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ULTRAVIOLET SPECTRA AND CHROMOSPHERES OF COOL CARBON STARS

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ABSTRACT

We assemble and discuss all available low-resolution *IUE* spectra of N-type carbon stars—including TW Hor, BL Ori, UU Aur, NP Pup, U Hya, T Ind, and TX Psc. Identification of spectral features is aided by a composite spectrum. Shortward of 2850 Å only emission lines of C II, Mg II, Al II, and Fe II are seen, while the spectrum longward of 2850 Å appears to be a photospheric absorption spectrum with a few superposed emission lines of Fe II. The most prominent absorption features are due to Fe I, CH, and CaCl. The emission feature at 2325 Å, second only to Mg II in strength, is conclusively identified as C II (UV 0.01). Ultraviolet spectra of N-type carbon stars are similar to, though the emission-line fluxes are generally weaker than, those of the coolest M-giant stars available, such as HD 18191 (M6 III).

Subject headings: line identifications — stars: carbon — stars: chromospheres — ultraviolet: spectra

I. INTRODUCTION

Cool (N-type) carbon stars are of great interest for several reasons (see the reviews by Alksne and Ikaunieks 1981 and Alksne, Alksnis, and Dzervitis 1983). Their unusual chemical composition and luminosity mark them as asymptotic giant branch (AGB) stars which, as they ascend the giant branch the second time, have begun to mix to the surface the products of interior nucleosynthesis (Iben and Renzini 1982; Iben 1984*a*, *b*; Jaschek 1985; Lambert *et al.* 1986). They are among the coolest of the irregularly variable stars (Ridgway, Wells, and Joyce 1977; Tusji 1981*b*; Querci 1986), and their outer atmospheres contain unusual regimes of temperature and pressure. Available photospheric models—still somewhat exploratory—are summarized by Johnson (1985, 1986) and Ekberg, Eriksson, and Gustafsson (1986). Attempts at chromospheric models are summarized by de la Reza (1986). It seems reasonable to expect that a comparison of ultraviolet spectra of carbon and M-giant stars, which differ principally in chemical composition, might provide useful constraints on the mechanisms which produce chromospheres and perhaps mass loss.

Although N-type carbon stars are very faint in the ultraviolet, spectra of a few have already been published: BL Ori, TX Psc, and T Ind (Johnson and O'Brien 1983) and TW Hor (Querci and Querci 1985). Several additional stars (Y CVn, WZ Cas, U Cyg, and SS Vir) proved too faint for their spectra to be recorded by *IUE*, and the implications of these upper limits have been examined (Querci *et al.* 1982). Spectra of three R8 stars (HD 25408, HD 37212, and HD 75021), similar to those of N-type carbon stars, have been published along with those of other R stars (Eaton *et al.* 1985). Striking and unexpected short-term variability of at least some of the emission lines have been found in TW Hor (Bouchet, Querci, and Querci 1983; Querci and Querci 1985) and in TX Psc (Johnson *et al.* 1986). A single, weak, high-resolution LWP spectrum of TX Psc shows the Mg II lines to be badly mutilated by overlying absorption (Eriksson *et al.* 1986). In this paper, we publish for the first time the spectra of the N-type stars UU Aur, NP Pup, and U Hya and of the R5 star S Cen and discuss the entire group of carbon stars. After describing the observations (§ II), we concentrate on the identification of the lines (§ III) and the measurement of the line and continuous fluxes (§ IV) to aid efforts toward quantitative chromospheric modeling.

II. OBSERVATIONS

All available spectra of N-type carbon stars with fairly high signal are listed in Table 1. These are all low-resolution, long-wavelength spectra obtained with *IUE* (Boggess *et al.* 1978*a*, *b*). The best spectrum of each individual star is displayed in Figures 1 and 2. Although S Cen is an R5 star, it is included in this paper (shown in Fig. 2) because its ultraviolet spectrum has not been previously published and clearly resembles that of an R8 or N-type star (note the presence of Mg II in emission) more than it does other R5 stars, which show no trace of the line (Eaton *et al.* 1985). Figure 3 displays for comparison spectra of the three R8 stars previously published. In the hope that our current knowledge might allow us to extract some additional information, we reexamined the weak spectra of the four N-type stars previously reported as too faint to be recorded (Querci *et al.* 1982), which were kindly traced for us by NASA. However, no spectral features are present above the noise.

III. LINE IDENTIFICATION

To overcome, at least partly, the obvious difficulty of securely identifying spectral features and measuring fluxes on these weak spectra, we formed a composite of the best spectrum of each of seven N-type carbon stars weighted by the exposure time. (The spectrum of S Cen was not included.) The resultant composite spectrum, with an equivalent exposure time of 24.3 hr, is displayed in Figure 4. The gain is not as large as it might appear at first sight, of course, for all N-type stars are not identical and they may well be variable, but, as a starting point, the composite spectrum is clearly superior to any single available spectrum. Strong spectral features which appear on individual spectra as well as the composite are marked in Figure 4 by the rest wavelengths of the strongest lines in the identified multiplets.

Table 2 lists all features in each star which we consider real. Identifications are carried out with the help of the *Ultraviolet Multiplet Table* (Moore 1955), the list of emission lines from the solar limb (Doschek, Feldman, and Cohen 1977), compari-

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[1] Guest Observer with the *International Ultraviolet Explorer*, operated by the National Aeronautics and Space Administration.

TABLE 1

Summary of Observations

Star	HD	Spectral Type	Exposure No.	Date	*t* (exp) (minutes)
N-Type Carbon Stars					
TW Hor	20234	N0 C7, 2	LWR 7774	1980 May 16	105
			LWR 9049	1980 Oct 15	105
			LWR 12834	1982 Mar 22	…
			LWR 12835	1982 Mar 22	…
			LWR 12842	1982 Mar 23	78
			LWR 14940	1982 Dec 28	…
			LWR 15115	1983 Jan 26	…
			LWR 15492	1983 Mar 15	102
			LWP 1852	1983 Apr 27	…
BL Ori	44984	N0 C6, 2	LWR 10176	1981 Mar 20	180
			LWR 15371	1983 Feb 25	60
UU Aur	46687	N3 C5, 3	LWR 15379	1983 Feb 26	300
			LWR 15493	1983 Mar 15	100
NP Pup	51208	N0 C7, 2	LWR 15374	1983 Feb 25	120
U Hya	92055	N2 C7, 3	LWR 14846	1982 Dec 19	270
T Ind	202874	N2 C7, 3	LWR 11842	1981 Oct 26	210
TX Psc	223075	N0 C6, 2	LWR 11843	1981 Oct 26	120
			LWR 14062	1982 Oct 01	90
			LWR 14939	1982 Dec 28	78
			LWR 15116	1983 Jan 26	66
			LWR 16373	1983 Jul 19	180
			LWP 2511	1983 Dec 19	300
			LWP 3468	1984 Jun 01	60
			LWP 3470	1984 Jun 01	60
			LWP 3929	1984 Aug 03	60
R-Type Carbon Stars					
UV Cam	25408	R8 C5, 3	LWP 2510	1983 Dec 27	180
	37212	R8 C7, 3	LWR 10181	1981 Mar 20	57
			LWR 11841	1981 Oct 25	120
	75021	R8 C5, 5	LWR 14074	1982 Sep 01	75
			LWP 2514	1983 Dec 28	60
S Cen	107957	R5, C4, 5?	LWR 15375	1983 Feb 25	90

sons with M-giant spectra (Wing, Carpenter, and Wahlgren 1983), and line identifications in Arcturus (Carpenter, Wing, and Stencel 1985). Absorption lines identified on these spectra are generally those of neutral metals expected from the presence of their lines in the visual portion of the spectrum. Because of the weak flux in S Cen, no line identifications were attempted.

On the single available high-resolution spectrum of an N-type carbon star (TX Psc), only the Mg II *h* and *k* lines, Fe II (UV 62) at 2755.7 Å, and Fe II (UV 60) at 2926.6 Å are definitely present. A few other Fe II lines are possibly present, but the continuum is not detected (Eriksson *et al.* 1986). In this high-resolution spectrum, the Mg II lines are badly absorbed by Fe I, Mn I, and Mg II in overlying material. Even though the present spectra are of lower resolution, the much longer exposures have less noise and therefore permit more secure identification of additional lines or clumps of lines, as shown in Figure 4.

