THE ASTROPHYSICAL JOURNAL, **245**:1018–1034, 1981 May 1

THE ABUNDANCES OF CARBON, NITROGEN, AND OXYGEN IN THE ATMOSPHERES OF CEPHEID VARIABLES: EVIDENCE FOR HELIUM ENRICHMENT

R. EARLE LUCK
Department of Physics and Astronomy, Louisiana State University
AND
DAVID L. LAMBERT[1]
Department of Astronomy, University of Texas
Received 1980 August 8; accepted 1980 October 31

ABSTRACT

A model-atmosphere analysis of Reticon spectra of 14 Cepheid variables and several nonvariable supergiants provides the effective temperatures, surface gravities, and abundances of carbon, nitrogen, oxygen, and metals ($Z > 10$). The internal accuracy of the results is $\pm$ 200 K in $T_{\rm eff}$, $\pm$ 0.3 in log g, and $\pm$ 0.2 dex in the abundances.

The CNO abundances show that CNO-processed material has been mixed into the atmospheres of all Cepheids and nonvariable supergiants. Standard stellar-evolution calculations predict that the dredge up at the base of the red-giant branch will lead to a C underabundance and a N overabundance. However, the abundance analysis shows that the stars experience a larger than predicted change in the C and N abundances and that these changes are accompanied by an unexpected reduction in the O abundance. The sum of CNO is observed to remain constant. It is tentatively suggested that core convection or meridional mixing induced by rapid rotation caused extensive mixing into the H-burning shell and ON-processing zone when the Cepheids were main-sequence OB stars. The red-giant dredge-up phase later brought the processed material to the surface.

The O depletion through the ON cycle implies a large-scale production of He. A method of inferring the directly unobservable surface He abundance for a Cepheid is sketched. It is shown that the double-mode Cepheid TU Cas with a low O abundance has a high He mass fraction ($Y \sim 0.8$) in its envelope.

Subject headings: stars: abundances — stars: atmospheres — stars: Cepheids — stars: evolution — stars: interiors — stars: supergiants

I. INTRODUCTION

The atmospheric abundances of carbon, nitrogen, and oxygen have proven to be sensitive monitors of predicted and unpredicted aspects of stellar evolution. Mass loss, mixing between the interior and the atmosphere, and explosive nucleosynthesis by high-mass and intermediate-mass stars are among the important problems that may be probed when information on the CNO abundances is available. We describe here the first attempts to define the atmospheric abundances of carbon, nitrogen, and oxygen in Cepheids. The results provide new and exciting evidence for a significant helium enrichment in some Cepheids and late-type supergiants.

Published abundance analyses of Cepheids have considered the iron-peak elements (e.g., Schmidt 1971; Schmidt, Rosendhal, and Jewsbury 1974) and reported no abundance difference between the Cepheids and nonvariable supergiants of similar spectral type. A sample of nonvariable supergiants (mostly stars to the red side of the Cepheid instability strip) were analyzed for CNO by Luck (1978), who found evidence for the deposition of large amounts of CNO-processed material in the atmosphere. We seek here to answer the questions: Do the CNO abundances of Cepheids provide evidence for a similar level of contamination with CNO-processed material? Do the CNO abundances correlate with absolute luminosity and, hence, provide a clue to the origin of the unexpected levels of contamination? Is it possible to infer the He abundance from the CNO abundances and to check the recent suggestion that Cepheid atmospheres have a high He abundance (Cox 1979)?

In this paper, we present an abundance analysis covering C, N, O, and 14 heavier elements in 14 Cepheids. Basic data on the Cepheids is provided in Table 1. We also analyze five nonvariables (see Table 1) in order to extend the sample of the nonvariable supergiants discussed by Luck (1977, 1978) to earlier spectral types.

II. OBSERVATIONS

Spectra of the program stars were obtained with the McDonald Observatory's 2.7 m reflector and Reticon-equipped coude spectrometer (Vogt, Tull, and Kelton 1978). Each exposure covered about 100 Å with a signal-to-noise ratio of 100 or greater and a resolution of 0.2 Å, which is less than the width of the lines in the Cepheid

[1] John Simon Guggenheim Memorial Fellow.

