

## THE VIOLET AND ULTRAVIOLET OPACITY PROBLEM FOR CARBON STARS

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### ABSTRACT

We attack the longstanding problem of the “violet opacity” in cool carbon stars by testing, through synthetic spectra, many new and previously suggested opacity sources, based on currently available model atmospheres for carbon stars and M giant stars. While several bound-free edges of neutral metals are important opacity sources, those of Na I at 2413 Å, Mg I at 2514 Å, and particularly Ca I at 2940 Å are especially significant. Collectively, thousands of atomic lines are important, and the enormous line of Mg I at 2852 Å influences the spectrum well into the visible. The pseudocontinuum of C<sub>3</sub> and the photoionization continuum of CH both play noticeable but secondary roles. Synthetic spectra from the carbon star models with and without polyatomic molecules fit nicely the collected observations of the well-observed carbon star TX Psc.

*Subject headings:* opacities — stars: carbon — stars: individual (TX Psc) — ultraviolet: spectra

### I. INTRODUCTION

Carbon stars are distinguished from K and M giant stars by the appearance in their visual spectra of C<sub>2</sub> bands instead of the usual TiO bands (cf. Cannon 1918; Keenan and Morgan 1941; Alksne and Ikaunieks 1983). An equally characteristic feature is the dramatic decrease in energy flux toward the blue and violet, and the relative faintness of the violet flux is used to classify the R and N stars (cf. Shane 1928). That the flux decreases faster toward shorter wavelengths in carbon stars (especially N type) than in either M giants or blackbodies has led to the idea that the flux is depressed by an unknown source of opacity, and this circumstance is called the “problem of the violet opacity.” Although the passing years have witnessed increasingly accurate measurements of the violet and even the ultraviolet flux, neither a specific agent nor location in the atmosphere has been unambiguously identified as the carrier of the “violet opacity.” In this paper we suggest and test old and new candidates and demonstrate that current theoretical models compare favorably with observation.

The observation that, in stars having strong depressions of the violet flux, absorption lines in the blue and violet spectral regions are weakened or veiled compared to similar lines in the red for both Ca II (Shajn and Struve 1947) and CN (King and Swings 1945; Wing 1967) seems to require the location of at least part of the violet opacity in the stellar photosphere. Another interesting piece of evidence is the presence in spectra of UU Aur and Y CVn of faint violet emission lines from low-excitation levels of Ti I, V I, and Zr I (Gilra 1976) in spite of the flux drop. This observation clearly demonstrates that the violet absorber must be located below the region of the formation of these lines, whether they arise from a chromosphere or a circumstellar gas cloud (Gilra 1976; Johnson and O’Brien 1983).

Some progress in understanding the violet opacity has come with better observations of its wavelength dependence into the far-violet. The strongest bands of the absorber near 4050 Å in Y CVn were identified with the well-known comet bands, due

to C<sub>3</sub>, and C<sub>3</sub> presently remains a candidate for the violet opacity. Furthermore, in the irregularly variable carbon star U Hya the C<sub>3</sub> bands, the Merrill-Sanford bands of SiC<sub>2</sub>, and the violet opacity share the same temperature variation, thus strengthening the idea that C<sub>3</sub> is responsible for (at least part of) the violet opacity (Swings, McKellar, and Rao 1953). In addition, the shape of the absorption expected from C<sub>3</sub> seems roughly to match the observations of the carbon stars Y CVn and U Hya (McKellar and Richardson 1955). However, it is not clear that C<sub>3</sub> absorption can account for the precise amount or shape of the depression in Y CVn revealed by later observations (Johnson, Mitchell, and Latham 1967). Furthermore, depressions of the violet flux similar to, but weaker than, those seen in cool (N type) carbon stars are observed in SC stars (Catchpole and Feast 1971), R stars, and S stars, but it is extremely unlikely that S stars or SC stars, in which C/O < 1 (Wykoff and Clegg 1978; Piccirillo 1980; Smith and Lambert 1985, 1986) can form significant bands of C<sub>3</sub>. The C<sub>3</sub> hypothesis is further tested in this paper.

A second line of reasoning suggests that the violet depression is caused by SiC grains, presumably in a circumstellar shell (Gilra 1973), and this idea received an apparent boost from the discovery of a corresponding emission feature in the 10–13 μm region in several N type stars (Treffers and Cohen 1974; Little-Marenin 1986). As a further test of the SiC hypothesis, equivalent widths and band strengths of SiC<sub>2</sub> (from which SiC condenses) were shown to be correlated with B–V colors (which indicate the degree of violet flux depression) for 40 southern carbon stars (Walker 1976), whereas no correlation was found between C<sub>2</sub> band strengths and B–V. However, far-violet spectrophotometry of several carbon stars seems to show, in four of six stars (Bregman and Bregman 1978), and two of two additional stars (Gunn and Stryker 1983), a slight upturn in flux shortward of 3800 Å, which requires an opacity decreasing with decreasing wavelength. This observation strongly contradicts the SiC hypothesis since SiC absorption must remain approximately constant toward shorter wavelengths; the C<sub>3</sub> hypothesis, however, is in accord with these observations. In the other two stars (both long-period variable stars) no upturn was seen, and the authors speculate that SiC may exist there (Bregman and Bregman 1978).

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In an entirely new approach to the problem, the Balmer decrement has been observed at several phases in the long-period variable carbon stars U Cyg, R CMi, SS Vir, and V CrB (Orlati 1987). Some information about the location in height of the violet opacity can be determined from the epochs of change of the decrement as the shock wave progresses outward through the stellar photosphere, chromosphere, and circumstellar region. Somewhat surprisingly, the changes occur rather deep in the photosphere, from which the authors conclude that the opacity source is definitely not grains in an outer layer and not molecules. However, no further identification can be made.

Intermediate-band photometry in the violet has recently been secured for 16 carbon stars and combined with infrared photometry taken both from the ground and by *IRAS* (Faulkner, Honeycutt, and Johnson 1988). Used with *IUE* data available for a few of these stars, these results provide a greatly increased short-wavelength baseline over which to investigate the shape of the energy flux curve. One of the more interesting results of this study is a clear lack of correlation between the emission at 11.5  $\mu\text{m}$ , presumably due to SiC grains, and the absorption in the violet. Wherever the location of the grains, this lack of correlation—in some cases the absorption is stronger, while in other cases the emission is stronger—greatly undermines the case for SiC grains, for which one must expect a strong correlation in the usual scenario (Gilra 1976). Apparently the hypothesis of SiC grain as the principal source of the violet opacity must be abandoned.

Recently, the opacity from the photodissociation of the CH molecule has been suggested as the violet opacity source in cool carbon stars (Tarafdar, van Dishoeck, and Kurucz 1987). The cross sections from this continuous opacity show a local maximum near 3800  $\text{\AA}$ , and this process is significant to the continuous opacity for a solar model (Kurucz, van Dishoeck, and Tarafdar 1987). We test this suggestion later.

In this paper, we calculate synthetic spectra from the ultraviolet through the visible spectral regions from available model atmospheres of carbon stars (reviewed, e.g., by Johnson 1986), and compare these spectra directly with observations of N type carbon stars to test the effect of a variety of photospheric opacities. In this way, we hope both to (1) identify the elusive opacity source and (2) test our present ability to match by spectral synthesis the observed violet and ultraviolet spectra.