Except for the rather obvious features, identifications are hampered by the low (6 Å) resolution, the weakness of the spectrum, and the occasional juxtaposition of emission and absorption features. For example, Fe II multiplets (1), (6), and (7) are clearly seen in the violet spectrum of some carbon stars (Bidelman and Pyper 1963; Bouchet, Querci, and Querci 1983), and certain lines of those multiplets are easily visible on our composite spectrum, but the relative strengths of lines within the multiplet do not match predictions and may be blended with absorption features. Further progress must await spectra of higher resolution (probably with the high-resolution spectrograph of Hubble Space Telescope) and careful synthetic spectra based on reliable model atmospheres.

An issue of some significance is the identification of the relatively strong peak at 2325–2335 Å. A similar feature at this approximate wavelength is commonly observed in late-type giant stars (Wu *et al.* 1983), and high-resolution spectra show it to be C II (UV 0.01) beyond any doubt. In fact, it is useful as a density diagnostic (Stencel *et al.* 1981; Brown and Carpenter 1984; Carpenter, Brown, and Stencel 1985; Lennon *et al.* 1985). If the corresponding feature seen at low resolution in carbon stars is attributed to C II, it becomes the line of highest excitation or ionization in the N-star chromosphere and therefore sets interesting constraints on chromospheric models and heating mechanisms (Avrett and Johnson 1984; de la Reza 1986). The only plausible candidates for producing this feature are Fe II (UV 2, UV 3), Ni II (UV 11), Si II (UV 0.01), and C II (UV 0.01), which we consider in turn. We note that Fe II multiplets (UV 1), (UV 4), (UV 5), (UV 60), (UV 62), (UV 63), and (1) are detected, but multiplets (UV 2) and (UV 3) are either marginally detected or not detected at all. The difference apparently arises both from the relative strengths of the multiplets and the density of lines within the multiplet. Those multiplets detected are dense multiplets with the stronger lines

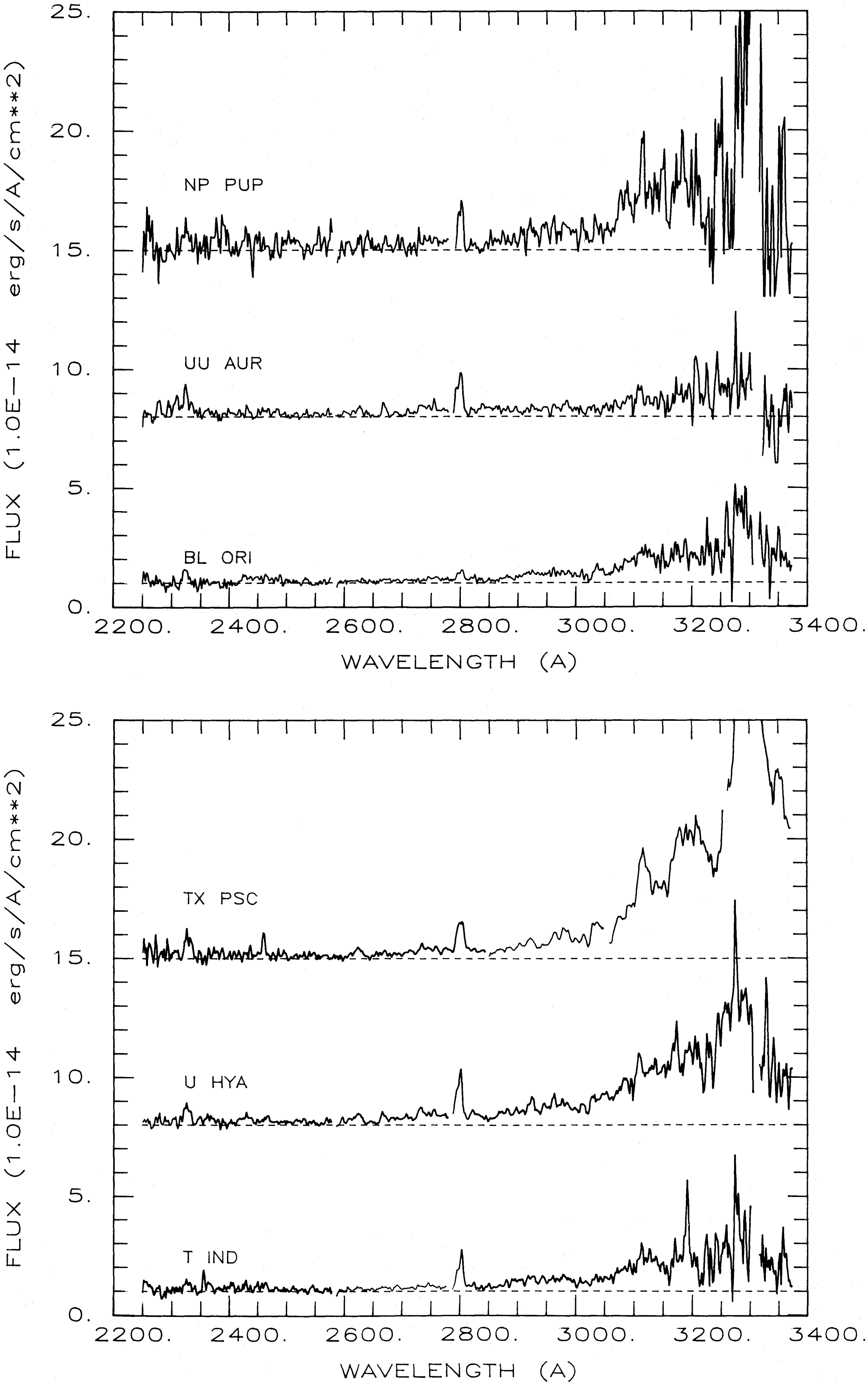

FIG. 1.—Low-dispersion spectra (observed flux vs. wavelength) of six N-type carbon stars from 2200 Å to 3400 Å. The stars are plotted in order of increasing right ascension, except that T Ind and U Hya have been interchanged for greater clarity of a peak at 3275 Å in U Hya. Dashed horizontal lines mark zero flux for each spectrum, and regions in the spectra where reseau marks occur are not plotted. A radiation hit shows as an emission feature in the spectrum of TX Psc at 2460 Å.

