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N-TYPE CARBON STARS AND THE 3-α PROCESS*

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High-dispersion yellow-red spectra of eight representative N-type carbon stars have been matched by Minneart model synthesis. CN, C_2, and Fe line strengths imply high abundances of free carbon, C − O, such that N-star surface carbon must originate from 3-α He-shell burning, rather than from CNO equilibrium processes. CN/C_2 ratios ranging from 4 to 200 imply values of log (C − O)/H from −2.7 to −4.5; these lead to C/O ratios from 2.9 to 1.033, if the oxygen abundances are solar. Nitrogen abundances for these stars are also essentially solar, with a mean value log (N/H) = −4.10 ± 0.18, also ruling out substantial contributions from CNO processing.

Values of the $^{12}C/^{13}C$ ratio range from 3.5 to > 25. Zr/Ti ratios are a factor of 2 to 10 greater than solar, similar to the S stars. Ba is enriched only in some high Zr stars. Rare-earth abundances are subject to severe error. Lithium abundances range from the meteoritic to below solar. The range of log g is −0.3 to 1.7. Excitation temperatures, both atomic and and molecular, are between 2500° K and 3150° K. Microturbulent velocities are in most cases near 6 km sec^{-1}. Relations to other red-giant stars are considered.

Key words: carbon stars — abundances — nucleosynthesis

I. Introduction

The carbon stars constitute the clearest example of stars which show products of stellar nucleosynthesis on their surfaces. R. H. Curtiss and C. D. Shane, as discussed by Russell (1934), first explained the appearance of the carbon stars: when the atmospheric abundance of carbon exceeds that of oxygen, the oxide bands common in the spectra of most red giants are replaced by bands of carbon compounds. In that case, the highly stable CO molecule ties up nearly all of the oxygen atoms, leaving the remaining carbon to form observable amounts of CN, C_2, and CH molecules. The C/O ratio is an exceedingly important parameter determining the appearance of the atmospheres of late-type peculiar stars.

The C/O ratio for the sun is 0.60, according to solar wind sampling (Lambert 1968*a*). Querci and Querci (1970) obtained for UU Aurigae, a typical N star, a C/O ratio of 3.3. Thompson, Schnopper, and Rose (1971), employing M-star atmospheres to study four N stars, found C/O ratios between 2 and 5, and also low C/H ratios; these results are based on measurements of infrared C_2 and CO bands, and are dependent on the very uncertain f-values assumed for the C_2 Ballik-Ramsey bands. High nitrogen-to-carbon ratios and low oxygen abundances, similar to CNO-cycle equilibrium, were assumed in both these studies of N-type carbon stars.

A quantity which should in principle be more easily determined, but so far has remained a bit of a problem, is the $^{12}C/^{13}C$ ratio, an important test for theories of red-giant evolution. In the solar system this ratio is 90. For cool carbon stars the isotopic ratio seems to be between 20 and 40, although values as low as 4 are indicated in several stars (Fujita 1970).

The coolest carbon stars, of spectral class N, show considerable enrichment of those heavy elements believed produced by the slow neutron capture process, the s-process. Collectively these elements shall here be denoted as s-p. Utsumi (1970) found all measured s-p elements to be quite enriched in 22 N stars. Technetium, an unstable s-p element (half-life at most 200,000 years), has been found in several N stars (Peery 1971).

Torres-Peimbert and Wallerstein (1966) found many carbon stars to be rich in Li (10–100 times the solar atmospheric abundance), and also found that two of them, WZ Cassiopeiae and WX Cygni, are super-rich (10^4 times solar). Boes-

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gaard (1970*b*) found some S stars to be similarly enriched.

The difficulties in determining chemical abundances of cool carbon stars are probably the most severe found among stars bright enough to analyze. The most obvious difficulty is posed by the ubiquitous nature of the molecular rotational lines, especially of CN, in the spectra. Even with high-dispersion spectrograms, the great majority of atomic lines are blended with molecular lines. The suggestion by Wallerstein (1971, 1973) that Utsumi's results, based on curve-of-growth analysis, were possibly subject to this and other problems, led us to perform our own analysis of the chemical abundances in several N-type carbon stars. We used the rather simple Minneart model spectrum synthesis, which enables proper allowance for the relative contributions of each atomic and molecular line to observed spectral features. The constant-temperature Minneart model, based on the Milne-Eddington theoretical atmosphere, conforms to empirical results. It averages any stratification effects, but still has marked advantages over previous methods of abundance determination for the N stars. More complicated model-atmospheric approaches would require accounting for effects of sphericity, non-LTE, and atmospheric motions. Also, to yield improved results for carbon star abundances, better knowledge of complex molecular opacities is needed.

In section II the sources of data are discussed, as well as the calculation of *f*-values. In section III is found a brief description of the line-formation model. Section IV discusses methods used for determination of physical parameters and abundances. In section V the synthesis fitting-procedure is described, together with problems encountered for each star. Section VI gives the numerical results, as well as comparisons with previous work. Section VII contains implications of the numerical results, and a summary.

II. Data

A. *Observations*

Spectrograms of several carbon stars were made available by George Wallerstein. The plates used were all taken with the 3.05-m telescope at Lick Observatory. The 1.02-m camera was used at the coudé focus; the grating, blazed at 6200 Å for use in the second order, yielded a reciprocal dispersion of 8 Å mm^{-1}. The plate emulsion is Eastman Kodak IIa–F, and a GG-11 filter was used. The spectral region from 5600 Å–6800 Å was covered. Details of the plate exposure times and dates will be found in Table V. For the final analysis eight stars were chosen, representing a variety of N stars.

Calibration strips for conversion of the plate densities to intensitites were exposed on each plate, though they were underexposed on the plate for Y Canum Venaticorum. Two of the plates were traced using the microphotometer at Berkeley, which, with the aid of an analog computer, produces a direct intensity tracing; those two plates were of 19 Piscium and HD 189711. All other plates were traced on the UCLA microphotometer in the density mode, to minimize electrical noise. For these stars, the computer-synthesized spectra were made to contain an intensity-density conversion for direct comparison with the tracings. All tracings magnified the plate scale by about 400 times, giving approximately 5 cm $Å^{-1}$.

B. *Identification of Spectral Features*

An extensive search for spectral features was made on the tracing for 19 Psc, a star which Utsumi found to be very rich in s-p elements, but one without too much ^{13}C, which would have masked some atomic features. Wavelengths for the ^{12}C molecular features were taken from the excellent Berkeley monographs on CN (Davis and Phillips 1963) and C_2 (Phillips and Davis 1968). Dr. Phillips also supplied computer cards for the relevant molecular features. A small number of CN features, about 100, were found in the star but not in the tables. These features were seen to be due to CN by interpolation in, and extrapolation (to higher excitation levels) of, the rotational spectral branches. With the ^{12}CN wavelengths and the molecular constants for CN found by Faÿ, Marenin, and Van Citters (1971), we calculated all relevant wavelengths for the isotopic molecule, $^{13}C^{14}N$, in the spectral region observed. The existence of these features in the spectrum of Y CVn, a star known to be rich in ^{13}C, confirmed the calculations to better than 0.1 Å. Wavelengths for $^{14}C^{14}N$ lines were also determined, but these features were unobservable in the spectra of U Hydrae and Y CVn. For all these calculations we used the nuclear isotopic

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masses of Wapstra and Gove (1971). The spin-orbit coupling constants, $Y(v') = A(v')/B(v')$, were taken from formulae given by Kovacs (1969).

Identifying so many molecular features (about 10 per Å) allowed easy identification of atomic features on the spectral tracings. Four lists of atomic lines were used: Moore, Minneart, and Houtgast (1966), Meggers, Corliss, and Scribner (1961), Moore (1959), and Harrison (1969).

C. *f-Values*

Atomic transition probabilities (*f*-values) and excitation energies of the lower electronic state were obtained from Corliss and Bozmann (1962) for some elements. For titanium, level-dependent *f*-value changes were made based on the work of Wolnik and Berthel (1972). Barium *f*-values were taken from Miles and Wiese (1969). For several elements, especially calcium and iron, astrophysical *f*-values were determined for lines observed in the sun, with the assumption of meteoritic abundances; for this we used the detailed solar synthesis program by Ross (1973). Further descriptions of the method used can be found in Ross (1971) and in Ross and Aller (1968). Recent work on sunspot spectra of lanthanum by Molnar (1972) also indicated a need for revised *f*-values. Those atomic lines used for abundance determination are listed in Table I, together with their energy levels and adopted *gf*-values.