In § II we discuss the technique used to calculate the synthetic spectra. Section III describes the strong influence of the bound-free and bound-bound opacities of neutral metals including the enormous line of Mg I at 2852  $\text{\AA}$ . Section IV describes the effect of molecular opacities—specifically, the  $\text{C}_3$  pseudocontinuum and the CH photodissociation continuum—on the flux calculation. Section V contains conclusions and discussion.

## II. SYNTHETIC SPECTRA

Synthetic spectra are calculated from previously converged model photospheres. These atmospheres, called henceforth the “Indiana” models, were constructed with the assumptions of hydrostatic equilibrium, energy flux constancy (with energy transport by both radiation and convection), and local thermodynamic equilibrium (LTE) in a plane-parallel, horizontally homogeneous, medium. Opacities include the relevant diatomic molecular and atomic lines, all treated by opacity sampling (Peytremann 1974; Sneden, Johnson, and Krupp 1976; Carbon 1984; Ekberg, Eriksson, and Gustafsson 1986). For carbon-star calculations, lines from the diatomic species

CN, CH,  $\text{C}_2$ , CO, NH, and MgH are included. For M star calculations, TiO and  $\text{H}_2\text{O}$  (the latter treated as a straight mean) replace  $\text{C}_2$ . A complete description of the models has already been given (Johnson, Bernat, and Krupp 1980; Johnson 1982).

Using the ATLAS6 model atmosphere code (Kurucz 1970; Johnson, Bernat, and Krupp 1980) with further improvements made for the synthetic flux calculation (i.e., a better treatment of strong atomic lines and the inclusion of additional opacities), we have computed synthetic spectra in the same geometry and with the same assumptions. Specifically, we use LTE to mean that all distribution functions have their equilibrium values and the monochromatic source function ( $S_\nu$ ) is described by

$$S = \frac{\kappa_\nu B_\nu + \sigma_\nu J_\nu}{\kappa_\nu + \sigma_\nu}, \quad (1)$$

where  $\kappa_\nu$  and  $\sigma_\nu$  are the absorption and scattering opacities, respectively;  $B_\nu$  is the Planck function; and  $J_\nu$  is the mean intensity. Solar abundances (Grevesse 1984) are assumed for all chemical elements except carbon, which is increased to give the desired carbon-to-oxygen ratio (C/O). Because the synthetic spectra reported here represent preliminary attempts to generate spectra for cool giants and supergiants, we make the approximation of pure absorption in the atomic and molecular lines for photospheric models.

Continuous opacity calculations include bound-free and free-free absorption H I,  $\text{H}_2$ , and  $\text{H}^-$ ; free-free absorption of  $\text{He}^-$ ; Rayleigh scattering of H I, He I, and  $\text{H}_2$ , and electron scattering (Kurucz 1970). Continuous opacities include bound-free opacities from eight levels of C I, Mg I, Al I, and Si I, 15 levels of Fe I (Vernazza, Avrett, and Loeser 1980), and eight levels of Na I and Ca I (E. H. Avrett 1987, private communication). Opacities of spectral lines are calculated with the opacity sampling technique. Molecular data are given by Johnson, Bernat, and Krupp (1980) and Johnson (1982), with recent additions and improvements. In particular, the effects of several new sources of opacity are tested.

The spectral calculations are made with a 12,912 frequency-point grid ranging from  $4.55 \times 10^4 \text{ cm}^{-1}$  ( $\sim 2200 \text{ \AA}$ ) to  $1.43 \times 10^3 \text{ cm}^{-1}$  ( $\sim 70,000 \text{ \AA}$ ) with a spacing of  $5 \text{ cm}^{-1}$  in the infrared and red portion of the spectrum and of  $2.5 \text{ cm}^{-1}$  ( $\sim 0.225 \text{ \AA}$ ) in the violet and ultraviolet regimes. For each frequency point, atomic lines within  $10 \text{ cm}^{-1}$  and molecular lines within four Doppler widths are included in the opacity calculation. Atomic absorption coefficients are assumed to be Voigt functions with the damping constant equal to the sum of 3 times the classical radiation damping constant and the van der Waals collisional damping parameter (Unsöld 1955). The Doppler parameter in the Voigt function includes a micro-turbulent velocity of  $5 \text{ km s}^{-1}$  at all depths for all models reported here. Molecular lines are assumed to have pure Doppler broadening.

The focus of this paper is the investigation of the synthetic flux from a model photosphere representing the N0 carbon star TX Psc (N0; C6, 2). We have chosen this star since considerable photometry has been published, it has a measured angular diameter ( $9.31 \pm 0.75 \text{ mas}$ ) from lunar occultation (Ridgway, Wells, and Joyce 1977), and its composition is known (Lambert *et al.* 1986). Table 1 lists the photometric and spectral observations of this star, and Figure 1 displays this data.

TABLE 1  
TX PISCUM OBSERVATIONS

Wavelength Range (Å)	Spectral Resolution (Å)	Reference
2600–3200 .....	50 (integrated flux)	<i>IUE</i> low-resolution spectra
3400–4520 .....	~100	Faulkner, Honeycutt, and Johnson 1988
3450–10620 .....	20 ( $\lambda < 6000$ Å)	Fay and Honeycutt 1972
	40 ( $\lambda > 6000$ Å)	
3600–34000 .....	~1000 ( <i>UBV</i> broad-band filters)	Mendoza and Johnson 1965
4290–4900 .....	2.3	E. M. Schlegel and R. K. Honeycutt 1987; private communication
4700–9800 .....	20	Cochran 1980
7810–10980 .....	30	Wing 1967

Initial calculations of the synthetic spectrum for the model photosphere of this star [3000/0/1.05 in the format  $T_{\text{eff}}/\log g/(C/O)$ ] demonstrated the importance of the opacity of the resonance transitions of neutral metals. To include the effect of the entire line wings of these strong lines, it was necessary to increase the opacity sampling window by a factor of 500 (a factor of 1500 for the Mg I line at 2852 Å). Strong atomic lines which are treated separately from the regular list include the following multiplets: Na I (V 1); Mg I (UV 1), (V 2); Mg II (UV 1); Al I (V 1); Ca I (V 2); Ca II (V 1); Cr I (V 1), (V 4); Mn I (V 2); Fe I (V 4), (V 5), (V 6), (V 9), (V 10), (UV 2), (UV 5); and Fe II (UV 1), (UV 2), (UV 3), (UV 4), (UV 60), (UV 61), (UV 62), and (UV 63). For these explicitly calculated lines, we set the radiation damping constant equal to the sum of the Einstein  $A$ -values of the transitions out of the common upper level.

