EFFECTS OF LINE BLANKETING ON THE SOLAR WINDOWS

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Abstract. The increasingly high flux predicted to the violet of 4500 Å by many model solar atmospheres stands in contradiction to the observations. Since one possible cause of the disagreement is that the solar 'windows' by which the observed continuum is established might be obscured by line wings, we have made detailed calculations of these narrow spectral regions. With the exception of a few windows affected by the wings of Balmer lines, those redward of the Balmer discontinuity appear free of line blanketing. Even the assumption that the ultraviolet continuum is depressed 5% by unseen lines not included in our calculations leaves substantial disagreements between the models and observations. The discrepancies could perhaps be explained by a veil of weak lines across the ultraviolet spectrum.

Our calculations indicate that the windows become narrower at shorter wavelengths. Many of the ambiguities to the violet of 3600 Å would be resolved if spectrophotometric tracings with a band pass of 10 mÅ were available.

1. Introduction

One of the most remarkable discrepancies between many model solar atmospheres and the observations is the increasingly high flux predicted to the violet of \( \lambda 4500 \) Å. (In the Bilderberg Continuum Atmosphere (GINGERICH and DE JAGER, 1968), this disagreement is less pronounced, but nevertheless present beyond the Balmer discontinuity.) This spectral region is graphed in Figure 1. The observed values quoted by

![Graph showing predicted and observed intensities at the center of the solar disk (\( \lambda \lambda 3100-5400 \) Å).](image)

Fig. 1. Predicted and observed intensities at the center of the solar disk (\( \lambda \lambda 3100-5400 \) Å).


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MINNAERT (1953) are based on a re-evaluation of earlier observations, especially those of CANAVAGGIA et al. (1950). The values of LABS and NECKEL (1962) redwards of 4010 Å are in reasonable agreement with those of Minnaert.

The 'observed' Balmer discontinuity given by Minnaert depends on the values of 3800 Å and 3700 Å, which have been extrapolated on the assumption that the color temperature remains the same between 3700 Å and 5000 Å. If an additional opacity source becomes important around 3900 Å and increases to the violet, then the foregoing assumption is faulty and the observed Balmer discontinuity is only an upper limit. The observations of HOUTGAST (1965) suggest that this might be the case; in this paper we shall investigate the alternative possibility that the observed windows have been depressed by line blanketing.

The models based on empirical $T(\tau)$ relations such as the Mutschlechner model (MÜLLER and MUTSCHLECHNER, 1964), the Utrecht Reference Photosphere (URP) (HEINTZE, HUBENET, and DE JAGER, 1964), and the Bilderberg Continuum Atmosphere (BCA) predict significantly higher intensities in the near ultraviolet than the observed values. Theoretical models driven to radiative equilibrium show similar disagreement with the observations in this wavelength region (GINGERICH, 1966; SWIHART, 1966).

Attempts to reduce the disagreement by changing the model atmospheres have not produced encouraging results. Although an increase in the efficiency of convective energy transport brings the predicted intensities into slightly better agreement, the improvement is inadequate. Furthermore, the URP and BCA models already take into account the convective gradient. While another continuous opacity source in the ultraviolet could reduce the emergent intensities, it would also diminish the size of the Balmer discontinuity in an unacceptable manner. To avoid the ambiguity of the observed Balmer discontinuity, we define a related parameter $I_\lambda(4000)/I_\lambda(3600)$. Table I shows that the predicted discontinuities are already too small.

| TABLE I |
|---|---|
| Observed and predicted log $I_\lambda(4000)/I_\lambda(3600)$ | |
| Observed: | 0.160 | Minnaert |
| | 0.136 | Houtgast |
| Predicted: | 0.117 | Mutschlechner model |
| | 0.100 | Utrecht Reference |
| | 0.093 | Bilderberg Atmosphere |

Finally, non-LTE effects in the major sources of continuous opacity – neutral hydrogen and H$^-$ – do not help. For stars of solar type, departures from LTE in neutral hydrogen lead to an over-population of the $n=3$ level and an under-population of the $n=2$ level (KALKOFEN, 1968). This will lead to an increased flux through the Balmer continuum and to a smaller Balmer discontinuity. Both results will increase the disagreement between theory and observation. Although non-LTE over-population of the bound state of H$^-$ would improve the situation, recent estimates of the col-
lisional cross-section of H\textsuperscript{-} for associative detachment indicate that H\textsuperscript{-} will be in LTE at the continuum-forming depths (Schmeltekopf, Fehrenfeld, and Ferguson, 1967; Dalgarno and Browne, 1967).

