The anomalous intensities of helium lines in a coronal hole

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ABSTRACT
Observations made at the quiet Sun-centre with the Coronal Diagnostic Spectrometer (CDS) and Solar Ultraviolet Measurements of Emitted Radiation (SUMER) instruments on the Solar and Heliospheric Observatory (SOHO) have shown that the intensities of the resonance lines of He I and He II are significantly larger than predicted by emission measure distributions found from other transition region lines. The intensities of the helium lines are observed to be lower in coronal holes than in the quiet Sun. Any theory proposed to account for the behaviour of the helium lines must explain the observations of both the quiet Sun and coronal holes. We use observations made with SOHO to find the physical conditions in a polar coronal hole. The electron pressure is found using the C III 1175-Å and N III 991.5-Å lines, as the C III line at 977.0 Å becomes optically thick in some regions at high latitudes. The mean electron pressure is a factor of ≈2 lower than that at the quiet Sun-centre. The mean coronal electron temperature is < 9.4 × 10⁵ K. The helium lines are enhanced with respect to other transition region lines but by factors which are ≈30 per cent smaller than at the quiet Sun-centre. The mean ratios of the intensities of the He I 537.0- and 584.3-Å lines and of the He I and He II 303.8-Å lines vary little with the type of region studied. These ratios are compared with those predicted by models of the transition region, taking into account the radiative transfer in the helium lines. No significant variation is found in the relative abundances of carbon and silicon.

Key words: line: formation – Sun: abundances – Sun: transition region – Sun: UV radiation.

1 INTRODUCTION
Early observations of the resonance lines of He I and He II in the extreme ultraviolet (EUV) solar spectrum showed that they did not behave in the same way as other transition region lines (Brueckner & Bartoe 1974). In particular, Jordan (1975) showed that in spatially averaged observations of the quiet Sun these lines are stronger than expected when compared with other transition region lines formed at similar temperatures. Until the launch of the Solar and Heliospheric Observatory (SOHO) (Domingo, Fleck & Poland 1995) in 1995 December, little progress could be made from an observational point of view owing to a lack of well-calibrated spectra obtained at high spatial and spectral resolution. Observations made with the Coronal Diagnostic Spectrometer (CDS) (Harrison et al. 1995) on board SOHO have led to a renewed interest in the lines of He I and He II (Andretta & Jones 1997; Andretta et al. 1997, 2000; Jordan et al. 1997; Macpherson & Jordan 1997, 1999; Peter 1999).

A summary of work on the He I and He II lines prior to the launch of SOHO can be found in Macpherson & Jordan (1999, hereafter Paper I) and in Hammer (1997). Paper I presented the results of a study of the helium lines in comparison to other transition region lines using observations of the quiet Sun made near Sun-centre with the SOHO Joint Observing Proposal (JOP) 62. These showed that the helium lines are enhanced in supergranulation cell boundaries and even more so in cell interiors. The total set of observations included high-latitude regions containing coronal holes. The present paper discusses observations including the southern polar coronal hole.

Early observations showed that the He I and He II resonance lines were significantly weaker in coronal holes than in the quiet Sun, whereas other transition region lines were only marginally weaker (Reeves & Parkinson 1970; Munroe & Withbroe 1972; Tousey et al. 1973; Brueckner & Bartoe 1974). This focussed attention on mechanisms which might reduce, rather than enhance, the helium line emission. However, by using emission measures \[ E_m(0.3) = \int_{\Delta \log T_e} N_e N_H \, dh \] where \( N_e \) and \( N_H \) are the electron and hydrogen number densities, respectively, and \( \Delta h \) corresponds to \( \Delta \log T_e = 0.3 \), calculated from the fluxes of other collisionally excited transition region lines, Jordan (1975) found that the resulting quiet Sun emission measure distribution (EMD) with \( T_e \) underestimated the He I and He II line fluxes by factors of about 15

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and 6, respectively. Since then, theoretical studies (e.g. Shoub 1983; Fontenla, Avrett & Loeser 1993; Anderson, Raymond & van Ballegooijen 1996) have concentrated on explaining this observed enhancement of the helium line fluxes in the quiet Sun. Work by Hansteen, Leer & Holzer (1994, 1997) (see these papers for earlier work) has investigated the relative effects of thermal, frictional and gravitational forces on the abundance of helium relative to hydrogen in regions where the magnetic field is open. They find that the abundance of helium in the corona can become large, but in the particular models they consider the helium abundance in the transition region is reduced rather than enhanced. They did not calculate the He I and He II line intensities.

Although variations in the helium abundance could in principle contribute to the apparent enhancement of the helium line intensities, recent observations of the inner corona with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) by Laming & Feldman (2001) suggest that the average value is about a factor of two smaller than the value proposed by Anders & Grevesse (1989).

Jordan (1975) proposed that any dynamical process which rapidly mixes ions formed at one temperature with higher temperature electrons could in principle account for the helium line enhancements. Such a process would affect the He lines selectively because of the relatively long ionization times of He I and He II and the greater sensitivity to temperature of the exp(−W/kT_e) term in the collisional rate excitation rate. Some dynamical processes, e.g. penetration of hot electrons from the corona and mass motions into regions of higher T_e (Jordan 1975, 1980) depend on the temperature gradient and N_e. It is therefore important to quantify the behaviour of the helium lines within coronal holes, where earlier work (e.g. Munro & Withbroe 1972) has shown that N_e, the temperature gradient and the mean coronal temperature are all lower compared with the quiet Sun.

Coronal hole studies are also important because the coronal radiation field is significantly weaker at wavelengths which can lead to photoionization of He I and He II. There has been debate over the role of photoionization, followed by recombination (PR), in the line formation process (see summary in Paper I). If PR were the dominant mechanism in the helium resonance line formation then these lines would be expected to be weaker in coronal holes, as found in the early and more recent observations (Andretta et al. 1997; Macpherson & Jordan 1997; Del Zanna & Bromage 1999; Peter 1999). The He I 584.3 Å line profile also provides information on the role of the PR process, as this produces a significant central reversal in the line, which is not apparent in the quiet Sun spectra (see Paper I). The variation of the intensity, line profile and wavelength-shift of the He I 584.3 Å line across the Sun, including coronal hole regions, has been studied by Peter (1999) from SUMER spectra. He finds that in coronal holes the intensity is reduced by a factor of 2, the linewidth increases towards the limb, and the line is blueshifted. The line profile becomes flat-topped, with a suggestion of self-reversal, indicating higher opacities.

Here we make a systematic study of the behaviour of the helium lines in a coronal hole, in comparison with other transition region lines and the coronal lines of Mg IX and Mg X. We also include studies of the electron density, the effects of limb brightening and line opacities, and a brief discussion of line profiles. The main aim is to provide a set of observational constraints for future theoretical work on the helium line formation. The observations used and the data reduction are discussed in Section 2. The systematic behaviour of the lines other than those of helium is described in Section 3. Transition region pressures and line opacities are derived in Section 4. The lines of helium and their behaviour with respect to other transition region lines are discussed in Section 5. Our conclusions are summarized in Section 6.

### 2 OBSERVATIONS AND DATA REDUCTION

The instruments involved in JOP 62 are described in Paper I. The observations used here were made using JOP 62 on 1997 October 30. Simultaneous observing sequences were designed for the CDS and SUMER instruments (see Paper I and the SOHO World Wide Web page).

<table>
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<tr>
<td>Lines studied</td>
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<tr>
<td>Duration (mins)</td>
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<tr>
<td>Solar X, Y (centred)</td>
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</tr>
<tr>
<td>Start Times of Observations</td>
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</table>

*Resolution in solar Y is 1.67 arcsec. *Includes dead-time between exposures.

<table>
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<td>Solar X, Y (centred)</td>
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</tr>
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### Table 1. Details of the CDS observing sequence.

### Table 2. Details of the SUMER observing sequences.

1 http://sohowww.nascom.nasa.gov/soc/JOPs

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while the SUMER lines cover the range $\log T_e = 4.0-5.0$, where the He lines are formed under equilibrium conditions. The He I 584-Å line is also observed with SUMER in second order. The SUMER sequences also contain lines of C III and N III whose intensity ratios we use to measure the electron density $N_e$.