The large extent of these explicit line wings may bring into question the validity of the impact approximation for collisional damping in the wings, which is assumed in the Voigt function. Table 2 lists the critical wavelength for the validity criterion of the impact approximation for van der Waals interactions of the resonance transition of Mg I at the listed depths of the model photosphere via

$$\Delta\lambda_c = \frac{\lambda^2}{c} \left( \frac{v}{2\pi} \right)^{6/5} C_6^{-1/5}, \quad (2)$$

where  $C_6$  is the van der Waals constant (Unsöld 1955) and  $v$  is the relative velocity of the radiating atom with respect to the perturbing hydrogen atoms. The impact approximation (eq. [3]) is valid when  $\Delta\lambda \ll \Delta\lambda_c$  and the quasi-static approx-

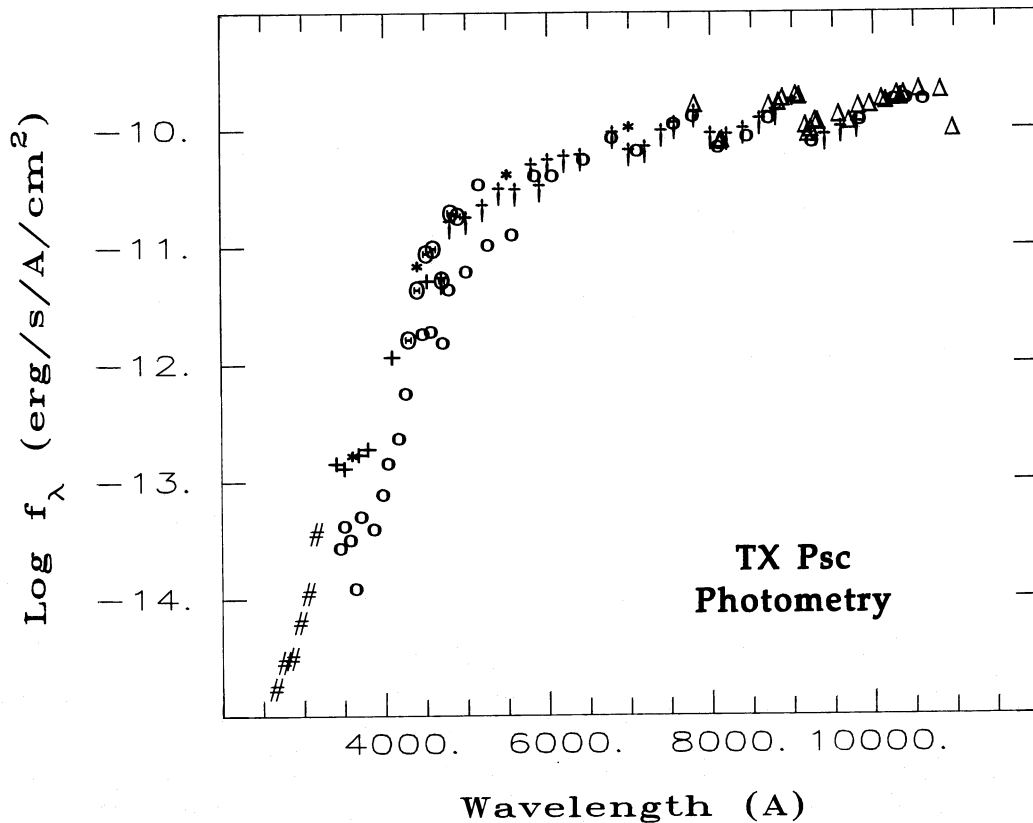


FIG. 1.—Photometric and spectral observations of TX Psc from 2000 Å to 12,000 Å. Symbols plotted: *number signs*, *IUE* low-resolution spectra; *open circles*, Fay and Honeycutt; *plus signs*, Faulkner, Honeycutt, and Johnson; *asterisks*, Mendoza and Johnson; *upper case thetas*, Schlegel and Honeycutt; *crosses*, Cochran; and *open triangles*, Wing. Characteristics of and references for the observations are listed in Table 1.

TABLE 2  
Mg I RESONANCE LINE BROADENING

A.					
Depth	Temperature (K)	Column Density (g cm <sup>-2</sup> )	$\Delta\lambda_c$ (Å) <sup>a</sup>	$N_H$ (cm <sup>-3</sup> )	$N_e$ (cm <sup>-3</sup> )
5.....	1215	0.0001	3.21	$1.4 \times 10^7$	$7.7 \times 10^1$
10.....	1225	0.029	3.23	$2.9 \times 10^8$	$2.3 \times 10^3$
15.....	1237	0.27	3.25	$1.1 \times 10^9$	$3.3 \times 10^3$
20.....	1256	0.83	3.28	$2.6 \times 10^9$	$2.1 \times 10^4$
25.....	1283	2.4	3.32	$6.8 \times 10^9$	$5.4 \times 10^4$
30.....	1402	22.0	3.50	$1.1 \times 10^{11}$	$8.9 \times 10^5$
35.....	1757	170.0	4.00	$1.2 \times 10^{13}$	$8.0 \times 10^7$
40.....	2060	340.0	4.41	$1.3 \times 10^{14}$	$6.0 \times 10^8$
45.....	2407	560.0	4.84	$7.5 \times 10^{14}$	$3.4 \times 10^9$
50.....	2886	880.0	5.40	$1.9 \times 10^{15}$	$1.1 \times 10^{10}$
55.....	3724	1600.0	6.29	$2.8 \times 10^{15}$	$1.1 \times 10^{11}$
60.....	5907	2800.0	8.30	$3.1 \times 10^{15}$	$3.3 \times 10^{12}$

B.				
$\Delta\lambda$ (Å) <sup>b</sup>	Formation <sup>c</sup> Depth	$\phi_c/\phi_R$ <sup>d</sup>	$\kappa_i/\kappa_T$ <sup>e</sup>	$C_{ji}/A_{ji}$ <sup>f</sup>
0.....	4	$1.9 \times 10^{-10}$	1.00	$8.6 \times 10^{-16}$
2.....	12	$1.9 \times 10^{-8}$	1.00	$2.4 \times 10^{-13}$
5.....	17	$6.4 \times 10^{-8}$	1.00	$8.0 \times 10^{-13}$
10.....	24	$3.2 \times 10^{-7}$	1.00	$2.9 \times 10^{-12}$
20.....	28	$2.0 \times 10^{-6}$	0.98	$1.3 \times 10^{-11}$
50.....	31	$3.7 \times 10^{-5}$	0.89	$1.5 \times 10^{-10}$
100.....	34	$1.1 \times 10^{-3}$	0.70	$3.0 \times 10^{-9}$
200.....	37	0.010	0.42	$1.4 \times 10^{-8}$
300.....	41	0.068	0.26	$6.9 \times 10^{-8}$
400.....	42	0.11	0.19	$1.0 \times 10^{-7}$
500.....	44	0.24	0.12	$2.0 \times 10^{-7}$
600.....	45	0.34	0.10	$2.6 \times 10^{-7}$
700.....	46	0.47	0.08	$3.4 \times 10^{-7}$

<sup>a</sup> Validity criterion of impact/quasi-static approximation (eq. [2]).

<sup>b</sup> Line center at  $\lambda_{vac} = 2852.958$  Å.

<sup>c</sup> Depth in the model atmosphere where  $\tau_v \approx 1$ .

<sup>d</sup> Ratio of collisional (neutral hydrogen perturbers) to radiative damping;  $\phi_c$  is calculated with eq. (3) when  $\Delta\lambda < \Delta\lambda_c$  or by eq. (4) when  $\Delta\lambda > \Delta\lambda_c$ .  $\phi_R$  is calculated with eq. (5).

<sup>e</sup> Ratio of Mg I (2852 Å) line opacity to Mg I line plus continuous opacity.