Because of the discrepancy between the models and the observations, we have re-examined the observational data. The observed values for the emergent intensity depend, of course, upon isolation of the continuum. The results quoted by Canavaggia et al. (1950) and by Labs and Neckel (1962) were obtained by correcting measurements taken at medium and low resolution for the effects of absorption lines. Houtgast’s (1965) results were obtained at much higher resolution and are believed to represent continuum intensities directly (Houtgast, 1967). Because the absorption lines become more and more crowded violetward of 5000 Å, the possibility arises that at these shorter wavelengths there are no intervals entirely free of the effects of line absorption. If the so-called solar ‘windows’ (Canavaggia and Chalonge, 1946; Canavaggia et al., 1950) used in the determination of the continuum intensities are significantly blanketed by the opacities in the wings of neighboring absorption lines, then the observed continuum will be depressed below the ‘true’ (unblanketed) continuum. Such blanketing could help to explain the discrepancies between the model-atmosphere results and the observations.

2. The Blanketing Calculations

In order to estimate the extent of the line blanketing, we have attempted to calculate the detailed spectrum in the vicinity of the solar windows. We have concentrated our efforts on the windows listed by Canavaggia et al. (1946, 1950), since these have been used most extensively by observers for establishing the level of the continuum. The atmospheric model used in our calculations was the BCA with the adopted microturbulent velocity of 2 km/sec (independent of depth). Goldberg, Müller, and Aller’s (1960) abundances were adopted for the metals. A He/H ratio of 0.10 by number was used. Unless otherwise noted, all results were obtained on the basis of this model. The continuous opacity sources included were neutral hydrogen, H\textsuperscript{-}, H\textsuperscript{+}, electron scattering, Rayleigh scattering, and bound-free transitions of silicon and magnesium. The parameters used for the calculation of the line opacities were taken primarily from the extensive table compiled by Strom and Kurucz (1966). This table provided gf values and excitation potentials for approximately two-thirds of the lines indicated by the Revised Rowland Table (Moore, Minnaert, and Houtgast, 1966) in the vicinity of the windows. With the exception of unidentified weak lines, the remaining third of the lines listed in the Revised Rowland Table fell into two groups. The first and larger group consisted of metallic lines for which no gf values, either theoretical or experimental, are available. The fewer remaining identified lines were due to CN, CH, and NH.

In the case of the metallic lines without gf values, preliminary gf values were assigned. These were subsequently adjusted in a fashion to be described later. Since our computer programs have not yet been adapted for molecular calculations, the
lines of CN, CH, and NH were approximated by artificial lines of C\textsubscript{1} having 7.7 eV excitation potential. Neutral carbon was chosen, since it would represent an upper limit on the abundances of the radicals, and because it has roughly the same mass and therefore, doppler width as CH and NH. The high-excitation potential was chosen to force the line formation down to the large optical depths indicated by the results of COHEN and STROM (1968) and of WITHBROE (1967). Since lines of low-excitation potential can be observed easily in the laboratory, most unidentified lines must be either higher-excitation lines of abundant metals or lines of rare elements. For this reason the unidentified lines in the vicinity of the windows were represented by artificial FeI lines of 3.3 eV excitation potential. We feel that these very crude approximations did not seriously influence the results of the investigation. The artificial lines were not great in number, generally weak in strength, and, in most cases, not close enough to any windows to influence the level of the continuum.

