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THE QUIET SUN CHROMOSPHERIC NETWORK OBSERVED FROM SKYLAB

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ABSTRACT

Spectra between 1200 and 1560 Å of a supergranulation cell interior and cell boundary observed near Sun center are discussed. Absolute intensities are given for selected lines of chromospheric and transition-zone ions. The spectra were obtained by the NRL normal-incidence spectrograph on Skylab. The spectral resolution is 0.06 Å, and the spatial resolution is 2″ x 60″. The width of the cell boundary was found to be ~10″ in lines of low-temperature ions such as C ii and O i, and ~6″ in lines of high-temperature ions such as O iv and N v. The brightness contrast between cell interior and boundary is an increasing function of the characteristic emitting temperature of the observed lines between ~8 x 10³ K and ~1.3 x 10⁵ K. The maximum contrast is observed in O iv and is about a factor of 5. Above and below the temperature of O iv the contrast falls, and is about 1.5 for lines of O i and Si i. The full widths at half-maximum (FWHM) of the optically thin lines are the same over cell interiors and cell boundaries, and agree with the widths observed in limb spectra. From the FWHM of the 1207 Å Si iii line, optical depths at line center of 5.8 and 1.6 are deduced for the cell boundary and cell interior, respectively. The electron density in the cell boundary appears to be nearly equal to the cell interior density. From the intensities of the intersystem lines of O iv (2s²2p² 2P_J°-2s²2p² 2P_J) measured above the limb in the quiet Sun, an electron density of 4.6 x 10⁹ cm⁻³ is derived for the O iv emitting region. This density does not change within the first 8000 km above the limb, and is about a factor of 1.6 lower in the north polar coronal hole. Assuming a constant pressure, the characteristic height of the Si iii emitting region is ~840 km in the boundary and ~380 km in the cell interior. The results are compared with a recent model by Gabriel.

Subject headings: line profiles — Sun: chromosphere — Sun: granulation — Sun: spectra — ultraviolet: spectra

I. INTRODUCTION

We have recently discussed solar limb spectra between 1100 and 1940 Å recorded by the NRL normal-incidence spectrograph on Skylab (Doschek, Feldman, and Tousey 1975; Doschek et al. 1976, hereafter Paper I; Feldman, Doschek, and Tousey 1975; Feldman et al. 1976, hereafter Paper II). The spectral resolution was 0.06 Å, and the projected slit area on the Sun was 2″ x 60″ (1450 km x 43,500 km). The spectra were recorded at positions relative to the white light limb that ranged from -12″ to +20″. The slit was tangent to the limb. Limb spectra obtained over a quiet Sun region and over the north polar coronal hole were compared. A third paper (Doschek, Feldman, and Bohlin 1976, hereafter Paper III) discussed Doppler shifts of transition zone lines relative to chromospheric lines. That paper considered spectra of the chromospheric network near Sun center, limb spectra, and spectra obtained over a coronal hole. In this paper we continue the analysis of chromospheric and transition zone spectra, and discuss spectra obtained near Sun center with the slit positioned at different locations relative to the supergranulation network and cell interiors.

The Skylab mission was organized into Joint Observing Programs (JOPs, Reeves, Noyes, and Withbroe 1972). Each JOP consists of a set of observations of a particular solar feature(s). JOP–1A is a sequence of observations across a supergranulation cell interior and boundary as observed in Ha. Observations began with the spectrograph slit positioned directly above and along the boundary of a supergranulation cell. Spectra were obtained at this position, and then spectra were successively recorded at other positions on either side of the boundary. The orientation of the slit at every position was the same; i.e., the slits remained parallel to the boundary. Only one complete sequence of this type is listed under the chromospheric network JOP in the NRL observing log. The spectra considered here were recorded on 1973 August 13 by Astronaut

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† Member, NRL Data Analysis Team.
Owen Garriott. It was difficult for the astronaut to accurately determine the slit positions relative to the network from the onboard Hα telescope. A relatively long and fairly straight cell boundary had to be chosen because of the 60" slit length. Table 1 gives a description of the slit positions according to the JOP instructions followed by the astronaut. The astronaut assumed that cell boundaries correspond to the locations of dark mottles in the Hα image. There is a close spatial correspondence between dark mottles in Hα and bright regions in XUV transition zone lines (Brueckner and Bartoe 1974). The transition zone cell boundary, which we define as the brightest regions in Hα, is spatially displaced by 5" from the dark Hα mottles selected for observation. In Table 1, the positions of the slit relative to the transition zone boundary are keyed by letters for further referencing. Table 1 also gives the start times of the exposures. The entire sequence took two orbits to complete. The observer Dr. Garriott reported changes in the shape of the cell and also brightness fluctuations in the boundary and cell over the time interval of the entire sequence.