Molecular absorption coefficients were calculated following the discussion of Tatum (1967*a*). The results of Kovacs (1969) were used to derive formulae for the Hönl-London factors, $S_{J''}$, in the CN red system; these factors agree within 1% with the values of Lambert (1968*b*). For the C_2 Swan bands the Hönl-London factors were calculated from formulae given by Phillips (1971) in the unmodified computer program MOLE2. At the large rotational quantum numbers observed, the formulae are essentially the same as those of Budo (1937), except for a factor of two, which correction was made, as Budo's are correctly normalized (Querci, Querci, and Kunde 1971).

We have assumed the *r*-centroid approximation in calculating the band oscillator strengths, $f_{v'v''}$, sometimes called the vibrational *f*-values. The required Franck-Condon factors, $q_{v'v''}$,

TABLE I

Atomic Lines for Abundance Determination

Wavelength	Species	χ	gf	gf-Source
5698.52	V I	1.06	0.76	R
5700.21	Sc I	1.43	4.0	R
5701.56	Fe I	2.56	0.0062	R
5702.68	Ti I	2.29	0.24	WB
5703.56	V I	1.05	0.56	R
5706.98	V I	1.04	0.34	R
5708.23	Ti I	2.32	0.14	WB
5708.61	Sc I	1.45	1.4	R
5708.89	Zr I	0.0	0.0015	R
5709.39	Fe I	3.37	0.069	R
5709.56	Ni I	1.68	0.012	R
5711.75	Sc I	1.43	0.80	R
5711.88	Ti I	2.31	0.23	WB
5711.90	Ni I	1.93	0.01	R
5712.40	La II	0.17	0.01	MCB
5713.92	Ti I	2.29	0.15	WB
5715.13	Ti I	2.25	0.31	WB
5716.48	Ti I	2.30	0.19	WB
5717.28	Sc I	1.44	0.58	R
5720.48	Ti I	2.29	0.13	WB
6124.84	Zr I	0.52	0.043	R
6126.22	Ti I	1.07	0.045	WB
6127.44	Zr I	0.15	0.056	R
6128.34	V I	1.05	0.027	R
6128.98	Ni I	1.68	0.0003	R
6134.55	Zr I	0.0	0.044	R
6135.38	V I	1.05	0.18	R
6136.62	Fe I	2.45	0.027	R
6137.00	Fe I	2.2	0.00081	R
6137.70	Fe I	2.59	0.029	R
6138.43	Y I	0.07	0.016	R
6140.46	Zr I	0.52	0.060	R
6141.72	Ba II	0.7	0.80	MW
6143.20	Zr I	0.07	0.026	R
6400.01	Fe I	3.60	0.51	R
6400.32	Fe I	0.91	0.000015	R
6402.01	Y I	0.70	0.0066	R
6407.00	Zr I	0.15	0.0025	R
6408.03	Fe I	3.69	0.045	R
6410.93	La I	0.37	3.00	M
6411.67	Fe I	3.65	0.20	R
6413.14	Ti I	0.05	0.00008	WB
6413.32	Sc I	0.02	0.012	R
6421.36	Fe I	2.28	0.0028	R
6439.08	Ca I	2.52	0.67	R
6445.72	Zr I	1.00	0.08	R
6448.10	Sc I	0.02	0.01	R
6449.82	Ca I	2.52	0.15	R
6450.85	Ba I	1.12	0.34	MW
6452.32	V I	1.19	0.11	R
6454.52	La I	0.33	1.2	MCB
6455.99	La I	0.13	1.9	MCB
6693.88	Ba I	1.19	0.96	MW
6703.58	Fe I	2.76	0.00059	R
6707.76	Li I	0.0	1.01	WSG
6707.91	Li I	0.0	0.50	WSG

NOTES TO TABLE I

These spectral features are the ones from which the atomic abundances have been determined. The sources from which the *gf*-values have been taken are the following:

MCB — Molnar (1972) corrections to Corliss and Bozmann (1962).

MW — Miles and Wiese (1969).

R — Astrophysical determinations using the solar-synthesis program of J. E. Ross (private communication) and equivalent widths from Moore, Minneart, and Houtgast (1966).

WB — Excitation-level-dependent corrections (Wolnik and Berthel 1972) made to the values found in Corliss and Bozmann (1962).

WSG — Wiese, Smith, and Glennon (1966).

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were taken from Spindler (1965), who gives them for the CN red and C_2 Swan band systems, using calculations from assumed Rydberg-Klein-Rees potential curves. According to Carbon (1973), isotopic effects will produce a negligible difference for $q_{v'v''}$ between ^{12}CN and ^{13}CN. The electronic transition moment for CN was taken from the shock-tube result of Arnold and Nicholls (1972). From their study this moment is almost independent of internuclear separation in the wavelength region considered for the CN red system. Consequently, $f_{v'v''} \propto q_{v'v''}/\lambda_{v'v''}$, a relation which was used. Others (Querci, Querci, and Kunde 1971; Lambert 1968*b*) have held differently: if their views were correct, then the CN abundances we obtain should be doubled. However, a private communication from Dr. Carbon regarding synthesis of solar molecular lines gives us considerable confidence in the CN *f*-values chosen here.

The C_2 Swan band oscillator strengths were taken from Danilewicz (1971). She determined relative vibrational *f*-values with an estimated uncertainty of 10% by studying relative integrated band intensities from a discharge tube, then normalizing to a value for f_{00} averaged from the literature. Our survey of recent results as reported by Grevesse and Sauval (1973) and Cooper (1973) leads us to accept the absolute scale chosen by Danilewicz. Her results for the C_2 Swan bands also imply $f_{v'v''} \propto q_{v'v''}/\lambda_{v'v''}$ in the spectral region of interest.

Thus the adopted molecular absolute *f*-values are

CN red system

$$f_{00} = 2.19 \times 10^{-3} \pm 20\%$$
$$f_{v'v''} = (4.5 \times 10^{-3} \pm 20\%) \times \frac{10{,}970\ \text{Å}}{\lambda_{v'v''}} q_{v'v''} \quad (1)$$

C_2 Swan system

$$f_{00} = (20 \pm 6) \times 10^{-3}$$
$$f_{v'v''} = (28 \pm 8) \times 10^{-3} \times \frac{5170\ \text{Å}}{\lambda_{v'v''}} q_{v'v''} \quad . \quad (2)$$

For the CN red system (5, 1) $Q_1(22)$ line at wavelength 6400.80 Å, we derive a Hönl-London factor, $S_{J''} = 20.59$. With $q_{v'v''} = 0.036$ from Spindler (1965), we then have from equation (1) $f_{v'v''} = 2.77 \times 10^{-4}$. This quantity multiplied by the Hönl-London factor gives $gf = 5.7 \times 10^{-3}$.

D. *Molecular Energy Levels*

The excitation levels of the lower state of the absorption transition were calculated with the formulae of Herzberg (1950) and the constants quoted by Tatum (1967*b*). There should not be sizable errors in these quantities. The changes in energy levels for the ^{13}CN molecule due to isotopic shift were not included explicitly. With the results of Faÿ (1971) for the isotopic change in partition function (about 5%), we found that, to the accuracy of our results, that change nearly counterbalanced the isotopic energy level shift and Boltzmann factor increase. Molecular bands used in this analysis are listed in Table II, together with the adopted vibrational *f*-values and other relevant parameters, including $G_{0v''}$, the $J = 0$ excitation energies.

E. *Partition Functions*

The partition function, $u = \Sigma(g \times 10^{-\theta\chi})$, represents the total availability of states in a particle. (Here g is the statistical weight of a state, χ its excitation energy, and $\theta = 5040/T$.) For atomic abundance determinations we used partition functions calculated by Drawin and Felenbok (1965), supplied by John Ross; these differ little from values found elsewhere in the literature. For CN and C_2 we used the values calculated by Tatum (1967*b*). The proper statistical weight to use with these values in calculation of molecular line strengths is $g = 2J + 1$, the rotational statistical weight alone. Then

TABLE II

CN	$q_{v'v''}$	$G_{0v''}(cm^{-1})$	$f_{v'v''}$	Y(v')	λ(Å)
(4,0)	0.011	0.0	8.5×10^{-5}	31.901	6180-5580
(5,1)	0.036	2042.42	2.7×10^{-4}	32.167	6320-6740
(6,2)	0.068	4058.55	5.0×10^{-4}	32.434	6466-6900
(7,3)	0.095	6048.39	7.0×10^{-4}	32.701	6620-7180
(5,0)	0.0028	0.0	2.4×10^{-5}	32.167	5600-5900
(7,2)	0.028	4058.55	2.3×10^{-4}	32.701	5850-6250
(8,3)	0.048	6048.39	3.9×10^{-4}	32.969	5990-6370
(9,4)	0.068	8011.94	5.3×10^{-4}	33.239	6130-6417
C_2					
(0,2)	0.047	3928.92	1.1×10^{-3}		5849-6191
(0,4)	0.025	7038.24	5.4×10^{-4}		6363-6762
(3,6)	0.065	10074.20	1.5×10^{-3}		6339-6599

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for molecular absorption lines, $gf = S_{J''} f_{v'v''}$.