The data reduction procedure is as described in Paper I. There the CDS intensities were derived using the absolute calibration supplied in the CDS software at that time, combined with the minor revisions suggested by Landi et al. (1997). A new CDS software absolute calibration was provided by W. Thompson on 1998 December 23, (CDS-SOFT mailing list), based on work by Brekke et al. (2000). (Adopting this would not have affected our main conclusions.) To aid comparisons with Paper I we adopt the same calibration as used there. Fig. 1 shows the factors required to convert our intensities to those which would be found using the most recent CDS absolute calibration.

As can be seen from Table 1 the CDS HELIUM sequence produces a rastered $40 \times 240$ arcsec$^2$ image containing 20 exposures, taking a total time of 26 min. Fig. 2 shows the two images obtained at high (southern) latitudes in the resonance lines of He I, He II, O IV, O V and Mg X, which have starting times of 10:16:13 (upper set) and 10:42:52 (lower set). Solar rotation was not taken into account during the observations.

The SUMER sequence is set out in Table 2. The SUMER instrument was not capable of producing rastered images at the time of the observations. At the latitude of the centre of the SUMER slit, a point on the solar surface would have rotated by $0.20$ arcsec during a CDS exposure, and by $0.26$ arcsec during a SUMER exposure. Thus solar rotation between adjacent exposures is not significant compared with the CDS slit width, but is comparable with the SUMER slit width. If the co-alignment of the two instruments were perfect, the difference in position between the exposures at a given time would be known. Given the starting times of the observations, the first CDS raster would have reached a position around $-4.3^\circ$ (to the left of its central position in Fig. 2, top set) by the time of the first SUMER exposure. It was therefore impossible to make simultaneous observations of the same location with the two instruments. The region at solar $X = 0^\circ$ was observed in the SUMER lines of N III and He I about 4 and 6.5 min later than in the CDS lines, respectively. Assuming that the basic structures present had not changed (see Fig. 2), we compared the variations in intensity (with solar $Y$) of the He I 584.3-Å and N III 991.5-Å lines observed with SUMER, with similar scans made at solar $X = 0^\circ$ in the He I 584.3 Å and O IV 554-Å lines observed with CDS. There was poor agreement between the structures observed, which we think is a result of the difference in the slit widths as well as changes with time. We also compared the variations with solar $Y$ of the above SUMER line intensities with those of the above CDS lines in each of the 20 exposures making up the first CDS raster. Although a reasonable fit occurs at solar $Y = +13^\circ$ in the CDS image, this offset is larger than expected. The boundary region at around solar $Y = -875^\circ$ in the SUMER scans is not as strong in any of the CDS scans, which suggests that this structure is small or short-lived. Because of the difficulties in matching the data from the two instruments, we treat them separately, and give results for typical cell boundary, cell interior and intermediate regions as observed in each instrument (see Section 2.1).

In Paper I we noted the existence of offsets of up to 5 arcsec between SUMER lines observed at different grating settings. This arises from a small angle between guide bars on the platform on which the grating is mounted (Lemaire, private communication; see also Paper I). Here we find that a 4-arcsec offset between the 977.0- and 1175-Å exposures provides the best match. By examining adjacent images which start two minutes apart, it appears that the cell interior region around $-828^\circ$ varies slowly with time, and matching this gives a reasonable fit to most other regions. The position for the C III 977.0-Å line is therefore solar $Y = (-811^\circ, -930^\circ)$, as listed in Table 2. Taking this as the reference position, the 1175-Å exposure is offset by $+4$ arcsec; the He I 584.3-Å line is observed in the same segment. The C III exposures are offset by $-4$ arcsec and the Si III 1206.5-Å exposures are offset by $+4$ arcsec. The N III lines are observed in the same window as C III 977.0 Å and the Si II lines are observed along with Si III 1206.5 Å. The C III 1175-Å multiplet appears again in this latter segment. The Si III 1299-Å exposures are offset by $+4$ arcsec. The above offsets have been included in all scans in solar $Y$ that are shown.

When examining the spatial variation of the ratio of the intensities of the He I 537.0- and 584.3-Å lines, which is remarkably constant, we noticed that there is an offset of 1 pixel between the supergranulation peaks and cell interior minima in these lines, in the region outside the coronal hole. The accuracy of the CDS de-slanting algorithm is quoted as being ‘to within about 1 pixel’ (Thompson, and also Pike, communications posted on CDS-SOFT mailing list), so this small offset between 537.0 and 584.3 Å is understandable. Similarly, in O V 629.7 Å these structures lie 1 pixel further inside the limb than do the corresponding ones in the O IV 554-Å multiplet. A shift in this sense is not expected, given the temperature stratification of the atmosphere. Thus the images in He I 537.0 Å and O IV 554 Å have been shifted to smaller (negative) solar $Y$ by 1 pixel. Longer wavelength lines do not show systematic shifts to within 1 pixel.

### 2.1 Intensity measurements

The line profiles observed with CDS are dominated by the instrumental width. An automatic Gaussian fitting routine was used to find the total intensity ($I_{\text{tot}}$) of a line by fitting the peak intensity ($I_{\text{peak}}$), wavelength, width (full width at half maximum, FWHM) and background level. Summing the intensity over the line profiles gives the same values for $I_{\text{tot}}$ to within expected uncertainties. When observed with the higher spectral resolution of SUMER, some optically thick lines formed in the lower transition region

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**Figure 1.** Factors required to convert the present absolute intensities to those given by the most recent CDS absolute calibration (Brekke et al. 2000).
have non-Gaussian profiles (see Section 5.4 for examples of He I 584.3-Å line profiles). The fitting routine was then used to estimate the background level and the intensity was summed over the whole line profile to obtain $I_{\text{tot}}$. For N III, line blends were taken into account by fitting Gaussian profiles to the individual lines. For the C III 1175-Å multiplet, the intensity of the whole multiplet was measured as well as fits to the individual lines. The summed intensity tends to be about 6 per cent larger than that calculated using Gaussian fits, suggesting slightly non-Gaussian profiles.

The sample is not sufficient to define supergranulation cell boundaries and interiors using a statistical approach. The optically thin lines of N III have been corrected for the limb brightening and then the categories used in Paper I have been applied, but without a separate category for strong boundaries (i.e. for cell boundaries

**Figure 2.** Images obtained on 1997 October 30 in lines observed with the CDS (upper set from the first raster, lower set from the second raster). The temperature of the line formation increases from left to right. The coronal hole is visible in the Mg X line. The hole is not obvious in the lines of O IV and O V but the He I and He II emission from supergranulation boundaries is clearly reduced within the coronal hole.
The intensities of the other SUMER lines were extracted at the locations observed. These were the four scans at solar X = −7 and the two scans at solar X = +11°7 and +13°9. Table 3 gives the intensities derived in regions inside the hole and Table 4 gives the intensities derived in regions outside the hole. The overall mean intensities are also given, where these are used in the analyses. The quiet Sun-centre intensities have been re-extracted to correspond to the same categories as defined above; these are given in Table 5.

It is difficult to define the position of the coronal hole uniquely,
because even in a given scan, changes in the absolute and relative line intensities occur at different values of solar \( Y \). From Figs 2 and 3, the MgX 625.0-Å line intensity begins to decrease by about solar \( Y = -850^\circ \). The ratio \( I(\text{Mg} \times)/I(\text{Mg} \times) \), which gives the temperature (see Section 4.1), and the helium line intensities, begin to decrease slightly closer to the limb, at around solar \( Y = -920^\circ \) corresponds to the end of the region observed and is not real. The MgX line intensity is from the CDS scan at solar \( X = -0^\circ.3 \).

Figure 3. The variation in intensity of the lines of He\(1\), He\(2\), O\(4\), O\(5\) and Mg\(9\) observed with the CDS instrument at solar \( X = -0^\circ.3 \) (left) and +13°9 (right). The coronal hole (beyond solar \( Y = -860^\circ \)) shows weaker emission in the Mg\(9\), He\(1\) and He\(2\) lines, while the O\(4\) and O\(5\) lines show the supergranulation structure plus gradual limb-brightening.

Figure 4. The variation with solar \( Y \) of the intensities of the lines of N\(3\), C\(3\), He\(1\), C\(2\) and Si\(3\) observed with the SUMER instrument, ordered from top to bottom by the time of observation. Note the change in the supergranulation cell structure with solar rotation and the absence of this structure in the He\(1\) line beyond solar \( Y = -880^\circ \). The drop in the C\(3\) 977-Å and N\(3\) line intensity at solar \( Y = -920^\circ \) corresponds to the end of the region observed and is not real. The Mg\(x\) line intensity is from the CDS scan at solar \( X = -0^\circ.3 \).

