THE EMISSION-LINE SPECTRUM ABOVE THE LIMB OF A
SOLAR CORONAL HOLE: 1175-1940 Å

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ABSTRACT

Spectra of a coronal hole obtained at positions within and above the solar white-light limb in the wavelength range from 1175 to 1940 Å are discussed. The coronal hole coincided with the north pole of the Sun. The spectra were obtained by the NRL slit spectrograph (S082-B) on Skylab. The spectral resolution is 0.06 Å and the projected slit area on the Sun was 2" x 60" (1450 x 43500 km). Relative line intensities and line profiles are presented for coronal-hole lines formed in the temperature region of the solar atmosphere from ~ 8 x 10^3 K to 2.2 x 10^5 K. The coronal-hole line intensities are compared with corresponding intensities obtained from recently published quiet-Sun spectra. Line profiles of both optically thin and optically thick lines are shown as a function of height above the limb. Random mass-motion velocities are deduced from the optically thin coronal-hole lines, and are compared with corresponding results deduced from quiet-Sun spectra.

Subject headings: Sun: corona — Sun: spectra — ultraviolet: spectra

I. INTRODUCTION

The NRL normal incidence slit spectrograph on Skylab (S082-B) obtained spectra within and above the solar white-light limb in the wavelength range from 970 to 3940 Å. The spectra were recorded above different solar regions, including quiet-Sun regions, active regions, and coronal holes. Spectra were recorded at the following positions relative to the limb (1° ≈ 725 km): -12", -4", -2", 0", +2", +4", +6", +8", +12", and +20". At each slit position, the slit was oriented to be tangent to the white-light limb. From these spectra, relative intensities of spectral lines formed in chromospheric temperature regions and in the lower transition zone can be derived as a function of height above the limb.

In this paper we give the intensity variations relative to the solar limb of chromospheric and transition-zone lines observed above a polar coronal hole. The measurements are in the wavelength range from 1175 to 1940 Å. Line profiles and full widths at half-maximum (FWHM) of the lines have been determined, and profiles of selected lines are presented. From the widths of the optically thin lines, the average mass motions in the transition zone of the coronal hole can be obtained as a function of the electron temperature, assuming ionization equilibrium. The purpose of this paper (Paper II) is to discuss the emission-line spectrum above the limb for the coronal hole, and to compare the line intensities and profiles with the corresponding spectra obtained above a quiet-Sun region (Doschek et al. 1976, Paper I). The spatial resolution of the spectrograph in the direction of height above the limb is 2" (1450 km). Therefore a higher spatial resolution comparison can be made between coronal-hole and quiet-Sun transition-zone emission than hitherto possible. The differences between coronal hole and quiet-Sun emission are substantial at temperatures of ~2 x 10^5 K, but decrease with decreasing temperature. The large number of XUV lines that fall in the 1175-1940 Å region are emitted in a wide range of temperatures covering the chromosphere and spicules, as well as higher temperatures in the transition zone up to 2 x 10^5 K.

The coronal hole was observed on 1973 August 14 from 1446 UT to 1823 UT, and coincided with the north pole of the Sun. Figure 1 (Plate 22) shows an image of the coronal hole in the 304 Å line of He ii, obtained with the NRL spectroheliograph (SO82-A) on Skylab. The 304 Å image of the quiet-Sun region selected for comparison with the coronal-hole data is also shown. The positions of the slit for the 0° position are marked. In the space between the two images three lines are drawn. These lines indicate the slit length and the extreme settings of the slit relative to the solar limb. The quiet-Sun region is about 7° farther west than a large coronal hole. The reduced emission of helium in the coronal hole relative to neighboring quiet-Sun regions is apparent.

In the following sections we also discuss the conversion of photographic densities of lines to intensities and the determination of intensity ratios between coronal hole and quiet-Sun lines. Some of our results concerning the comparison of coronal-hole and quiet-Sun emission have been published previously (Doschek, Feldman, and Tousey 1975; Feldman, Doschek, and Tousey 1975). The quiet-Sun spectra are discussed in detail in Paper I.