III. The Minneart Model

To create a synthetic stellar spectrum, one must begin with a stellar atmospheric model. With our present understanding of carbon stars, the Minneart formula (Minneart 1935) seems an appropriate choice. With that formula, equivalent to the Milne-Eddington and Schuster-Schwarzchild atmospheric models, good synthetic representations of the observed stellar spectrum can be obtained. Also, one obtains internally and externally consistent results for the physical parameters and abundance ratios (see Collins and Mutschlecner 1972).

The Minneart formula is

$$\frac{1}{R_v} = \frac{1}{R_c} + \frac{1}{\mathrm{NH}\alpha_\nu} \quad , \tag{3}$$

where R_v is the residual intensity (absorbed fraction of continuum radiation), R_c is the limiting residual intensity, NH is the column number density, and α_ν is the particle-photon cross section. The treatment assumes α_ν is due to pure absorption and is invariant with depth in the atmosphere.

Macroturbulence and instrumental effects were assumed to produce an observed spectrum showing Gaussian smearing of the absorption features due to a localized region of the star. Therefore a single combined Gaussian smearing function was applied to the residual intensities calculated by the Minneart formula for the synthesized spectrum.

Microturbulence, which may be a real hydrodynamic effect (van Paradijs 1972), was accounted for in the syntheses. No reasonable fit of computed to observed line profiles could be made without substantial microturbulence. For more details on the synthesis program see Kilston (1973).

IV. Determination of Atmospheric Parameters

A. *Temperature*

Four Fe lines in the 6400 Å region determined the atomic temperature. These lines, 6400.01 Å, 6400.32 Å, 6411.67 Å, and 6421.36 Å, were nearly free from blending problems, have good astrophysical gf-values from Ross's solar work, and cover a wide range in excitation potential (0.91 eV to 3.65 eV). For each star these lines gave a very consistent temperature.

The molecular temperature was determined from comparison of lines of several excitation potentials, differing in both rotational and vibrational quantum numbers. The result is a combined rotational-vibrational excitation temperature. Becuase of less variation in the excitation potential for molecular than for atomic lines, the molecular temperature was less well determined. Yet a single molecular temperature did seem able to fit all the regions in a given star. For this reason, the atomic temperature was also generally assumed constant with wavelength. The molecular temperature was determined primarily from CN lines, which were by far the most numerous in the spectra, but the temperatures so found also agreed with C_2 line strengths.

B. *Electron Pressure*

Because of the cool temperatures of carbon stars, most elements are found mainly in one stage of ionization. In fact, the only certain identifications we could make regarding neutral and ionized lines for the same element were for Ba and La, and in several stars the neutral lines were not very evident. Thus we were forced to resort to an indirect method to help determine the electron pressure, a very important quantity in analyzing both the stellar abundances and physical properties, as explained by Aller (1963).

From the Saha ionization equation, one finds

$$\log P_e = 2.5 \log T_I - \theta_I \chi_I - 0.48 - \log \frac{N_1}{N_0} + \log \frac{2u_1(T_I)}{u_0(T_I)} \quad , \tag{4}$$

where the subscript I stands for ionization and the subscripts 1 and 0 stand for singly ionized and neutral atoms, respectively. We took the ionization temperature to equal the atomic excitation temperature, which follows from assumption of local thermodynamic equilibrium in a Schuster-Schwarzschild model. The abundance of Fe is essentially that of the neutral Fe observed, at the temperatures found. The observed ratio of neutral calcium to iron is then compared to the solar ratio of their total elemental abundances, which is assumed characteristic of carbon stars also. Any relative deficiency in neutral calcium is attributed to a complementary (but unobservable) abundance of ionized calcium. Similar assumptions are made for Sc, Ti, and V,

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although these cannot be used in every case, as can be done for Ca. These inferred abundances of the ionized species then can be used in the Saha equation. Where available, abundances for neutral and ionized Ba were combined to compute a pressure. A weighted average of the values so obtained for log P_e was determined for each star. These calculations are summarized in Table III. There it is also seen that a likely probable error in log P_e is about 0.5 dex, as the scatter indicates. Further indications that these are meaningful pressures are given later.

C. *Gas Pressure*

A gas pressure can be estimated from the ionization temperature and electron pressure, assuming that the major electron donors are potassium, sodium, and calcium in essentially solar system abundances. This was done by using a graph of the results of Tsuji (1973). This pressure was taken to be the total pressure in the molecular line-formation region, since the temperatures found for atoms and molecules agreed to within their error limits.

TABLE III

P_e Determination

Entries, by element, refer to Weight, W(el) log N_{II}/N_I log P_e(el), respectively.

Only the ionization ratios for barium result from measurements of both species; for the other elements, only lines of the neutral species were considered, and ion abundances inferred from assumed solar system values for the total elemental abundances gave the ratios. Then log $P_e = \alpha/\beta$, where $\beta \equiv \Sigma W(el)$, $\alpha \equiv \Sigma\{W(el)\cdot \log P_e(el)\}$

Star TI	Ca	Sc	Ti	V	Ba	β α	log P_e	log P_g
RZ Peg	1	--	0.5	--	1	2.5		
2500	1.5	--	0.2	--	0.5:		-4.0:	1.4:
	-5.2	--	-5.3	--	-2.3	-10.1		
V CrB	1	1	0.5	0.5	--	3		
2800	1.9	0.4	-0.4:	-0.3	--		-3.7	1.4
	-4.2	-3.6	-3.2:	-3.5	--	-11.2		
19 Psc	1	1	0.5	--	0.5	3		
2860	1.7	0.5	-0.6	--	2.6		-3.4	1.9
	-3.8	-3.5	-2.7	--	-3.0	-10.2		
U Hya	1	1	--	--	0.5	2.5		
2800	1.6	0.4	--	--	2.4:		-3.6	1.8
	-3.9	-3.6	--	--	-3.0	-9.0		
RX Peg	1	0.5	0.5	--	--	2		
2900	1.7	0.5:	-0.5	--	--		-3.3	1.9
	-3.6	-3.3:	-2.6	--	--	-6.6		
Y CVn	1	1	0.5	--	--	2.5		
3000	1.9	0.6	-0.7	--	--		-3.0	1.9
	-3.4	-3.0	-2.0	--	--	-7.4		
V Aql	1	1	--	0.5	0.5	3		
3000	1.6	0.5	--	-0.2	2.3:		-2.8	2.2
	-3.1	-2.9	--	-2.7	-2.1:	-8.4		
HD	1	1	0.5	0.5	--	3		
189711	2.1	0.8	-0.2	-0.2	--		-2.4	2.4
3150	-3.0	-2.4	-1.8	-2.0	--	-7.3		

D. *Abundances*

Becuase of the evident opacity variation with wavelength, seen from the consistent variation of line strengths of several elements, all atomic abundances were normalized to the Fe abundance in the wavelength region where they were measured, then weighted and averaged for the whole star. The numerical abundances for each star, the contributions calculated for unobserved ionization states (denoted by parentheses) with the adopted electron pressures, and the apparent variations of abundance with wavelength region are all listed in Table IV. The rather large error, about 0.5 dex, in determining the electron pressure is the major limitation on accuracy for most atomic abundances. Undoubtedly, the distribution within the stellar atmosphere of elements widely differing in ionization potential accounts for much of the difficulty with the electron pressure, which could not really have a single value throughout the line-formation region. However, it is felt that the abundances found are sufficiently accurate to distinguish between certain types of carbon stars. For some quantities, such as the Ti/Zr ratio, the electron pressure cancels out, and these can be determined with uncertainty of only 0.3 dex.