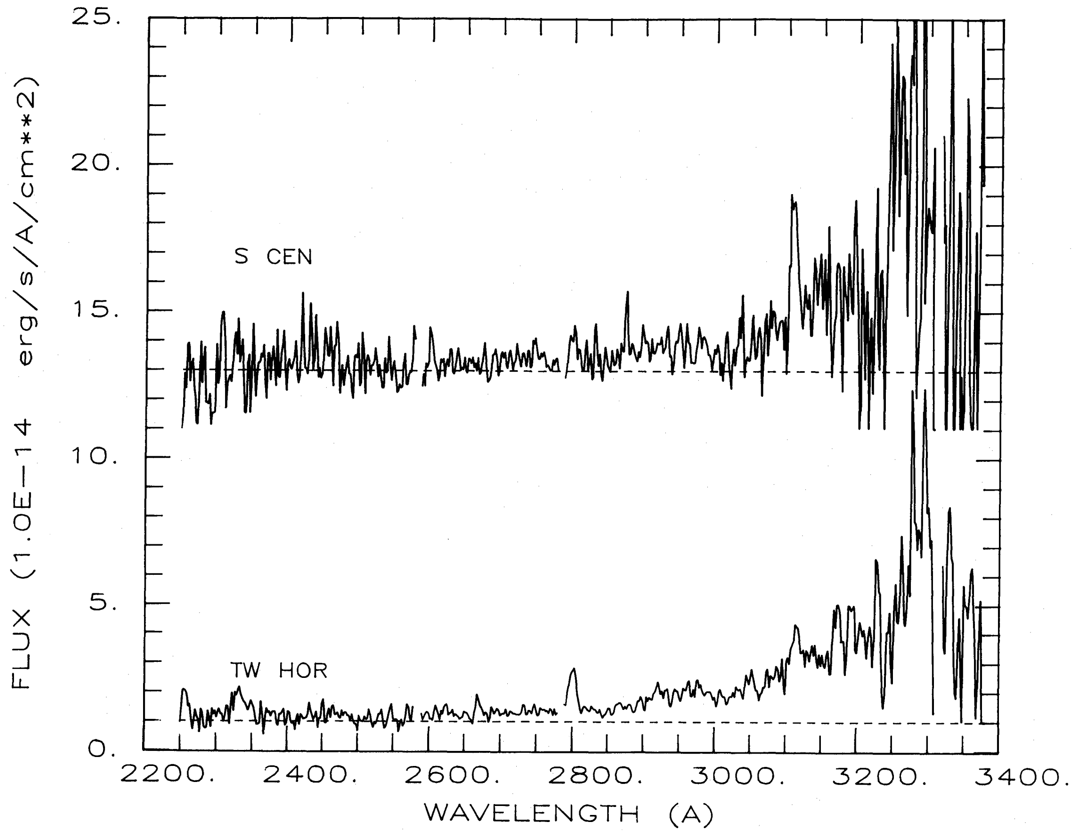

FIG. 2.—Comparison of the low-dispersion *IUE* spectra of TW Hor and S Cen in the wavelength region 2200–3400 Å. The spectrum of TW Hor is a composite of two observations supplied by F. Querci and M. Querci. Although S Cen is listed as an R5 carbon star, it more closely resembles an N-type star.

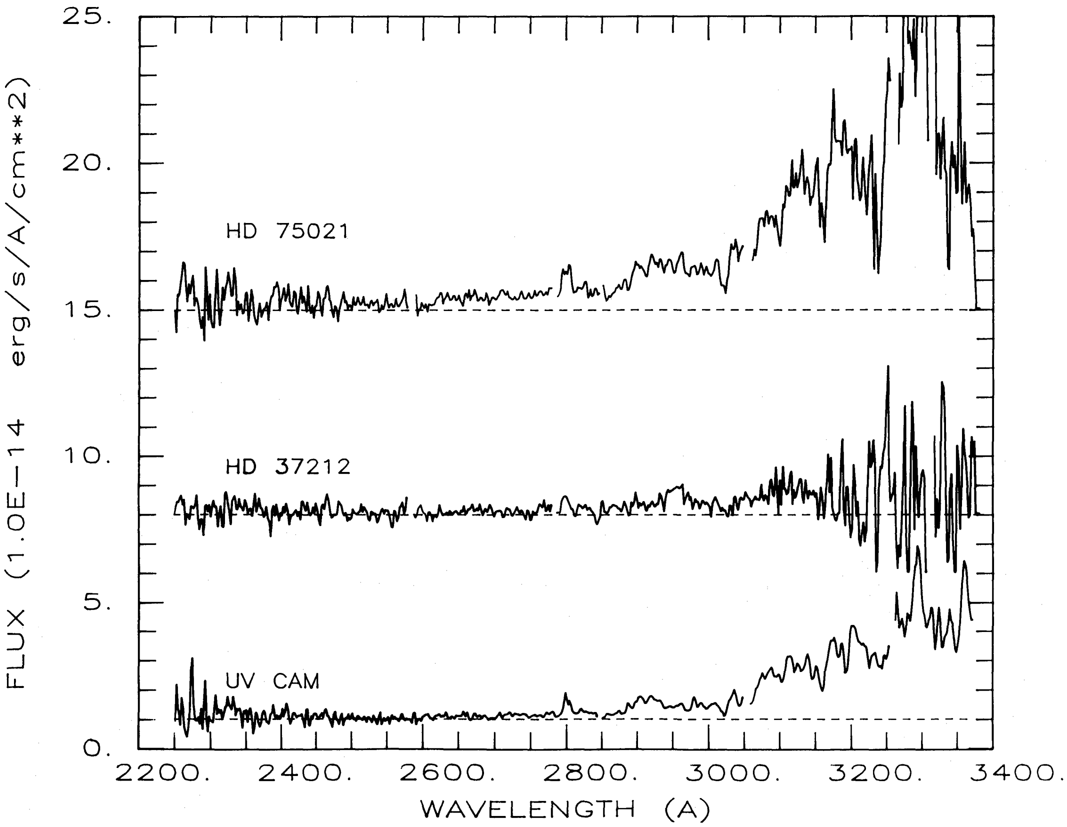

FIG. 3.—Low-dispersion *IUE* spectra of three R-type carbon stars over the wavelength range 2200–3400 Å for comparison with the N-type carbon stars. To achieve a better signal-to-noise ratio for HD 75021 and HD 37212, composite spectra are generated from two exposures for each star.

TABLE 2

SUGGESTED IDENTIFICATIONS OF SPECTRAL FEATURES IN SEVEN CARBON STARS

OBSERVED FEATURE (Å)	STAR[a]							IDENTIFICATION
	BL Ori	UU Aur	NP Pup	T Ind	U Hya	TX Psc	TW Hor	
2254–2264	p, m[b]	p, w[b]	p, s[b]	p, m	...	...	p, m	Fe II (UV 4, 5)
2290	v, w[b]	v, s[b]	v, s[b]	...	...	v, w[b]	v, w	Fe I (UV 14, 15)?
2302	v, w[b]	v, m[b]	v, s[b]	...	v, w	v, w[b]	...	Fe I (UV 14, 15)?
2320–2340	p, s	p, m[b]	p, s[b]	p, m	p, s	p, s	p, s	C II (UV 0.01), Si II (UV 0.01)
2390	v, w	...	p, s[b]	...	p, w	p, w	p, w	Fe II (UV 2)?
2405	...	...	...	p, w	p, w	...	p, w	Fe II (UV 2)?
2431	p, m	p, w	p, m[b]	p, w	p, s	...	...	?
2464	p, w	p, w	p, m[b]	p, w	p, s	p, s[c]	...	?
2490	...	v, w	v, s[b]	v, w	...	v, w	...	Fe I (UV 9)?
2523	v, w	v, w	...	...	...	v, w	v, w	Fe I (UV 7)?
2607–2635	...	p, m	p, w[b]	p, w	p, s	p, s	p, w	Fe II (UV 1)
2670	p, w	p, s	p, w[b]	p, w	p, s	p, m	p, m	Al II (UV 1)
2720	...	v, w	v, w	v, w	v, w	v, w	v, w	Fe I (UV 5)?
2735–2760	p, w	p, s	p, m	p, w	p, s	p, m	p, w	Fe II (UV 62, 63)
2800	p, s	p, s	p, s	p, s	p, s	p, s	p, s	Mg II (UV 1)
2884	...	...	p, w	p, w	p, w	p, w	...	Ti II (UV 14)?
2913	...	v, m	v, s	v, s	v, m	v, s	v, m	Fe I (UV 1)
2922	...	p, w	p, w	p, w	p, s	p, s	p, m	Fe II (UV 60)
2938	v, w	v, w	v, m	v, s	v, s	v, s	v, m	Fe I (UV 1)
2944	...	p, w	p, m	p, m	p, w	p, w	p, w	Fe II (8)
2955	v, w	v, s	v, s	v, s	v, s	v, m	v, w	Fe I (UV 1)
2963	p, w	p, m	p, s	p, s	p, m	p, m	p, w	Fe II (8), Fe II (UV 60)?
2972	v, w	v, w	v, m	v, w	v, m	v, s	v, m	Fe I (UV 1)
2980	...	p, m	p, w	p, w	p, w	p, s	p, w	Fe II (8), Fe II (UV 60)
2994	v, w	v, m	v, w	v, w	v, m	v, s	v, w	Fe I (9), Mg I (5)?
3005	v, w	v, w	v, s	v, s	v, s	v, m	v, s	Fe I (9), Fe I (30), Ni I (26)
3018–3024	v, s	v, s	v, s	v, s	v, s	v, s	v, s	Fe I (9)
3040	v, w	v, w	v, m	v, w	v, m	...	v, w	Fe I (9), Fe I (30), Ni I (25)
3048	v, m	...	v, m	...	v, w	[d]	v, w	Fe I (9), Ni I (25)
3055–3070	v, m	...	v, m	v, w	v, w	v, s	v, s	Fe I (9), V I (17), Ni I (25, 26)
3098	v, m	v, s	v, s	v, m	v, s	v, w	v, m	Fe I (28), Ni I (25)
3110–3117	...	p, m	p, s	p, w	p, s	p, s	p, m	V II (1)?
3123	v, w	v, m	v, m	v, m	v, m	v, s	v, w	Fe I (28)
3134	v, w	v, m	v, s	v, m	v, m	v, m	v, w	Fe I (28), Ni I (25)
3142–3146	v, m	v, m	v, m	v, m	v, s	v, m	v, w	CH (0, 0)
3156	v, m	v, m	v, s	v, s	v, m	v, s	v, m	CH (1, 1)
3161	v, s	v, m	v, s	v, s	v, w	v, s	v, s	CaCl (2, 1)
3168	v, m	v, w	v, m	v, w	v, w	v, w	v, w	CaCl (1, 0)
3182	v, s	v, m	v, s	v, s	v, s	v, s	v, s	V I (14)
3188–3195	p, m	...	...	p, s	p, w	p, w	p, m	Fe II (7)?
3192	...	v, w	v, w	...	v, w	v, w	v, w	Ti I (27)
3202	v, s[b]	v, s[b]	v, s[b]	v, s[b]	v, m	v, m	v, m	Ti I (27), V I (14)?
3208	...	p, s[b]	p, w[b]	p, w[b]	p, w	p, w	...	Fe II (6)?, Ni I (8)?
3220	v, m[b]	v, s[b]	v, s[b]	v, s[b]	v, s	v, m	v, s	CaCl (0, 0)?
3238	v, s[b]	v, s[b]	v, s[b]	v, m[b]	v, s	v, s	v, s	CaCl (1, 2), Ti II (2)?
3250	v, s[b]	v, m[b]	v, m[b]	v, s[b]	v, s	v, s	v, s[b]	CaCl (0, 1), Cu I (1)?
3270	v, s[b]	v, m[b]	v, s[b]	v, s[b]	v, m	v, w	v, m[b]	Cu I (1)?
3276	p, w[b]	p, m[b]	...	p, m[b]	p, s	p, s	p, s[b]	Fe II (1)
3290	v, w[b]	v, s[b]	v, s[b]	v, s[b]	v, s	v, s	v, s[b]	CaCl (0, 2)
3302	...	p, w[b]	...	[d]	...	p, s	p, s[b]	Fe II (1)
3330	p, w[b]	p, w[b]	p, w[b]	...	p, s[b]	...	p, m[b]	Ti II (7)?
3335	v, w[b]	v, w[b]	v, w[b]	...	v, m[b]	...	v, s[b]	Mg I (4)?
3340	p, w[b]	p, w[b]	p, w[b]	v, w[b]	p, w[b]	v, w	p, w[b]	Ti II (7)?
3348	...	v, s[b]	v, s[b]	v, s[b]	v, w[b]	v, s	v, s[b]	?
3355	...	p, w[b]	p, s[b]	...	...	p, s	p, w[b]	Ti II (1)?