According to Dr. Garriott, the length of the cell boundary in the Hα mottles was 45" for spectra A, B, and C in Table 1, and had increased to a full arc minute by the time spectra D, E, and F were obtained during the second orbit. Assuming that a similar increase occurred for the XUV transition zone boundary, the intensity increase for the second orbit scans would be ~25 percent, which is much less than the intensity variations between cell boundary and cell interior that are discussed below.

It should be kept in mind that the entire sequence of NRL observations was made in a 1 hour and 40 minute time interval over a relatively long segment of cell boundary. Thus the observations are spatial and temporal averages over the fine-structure inhomogeneous regions that define the cell boundary. In § III we compare our results with a larger statistical sampling from the Harvard data published by Reeves (1976). From this comparison we conclude that the NRL cell boundary region was representative of a typical boundary region.

Below we discuss the relative intensities and profiles of selected optically thin and optically thick lines over the cell interior, cell boundary, and intermediate positions; we compare the results with the spectra obtained at the limb (Papers I and II). Absolute intensities are also given. We derive the characteristic lengths along the line of sight for the Si III emitting region, and compare the results of this paper with a recent model proposed by Gabriel (1975).

II. DATA REDUCTION

We have obtained intensities and half-widths for lines falling below 1560 Å. At longer wavelengths in the disk spectra, the intense continuum imposes limitations on the accuracy of the results. The spectra were recorded on Kodak 104 film, and were scanned with a Grant microdensitometer. Exposures of 10, 40, and 160 s were obtained at each slit position, from which a characteristic curve for the film used in the Skylab mission. Line intensity ratios between the same lines in different spectra can be obtained to within an accuracy of 15 percent. The principal source of error in this case is the irregularity of the photographic film. Absolute line intensities in ergs cm⁻² s⁻¹ sr⁻¹ were obtained from a comparison of our relative continuum intensities with the absolute continuum intensities published by Samain et al. (1975). A more complete description of the procedure is given in Doschek, Feldman, and Cohen (1976). The accuracy of the absolute intensities is believed to be within a factor of 2. Also, these intensities are averaged over the slit area. The full widths at half-maximum (FWHM) of the lines are not sensitive to irregularities in the film grain, but irregular or asymmetric features on the profiles should be regarded with caution unless they appear on several lines formed in the same atmospheric regions. The FWHM are accurate to within 10 percent, provided the line widths are substantially greater than the instrument FWHM (0.06 Å). Further details covering the data reduction can be found in Papers I and II. The instrument is discussed in Bartoe et al. (1974).

III. INTENSITY DISTRIBUTIONS OVER CELL BOUNDARY

For the comparison between network and cell regions, we have selected lines emitted by ions that are formed within a temperature range from ~10⁴ K to 1.8 × 10⁶ K. There are no strong lines between 1175 and 1560 Å that are emitted by ions formed at temperatures greater than 2.2 × 10⁶ K. Only one strong line is emitted from 2.2 × 10⁶ K regions, i.e., O v λ1218.35, and this line is blended in the disk spectra with the wings of hydrogen Lα. Figures 1–10 show the profiles and relative intensities of the selected lines at the slit positions described in Table 1. The shapes of the profiles in the far wings of the lines at low intensities are distorted by the conversion of the fog level.
Fig. 1.—Line profiles of XUV transition zone lines observed at different locations relative to the interior and boundary of a supergranulation cell. The letters correspond to the slit positions described in Table 1. The wavelength dispersion is indicated.

Fig. 2.—Same as Fig. 1

of the film into intensity. Figures 1–10 show the variations in relative intensity and line width among lines emitted by the supergranule cell interior, cell boundary, and intermediate regions. The absolute intensities of the lines are given in Table 2.