<sup>f</sup> Ratio of the collisional transition rate (electron perturbers) to the Einstein spontaneous-emission rate of Mg I (2852 Å).

imation (eq. [4]) is valid when  $\Delta\lambda \gg \Delta\lambda_c$  (Margenau 1935). Table 2 also lists the relative importance of the radiative ( $\phi_R$ ) and collisional ( $\phi_c$ : impact and/or quasi-static where appropriate) damping to the line opacity at selected wavelengths via

$$\phi_c = \frac{\Gamma_I/4\pi^2}{(v - v_0)^2 + (\Gamma_I/4\pi)^2} \quad (\Delta\lambda < \Delta\lambda_c) \quad (3)$$

and

$$\phi_c = \frac{\Gamma_{QS}}{(v - v_0)^{3/2}} \exp\left[\frac{-\pi\Gamma_{QS}^2}{(v - v_0)}\right] \quad (\Delta\lambda > \Delta\lambda_c, \lambda > \lambda_0) \quad (4)$$

$$\phi_R = \frac{\Gamma_R/4\pi^2}{(v - v_0)^2 + (\Gamma_R/4\pi)^2}, \quad (5)$$

where

$$\Gamma_I = 17C_6^{0.4}v^{0.6}N_H, \quad \Gamma_{QS} = 2\pi N_H C_6^{0.5}, \quad \Gamma_R = \sum_{i < j} A_{ji},$$

and  $N_H$  is the density of H I.

Table 2 clearly shows that the density is low enough throughout this model that collisional processes are unimportant in the shape of the line profile (as should be expected for a

resonance line) except for the extreme line wings where the quasi-static approximation for collisional broadening must be used in the convolution with radiative damping (see eq. [18] of Margenau 1935). This indicates our assumption of pure absorption is not valid for these strong lines as noted by the depth of formation (i.e.,  $\tau_v \approx 1$ ) of the line profile at the wavelengths listed in Table 2. The strength of these lines will be diminished when  $S_l = J_v$  since  $J_v \approx B_v(T_{rad} \approx T_{eff}) > B_v(T_e)$  for depths where the line is formed (see Table 2). Since the extreme line wings are formed at layers where  $J_v$  begins to approach  $B_v(T_e)$ , the opacity from the extreme wings will not be altered by a great amount.

A second question arises of the validity of the radiative part of the Voigt function (i.e., eq. [5]) at wavelengths far from line center. In this domain (i.e.,  $\lambda \gg \lambda_0$ ) the radiative line opacity becomes Rayleigh scattering. The uncertainty in the underlying physics of strong neutral metal lines in these cool stellar atmospheres would make a careful quantum-mechanical treatment of the absorption coefficient far from line center valuable.

### III. THE ROLE OF NEUTRAL METAL OPACITIES

The cool extended atmospheres of carbon stars open a new arena of stellar atmospheric research. Table 2 demonstrates

that electron collisions are negligible compared to neutral hydrogen collisions ( $C_{ji}/A_{ji}$  is small compared to  $\phi_c/\phi_R$ ). The electron population is determined mainly by carbon, sodium, magnesium, aluminum, silicon, potassium, calcium, and iron. Nearly all the electrons of these neutral metals are in the ground state and low-lying metastable states, and as such, bound-free opacities from these states should have a large effect on the continuous flux in the violet and ultraviolet regions. By the same argument, Bound-bound transitions from these same states should also be strong.

In a calculation of ultraviolet spectra, we found that, in a model with effective temperature of 3000 K, the long-wavelength wing of the enormous Mg I resonance line at 2852 Å dominates the continuous opacity at 4000 Å! The short-wavelength wing of the Mg I line has far less influence of course, because of the lack of photospheric flux in this spectral region and especially because of the overlying chromospheric emission lines of Mg II and Fe II which dominate the spectrum for wavelengths less than 2850 Å. Figure 2 illustrates the effects of various opacities on the emergent flux and compares them to the photometry of Figure 1 including additional photometry (50 Å resolution) from a low-resolution IUE spectrum of TX Psc in the 2200–3400 Å region (Johnson and Luttermoser 1987). Synthetic spectrum A displays a flux curve calculated with the model atmosphere and bound-free and free-free opacities of hydrogen and helium and electron scattering described in § II. Synthetic spectrum B includes all the opacities in A plus the bound-free opacities of the seven neutral metals described

in § II. Spectrum C adds the Mg I resonance line to the opacities of spectrum B. This calculation was carried out with a microturbulent velocity of 5 km s<sup>-1</sup>. However, since radiative damping dominates, this value is unimportant, and lowering it to 2 km s<sup>-1</sup> has no effect on such strong lines. These synthetic spectra are all normalized to the angular diameter of TX Psc. Figure 3 displays spectrum B as a brightness temperature and labels the prominent bound-free edges.

There are several significant observations to be made from Figures 2 and 3.

1. Three bound-free opacities play major roles in the continuum in the long-wavelength range of IUE: the ground state of neutral sodium ( $3s^2S$ ) at 2413 Å; the metastable state of neutral magnesium ( $3p^3P^0$ ) at 2514 Å; and the metastable state of neutral calcium ( $4p^3P^0$ ) at 2940 Å. Four additional neutral metal bound-free opacities between 3400 Å and 4200 Å are significant to the continuous flux (Fig. 3) although they do not dominate the total opacity. However, increasing the bound-free opacity of the Na I  $3p^2P^0$  (upper level of Na I D lines) by a factor of 10, decreases the flux at the 4085 Å absorption edge by a factor of 5. If non-LTE effects or resonance-line saturation can overpopulate this level (and the similar levels of Mg I  $3p^1P^0$  at 3757 Å and of Ca I  $4p^1P^0$  at 3899 Å) for the extended cool atmospheres of the carbon stars, the flux will fall off even faster shortward of 4100 Å.

2. The Mg I (2852 Å) redward line wing effects the continuum over 1500 Å from line center in this pure absorption calculation.