The molecular abundances are quite well determined, if one can assume that the *f*-values are reasonably accurate. The $^{12}CN/^{13}CN$ ratio is independent of *f*-value uncertainty; in most stars it is easily determined to within 20%. The CN/C_2 ratio, while dependent on *f*-value choice, should be fairly independent of assumed model or stratification effects for the star, since the distribution of both molecules is nearly identical in the atmosphere, according to Scalo (1973*a*). The CN/Fe ratio might vary with wavelength region, because the extents of Fe atoms and CN molecules need not be similar; thus, viewing different depths in each region could affect the ratio. As shown in Table IV, all wavelength regions gave quite consistent solutions for CN/Fe, with the single exception of the 6130 Å region. There the Fe abundance seems regularly about half that in the other regions; this effect can be seen in the CN/Fe table also. The 6130 Å region has the strongest C_2 features of any synthesized region, thus a simple explanation of the above effect could be increased

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TABLE IV

Neutral Atoms and Ions: Abundances relative to Fe = 8.9×10^5 (~Si=10^6)

Species	RZ Peg	V CrB	19 Psc	U Hya	RX Peg	Y CVn	V Aql	HD 189711	Solar System
Li I	0.014:	0.0035:	0.018	0.014	0.28:	0.50	0.20	0.006:	49.5
(II)	0.22:	0.028:	1.8	1.4	35:	80	20	0.7:	
Ca I	1800	800	1400	2000	1200	950	2000	520	66600
(II)	3600	20000	28000	40000	30000	30000	40000	16000	
Sc I	19:	10	8	10	9:	7	8	5	35
(II)	5:	31	20	25	30:	28	20	31	
Ti I	1000	1800:	2000	2700	1900	2100	2500:	1500	2500
(II)	80:	2300:	2500	2700	3000	4200	2900:	3800	
V I	320	190	500:	350	280:	280:	180	180	298
(II)	20:	150	400:	210	280:	350:	145	300	
Ni I	--	80000:	60000:	20000:	50000:	60000:	50000:	140000:	45700
(II)	--	--	--	--	--	--	--	--	
Y I	20	16	21	21	3.5:	11:	43	8	4.6
(II)	8:	64	84	66	18:	70:	170	50	
Zr I	90	100	160	110	40:	60:	160	30	26
(II)	7:	125	200	110	63:	120:	180	75	
Ba I	1.2:	0.2:	0.3	0.2:	0.04	0.04	0.4	0.14	4.7
II	4:	3.5:	110	50	3.5	1.5:	80:	20:	
La I	0.3	0.03:	0.11	0.09:	0.014:	0.04	0.3	0.014:	0.37
II	≤5.0	≤35:	≤16	≤8	≤2:	≤8:	≤25	≤50:	

Wavelength Dependencies

λ region	log Fe (number/cm^2)							
5700 Å	--	20.65	20.98	21.09	20.92	20.63	20.78	20.49
6130	20.76	20.35	20.58	20.49	20.39	20.18	20.02	19.54
6400	20.98	20.45	20.58	20.53	20.87	20.41	20.15	20.19
6700	21.16:	20.88:	20.76:	20.73:	20.92:	20.51:	20.21:	20.41:

CN/Fe

5700 Å	--	0.040	0.032	0.033	0.098	0.24	0.20	0.065
6130	0.065	0.15	0.16	0.18	0.32	0.46	0.65	0.68
6400	0.008	0.043	0.047	0.085	0.071	0.13	0.15	0.078
6440	0.011:	0.065:	0.067:	0.085:	0.062:	0.13:	0.21:	0.11:
6700	0.006:	0.040:	0.045:	0.053:	0.048:	0.085:	0.12:	0.065:

CN/C_2

6130 Å	200:	27	40	20	8	13.3	7	35:
6400	--	≥3	23:	20:	8	10:	2.1	12:
6700	--	25	33	14	6	8	3.8	12:

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opacity in that region, due to a blanketing from overlapping wings of the molecular lines. Fe atoms should exist throughout the photosphere, while molecules may exist just in its outer part (because of dissociation occurring in deeper layers). Thus we might get a more reasonable estimate of a localized CN/Fe ratio by using that ratio found in the blanketed spectral region (where we may not be seeing Fe "below" the molecules). For this reason, we have weighted the average CN/Fe twice as much toward the value found in the 6130 Å region as toward the combined value for the other regions. The near constancy of CN/C_2 with wavelength, as the table shows, implies that the average value used for that quantity should be adequate.

E. *Deduction of C, N, and O Abundances*

Molecular abundances can be used to give a meaningful solution for the abundance parameters (C−O)/H and N/H. The necessary assumptions are that nearly all atmospheric oxygen in carbon stars is bound up in the form of CO molecules, and that the effect of polyatomic molecules is slight. The stars are cool enough for the first, and hot enough for the second assumption to be valid.

The molecular equilibrium equation for C_2 is $P_{C_2} = (P_C)^2 K_{C_2}$, where K_{C_2} is the pressure equilibrium constant. As assumed, the available carbon is the excess of carbon over oxygen, thus $P_C = P_H(C-O)/H$; there follows

$$\log\left(\frac{C-O}{H}\right) = \frac{1}{2}\left(\log K_{C_2} + \log\frac{C_2}{H} - \log P_H\right) \quad . \tag{5}$$

P_H is essentially equal to P_g, since the stars are assumed to have a surface hydrogen number abundance of 90%. This assumption does not affect the conclusions reached below. Because P_g varies slightly faster than P_e, at least one-half of the error in $\log P_e$ will be found in log (C−O)/H.

The C_2/H ratio is determined from the CN/Fe and CN/C_2 ratios, together with the assumption of log (Fe/H) = −4.4, as found for the solar system. If the N stars are as strongly concentrated to the galactic plane as they seem, then we would expect their iron abundances to be those "typical" of galactic disk stars like our sun. It should be noted that the *f*-value effects on the C_2/H ratio do not involve the *f*-value for CN. At small (C−O)/H the effects of forming the CS molecule become significant. For RZ Pegasi and 19 Psc corrections of less than 0.2 in log (C−O)/H have been made, following Scalo (1973*a*).

To derive the nitrogen abundance, we have used the CN equilibrium equation. Scalo (1973*a*) finds most of the atmospheric nitrogen to be in N_2 molecules. Then using also the N_2 equilibrium equation, $P_{N_2} = (P_N)^2/K_{N_2}$, we have

$$\frac{CN}{H} = \frac{P_{CN}}{P_H} = P_C(P_{N_2}K_{N_2})^{1/2}/(P_H K_{CN}) \quad .$$

But

$$\frac{P_{N_2}}{P_H} = \frac{N}{2H} \quad ,$$

so

$$\frac{CN}{H} = P_C(K_{N_2}P_H N/2H)^{1/2}/(P_H K_{CN}) \quad .$$

Using equation (5), we obtain

$$\log\frac{N}{H} = \log\frac{CN}{C_2} + \log\frac{CN}{H} + 2\log K_{CN} - \log K_{C_2}K_{N_2} + \log 2 \quad . \tag{6}$$

Again we use the solar-system Fe/H ratio for finding the abundances relative to hydrogen. The temperature-dependent expressions for the equilibrium constants were taken from Tsuji (1973); they should be considerably more accurate than the observed abundance ratios, at least in the cases of C_2 and N_2. The same probably applies to CN, considering the results and discussion of Arnold and Nicholls (1972). However, it should be noted that an error in the dissociation energy of 0.2 eV would result in an error of a factor of 3 at 2500° K.

The detailed molecular-equilibrium program described by Scalo (1973*a*, *b*) was used to verify these calculations. The resulting abundances agreed to within 0.05 dex in all cases, when compared with the results of the approximate formulae used, both for C−O and for N.

V. Sample Fittings and Fitting Procedure

Five spectral regions were synthesized for

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each star. These regions were 5699 Å–5719 Å, 6123 Å–6147 Å, 6398 Å–6423 Å, 6436 Å–6457 Å, and 6690 Å–6709 Å. Information from other regions was also considered in checking the results from these regions for consistency. Two sample fittings are shown: Figure 1 shows the 6400 Å region for 19 Psc, and Figure 2 shows the 6130 Å region for U Hya. Many minor molecular and atomic features were included in the syntheses, but only the major features are identified in the sample fittings.