Reeves (1976) has recently discussed observations of the XUV chromospheric network in the quiet Sun obtained from the Harvard spectroheliometer on Skylab. This instrument recorded data photoelectrically with a spatial resolution of 5" x 5", and images of the network in selected spectral lines could be obtained over 5" x 5" areas. Thus the chromospheric network was observed over a relatively sizable area of the quiet Sun. The Harvard data form a good statistical base from which average properties (at 5" x 5" resolution) of the network and cell interiors can be derived. The NRL observations described here cover only one particular cell boundary, so it is important to determine

**TABLE 2**

**ABSOLUTE LINE INTENSITIES**

<table>
<thead>
<tr>
<th>Ion</th>
<th>(\lambda (\text{Å}))</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>C Ⅱ</td>
<td>1334</td>
<td>360</td>
<td>550</td>
<td>860</td>
<td>1450</td>
<td>700</td>
<td>490</td>
</tr>
<tr>
<td>C Ⅲ</td>
<td>1335</td>
<td>590</td>
<td>910</td>
<td>1290</td>
<td>2040</td>
<td>1160</td>
<td>740</td>
</tr>
<tr>
<td>C Ⅳ</td>
<td>1548</td>
<td>350</td>
<td>630</td>
<td>800</td>
<td>1500</td>
<td>700</td>
<td>410</td>
</tr>
<tr>
<td>N Ⅴ</td>
<td>1239</td>
<td>25</td>
<td>40</td>
<td>50</td>
<td>150</td>
<td>45</td>
<td>30</td>
</tr>
<tr>
<td>O Ⅰ</td>
<td>1356</td>
<td>25</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>150</td>
<td>40</td>
</tr>
<tr>
<td>O Ⅳ</td>
<td>1401</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>100</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>Si Ⅱ</td>
<td>1304</td>
<td>25</td>
<td>30</td>
<td>50</td>
<td>60</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Si Ⅲ</td>
<td>1207</td>
<td>150</td>
<td>410</td>
<td>620</td>
<td>1100</td>
<td>450</td>
<td>250</td>
</tr>
<tr>
<td>Si Ⅳ</td>
<td>1394</td>
<td>80</td>
<td>180</td>
<td>250</td>
<td>590</td>
<td>180</td>
<td>130</td>
</tr>
<tr>
<td>S Ⅰ</td>
<td>1473</td>
<td>85</td>
<td>75</td>
<td>100</td>
<td>120</td>
<td>85</td>
<td>75</td>
</tr>
</tbody>
</table>

* The intensities are averaged over the projected slit area.
whether or not the observed cell was a typical network cell. The NRL instrument has better spatial resolution in one dimension (2") than the Harvard instrument, and the high spectral resolution of the NRL instrument allows wavelengths and line profiles to be determined over the different network regions. Thus, the NRL and Harvard data are complementary and form a fairly complete description of XUV emission line behavior in the chromospheric network.

The data in Figures 1–10 are displayed in two different ways in Figures 11 and 12. In Figure 11 the intensities of lines formed at different temperatures are normalized to unity at peak emission, i.e., position D in the boundary, and are plotted as functions of position relative to the point of peak emission. It can be seen that the width of the cell boundary, which we define as the FWHM of the intensity distribution in different lines, is ~6" for the high-temperature ions represented by N v, O iv, and Si iv. For the other ions, i.e., S i, O i, C ii, and Si m, the FWHM is about 10". We define the intensity of each line at −15" and +10" as the cell interior intensity. We defined the FWHM as the points where the interpolated intensities equal half of the difference between the cell interior and maximum network intensities. The lower-temperature width of 10" is the same as Reeves’s (1976) value for an average boundary width. The smaller value we obtain for the high-temperature lines may result from fine structures in the boundary less than 5" in size. The reality of such structures was demonstrated by Reeves (1976) using statistical arguments, and is also clear from the recently obtained very high resolution (1") stigmatic XUV spectra (Bartoe and Brueckner 1975). Clearly no two cell boundaries are alike, and considerable variations in sizes, shapes, and brightnesses among cells are evident in all the high-spatial-resolution XUV data that have recently become available. Furthermore, transient phenomena involving convective motions at the temperatures characterizing the lower transition zone lines may also occur in network regions (see Paper III).

