THE EFFECT OF SILICON AND CARBON OPACITY ON ULTRAVIOLET STELLAR SPECTRA

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Abstract. Silicon and especially carbon bound-free absorptions considerably reduce the emergent flux in the ultraviolet for stars near spectral type A0 ($T_{\mathrm{eff}} = 10000\,\mathrm{K}$). An overabundance of silicon and/or an underabundance of carbon can affect the Balmer discontinuity and the Paschen continuum by a few per cent at most. However, the abundances of these ultraviolet absorbers will have little effect on the temperature distribution calculated for a star if the model is chosen to match the visual spectrum. An examination of the ultraviolet spectrum of Sirius shows that still more opacity is needed; part of this absorption can be supplied by line blanketing.

The importance of bound-free silicon opacity in the ultraviolet spectra of solar-type stars has been appreciated for at least half a dozen years. After the identification in the solar spectrum of the ground-state emission edge by Tousey (1963) and the absorption edge from the first excited level by Gingerich and Rich (1966), computations made at the Smithsonian Astrophysical Observatory predicted that these edges should be visible in hotter stars in spite of the fact that over 99% of the silicon was ionized. Because a negligible amount of the solar flux emerges in the ultraviolet, the silicon absorption has comparatively little effect on the radiation balance. For hotter stars, however, the silicon can play an important role, especially when its abundance is enhanced.

The upper portion of Figure 1 shows the part of the continuous spectrum that can be observed from the ground for a main-sequence A0 star. Two observational parameters are shown: the Balmer discontinuity D_{B} and the slope of the Paschen continuum S_{P}. In spite of the different names attached to these parameters, they are both essentially color indices. In effect, they give us a means of comparing temperatures at different depths in the stellar atmosphere. This can be seen more readily from the lower part of the graph, where we have plotted nonobservable information available from the model-atmosphere calculation. On this graph we have plotted, as a function of wavelength, the relative location of optical depth unity. Where the atmosphere is comparatively transparent (for example, just redward of the Balmer discontinuity), we can see to deep, hot layers. In the more opaque regions (such as just to the violet of the Balmer discontinuity), the radiation arises from the higher, cooler layers. Hence, the Balmer decrement gives information about the temperature difference between a deep layer and a shallow layer in the atmosphere, while the slope of the Paschen continuum measures the relative temperature of an intermediate layer.

In Figure 2, this same graph has been extended into the ultraviolet. When the silicon is increased 10 times over the solar abundance, the augmented ultraviolet opacity raises the depth of formation of the continuum below 1527 Å. Now, in this ultraviolet region the tail of the Planck curve is rising increasingly rapidly with increasing temper-

Houziaux and Butler (eds.), Ultraviolet Stellar Spectra and Ground-Based Observations, 64–70.

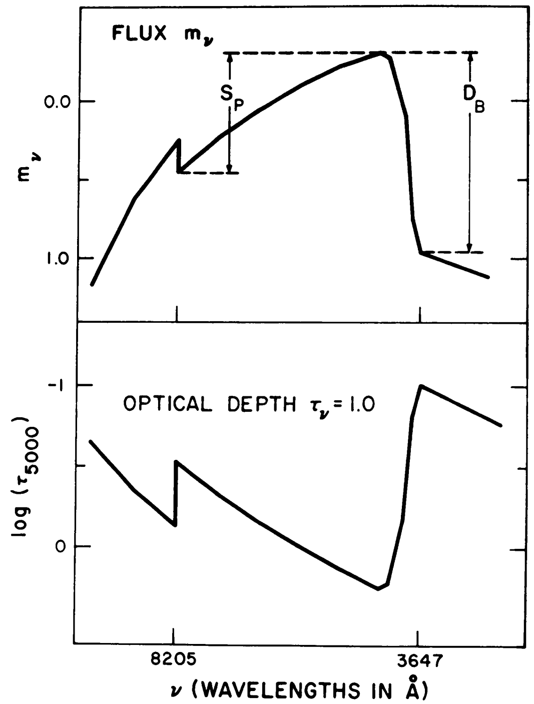

Fig. 1.

ature, and therefore with increasing depth, so that an appreciable fraction of the energy flowing into the outer layers of the atmosphere actually comes from much deeper layers than the optical-depth-unity curve suggests. Increasing the silicon opacity in this part of the ultraviolet effectively blocks this source of energy, and consequently the temperature of the overlying layers must increase in order to maintain the same total flux. With the outermost layers about 200 ° warmer, the temperature difference on the two sides of the Balmer discontinuity becomes less, and the discontinuity, as measured in magnitudes, becomes less negative. This effect from the silicon opacity alone has been discussed by Strom and Strom (1969).