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Fig. 1.—Images in the He II 304 Å line of the quiet-Sun and north polar coronal-hole regions discussed in the text. The orientation and maximum excursions of the slit relative to the limb are indicated.

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II. THE INSTRUMENT

The NRL slit spectrograph on Skylab consists of two main systems, a telescope and the spectrograph. The instrument can operate in either of two wavelength ranges, 970–1940 Å, or 1940–3940 Å. An off-axis paraboloidal mirror images the Sun on the entrance slit of the spectrograph. The projected slit dimensions on the Sun are 2° × 60" (1450 × 43,500 km). The reflection of the Sun’s image from the exterior of the slit mount is fed into an image dissector tube that drives the telescope mirror such that the image of the solar limb can be set at predetermined locations relative to the slit. The light passing through the slit is dispersed by either of two predispersers, depending on the wavelength range desired. A 300 line mm⁻¹ predisperser is used for the wavelength range from 970 to 1940 Å, and a 150 line mm⁻¹ predisperser is used for the 1940 to 3940 Å region. The radiation from the predisperser is diffracted by the 600 line mm⁻¹ main grating, and focused onto either Kodak 101 or 104 photographic film. All the gratings are Bausch and Lomb aluminum replica gratings coated with a protective layer of MgF₂. The spectral resolution of the complete system is 0.06 Å. The dispersion at the film plane for the short-wavelength range is 4.16 Å mm⁻¹. Two hundred film strips were held in the camera, and eight spectra were recorded on each film strip. The total reflectance of the instrument, excluding the efficiency of the film, is shown in Figure 2. A complete description of the instrument is given by Bartoe et al. (1974).

III. DATA REDUCTION

The conversion of photographic density to intensity was accomplished by comparing the photographic densities of the same lines on spectra taken with different exposure times. The coronal-hole spectra were recorded on Kodak 104 film at 10 different slit positions relative to the solar limb. At each position three or four spectra were taken with different exposures. It was found empirically that a single consistent characteristic curve could not be established for the entire wavelength range from 1100 to 1940 Å, due to the wavelength dependence of the film sensitivity. However, it was possible to construct a single characteristic curve for each of the wavelength intervals: 1175 to 1330 Å, 1330 to 1420 Å, and 1420 to 1940 Å. The wavelength boundaries are not well defined, and for the quiet-Sun data (Paper I), the characteristic curve for the 1330–1420 Å interval was found to be identical with the curve for the longest wavelength region.

The photographic densities were obtained by scanning the spectra with a Grant microdensitometer. The slit width was 12 µ and the slit length was 200 µ, which is two-thirds the length of a spectral line on the film. The data were digitized and read onto magnetic tape by a PDP minicomputer. These data could then be plotted with the desired wavelength dispersion onto chart paper. Once the characteristic curves were determined, the data could be plotted in intensity units, and line profiles could be measured. The slit width of 12 µ corresponds to 0.05 Å on the plates, and is sufficiently narrow to obtain accurate widths of transition-zone lines. The narrowest lines observed in the spectrum are 0.07 Å wide, only 0.01 Å wider than the theoretical instrument resolution. These lines are the spin forbidden lines of Si at 1900 Å. Si emits near 8 × 10³ K.

Figure 3 shows the characteristic curves for the coronal-hole spectra. Each point near the curves represents a spectral line, and the scatter from the curves is about 15 percent. This scatter defines the approximate accuracy of our intensities. Although the film saturates at low densities (~0.5–0.6 density units), it was possible to choose a line from one of the three or four exposures made at each slit position that had a peak density, and half-peak density, on the linear portion of the appropriate characteristic curve.
Fig. 3.—Characteristic curves derived from the coronal-hole spectra obtained on 1973 August 14.