1981ApJ...245.1018L

TABLE 1

BASIC DATA FOR THE PROGRAM STARS

	RA (1900)	DEC	L	B	SPECTRAL TYPE RANGE	V MAX	V MIN	PERIOD (DAYS)	EPOCH (JD-2400000)	DISTANCE (KPC) R_{SUN}	DISTANCE (KPC) R_{GC}	NOTES
					CEPHEIDS							
SU CAS	02 43 03	68 28.4	133.5	8.5	F4 - F7 IB	5.78	6.16	1.949319	38000.598	0.33	8.73	2
TU CAS	00 20 55	50 43.6	118.9	-11.4	F3 - F5 II	7.24	8.06	2.139330	37490.391			2
DT CYG	21 02 18	30 47.0	76.5	-10.8	F6 - F7 II	5.63	5.92	2.499140	36074.469	0.43	8.41	2
RT AUR	06 22 08	30 33.3	183.1	8.9	F4 - G1 IB	5.02	5.82	3.728261	37000.185	0.33	8.83	1
T VUL	20 47 13	27 52.5	72.1	-10.2	F5 - G0 IB	5.44	6.06	4.435578	37939.60	0.59	8.34	1
DELTA CEP	22 25 27	57 54.2	105.2	0.5	F5 - G1 IB	3.48	4.34	5.366341	36075.445	0.26	8.44	1
X SGR	17 41 16	-27 47.6	1.2	0.2	F5 - G1	4.24	4.84	7.01225	36968.852	0.37	8.13	2
ETA AQL	19 47 23	00 44.9	40.9	-13.1	F6 - G4 IB	3.50	4.30	7.176641	36075.445	0.27	8.30	1
W SGR	17 58 38	-29 35.1	1.6	-4.0	F4 - G1	4.30	5.08	7.594710	37678.578	0.43	8.07	2
ZETA GEM	06 58 11	20 43.1	195.7	11.9	F7 - G3 IB	3.66	4.16	10.153527	10639.801	0.38	8.87	3
X CYG	20 39 29	35 13.6	76.9	-4.3	F7 - G8 IB	5.87	6.86	16.3866	35915.918	1.12	8.32	1
T MON	06 19 49	07 08.4	203.6	-2.6	F7 - K1 IAB	5.59	6.60	27.0205	36137.090	1.76	10.14	1
RS PUP	08 09 14	-34 16.6	252.4	-0.2	F9 - G7	6.53	7.62	41.3876	35734.426	1.64	9.13	2
SV VUL	19 47 25	27 12.3	63.9	0.3	F7 - K0 IAB	6.73	7.76	45.035	38268.9	2.12:	7.80:	2
					NON-VARIABLE SUPERGIANTS							
DELTA CMA	07 04 20	-26 14.0	238.4	-8.3	F8 IA	1.84						
BETA DRA	17 28 10	52 23.0	79.6	33.3	G2 II	2.87						
GAMMA CYG	20 18 38	39 56.0	78.2	1.9	F8 IB	2.24						
BETA AQR	21 26 18	-06 01.0	48.0	-37.9	G0 IB	2.89						
ALPHA AQR	22 00 39	-00 48.0	59.9	-42.0	G2 IB	2.93						

NOTES : DISTANCE AND PERIOD SOURCES
1) BARNES ET AL 1977
2) DISTANCE FROM FERNIE AND HUBE 1968 ; PERIOD DATA FROM GENERAL CATALOG OF VARIABLE STARS
3) DISTANCE FROM BARNES ET AL 1977 ; PERIOD DATA FROM ABT AND LEVY (1974)
DATA FOR NON-VARIABLES FROM BRIGHT STAR CATALOG HOFFLEIT 1963

spectra. Central wavelengths in the standard set of six exposures were at 5380, 6300, 6385, 6425, 6560, and 8710 Å. A rapidly rotating early-type star was observed at 6300 Å and at the same air mass as the Cepheid in order to divide out the telluric lines near the [O I] line at 6300.3 Å. On occasion, the resolution was lowered to 0.4 Å and the number of exposures reduced. Dates of observation with other information are given in Table 2. The nonvariable supergiants were observed at the standard wavelengths and reduced in the same way as the Cepheid observations.