However, when we include bound-free carbon opacity, which is far more important than silicon at these temperatures, the situation is no longer so straightforward. Figure 2 shows how a normal carbon abundance raises the depth of formation of the ultraviolet spectrum below 1239 Å. The opacity from a normal carbon abundance is so severe that in this wavelength region any given atmospheric layer is not much affected by radiation from adjacent layers. For the same reasons as before, the temperature in the outer layers must increase, but this time the effect reaches deeper and the Paschen continuum as well as the Balmer discontinuity will register a change. Even with the carbon abundance reduced to $\frac{1}{10}$ the solar value, it still dominates the ultraviolet opacity, but the effect on the Balmer discontinuity and Paschen continuum is comparable to enhancing the silicon opacity by a factor of 10.

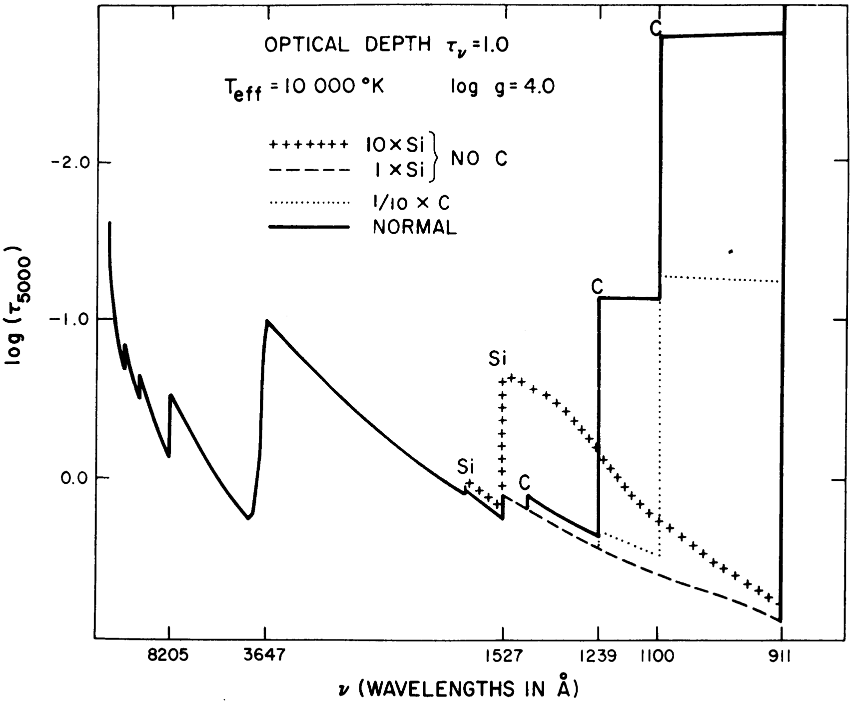

Fig. 2.

The observational effects of including carbon as well as silicon opacity are shown in Figure 3, where the Balmer discontinuity is plotted vs. the slope of the Paschen continuum. In the absence of the carbon opacity, we find the effect reported by the Stroms. When normal carbon is added, the effect of increasing the silicon abundance is halved, so that it becomes only marginally observable. On the basis of these results, we believe that it would be premature to attempt to deduce carbon or silicon abundances from ground-based observations of the continuous spectrum. An additional uncertainty exists on account of the line blocking due to the many strong ultraviolet resonance lines, not included in these models.

On the other hand, the ultraviolet continuum of late B- and A-type stars should be comparatively sensitive to enhanced abundances of silicon or reduced abundances of carbon. Predicted ultraviolet continuum fluxes for several cases are shown in Figure 4. The size of the discontinuity at 1527 Å should provide some indication of any overabundance of silicon, while those at 1100 and 1239 Å could indicate any underabundance of carbon. Notice the enormous change in the flux below 1200 Å in the various models.