Figure 5. The ratios \( I(\text{O} \text{III} 599.6 \AA)/I(\text{O} \text{IV} 554 \AA) \) and \( I(\text{O} \text{V} 629.7 \AA)/I(\text{O} \text{IV} 554 \AA) \) showing their small variation as a function of solar \( Y \) and as \( I(\text{O} \text{IV} 554 \AA) \) varies. The scan shown is at solar \( Y = -0^\circ.3 \). A cosmic ray hit causes the loss of data in the O\(4\) lines.

nearby boundary have been scattered into the narrow SUMER slit. Otherwise, the width of the boundary is larger in the He\(1\) line. In deriving the SUMER intensities given in Tables 3 and 4 the hole was also defined to begin at solar \( Y = -860^\circ \), but given the uncertainty in the hole position, results for the hole beginning at solar \( Y = -880^\circ \) are discussed in Sections 4 and 5.

3 SYSTEMATIC BEHAVIOUR OF THE OBSERVED LINES

As can be seen from Fig. 2 the helium lines have a spatial variation which is different from that of other transition region lines. Such differences were noticed in early observations (e.g. see Brueckner & Bartoe 1974). The supergranulation network outside the coronal hole appears in the transition region lines and in the helium lines, although there is not a one-to-one correspondence between the brightest parts of the structures in these two classes of lines. Within the coronal hole defined from the Mg\(x\) image, the transition region lines still show the supergranulation network and also distinct limb brightening (the solar optical limb is at solar \( Y = -976^\circ.3 \)). However, the network is fainter in the helium lines and there is
little limb-brightening. This behaviour is quantified in Fig. 3, which shows the CDS line intensities as a function of solar $X$, at solar $X = -0.3$ and $+13'9$. The lack of (or lower) limb brightening in the helium lines is qualitatively consistent with their higher optical depth.

Fig. 4 shows the line intensities measured with SUMER as a function of solar $Y$, ordered by the time of the observations, plus the Mg X line from the CDS observations at solar $X = -0.3$. Network boundary features beyond solar $Y$, apparent in the simultaneous (or nearly so) scans in C III and N III, do not appear in He I. The offsets discussed in Section 2 have been applied, so only the C III 977-Å and N III lines show the sudden cut-off that occurs at the end of the scan. Differences in the detailed structure observed in the normal transition region lines are caused by solar rotation and any intrinsic changes with time.

Because the CDS and SUMER observations are not obtained at the same time and place, and because some SUMER lines are optically thick, the absolute line intensities cannot be used to derive the full EMD for a particular feature. Instead, we consider the ratios of the intensities of various pairs of lines and compare these with the corresponding ratios at the Sun-centre. The variations in the line intensities which occur as the Sun rotates under the SUMER slit are also discussed, because these and any intrinsic changes with time are unavoidable when estimating $N_e$.

### 3.1 The normal transition region lines in the CDS spectra

Fig. 5 shows the ratios $I$(O III 599.6 Å)/$I$(O IV 554 Å) and $I$(O V 629.7 Å)/$I$(O IV 554 Å) as a function of solar $Y$ at solar $X = -0.3$, with $I$(554 Å) shown for comparison. These ratios vary little about their means. Nor do these ratios show any evidence of differences in line opacities as the limb is crossed. The spatially averaged intensity ratios shown are not significantly different from those observed at the Sun-centre (see table 3 in Paper I). The same is true for the ratios found from other scans in solar $Y$. The ratios of the neon lines (not shown) have a larger scatter, but the mean ratios do not differ significantly as a function of solar $Y$, again including the Sun-centre observations. The ratios of the neon to the oxygen lines show a slight tendency to be lower in the coronal hole in all the regions scanned. As the Ne IV and O IV lines are formed at essentially the same temperature according to the ion populations calculated by Arnaud & Rothenflug (1985), a small reduction in the neon to oxygen abundance ratio cannot strictly be excluded. However, the neon lines are relatively weak and the presence of nearby lines makes it difficult to obtain an accurate fit to the background, which may be overestimated. The persistent bright feature near the limb (around solar $Y = -970'$, solar $X = -7.5$, see Fig. 2) also has relative intensities that are the same as in the cell boundary regions. Thus for the temperature range 1–3 $\times 10^5$ K, the near constancy of the line ratios shows that the EMDs have essentially the same shape in all regions, although the absolute intensities differ. None of the above CDS lines has a significant sensitivity to $N_e$ over the relevant range of densities.
3.2 The normal transition region lines in the SUMER spectra

The ratios of lines observed with SUMER can also be examined in the same way. First, lines which are observed simultaneously are considered. Their ratios are given in Fig. 6, together with the absolute intensity of the N \textsc{iii} 991.5-Å lines to show the supergranulation cell structure at 10:32:48. Non-constant ratios for these lines must be caused by variations in the plasma parameters, such as $N_e$ and line opacities. The ratio of the C \textsc{iii} 977.0-Å and N \textsc{iii} line intensities (obtained at 10:32:48) shows more variation than the CDS line ratios do. This is likely to be caused by the C \textsc{iii} 977.0-Å line becoming optically thick at some locations, leading to photons being scattered out of the line of sight (see Section 4.3 for opacity estimates). The most obvious example of this is around solar $Y = -910^\circ$. The N \textsc{iii} lines are estimated to be optically thin. A lower electron density in the coronal hole (see Section 4.2) would be expected to increase the ratio, but by less than 10 per cent. The mean intensity ratio in the boundaries inside the coronal hole is 0.16 dex lower than that at Sun-centre. The means in the other regions are within 0.06 dex of those at Sun-centre.

The ratio $I$(Si \textsc{iii} 1206.5 Å)/$I$(C \textsc{iii} 1175 Å) (obtained at 11:13:03) is expected to increase as $N_e$ decreases, and to be smallest where the opacity in the 1206.5-Å line is largest. As the line-of-sight opacity in the coronal hole is expected to be higher than outside the hole, the larger maximum ratios in the hole suggest lower values of $N_e$. The minima correspond roughly to the positions of cell boundaries at 11:13:03. The mean intensity ratio outside the hole is slightly smaller than that at Sun-centre, compatible with the higher optical depth in the Si \textsc{iii} line at high latitudes. Note that the region around solar $Y = -910^\circ$ will not be the same as in the C \textsc{iii} 977.0-Å and N \textsc{iii} lines, owing to solar rotation.

The ratio $I$(Si \textsc{iii} 1206.5 Å)/$I$(Si \textsc{iii} 1190.4 Å) (obtained at 11:13:03) on average tends to be larger than in the Sun-centre spectra. The trend for the ratio to be largest in cell interior regions (see Figs 4 and 6), is compatible with the Si \textsc{iii} 1206.5-Å line becoming optically thin.

Averaged over regions inside or outside the hole, the ratios of all the normal transition region lines (excluding the $N_e$ sensitive C \textsc{iii} 1175-Å lines) do not differ substantially from those observed at Sun-centre; the differences are understandable in terms of higher optical depths at high latitudes. Thus the EMD has essentially the same dependence on $T_e$ as at Sun-centre, over the range from $T_e = 1.3 \times 10^4$ K to $6 \times 10^4$ K. Spatially integrated observations of stellar transition regions give a similar result (see e.g. Jordan et al. 1987) and the origin and implications of this result are discussed by Jordan (2000).

3.2.1 Variations with time in the SUMER spectra

As shown in Table 2, two or more exposures were made in each spectral range observed, which allow the typical changes with time in a given line to be investigated. These arise as structures pass through the slit, or as features brighten or fade. It is important to examine these variations because adjacent rather than simultaneous exposures have to be used to find the electron densities. Fig. 7 shows (from top to bottom) the intensity of the N \textsc{iii} 991.5-Å lines at 10:32:48 as a function of solar $Y$; and the ratio of the intensities observed at 10:32:48 and 10:30:53; the intensity of the C \textsc{iii} 1175-Å lines at 10:34:58 and the ratio of the intensities at 10:36:13 and 10:34:58, and the intensity of the C \textsc{iii} 1335-Å lines at 10:40:01 and the ratio of the intensities observed at 10:41:56 and 10:40:01. Comparing the ratios of the normal transition region lines shown in Figs 6 and 7, it can be seen that the degree of variation with time is (with the exception of the region around solar $Y = -809^\circ$ in Fig. 7, top panel) less than or comparable to that of the spatial variations seen in Fig. 6. In Fig. 7 (bottom panel) the variations are smaller because a wider slit (1 arcsec rather than 0.3 arcsec) was used, so particular structures remain within the slit for longer.