Sample spectra are shown in Figures 1, 2, and 3. Figure 1 covers Hα, which varies widely from Cepheid to Cepheid. Emission can occur in Cepheids and the nonvariable supergiants. Figure 2 shows the [O I] line at 6300.3 Å, which is one of the two [O I] lines providing the abundance. The N I lines near 8700 Å are our N abundance indicator. These and the [C I] line at 8727 Å are shown in Figure 3. CN lines are present in our spectrum of T Mon.

A computer code is supplied with a fast-Fourier smoothed version of the observed spectrum, continuum points, wavelength calibration, and a line list. After continuum points are set by visual inspection, the code computes the equivalent widths from the Gaussian formula:

$$W = 1.06 \Delta\lambda D ,$$

where D is the line depth and $\Delta\lambda$ is the full width at half-maximum. A Gaussian approximation is appropriate, as Luck (1977, 1978) has shown that supergiant line profiles are Gaussian in shape. The line list (Luck 1979) was compiled for an analysis of F, G, and K supergiants from 0.2 Å resolution red data. A comparison of equivalent widths obtained from overlapping spectra indicates an accuracy of $\pm$ 5%. The number of lines measured for each Cepheid at each phase varied between 150 and 250. These totals include strong lines not included in the abundance analysis. The obvious bulk of the total line list precludes its publication. The measures are available upon request.

A major reason for the omission of CNO from previous abundance analyses was the difficulty of obtaining the necessary photographic spectra in the red and near-infrared. In particular, the N abundance is dependent on the near-infrared N I or CN lines beyond 7400 Å. The Reticon detector is one of several new detectors which now open up the red and near-infrared to high-resolution spectroscopy. This wavelength interval is the key to CNO abundance determination in Cepheids and many other stars.

III. THE ABUNDANCE ANALYSIS

Our approach to the abundance analysis was to employ model atmospheres and a spectrum-synthesis computer code. The original code was written by Sneden (1973) and modified by one of us (R.E.L.).

Model atmospheres were taken from the grid published by Gustafsson *et al.* (1975) with additional models from Gustafsson (1979) and calculations performed at Louisiana State University using the MARCS code of Gustafsson *et al.* We note that observations of a Cepheid were completed in a small fraction of a period ($\Delta T/P <$ 0.11, see Table 2) so that a single model is applicable. It may be suspected that hydrostatic equilibrium, which is a core assumption of the MARCS code, is inappropriate for Cepheid atmospheres. However, in a comparison of a hydrodynamic model for a 11.5 day Cepheid with a standard hydrostatic model atmosphere, Keller and

TABLE 2

DATES AND PHASES OF OBSERVATIONS

STAR	DATE	MEAN UT	ΔT/P	PHASE
SU CAS	31-12-79	06 31	0.064	0.18
TU CAS	12-10-79	07 30	0.108	0.06
DT CYG	08-09-79	03 16	0.058	0.17
RT AUR	21-12-79	06 44	0.036	0.87
T VUL	29-08-79	08 28	0.022	0.21
DELTA CEP	26-12-78	01 29	0.008	0.22
	30-08-79	06 42	0.012	0.29
X SGR	23-06-78	08 26	0.012	0.47
	11-07-79	04 27	0.010	0.06
ETA AQL	21-06-78	07 40	0.015	0.74
	11-07-79	06 07	0.008	0.38
W SGR	02-08-79	03 17	0.008	0.88
ZETA GEM	02-04-78	03 17	0.007	0.78
	20-12-78	07 33	0.006	0.58
	04-06-80	03 37	0.009	0.17
X CYG	10-09-79	06 04	0.007	0.07
T MON	25-03-78	03 19	0.004	0.92
	07-02-79	05 17	0.008	0.73
	07-04-80	02 52	0.003	0.46
RS PUP	08-04-80	03 19	0.003	0.86
SV VUL	07-09-79	05 18	0.003	0.12