[a] p, peak; v, valley. s, strong; m, moderate; w, weak. *Ellipsis dots*, not seen.

[b] Noisy.

[c] Hit.

[d] Reseau.

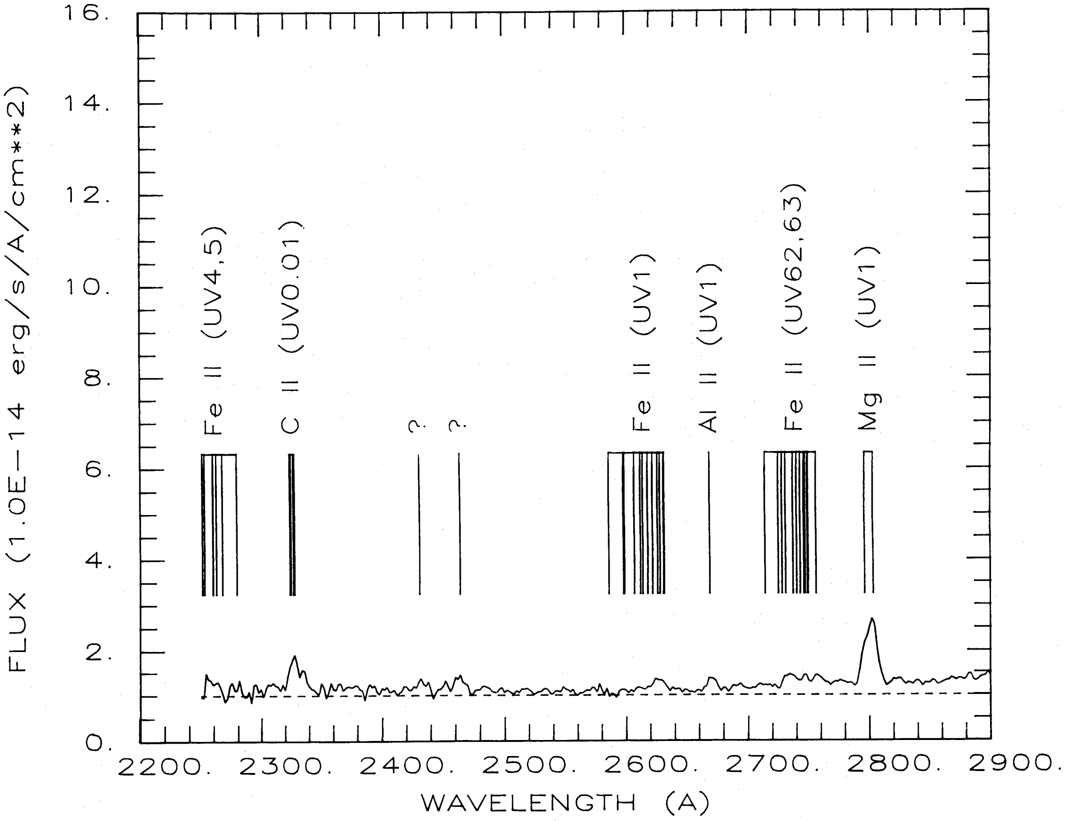

FIG. 4*a*

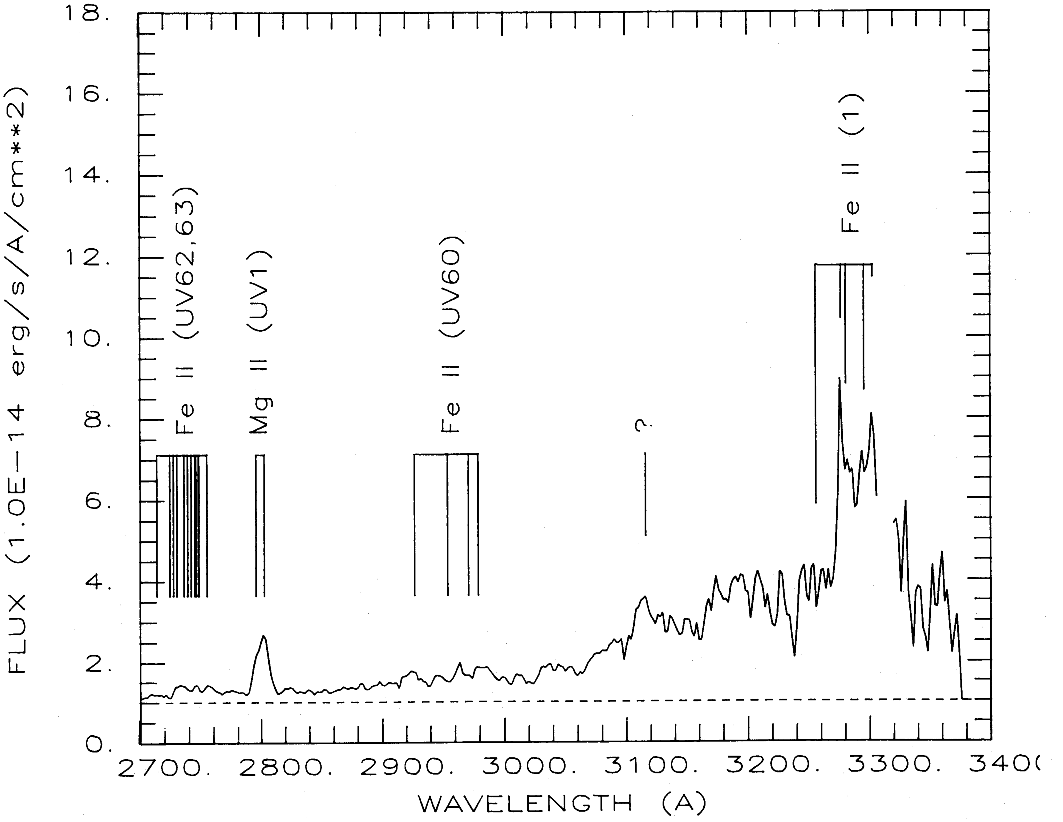

FIG. 4*b*

FIG. 4.—Composite spectrum made by co-adding the best *IUE* spectrum of each of seven N-type carbon stars (BL Ori, UU Aur, NP Pup, U Hya, T Ind, TX Psc, and TW Hor). Reseaus and radiation hits were deleted before the spectra were added. The effect of this composition is to simulate an exposure of 24.3 hr. For clarity, the spectrum is divided into two wavelength regions; strong emission lines are identified in (*a*) and (*b*), and strong absorption lines are identified in (*c*).

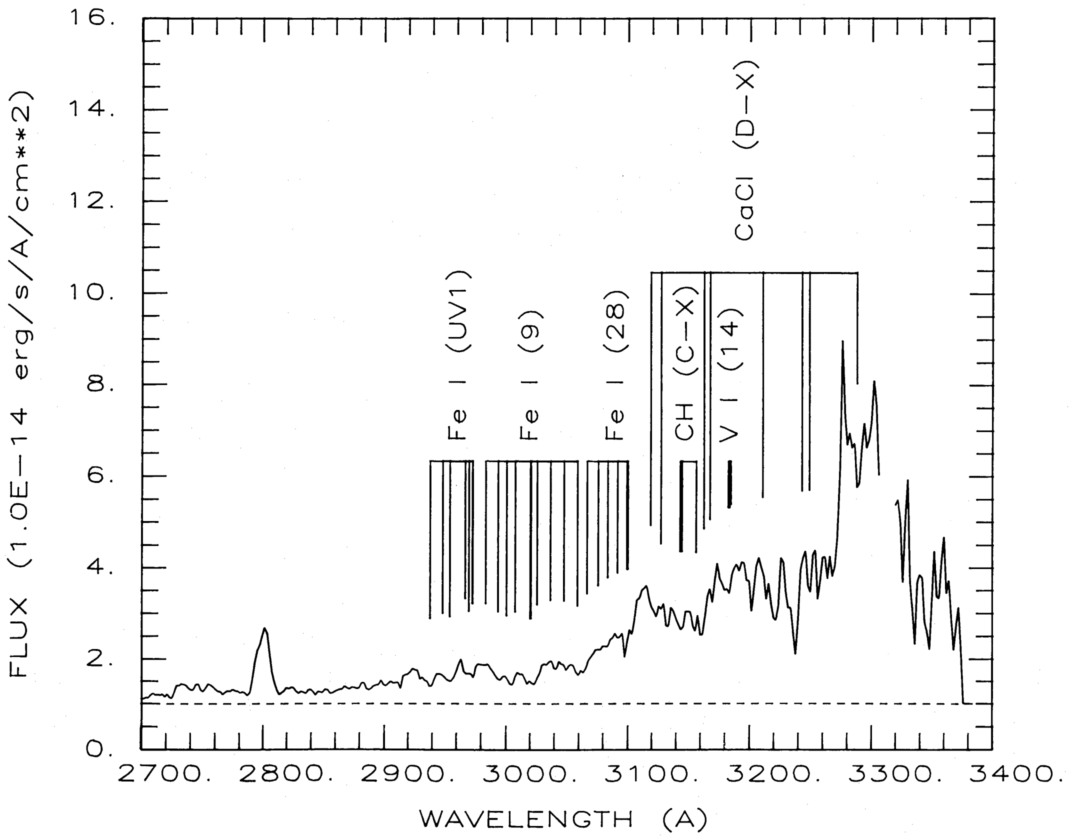

FIG. 4c

packed within 20–30 Å (except for [1] and [UV 62, 63], which are spread over 40 Å), and all have noticeable clumps of lines. By contrast, (UV 2) and (UV 3) are spread over 50–80 Å, and even their strongest clump of lines (at 2343–2344 Å) is absent, which appears to rule out any significant contribution of these multiplets to the peak at 2325–2335 Å. Also, the strengths of (UV 2) and (UV 3) are not as large as those of the observed Fe II multiplets, except for (1), which is a semiforbidden multiplet, the observed strength of which is enhanced by nonequilibrium effects (perhaps parallel to those of C II [UV 0.01]). There is no evidence for the strongest lines of Ni II (UV 11) at 2297, 2302, and 2316 Å; the emission rises sharply between 2320 and 2325 Å on each spectrum with no emission immediately shortward. Apparently, then, Ni II (UV 11) does not contribute to the peak at 2325 Å. Because of its lower abundance, silicon lines are expected to be weaker than corresponding carbon lines, but Si II (UV 0.01) emission lines are as strong as C II (UV 0.01) lines in Arcturus (Carpenter, Wing, and Stencel 1985); and they are probably present, though relatively weaker, in *ρ* Per (Eaton and Johnson 1986). Because they lie at slightly longer wavelengths (2334, 2344, and 2359 Å), they cannot be responsible for the primary peak at 2325 Å, but the stronger lines may contribute to the secondary peak at 2335 Å. The lack of any reasonable alternative identification for the strong features at 2325 Å, its strength in the individual spectrum of each star as well as in the composite spectrum (Fig. 4), and its appearance in other cool giant stars argue convincingly that the feature seen at 2325 Å in N-type carbon stars is due largely or completely to C II.