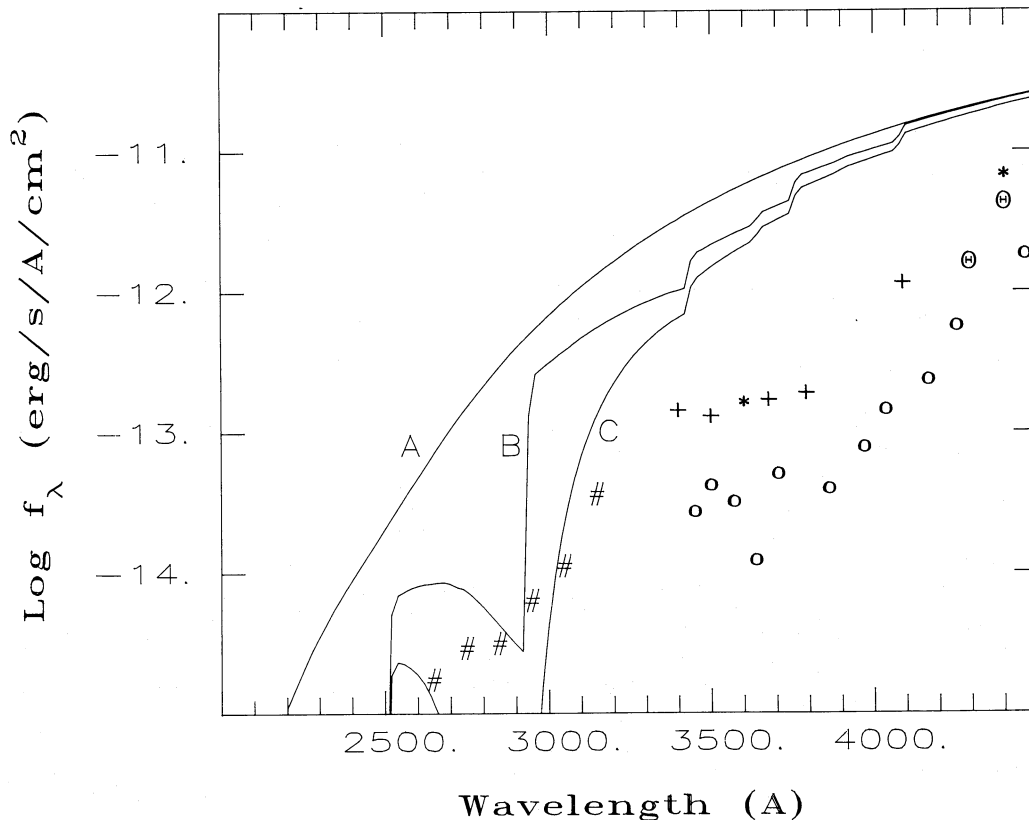


FIG. 2.—Synthetic spectra are compared to the photometric observations of Fig. 1. Synthetic spectrum A shows a flux calculated with the various H and He bound-free and free-free opacities and continuous scattering. Spectrum B also includes neutral metal bound-free opacities. Spectrum C includes the Mg I resonance line at 2852 Å in the flux calculation of B. All synthetic spectra have been calibrated to the angular diameter of TX Psc (0'00931).

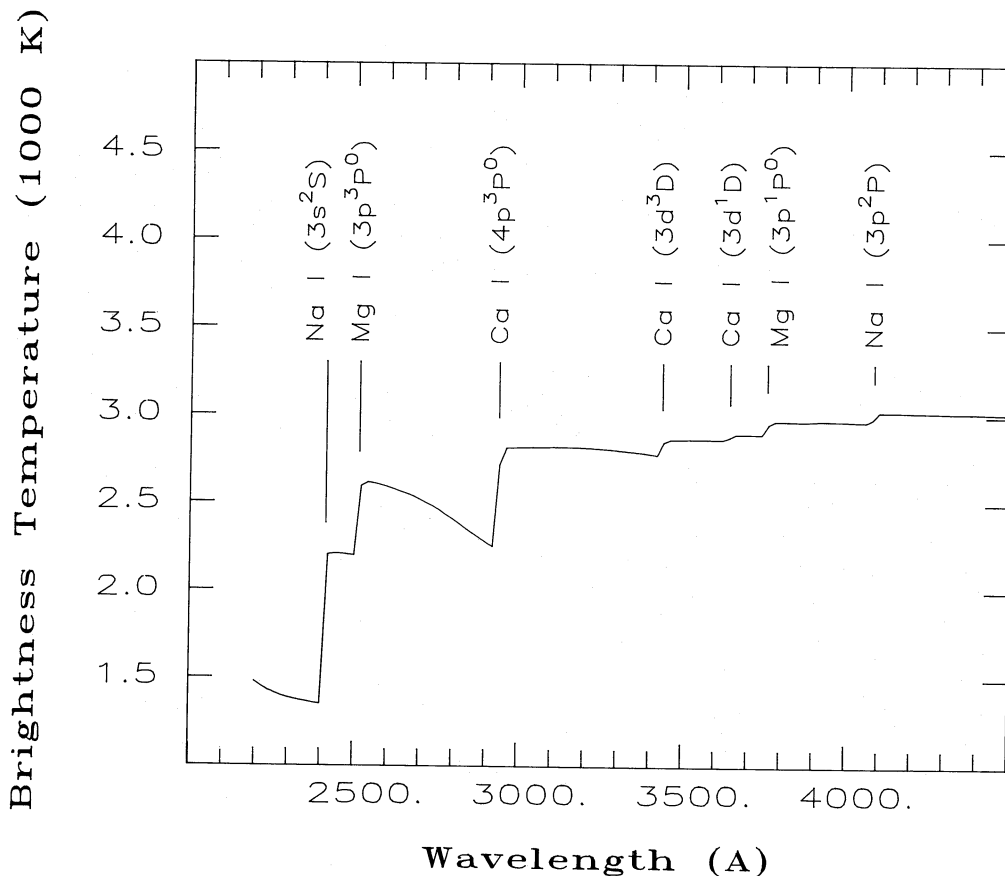


FIG. 3.—Brightness temperature for the ultraviolet and violet regions of spectrum B are plotted, and the bound free continua of spectrum B are identified

3. Additional opacity is required to fit the observations between 3000 Å and 5000 Å.

4. The match with observations is quite good even on an absolute scale.

Figure 4 compares the photometry of TX Psc to a synthetic spectrum calculated with all bound-free and bound-bound transitions included. Because the observations are taken from different authors (see Table 1) and at random light phases of this variable star, we do not smear the synthetic spectrum with a convolution of an instrument profiles. Instead, we simply average the synthetic spectrum over a 30 Å running-box. The overall shape of the synthetic spectrum is in good agreement with the photometry although the synthetic flux, normalized to the angular size of 9.31 mas, is slightly lower than the photometry. The best fit is achieved for an angular diameter of 11 mas, which is outside the uncertainty of the measurement but certainly not impossible. A slightly higher temperature ( $\sim 3200$  K), would also improve the fit. (A higher effective temperature would also help remove the discrepancy between observed and computed CH line strengths found by Lambert *et al.* 1986.) The *IUE* data points lie well above the synthetic flux shortward of 3000 Å. This discrepancy arises from emission lines formed in the chromosphere of TX Psc which are seen in the *IUE* spectra of this star (Johnson and Luttermoser 1987), whereas our flux was calculated from a photospheric model alone. Including the effects of a model chromosphere produces much better agreement with *IUE* spectra (Luttermoser *et al.* 1987).

To test the effect of these neutral opacities with varying C/O

ratios and effective temperatures, we calculated fluxes for a 3000/0/solar (M supergiant) and a 2500/0/1.05 (carbon star) model atmosphere. Figure 5 displays the synthetic flux for two model atmospheres with different carbon-to-oxygen ratios. The CO cooling of the outer layer extends deeper in the 3000 K carbon star than in the 3000 K oxygen-rich star (Johnson 1982). For the oxygen-rich star, this higher temperature produces more excitation and ionization and hence weaker resonance lines and bound-free opacities from low-lying states which results in enhanced violet and ultraviolet fluxes.

A flux comparison between two model atmospheres for carbon stars which differ only in effective temperature (3000/0/1.05 and 2500/0/1.05) shows a definite increase in line broadening for the natural resonance lines for the 2500 K model (Fig. 6). From comparison of the models in Figures 5 and 6 we conclude that the violet flux depression in the N type carbon stars is a temperature effect. Of secondary importance is the effect of composition change (i.e., increased carbon abundance)—not in the sense of enhanced carbon compound opacities, but in the effect of cooling of the outer layers by the carbon monoxide molecule—an indirect temperature effect.