ΔT/P IS THE FRACTION OF THE PERIOD OVER WHICH THE OBSERVATIONS WERE ACQUIRED

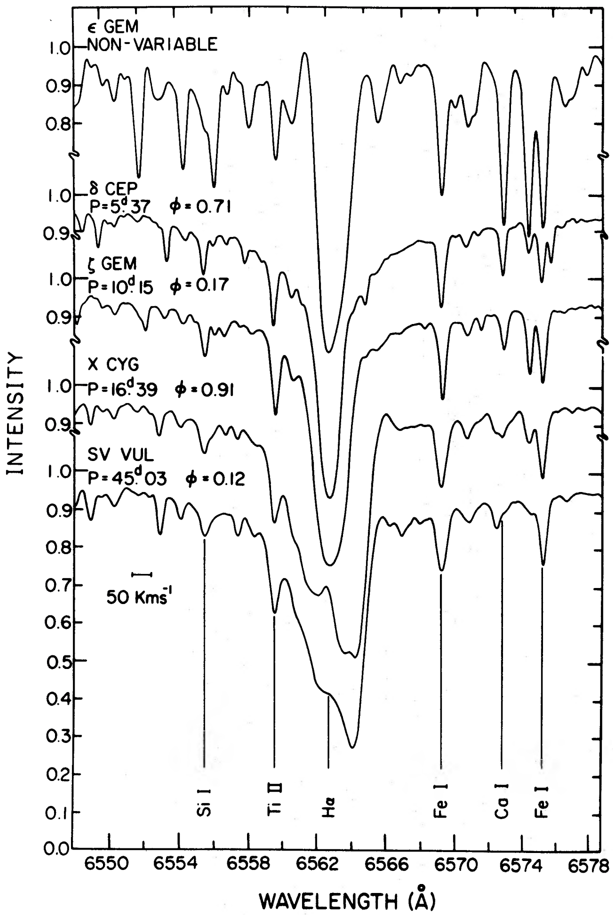

FIG. 1.—Hα in spectra of Cepheids and the nonvariable supergiant ϵ Gem. The intensity scale is normalized to the highest point of the 100 Å interval covered by each exposure. The local continuum may be judged from the region near 6578 Å. Note the complex Hα profile shown by the long-period Cepheids X Cyg and SV Vul. Weak emission is seen in the ϵ Gem profile. These profiles suggest that Hα is not a reliable temperature indicator in these supergiants.

Mutschlecner (1970) pointed out that the pressure-temperature profiles were quite similar. Pel (1978) also noted that the hydrostatic models could be used to interpret continuum colors of Cepheids.

Oscillator strengths for metallic ($Z > 10$) lines were computed from solar equivalent widths (Moore, Minnaert, and Houtgast 1966). We adopted the Holweger-Müller (1974) solar model atmosphere with a depth-independent microturbulence of 1.0 km s^{-1} (Smith, Testerman, and Evans 1976). Solar abundances of Si and Ca were taken from Lambert and Luck (1978). Abundances of other elements were set equal to the values recommended by Ross and Aller (1976).

Our procedure for deriving the effective temperature, surface gravity, microturbulence, and metal abundance was described by Luck (1979). Atmospheric parameters are given in Table 3. Metal abundances are listed in Table 4.

Our CNO analysis is an adaptation of an approach (Luck 1978) developed for G and K supergiants. As in the earlier study, the [C I] line at 8727 Å is used as a C abundance indicator. This line is blended with an Fe I line, but our tests show this to contribute not more than 1 mÅ to the equivalent width for Cepheids and similar supergiants. CN lines may also interfere with the [C I] line, but CN (see below) is not detectable in most Cepheids. The [C I] line is in the wing of a fairly strong Si I line and was analyzed by spectrum synthesis to allow for the Si I and CN blending. Figure 3 shows examples of such syntheses. After the observed profile has been matched, the unblended equivalent width can be computed quite trivially. These values are given in Table 5. The adopted [C I] *gf*-value is that recommended by Lambert (1978).

The permitted C I line at 5380.3 Å was also analyzed by spectrum synthesis. The derived equivalent widths are given in Table 5. The *gf*-value used for this line is a solar *gf*-value (Tomkin and Lambert 1978).