Two weak emission features on the composite spectrum at 2431 Å and 2464 Å have not yet been identified. Since the spectra of certain individual stars (e.g., U Hya) also show features at these wavelengths, they may be real even though they are not seen in Arcturus (Carpenter, Wing, and Stencel 1985) or *ρ* Per (Eaton and Johnson 1986). (Although the spectrum of TX Psc has a few hits in the 2460 Å region, hits and reseaus have not been included in the composite.) The search for identifications among chromospheric-type lines—singly ionized species of fairly abundant atoms—produces no good candidates. Candidates among such weaker multiplets as V II (UV 22, UV 24, UV 91, UV 92); Fe II (UV 148, UV 164, UV 180, UV 208, UV 209, UV 375), and Ni II (UV 19) either have lower state energies that would appear to be too great for the expected temperature regime in the chromospheres of these stars or are rendered doubtful at low resolution by the absence of stronger lines or multiplets. Lines fluoresced by observed strong emission lines also do not seem likely. Possible candidates are Fe I (UV 62) at 2458 Å, which might be pumped through Fe I (UV 92) at 2806 Å by the Mg II *h* line; and Fe I (UV 65) at both 2464 Å and 2479 Å, which might be pumped through Fe I (UV 96) at 2797 Å by the Mg II *k* line. Fe I (UV 62) and (UV 92) share a common upper state, as do Fe I (UV 65) and (UV 96), and the corresponding lines share the same *J*-value in the common upper state. Fe I (UV 44) at 2823 Å and 2844 Å, pumped by an Fe I (UV 44) line at 2797 Å in the Mg II *k* line, is fairly prominent in M-giant stars (Carpenter, Wing, and Stencel 1985; Eaton and Johnson 1986). However, since Fe I (UV 44) fluorescence is not seen in these N stars, it seems unlikely that these other, weaker fluoresced lines would be present. Fluorescence from such other emission lines as C II (UV 0.01), Fe II (UV 1), and Al II (UV 1) have likewise been tested with negative results.

Consistent identification requires two steps: a search in line lists for all stellar features regarded as real, and a search in the stellar spectrum for lines whose presence is considered probable. Special care must be exercised on such noisy and low-resolution spectra as these. We here summarize our findings, by element and stage of ionization, regarding any observed or suspected line.