Fig. 8 shows the intensity ratios of some SUMER lines that are not observed simultaneously. The ratio $I$(Si \textsc{iii} 1206.5 Å)/$I$(C \textsc{iii} 1335.7 Å), obtained from exposures 12 min apart, varies about the mean by only 0.20 dex, which is comparable to the variations with time in the C \textsc{iii} 1175-Å lines. The ratio does not, on average, differ between the regions inside and outside the coronal hole (or between these and Sun-centre) and the spatial scale of the variations resembles that of the variations with time in Fig. 7 (top and middle panels), rather than the scale of the supergranulation structure. The lines are estimated to have similar optical depths and their ratio varies little with $N_e$. Thus any spatial variations in the relative abundances of silicon (low first ionization potential, or FIP) and carbon (high FIP) are at most comparable with the variations with time expected in the Si \textsc{iii} 1206.5-Å line.

The density-sensitive ratios $I$(C \textsc{iii} 1175 Å)/$I$(N \textsc{iii}) and $I$(C \textsc{iii} 1175 Å)/$I$(C \textsc{iii} 977.0 Å) are also shown. As discussed above (and in Section 4.3) the C \textsc{iii} 977.0-Å line is estimated to be optically thick at several locations, the C \textsc{iii} 1175-Å lines may be optically thick in the region around solar $Y = -915^\circ$, but the N \textsc{iii} 991-Å

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lines are estimated to be optically thin at all locations. Because the 
N \text{III} lines are not sensitive to \( N_e \), while the C \text{III} lines are, the 1175-
to 991.5-Å ratio gives an opacity free indicator of the variation of 
\( N_e \) (see Section 4.2). The variations in the density-sensitive ratios 
are larger than the variations with time in Fig. 7 (top and middle 
panels) (with the exception noted earlier). Nevertheless, it is clear 
that the variations with time between the two exposures are a major 
limitation on using these lines to measure \( N_e \).

3.3 Limb brightening

Although the intensities of the oxygen lines have constant ratios, 
there is a gradual increase in their absolute intensities towards the 
limb, owing to the geometrical affects of an increased path length 
with solar latitude. This must be taken into account when the 
relative intensities of the helium lines and optically thin transition 
region lines in the coronal hole are compared with the values found 
at Sun-centre. For a spherically symmetric layer, a sec \( \theta \) limb 
brightening function (where \( \sin \theta = Y/Y_{\text{limb}} \)) can be applied up to 
solar \( Y = -950^\circ \) for a realistic range of layer thickness and height. 
The degree to which the observed intensities follow a sec \( \theta \) function 
varies with the location of the scan and depends on the strength of 
the individual cell boundaries and cell interiors present. In Fig. 3, the scan at solar \( X = +13^\circ 9 \) is fitted quite well by this 
function, but in the scan at solar \( X = -0^\circ 3 \) there are stronger 
boundaries in the region outside the hole. Fig. 9 shows the O \text{IV} 
554-Å lines in the scan at solar \( X = -0^\circ 3 \), with and without limb 
brightening. (The helium lines are discussed in Section 5.3.)

None of the optically thin lines show an obvious change in the 
degree of limb-brightening (relative to Sun-centre) as the scans 
pass across the coronal hole boundary around solar \( Y = -860^\circ \). 
This implies that the absolute intensities of the lines if viewed in the 
radial direction must be very similar to those at Sun-centre. 
This is consistent with earlier work (e.g. by Munro & Withbroe 
1972) which showed that the absolute intensities of transition 
region lines in coronal holes observed at Sun-centre are the same as 
those in the quiet Sun to with about \( \pm 13\% \) per cent. Thus we confirm 
that in this polar hole, the product \( N_e^2 \Delta h \) (where \( \Delta h \) is the extent in the 
radial direction) is similar to that at the quiet Sun-centre, 
albeit \( N_e \) and \( \Delta h \) may be different.

Beyond solar \( Y = -950^\circ \) projection effects and spatial 
inhomogeneities, e.g. caused by spicules, give intensities that are 
smaller than expected with limb brightening in a plane parallel 
layer. Also, close to the limb even optically thin lines can be 
absorbed by the H Lyman continuum (Withbroe 1970). From 
previous observations of limb-to-disc ratios of lines formed above 
and below the H Lyman edge at 911 Å by Burton et al. (1973), the 
absorption at the limb amounted to about a factor of 3 for lines at 
around 790 Å, and a factor of 1.7 for the O \text{v} line at 629.7 Å.

4 CORONAL AND TRANSITION REGION 
PARAMETERS

The coronal temperature and the electron densities are important 
parameters in theories which predict the penetration of electrons, in 
the high-energy tail of the coronal Maxwellian velocity 
distribution, down to the transition region where the helium lines 
are formed. The electron pressures are also important in modelling 
the structure of the atmosphere. Once these are known they can be 
used in estimates of the line of sight optical depths in the various 
lines.

4.1 Mean temperatures from the coronal lines

Fig. 10 shows the ratio \( I(\text{Mg} \text{X})/I(\text{Mg} \text{IX}) \) at solar \( Y = -0^\circ 3 \), and the 
Mg X absolute intensity. The Mg X lines are weak and the signal-
to-noise ratio becomes low in the central part of the coronal hole. 
For this reason the ratios from three scans in solar \( Y = +13^\circ 9, -0^\circ 3 \) and +3\% are shown. Mean ratios are found 
from regions not affected by the noise; outside the coronal hole 
(solar \( Y = -775^\circ \) to \(-840^\circ \)) the mean ratio is 0.45, similar to the value of 0.47 found at the solar centre above boundary regions. The ratios 
close to and just above the limb (solar \( Y = -970^\circ \) to 
\(-1000^\circ \)) are a factor of 2.4 lower than the quiet Sun value. At Sun-
centre, the emission measure distribution derived from the mean 
boundary intensities is still increasing with \( T_e \) at \( 1.1 \times 10^6 \) K (see 
Paper I). A decrease of a factor of 2.4 in the above ratio leads to an 
emission measure distribution that peaks at or below the optimum 
temperature for the formation of the Mg \text{X} line, leading to 
\( T_e \approx 9.4 \times 10^5 \) K. This estimate does not include any possible 
effects of opacities in the lines or the H Lyman continuum (see 
Section 3.3). The Mg \text{X} to Mg \text{IX} intensity ratio \( \delta \) does depend 
on the instrumental calibrations used. Adopting the calibration factors 
of Brekke et al. (2000), the emission measure distribution derived 
from the quiet solar centre spectra and from the spectra outside the 
coronal hole would peak at \( 10^6 \) K, which is somewhat lower than 
usually found. The upper limit from the coronal hole spectra 
would remain the same. Thus, as in coronal holes studied previously, the 
coronal temperature is lower than in the average quiet Sun, and in 
the hole studied here, is \(<9.4 \times 10^5 \) K.