Figure 12 shows the intensities of lines (contrast) at the boundary position (0") compared with the averaged intensities in the cell interior at −15" and +10", plotted as a function of temperature of formation of the lines. This figure should be compared with the same type of plot shown as Figure 7 in Reeves (1976). Part of the data in Figure 7 of Reeves’s paper is the Harvard data for the same cell boundary that we have observed, obtained simultaneously. Both Figures 11 and 12 are in qualitative agreement with the conclusions of Reeves (1976). The contrast in Figure 12 is greatest for a temperature near $7 \times 10^4$ K, and falls at lower and higher temperatures. However, the maximum is quite broad, and there is some scatter in the data. Reeves (1976) maximum averaged contrast...
The contrast range shown in Figure 12 is well within the limits reported by Reeves (1976). The contrast is about a factor of 5 between boundary and cell interior for maximum contrast temperatures.

We may conclude that the NRL data are representative of a fairly typical cell interior and boundary, based on the agreement between the results shown in Figures 11 and 12 with the results for average cells and network regions reported by Reeves (1976).

IV. LINE PROFILES IN THE CELL INTERIOR AND NETWORK

Table 3 gives the FWHM of the lines in Figures 1–10 as a function of position over the network and cell.

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda$ (Å)</th>
<th>$T_e$ (K)*</th>
<th>$FWHM_{\text{DL}}$ (Å)</th>
<th>$FWHM_{\text{B}}$ (Å)</th>
<th>A§</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II</td>
<td>1334.53</td>
<td>$2.5 \times 10^4$</td>
<td>0.044</td>
<td>0.14</td>
<td>0.19</td>
<td>0.19</td>
<td>0.20</td>
<td>0.18</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>C II</td>
<td>1335.71</td>
<td>$2.5 \times 10^4$</td>
<td>0.044</td>
<td>0.17</td>
<td>0.22</td>
<td>0.22</td>
<td>0.25</td>
<td>0.25</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>C IV</td>
<td>1548.22</td>
<td>$10^6$</td>
<td>0.100</td>
<td>0.020</td>
<td>0.21</td>
<td>0.23</td>
<td>0.22</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>N V</td>
<td>1238.82</td>
<td>$1.8 \times 10^5$</td>
<td>0.100</td>
<td>0.20</td>
<td>0.21</td>
<td>0.24</td>
<td>0.25</td>
<td>0.24</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>O I</td>
<td>1355.58</td>
<td>$\approx 10^4$</td>
<td>0.024</td>
<td>0.08</td>
<td>0.07</td>
<td>0.08</td>
<td>0.07</td>
<td>0.07</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>O IV</td>
<td>1401.16</td>
<td>$1.3 \times 10^6$</td>
<td>0.050</td>
<td>0.18</td>
<td>0.25</td>
<td>0.25</td>
<td>0.20</td>
<td>0.26</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>Si II</td>
<td>1304.37</td>
<td>$1.6 \times 10^8$</td>
<td>0.022</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Si III</td>
<td>1206.52</td>
<td>$3.6 \times 10^8$</td>
<td>0.031</td>
<td>0.16</td>
<td>0.17</td>
<td>0.18</td>
<td>0.21</td>
<td>0.20</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Si IV</td>
<td>1393.76</td>
<td>$7.1 \times 10^8$</td>
<td>0.050</td>
<td>0.14</td>
<td>0.17</td>
<td>0.16</td>
<td>0.17</td>
<td>0.17</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>S I</td>
<td>1472.96</td>
<td>$\approx 8 \times 10^8$</td>
<td>0.017</td>
<td>0.10</td>
<td>0.10</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td></td>
</tr>
</tbody>
</table>

* Temperatures obtained from Jordan 1969.
† Thermal Doppler FWHM.
‡ Observed FWHM. The instrumental FWHM ($=0.06$ Å) has not been removed.
§ The profiles of N v, O iv, and Si iv are narrower in position A than in the other positions. While this may be due to the low intensity of the line in position A, i.e., a statistical fluctuation, we cannot rule out the possibility that the mass motions are locally less in this region.
The electron temperature $T_e$ and the theoretical FWHM of the lines assuming ionization equilibrium are also given. As has been reported previously (Brueckner and Moe 1972; Boland et al. 1975; Chipman and Bruner 1975; Papers I and II), optically thin transition zone lines show excess broadening indicating nonthermal motions in the plasma. Inspection of Table 3 reveals the following results:

1. The FWHM of the optically thin lines of N v, O iv, Si iv, C iv, O i (1356 Å) and S i are the same in the network as in the cell interiors, and agree within experimental error with the widths observed above the limb and reported earlier (Feldman, Doschek, and Tousey 1975; Papers I and II). Both C iv and Si iv are slightly broadened by opacity at the limb. Some of the lines such as the 1401 Å O iv line are quite weak in the cell interior regions. This is probably the cause of some of the larger fluctuations in the line widths.