The intensities derived using the above technique are expressed in arbitrary units. Relative line intensities may be obtained from Figure 2, assuming that the film efficiency (in ergs cm\(^{-2}\)) is not strongly wavelength-dependent. Eventually it will be possible to convert the intensities into absolute intensities by using the calibration curves derived by Moe (1975). These curves are based on results obtained from the calibration rockets (CALROC) flown by NRL during the Skylab mission.

However, for the comparison between the quiet-Sun and coronal-hole spectra, it is necessary to obtain a relative calibration between the different films used for the quiet-Sun and the coronal-hole observations. The quiet-Sun and coronal-hole observations are separated by two weeks, and the film used for both sets of observations came from the same film batch. Based on previous experience, we expected that the characteristics of film from the same batch would be similar, and this was found to be the case. The spectrograph slit at \(-12^\circ\) in the quiet-Sun limb scans (Paper I) was actually located above a coronal-hole region rather than over the quiet-Sun area. This is clear by inspection of Figure 1. By comparing the \(-12^\circ\) and \(-4^\circ\) photospheric continuum spectrum between \(\sim 1600\) and \(1900\,\AA\) in the quiet-Sun limb scans, we found that the \(-12^\circ\) coronal-hole continuum intensity is the same to within 15 percent as the quiet-Sun continuum intensity at \(-4^\circ\). By comparing the \(-12^\circ\) and \(-4^\circ\) spectra from the polar coronal-hole limb scans, we verified that no significant change in the 1600 to 1900 \(\AA\) continuum occurs between \(-12^\circ\) and \(-4^\circ\). We therefore assumed that the 1600 to 1900 \(\AA\) continuum intensity in the quiet Sun is the same as the continuum intensity in the polar coronal hole. Using this assumption, we found that the characteristic curves for the quiet-Sun spectra and coronal-hole spectra were in agreement to within experimental error. The film sensitivities for the two different spectra thus appear to be equal, which is expected.

The continuum at long wavelengths in the disk spectra is real, but no observable continuum above the limb in the 1900 \(\AA\) region is apparent. A very weak photospheric continuum above \(\sim 2000\,\AA\) is observed above the limb on long-exposure spectra. This is due to the increased efficiency of the spectrograph above 2000 \(\AA\) (see Fig. 2). Also, the intensity of the continuum increases with wavelength. This continuum is probably due to scattered light. By comparing spectra of different exposure times, it is possible to derive a scattered-light curve for the instrument. This curve is shown in Figure 4. The scattered light at +2\(^\circ\) above the limb is \(\sim 30\) times weaker than the actual emission at 0\(^\circ\), and at +12\(^\circ\) it is an order of magnitude weaker than at +2\(^\circ\). For most of the limb-brightening curves to be discussed, the scattered-light contribution is insignificant.

Fig. 4.—Scattered light contribution from solar disk features as a function of height above the limb.
<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition</th>
<th>$\lambda$ (Å)</th>
<th>Arc Seconds Relative to Visible Limb</th>
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<tr>
<td></td>
<td></td>
<td>$-12^\circ$</td>
<td>$-4^\circ$</td>
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<tr>
<td>C I</td>
<td>$2p^2 1d - 2p^3 1d_{3/2}$</td>
<td>1481.76</td>
<td>1.40</td>
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<td>C II</td>
<td>$2s^2 2p^3 1s_{1/2} - 2p^2 2s^2 1s_{3/2}$</td>
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<td>4.60</td>
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<td>C III</td>
<td>$2s^2 2p^2 1s_{1/2} - 2p^2 2s^2 3p_{0}$</td>
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<td>5.00</td>
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<td>C IV</td>
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<td>5.00</td>
</tr>
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<td>N III</td>
<td>$2s^2 2p^2 3s_{3/2} - 2p^2 2s^2 3p_{1/2}$</td>
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<td>N IV</td>
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<td>O I</td>
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<td>1966.09</td>
<td>6.00</td>
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<td>5.50</td>
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<tr>
<td>Ni II</td>
<td>$3d^2 3p_{3/2} - 3d^2 (3p_{3/2})^4 4p_{3/2}$</td>
<td>1561.94</td>
<td>0.11</td>
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</tbody>
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* B = blend.
IV. RESULTS

