ULTRAVIOLET CONTINUUM ABSORPTION ($\lesssim 1000$ Å) ABOVE THE QUIET SUN TRANSITION REGION

G. A. DOSCHEK AND U. FELDMAN

E. O. Hulburt Center for Space Research, Naval Research Laboratory

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ABSTRACT

We investigate Lyman continuum absorption shortward of 912 Å in the quiet Sun solar transition region by combining spectra obtained by NRL and HCO from the Apollo Telescope Mount experiments on Skylab. The most recent atomic data are used to compute line intensities for lines that fall on both sides of the Lyman limit. Lines of O III, O IV, O V, and S IV are considered. The computed intensity ratios of most lines from O IV, O V, and S IV agree with the experimental ratios to within a factor of 2. However, the discrepancies show no apparent wavelength dependence. From this fact, we conclude that at least part of the discrepancy between theory and observation for lines of these ions can be accounted for by uncertainties in instrumental calibration and atomic data. However, difficulties remain in reconciling observation and theory, particularly for lines of O III, and one line of S IV. Some continuum absorption may account for part of the discrepancies. We also discuss the other recent results of Schmahl and Orrall in terms of the newer atomic data.

Subject headings: Sun: atmosphere — Sun: spectra — ultraviolet: spectra

I. INTRODUCTION

In the last several years there has been considerable interest in the structure and energy balance of the solar atmosphere, both from the theoretical and observational point of view (e.g., Feldman, Doschek, and Mariska 1979; Jordan 1980; Raymond and Doyle 1981a). Usually the comparison of observation to theory relies heavily on UV, XUV, and X-ray data obtained from spaceborne instrumentation. In particular, the observational investigation of the transition region of the solar atmosphere ($\approx 2 \times 10^4 - 1.5 \times 10^6$ K) involves the interpretation of XUV and UV emission line intensities and profiles obtained from spectrometers and spectrographs on the Orbiting Solar Observatories (OSO) series of spacecraft, the Skylab Apollo Telescope Mount (ATM), and on rockets (e.g., Brueckner, Bartoe, and VanHoosier 1977). The important emission lines for the transition region fall between 300 and 2000 Å. Most of the spectra used for analyses between 300 and 1340 Å have been recorded by NRL and HCO from the Apollo Telescope Mount (ATM) spectrograph on Skylab. Rocket spectra obtained by Brueckner, Bartoe and VanHoosier (1977) are also available. The wavelength ranges of these instruments were dictated by instrumental capabilities, and not by plasma diagnostic considerations.

Effects due to opacity are usually ignored in the analyses of spectral lines formed in the transition region. However, rather recently Schmahl and Orrall (1979) and Kanno (1979) have reported the surprising result that opacity due to Lyman continuum scattering is significant, even in spectra recorded at Sun center. (Absorption due to hydrogen has been known for some time to be significant outside and near the solar limb [Withbroe 1970].) The possibility of absorption at Sun center was first suggested by Withbroe 1977.) These investigators used OSO and Skylab HCO spectra. Schmahl and Orrall (1979) obtained a mean opacity $\tau_0$ (averaged over several solar spectra of different atmospheric regions) of 4.75 at 912 Å. Kanno (1979) obtained an opacity of about 2 at 912 Å. These opacities, if correct, produce significant decreases in emission line intensities for those lines relatively close to the Lyman edge. There are a number of such lines that are used to construct differential emission measure distributions for the solar atmosphere. For example, if $\tau_0 = 4.8$, then the strong O V resonance line at 629 Å would be attenuated by a factor of 4.83. (The absorption cross section is proportional to $\lambda^3$.) Similarly, the strong O III lines near 703 Å would be attenuated by a factor of 9.0. If such opacities do indeed exist, they must clearly be taken into consideration in constructing atmospheric models.