2. The 1207 Å Si iii line is self-reversed between +2" and +8" above the limb (see Paper I). Near Sun center the opacity of the line is considerably less, and varies over different locations relative to the cell boundary. The FWHM of this line ranges from 0.16 Å in the cell interior to 0.21 Å over the brightest region of the network.

3. The lines of C ii are strongly self-reversed at the limb. Over the network and cell regions near Sun center the self-reversal has disappeared, but the lines still appear somewhat flat-topped and are wider over the cell boundary than over the cell interior.

One conclusion that is obvious from the above results is that the nonthermal motions are isotropic, because the FWHM of the optically thin lines are the same at the limb as near Sun center. We reached the same conclusion in Paper I from a comparison of our limb results with the more intense lines observed at Sun center by Boland et al. (1975). It can now be stated in addition that the nonthermal motions are the same for the cell interior as for the cell boundary. We also found (Paper II) that the nonthermal motions in the north polar coronal hole above the limb agreed to within experimental error with the quiet Sun limb results. Measurements (not discussed in this paper) of line widths in coronal hole spectra obtained near Sun center show no detectable difference from any of the above results.

We may use the FWHM of the optically thin Si iii 1892 Å line obtained from the limb data to estimate the opacity in the Si iii 1207 Å line over the cell interior and network. Assuming complete frequency redistribution, the intensity $I(\tau_0, \lambda)$ at a point $\lambda$ in the
The profile of the Si line observed over the network and cell is given by

$$I(\tau_0, x) = \frac{\phi(x)}{\sqrt{\pi}} \int_{0}^{\tau_0} S(\tau) e^{-\tau x^2} d\tau. \quad (1)$$

Geometric area and solid angle factors are not included in equation (1) because they will not affect the discussion. $S(\tau)$ is the source function, $\phi$ is the Voigt profile, and $x$ is the dimensionless frequency defined as $x = (\lambda - \lambda_0)/\Delta \lambda_r$, where $\Delta \lambda_r$ is the FWHM of the Si line divided by the factor $2(\ln 2)^{1/2}$ and by $(1892/1207)$. Zero optical depth is defined as the top of the Si emitting region in the lower transition zone, and $\tau_0$ is the Sun center opacity at line center in the 1207 Å line. We assume that $\phi$ is Gaussian, i.e.,

$$\phi(x) = \exp(-x^2). \quad (2)$$

The factor $1/\sqrt{\pi}$ in equation (1) is included so that integration of the frequency dependent source function over $x$ yields $S(\tau)$. Equation (1) is interpreted as representing the average intensity of Si emission over the area of the slit ($2'' \times 60''$). In reality, fine structures exist on a scale smaller than $5''$; brightness fluctuations occur in these structures, and motions are evident. Furthermore, the shapes of the structures are unknown, and may resemble clouds or spicule-type features. The radiative transfer problem in the lower transition zone region is therefore quite complex geometrically. The plane-parallel approximation is certainly not valid in the network, although it may provide a satisfactory approximation over a cell interior. The solution of equation (1), therefore, represents a spatial and time-averaged view of the Si emitting region. In order to make equation (1) tractable, we assume that $S(\tau)$ is constant, in which case we obtain

$$I(\tau_0, x) = \frac{S}{\sqrt{\pi}} \left[1 - \exp\left(-\tau_0 \exp(-x^2)\right)\right]. \quad (3)$$

In the limit of very small opacity the intensity distribution becomes Gaussian as expected, i.e.,

$$I(\tau_0 \ll 1, x) = \frac{S}{\sqrt{\pi}} \tau_0 \exp(-x^2). \quad (4)$$

The assumption of a constant source function for equation (1) is approximately valid only provided that substantial emission in the line does not arise from large optical depths in the chromosphere. Our limb brightening results for optically thin lines of Si (Papers I and II) indicate that most of the Si emission arises in the transition zone, and therefore we neglect the effects of chromospheric emission. The same assumption, however, is not necessarily valid for the lines shown in Figures 1 and 2.
Fig. 11.—Total intensities of lines relative to the peak line emission in the cell boundary, as a function of position across the boundary. The peak intensity point (position D in Table 1) is defined to be at 0'.

