HELIO LINE STUDIES USING CDS AND SUMER

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ABSTRACT

Previous studies (Jordan 1975, 1980) have found that the resonance lines of He I and He II appear to have higher fluxes than expected from models made using other transition region lines formed at similar temperatures. The enhancement factor was shown to be less in coronal holes than in the quiet Sun. These results referred to observations made with low spatial resolution. Using the higher spatial resolution provided by the CDS instrument onboard SOHO, we have started a systematic re-examination of the behaviour of the He I and He II line fluxes by examining several quiet Sun regions, from Sun-centre to near the limb, including a coronal hole. While the helium line fluxes are overall relatively lower in the coronal hole, their behaviour in the quiet Sun differs between the supergranular cell boundaries and cell interiors. New simultaneous observations with the SUMER instrument are being used to investigate possible correlations between the electron density, non-thermal velocities and the helium line fluxes. We comment in passing on the necessity of the calibration of the CDS / NIS2 spectra.

Key words: Helium lines, SoHO CDS

1. INTRODUCTION

The purpose of this work is to investigate to what extent models made from collisionally excited transition region lines can reproduce the observed fluxes in the EUV lines of He I and He II. These lines have been studied for many years and observations have shown that they do not behave in a similar way to other chromospheric or transition region lines (Brueckner & Bartoe 1974, Jordan 1975). In particular, using emission measures derived from other collisionally excited transition region lines, Jordan (1975) found that the emission measure distribution failed to account for the He I line by a factor of 15 and for the He II line by about a factor of 8.

Jordan (1975, 1980) suggested that these observations could be explained by some dynamical process which rapidly mixes ions formed at one temperature with higher temperature electrons before ionisation equilibrium is reached. Such a process would affect He lines because of the sensitivity to temperature of the exp(-W/kT_e) term in the collisional excitation rate, W/kT_e, being much higher for these helium lines than for other transition region lines.

Hearn (1969a, 1969b) gave a detailed interpretation of the absolute and relative fluxes of the He I 584.3Å and 537.0Å lines and the He II 303.8Å line based on the early rocket observations of Hinteregger et al. (1965). Using the notation of E(λ) to denote the intensity of a line, wavelength λ, Hinteregger et al. (1965) found that E(537.0)/E(584.3) = 0.128.

In this work, we use the Coronal Diagnostic Spectrometer (CDS) (see Harrison et al. 1995) onboard the Solar and Heliospheric Observatory (SoHO) to re-examine the helium problem using the superior spatial and spectral resolution of the CDS instrument. We have not yet repeated the calculations of Hearn using current atomic data and so comment in detail only on the 537.0Å/584.3Å flux ratio. We also take advantage of the greater spatial resolution of CDS to examine the helium enhancement effect in relation to the supergranular structure.

2. OBSERVATIONS FROM CDS

The CDS observations which we study here have been obtained with the Normal Incidence Spectrometer (NIS) of CDS. Band 2 of the NIS, covering the wavelength range 513 – 633Å allows us to study the He I lines as well as the He II 303.8Å line in second order. The CDS synoptic observation program NISAT provides for full spectral information in a randomly selected 20″ × 20″ area of the solar disk each day. This corresponds to 10 raster positions of the 2″ × 240″ NIS slit.

The data are first debiased, calibrated and then corrected for the spectral slant which is apparent in the NIS full spectra. At a given solar X position, scanning down the 240″ slit in the solar Y direction at the He I 537.0Å and 584.3Å lines shows clearly the close correlation in the behaviour of the two lines. A typical example is shown in Figure 1, with the He I 537.0Å line multiplied by 4 to provide a better scale.
We calculate the ratio \( E(537.0)/E(584.3) \) at each pixel in the slit direction and plot the result as a function of the He I 584.3 Å flux (Figure 2). We note the very small spread in the value of the ratio as well as confirming the trend, first observed by Hearn et al. (1969), that this He I ratio decreases as the He I 584.3 Å flux increases. The scatter in the value of the ratio as we scan through the slit is considerably tighter than the earlier observations, owing to the superior CDS resolution.