Models for carbon stars which include, in addition to the opacities used here, the opacities of the polyatomic molecules HCN and  $C_2H_2$ , have recently been calculated (Ekberg, Eriksson, and Gustafsson 1986; Lambert *et al.* 1986). Compared to the models used in this paper ("Indiana" models), these newer "polyatomic" models have very similar thermal structure (temperature against Rosseland optical depth), but sharply lower pressures and densities in the outer layers because of the

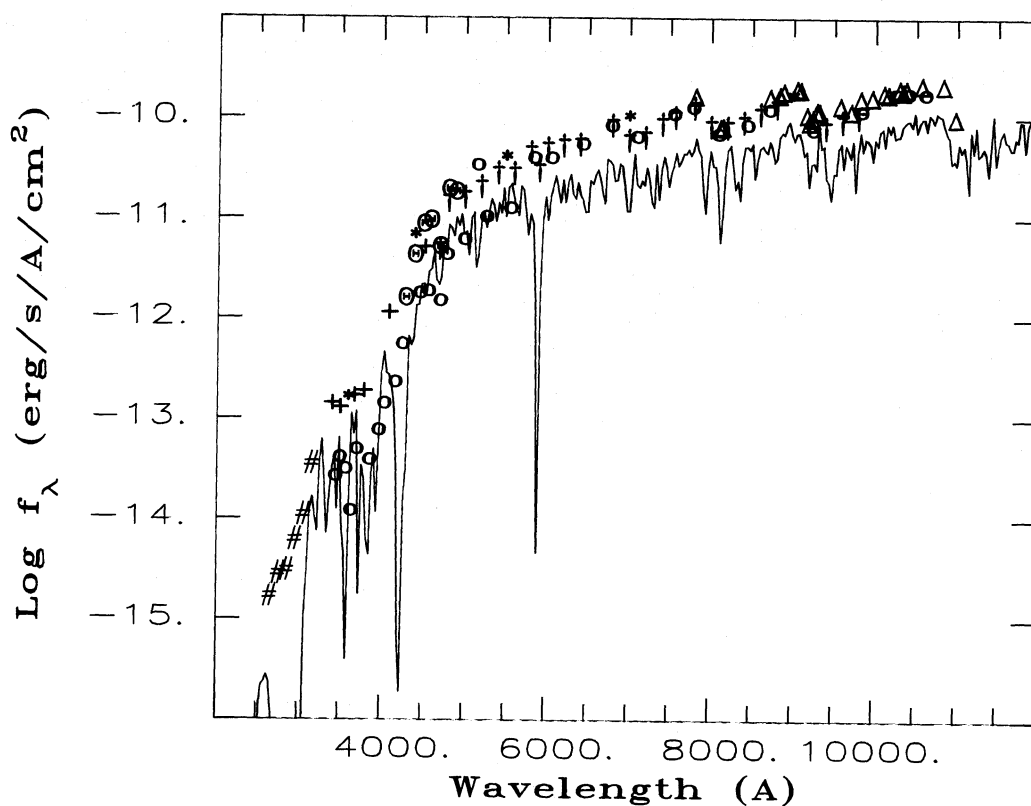


FIG. 4.—Comparison between a synthetic spectrum including continuous and line opacities and the photometry of Fig. 1, with the synthetic spectrum averaged (running-box) over 30  $\text{\AA}$  bins and scaled to the angular diameter of TX Psc.

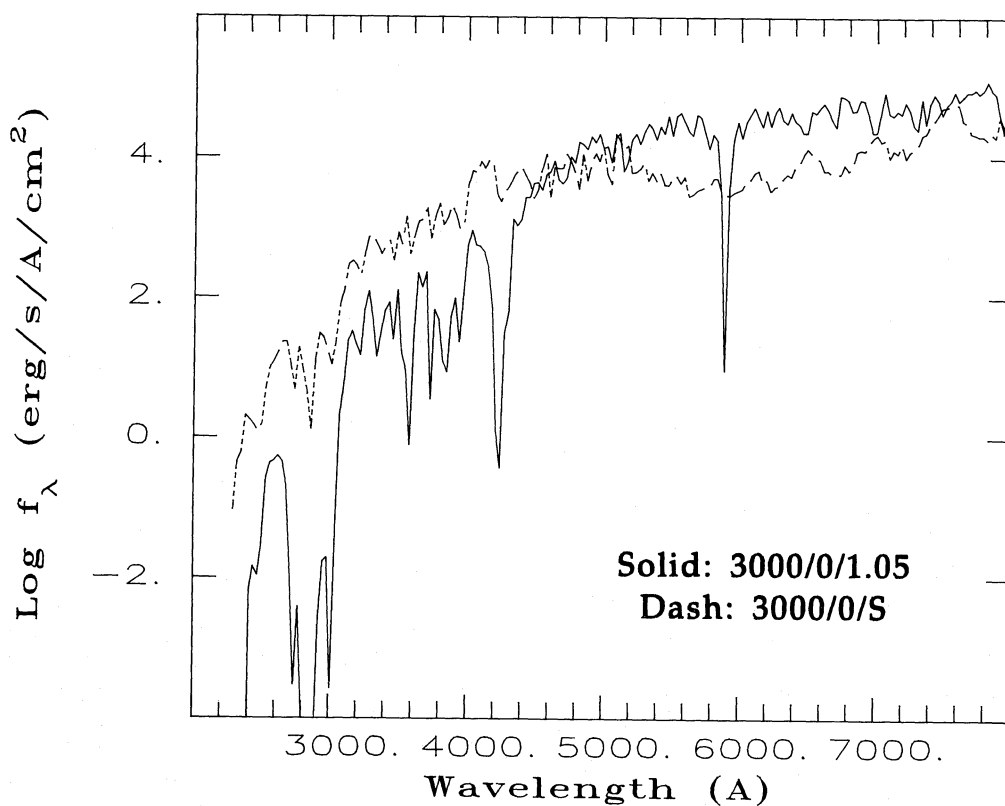


FIG. 5.—Comparison of synthetic emergent spectra for the 3000/0/1.05 model (Fig. 4) and a 3000/0/S (S = solar C/O) model both averaged (running-box) over 30  $\text{\AA}$  bins. The large increase in opacity of the neutral metal resonance transitions for the carbon star can easily be seen.

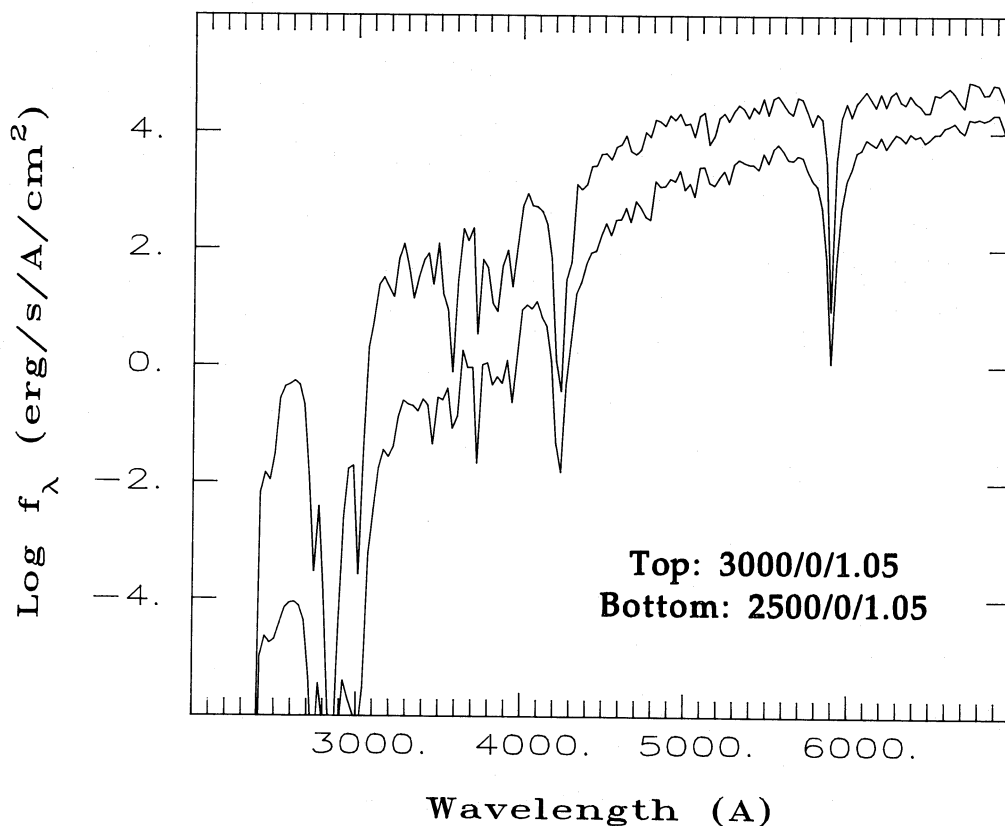


FIG. 6.—Comparison of synthetic spectra including continuous and line opacities at the stellar surface between a 2500/0/1.05 model and the 3000/0/1.05 model (Fig. 4) of TX Psc.