4.2 Electron pressures

In Paper I we used the C \text{III} (1175 Å)/(977.0 Å) intensity ratio to 
derive the electron density. The variation of this ratio with \( P_e \) and \( T_e \) 
was calculated using atomic data in the CHIANTI data base (Dere 
et al. 1997; Landi et al. 1999) and is given in fig. 9 of Paper I. At 
high latitudes we have found that the C \text{III} 977.0-Å line becomes 
optically thick in some boundary regions (see Sections 3.2 and 4.3, 
and Fig. 6). However, the lines within the C \text{III} 1175-Å multiplet 
appear to be optically thin except in the region around solar 
\( Y = -910^\circ \). The ratio \( I(\text{C} \text{III})/I(\text{N} \text{III}) \) thus provides 
an alternative means of deriving \( N_e \), using atomic data from 
CHIANTI and including the relative element abundances (photospheric 
values from Anders & Grevesse 1989; Grevesse, Noels &
Table 6. Summary of electron pressures derived the ratio \( I(\text{C}\,\text{iii}\,1175\,\AA})/I(\text{N}\,\text{iii}\,991.5\,\AA) \) at \( log T_e = 4.75 \):

<table>
<thead>
<tr>
<th>Feature [range of ( I(\text{N},\text{iii},991.5,\AA) )]</th>
<th>Intensity Ratio</th>
<th>( log P_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Inside the hole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Interior (&lt;22.6)°</td>
<td>5.26 ± 0.83°</td>
<td>14.72°15.37°</td>
</tr>
<tr>
<td>Intermediate (22.6–37.7)</td>
<td>4.50 ± 1.08</td>
<td>14.08 ± 0.36</td>
</tr>
<tr>
<td>Cell Boundary (&gt;37.7)</td>
<td>4.90 ± 0.84</td>
<td>14.20 ± 0.27</td>
</tr>
<tr>
<td>Overall Mean</td>
<td>4.91 ± 0.86</td>
<td>14.21 ± 0.29</td>
</tr>
<tr>
<td>(b) Outside the hole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Interior (&lt;22.6)</td>
<td>4.75 ± 0.69</td>
<td>14.16 ± 0.22</td>
</tr>
<tr>
<td>Intermediate (22.6–37.7)</td>
<td>5.38 ± 0.46</td>
<td>14.37 ± 0.16</td>
</tr>
<tr>
<td>Cell Boundary (&gt;37.7)</td>
<td>5.31 ± 0.66</td>
<td>14.34 ± 0.23</td>
</tr>
<tr>
<td>Overall Mean</td>
<td>5.23 ± 0.65</td>
<td>14.32 ± 0.22</td>
</tr>
<tr>
<td>(c) Quiet Sun</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Interior</td>
<td>6.79 ± 1.30</td>
<td>15.00°15.05°</td>
</tr>
<tr>
<td>Intermediate</td>
<td>5.42 ± 1.27</td>
<td>14.37°15.05°</td>
</tr>
<tr>
<td>Cell Boundary</td>
<td>5.00 ± 0.92</td>
<td>14.23°15.26°</td>
</tr>
<tr>
<td>Overall Mean</td>
<td>5.85 ± 1.42</td>
<td>14.52°15.18°</td>
</tr>
</tbody>
</table>

*\( P_e \) is defined as \( N_e T_e \) cm\(^{-3}\) K. **Intensity in erg cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\). °The ± values give the standard deviation in the mean ratio. The ± values are found from the standard deviations in the mean ratios. The upper limit to the ratio exceeds the limiting value at high densities.

Figure 11. The ratio \( I(\text{C}\,\text{iii}\,1175\,\AA})/I(\text{N}\,\text{iii}\,991.5\,\AA) \) as a function of \( I(\text{N}\,\text{iii}\,991.5\,\AA) \), corrected for limb brightening; the left-hand plot is for the region inside the coronal hole; the right-hand plot is for the region outside the coronal hole.

Helium lines in a coronal hole

Sauval (1992) and the relative ion populations of Arnaud & Rothenflug (1985). Both carbon and nitrogen are high-FIP elements, so any possible variations in their relative abundance should be small. A temperature of \( log T_e = 4.75 \) was adopted, based on the mean emission measure distributions of Paper I.

Because the assumption that the lines are formed at the same value of \( T_e \) is only approximate, the calculated ratios have been checked by comparing the values of \( N_e \) that they produce at Sun-centre with the values found from the \( \text{C}\,\text{iii} \) intensity ratios. Various procedures were used to try to take account of the effects of high opacities and time changes in the Sun-centre data. The ratios \( I(977.0\,\AA)/I(991.5\,\AA) \) and \( I(1175\,\AA)/I(991.5\,\AA) \) were examined to find regions where these were both smaller or larger (respectively) than the theoretical values in the limits of high pressures (\( P_e = N_e T_e \approx 10^{16} \) cm\(^{-3}\) K). These were attributed to high opacities in the 977.0-Å line. Only four such points were found and were excluded from samples involving the 977.0-Å line. A further nine points were excluded since both the ratios \( I(1175\,\AA)/I(977.0\,\AA) \) and \( I(1175\,\AA)/I(991.5\,\AA) \) gave values of \( N_e \) above the high-density limits, these being attributed to changes with time. For consistency, the same number of points where both ratios were small were also excluded. The overall mean pressure from the \( I(1175\,\AA)/I(977.0\,\AA) \) ratio in the solar centre observations is \( log P_e = 14.47 \) (adopting \( log T_e = 4.75 \)), slightly smaller than the value of 14.58 found by using all points. The value from the \( I(1175\,\AA)/I(991.5\,\AA) \) ratio is 14.52, which is not significantly different from the above value of 14.47. This is effectively a normalization procedure which takes into account the uncertainties in the relative values of the ion populations and abundances of \( \text{C}\,\text{iii} \) and \( \text{N}\,\text{iii} \). Thus the \( I(1175\,\AA)/I(991.5\,\AA) \) ratio can be applied with confidence to the high latitude data, to derive pressures relative to those at Sun-centre.

A similar approach has been used to find electron pressures from the high latitude data. With the limb-brightening removed, the definitions of boundaries, intermediate and cell interiors given in Section 2 were applied to the \( \text{N}\,\text{iii} \) lines. Fig. 11 shows all the observed ratios, plotted against the \( \text{N}\,\text{iii} \) intensity, corrected for limb brightening. The results for the regions inside the hole and outside the hole are shown separately. As the ratios which exceed the theoretical value of 7.35 (at \( P_e = 10^{16} \) cm\(^{-3}\) K) are found in regions where significant changes occur with time (as observed from the ratios of adjacent scans), the 10 pixels with such ratios are excluded, together with the 10 smallest ratios. The pressures which result are given in Table 6.

Outside the hole, the mean pressure in the boundaries is \( log P_e = 14.34 \), which is marginally larger than the mean value of \( log P_e = 14.23 \) found for boundaries at Sun-centre, using the \( I(1175\,\AA)/I(991.5\,\AA) \) ratio. However, the regions classed as cell interiors have a lower mean pressure (\( log P_e = 14.16 \)) than the boundaries, in contrast with the result found at Sun-centre, where all the cell interior regions have pressures greater than in any boundary and for which the mean value is \( log P_e = 15.00 \). As discussed in Paper I, changes with time could have caused the unphysically large \( I(1175\,\AA)/I(977.0\,\AA) \) ratios found in some cell interior regions at Sun-centre, but even when such points are excluded, as described above, the trend for higher pressures at low values of \( I(977.0\,\AA) \) in the Sun-centre data remains. Thus cell interior regions do not appear to have a unique pressure. The regions classed as ‘intermediate’ have a mean pressure of \( log P_e = 14.37 \), which is the same as the value found at Sun-centre. The overall mean pressure outside the hole is \( log P_e = 14.32 \), lower than the value of 14.52 found at Sun-centre. The
main difference between the region outside the hole and the region at Sun-centre is the lower pressure in the cell interiors.

There are fewer usable boundary points within the coronal hole, apart from those in the region around solar \( Y = -910^\circ \) to \(-920^\circ \), these have a lower mean pressure (log \( P_e = 14.12 \)) than the boundaries outside the hole or at Sun-centre do. As discussed in Section 3.2 the above region appears to have a high opacity, as the ratio \( I(CIII) 977.0 \text{ Å}/I(NIII) 991.5 \text{ Å} \) is unusually small (see Fig. 6). However, the ratio \( I(CIII) 1175 \text{ Å}/I(NIII) 991.5 \text{ Å} \) is also larger than that in the high-density limit. We suspect that a short-lived brightening has occurred between the two exposures used. Only 4 pixels are usable, so the mean pressure found (log \( P_e = 14.49 \)) cannot be considered as reliable. The mean boundary pressure inside the hole is log \( P_e = 14.20 \), similar to that at Sun-centre. The two cell interior regions inside the hole have very different pressures (log \( P_e = 14.14 \) and 14.52). These values are both lower than those found for the cell interiors at Sun-centre. The smallest pressures in the hole are found in the regions classed as ‘intermediate’, for which log \( P_e = 14.08 \). The overall mean pressure within the hole is log \( P_e = 14.21 \).

Placing the coronal hole–outside hole boundary at solar \( Y = -880^\circ \) only affects the mean pressures derived for the cell boundaries, and hence the overall means. The cell boundary points between solar \( Y = -860^\circ \) and \(-879^\circ \) give relatively low pressures. The mean pressure in the boundaries and the overall mean outside the hole become log \( P_e = 14.28 \) and 14.29, respectively, while inside the hole the corresponding values become 14.26 and 14.22. In view of the standard deviations given in Table 6, these are not significant differences.