Figure 2. The He I ratio calculated at each pixel down the slit in the Solar Y direction. The scatter in the ratio is extremely small although the trend that the ratio should decrease slightly with increasing He I 584.3 Å flux (Hearn et al. 1969) is confirmed.

We repeat the calculation of the mean and variance of the ratio \( E(537.0)/E(584.3) \) over solar Y for each of the 10 solar X positions making up a NISAT raster.

Figure 3 shows the measured \( E(537.0)/E(584.3) \) ratio over the whole raster from the typical CDS NISAT synoptic spectral scan used also in Figure 2. The mean plus variance for each solar X is plotted. It can be seen that the ratio hardly varies over the raster, with an average value over the region of 0.086. This is significantly lower than the expected value of 0.128 given by previous observations (Hinteregger et al. 1965).

We have repeated this calculation for several Quiet Sun NISAT spectral scans and found the same result in all cases, namely that the observed ratio is a factor of \( \approx 35\% \) lower than previous observations would suggest. Given this consistent result, two possible explanations for this are:

- There is an error in the relative calibration of NIS 2.
- Previous rocket observations were at lower spectral resolution (\( \Delta \lambda = 1 \) Å) and so measurements of He I 537.0 Å may have included a blend with the C III and/or O II lines longward of 537 Å, and thus the true \( E(537.0)/E(584.3) \) ratio is lower.

To investigate these possibilities, we have looked at possible tests of the CDS / NIS 2 calibration and these are described in the next section. To investigate the second possibility, we have rebinned the CDS data to simulate the 1 Å resolution available to Hinteregger et al. (1965) and found that this can introduce an error of up to 20% in the measurement of the \( E(537.0)/E(584.3) \) ratio. This partly accounts for the observed discrepancy.

2.1. Tests of the CDS / NIS 2 Calibration

To test the relative calibration of NIS 2, we have concentrated on looking at three O III lines in the NIS 2 range, the \( ^1D \rightarrow ^1D^0 \) transition at 599.6 Å.
the $1D - 1P^0$ transition at 525.8Å and the 597.8Å line given by the $1S - 1P^0$ transition. We compare the observed and calculated line intensity ratios for $E(599.6) / E(525.8)$ and $E(525.8) / E(597.8)$. The latter ratio depends only on ratio of transition probabilities and so in principle is a good way to test the calibration. However, the 597.8Å line is weak and may contain a blend with Ca VIII 597.9Å, thus making it more difficult to observe accurately.

The value of $E(599.6) / E(525.8)$ calculated from the CHIANTI database (Dere et al. 1997) is 2.45, at $T_e = 8 \times 10^5 K$, the peak of the 599.6Å line contribution function, using the 'solar' ion populations of Jordan (1969). The ratio does not depend on $N_e$ at typical quiet Sun densities.

The ratio increases if a lower temperature is used, but using other calculations of the ion populations (eg. Arnaud & Rothenflug 1985) would lead to the 599.6Å line being formed at higher temperatures. Previous observations show that the emission measure does not increase substantially with decreasing temperature (see also Figure 9).

In Figure 4 we show the extracted ratio for 599.6Å / 525.8Å for the same region as Figure 3. The average over the raster is measured as 2.91, a factor of $\approx 20\%$ different from the calculated ratio, with the error in the same sense as for the helium ratio.

For $E(525.8) / E(597.8)$, since the O III 597.8Å line is weak, we have tried to use only data in which the line shows up relatively strongly against the background. Figure 5 shows one such region.

The Ca VIII 597.9Å line is the weakest of the multiplet and should not contribute much to the O III 597.8Å line. We estimate the strength of the Ca VIII line using the branching ratio with Ca VIII 582.8Å. Figure 6 shows the extracted ratio both before and after correction for Ca VIII blending. We measure the ratio only over the 4 points where both the signal-to-noise ratio is over 2 (as shown in Figure 5) and the amount of blending is estimated to be very small. This gives an observed value of $E(525.8) / E(597.8) = 6.58$, which is again about 20% lower than the value of 7.50 calculated from the CHIANTI data.