C II.—Multiplet (UV 0.01) at 2325 Å is clearly present as the strongest peak after Mg II (UV 1).

Na I.—If present, multiplet (2) (3^2S–4^2P^o) at 3302 Å is lost in the strong peak due to Fe II (1).

Mg I.—Multiplet (UV 1) at 2852 Å would be expected to form a very strong absorption line in the photosphere. While a broad depression may be present in certain stars (e.g., BL Ori and U Hya), the composite shows no distinct feature at all, and perhaps the continuous flux has fallen to zero at this wavelength or the dark photospheric line core has been filled in with emission, from either the chromosphere or a cooler circumstellar cloud or shell. Spectra of the R8 stars are similar; altogether the Mg I line presents a real puzzle.

Multiplet (5), which has the metastable level 3^3P as its lower level, coincides with a valley at 3095 Å. If this line arises from the photosphere, the opacity of the region which produces the emission to fill in the line at 2852 Å must be insufficient to fill in this line.

Mg II.—Multiplet (UV 1) at 2796 Å and 2803 Å are blended together on these low-resolution spectra. This feature is the strongest peak on every spectrum.

Al II.—Multiplet (UV 1) at 2669 Å is clearly present in the composite spectrum. Among individual spectra it is quite variable, being strong in some and absent in others, but this may at least partly result from the noise at the low exposure levels in these spectra.

Ti I.—Multiplet (27) may be present between 3186 and 3200 Å; multiplet (30) may be blended with the stronger Fe I (9) at 2956 Å. Multiplets (UV 1) near 2956 Å, (UV 2) near 2675 Å, (UV 5) near 2645 Å, and (UV 6) near 2605 Å may be present.

Ti II.—Lines of multiplet (1) coincide with peaks at 3350, 3364, and 3373 Å, and multiplet (2) coincides with a peak at 3340 Å, but the spectrum in this region is too noisy to allow any sure identification. Other strong multiplets are even less obvious.

V I.—The strong multiplets (14) and (17) coincide with deep valleys at 3185 Å and 3060 Å respectively, the latter also coinciding with the strong multiplet Fe I (9).

V II.—Lines of the very strong multiplet (1) may be present as a weak peak near 3095 Å and the strong, broad peak near 3116 Å, but they unfortunately fall among strong absorption features of Fe I (28). It seems very unlikely that V II (1) could be responsible for the large peak at 3116 Å. Multiplet (7) may contribute to the strong peak at 3276 Å, which is surely due mostly to Fe II (1), and multiplet (8) coincides with a local peak at 3190 Å. Higher spectral resolution is necessary before more sure identifications can be made. Lines of V II (7) and Fe II (1) have been identified in ground-based ultraviolet spectra of TW Hor (Bouchet, Querci, and Querci 1983).

Cr II.—Multiplets (3) and (4) are not apparent.

Mn I.—The resonance multiplet (UV 1) falls on the Mg II emission peaks, where it contributes significant absorption, as seen on a weak, high-resolution spectrum of TX Psc (Eriksson *et al.* 1986).

Fe I.—Strong multiplets (9), (10 = UV 1), (28), and (30) produce obvious valleys. If (UV 5) is present at 2720, it becomes the absorption line of shortest wavelength identified. (Lines of this multiplet are strong in ρ Per.) Multiplets (UV 7), (UV 9), and (UV 14, 15) coincide with absorption features at 2505, 2490, and 2300 Å of approximately the same strength as the noise.

Fe II.—Most of the emission features in the spectrum are due to Fe II; at least multiplets (1), (2 = UV 60), (UV 1), (UV 4), (UV 5), (UV 62), and (UV 63) are present. Multiplets (6), (7), and (8 = UV 78) are likely present. We find no evidence for multiplets (UV 30) and (UV 64), which might have been expected. The absence of multiplets (UV 2) and (UV 3) has been discussed earlier.

Co I.—Multiplet (UV 3) coincides with a weak trough near 2525 Å, which also might be Fe I (UV 7) or simply noise.

Ni I.—Multiplets (25) and (26) are likely present, but they are blended with strong features of Fe I (9), (28), and (30); multiplet (8) may be present.

Cu I.—The stronger line of the resonance multiplet (1) at 3247.5 Å coincides with a deep valley which could also be due to CaCl; the other line (3274.0 Å) falls on the wing of the Fe II (1) line at 3277.3 Å.

Except for the two strong bandheads of the CH system at 3144 and 3156 Å, evidence for molecular features is scanty. Bands of CaCl are coincident with several strong unidentified features longward of 3000 Å, and this identification is probable (Bennett and Johnson 1985). We have searched for the stronger bands of the Fox-Herzberg system of C_2 (2732, 2772, 2855, 2987, and 3129 Å), but the weakness of the background "continuous" emission makes identification impossible.

It is interesting to compare these spectra with those of the coolest giants in the *IUE Ultraviolet Spectral Atlas* (Wu *et al.* 1983), HD 44478 (M3 IIIab) and HD 19058 (ρ Per; M4 II–III), and with even cooler M-giant stars. The same emission lines are seen, but these are relatively much weaker in the N-type stars. The continuum is also weaker in the N-type stars, being detected with certainty only down to 2850 Å, while it can be traced to much shorter wavelengths in the M giants. The Al II (UV 1) line is weaker relative to Fe II (UV 1) in the carbon stars, or the iron lines are relatively stronger, compared to the M giants. Spectra of TX Psc do not show the cluster of emission lines near 2510 Å which is present in M-star spectra and is likely due to Fe II (UV 33) (Wing, Carpenter, and Wahlgren 1983). Quantitative comparisons are presented in § IV.

Figure 5 shows an LWP spectrum of HD 18191 (RZ Ari; M6 III) taken on 1983 February 25 with an exposure of 60 minutes. An M6 giant star has an effective temperature of 3250 K (Ridgway *et al.* 1980; Tsuji 1981*a*), very close to, or slightly warmer than, the N-type carbon stars of interest here (Ridgway, Wells, and Joyce 1977; Tsuji 1981*b*). As can be seen from a comparison of Figures 1 and 5, there are similarities and differences in both absorption and emission features. An obvious difference between these two spectra is the much greater relative flux in the Mg II and Fe II lines in the M star, while the C II features are somewhat more similar.

IV. DISCUSSION

Fluxes for several prominent emission lines in the N-type stars are listed in Table 3. These were obtained from the spectra using the absolute calibration of Bohlin and Holm (1980) and Bohlin (1986). Fluxes for other interesting lines are not listed because of the large uncertainty due to their low values. One can estimate the uncertainty of the Mg II line fluxes by noting that two low-resolution spectra of TX Psc (Johnson

TABLE 3

Fluxes in Prominent Emission Lines

	Observed[a] Flux (10^{-14} ergs s^{-1} cm^{-2})												
Star	Fe II (UV 4, 5)	C II (UV 0.01)	Fe II (UV 1)	Fe II (UV 62, 63)	Mg II (UV 1)	f(cont)[b]	$10^8 \times f$(bol)[c]	$10^6 \times \frac{f(\text{cont})}{f(\text{bol})}$	$10 \times \frac{f(\text{C II})}{f(\text{cont})}$	$10 \times \frac{f(\text{Mg II})}{f(\text{cont})}$	$10^8 \times \frac{f\text{C II})}{f(\text{bol})}$	$10^8 \times \frac{f(\text{Mg II})}{f(\text{bol})}$	$\frac{f(\text{Mg II})}{f(\text{C II})}$
BL Ori	3[d]	7	Not seen	8	8	53	81	0.7	1.2	1.4	8.1	9.4	1.2
UU Aur	Not seen	15	6	16	22[e]	38	284	0.1	3.9	6.0	5.3	7.7	1.5
NP Pup	13[d]	11[d]	4[d]	15	22	109	...	...	1.0	2.0	...	...	2.0
U Hya	Not seen	11	9	20	27[f]	119	269	0.4	0.9	2.3	4.0	10	2.5
T Ind	5	5[d]	3	10	18	60	86	0.7	0.9	3.1	6.5	21	3.2
TX Psc	Noisy	13[d]	7	16	23[d]	127	260	0.5	1.0	1.8	5.0	8.8	1.7
TW Hor[g]	11	17	11	16	26	123	127	1.0	1.3	2.1	13.4	20	1.5
Composite	4.6	11	6.7	15	22	90	...	...	1.2	2.5	...	...	2.0

[a] From Earth.