Thus, compared with the quiet Sun-centre, the mean pressure within the hole (to solar \( Y = -920^\circ \)) is smaller by a factor of 2. This mean reduction factor is similar to those found from early studies of coronal holes (e.g. Munro & Withbroe 1972). More recent studies by Del Zanna & Bromage (1999), using instruments on SOHO and lines of O IV, lead to much higher pressures (log \( P_e = 15.23 \) and 15.39 for cell boundaries and interiors in the hole, respectively). However, they also find that in the quiet Sun the cell interiors have a higher pressure than do the cell boundaries, and that the cell interior pressure in the hole is lower than in the quiet Sun. Some of the differences between our pressures and those derived by Del Zanna & Bromage (1999) may be caused by uncertainties in the atomic data used. However, the lines of Si IX used by Del Zanna & Bromage (1999) lead to pressures that are closer to our mean values. Doschek et al. (1997) also find a reduction of a factor of 2 in polar coronal holes compared with the quiet Sun, using lines of Si VIII and S VIII, and their mean coronal hole pressure of log \( P_e = 14.0 \) is compatible with our mean transition region pressure in the hole.

The standard deviations about the means are given in Table 6. These are larger for the quiet Sun than for the high-latitude data, probably because the signal to noise is higher in the latter, as a result of limb brightening. We have no way of distinguishing between a real range of pressures within a given boundary or cell interior and the effects of changes with time between the exposures used. Further observations of the density-sensitive lines will be used to investigate this point. Although the absolute pressures obtained are subject to uncertainties in the atomic data and the mean value of \( T_e \) adopted, here we are most concerned with the relative pressures in the different regions.

Another way of estimating the electron pressure in the hole is to use the decrease in the intensity of the Mg X line, allowing for the lower temperature of formation in the hole, and assuming that the relative path lengths outside and inside the hole are proportional to the isothermal scaleheights. The maximum decrease is a factor of 8, compared with the region outside the hole. This gives a maximum pressure reduction of a factor of 2.5 between the deepest region of the hole and the region outside the hole.

### 4.3 Line optical depths

At Sun-centre, lines formed at \( T_e \geq 3 	imes 10^4 \text{ K} \) (except those of He I) have optical depths at line centre which are \( \leq 1 \). As the optical depth at line centre, \( \tau_0 \), depends on \( \int N_e dr \), whereas the emission measure depends on \( \int N_e N_H \text{d}r \) (where \( \text{d}r \) is in the radial direction), \( \tau_0 \) can also be expressed in terms of either the emission measure \( [\text{Em}(0.3)] \) and \( N_e \), or the line intensity and \( N_p \) (see Jordan & Brown 1981). The relation between the intensity of an optically thin line and \( \text{Em}(0.3) \) can be found using the atomic data in CHIANTI. Thus one can write

\[
\tau_0 = F(T_e) \frac{\text{Em}(0.3) T_e}{P_e},
\]

where \( F(T_e) \) contains all the other factors in the standard definition of \( \tau_0 \) for a Doppler broadened line. The optical depths in the radial direction in the mean boundaries and cell interiors at the solar centre have been found from equation (1), using the emission measures and pressures derived in Paper I, assuming that the lines are optically thin. The optical depths in the line of sight at high latitudes can then be estimated using

\[
\tau_0(s) = \tau_0(r) \frac{P_e(s)}{P_e(r)} \sec \theta.
\]

We have shown earlier that the shapes of the emission measure distributions at high latitudes are similar to that at Sun-centre.

Equation (1) cannot be used at high latitudes because the fraction of the photons created in the line which escape in the observed line of sight, \( W_e \), is not known. For a single, effectively thin transition decaying from a particular upper level, \( W_e \) is determined by \( q_0/q_t \), where \( q_0 \) and \( q_t \) are the probability of escape per emission of a photon, in the line of sight and radial direction, respectively (see Jordan 1967 for details).

The N III 991.5-Å lines are found to be optically thin at all locations. The optical depths are largest in the cell boundaries, where the mean value is \( = 0.03 \). The mean optical depths in the cell interiors are at least an order of magnitude smaller. In contrast, the C III 977.0-Å line has a mean optical depth of \( = 1 \) in the boundaries. Thus it is likely that this line is optically thick at least in some parts of the boundaries. This is qualitatively consistent with the variations with solar \( Y \) in the C III 977.0-Å to N III 991.5-Å intensity ratio shown in Fig. 6. Unfortunately, the value of \( P_e \) cannot be determined in the region around solar \( Y = -910^\circ \) (see previous section), so the optical depth cannot be found for this region, where the above ratio indicates an unusually high opacity. The optical depth in the C III 1175-Å lines depends on the variation with \( N_e \) of the \( ^3 \text{P} \) lower level populations. Using typical values of \( N_e \), the optical depth in the line at 1175.7 Å is around a factor of 4 to 9 smaller than in the 977.0-Å line. The lines in the 1175-Å multiplet are then expected to be optically thin in all regions except around solar \( Y = -914^\circ \) to \(-915^\circ \) where the line ratios within the multiplet indicate \( \tau_0 = 1 \) in the 1175.7-Å line (see also Section 5.4.1).

The He II 303.8-Å line is estimated to have an optical depth which is \( = 1 \) in the Sun-centre boundaries (a factor of \( = 10^2 \) larger than that of the N III lines). This implies that the 303.8-Å line will
be optically thick at high latitudes, except in some regions of the cell interiors.

Lines formed below \(3 \times 10^4 \text{K}\) are estimated to be optically thick in boundary regions at Sun-centre (see Paper I). The mean EMD was derived by assuming that only half the photons created escape in the line of sight, and does not take into account the fraction of photons escaping in the observed direction in the various lines. To do so requires radiative transfer calculations in a realistic two-component geometry. For lines which are optically thick on the disc, using the above approach with a plane-parallel geometry will give only approximate results. For the He I 584.3-Å line, the method predicts that \(\tau_0 \geq 10\) in the boundaries and that the line may be optically thin at only a few locations in the cell interior regions. Because the He I 537.0-Å line has an optical depth about a factor of 3 to 4 smaller, this line should also be optically thick except in some cell interior regions (see also Sections 5.1 and 5.3).

The optical depths in the C II 1335.71-Å and Si III 1206.0-Å lines are both estimated to be about an order of magnitude larger than that of the C III 977.0-Å line, so they will be optically thick in the boundaries. This accounts for the lower contrast observed in the former lines compared with that in the C III 977.0-Å line, as is apparent in Fig. 4. The Si II 1190.4-Å line has an optical depth at least a factor of 10 larger than that in the Si III 1206.0-Å line, and is likely to be optically thick at all locations. These estimates are only used to account for the variations in intensities or intensity ratios apparent in Figs 4, 6 and 8.

5 SYSTEMATIC BEHAVIOUR OF THE HELIUM LINES

5.1 Relative fluxes of the He I lines

The higher spectral resolution of the CDS instrument compared with that of the Harvard instrument on Skylab (see Paper I), and the simultaneous measurement of the intensities, allows us to make improved comparisons of the intensity ratio of the He I 537.0- and 584.3-Å lines in the quiet Sun and a coronal hole. However, the ratios derived agree with those found by Vernazza & Reeves (1978) to within the uncertainties in the intensity calibrations of both instruments. Fig. 12 shows the ratio \(I(\text{He I} 537.0 \text{Å})/I(\text{He I} 584.3 \text{Å})\) as a function of solar \(Y\) at three values of solar \(X\), and \(I(\text{He I} 584.3 \text{Å})\) at solar \(X = -0.3\). Averaged over all scans used the ratio is slightly larger within the coronal hole.

![Figure 12](image1.png)

Figure 12. The ratio \(I(\text{He I} 537.0 \text{Å})/I(\text{He I} 584.3 \text{Å})\) as a function of solar \(Y\) at three values of solar \(X\), and \(I(\text{He I} 584.3 \text{Å})\) at solar \(X = -0.3\). Averaged over all scans used the ratio is slightly larger within the coronal hole.

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also predicts a larger ratio (0.134) in the case of zero coronal illumination, thus giving a trend in the direction observed.