Since the solar windows were chosen far from strong lines, any blanketing should be due to weaker lines in the immediate vicinity of the windows. We have, therefore, attempted to reproduce the detailed spectrum for 1.25 Å on either side of the window wavelengths given by Canavaggia et al. To do this, a list was made containing every line inside a 4-Å interval centered on the window wavelength. At every 0.01 Å in this 4-Å interval, the opacity from each line in the interval was calculated using a Voigt profile and the atomic parameters described above. For the windows redward of the Balmer discontinuity, the opacities from the wings of the nearer hydrogen lines were also calculated. If the opacity due to any line at a particular point exceeded 0.0001 times the local continuous opacity, it was included in the calculation of the total opacity at that point; otherwise, it was neglected. This procedure was repeated at each of the 400 wavelength points for 30 depths in the model atmosphere (from $\tau_{5000} = 10^{-6}$ to $\tau_{5000} = 17.8$). These opacities were then used in an LTE calculation of the emergent intensity $I_x(0,1)$ at every 10 mÅ for the central 2.50 Å of the 4-Å interval.

We then compared the emergent spectrum obtained in this manner with available atlases of the solar spectrum. These were the two unpublished high-dispersion atlases, the McMath-Hulbert Atlas of the Solar Spectrum, and the Atlas of the Solar Spectrum from 3000 to 7500 Å (Delbouille, Neven, and Roland, to be published) as well as the lower dispersion Photometric Atlas of the Near Ultraviolet Solar Spectrum (BRUCKNER, 1960) and the Utrecht Photometric Atlas (MINNAERT, MULDERS, and HOUTGAST, 1940). Since the instrumental profiles were known for the McMath-Hulbert Atlas (GATHIER, 1962), the Brückner Atlas, and the Utrecht Atlas, direct comparisons could be made with these atlases simply by folding the calculated spectra through the instrumental profiles. Comparing the calculated spectra with the observed provided a check on the preliminarily assigned gf values. Whenever the calculated line strengths differed significantly from the observed, the gf values were altered to bring the strengths into better agreement. For the lines from the tabulation by Strom and Kurucz, any changes in gf values found necessary were usually within the tentative error brackets of 0.3 in log gf assigned by them. The spectrum was then recalculated with the new gf values, and another comparison made. Quite reasonable agreement between the observed and
calculated spectra could usually be achieved after three to six trial calculations. Figures 2 and 3 show two examples of solar windows. In these graphs the intensity at the center of the disk has been normalized to the true continuum.

Fig. 2. Computed and observed spectra near the solar window at 3504 Å. The Utrecht Atlas trace is for the integrated disk; the remaining traces represent intensities at the center of the disk.

We wish to note explicitly several interesting results obtained in the process of performing these calculations. In our initial calculations we included no microturbulence in the line broadening. We found that the predicted line profiles were noticeably narrower and deeper than was observed. In subsequent calculations we used the 2 km/sec microturbulent velocity distribution adopted at the Bilderberg Conference. As may be seen from Figures 2 and 3, the line profiles calculated with this velocity distribution are in reasonable agreement with the observed profiles. Additional experimentation showed that a microturbulent velocity distribution that is increasing with depth provides even better agreement when calculated line wings are compared.
Fig. 3. Computed and observed spectra near the solar window at 4000 Å. All traces represent intensities at the center of the disk.

with the observed. However, since there seems to be no firm basis for choosing any particular depth-dependent microturbulent velocity distribution, we have chosen the 2 km/sec distribution for our calculations.

Second, we note that the profiles of lines of moderate equivalent width calculated using the URP $T(\tau)$ relation show prominent central reversals even at the center of the disk. These reversals are not apparent in any of the atlas traces of the lines. The BCA model, with its much broader temperature minimum, predicts no reversals for the lines included in our calculations.