increased opacity there. Fluxes from the polyatomic models agree very well with fluxes from the models used here in the wavelength region 2500–10,000 Å. The small difference is that the polyatomic models give slightly larger fluxes both in the visual (where they fit the observations slightly better than do the Indiana models) and the ultraviolet (where they have slightly too much flux).

#### IV. THE ROLE OF MOLECULAR OPACITIES

Atomic opacities do not act alone in the violet and ultraviolet. Strong bands of the violet system of CN fall near 3800 Å, and these make a small contribution to the violet flux decrement. The ultraviolet system (3000–3300 Å) of the temperature-sensitive molecule CaCl may contribute to the opacity in these cool objects (Bennett and Johnson 1985), especially to the stronger ultraviolet depression seen in later N type stars. Photodissociation of such hydride molecules as CH may be important as well (Kurucz, van Dishoeck, and Tarafdar 1987). Figure 7a displays the substantial effect of the opacity from the CH photodissociation on the continuous flux between 3000 Å and 4500 Å for the 3000/0/1.05 model (cross section data kindly supplied by R. L. Kurucz).

Bands of C<sub>3</sub> may become important shortward of 5000 Å (Cooper and Jones 1979; Snow and Wells 1980). The importance of the violet C<sub>3</sub> Swings band, which mimics a continuum, on the emergent flux can be judged by the results from a run with this opacity included (Fig. 7a). The C<sub>3</sub> cross section data were taken from Cooper and Jones (1979). We interpolated the cross sections in a coarse wavelength grid ( $\Delta\lambda = 400$  Å) between 3000 Å and 5000 Å from 3200 K to 4000 K plotted by

Cooper and Jones (1979). We arbitrarily set the C<sub>3</sub> opacity equal to zero for  $\lambda < 2900$  Å and  $\lambda > 5000$  Å and extrapolate their cross sections between 2900 Å and 3000 Å (to smooth an abrupt edge seen at 3000 Å in preliminary calculations). The logarithms of the cross sections are interpolated linearly in the wavelength grid mentioned above and linearly in temperature for  $3200 \text{ K} < T < 4000 \text{ K}$ . For  $T < 3200 \text{ K}$ , we keep the cross section constant at the 3200 K value and for  $T > 4000 \text{ K}$ , constant at the 4000 K value.

The pseudocontinuum of C<sub>3</sub> and the photodissociation of CH are equally important to the continuous flux in the violet in our 3000/0/1.05 model. However, as displayed in Figure 7b, the bound-bound transitions from the neutral metals still dominate all opacities in this spectral region, although the additional opacity from C<sub>3</sub> and CH help reduce the flux between the strong lines.

Continuous fluxes including CH dissociation and C<sub>3</sub> Swings bands were also generated for the 2500/0/1.05 model. Again, C<sub>3</sub> and CH had a similar effect on the violet flux but, surprisingly, had a much smaller effect than with the 3000 K model. This occurs from a competition with other continuous opacities—the cooler model allows more H<sub>2</sub> to form and as such, increases the opacity of H<sub>2</sub> Rayleigh scattering at the  $\tau_c \approx 1$  level in the violet. At 3600 Å, for example, for the 3000 K model CH photodissociation amounts to a fraction 0.55 of the continuous opacity, the C<sub>3</sub> pseudocontinuum amounts to 0.32, and H<sub>2</sub> Rayleigh scattering is 0.03. For the same wavelength in the 2500 K model, CH photodissociation amounts to a fraction 0.31, C<sub>3</sub> to 0.15, and H<sub>2</sub> Rayleigh scattering to 0.35 of the continuous opacity.