One possible difficulty with the work of Schmahl and Orrall (1979) and Kanno (1979) is that the atomic data they use are not as accurate as the more recent data now available, or ambiguities exist regarding the temperature of line formation such as for C II in Kanno’s work (see Raymond and Doyle 1981a). We therefore feel that further work on the opacity question is needed. We investigate the opacity problem using the best atomic data available, and observational data from both the NRL and HCO instruments.

Finally, we note that very recently Foukal (1981) has suggested that absorption into the $2p^2 3P$ continuum of...
C i below 1100 Å may also be important in some instances. His work provides a further motivation for the analysis discussed below.

II. ANALYSIS AND DISCUSSION

A good way to approach the opacity problem is to determine the intensity ratios of two lines of a common ion, one line shortward of 912 Å, and one line longward of the Lyman limit. Using lines from a common ion removes uncertainties in elemental abundances and ionization equilibrium distributions, and using lines formed on both sides of the Lyman limit maximizes the sensitivity of a ratio to the opacity effect, because only one line is attenuated. Unfortunately, due to the resolution of the HCO spectrometers and their long wavelength cutoffs, not many such line pairs are available in the HCO spectra.

However, we have found that the NRL and HCO quiet Sun spectra can be combined, and ratios of lines from common ions formed on both sides of the Lyman edge can thereby be obtained. The resonance lines of ions such as O iii, O iv, O v, and S iv fall shortward of 912 Å and are observed by the HCO spectrometer, while intercombination lines of these ions fall in the wavelength range of the NRL Skylab spectrograph. It is possible to combine the data sets because: (1) the N v doublet at 1240 Å is well observed by both instruments, and (2) extensive analysis of the NRL quiet Sun data has shown that ratios of the intercombination lines to the N v lines, such as O iv (λ1401)/N v (λ1240), are nearly the same in all such regions examined. This particular ratio is also about the same in supergranulation cell center regions as in the network, so the different spatial resolutions of the HCO (5° x 5°) and NRL (2° x 60°) instruments do not appear to be a complicating factor in combining the data sets. The spectra are combined by determining the intensity ratios of the intercombination lines to the N v lines using the HCO spectra and then determining the intensities of the intercombination lines for comparison to the resonance lines in the HCO spectra by multiplying these ratios by the observed HCO N v intensities.

The following sources of quiet Sun data are used in our analysis: Vernazza and Reeves (1978, hereafter VR); Feldman, Doschek, and Patterson (1976, hereafter FDP); Doschek et al. (1976, hereafter DFVB); Kjeldseth Moe and Nicolas (1977, hereafter KMN); and Mariska, Feldman, and Doschek (1978, hereafter MFD) (The N v and S iv data for the MFD quiet Sun spectra were not published but are available [Mariska 1980].) In determining intensity ratios of the intercombination lines to the N v lines using the NRL data, we used the calibration described by Nicolas et al. (1977). Intensity ratios determined using this calibration can be as much as about a factor of 2 different from ratios calculated using the calibrations described in the above mentioned papers.

The data given in DFVB, KMN, and MFD are limb spectra. We used only the spectra recorded at +2° and +4° outside the limb for S iv and O iii lines, and spectra recorded at +2°, +4°, and +6° for O iv and O v lines. These are about the heights of peak emission from the lower transition region, and the spectra recorded at these heights are compared to the HCO disk spectra given in VR. The N v lines exhibit negligible opacity effects at the limb (Doschek, Mariska, and Feldman 1981). The spectra discussed in FDP and VR were recorded over network and cell center regions.