Our primary modification of the Luck (1978) method is our use of permitted N I lines instead of CN to obtain the N abundance. This change is necessary because most Cepheids are too hot to have observable CN lines. The

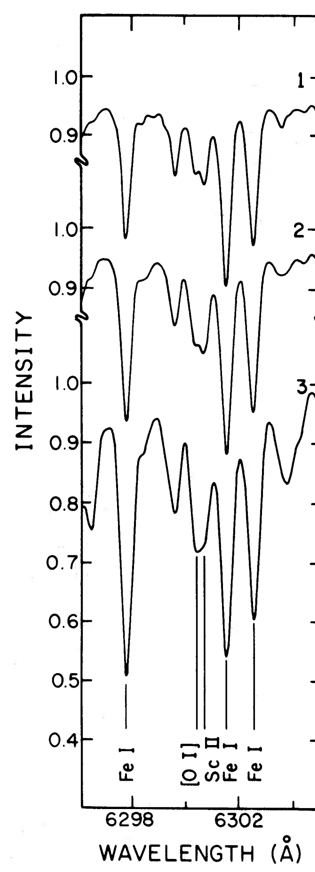

FIG. 2.—The [O I] line at 6300 Å in three Cepheids: (1) δ Cep, (2) ζ Gem, and (3) T Mon. Note that the [O I] line is blended with a Sc II line. The illustrated spectra are Fourier-transform smoothed versions of the raw data. See legend to Fig. 1 for a note about the intensity scale.

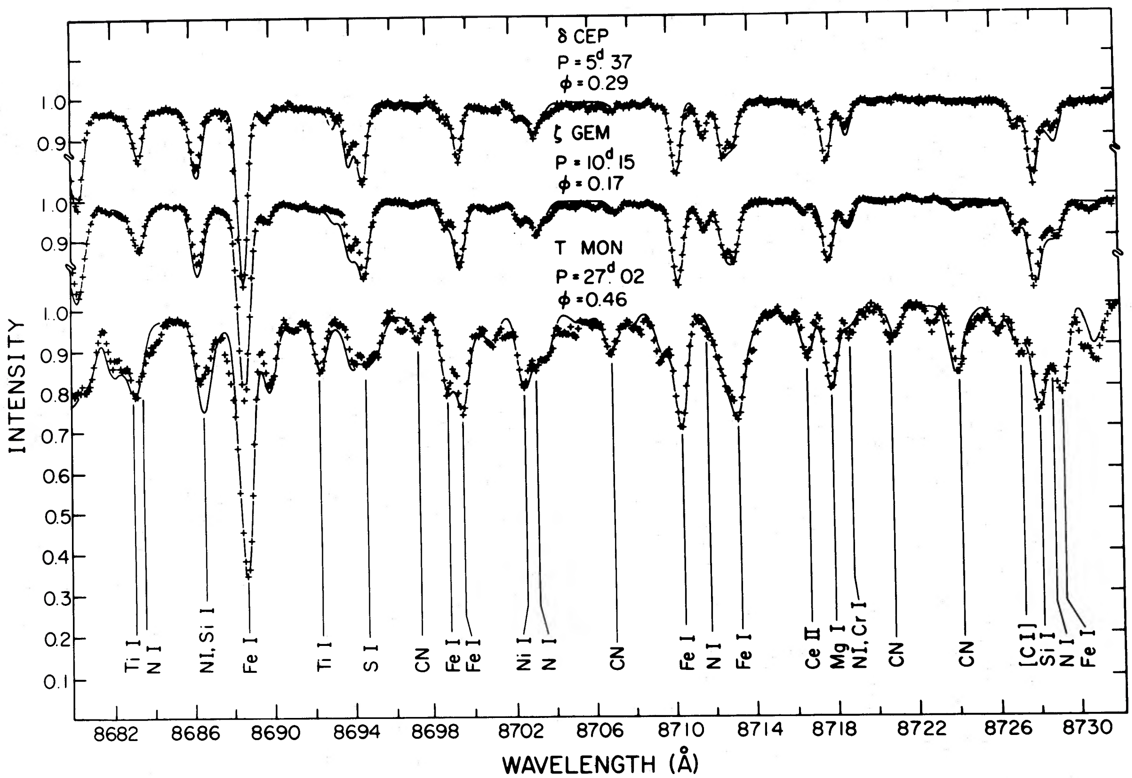

FIG. 3.—The 8710 Å region in the Cepheids δ Cep, ζ Gem, and T Mon. Note the N I lines and the [C I] line at 8727 Å. The cooler Cepheid T Mon shows CN lines. The crosses are the original data points. The solid lines are the synthetic spectra. See legend to Fig. 1 for a note about the intensity scale.