a) Line Intensities

Table 1 gives line intensities in arbitrary units for selected lines emitted in temperature regions characteristic of the chromosphere and the lower transition zone (~8 × 10^3 to 2.2 × 10^5 K). Significant emission in transition zone lines is seen as far as 20° above the limb. Low-temperature regions (~10^4 K) are represented by lines of C I, S I, and O I. Temperatures slightly higher (~2 × 10^4 K) are represented by lines of C II, Si II, S II, Fe II, and Ni II. The other lines are formed at higher temperatures up to 2.2 × 10^5 K, the temperature of maximum ion concentration of O V in ionization equilibrium (Jordan 1969). Strong lines formed at temperatures above 2.2 × 10^6 K fall at wavelengths shorter than 1175 Å, and therefore these regions are not represented in our spectra. A few weak coronal forbidden lines fall within the 1175 to 1940 Å wavelength range, and these lines are given in Paper I. The coronal forbidden lines are observed in quiet-Sun spectra, and are not observed in the coronal-hole spectra, even for the longest exposures. This suggests that the coronal forbidden lines are at least a factor of 4 fainter in the coronal hole relative to the quiet Sun. This result is based on the limiting film sensitivity.

Table 1 includes lines that are optically thin and optically thick at the limb. The optically thin lines double in intensity above the limb, as expected. However, care must be exercised in deciding that a line is completely optically thin. Some lines nearly double in intensity above the limb, but are slightly affected by opacity. This effect can easily be seen for the two lines of the lithium-like ions C IV and Si IV. Their intensity ratios change slightly, but significantly, as a function of height above the limb.

The intensities in Table 1 are the peak intensities of the lines, and not the areas under the lines. For the optically thick lines, the peak intensities of the profiles are given. These intensities are not determined at line center for self-reversed lines. Below, we give representative profiles of the optically thick lines, from which the correct intensities (areas under the profiles) may be determined by the reader.

b) Line Profiles

Representative line profiles for each ion in Table 1 are shown as a function of height above the limb in Figures 5–27. For profiles of lines above the limb, the base of the line is the zero point of the ordinate, and not the apparent “continuum” level of the profile. In these cases the “continuum” is simply the fog level converted into intensity units. For lines observed within the limb, the continuum level for the longer wavelength (λ > 1600 Å) lines is real. In obtaining half-widths of lines, the effects of fog and true continuum were evaluated accordingly.

The intensity scales used in Figures 5–27 are the same scales used for the similar display of quiet-Sun profiles shown in Paper I. Because, as discussed, the calibration factor between the quiet-Sun and coronal-hole intensity scales is unity to within experimental error, the reader may directly compare the intensities of lines in the two regions. These scales, are, however, not related to the intensity scale used in Table 1. The intensity scales in the figures are individually adjusted such that the line intensity in each limb scan in Paper I reaches approximately full scale. It is apparent from some of the coronal-hole profile figures that the line intensities at −12°, −4°, −2°, and 0° show variations in intensity, even though the path length through the emitting material is, from the point of view of a homogeneous shell, nearly the same at each position of the spectrograph slit. These intensity variations are probably a result of inhomogeneities in the solar atmosphere.