After the data for a region were entered into the computer and a first guess at the synthesized spectrum was produced, a transparent overlay

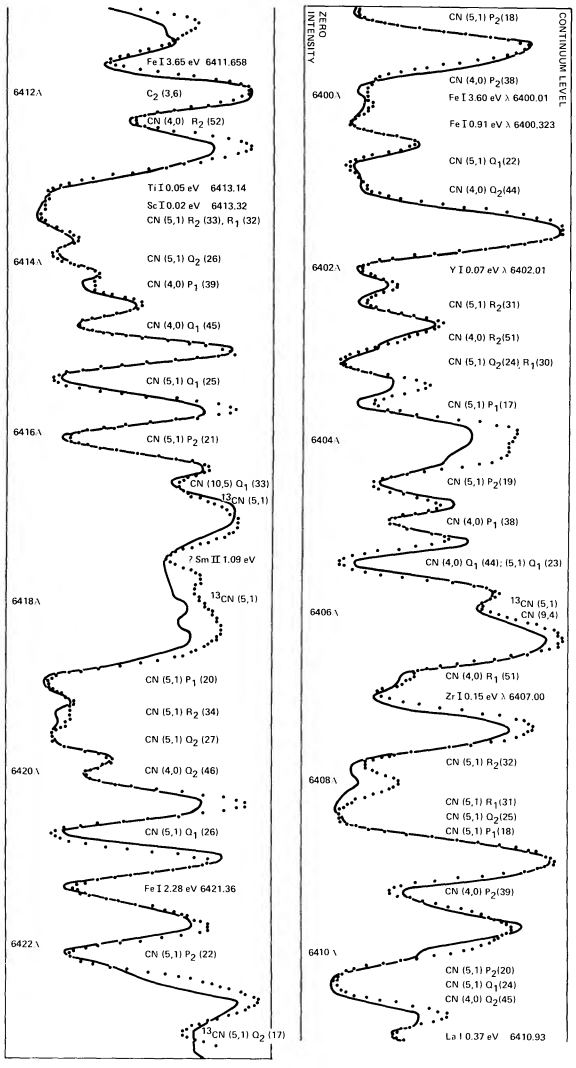

FIG. 1 — 19 Psc spectrum, observed intensity (_____) and computed intensity (. . . . .), 6398 Å–6423 Å.

of the actual stellar spectrum was placed upon the computer plot and compared with it. The vertical scaling factor was adjusted to match the interline features of greatest intensity. In most regions the resulting continuum level for the plot was never quite reached by the observed or computed spectrum; there were far too many spectral features, approximately ten molecular lines per Angstrom. The abundances, R_c, and the temperatures were manipulated to provide the best match for the strongest lines. The general shape of isolated lines provided the best clue for adjusting the microturbulence, which in turn affected the line depths. The Gaussian broadening parameter was determined both by the height of the domain between barely blending lines, and by the limit which the observed residual intensity placed upon smearing. The Lorentzian parameter, a, was generally found to be essentially zero; this was partly due to the large contribution of microturbulent velocity (typically about 6 km sec^{-1}) to the Doppler broadening, and also due to the small collisional broadening expected at the small densities found in atmospheres as extended as those in carbon stars. For further discussion of this point see Yamashita and Utsumi (1962).

Adjustment of parameters was continued until a best fit was obtained for each region of each stellar spectrum. The fits for RZ Peg were generally inferior to those for the other stars. Results for that star are less certain due to considerable noise in the spectrum, as well as to a larger number of unidentified features attributable to the cool atmosphere. The problems were sufficient to prevent analysis of the λ5700 region for RZ Peg.

The spectra of V Coronae Borealis, 19 Psc, and U Hya presented little difficulty. There were relatively few strong C_2 or isotopic molecular features to interfere with the lines used for determining atomic abundances. The spectra had good resolution and little noise.

The remaining four spectra did have some blending problems due to the greater number of significant molecular features, but a useful choice of atomic lines was possible. There were no problems with noise. For RX Peg the plate exposure caused the lower section of the density-intensity curve to be poorly determined, but this effect was significant only in making the

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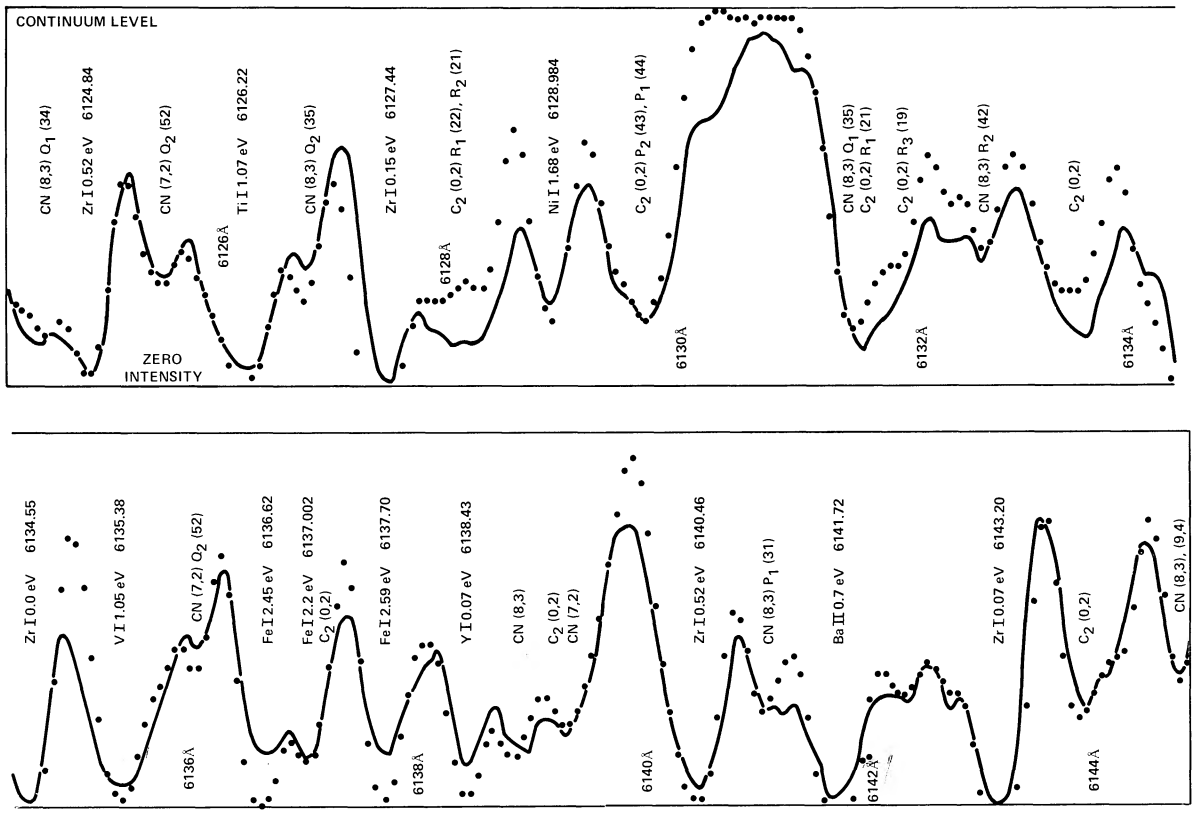

FIG. 2 — U Hya spectrum, observed density (———) and computed density (. . . . .), 6123 Å–6145 Å.

λ6708 Li-line core synthesis difficult, as well as for the Zr lines near λ6130. The highest-temperature star, HD 189711, had the fewest unidentified features, presumably due to greater molecular dissociation.

VI. Results and Comparisons

A. *Atomic Abundances*

The primary results of this analysis are found in Table V, together with most other information known about the stars observed. The results for the atomic abundances are presented first. In the usual way, the logarithmic ratio of abundances relative to iron are given in comparison to supposedly primordial solar-system abundances determined from sun and meteorite studies, such as by Urey (1972). These adopted solar-system abundances are also listed in Table V.

The line-of-sight Fe number abundances given were those found for the 6400 Å region, where they are best determined. All other quantities came from joint consideration of all wavelength regions. The microturbulence is given in km sec^{-1}, while the instrumental broadening and total Gaussian broadening parameters are given in Å and are half-intensity full widths, rather than the *e*-folding half-width representing the microturbulent velocity.

The errors quoted in Table V are the total of random and systematic errors, as best as can be determined. For many of the abundances the largest part of the error is caused by uncertainties in the pressure or *f*-values. It should be pointed out that the differences between stars are probably free of the largest part of the listed errors.

The Zr/Ti ratio (relative to that of the solar system, and logarithmic) is listed separately, since it is independent of the electron pressure (Zr and Ti have the same ionization potential). Boesgaard (1970*a*) determined this ratio for S- and other late-type stars, but she used solar abundances (from Goldberg, Müller, and Aller 1960) instead of meteoritic comparison abundances. This implies her results for Zr/Ti should be decreased by 0.25 dex when weighed against