The A-values in CHIANTI are from Bhatia & Kastner (1993). Similar results were obtained by Aggarwal & Hibbert (1991) and Luo et al. (1989). However, the most recent calculations by Aggarwal et al. (1997) lead to a larger intensity ratio of 8.12.

Our study of the O III ratios thus suggest that there is a relative calibration error of $\approx 1.20$ in the sense that the O III 525.8Å line flux should be increased. This would also indicate that the He I 537.0Å flux should be increased by a similar amount, raising our mean helium ratio to 0.104.

3. HELIUM ENHANCEMENT

The enhancement of the helium lines compared with other transitions region lines can be demonstrated by examining the ratios of various pairs of lines. Figure 7 shows a plot of the absolute flux of the O III 599.6Å line as we scan through the slit in the solar Y direction. This is representative of the 'normal' emission and the supergranulation structure is clearly visible (solid line). For comparison, we overlay a plot of $E(607.6) / E(599.6)$ (dashed line), using the He II 303.8Å resonance line in second order. We see from this that there are many regions of enhanced He II emission. These are anti-correlated with the supergranulation structure, indicating that any enhancement factors are larger in the cell interior than they are in the network boundary. Although this has
been observed previously as a lower network boundary / cell interior contrast in the helium lines than other transition region lines (Brueckner & Bartoe 1974, Reeves 1976), the CDS observations will allow a quantitative analysis.

This lower contrast could occur if the supergranulation boundaries contain structures which are optically thick in the ‘radial’ direction, but have lower optical depth in the direction towards the cell interiors. This would tend to reduce the flux from the boundaries, and if photons were further scattered in the cell interior region, this would enhance the cell interior flux. However, as shown below an enhancement does appear to occur over the boundaries.

Studies of the ratio $E(584.3) / E(607.8)$ show that this varies by about ±24%, while $E(584.3)$ varies by about a factor of 3 (Figure 8). Within this small variation there is a tendency for the ratio to vary with the He I 584.3 Å intensity, suggesting a larger enhancement of He I compared with He II.

We now calculate the helium enhancement factors which are indicated by the CDS observations. Figure 9 plots an emission measure (EM = $fN_eN_H^2$) calculation to show the observed helium enhancements. The mean intensities have been found from five supergranulation cell boundary regions and five cell interior regions. These have been combined using fractional area of 35% for the boundaries and 65% for the cell interiors (Reeves 1976). Although to obtain accurate mean absolute values, a larger sample is required, here we are concerned mainly with relative values. This figure has been constructed using the following data:

He I 584: The emission measures required to account for $E(584.3)$, as found from the work of Hearn (1969a), are $\sim 10^{28}$ cm$^{-5}$, much larger than the mean EM distribution scaled from other main-sequence stars (see Figure 9). Previous work by Jordan et al. (1987) showed that the EM distribution has the same shape in different main-sequence stars. Using more recent models for 4 main-sequence stars (Philippides 1999), an average shape can be found. This average EM distribution is shown in Figure 9, normalised to O IV at log $T_e = 5.2 K$. Using effective collision strengths for $^{1}S$ → $^{1}S$ and $^{1}L$ transitions, and branching ratios from Sawey & Berrington (1993), at $T_e = 3 \times 10^4 K$, and the He I / He fraction from Arnaud & Rothenflug (1985) (which does not include photoionisation and should thus give a maximum value), the EM for the mean $E(584.3)$ is $2.3 \times 10^{27}$ cm$^{-5}$. From Hearn (1969a) one finds that about 40% of the total flux at $T_e = 3 \times 10^4 K$ and $N_e = 2 \times 10^{10}$ cm$^{-3}$ (typical of the quiet Sun) originates from such collisions. Thus the maximum EM could be about $9.2 \times 10^{26}$ cm$^{-5}$. This is still a rough estimate which must be replaced with a full calculation, but is about an order of magnitude larger than the mean EM distribution shown. A helium abundance of $\frac{N_He}{N_H} = 0.098$ was used (Grevesse et al. 1992). It was assumed that the 584.3 Å line is effectively optically thin and that all photons created escaped.