We wish to make two separate but intimately related points: (1) If the opacity from a normal carbon abundance is omitted and the model is fitted to the visual continuum, then the total predicted flux would be about 10% too high, which is 250° in effective temperature. (2) Nevertheless, the temperature distribution established by fitting the visual continuum will have only a weak dependence on the detailed choice of the ultraviolet opacities, as we have just shown, and hence abundance analyses based on visual lines will not be critically affected by the amount of carbon or silicon absorption. In other words, *a correct fit of the models in the visual does not necessarily yield the true bolometric correction*; conversely, *a change in the ultraviolet opacities* (and hence in the bolometric correction) *will not vitiate the fit in the visual if the effective temperature is adjusted appropriately.*

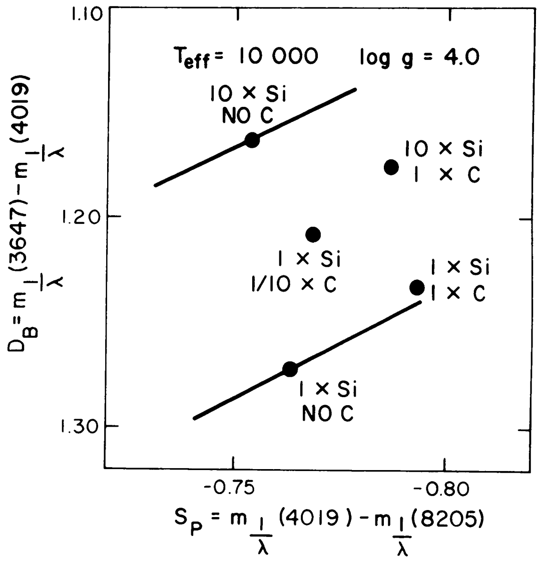

Fig. 3.

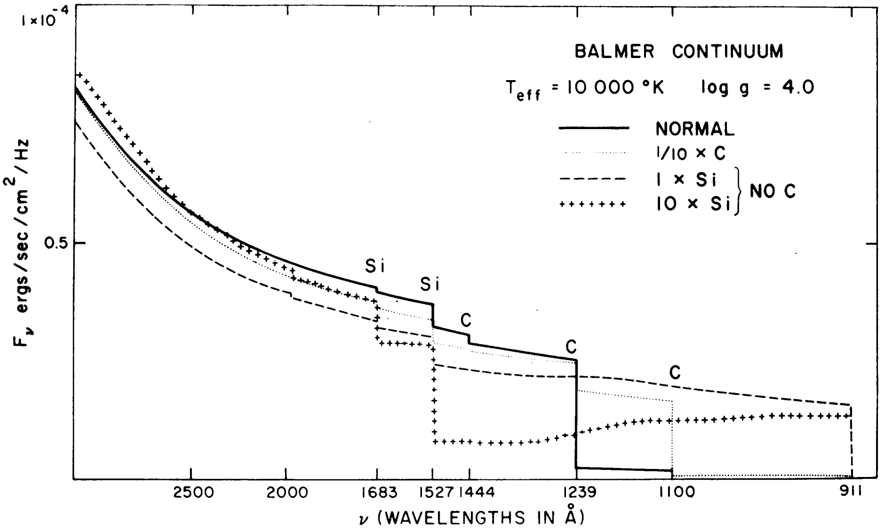

Fig. 4.