5.2 The relative intensities of the He I and He II lines

The ratios of the intensities of the He I 584.3-Å and He II 303.8-Å lines are shown in Fig. 13 at three values of solar X. There are fluctuations in the ratio, and a decrease above the solar limb, which is likely to be caused by the higher opacity of the 584.3-Å line, and/or absorption by the H Lyman α continuum. Otherwise, there are no large differences between the regions inside and outside the coronal hole. Averaged over the six scans used, the mean ratio inside the coronal hole (defined as beginning at solar $Y = -860^0$) is $0.0740 \pm 0.0153$, and is $0.0757 \pm 0.0080$ outside the hole. In all the individual scans the mean ratio inside the hole is very slightly smaller than the mean outside the hole, but the difference is less than the standard deviations. Similarly, neither of the ratios inside or outside the hole are significantly different from the mean value of $0.0740 \pm 0.0083$ found at Sun-centre. Placing the coronal hole boundary at solar $Y = -870^0$ does not cause any significant changes in the above ratios. The near constancy of the ratio $I(\text{He I} 584.3 \text{Å})/I(\text{He II} 303.8 \text{Å})$ in both the quiet Sun and a coronal hole is a new result which must be accounted for by any theory for the formation of the helium lines. The ratios found by Vernazza & Reeves (1978), while broadly similar to those we observe, vary considerably more than the quiet Sun and meet coronal hole and between cell boundaries and interiors within these regions; this could be due to the difference in time between the measurements of the line intensities in the Skylab observations. With a second order calibration factor of 42 for the He II 303.8-Å line, all the above ratios would be increased by a factor of 1.3. [In figs 5 and 6 of Paper I, the ratio $I(\text{He I} 584.3 \text{Å})/I(\text{He II} 303.8 \text{Å})$ was inadvertently plotted using an earlier second-order calibration factor of 25.]

Smith’s (2001) calculations show that the VAL C model overestimates the observed quiet Sun ratio by about a factor of 2.7. His new network model also gives a ratio that is too large, but by a smaller factor of 1.4. Both models predict smaller ratios when the coronal radiation field is set to zero. Details of Smith’s work will be given in a forthcoming paper.

5.3 Helium line enhancement factors

We examine the behaviour of the absolute intensities of the He I 584.3-Å and He II 304-Å lines and their intensities relative to that of the O IV 554-Å lines, in order to investigate the helium line-enhancement factors in the high-latitude regions. The values at solar $X = -0.3^0$ are shown in Fig. 9.

First we consider the absolute intensity in the 584.3-Å line, as measured from the CDS spectra. Compared with the mean value at Sun-centre, the mean intensity outside the hole is a factor of 1.4 larger, while inside the hole ($-860^0$ to $-950^0$), the mean intensity is a factor of 1.5 smaller. Compared with the Sun-centre values, the mean intensity in the boundary regions in the hole is reduced by a smaller factor (around 1.3) than is the mean cell interior intensity (around 1.6). This result does depend on where the hole is defined to begin. If the hole begins at solar $Y = -870^0$ then the mean intensity in the hole is smaller than at Sun-centre by a factor of 1.7, closer to the value of 2 found by Peter (1999). The boundary and cell interior intensities are both smaller by a factor of 1.6. From Fig. 2 the network boundaries are clearly reduced in intensity in the hole, but from the grey-scale used the behaviour in the cell interiors is less obvious. (Note that the regions are defined in the O IV 554-Å lines.) The mean intensities derived show that with the hole beginning at solar $Y = -870^0$, the intensity in the boundaries in the hole is similar to that in the cell interiors outside the hole. The results for the He II 303.8-Å line are the same to within a few per cent.

The He I 584.3-Å line is also observed with SUMER, but the regions observed cannot be assumed to be the same as those observed with CDS. With the hole defined to begin at solar $Y = -860^0$, the mean intensity outside the coronal hole is a factor of 1.3 larger than at Sun-centre, while inside the hole, the mean intensity is a factor of 1.2 smaller than at Sun-centre. The reduction factor inside the hole is sensitive to the defined extent of the hole, and becomes a factor of 1.5 if the hole is defined to begin at solar $Y = -880^0$. In both cases the mean boundary intensities are reduced by more than the cell interior intensities.

The enhancements in the intensities of the helium lines relative to those of the normal transition region lines are now considered. At Sun-centre we found that in the boundary regions the mean emission measure distribution, derived from the normal transition region lines, failed to account for the intensities of the He I 584-Å and He II lines by factors of at least 10 and 13, assuming that all photons created escape outwards in the helium lines, but only half the photons escape outwards in the optically thin transition region lines. We make comparisons with the O IV lines in the CDS spectra and with the N III lines in the SUMER spectra, as these lines appear to remain optically thin in the high latitude spectra (see Sections 3 and 4). As we have shown that the EMDs have a basically similar form as at Sun-centre, the choice of optically thin line is not important.

Given the high opacities of the He I and He II lines, as a first approximation we treat the helium lines as having no limb brightening or darkening (up to solar $Y = -950^0$), but before comparing line ratios we remove the limb-brightening in the lines of O IV and N III (see Fig. 9). This will give lower limits to the enhancement factors by up to the factor of sec θ. Because of the likely photon scattering between the boundaries and cell interiors in the helium lines we compare the ratio of the overall mean values ($I_m$) in each region. At Sun-centre, the ratio $I_m(\text{He I})/I_m(\text{O IV})$ is 2.38. Outside the hole the value is 2.89, while inside the hole the value is 1.90. Thus the enhancement factor for the He I line inside the hole is a factor of 1.3 smaller than at Sun-centre, while outside the hole the enhancement factor is a factor of 1.2 larger than at Sun-centre. The enhancement factors for the He II line are essentially the same as those for the He I line. Thus, although the helium lines are reduced in intensity inside the hole, they are still enhanced relative to the normal transition region lines. The minimum mean enhancement factors for the He I and He II lines are 10 and 13, respectively, compared with the quiet Sun mean values of 13 and 17. If the hole is defined to begin at solar $Y = -870^0$, these factors are the same to two significant figures.

When the boundary and cell interior regions in the hole are considered separately, the enhancement factors are larger in the cell interiors, as found also at Sun-centre. This could be caused by the scattering of photons from the boundaries into the cell interiors, but the difference is not as large as at Sun-centre. A quantitative interpretation of these differences will require two-dimensional radiative transfer.

The enhancement factors in the hole are not as large as the decreases in the mean helium line intensities because the O IV lines are also reduced in the coronal hole by a factor of 1.2 (when the limb-brightening correction is applied). This reduction in the O IV lines occurs predominantly in the boundary regions. Either the
Figure 14. Examples of the He I 584.3 Å line profile as observed in second order with SUMER. From top to bottom, the pairs refer to a boundary outside the hole, a boundary near the edge of the hole, a cell interior and a boundary within the hole. The widths given include correction for the instrumental widths.
limb-brightening correction is too large or there is a small difference in the transition region structure within the coronal hole compared with the quiet Sun. A small reduction in the transition region intensities in coronal holes has been noted in earlier work (see Section 1).

The results using the relative intensities observed with SUMER are affected by the larger proportion of deep cell interior regions in the hole compared with Sun-centre. The \( \text{N} \text{iii} \) mean intensity is lower than at Sun-centre by a factor of 1.2, this being dominated by the cell interior regions. The \( \text{He} \text{i} \) mean intensity is also reduced by a factor of 1.2, which is dominated by the reduction in the boundary regions. Thus the mean enhancement is the same as in the quiet Sun spectra. This result does depend on the definition of the hole location, and with the hole defined to begin at solar \( Y = -880^\circ \), there is a reduction in the enhancement by a factor of 1.1. Because of the smaller SUMER slit width, scattering of photons out of and into the slit will be more important than in the CDS spectra, and the CDS mean results should be more representative.