Fig. 12.—The intensities of lines at peak emission in the cell boundary (position D in Table 1) relative to the intensities in the cell interior (positions A and F in Table 1), given as a function of the temperature of formation of the ion. The data at $7 \times 10^5$ K are from Reeves (1976), and the point at $10^6$ K reflects the fact that the network structures do not exist at coronal temperatures.
and 2 (Chipman 1971). In this case, the assumption of a constant source function gives opacities that measure only the transition zone contribution to the line profile, and can underestimate the total opacity in the line by several orders of magnitude.

The frequency $\nu_1$, at which the intensity of the optically thick 1207 Å line is half the peak intensity at line center, can be found from equation (3) and satisfies the expression,

$$1 - \exp \left[ -\tau_0 \exp \left( -\frac{\nu_1^2}{2} \right) \right] = 0.5.$$  \hspace{1cm} (5)

The corresponding frequency for an optically thin Si iv 1892 Å line is given by $\nu_2 = (\ln 2)^{1/2}$. The ratio of $x_2$ to $x_1$ is known from the observed FWHM of the optically thin 1892 Å line, and from the FWHM of the optically thick 1207 Å line, i.e.,

$$r = \frac{x_2}{x_1} = \frac{(\text{FWHM})_{1892}}{(\text{FWHM})_{1207}}.$$  \hspace{1cm} (6)

In terms of $r$, equation (5) becomes

$$1 - \exp \left[ -\tau_0 \exp \left( -\frac{\ln(2r^2)}{2} \right) \right] = 0.5.$$  \hspace{1cm} (7)

Equation (7) depends only on $\tau_0$ and the observed ratio $r$. The ratio of $r$ over the network and cell is given in Table 4, along with the values of $\tau_0$ that satisfy equation (7). From Paper I, the calculated FWHM of the optically thin 1207 Å line is 0.115 Å.

The opacities in Table 4 and the relative line intensities can be used to derive the ratios of electron densities and path lengths through the different Si iv emitting regions of the cell and network. The intensity of the 1207 Å line is proportional to $N_e^2 h$, where $N_e$ is the characteristic electron density along the line of sight, $h$ is the characteristic path length through the emitting material, and $A$ is the illuminated area of the slit. The opacity at line center is proportional to $N_e h A$, where $N_e$ is the density and path length through the emitting material, and $A$ is the illuminated area of the slit.

$$\frac{N_i}{N_{i0}} \approx \tau_{0D} I_i$$

and

$$\frac{h_i}{h_0} \approx \frac{\tau_{D0} I_i}{\tau_{0D} I_D},$$  \hspace{1cm} (8)

where $i$ denotes a slit position other than position D. In equations (8), density and path length are determined relative to position D, which is the cell boundary. Also, we are assuming that $A$ does not vary over the cell boundary and interior. Using the derived opacities and the intensities obtained from Figure 8 in equations (8), we obtain the results shown in Table 4. Also shown are the intensities relative to position D. These results indicate that the reduced intensity of Si iv in the cell is due to a lower density in the cell by a factor that can be as much as 2 combined with a path length reduced by a similar factor. However, the densities in the cell and network are almost equal in position F, which is also within the cell. We may conclude that the density ratio between cell boundary and cell interior is small and is about a factor of 2 or less. Reeves (1976) finds from C iii and O iv density-sensitive line ratios that the electron densities in cell and network regions appear to be about equal, but the tendency is for the density in the cell interior to be greater than in the boundary by about a factor of 2. The difference between our result and Reeves’s conclusions may be due to using two different techniques for the determination of density.