Some comment is needed to justify the direct comparison of NRL limb spectra to the HCO disk spectra. We have shown previously (DFVB) that the limb brightening curves are different for transition region lines formed at substantially different temperatures. For example, the ratio of O iii λ1666.15 to the N v lines is about 2.3 times smaller at +8° than the value at +2° or 4°. However, the N v intensity at 8° is only 29% of its value at 2° or 4°. The point is that most of the transition region emission arises at heights between about 2° and 4°, and ratios obtained at these heights are therefore approximately the values that would be obtained on the average in disk spectra. On the disk, λ1666.15 is difficult to measure because of the continuum, λ1406.00 is weak, and λ1218.35 is blended with the wing of Lyman-α; λ1401.16 is a relatively good line. With these latter remarks in mind, note that at —12° in DFVB, the ratios λ1406.16/N v, λ1218.35/N v, λ1406.00/N v and λ1666.15/N v are 1.03, 1.23, 1.08, and 1.48 times their values averaged over 2° and 4°. If the ratios at —12° and —4° are averaged, these factors change to 0.91, 1.31, 0.94, 1.01. Both sets of values are reasonably close to unity, considering the difficulty in measuring some of the lines, which supports the contention that the spectra at +2° and +4° are suitable for comparison to disk spectra. However, optically thick lines must be corrected for such a comparison.

Further support for this claim can be obtained by comparing intensities of lines relative to the λ1238.82 N v line in the cell center and network disk spectra discussed in FDP, with corresponding ratios in DFVB at 2° and 4° outside the limb. The FDP ratio averaged over cell center and network regions, for C iv λ1548.20 to N v λ1238.82, is 14.2 (using the DFVB calibration for the purpose of illustration). The corresponding average of the value at 2° and 4° outside the limb is 11.6, only about 20% smaller than the disk value and within the errors of measurement and intrinsic fluctuations from one region to another. Similarly, the average FDP λ1401.16/λ1238.82 ratio is 0.81, while the corresponding limb value is 0.72, about 12% smaller. Finally, the average FDP Si iv λ1393.76/λ1238.82 ratio is 4.2, while the limb value averaged over 2° and 4° is 5.4, about 1.3 times larger. We have corrected the DFVB Si iv and C iv limb intensities for opacity using Table 3 and equation (4) in Doschek, Mariska, and Feldman (1981). The Si iv and C iv lines are formed at temperatures close to the temperature of formation of O iii, S iv, and O iv. Note that the comparison we have been making would not be valid for lines like C ii λ1334 and λ1335, because the contrast between cell and network regions is much less for very low temperature lines than for the higher temperature lines (Reeves 1976 and FDP).

Intercombination to N v line ratios are given in Table 1 for O v (λ1218.35), O iv (λ1401.16), O iii (λ1666.15),
We have chosen the sum of the two N v lines, in both the NRL and HCO spectra, for calculating ratios. The intensities at +2", +4", and +6" outside the limb in the MFD (DFVB) spectra (Doschek et al. 1976). The use of the other lines in the intercombination line multiplets would not necessarily improve statistics compared to the N v line in quiet Sun disk spectra. Use of the intercombination to allowed lines for common ions are slightly. Use of the other lines in the intercombination line multiplets would not necessarily improve statistics since they are fairly weak. The strongest intercombination line of each multiplet is used in our analysis.

The N v data for the 4" and 6" spectra are not published in FDP. The average ratio from FDP is 0.29. All intensities relative to the sum of the N v lines at 1238.82 Å and 1242.80 Å. Intensities are measured in ergs (not photons). The intensities used to derive these ratios are calculated using the calibration described by Nicolas et al. 1977 (N). The factor, b, is defined as I(N) = b I(DFVB), where I(N) are intensities obtained from the calibration described in N, and I(DFVB) are intensities obtained using the calibration described in DFVB. With this definition, we have b = 2.24 for λ1218 and λ1230, b = 1.07 for λ1401 and λ1406, and b = 0 for λ1666.

The average ratio from FDP is 0.29. The N v data for the 4" and 6" spectra are not published in FDP but are available (Mariska 1980).