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TABLE V

[M]	Abund	RZ Peg	V CrB	19 Psc	U Hya	RX Peg	Y CVn	V Aql	HD 189711	Source Err
[Li]	3.34	-2.7:	-3.2:	-1.4	-1.5	≥-0.1:	0.2	-0.4	-1.8:	0.6
[Ca]	6.47	-1.2:	-0.5	-0.4	-0.2	-0.3	-0.3	-0.2	-0.6	0.5
[Sc]	3.19	≥-0.2:	0.1	-0.1	0.0	0.0:	0.0	-0.1	0.0	0.5
[Ti]	5.05	-0.4	0.2:	0.3	0.3	0.3	0.4	0.3:	0.3	0.5
[V]	4.12	0.1	0.1	0.5:	0.3	0.3:	0.3:	0.0	0.2	0.6
[Ni]	6.31	---	0.2	0.1	-0.4	0.0	0.1	0.0	0.5	0.5
[Y]	2.31	0.8	1.2	1.4	1.3	0.7:	1.2:	1.7	1.1	0.6
[Zr]	3.06	0.6	0.9	1.1	0.9	0.6:	0.8:	1.1	0.6	0.5
[Ba]	2.32	0.1:	-0.1	1.4	1.0	-0.1	-0.5:	1.2:	0.6:	0.4
[La]	1.20	0.6:	≤2.0	≤1.7	≤1.4	≤0.7:	≤1.3:	≤1.8	≤2.1	?
[Zr/Ti]	---	1.0	0.7:	0.8	0.6	0.3:	0.4:	0.8:	0.3	0.3
log (CN/Fe)		-1.49	-1.00	-0.96	-0.89	-0.70	-0.47	-0.38	-0.47	0.3
CN/C_2		200:	25	40	20	8	11	4	20:	40%
$^{12}CN/^{13}CN$		20	≥25	20	13	6	3.5	10:	6	20%
$\log \frac{C-O}{H}$		-4.5:	-3.62	-4.05	-3.60	-3.04	-3.00	-2.70	-2.97	0.3
C/O		1.033:	1.23	1.085	1.24	1.87	1.95	2.9	2.02:	?
log (N/H)		-4.13:	-4.12	-4.05	-4.11	-4.30	-3.93	-4.28	-3.66:	0.4
log Fe_{6400}		20.98	20.45	20.58	20.53	20.87	20.41	20.15	20.19	0.1
T_{molec} (°K)		2500	2700	2600	2750	2900	2900	3000:	3150	200
T_{atomic} "		2500	2800	2860	2800	2900	3000	3000	3150	100
$T_{effective}$ "		2650:	2950:	3010	2950:	3100:	3300	3300:	3500:	Wing
log P_e		-4.0:	-3.7	-3.4	-3.6	-3.3	-3.0	-2.8	-2.4	0.5
log P_g		1.4:	1.4	1.7	1.6	1.8	2.0	2.2	2.6	0.5
log g		-0.3:	0.2	0.4	0.3	0.2	0.8	1.3	1.7	0.6
log $R/R_\odot$ ($\frac{M}{M_\odot}$=3)		2.6:	2.4	2.3	2.3	2.4	2.1	1.8	1.6	0.3
Mag_{bolom} "		-5.0:	-4.5	-4.1	-4.0	-4.8	-3.5	-2.0	-1.2	1.6
$Vel_{microturb}$ ($\frac{km}{s}$)		7.0	6.0	5.6	6.0	6.0	6.3	6.0	4.8	15%
Gaussian Δλ(Å)		0.22	0.20	0.18	0.18	0.20	0.16	0.20	0.16	10%
$\overline{R_c}$		0.92	0.92	0.93	0.95	0.94	0.92	0.90	0.88	2%
Spectrum		C9e	C6,2e	C6,2	C7,3	C4,5e	C5,4	C6,4	N6-R8?	TPW
Var. Type		M	M	Lb	SRb	SRb	SRb	SRb	---	K
Period		439^d	358^d	---	450^d+	629^d:	158^d	353^d	---	K
V_{rad} ($\frac{km}{s}$)		-27	-115	+11	-26	-27	+12	+37	-168	Yam
μ ("/yr)		.012	.026	.042	.050	.009	.009	.013	.029	Yam
mag_{visual}	7.6-13.6	6.9-12.2	5.3	4.8-5.9	7.7-8.6	4.8-6.0	6.7-8.2	8.48		Yam
Lithium		1	0	1	1	1	3	1	0	TPW
Technetium		yes		yes	yes		no			Peery
Plate (EC#)		3269	2660	3407	2760	3300	2668	3266	3299	
Date (1964)		8/21	1/28	6/12/65	2/29	8/23	1/30	8/21	8/23	
Exposure (min)		112	230	52	20	83	70	49	175	
Var. Phase		Max-30^d	Max+5^d	---	---	---	---	---	---	

NOTES TO TABLE V

[*M*]: for the elements in brackets, the numbers given for each star are the logarithmic ratios of $(M/Fe)_{star}/(M/Fe)_{solar\ system}$, where *M* is any element.

Abund gives the solar system ratio, log M/H + 12 (Urey 1972).

Source Err gives either the total error estimate for our calculation, or the source of determinations of someone else. The relevant abbreviations are: K — Kukarkin et al. (1969); Peery — Peery (1971) or Peery et al. (1971); TPW — Torres-Peimbert and Wallerstein (1966); Wing — Wing (1967); Yam — Yamashita (1972).

Var. Type: M = Mira variable, Lb = Irregular, SRb = Semiregular.

Only two of the effective temperatures are actually from Wing. The remainder are uncertainly extrapolated and are indicated with colons. Colons also are used to designate all quantities with errors possibly larger than that listed in the last column.

V_{rad} is the star's radial velocity relative to the solar system. μ is the star's angular velocity relative to very distant stars, measured in arc seconds per year. It is hoped that all other quantities are clear, from the text.

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ours. Then her results for S stars would range from 0.2 to 0.95, precisely the extent of values we find for the eight N stars here. It should also be noted that the three observed stars in which the unstable s-process element Tc has been found are among the strongest also in the s-process element Zr (as measured by Zr/Ti). Tc results are from Peery (1971) and Peery, Keenan, and Marenin (1971).

Boesgaard (1970*b*) gives Li abundances for S, MS, and Ba II stars. Most of the Li is ionized; she assumes that all of her cooler stars have $\log P_e = -2.0$, not likely too good an approximation. On the same scale as our logarithmic abundance ratios her results range from -3.1 to $+1.2$ for S stars, from -3.0 to -2.5 for MS stars, and from -2.7 to -1.4 for Ba II stars. It is known that some carbon stars may have more lithium even than the most enriched S star, but, in general, our results do show that the range of Li abundances observed in N stars is roughly similar to that for S stars. The wavelength of the observed Li feature in all stars indicated that the isotopic population is essentially all ^{7}Li. For a discussion of this problem see the work of Cohen (1972).

The major published work on atomic abundances in carbon stars has been done by Utsumi (1970). He performed curve-of-growth analyses of 22 N stars. An attempt was made to choose the lines used from a region relatively free of molecular lines, but many of the lines actually used had to be chosen from outside that region. No allowance for possible confusion with ^{13}CN or $^{13}C_2$ lines was included. The electron pressure was calculated entirely from the ionization balance of yttrium, yet one of the three lines of ionized Y used was essentially coincident with a Zr line, and in several stars it was one of only two such lines used. The astrophysically determined *f*-values we used are preferable to the results of Corliss and Bozmann (1962) and Corliss and Warner (1964) which Utsumi used; these latter *f*-values are known to contain systematic errors, often caused by not knowing the true temperature in the arc source measured. Large errors in abundance could result, particularly for the rare-earth elements which have had few subsequent *f*-value determinations. From the work of Molnar (1972) on Eu, La, and Sm, for example, in the sunspot spectrum, it seems that some of the *f*-values from Corliss and Bozmann for La and Sm are off by at least a factor of 10. For all of these reasons we cannot agree with Utsumi's estimate that the error in his abundance determinations is only 0.4 dex, especially in the case of the rare earths. It seems that Utsumi's spectral region is richer than ours in good rare-earth lines, but the sum of the mentioned difficulties still leads to the conclusion that his true probable error must be at least 1.0 dex for rare-earth elements.

For the three stars which both Utsumi's and the present analyses had in common, qualitatively similar results were obtained in both studies, in spite of the above problems. U Hya and 19 (TX) Psc shared relatively high Zr/Ti ratios and Ba abundances; their La abundances are also probably high. In contrast, Y CVn was low in these s-process element enrichments. (In Y CVn, Utsumi found La low, but we found it high.) Here the words low and high are most meaningful when they are taken to imply comparisons with the other carbon stars analyzed.

We found excellent agreement with the excitation temperatures Utsumi determined for the three stars we studied in common. His microturbulent velocities average more than 30% larger than ours; this could well be an effect of systematic errors in *f*-values (Evans and Schroeder 1972). Utsumi's microturbulent velocities are derived from the classical curve of growth, whereas ours are found perhaps more directly from fitting profiles.

B. *Molecular Abundances*

There have been few previous quantitative determinations of the CN/C_2 ratio in carbon stars. The star UU Aur was the subject of work by Querci and Querci (1970), who found a CN/C_2 ratio of 116 from a curve-of-growth analysis. We must admit to being puzzled by their procedure, which adjusts the continuum level to give decent equivalent widths for weak lines, but makes absolutely no allowance for the effects of microturbulence. They also find an extremely small $\log P_e = -5.6$, and give no error estimates. Marenin (1970) estimated CN/C_2 ratios of > 100 for 19 Psc and > 35 for Y CVn. She used a synthesis technique similar to ours, but worked in the 7700 Å region. She observed no C_2 lines and thus only set lower limits. The molecular excita-

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tion temperatures she determined were about 400° K lower than ours for those two stars, possibly indicating that the shallower depths of the atmosphere were seen in her spectral region. For $^{12}C/^{13}C$ she obtained values of 12–22 for 19 Psc, and 2.5–4 for Y CVn, in good agreement with the present determinations. Faÿ (1971) obtained similar isotopic ratios from synthetic spectra in the farther infrared regions of these two stars. Faÿ and Marenin both used a microturbulent velocity of 10 km sec^{-1} in their studies; our synthetic spectra would have been too smeared out, compared to the observed spectrum, had we used such a large turbulence.