From the calculations of Flower and Nussbaumer (1975), we have obtained an electron density of $4.6 \times 10^9$ cm$^{-3}$ from the intercombination lines 2s$^2$2p $^2P_{1/2}$ - 2s2p$^2$ $^4P_{3/2}$ of O iv near 1400 Å. These lines are too weak to be observed in the cell interior and cell boundary spectra, but the lines are strong in the limb spectra of a quiet Sun region and the north polar coronal hole discussed in Papers I and II. Because O iv lines are about 5 times stronger in the cell boundary than in the cell interior, much of the emission observed above the limb may arise in the cell boundary regions. The two line ratios that are density-sensitive are (2s$^2$2p $^2P_{1/2}$ - 2s2p$^2$ $^4P_{3/2}$) and (2s$^2$2p $^2P_{1/2}$ - 2s2p$^2$ $^4P_{1/2}$). The wavelengths are 1404.81 Å/1401.16 Å and 1407.39 Å/1401.16 Å, respectively. Neither ratio varies significantly with height above the limb between 2” and 12”, but the ratios are slightly different in the quiet Sun and coronal hole spectra. If O iv is formed at the same temperature in all the cell boundary regions, then the electron density, and hence the electron pressure, is independent of the height of the boundary regions above the limb. The quiet Sun value we obtain for the first ratio above is 0.46, and the value for the second ratio is 0.17. Both of these ratios give an electron density of $\sim 4.6 \times 10^9$ cm$^{-3}$, using Figure 2 in Flower and Nussbaumer (1975). The 1407.39 Å/1401.16 Å ratio is not very sensitive to density in this range because the ratio is close to the low-density limit. From the coronal hole limb spectra, we find that the electron density is about a factor of 1.6 less in the coronal hole compared to the quiet Sun. The O iv line ratios, 1399.77 Å/1407.39 Å and 1397.20 Å/1404.81 Å, are

$\begin{array}{cccccc}
\text{Slit} & I/I_0 & r & \tau_0 & N_i/N_{i0} & h/h_0 \\
\text{A} & 0.14 & 0.78 & 1.6 & 0.5 & 0.6 \\
\text{B} & 0.38 & 0.72 & 2.3 & 0.9 & 0.4 \\
\text{C} & 0.57 & 0.68 & 2.8 & 1.2 & 0.4 \\
\text{D} & 1 & 0.57 & 5.8 & 1 & 1 \\
\text{E} & 0.42 & 0.60 & 4.7 & 0.5 & 1.6 \\
\text{F} & 0.23 & 0.78 & 1.6 & 0.8 & 0.3 \\
\end{array}$

* The average error in determining $\tau_0$ is $\sim 50\%$. This is the error due to the 10% error in measuring half-widths of lines, and should be mostly systematic for the measurements of the 1207 Å and 1892 Å lines. The errors in $N_i/N_{i0}$ and $h/h_0$ are also $\sim 50\%$. 

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independent of excitation processes because the upper levels of the transitions for each ratio are the same. The ratios depend only on relative transition probabilities. Flower and Nussbaumer (1975) predict values of 1 and 0.13, respectively, for these ratios. From the limb spectra we obtain the same values. The good agreement for the 1397.20 Å/1404.81 Å ratio implies that the blend of the 1404.81 Å line with the 1404.77 Å line, and the other undefined symbols have the usual meaning. $N_e$ is the ground-state number density of Si iii, $f_i$ is the oscillator strength of the 1207 Å line, and the other undefined symbols have the usual meaning. $N_e = f(T_e)A_i(0.8)N_e$, where $F(T_e)$ is the fractional abundance of Si iii at an electron temperature $T_e = 3.6 \times 10^4$ K, $A_i = 3.2 \times 10^{-5}$ is the silicon abundance relative to hydrogen (Withbroe 1971), and 0.8 is the proton-electron density ratio. $F(T_e)$ forms a broad maximum near $3.6 \times 10^4$ K and is $\sim 0.9$ (Jordan 1969). Using the above values in equation (9) gives $h \approx 840$ km for position D over the cell boundary. At positions A and F, $h \approx 380$ km.

Finally, we briefly compare our profile results with results obtained by other groups. Boland et al. (1975) have published line profiles of transition zone lines averaged over the entire Sun. Their results have been compared with our limb profile results in Papers I and II, and are in good agreement except for lines that are weak or blended in their data. In the case of weak lines, the characteristic path lengths derived in § IV from the Si iii profiles are greater by about a factor of 3 than predicted by the model, although this result depends on the accuracy of the calculations of Flower and Nussbaumer (1975), and the assumption of constant pressure in the transition zone.