V. DISCUSSION

a) Line Intensities—Optically Thin Lines

The intensity behavior as a function of height above the limb for the optically thin lines in Table 1 is shown in Figure 28. The lines are grouped according to temperature of formation in ionization equilibrium, and the average limb-brightening curves for different temperature regions are shown. The intensities are normalized to the peak intensities of the lines above the limb. The emission from the highest temperature lines such as O V (1218 Å) extends to large heights over the limb in the coronal hole, falling to 10 percent of the peak intensity at +16° (11,600 km) above the limb.
Fig. 6.—Same as Fig. 5

Fig. 7.—Same as Fig. 5
Fig. 8.—Same as Fig. 5

Fig. 9.—Same as Fig. 5
Fig. 10.—Same as Fig. 5

Fig. 11.—Same as Fig. 5
The emission from lines formed at lower temperatures falls off progressively faster with decreasing temperature of formation of the ion. Although the limb-brightening curve of the O iv and N iv group appears quite similar to the (N v, O v) curve, the intensity ratios of O iv and N iv lines to N v or O v lines actually decrease considerably with height above the limb. This can be seen in Figure 29, which shows the intensity ratios of the O iv and N iv lines to the lines of N v, for both the quiet Sun and the coronal hole. At +6° in the coronal hole, the ratio is 0.84; at +20° the ratio is about a factor of 2 smaller. This effect is even larger for lines formed in the $3.5 \times 10^4$ to $6.3 \times 10^4$ K region. The structure of the atmosphere between $3.5 \times 10^4$ and $4 \times 10^5$ K is highly inhomogeneous (Brueckner and Bartoe 1974). The implication is that multithermal inhomogeneous regions with maximum temperatures of $\sim 10^5$ K are more abundant near the limb than far above the limb (see the discussion in Paper I). Alternatively, all the inhomogeneous regions may possess a range of temperatures from $\sim 10^4$ K to a coronal temperature of $\sim 10^6$ K. However, the proportions of plasma at various temperatures are different for inhomogeneous regions at different heights above the limb. Regions near the limb have a greater fraction of cooler material, while regions far above the limb have a greater percentage of hot plasma.

The emission from the low-temperature lines of S i, C i, and O i falls very quickly above the limb. The emission from O i above the limb may be produced by spicules, because the decrease of intensity above the limb is consistent with the spicular counts given by Beckers (1972). The decrease of S i emission above the limb is distinctly faster than that of C i emission. This may be due to a slight opacity in the C i line, or may reflect a temperature effect. The difference between S i and C i emission was also noted in the quiet Sun (Paper I). Because the effect is found in both the quiet-Sun and coronal-hole spectra, the difference is probably real.
Fig. 14.—Same as Fig. 5

Fig. 15.—Same as Fig. 5
Fig. 16.—Same as Fig. 5

Fig. 17.—Same as Fig. 5
Fig. 18.—Same as Fig. 5

Fig. 19.—Same as Fig. 5
Fig. 20.—Same as Fig. 5

Fig. 21.—Same as Fig. 5
Fig. 22.—Same as Fig. 5

Fig. 23.—Same as Fig. 5
Fig. 24.—Same as Fig. 5

Fig. 25.—Same as Fig. 5
Fig. 26.—Same as Fig. 5

Fig. 27.—Same as Fig. 5
The line ratios shown in Figure 31 are grouped according to temperature. The highest temperature represented is \( \sim 2 \times 10^5 \) K (O v and N v), and the lowest temperature for which data exist is \( \leq 10^4 \) K (O i, C i, S i). If the quiet-Sun and coronal-hole regions were the same, then the average intensity ratio would be unity for all the lines at all heights above the limb, and the data in Figure 31 would be well fitted by horizontal straight lines. This is seen to be the case for the low-temperature O i, C i, and S i lines. Thus for these lines the coronal hole and quiet-Sun region are indistinguishable. For lines formed at higher temperatures, the difference between the coronal hole and quiet-Sun region is apparent. The peak emission for most of the transition zone lines in both the quiet Sun and coronal hole is \( +4^\circ \pm 2^\circ \). At this height the emission of the higher temperature lines (\( \sim 10^5 \) K) is definitely enhanced in the quiet Sun relative to the coronal hole. The difference is about a factor of 1.7. For lines formed at temperatures between \( 3.6 \times 10^4 \) and \( 10^5 \) K the difference is smaller, and is about a factor of 1.3. At heights above the peak emission the ratios decrease because of the greater extension of coronal-hole emission above the limb relative to quiet-Sun emission. This effect can be seen from a comparison of Figure 28 of Paper I with Figure 28 of this paper. The ratios are unity at \(+8^\circ\) for the lines formed between \( \sim 1.6 \times 10^5 \) and \( 2.2 \times 10^5 \) K. For the lines formed near \( 1.3 \times 10^5 \) K, the ratios are unity at \(+7^\circ\). For the other two groups of transition-zone lines, the ratio is 1 at \(+6^\circ\). At these heights above the limb, the emission measure along the line of sight is the same in both the quiet-Sun region and over the polar coronal hole, for the different temperature regions represented in Figure 31. If the electron density is on the average smaller in coronal holes than in quiet-Sun regions, i.e., the electron pressure is less (Munro and Withbroe 1972), the implication is that the path length through emitting plasma is greater in the coronal hole than in the quiet Sun at the unity ratio heights. If the line excitation is proportional to \( N_e^2 \), where \( N_e \) is the electron density, then at unity ratio heights the emission length \( L_{\text{CH}} \) through the coronal hole is related to the emission length \( L_{\text{QS}} \) through the quiet-Sun region by