<table>
<thead>
<tr>
<th>Source</th>
<th>λ1218.35</th>
<th>λ1401.16</th>
<th>λ1666.15</th>
<th>λ1406.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFVB (+2&quot;)</td>
<td>0.46</td>
<td>0.20</td>
<td>0.29</td>
<td>0.040</td>
</tr>
<tr>
<td>DFVB (+4&quot;)</td>
<td>0.59</td>
<td>0.28</td>
<td>0.27</td>
<td>0.044</td>
</tr>
<tr>
<td>DFVB (+6&quot;)</td>
<td>0.76</td>
<td>0.20</td>
<td>0.26</td>
<td>0.032</td>
</tr>
<tr>
<td>MFD (+2&quot;)</td>
<td>0.54</td>
<td>0.31</td>
<td>0.45</td>
<td>0.052</td>
</tr>
<tr>
<td>MFD (+4&quot;)</td>
<td>0.46</td>
<td>0.26</td>
<td>0.37</td>
<td>0.037</td>
</tr>
<tr>
<td>MFD (+6&quot;)</td>
<td>0.44</td>
<td>0.23</td>
<td>0.37</td>
<td>0.037</td>
</tr>
<tr>
<td>KMN (+2&quot;)</td>
<td>0.42</td>
<td>0.22</td>
<td>0.31</td>
<td>0.040</td>
</tr>
<tr>
<td>KMN (+4&quot;)</td>
<td>0.49</td>
<td>0.22</td>
<td>0.31</td>
<td>0.040</td>
</tr>
<tr>
<td>KMN (+6&quot;)</td>
<td>0.52</td>
<td>0.23</td>
<td>0.37</td>
<td>0.037</td>
</tr>
<tr>
<td>Average</td>
<td>0.52</td>
<td>0.24</td>
<td>0.34</td>
<td>0.043</td>
</tr>
</tbody>
</table>

* Intensities relative to the sum of the N v lines at 1238.82 Å and 1242.80 Å. Intensities are measured in ergs (not photons). The intensities used to derive these ratios are calculated using the calibration described by Nicolas et al. 1977 (N). The factor, b, is defined as I(N) = b I(DFVB), where I(N) are intensities obtained from the calibration described in N, and I(DFVB) are intensities obtained using the calibration described in DFVB. With this definition, we have b = 2.24 for λ1218 and λ1230, b = 1.07 for λ1401 and λ1406, and b = 0 for λ1666.

The theoretical ratios for comparison to the measured ratios are shown in Table 2, for comparison to the experimental values. It is important in interpreting these results to consider separately the results for ions formed at substantially different temperatures, since the opacity might be a function of temperature. Excluding for the moment the O m ratios, and the 1062.67 Å S iv line, the observed ratios for the other lines are larger than the theoretical ratios by about a factor of 2. It is difficult to interpret these differences as due to opacity alone, because there is no wavelength dependent difference. For example, if the factor of 2 difference for the λ1401.16/2554 ratio is interpreted as due...
enormously to opacity, then the opacity at 912 Å would be 2.57; however, the difference between the observed and theoretical (1.401.16/2790 ratio would then be 5.3, instead of 2.1 as observed. Use of the calculations given in Raymond and Doyle (1981b), obtained using a different ionization balance, gives essentially the same results as we have derived. Although all the observed ratios are larger than the calculated ones (again with the exception of the O III ratios), we feel that the differences could be within the calibration errors of the instruments and the uncertainties in the atomic data. Because they are similar and in the same direction, calibration errors seem a likely source of at least part of the discrepancy between observation and theory.

The O III ratios present a special problem. The discrepancy between observation and theory is a factor of 3 for the λ1666.15/λ2703 ratio, but the discrepancy is actually less than 1 (0.65) for the λ1666.15/λ2525.80 ratio. Part of the problem is that the theoretical ratio λ703/λ525.80 is a factor of 4.7 larger than observed. This difference is much larger than expected from inaccuracies in atomic data. However, an explanation in terms of opacity is inconsistent with the other data discussed above, unless it is postulated that the opacity is a function of temperature of line formation. Transition region lines formed at low temperatures are formed somewhat lower in the atmosphere on the average than lines formed at higher temperatures (see Fig. 1 in Feldman, Doschek, and Mariska 1979). A combination of inaccuracies in the atomic data and possible blending of the 525.80 Å line may account for part of the discrepancy, with some opacity accounting for the remainder.