### 5.4 \( \text{He} \text{i} \) 584.3-Å line profiles

In Paper I we showed typical examples of the \( \text{He} \text{i} \) 584.3-Å line profiles observed with SUMER in second order. These profiles were all essentially Gaussian in shape, apart from the cell interior profile which showed a slight suggestion of self-reversal. The profiles at high latitudes (see Fig. 14) show more cases of deviations from Gaussian profiles with signs of self-reversal as well as asymmetries possibly caused by flows. The profiles at solar \( Y = -860^\circ \) and \(-862^\circ \) are from the strongest part of the boundary which appears in \( \text{He} \text{i} \), but not in the lines of \( \text{C} \text{iii} \) and \( \text{N} \text{iii} \), (see Section 2.1). The line profile at solar \( Y = -860^\circ \) is Gaussian, but other profiles in this region, e.g. that at solar \( Y = -862^\circ \), are self-reversed and asymmetric. The profiles in the boundary at solar \( Y = -875^\circ \) and \(-877^\circ \), near the edge of the hole defined in the \( \text{He} \text{i} \) line, are not fitted well by Gaussians; they show some self-reversal and are broader than average. As discussed in Section 2.1, we suspect that this region is small or short-lived. The third pair of profiles are from a cell interior region (defined in \( \text{N} \text{iii} \)) in the hole at solar \( Y = -891^\circ \) and \(-893^\circ \). These are also not fitted well by Gaussians. This cell interior is the one with a relatively low mean pressure. The fourth pair of profiles are from the region at solar \( Y = -914^\circ \) and \(-915^\circ \) in the hole, which appears as a boundary in \( \text{N} \text{iii} \) but not in \( \text{He} \text{i} \), and where the ratio \( i(\text{C} \text{iii} \) 977.0 Å)/\( i(\text{N} \text{iii} \) 991.5 Å) indicates a high optical depth. These profiles are self reversed and broader than average, consistent with a high opacity. The linewidths (FWHM corrected for the instrumental broadening) are given in Table 7, together with the values for the Sun-centre profiles shown in Paper I. The \( \text{He} \text{i} \) linewidth is on average larger in the coronal hole than at the quiet Sun-centre, and is largest where the intensity of the \( \text{He} \text{i} \) line, relative to that of \( \text{C} \text{iii} \) 1175 Å, is lowest.

Peter (1999) has studied the \( \text{He} \text{i} \) 584-Å line with SUMER over the whole solar disc, including northern and southern coronal holes. We agree with his result that the linewidths are overall larger in the hole than at the quiet Sun-centre. Within the holes he found a systematic increase in the linewidth with increasing intensity. We do not find such regular behaviour, but our sample is much smaller. For example, the linewidths in the cell interior region around solar \( Y = -890^\circ \) to \(-894^\circ \) are comparable to those in the region around solar \( Y = -860^\circ \) where the helium line is strong. The widths in the region around solar \( Y = -914^\circ \), where the helium line is weak, are comparable to those in the boundary around solar \( Y = -875^\circ \). Peter (1999) found that the helium line is relatively blueshifted within the coronal hole, and that these shifts tend to increase as the intensity decreases. We have not investigated absolute wavelength shifts; the relative line positions given in Fig. 14 are similar to each other, except for the boundary region around solar \( Y = -914^\circ \) and \(-915^\circ \), where there is a relative blueshift. Peter (1999) suggests that higher opacities in the coronal hole are the main cause of the trends that he finds. This is consistent with the lower density but larger thickness of the coronal hole transition region, as compared to the quiet solar centre, compounded by the increase in the line-of-sight path length towards the limb. Although different in detail, the linewidths derived support his overall conclusion.

#### 5.4.1 Comparison with the profiles of the \( \text{C} \text{iii} \) lines

The widths of the \( \text{C} \text{iii} \) lines at 977.0, 1174.9 and 1176.4 Å have been measured by fitting Gaussian profiles. Large linewidths can be caused either by high opacities or by large turbulent velocities in the line of sight. In the region outside the hole the largest linewidths in the \( \text{He} \text{i} \) 584.3-Å and \( \text{C} \text{iii} \) 977.0-Å lines occur in the boundary around solar \( Y = 835^\circ \) to \( 841^\circ \). The widths of the lines in the 1175-Å multiplet are also large in this region, but the subsequent line blending prevents accurate measurements of opacity sensitive line ratios. However, since this region has a relatively small \( I(977.0 \text{ Å})/I(991.5 \text{ Å}) \) ratio, a high local opacity could be present as well as high turbulent velocities.

The \( \text{He} \text{i} \) 584.3-Å and \( \text{C} \text{iii} \) 977-Å lines are also broad in the region around solar \( Y = -914^\circ \) to \(-915^\circ \). The ratio \( I(\text{C} \text{iii} 977 \text{ Å})/I(\text{N} \text{iii} 991 \text{ Å}) \) indicates a high opacity in this region (see Section 3.2). However, the lines of \( \text{C} \text{iii} \) at 1174.9 and 1176.4 Å are unusually narrow, which makes line ratios easy to measure. The opacity-sensitive ratio \( I(1175.7 \text{ Å} + 1175.6 \text{ Å})/I(1174.9 \text{ Å}) \) indicates that at least the 1175.7-Å line is optically thick. Thus this region is one with high opacities and small turbulent velocities in the line of sight. Elsewhere, where they can be measured, the line intensity ratios within the \( \text{C} \text{iii} \) 1175-Å multiplet are consistent with low optical depths, so their widths should reflect only non-thermal broadening.

### 6 CONCLUSIONS

The mean properties of the polar coronal hole studied here are...
similar to those found from previous work; the coronal temperature is reduced to \( <9.4 \times 10^5 \) K and \( P_s \) is about a factor of 2 lower than at the quiet Sun-centre. The pressures have been found using the ratio of the \( \text{C} \text{\textsc{iii}} 1175-\text{Å} \) and \( \text{N} \text{\textsc{ii}} 991.5-\text{Å} \) line intensities, as the \( \text{C} \text{\textsc{iii}} 977.0-\text{Å} \) line becomes optically thick in the line of sight in some high-latitude regions. It is difficult to establish the mean pressure in supergranulation cell boundaries within the hole, because the main region in this category appears to be subject to a brightening between adjacent exposures. Although the cell interiors in the hole have pressures which are lower than those at Sun-centre, the two such regions present have very different pressures. The regions classed as ‘intermediate’ between cell boundaries and cell interiors have the lowest pressures. The maximum decrease in the intensity of the Mg x 624.9-Å line gives a maximum pressure reduction of a factor of 2.5, compared with the region outside the hole.

The mean pressure in the region outside the hole is only marginally larger than that within the hole. The cell boundary regions have pressures which are very similar to those at Sun-centre. The main factor contributing to the lower mean pressure, compared with Sun-centre, is the low pressure found for the cell interior region outside the hole. Further studies of other high-latitude regions near coronal holes are required to establish whether the region observed is unusual in this respect.

By examining line ratios we find that there is no systematic variation with position in the relative abundances of silicon (low FIP) and carbon (high FIP). The variations observed are consistent with changes in time as a result of solar rotation.

Improved measurements have been made of the variation of the relative intensities of the \( \text{He} \text{\textsc{i}} 537.0-\text{Å} \) and \( \text{He} \text{\textsc{ii}} 584.3-\text{Å} \) lines between the quiet Sun and a coronal hole. This ratio is about 10 per cent larger within the coronal hole than at Sun-centre, but is the same within quiet Sun and a coronal hole. This ratio is about 10 per cent larger than at Sun-centre. The pressures have been found using the EMD found in Paper I, but the VAL C model predictions of a new network boundary model by Smith (2001), for the boundary regions at Sun-centre agrees well with the results.

A full chromosphere to corona model for a coronal hole is now required.

The relative intensities of the \( \text{He} \text{\textsc{i}} 584.3-\text{Å} \) and \( \text{He} \text{\textsc{ii}} 303.8-\text{Å} \) lines are remarkably similar in all the regions studied. The near constancy of this ratio, and its value, provides a crucial test of any helium line enhancement mechanism. Both the VAL C model and Smith’s new model predict ratios which are factors of 2.7 and 1.4 too large, respectively.

The absolute intensities of all the helium lines are reduced by about a factor of 1.5 to 1.7 within the coronal hole, compared with values at Sun-centre. Taking into account limb brightening in the optically thin transition region lines, in the coronal hole the helium lines are still enhanced with respect to the transition region lines, but by factors which are about 30 per cent smaller than at Sun-centre. The helium line enhancement in the region outside the hole is larger than at Sun-centre, by about 20 per cent.

The intensity of the Mg x line in the hole gives an indication of the minimum reduction in the intensities of lines at shorter wavelengths which can photoionize \( \text{He} \text{\textsc{i}} \) and \( \text{He} \text{\textsc{ii}} \). The observed reduction of a factor of 8 does not appear to cause a significant change in the \( \text{He} \text{\textsc{i}}/\text{He} \text{\textsc{ii}} \) intensity ratio.

All the above parameters and line ratios provide important constraints on models of the helium line formation currently under investigation.

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