\[
(N_e^2)_{\text{QS}}L_{\text{QS}} = (N_e^2)_{\text{CH}}L_{\text{CH}},
\]

assuming that the filling factor over the slit area is the same in the quiet Sun and coronal hole. Thus if \( (N_eT_e)^{\text{QS}} \sim 3(N_eT_e)^{\text{CH}} \), as reported by Munro and Withbroe (1972), then \( L_{\text{CH}} \) is about an order of magnitude larger than \( L_{\text{QS}} \), because the lines are formed at the same temperature in the quiet Sun and in the coronal hole. We have not attempted to derive electron densities in the quiet Sun and polar hole region using density-sensitive line ratios because of the uncertainties in cross section and atomic data that currently exist for the suitable lines in our spectral range. For instance, considerable problems still seem to exist for the Be-like line ratios (Jordan 1974).
As mentioned, the $-12''$ spectrum in the quiet-Sun scans is actually a coronal-hole spectrum. By comparing the $-12''$ and $-4''$ intensities for the scans given in Figures 5–27 in Paper I, an independent comparison of quiet-Sun and coronal-hole line intensities can be made. In general, the results of this comparison are in agreement with the polar coronal-hole results. However, some notable exceptions are apparent which can perhaps be explained by local inhomogeneities. The $-12''$ spectrum is quite close to the coronal hole–quiet Sun boundary.

Finally, we note that the integrals of the source functions (Eq. [1]) over height are nearly the same for both the quiet Sun and the coronal hole. The coronal hole values are $\sim 20$ percent less for the high-temperature ions such as O v. Thus there would be little difference in intensity in transition-zone radiation between the quiet Sun and polar coronal hole if both were viewed along a solar radius.

**b) Line Profiles—Optically Thin Lines**

The full widths at half-maximum (FWHM) of the optically thin lines in Figures 5–27 can be interpreted in terms of thermal Doppler broadening and Doppler broadening due to nonthermal random motions of the plasma. Thermal Doppler broadening alone is insufficient to explain the line widths. The nonthermal component can be due to two physically distinct, but indistinguishable causes. The random motions may occur in each separate inhomogeneity along the line of sight (microturbulence), in which case the motions may be due to magnetohydrodynamic or acoustic wave propagation as suggested by Boland et al. (1975). Alternatively, the broadening may be due completely or in part to relative random motions of the different inhomogeneities along the line of sight (macroturbulence), as we have noted earlier (Feldman, Doschek,
and Tousey 1975). In this case, the motions within each inhomogeneity could be entirely thermal.

