reeves (1978). As is often the case, Raymond & Doyle plotted the emission measure distribution as \(\log N^2 dh\) versus \(\log T_e\). As noted by Raymond & Doyle (1981a), the emission measure distribution at temperatures below 40,000 K is based primarily on the C II 1335 Å multiplet. The main contribution to the emissivity of the 1335 Å multiplet comes from the temperature region centered around 25,000 K. Published plots of the emission measure between 25,000 K and 60,000 K can be approximately fitted by a straight line, which implies that \(\int N^2 dh \propto T_e^{-2}\). On the basis of an energy balance argument it might appear that the emission measure plot below \(T = 1 \times 10^5\) K should closely follow the inverse of the radiative loss function. The existence of a “plateau region” in both the radiative loss curve at \(T \approx 4.5\) (see Cook et al. 1989) and in the presently proposed emission measure curve (Fig. 2) make this suggestion attractive. However, one problem with the interpretation should be noted. In the radiative loss rates published by Cook et al. (1989), the total change in the energy loss rate between \(\log T = 4.2\) and \(\log T = 5\) is no more than 0.8 dex. This compares with a total range of 2.3 dex in the observed emission measure over the same temperature interval. Hence, the behavior of the branch of the emission measure plot for \(\log T < 5.0\) cannot completely be explained as the inverse of the radiative loss function.

The main contribution to the emissivity of the O II 834 Å multiplet comes from the temperature region between 30,000 K and 50,000 K, while the main contribution to the O III 834 Å multiplet comes from the temperature regions above 60,000 K. The observed emissivity ratio of 834 Å O II/O III multiplets can therefore be used to provide an additional experimental estimate of the emission measure in the region between 25,000 K and 60,000 K.

When the emission measure distribution of Raymond & Doyle (1981a) is used together with atomic data for O II (Ho & Henry 1983) and O III (Aggarwal 1985) and temperature-dependent ionization fractions for O II and O III from Arnaud & Rothenflug (1983), the emissivity ratio of the O II 834 Å multiplet relative to the O III 834 Å multiplet is predicted to be 0.6. This is nearly a factor of 2 larger than the observed O II/ O III multiplet ratio of 0.35 (see Fig. 1). The predicted value, however, can be improved by lowering the emission measure curve around 40,000 K by approximately a factor of 2.

Raymond & Doyle (1981b) have also noted that their emission measure curve for the quiet Sun predicts the intensities of the shorter wavelength lines of C II at 1036, 1010, and 904 Å to be 2-4 times stronger than the observed values. The emission of these lines is expected to arise from temperature regions of around 35,000-40,000 K. Again, lowering the emission measure curve in the vicinity of 40,000 K will improve the agreement between predicted and observed intensities. The C II results are therefore consistent with the O II results, and both suggest that the Raymond & Doyle (1981a) emission measure curve in the vicinity of 40,000 K is too high by about a factor of 2.

Raymond & Doyle (1981a) also used the intensity of Si III 1206 Å to establish an emission measure point at \(4 \times 10^4\) K. Using the Raymond & Doyle emission measure curve and the Withbroe (1975) abundances we find that the predicted intensity of Si III 1206 Å is 65% of the average quiet Sun intensity reported by Vernazza & Reeves (1978). If the modified emission measure curve suggested in this paper is used, the predicted intensity is 50% of the observed Si III 1206 Å intensity. Although this comparison would suggest that the original emission measure curve is better—or should even be raised—the question of abundances in the outer solar atmosphere needs to be reconsidered. With the exception of Si III 1206 Å, the Raymond & Doyle curve is based on the observed inten-
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sities of abundant ions of C, N, O, and neon used in conjunction with the Withbroe (1975) abundances. These abundances are a mean of observed photospheric and coronal abundances in which, for example, the C/Si abundance ratio is 7.8. It is becoming clear that the "coronal" abundances of elements with low first-ionization potentials, such as Mg, Si, Ca, and Fe are enhanced in the \( T > 2 \times 10^4 \) K atmosphere of the quiet Sun by a factor of ~3 relative to their values in the photosphere (Meyer 1985). Adopting representative photospheric abundances from (Grevesse & Anders 1989) and taking the enhancement factor of 3 for silicon into account we derive a "coronal" C/Si abundance ratio of 3.4. This implies a silicon abundance in the outer solar atmosphere approximately a factor of 2 larger than the value used by Raymond & Doyle (1981a). Taking the larger silicon abundance into account will lower the emission measure derived from the Si \( \text{III} \) 1206 Å line by approximately a factor of 2, in agreement with the change in the Raymond & Doyle (1981a) emission measure curve required by the O \( \text{III} \)/O \( \text{III} \) ratio.

5. DISCUSSION AND CONCLUSIONS

Intensity measurements of spectral lines as a function of their height of formation above the photosphere reveal the different nature of the solar plasmas at temperatures above and below 25,000 K. Solar plasmas at temperatures below 25,000 K have traditionally been identified as the chromosphere, while plasmas at greater temperatures have been referred to as the "transition zone" and corona. Feldman (1983) has documented the observational properties of the two different regions and has argued that they are independent entities. For the plasma region above 25,000 K, he suggested the name "Unresolved Fine Structures."

Since the two regions are different in nature, it would be surprising if their functional dependences on temperature near 25,000 K were identical. That is, it is unlikely that the respective plots of \( \int N^2 \, dh \propto T_{\ast}^{m} \) should join exactly in slope and absolute value near 20,000 K. Rather, it would seem more reasonable to expect the emission measure of the chromosphere to decrease sharply at about 25,000 K, while the emission measure from the "Unresolved Fine Structures" to increase above that temperature. The combination of the two emission measure curves may then resemble the schematic curve in Figure 2.

Valuable discussions about the solar spectra were held with R. Tousey. Scott Bailey provided densitometry support.

REFERENCES


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