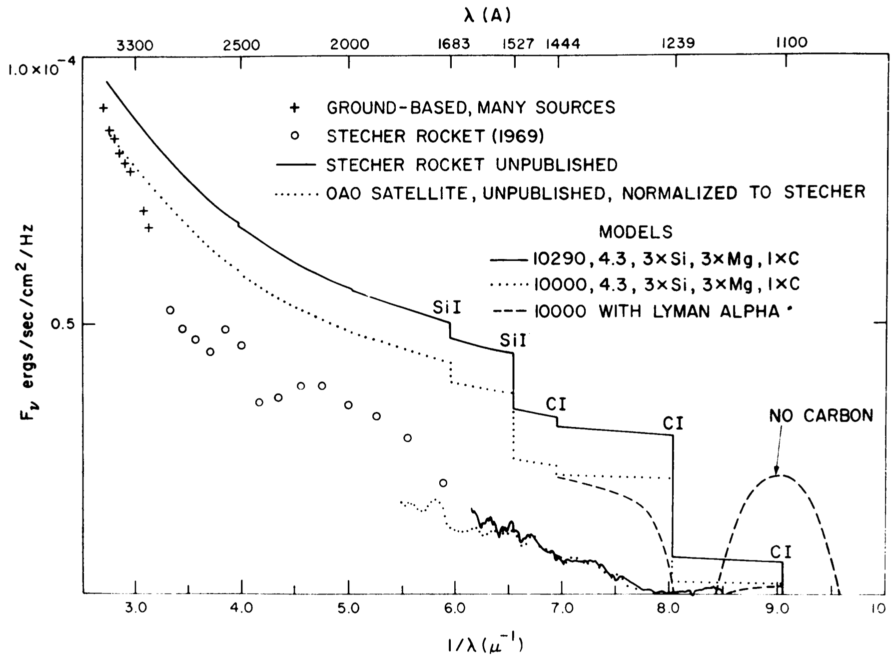

Fig. 5.

We must now inquire to what extent actual observations can be compared against these models. As yet, we have access to comparatively few data, either from direct ultraviolet spectrum scans or from the Celescope experiment. The Celescope filters overlap in just such a way as to make the color index U4-U3 a measure of the flux blocked by the carbon opacity, and U3-U2 a measure of the silicon. However, for the models shown here, the maximum effect on U4-U3 would be about 10%, and on U3-U2, about 30%. Whether the final reductions of the Celescope data will allow us to deduce silicon or carbon abundance differences remains to be seen.

In Figure 5 we compare two models with some recent ultraviolet observations of Sirius. We wish to thank Arthur Code and Theodore Stecher for permission to use some of their data in advance of publication. The slightly enhanced silicon and magnesium abundances of these models have been deduced in Latham's thesis research on the visible spectrum of Sirius. The effective temperatures of the two models differ by only 290°, but at the shortest wavelength this results in a rather dramatic difference in the predicted continuous spectrum. However, the 10000° model is at the cooler limit of matching the visual observations; that is, it just barely matches both the monochromatic surface flux in the visual and the shape of the spectral-energy distribution from 11000 to 3000 Å. A cooler model would require the error of both these observations to exceed 5%. The absolute calibrations of the ground-based observations and Stecher's rocket measurements are independent (Stecher, 1969); but if Stecher's calibration in the middle ultraviolet turns out to be 10 to 20% too low, then the rocket observations would match the ground-based data better at 3000 Å, where the two sets of measurements join. However, the observations would still lie well below the predicted curves throughout the ultraviolet regions. We have adjusted the relative photometry of the Wisconsin Orbiting Astronomical Observatory to match Stecher's curve, but have adjusted his wavelength scale to match the Wisconsin features.

Just longward of the carbon edge at 1239 Å, there are numerous strong resonance lines of C I, Si II, S I, and S II. We have calculated profiles for about 30 of them; we find that many of the equivalent widths exceed 1 Å. In the first 70 Å longward of the carbon edge, our incomplete set of calculations shows that about 50% of the flux would be blocked by resonance lines. Thus, we conclude that the strong bound-free absorption by carbon below 1239 Å is present, but that the sharp absorption edge is entirely smoothed out by lines. On the other hand, we have no explanation for the apparent absence of the silicon edge at 1527 Å. Until many more detailed calculations taking lines into account are available, it will probably be rather difficult to deduce carbon or silicon abundances solely from the approximate level of the far-ultraviolet spectrum.

References

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Stecher, T. P.: 1969, *Astron. J.* **74**, 98.
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Discussion

Stecher: I would believe that hydrogen Lyman-α and Lyman-β would completely obscure the effects of C I since the Lyman lines should be the strongest lines in the spectrum of an A star.