If the broadening due to the thermal and nonthermal motions, and to the instrument, is assumed to be Gaussian, then the FWHM is given by

\[
\text{FWHM} = \left[ \Delta \lambda_t^2 + 4 \ln 2 \frac{(\lambda/c)^2}{M} \left( \frac{2kT_i}{M} + \xi_0^2 \right) \right]^{1/2},
\]

(3)

where \(\Delta \lambda_t\) is the instrumental FWHM (= 0.06 Å), \(\lambda\) is the wavelength, \(\xi_0\) is the most probable velocity, \(T_i\) is the ion temperature, and the other symbols have the usual meanings. If \(T_i\) is assumed equal to the electron temperature of maximum ion concentration, then the nonthermal velocities may be deduced from the line widths in Figures 5–27. We have found that the FWHM of the coronal-hole lines is independent of height above the limb, as is the case for the quiet-Sun lines discussed in Paper I. We may therefore average the line widths for the optically thin lines in the limb scans. Table 2 gives the average FWHM for selected lines. The temperatures of maximum ion concentration are also given in Table 2 along with the nonthermal velocities deduced from equation (3). These velocities are plotted in Figure 32 with the velocities derived in Paper I for the quiet Sun. The error bars for the coronal-hole results are not plotted. They are about the same as the plotted error bars for the quiet-Sun results. The interesting point shown by Figure 32 is that the velocities in the coronal hole appear to be the same as in the quiet Sun. Although the coronal-hole velocities are systematically higher than the quiet-Sun velocities, the values are within most of the error bars on both sets of results. However, the differences may be significant. This result would appear to favor a macroturbulence explanation for at least a part of the nonthermal motions. The results of Boland et al. (1975) are also shown in Figure 32, and are discussed in Paper I.

c) Optically Thick Lines

A number of the lines in Table 1 are optically thick at the limb. The opacity in some of the lines, e.g., C IV (1548 Å) and Si IV (1394 Å), is quite small but can nevertheless be detected by comparing the ratio of peak intensities of lines of the same multiplet. The effect of the opacity is to lower the peak intensity and broaden the line. For instance, the intensity ratio of the 1548 Å C IV line to the 1551 Å C IV line is smaller at limb heights near maximum intensities of the lines than at heights far from the limb, where the opacity is negligible. The intensity ratio of these two lines should be approximately the same as the oscillator strength ratio, which is the case far above the limb. A similar situation exists for the quiet-Sun lines, and is discussed in Paper I.

Aside from the lines for which the opacity is only marginal, there are other lines in Table 1 sufficiently affected by multiple scattering such that an obvious broadening or self-reversal of the line profile is apparent. The C II (1334 Å), Si II (1533 Å), and Si III (1206 Å) lines show pronounced central reversals. In Paper I we discussed the Si III 1206 Å line in the quiet-Sun spectrum in some detail. We obtained an opacity of about 50 for this line along the line of sight at about +4" above the limb.

The optically thick lines of C II, Si II, and Si III also show pronounced central reversals in the coronal-hole spectra. However, the line shapes as a function of limb height are different in the coronal-hole spectra than in the quiet-Sun limb scans. As an example, we consider the Si II 1533 Å line (Fig. 17). In the quiet-Sun spectra (Fig. 17 in Paper I) a strong central reversal in this line

The optically thick lines have a much more complex structure, with a central reversal and additional structure on both sides of the line center. The central reversal is weaker in the coronal-hole spectra than in the quiet-Sun spectra, and the additional structure is more pronounced. This is consistent with the lower ionization conditions in the coronal hole compared to the quiet Sun.

One possible explanation for the difference in line shapes is that the coronal-hole plasma is cooler than the quiet Sun plasma. The cooler temperature would result in a smaller central peak and a stronger central reversal, as observed. However, this explanation is not consistent with the observed nonthermal velocities, which are similar in both the coronal hole and the quiet Sun.

Another possible explanation is that the coronal-hole plasma is more turbulent than the quiet Sun plasma. The increased turbulence would result in a broader line profile, as observed. However, this explanation is not consistent with the observed nonthermal velocities, which are similar in both the coronal hole and the quiet Sun.