He II 304: The values of $\frac{D_{HeII}}{D_{HeI}}$ were taken from Arnaud & Rothenflug (1985) to give upper limits, since photoionisation of He II would reduce the values in the temperature range of interest. The 2nd order calibration factor is estimated to be 25 - 50 (D. Pike 1997, private communication), and so to minimise the He II emission measure we have adopted the value of 25. We have assumed that all photons created escape. Collision rates from Aggarwal et al. (1992) were adopted, which are slightly lower than those used by Hearn (1969b). Collisions to $n = 3$ were included, but make a contribution of only a few percent.
Figure 8. The solid line shows the behaviour of the He I 584.3 Å line. The dashed line is the ratio of $E(584.3) / E(607.8)$. The variation of this ratio compared to the behaviour of the He I 584.3 Å suggests a larger enhancement of He I compared with He II.

O III 599.6: An oxygen abundance of $\log N_{O} / N_{C} = 8.87$ was used (Grevesse et al. (1992) - the best photospheric value). Effective collision strengths from Aggarwal (1985) were adopted. The ion populations calculated for solar $N_{C}$'s by Jordan (1969) were used. The difference between the O III and He II emission measures would be larger if low $N_{C}$ calculations (e.g. Arnaud & Rothenflug 1985) were used. It is assumed that only half the photons created escape.

O IV 554: The effective collision strengths of Blum & Pradhan (1992) were used - at their highest T of $4 \times 10^4 K$. (The actual values may be larger, so $EM = \int N_{C}N_{H}dh$ will be lower.) It is assumed that only half the photons created escape.

The various assumptions used above, notably that all photons from the helium lines escape as opposed to half for O III and O IV, will all tend to minimise the differences between the emission measure of helium and the other lines. It is clear from this figure that the He I emission measure is enhanced by about an order of magnitude while the He II emission measures lie at least a factor of 4.7 above the mean for the relevant temperatures. These values are consistent with the previous results of Jordan (1975). Using data taken from the SUMER experiment (see Wilhelm et al. 1995) onboard SoHO as well as additional transition region lines within the CDS range, we will be able to determine a fuller emission measure distribution and improve the measurements of helium enhancement. This will be done in later work.

Finally, a qualitative examination of the spatial distribution of the helium lines and the Mg X 625 Å line shows that the helium line enhancements do not always occur in regions where Mg X is strong, suggesting that photoionisation by the coronal radiation field is not the only factor controlling the helium line emission.

Figure 9. This is a plot of EM vs log T (K). The mean emission measure curve is derived from 4 main sequence stars, normalised to the O IV emission at log T = 5.2 K. The He I and He II emission is clearly enhanced over the other ions.

4. DISCUSSION

Our initial studies have provided the following results:

- A small but systematic 20% discrepancy in 3 independent ratios (He I $E(537.0) / E(584.3)$, O III $E(599.6) / E(525.8)$ and $E(525.8) / E(597.8)$) suggests that there is a small error in the relative calibration across the CDS NIS 2 range.

- Simulating the 1Å resolution available to Hinteregger et al. (1965) suggests that this can introduce an error of order 20% in the He I 537.0Å flux due to blending with C III / O II lines longward of 537Å. This could explain the additional factor of 1.2 discrepancy in the He I ratio, suggesting that this ratio has previously been overestimated.

- An initial calculation of emission measures demonstrates significant He I and He II enhancement over the mean distribution, the shape of which is found from typical stellar dwarf emission measure distributions.

- Our studies of the spatial variation of the He II 303.8Å / O III 599.6Å ratio show that the enhancement factor is larger over supergranulation cell interiors than in the network.

- Our studies of coronal holes with CDS have confirmed earlier results (Tousey et al. 1973) that the He enhancement is less in coronal holes.

These results suggest the need for the following aspects to be investigated further:

- Longer exposure observations of the O III 597.8Å and Ca VIII lines to give a better determination of the O III branching ratio, and hence the calibration.
• Analysis of CDS and SUMER data from SOHO JOP 62 to investigate correlations between the electron density, non-thermal velocities and the helium line fluxes, to follow up proposals in Jordan (1980).

• New radiative transfer calculations for the He I and He II lines.

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