The thickness of the transition zone implied by our results for Si iii, but more especially by our recently published limb results (Papers I and II) discussed in the next section, indicates that the transition zone may be substantially thicker than predicted by Gabriel's model, and similar models. Also, our recent observation of motions in the transition zone (Doschek et al. 1967b) imply dynamical effects that have so far been neglected in all models of the transition zone. In our opinion, while models such as Gabriel's can successfully predict some of the gross observations of the transition zone, a fully satisfactory model of the transition zone cannot be developed unless dynamical effects are considered.

VI. COMPARISON WITH LIMB SPECTRA

In Papers I and II we obtained limb brightening curves for lines formed in different temperature regimes in the lower transition zone and chromosphere (Figs. 28 in those papers). Paper I dealt with a quiet Sun region, and Paper II considered the limb above the north polar coronal hole. By assuming a spherically symmetric distribution for the emitting regions and inverting Abel's integral, corresponding source functions for the different lines were derived. These functions give the relative distribution of emitting material in narrow temperature ranges as a function of height above the limb. The source functions for the transition zone lines reach a peak value between 4° and 6° above the limb, and fall to half-maximum intensity on each side of the peak over a total height interval slightly smaller than 4°. The functions are also markedly skewed toward greater heights. The distributions of emitting material with height above the limb revealed by the source functions not only reflect the distribution of material within each cell boundary and cell interior, but also reflect height differences from one cell region to another. Much of the emission above the limb may account of the network properties of the transition zone with the exception of convective motion, pressure effects due to wave propagation, and spicules.

The cell boundary width predicted by Gabriel is $\sim 10^°$. Gabriel (1975) also predicts that the distribution of intensity across the cell boundary should be uniform, assuming that the predicted brightening at the edges of the boundary is actually smeared out (see Fig. 7 in Gabriel 1975). We do not observe a uniform brightening across the boundary in the observed lines, but the uniform brightening predicted by Gabriel (1975) could be unobservable due to variations among fine-structure inhomogeneities on the order of a few arc seconds in size. Gabriel (1975) also predicts that the electron density should be lower in the cell boundary than in the cell interior, a result that is contrary to our deductions given in Table 3.

VI. COMPARISON OF RESULTS WITH A RECENT MODEL BY GABRIEL

The results discussed in §§ III and IV can be compared with a recent model proposed by Gabriel (1975). This model is a two-dimensional model that takes
Fig. 13.—Empirical temperature versus height distribution for the transition zone over a quiet Sun region and over the north polar coronal hole. The curves are derived as described in the text from limb brightening curves given in Papers I and II. The curves are uncertain below \(3.6 \times 10^4\) K and extrapolated above \(2.2 \times 10^5\) K to the data reported by Huber et al. (1974).

arise from the cell boundaries, because of the high cell interior-to-boundary contrast.

If all the emission observed above the limb is assumed to arise in cell boundaries, then the limb brightening curves and source functions given in Paper I, combined with Figure 11 of this paper, allow an empirical two-dimensional model of the quiet Sun lower transition zone to be determined. The limb results may be condensed for this purpose. We assume that the temperature in the cell boundary at a given height above the white light limb is determined by the source functions. The height for a particular temperature is found by integrating over height the source functions of lines emitted at the particular temperature. The height \(h\) is chosen such that the values of the integral above and below \(h\) are equal. This allows an empirical distribution of temperature with height to be determined for both the quiet Sun and the coronal hole limb data. As can be seen, the temperature region from \(3.6 \times 10^4\) K to about \(2 \times 10^5\) K spans a height of nearly 1000 km in the quiet Sun, and about 1600 km in the coronal hole. This height range is greater than predicted by thin transition zone models.

It is not clear from the results given in this paper or in our previous papers (Papers I, II, and III) exactly what geometric forms the transition zone inhomogeneities occur in, and how the emitting regions interact with the magnetic fields. Most of the inhomogeneous models proposed to date (e.g., Kopp and Kuperus 1968; Gabriel 1975) have assumed open magnetic field lines. It is worth mentioning that, to the authors' knowledge, there is no strong observational evidence that rules out the existence of loops in chromospheric cell boundary regions. Very high resolution magnetograms show a mixture of both magnetic polarities in cell boundaries (Harvey 1975).

A loop-like structure of the transition zone inhomogeneities would be fully consistent with our observational results.

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