Similarly, the S IV 1062.67 Å line is too intense relative to the 661.42 Å line by a factor of 3.3. In this case, part of the difficulty may lie in the experimental data for the 1062.67 Å line. The line is weak and the region around the line appears rather crowded (see Fig. 1 in VR). Unfortunately, only this one line from the multiplet is apparently unblended in the spectrum.

We have compared some of our atomic data with the data used by Schmahl and Orrall (1979), and we find significant differences in collisional excitation rate coefficients in some cases. The overall result of applying correction factors to their atomic data is to lessen the difference between their derived differential emission measures obtained using lines formed longward or shortward of the Lyman limit. The ratios of rate coefficients calculated using the more recent atomic data to the equivalent rate coefficients used by Schmahl and Orrall (1979) are: 0.25 for S IV (λ661.42), 0.53 for S IV (λ1062.67), 0.54 for O III (λ703), 0.84 for O IV (λ790), 0.50 for O IV (λ554), 0.63 for O V (λ629.73), 0.68 for C III (λ977.02), 1.0 for N V (λ1238.82) and 1.0 for S VI (λ933.38). We used the N V data from van Wyngaarden and Henry (1976) and S VI data from Flower and Nussbaumer (1975). In terms of the differential emission measure, if Schmahl and Orrall (1979) had used our atomic data, their differential emission measures derived for these lines would be changed by factors that are roughly the inverse of the ratios of the rate coefficients given above. For example, their differential emission measure for S IV (λ661.42) would be increased by 1/0.25 = 4. For the quiet Sun, the net attenuation they would derive would be reduced from 6 to about 3.

In summary, factors of about 2 discrepancies in line ratios are found between observation and theory when the HCO and NRL spectra are combined. It seems reasonable to conclude that some of these discrepancies result from remaining inaccuracies in atomic data and in instrumental calibrations, rather than from opacity. This conclusion is based on the apparent lack of a wavelength dependent discrepancy for most of the ratios. For lines formed at the low temperatures of O III, opacity may account for part of the discrepancy, but this conclusion should be regarded with considerable caution. It is nevertheless disturbing that even a discrepancy of a factor of 2 or less still exists for some of the lines. For example, both the atomic data and experimental data are excellent for the λ1218.35/λ629.73 ratio, and furthermore, no internal NRL calibration problem can affect the λ1218.35 to N v ratio in the NRL data because the lines are so close in wavelength. Also, as mentioned, differences in the differential emission measures derived by Schmahl and Orrall (1979) remain even after application of better atomic data. At this stage it is perhaps safest to conclude that any real opacity effects in line intensities are at least a factor of 2 less than reported by Schmahl and Orrall (1979), but some reduction in intensity of lines shortward of 912 Å may occur because of opacity. More work on the problem, both theoretical and experimental, is needed.

We suggest that close coupling calculations of the type carried out by Dufon et al. (1978) be undertaken for the ions O III, O IV, and other important transition region and coronal ions. (Calculations for S IV and Si III are already underway.) Further theoretical work on time-dependent ionization balance in the transition zone is also needed. On the experimental side, it is well worthwhile to consider a possible Shuttle experiment consisting of a spectrometer with sufficient spectral resolution to resolve diagnostically important lines, and with a long wavelength cutoff that is slightly longer than achieved by the HCO Skylab spectrometer. Such an instrument could record the O IV and S IV intercombination lines, and the important Si IV resonance lines, all of which lie very close to 1400 Å. The instrument should also have high spatial resolution, better than 1", since individual transition zone structures are quite small.

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REFERENCES


G. A. DOSCHEK: Code 4170, Naval Research Laboratory, Washington, DC 20375

U. FELDMAN: Code 4174, Naval Research Laboratory, Washington, DC 20375

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