The $^{12}C/^{13}C$ ratio is one of the best-determined quantities we have measured, as it is almost certainly free of atmospheric stratification. We have already quoted previous results in agreement with two of ours. Fujita (1970) also agrees (within 20%) with the present result for U Hya, using the molecular excitation temperature determined here.

Qualitative results with which the analysis presented here is in agreement exist also. Wing (1967) found Y CVn to be among the group of carbon stars with strongest CN, as is found here. He also found a correlation between CN strength and temperature. Our results also show this effect, despite a difference in wavelength regions used. Faÿ, Honeycutt, and Warren (1973) found a clear correlation between their C_2 band-strength index and Baumert's (1971) CN index, as did we for the quantitative results shown in Figure 3.

The value of (C−O)/H had not previously been determined for carbon stars, at least not without severe assumptions, such as presumed CNO equilibrium abundances. As discussed in section IV(D), there is some wavelength-dependent variation of the C_2/Fe ratios needed for the calculation, and the gas pressure certainly is only known to within 0.5 dex. Equation (5) still allows us to calculate log (C−O)/H accurate to 0.3 dex for seven stars, assuming these stars have solar-system Fe/H. For RZ Peg there is greater observational and theoretical error, the latter resulting from the free carbon abundance departing from C−O at very low C−O. The assumption of a solar-system O/H ratio, log (O/H) = −2.98, should be valid for all the stars also, as demonstrated below.

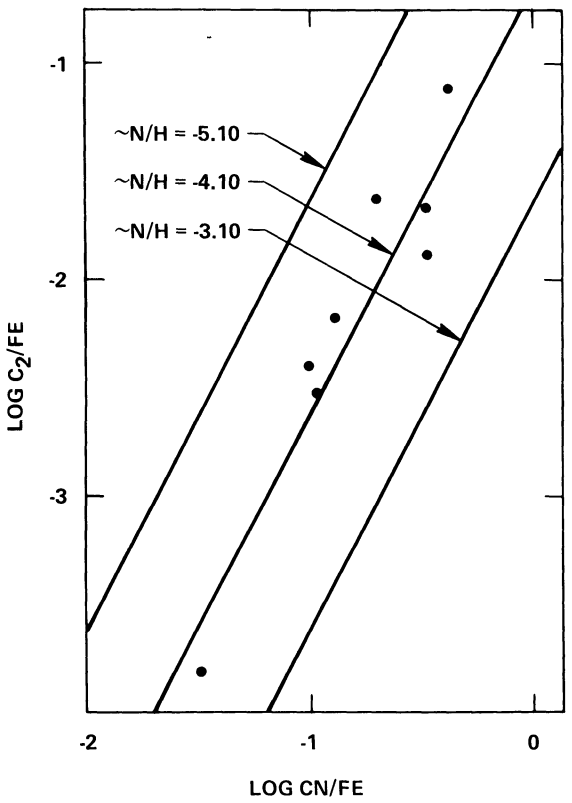

FIG. 3 — C_2 and CN abundances for the eight N stars. Constant-temperature isoabundance lines of nitrogen are plotted; temperature corrections for the equilibrium constants confirm the essentially solar abundances for the eight stars. (N/H value shown as log.)

The first conclusion to be drawn from the nitrogen-abundance determinations is that the N/H, or at least the N/Fe, ratio is essentially solar for all the stars observed. This supports the assumption of a constant and solar O/H ratio in determining C/O, because any scheme for the evolution of carbon stars having no variation in the nitrogen abundance also requires little variation in the oxygen abundance. The N/H value averaged over all stars is within 0.2 dex of the solar-system value, log N/H = −3.96.

C. *Physical Properties*

So many different temperature estimates have been made for carbon stars that one has to use great care in accepting any one. For example, Marenin (1970) obtained a molecular excitation temperature of 2200° K for 19 Psc, while Phillips and Leung (1973) suggest a molecular temperature of at least 3000° K. The present analysis

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yielded a value of 2600° K, in the middle of the range. The temperature found for a star depends on the wavelength region observed, especially where there is variation of mean opacity to the degree found in carbon stars. So it is most important that the temperature used in an abundance analysis applies to the wavelength region used, and the quality of our synthesis-fits convinces me that this criterion is met. Only for some of the most stratified species, such as Ba and La, does the analysis meet with difficulty. That the atomic and molecular excitation temperatures obtained show little difference helps to justify the use of identical synthesis parameters (for example, R_c and the microturbulent velocity) for all lines in a spectral region.

The electron and gas pressures found seem to be in a reasonable range. Since these quantities in carbon stars are not known with great accuracy, we can check the gas pressures in the following way. If we assume that the observed pressure is due to the weight of the overlying stellar atmosphere, then the stellar gravitational acceleration times the line-of-sight mass must equal the pressure. It seems plausible that the observed pressure is characteristic of the atmospheric depth about halfway along the line of sight of Fe atoms in the 6400 Å region. We assume that 70% of the stellar mass is hydrogen, an amount typical for the younger stars in our galaxy. We can then get the pressure-producing column mass for each star, assuming log Fe/H $= -4.4$, as for the solar system. The results range from 55 gm cm^{-2} for RZ Peg, to 8 gm cm^{-2} for V Aquilae. Dividing the pressure by this mass gives the gravitational acceleration, which ranges from $\log g = -0.3$ for RZ Peg, to $\log g = 1.7$ for HD 189711. Here it is interesting to note that the same three stars in our sample which show hydrogen emission lines are just those which have the lowest surface gravity: RZ Peg, V CrB, and RX Pegasi. Emission lines would be expected from the more extended stellar atmospheres in the sample.

If one assumes a stellar mass, one can infer a radius from the calculated gravity. It is generally thought that the N stars lie in the range from perhaps 2 to 10 solar masses; we shall use 3 solar masses as an arbitrary guess. Then the calculated radii range from 400 solar radii for RZ Peg, to 40 solar radii for HD 189711. With an effective temperature for each star, one can then calculate the absolute bolometric magnitude, which tells us the luminosity of the star. We find magnitudes ranging from $M_{bol} = -5^m0$ for RZ Peg, to $M_{bol} = -1^m2$ for HD 189711, if these stars are each 3 solar masses. Increasing the assumed mass by a factor of two would decrease (brighten) M_{bol} by 0^m75.

There is not much agreement about what are the actual absolute magnitudes for individual N stars. None of the stars in this study has a known distance, so the fact that the calculated magnitudes fall in the range set by Gordon (1968*a*), Scalo (1974), and Eggen (1972) is doubtless partly fortuitous. Still, if we work our way back through the procedure that resulted in the present magnitude estimates, the degree of agreement in magnitudes (ours are almost certainly correct within two magnitudes) gives some support to our pressure results, from which the gravities, radii, and luminosities have been found.

Figure 4 shows a strong correlation between the atomic excitation temperature and the electron pressure. This can also be found in Utsumi's work. There is no reason why this could not be a real effect, because cooler stars, when evolved, usually do have more tenuous atmospheres.

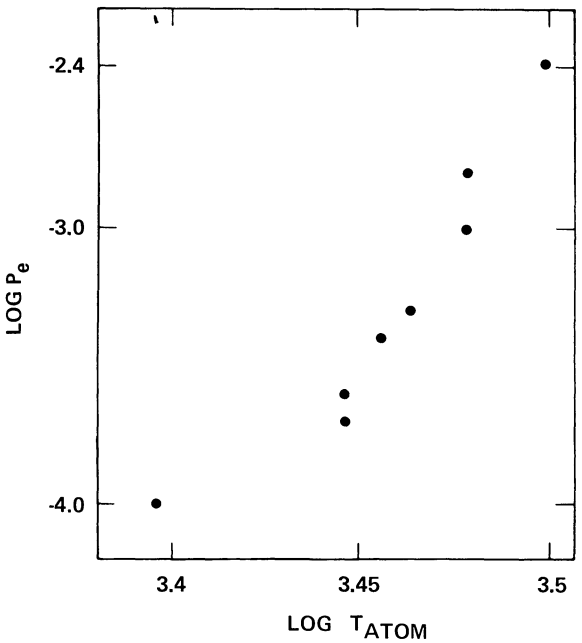

FIG. 4 — Electron pressure versus atomic excitation temperature; a strong correlation.