Gingerich: D. Peterson's calculation of the Lyman-α profile, based on the Griem Theory, indicated that carbon would be a much more important cause of opacity since it covers a wider wavelength region. Consequently we identified the Lyman-α core with a smaller feature on your spectrum, and Latham found that a good agreement with individual features of the Wisconsin OAO data could be obtained by sliding your spectrum by 30 Å.

Underhill: It is quite possible that if you included, in a schematic manner, the opacity due to the series of resonance lines approaching the C I and Si I limits you would get a model with the same structure (T, P_e) as for one without lines. This is because the gf value of the lines together is 3 or so times that of the continuum, at least. Your total opacity depends on Ngf and if you increase gf it is not necessary to increase N.

Gingerich: I agree that line blocking can be represented fairly well in a schematic way, as we are doing in the new Smithsonian grid of models. However, if I understand the reason for your remarks, you are suggesting that we use line blocking to replace the extra opacity from the enhanced silicon. This abundance is based on Latham's line analysis in the visual spectrum, not on an attempt to fit the UV. In any event, we need *more* UV opacity, which could be supplied by resonance line blocking.

Praderie: One must stress the urgent need for space ultraviolet observations for late A, F, and G type stars. A proposal for the observation of metallic discontinuities in such stars has been made by Dr. Bonnet and myself as guest observers on the OAO 2. The basis for such a proposal is twofold: firstly to study the variations with temperature and electron pressure of the 2076 Å discontinuity observed by Bonnet (1968, *Ann. Astrophys.* **31**) in the solar spectrum, which is sensitive to temperature as shown from the center to limb variation; secondly to study the variation of the silicon edges at 1520 Å and 1680 Å with spectral type. The magnitude of these predicted discontinuities varies strongly with T_{eff}: at 8000 K, $\log g = 3.9$ and with a normal silicon abundance, $\Delta \log F_\nu =$ 1.26 at 1520 Å and $\Delta \log F_\nu = 0.94$ at 1680 Å. These values should be compared with the values computed by Gingerich for a 10000 K star. Moreover, the ratio of the predicted silicon steps depends on the silicon abundance (Praderie, 1968, Third Harvard Conference).

The aspect of the solar silicon edges cannot be interpreted using a classical radiative equilibrium solar model atmosphere; even with a realistic low chromosphere model, an extra absorber must be invoked to account for the 1680 Å discontinuity. Coming back to the observed ultraviolet spectrum of Sirius, one may wonder if such an absorber is still present, due to the absence of the 1520 Å discontinuity. Considering also that the theoretical flux computed by Gingerich is higher than the one observed, the chosen model for Sirius may be questioned as far as the outer layers are concerned; the log (τ_{5000}) vs. λ curve for $\tau_\lambda = 1$ seems to exclude this possibility for an A0 star. But for late A type stars, the UV spectrum emerges from higher layers than in A0 stars and chromospheres are not improbable. A recent and preliminary result on the K line of γ Boo (A7III), observed at 2.5 Å mm^{-1} by Le Contel and myself, favours a chromospheric temperature rise: the K line shows a small reversal.

Bonnet: I would like to stress that two features observed in the Sirius spectrum do appear also in the solar spectrum:

(1) For wavelength longer than 2000 Å a difference appears between computed and measured value of the intensities the latter lying below the former. This could be due either to a new source of opacity or to crowded absorption lines. This last possibility might be settled easily since many *gf* values are now available and the spectra can be computed taking this effect into account.

(2) The main discontinuities are almost completely absent in the spectra of the sun and Sirius. This might be due either to LTE departures or to the existence of a lower temperature gradient than of the models used in the computations.

Gingerich answers to both Praderie and Bonnet:

Mrs Praderie's calculations remind us of the fact that for F stars the ultraviolet opacity (and hence the depth of formation) varies over a much greater range than for A0, and therefore we have the possibility of constructing empirical temperature distributions for F stars from observed UV intensities, just as we can do for the Sun. On the other hand, at 10000° the 1520 Å Si discontinuity is formed at about the same depth as the Balmer discontinuity, so we cannot introduce a lower temperature gradient to explain the absence of the Si edge in Sirius. Non-LTE will tend to wash out the discontinuities, but I believe that numerous absorption lines may be even more effective.