A third point of interest concerns the strengths of the wings of the Balmer lines at the window wavelengths. We used the most recent broadening theory due to GRIEM (1967) in our calculations. The degree of depression of the continuum caused by hydrogen-line blanketing in the BCA is shown in Table II, column two, for those windows that were significantly affected.
TABLE II
Depression of continuum by hydrogen lines

<table>
<thead>
<tr>
<th>Window (Å)</th>
<th>BCA (%)</th>
<th>Mutschlechner (%)</th>
<th>URP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3659</td>
<td>7</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>3665</td>
<td>10</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>3692</td>
<td>12</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>4000</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>4117</td>
<td>&lt; 1</td>
<td>2</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>4365</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>4880</td>
<td>&lt; 1</td>
<td>2</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

It must be stressed that the degree of depression of the continuum is dependent upon the choice of model atmosphere. As shown in columns three and four, both the Mutschlechner and the URP $T(\tau)$ relations predict greater depressions than the BCA. The difference between the BCA and the Mutschlechner models arises because the temperatures where much of the continuum is formed ($\tau_{5000} \approx 1-2$) are higher in the latter model. Hence it might be more appropriate to speak of the increase in the continuum rather than the depression of the hydrogen wings.

3. Conclusions

The windows that we examined were measured by Canavaggia et al. (1946, 1950), and they also correspond to the highest points reported by Houtgast (1965). We have found that the windows redward of the Balmer discontinuity are free of line blanketing, with the exception of those listed in Table II.

In the region to the red of 3900 Å, the McMath-Hulbert Atlas, with its very high resolution, allowed us to compare the calculated and observed spectra with very little difficulty. On the violet side of the discontinuity the situation is slightly ambiguous. The lower dispersion of the available atlases for the ultraviolet made the comparison between predicted and observed spectra troublesome. Only lines that appeared in the atlas traces could be taken into account in the calculations. The low resolution of the available atlases leaves open the possibility that the apparent windows are blanketed by crucially placed, unseen lines of a few milliangstrom equivalent width. Such lines could perhaps introduce as much as 5% ambiguity into the level of the apparent continuum. Within this uncertainty, however, we find that the windows in the ultraviolet are essentially unblanketed by recognized lines.

Even assuming that the continuum is depressed 5% by blanketing in the ultraviolet still leaves a large discrepancy between the models and observations. We feel that we cannot justifiably account for these disagreements on the basis of blanketing from the lines included in our calculations. These results contradict the investigation mentioned by Pecker (in the discussion following Gingerich, 1966). Pecker and Gökdogan found a correlation between abundance and wavelength from a curve-of-growth.
analysis of solar iron lines; this discrepancy could be removed by assuming a higher true continuum (and therefore larger equivalent widths) in the ultraviolet region. However, their indirect procedure was probably biased by systematic normalization errors in the gf values for ultraviolet iron lines.

Although introducing more microturbulence into the models at large depths would put more blanketing opacity into the line wings, enough microturbulence to blanket the windows significantly would grossly distort line profiles that now agree fairly well with the observations.

Both our calculations and the high-dispersion atlases indicate that the windows become narrower at shorter wavelengths. Because the intervals of continuum at shorter wavelengths are so narrow, it is possible that the highest points registered in the Utrecht Atlas are not representative of true continuum, but are depressed by instrumental broadening. If this is the case, then the corrections for blanketing applied by Canavaggia et al. (1950) are not great enough. Since the resolving power of $10^5$ reported by Houtgast (1965) is comparable to that of the Utrecht Atlas, his results may also represent a continuum depressed by instrumental broadening. It appears possible to estimate the importance, if any, of this effect by comparing the blanketing corrections calculated on the basis of the Utrecht Atlas with those obtained from the high-resolution atlases.

The discrepancies could be explained by postulating a veil of weak lines across the ultraviolet spectrum. Since these lines must be very closely spaced to produce the required effect, the veil would act as an additional continuous opacity source similar to bound-free absorption. If the distribution in wavelength of such weak lines resembled the distribution of stronger lines (that, is concentrated toward the violet), it might be possible to circumvent the difficulty mentioned earlier, namely, that an additional opacity source would tend to diminish the $I_\lambda(4000)/I_\lambda(3600)$ ratio.

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**References**