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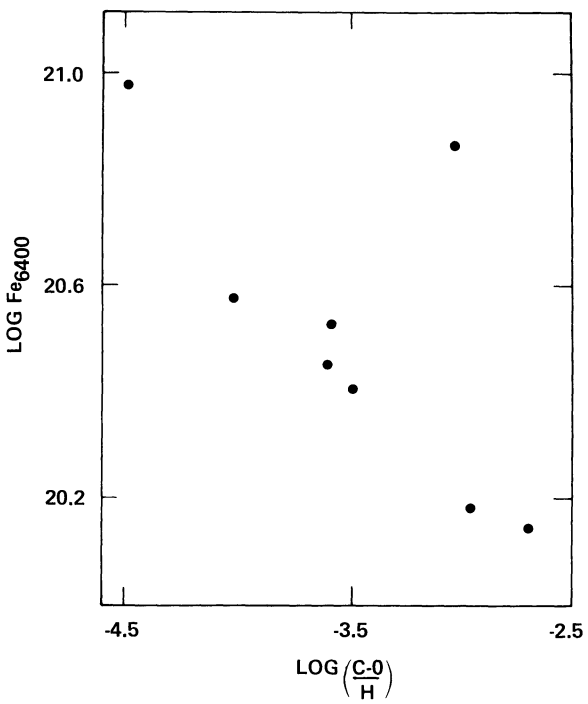

FIG. 5 — Line-of-sight Fe abundance (at 6400 Å) versus free-carbon abundance. Except for RX Peg, one can see into greater depths in the stars with less molecular carbon opacity.

However, there may also be some systematic effect present that the present study cannot uncover.

Except for RX Peg, which seems somewhat of a maverick star, Figure 5 shows an excellent correlation between the free carbon abundance and decreased line-of-sight Fe. This most likely demonstrates that carbon molecules add to the opacity and decrease the physical depth into which we can look.

The present analysis really cannot say much about the motions in these star's atmospheres. Microturbulent velocities of considerable magnitude definitely are needed to fit the observed line profiles. We found that the measured instrumental broadening was in all cases fairly close to the total Gaussian parameter used in the computer synthesis, and sometimes it was actually slightly larger. Thus the macroturbulent velocity was not at all well determined from this study. One could conclude, though, that the macroturbulent velocity could not be significantly greater than the microturbulent, but it could be somewhat less. Both are subsonic velocities.

The hydrogen emission lines in both RZ Peg and V CrB were measured to be blueshifted by about 20 km sec^{-1}, with respect to the molecular lines. This could indicate that some region of the star's atmosphere is expanding toward us. In those two stars the lines of neutral atoms of low ionization potential, such as Li, La, and Ca, also seem to be blueshifted slightly less than hydrogen. Perhaps any complete analysis of those stars, in particular, must include velocity effects.

VII. Interpretation of Results

We would like to know how a star gets to be a carbon star, and we would like to understand the differences and similarities between the N stars and the other late-type peculiar stars. Then we may get closer to a resolution of Bidelman's (1956) "single problem of great complexity," the integrated understanding of the late-type giant stars.

Schlesinger (1972) finds that the N stars are so red that they must have exhausted their core helium. Stellar models for stars in this stage have two energy-producing shells, helium burning in the inner, hydrogen in the outer. The helium-shell source can develop a thermal instability, the helium flash (Schwarzschild and Härm 1965; Weigert 1966).

Scalo and Ulrich (1973) have shown that for models in which the helium flash reaches out to the hydrogen shell, convection mixes protons down into hot regions containing helium and carbon. The resulting carbon-cycle energy production could then drive plumes upward to the convective envelope. Once in the convective envelope, elements produced in the stellar interior would soon be evident at the stellar surface. The carbon produced in this model results from the shell helium burning, where the 3-α process forms ^{12}C from ^{4}He. When sufficient carbon reaches the stellar surface, the oxygen is outnumbered, and the star becomes a carbon star. The deep-mixing model of Sackman, Smith, and Despain (1974) predicts similar results for mixing times of short duration.

There is an alternate scheme, however, which can produce the excess of carbon over oxygen. It involves the CNO equilibrium reactions: this results in a greatly increased nitrogen abun-

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dance, as well as a decrease in carbon, together with a much greater diminution of oxygen. For this scheme the envelope material must have been subjected to temperatures of 4 to 8×10^{7} ° K. The results reported here invalidate this scheme, because a substantial increase in the carbon abundance has been found, while the nitrogen has not increased at all.

The measurements relevant to the nitrogen abundance are plotted in Figure 3. For the solar system, $\log N/H = -3.96$, while for the CNO equilibrium model it must be at least -3.0. The lack of observed nitrogen enrichment will not allow that model, or any model requiring significant production of nitrogen in the outer layers of the stars.

The values of $\log (C-O)/H$ in Table V are far too great to be consistent with CNO equilibrium, except possibly for RZ Peg. In fact, in almost all cases, *the excess of carbon over oxygen is itself greater than the nitrogen abundance.* For half the stars this carbon excess is itself greater than the solar-system carbon abundance, $\log C/H = -3.22$. This makes it clear that substantial carbon must have been added to the stellar surface. The lack of unevolved carbon stars implies that this carbon must have been synthesized in the helium shells of these stars.

The results of Truran (1973) show that the low N/C and low $^{12}C/^{13}C$ ratios, found particularly in RX Peg, YCVn, V Aql, and HD 189711, require less than or about one proton to be captured by each of the ^{12}C nuclei mixed from the convective helium-burning shell to the surface. Three of these stars seem to have the lowest luminosities in our sample, thus a mass-dependent effect might be in operation. We do not know precisely what the evolutionary tracks look like in this section of the Hertzsprung-Russell diagram, but the lower luminosity stars are likely lower in mass. Many evolutionary calculations indicate that it is much easier to convert a low-mass star into a carbon star than to convert a high-mass star. The low-mass star has a much greater mass between its two burning shells, as well as much less mass in its convective envelope. Thus the low-mass star can mix carbon-rich material to its surface with far less dilution. This could produce the correlation between carbon abundance and lower luminosity that has been found in this study.

There is a slight anticorrelation between the inferred Zr/Ti and the $(C-O)/H$ abundance ratios, and also a correlation of the latter with the excitation temperatures. These correlations agree with the expected influence of the $(C-O/H$ ratio, through the opacity, on the relative strengths of lines (Scalo 1973*b*). Results similar to the anticorrelation between Zr and ^{13}C found by Utsumi (1970) are also evident; this also may be due to opacity effects. Finally, the well-known weak correlation between the Li and ^{13}C abundances is found.

Cameron (1955) first presented a scheme whereby physical and chemical evolution of a star might carry its spectrum from type M to S, and then to R or N, as the stellar surface became enriched in carbon and heavy elements. This is an appealing picture, but we feel that our results show that the truth may not be that simple.

The range of Ti/Zr found here for N stars seems to be about the same as Boesgaard found for S stars, which also have less carbon. It could still be possible that S stars become carbon stars, as is perhaps implied by the existence of CS stars, but it would seem then that the s-process elements might be produced mainly in the S-star stage. No mechanism has yet been suggested to effect this, though that should not deter us.

Wallerstein (1973) has presented a scheme wherein the N stars come directly from the M stars. The lack of observed MN stars, together with the at least slight enhancement of heavy elements in all N stars leads to difficulties for that scheme. He would also have N stars become Ba II stars. Both groups show enhancements of carbon and heavy elements, but the Ba II stars are generally thought to be much fainter than the N stars. The evidence of Gordon (1968*b*) and Wallerstein does imply a definite lack of similarity between the R stars, which seem to lack heavy-element enrichment, and the Ba II and N stars. Warner (1965) states that the Ba II stars have little ^{13}C visible in their spectra. This would seem to place them closest to the coolest stars in our sample, also low in ^{13}C. If these cool stars are to evolve to the much hotter Ba II stage, we might expect the appearance of stars halfway through the change. It would require quite a search to find such a star among

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those known.

In summary, it has been shown here that the *carbon excess found in N stars is due to transport of triple-alpha carbon made in the star's helium-burning shell.* Previous arguments that high ^{13}C abundances in some N stars were due to CNO equilibrium processes are unrealistic. Nitrogen abundances in these stars are entirely normal. The range of C/O ratios found shows that the N stars represent a succession of carbon enrichment stages. However, the derived s-process abundances indicate that the stars with more carbon are not later stages of the types poorer in carbon. What future development these stars might have is problematical. It behooves us to assemble additional data adequate to resolve the "great complexity" of the peculiar red giants.

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