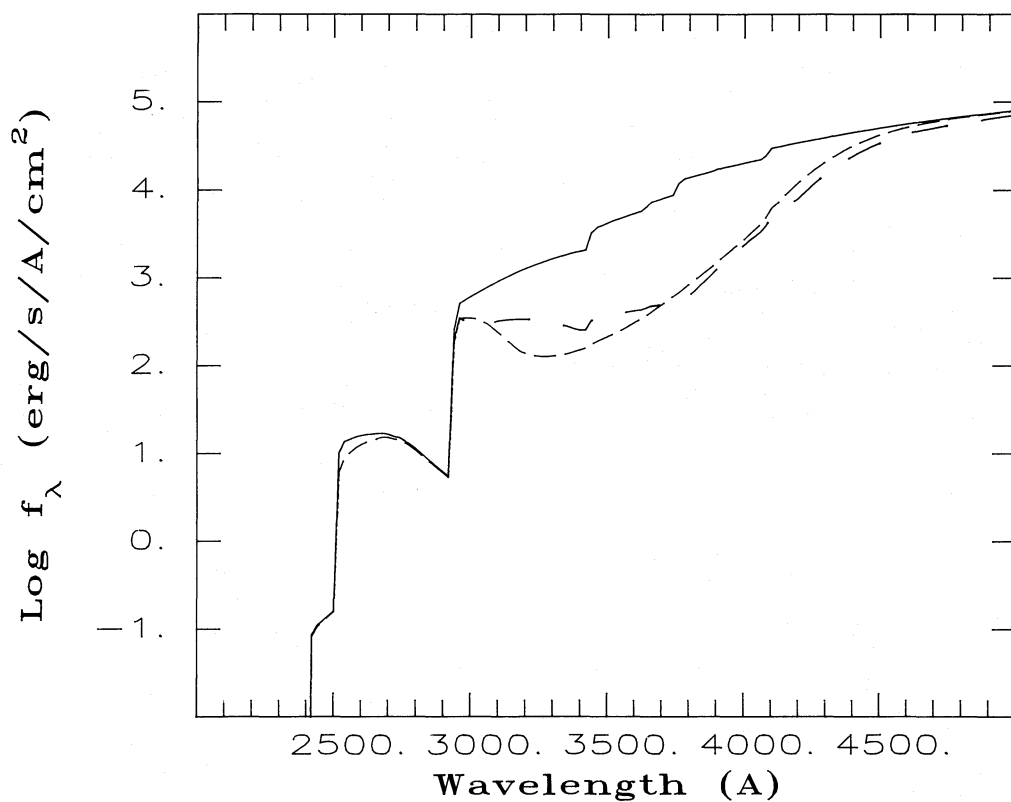


FIG. 7a

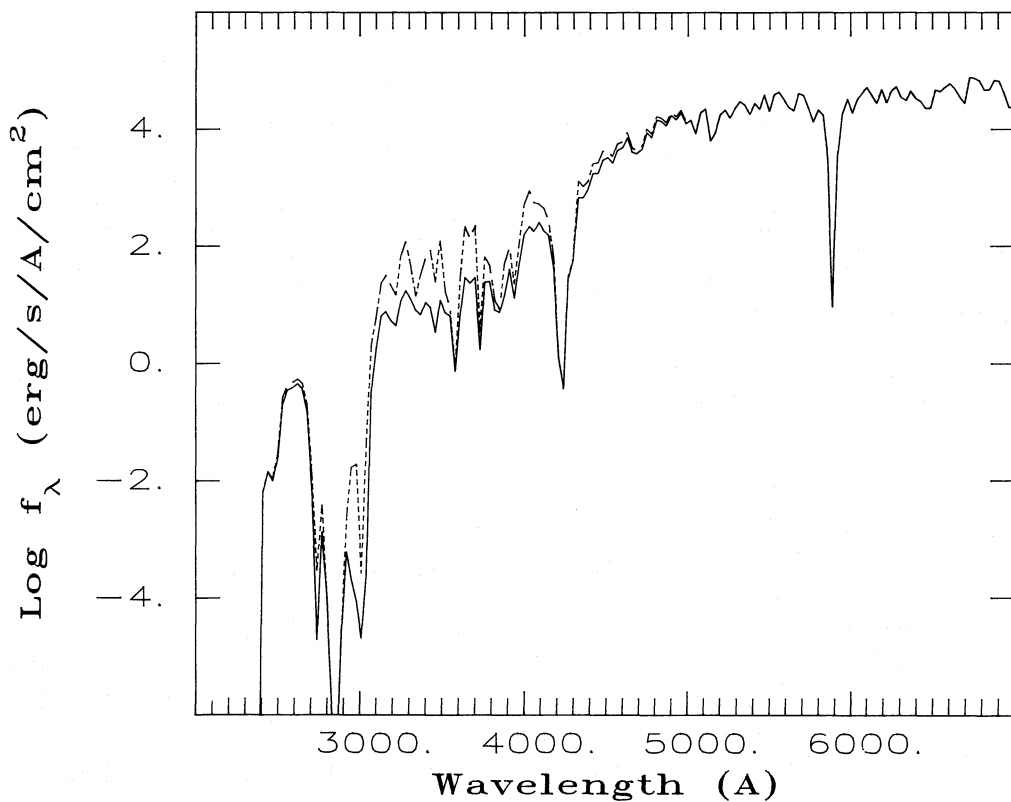


FIG. 7b

FIG. 7.—(a) Synthetic continua with the CH photodissociation opacity (*short dash*) and the  $C_3$  pseudocontinuum (*long dash*) included in the calculations for the 3000/0/1.05 model and compared to the spectrum B of Fig. 2. (b) Comparison of the synthetic flux of Fig. 4 (*dash*) and the synthetic flux from the same model with CH and  $C_3$  opacities included (*solid*).

## V. CONCLUSIONS AND DISCUSSION

A long-standing, unsolved problem in red giant stars is the remarkable decrease in energy flux toward the violet spectral region in carbon stars compared to M giants or the blackbodies. An unknown opacity seems necessary, and the phenomenon is called the "violet opacity" problem for cool carbon stars. Increasing evidence in recent years has forced abandonment of the hypothesis of SiC grains in a circumstellar shell and now favors location of the opacity in the lower photosphere.

To test directly the effects of several violet and ultraviolet absorbers, we have calculated synthetic spectra of carbon stars and oxygen stars from available atmospheric models and have compared the results to violet and ultraviolet observations of the well-studied N type carbon star TX Psc.

From this investigation we are able to draw several interesting conclusions.

1. The long sought violet opacity in the N type carbon stars appears to be the cumulative effect of several opacity sources: bound-bound opacities from low-lying states of Mg I, Ca I, and Fe I; bound-free opacities from Na I, Mg I, and Ca I; and, to a lesser extent, CH photodissociation and C<sub>3</sub> pseudocontinuum. The Mg I resonance line at 2852 Å and the Ca I  $4p^3P^0$  bound-free opacity are the *dominant* photospheric opacity sources in the long-wavelength region of IUE (2200–3200 Å).

2. The violet flux falloff of these carbon stars is primarily a temperature effect. Carbon abundance plays an indirect role in determining the amount and depth of CO cooling.

While the CH photodissociation opacity and the C<sub>3</sub> pseudocontinuum are significant opacities for stars with  $T_{\text{eff}} = 3000$  K, these opacities are effectively decreased in cooler stars both because H<sub>2</sub> Rayleigh scattering increases and because their relative number densities decrease as more complicated molecules form. Since later N type stars tend to be cooler and show more dramatic decreases in violet flux than the N0 stars, these cannot be the primary opacity sources responsible for the decrease in flux.

What conditions are necessary in a stellar atmosphere for the appearance of strong opacity due to bound-bound and bound-free opacities of neutral metals? Nothing more is required than a sufficiently cool outer photosphere where metals are generally neutral. The absorption due to Mg I and other neutral metals are therefore not directly sensitive to composition changes. We note, however, that as carbon enhancement proceeds for a given effective temperature, the CO

cooling extends deeper into the atmosphere, leading to an increasingly wider cool layer (Johnson 1982), and therefore promoting the formation of neutral metals. A carbon star (C/O > 1) therefore has a deeper cool outer layer and larger neutral metal opacity than a cool M star of the same effective temperature.

The amount of the violet opacity in carbon stars may have been inadvertently overestimated by early workers who measured the violet flux relative to K or M giants or supergiants, which were actually much hotter. For example, Betelgeuse, a common comparison star, has an effective temperature near 3800 K (Tsuji 1976; Bonneau *et al.* 1982); even an M6 giant star has an effective temperature of 3250 K (Ridgway *et al.* 1980). Effective temperatures of carbon stars are distinctly lower, being in the range 2500–3200 K (Tsuji 1981; Lambert *et al.* 1986). Violet fluxes from objects at such different temperatures would be so different as to invite conjecture regarding an extra violet opacity agent in the cooler star even if none existed. Early workers also compared the violet flux of an N type star to that of a blackbody. Yet in almost all intermediate and cool stars (including the Sun), the violet flux falls below that of a blackbody at the color temperature of the visual region simply because the increasing atomic opacity toward shorter wavelengths means one "sees" to shallower, cooler depths. Again, a violet opacity can needlessly be called for. This is not to suggest that all the supposed violet opacity is uncalled for, but a part of it clearly may be. With calibrated spectrophotometry we have attempted to attack the problem directly and quantitatively.

The work would not have been possible without contributions from several sources. Violet photometry from KPNO by one of the authors (D. R. F.) and ultraviolet spectrophotometry from IUE by another (H. R. J.) considerably extended the wavelength region over which the flux could be observed. The IUE observations and reductions were supported by NASA grant NSG 5-182. Photospheric models were supported by NSF grant 8205800, and the synthetic spectra calculations were supported by NSF grant 8520539 and by Indiana University through the Wrubel Computing Center. All of this support is appreciated. We are grateful for enlightening discussions with R. F. Wing, B. Gustafsson, and E. H. Avrett; to R. L. Kurucz for data on the photodissociation cross sections of CH; and to J. A. Brown and R. L. Kurucz (the referee) for several useful comments on the manuscript.

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