[b] Integrated flux from 3000 Å to 3100 Å.

[c] From Tsuji 1981*b*, except TW Hor from Querci and Querci 1985; f(bol) in units of ergs s^{-1} cm^{-2}.

[d] Spectrum is noisy in this region.

[e] Nine pixels saturated.

[f] Seven pixels saturated.

[g] Line fluxes calculated from the composite of two spectra.

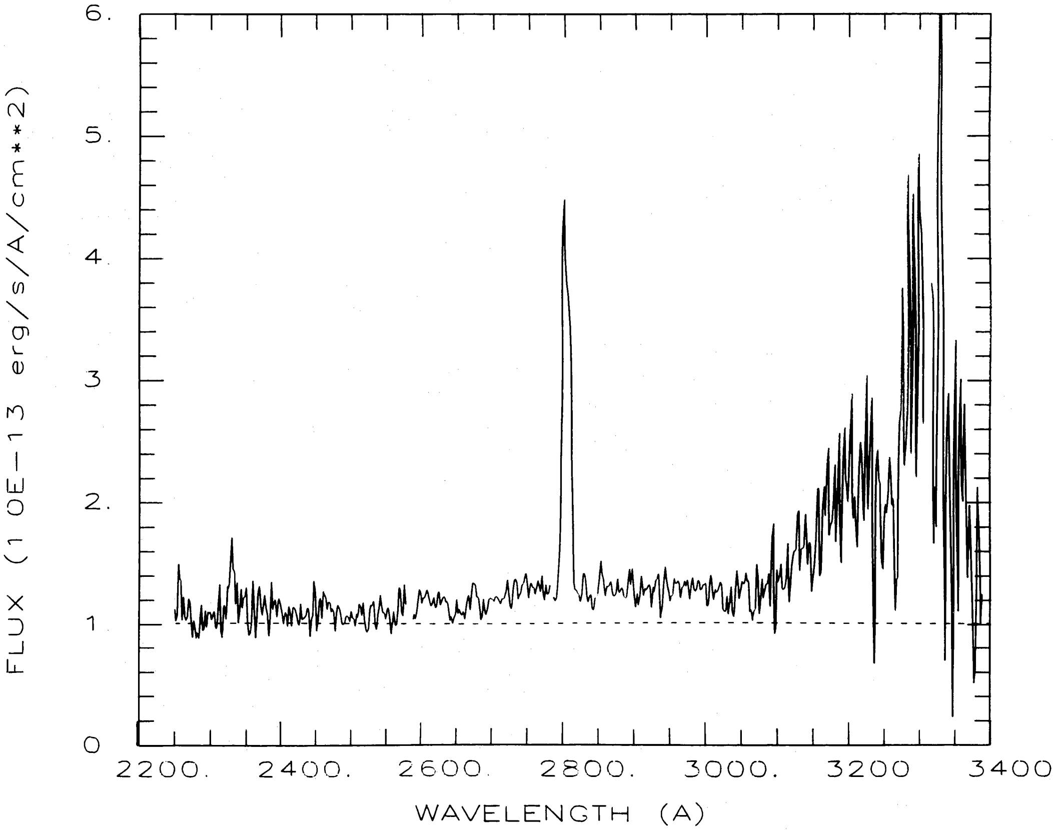

FIG. 5.—Low-dispersion *IUE* spectrum of the M6 giant HD 18191 (RZ Ari) is shown for comparison with the N-type carbon stars. As with the previous figures, reseau marks are not plotted, and the horizontal dashed line indicates the zero flux level. Note the fluoresced Fe I (UV 44) lines at 2823 Å and 2844 Å, which are quite strong in M-type giants but are not seen in the N-type stars.

et al. 1986) and a high-resolution spectrum taken the same day (Eriksson *et al.* 1986) yield (combined) line fluxes of 51, 49, and 67×10^{-14} ergs cm^{-2} s^{-1}. This uncertainty of $\sim 10\%$ in this strongest line probably increases to a factor of 2–3 in weaker lines. As a measure of the flux not dominated by chromospheric emission lines, and hopefully therefore photospheric, we take the integrated flux between 3000 and 3100 Å. We call this integrated flux f(cont) and list it in the seventh column of Table 3. Following it in Table 3 are shown ratios of selected line fluxes to these integrated fluxes [f(cont)] and to bolometric fluxes.

As with the strong emission of Mg II, there is a possibility of circumstellar absorption lines modifying the emission profiles of this C II feature; possible candidates are V I (UV 31 and UV 32) and Ni I (UV 8 and UV 9). The single high-resolution spectrum of TX Psc did not record this C II feature, and there is no way to determine if circumstellar absorption from these species are present. It is worth noting, however, that the spectra of Arcturus (Carpenter, Wing, and Stencel 1985) and Betelgeuse (Carpenter 1984) do not show any absorption in their C II (UV 0.01) lines.

A characteristic of violet spectra of carbon stars is a much more rapid decrease in flux with decreasing wavelength than is seen in M-giant stars, and this flux deficiency is termed the "violet opacity" (cf. Shane 1928; Walker 1976; Bregman and Bregman 1978; Querci *et al.* 1982). The star UU Aur, which at N3 is expected to have the strongest ultraviolet flux depression of stars in this sample, does have by far the lowest ratio of f(cont)/f(bol). The star U Hya (N2) is next, as expected, although it is not significantly different from some others. The "bluest" star is easily TW Hor. Because of the weak observed pseudocontinuous flux, the ratios of line flux to the integrated flux from 3000 to 3100 Å are noticeably higher for UU Aur, but the ratios of line flux to bolometric flux are normal. In fact, the carbon stars all have relative C II line fluxes within a factor of 3 (which would be 2 except for TW Hor); relative Mg II line fluxes for all stars are within a factor of 3 as well. One might cautiously conclude from the relative behavior of ultraviolet continua and lines that the well-known violet opacity observed for R and N stars acts more strongly on the continuum than on the emission lines and is therefore photospheric in origin.

It was noted earlier (Johnson and O'Brien 1983) that the emission-line fluxes of Mg II (relative to the bolometric fluxes) in carbon stars are substantially lower than in K and early M giants and supergiants. Relative Mg II fluxes of later M-giant stars (Steiman-Cameron, Johnson, and Honeycutt 1985) show a steady, sharp decrease with advancing spectral type. According to that paper, the coolest M-giant stars observed—HD 172816 (= BS 7023 = V3879 Sgr; M4 III) and HD 18191 (= BS 867 = RZ Ari; M6 III)—have relative Mg II line fluxes of 43.1 and 112×10^{-8} ergs cm^{-2} s^{-1} respectively. (We obtain 95×10^{-8} ergs cm^{-2} s^{-1} for RZ Ari, quite acceptable agreement.) Even these fluxes are well above those of the carbon stars, as is shown by the quantitative comparison in Table 4. The relative flux of all ultraviolet emission lines (C II, Fe II, and Mg II) decreases with advancing spectral type for our limited

TABLE 4

EMISSION-LINE FLUXES IN M AND C STARS

Star	Spectral Type[a]	$10^8 \times f(\text{bol})$[a]	$10^{14} \times f(\text{cont})$[a]	$10^6 \times f(\text{cont})/f(\text{bol})$	$10^8 \times f(\text{C II})/f(\text{bol})$	$10^8 \times f(\text{Fe II})$[b]$/f(\text{bol})$	$10^8 \times f(\text{Mg II})/f(\text{bol})$
HD 123934	M1.5 III	152	1270	8.4	62.3[c]	155	433
HD 44478 (μ Gem)	M3.3 II	1170	11,100	9.5	37.2[c]	178	343
HD 18191 (RZ Ari)	M6 III	433	257	0.6	13.4	27.7	95.4
HD 122250 (θ Aps)	M7 III	1590[d]	124	0.08	2.9	2.9	9.8
HD 223075 (TX Psc)	N0	260	127	0.5	5.0	6.2	8.8

NOTE.—Integrated fluxes from all stars were measured from low-resolution spectra.