One possible explanation is that the coronal-hole plasma is a mixture of cooler and hotter plasma, with the hotter plasma dominating at the limb. This would result in a line profile with a central reversal and additional structure on both sides of the line center, as observed. This explanation is consistent with the observed nonthermal velocities, which are similar in both the coronal hole and the quiet Sun.

The exact cause of the difference in line shapes between the coronal hole and the quiet Sun is not yet understood. Further study is needed to clarify this issue.
Fig. 31.—Intensity ratios of quiet-Sun and coronal-hole lines as a function of height above the limb.
SPECTRUM ABOVE A SOLAR CORONAL HOLE

Fig. 32.—Random mass motions in the coronal hole obtained from the FWHM of optically thin lines. The quiet-Sun results of Doschek et al. (1976) and Boland et al. (1975) are also shown. The vertical lines through two of the quiet-Sun values (solid circles) indicate that these values are suspect because the lines may be slightly optically thick at the limb. The Boland et al. velocities are rms velocities.

is apparent in the 0° and +2° profiles. Slight reversals are seen in the −12° scan (really a coronal-hole spectrum) and in the +4° scan. However, in the polar coronal hole the strongest reversals occur in the −12°, −4°, and −2° scans. Only small reversals are apparent in the 0° and +2° scans. Similar results hold for the optically thick lines of C II and Si III. It is tempting to conclude that these lines are optically thinner above the limb in the coronal-hole spectrum than in the quiet-Sun spectrum, because the central reversals in the coronal-hole profiles are smaller above the limb. However, a comparison of the widths of the optically thick lines in both the coronal-hole and quiet-Sun spectra shows that the coronal-hole lines are in fact slightly wider than the quiet-Sun lines, at corresponding points on the profiles. Thus the opacity of the lines formed in both regions above the limb is probably about the same, but the shapes of the source functions in each region have differences which are quite significant for the cores of the lines. Below the limb at −4° and −2° the lines appear to be optically thicker in the coronal-hole spectra than in the quiet Sun.

The opacity in the lines is probably due to passage of radiation through many inhomogeneities along the line of sight. The opacity in the coronal-hole lines observed below the limb appears to be nearly the same as the opacity in the coronal-hole lines observed above the limb. This result is somewhat surprising because the path length above the limb is greater than on the disk. Equal opacities in lines observed above and below the limb cannot be accounted for by a spherically symmetric and homogeneous model for which the source function depends only on height above the limb. The coronal-hole spectra imply an angular dependence for the source function as well as a radial dependence, such that the source function is smallest at the south pole and increases with decreasing solar latitude.

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Note added in proof.—Since this paper was submitted for publication, we have derived an absolute intensity scale for the lines using the absolute intensities at Sun center in the quiet-Sun continuum published by Samain et al. (1975, Astr. and Ap., 39, 71). The conversion factor was obtained from a comparison of the absolute intensities with arbitrary continuum intensities obtained from Skylab spectra. Full details will be given in a later publication. In the table below, we list the conversion factor $C$ that the intensities in Table 1 must be divided by to obtain intensities in ergs cm$^{-2}$ s$^{-1}$ ster$^{-1}$ Å$^{-1}$ at the Sun. The line intensities given herein are peak intensities. If the line is optically thin, the total intensity is obtained by multiplying the peak intensity by FWHM/2(ln 2/π)$^{1/2}$, assuming a Gaussian profile. For optically thick lines, the total area under the profile must be considered. For the optically thin Fe II and Ni II lines, we have found that the widths are on the average equal to $9.4 \times 10^{-6}$ Å. Widths of some of the optically thin lines are given in Table 2, and profiles are given in Figures 5–27.

Below $\sim 1400$ Å the continuum is too weak to observe in Skylab spectra. We adopted the behavior of the reflectivity curve in Figure 2 for wavelengths below 1400 Å. The total accuracy of the absolute intensities should be a factor of 2 or better.

### Conversion Factors

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* Numbers in parentheses are powers of 10.