[a] From Ridgway *et al.* 1980, based on *UBVRI* and *KLMN* photometry, except TX Psc from Tsuji 1981*b*.

[b] Flux from the two Fe II multiplets (UV 62) and (UV 63).

[c] Spectrum is noisy in this region.

[d] $f(\text{bol})$ calculated by $m(\text{bol}) = -2.5 \log [f(\text{bol})] + 8.50$, where $f(\text{bol})$ is in units of 10^{-8} ergs cm^{-2} s^{-1} as seen from Earth. The value for m_{bol} is taken as the average calculated from measured V magnitudes and bolometric corrections from Eaton and Poe 1984 and from Johnson 1966 based on the extrapolated data of the spectral types listed. The total uncertainty is close to a factor of 0.50.

sample. On this scale the typical N-type star TX Psc and the composite N-type star both have relative line fluxes far lower than those of an M6 III star.

Table 4 also shows the relative fluxes from a recent spectrogram of an even cooler star—the M6.5–7 III star HD 122250 (= BS 5261 = θ Aps). At face value, it appears that we may have obtained a spectrum of an M-giant star sufficiently cool that its emission-line fluxes are comparable to those of N-type carbon stars. Unfortunately, the bolometric correction for θ Aps is poorly known, and the bolometric flux is uncertain by at least a factor of 2. In fact, the relative line fluxes in θ Aps seem strikingly weak compared to RZ Ari, and θ Aps may perhaps have an unusually weak chromosphere for its spectral type. According to the standard calibrations (Ridgway *et al.* 1980; Tsuji 1981*a*), the temperature of an M6 III star is 3250 K, and we suppose that of an M6.5–7.0 star to be close to 3000 K. These temperatures are similar to, or just above, those of the N-type carbon stars (Tsuji 1981*b*). If θ Aps is not atypical, it appears that N-type stars may have chromospheric strengths similar to those of M giants of *similar* temperatures, and their chromospheres only appear weak when compared to *earlier* M stars. The relative emission of Mg II in carbon stars may be even greater than measured here, for a high-resolution *IUE* spectrum of TX Psc shows that the Mg II emission is weakened by considerable overlying absorption in the circumstellar shells surrounding these stars (Eriksson *et al.* 1986). It is, consequently, tempting to conclude that apparent chromospheric activity steadily decreases as stellar evolution carries stars to lower temperatures, because either chromospheres actually weaken or circumstellar obscuration of the emission lines increases. Composition has, in this scenario, only secondary importance. In view of the uncertainties arising from the small number of stars yet observed, however, this conclusion is clearly tentative. Additional observations of the coolest red giants would appear to be very profitable.

Beyond the ultraviolet emission lines, chromospheric spectral indicators are scarce. This is not surprising, for these carbon stars lie far to the right of the line in the H-R diagram which divides those stars with hot coronae (solar-like) from those stars with cool stellar winds (non–solar-like) (Linsky and Haisch 1979) which falls near K0 ($V-R$ = 0.7–0.8) for giants. Stars are divided into approximately the same sets by the appearance or nonappearance of soft X-ray emission (Ayres *et al.* 1981; cf. Linsky 1982; Baliunas 1984). In a survey of the He I λ10830 line (presumably excited by coronal emission) in 455 stars (Zirin 1982), six carbon stars were observed. No λ10830 line was seen in TX Psc, and no decsion could be reached for the others due to severe line blending. The line is also not seen in two S stars (R Gem, χ Cyg) and is absent in "normal" M giants and supergiants. Ultraviolet lines of Fe II (multiplets 1, 6, and 7) do not appear in earlier stars but are nearly universal in the spectra of M giants and supergiants, where they correlate well with Ca II H and K emission strengths (Boesgaard and Boesgaard 1976). As noted earlier, they are also seen in certain N-type carbon stars (Bidelman and Pyper 1963), where they constitute the earliest known chromospheric indicators. In contrast to M-giant stars, whose spectra exhibit strong Balmer lines and Ca II K emission cores (Zarro and Rodgers 1983), spectra of N-type carbon stars typically exhibit very weak or no Balmer lines (Utsumi 1970; Yamashita 1972, 1975) and no emission in Ca II K (Bouchet, Querci, and Querci 1983).

The time variability of several emission lines is obvious on a series of spectra of both TW Hor (Querci and Querci 1985) and TX Psc (Johnson *et al.* 1986). The variation is remarkably large; the line flux appears to vary in TX Psc by a factor of at least 6–8. The continuous flux appears not to vary, or to vary by a smaller amount. Possible mechanisms for the variability include the passage of a shock wave through the atmosphere, a variation in the amount of acoustic energy being dissipated in a permanent chromosphere, changes in the area or magnetic field of large plages, or changes in the distribution of the circumstellar clouds or shell which are responsible for the absorption of the Mg II lines (Querci and Querci 1985). Another star, HD 46687 = UU Aur (N3; C5, 3), can also now be added to the list of N-type stars whose ultraviolet emission lines exhibit large variations in strength. Besides the two spectra shown in Table 1, there exists a third spectrum of UU Aur—LWR 14072—taken 1982 September 1 with an exposure time of 150 minutes. Although this exposure is significantly longer than that of LWR 15493 (100 minutes), there is essentially no spectrum above the noise level, while the spectrum on LWR 15493, albeit weak, is definitely present. Specifically, while the fluxes of Mg II and C II on 15493 are comparable to those on the long exposure (LWR 15379) described in Table 3, LWR 14072 has $f(\text{C II}) \lesssim 4 \times 10^{-14}$ ergs s^{-1} cm^{-2} and

$f(\mathrm{Mg\ II}) \lesssim 5 \times 10^{-14}$ ergs s^{-1} cm^{-2}, and even these low values may be partly noise. A difference of a factor of at least 3–5 is clearly indicated.

Chromospheric modeling for the coolest red giants has barely begun. In a pioneering non–LTE study, Avrett and Johnson (1984) found a chromospheric model which predicted the observed Mg II emission in TX Psc to within a factor of 2–5 without producing any Balmer-α emission. To produce the C II line requires rather higher chromospheric temperatures than are required for Mg II, because carbon is harder to ionize.

We summarize here our principal conclusions. (1) Shortward of 2850 Å the spectra consist only of *emission* lines of C II, Fe II, Al II, and Mg II, while the spectrum longward has a continuum with *absorption* lines of Fe I, CH, probably CaCl in some stars, and possibly a few other neutral atoms. Emission lines of Fe II and possibly V II are also seen at longer wavelengths. If the flux from the wavelength range near 2850 Å arises from the region of the temperature minimum (Johnson and O'Brien 1983), it is the first such identification in a cool giant star. (2) A complete list of lines and identifications is given. (3) We conclude that the strong emission feature at 2325 Å is solely or principally due to C II (UV 0.01), with a possible contribution from Si II (UV 0.01) on the longward side. (4) Fluxes are measured for the strongest lines, where such measurement has significance. (5) Emission-line fluxes of Mg II, C II, and Fe II—relative to bolometric fluxes—are less than those of the M6 III star RZ Ari by factors of 3–10 (C II being relatively strongest) and far less than those of earlier M-giant stars. However, emission-line fluxes equal those of the M6.5–7.0 III star θ Aps, which may be closer to the N-type carbon stars in effective temperature. If this star does not have unusually weak chromospheric emission lines, it would seem that relative emission-line fluxes in carbon stars are similar to those of M-giant stars of similar effective temperatures. (6) Several other significant differences appear between spectra of N-type stars and the coolest M-giant stars: (*a*) absorption features from neutral elements and molecules tend to be stronger in the carbon stars; (*b*) carbon stars do not show the fluoresced lines of Fe I (UV 44) at 2823, 2844 Å; (*c*) carbon stars do not show the Fe II (UV 33) emission feature at 2510 Å. (7) Relative emission-line fluxes of carbon stars are all within a factor of 2–3, while the relative continuous flux in the range 3000–3100 Å varies by a factor of 6–8, with the later N-type stars having lower continuous fluxes. Apparently the well-known violet opacity affects the continuous flux more than it does the emission lines.

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