TABLE 3

PARAMETERS FOR CEPHEIDS

STAR	PHASE	T_{EFF}	LOG G	V_T	V_M	FE
SU CAS	0.18	6250	1.7	2.5	10	7.38
TU CAS	0.06	5875	1.2	2.5	10	7.37
DT CYG	0.17	6250	1.8	2.5	12	7.63
RT AUR	0.87	6500	1.5	2.5	12	7.60
T VUL	0.21	5750	1.1	2.5	12	7.45
DELTA CEP	0.22	6000	1.9	3.0	10	7.65
	0.29	5750	1.4	3.0	10	7.48
X SGR	0.47	5750	1.8	3.5	18	7.54
	0.06	6500	2.0	2.5	20	7.49
ETA AQL	0.74	5500	1.5	4.0	12	7.51
	0.38	6000	1.5	3.0	12	7.60
W SGR	0.88	6500	2.3	4.0	14	7.78
ZETA GEM	0.78	5750	1.5	3.0	12	7.99
	0.58	5750	1.9	4.0	14	7.83
	0.17	5750	1.5	3.0	12	7.71
X CYG	0.07	5500	0.4	2.5	14	7.65
T MON	0.92	5500	1.0	4.5	20	7.73
	0.73	5000	0.9	5.0	18	7.66
	0.46	4750	0.5	4.0	12	7.47
RS PUP	0.86	5150	0.4	3.5	12	7.43
SV VUL	0.12	6000	1.0	4.0	12	7.78

NOTES: IRON ABUNDANCES ARE WITH RESPECT TO H = 12
SOLAR IRON ABUNDANCE = 7.50

TABLE 4

CEPHEID ABUNDANCES WITH RESPECT TO SOLAR VALUES

SPECIES	Z	LINES MAX	LINES MIN	SU CAS $\phi=0.18$	TU CAS $\phi=0.06$	DT CYG $\phi=0.17$	RT AUR $\phi=0.87$	T VUL $\phi=0.21$	DELTA CEP $\phi=0.22$	DELTA CEP $\phi=0.29$
SI I	14	8	4	-0.07	0.22	0.41	0.17	0.16	0.24	0.16
SI II		2	1		0.58	0.57		0.40		
CA I	20	9	4	0.04	0.24	0.68	0.16	0.25	0.28	0.25
SC II	21	4	3	-0.28	-0.17	0.01	-0.12	-0.33	0.17	0.08
TI I	22	13	3	-0.14	-0.16	0.47	0.46	-0.29	0.18	0.03
TI II		4	2	-0.07	-0.35	0.06	0.36	0.15	0.21	0.07
V I	23	12	5		0.20	0.45	0.73	-0.02	0.21	0.07
CR I	24	9	3	-0.49	-0.20	0.24	-0.14	0.05	0.02	
FE I	26	84	49	-0.13	-0.13	0.13	0.10	-0.05	0.14	-0.02
FE II		12	9	-0.11	-0.14	0.11	0.03	-0.04	0.14	-0.03
CO I	27	5	1		0.10	0.0	-0.08	-0.01	0.27	0.03
NI I	28	15	6	-0.14	-0.12	0.06	-0.03	-0.15	0.03	-0.10
ZN I	30	1	1		-0.10	0.0	0.26		0.16	0.07
Y II		1	1	-0.08	-0.21	0.07	-0.04	-0.24	0.21	-0.10
LA II	57	4	2	-0.15	0.01	0.24	-0.05	-0.14	0.36	
CE II	58	1	1						0.27	0.01
ND II	60	3	1	-0.20	-0.36	0.12		-0.15	0.10	-0.12

SPECIES	Z	LINES MAX	LINES MIN	X SGR $\phi=0.47$	X SGR $\phi=0.06$	ETA AQL $\phi=0.74$	ETA AQL $\phi=0.38$	W SGR $\phi=0.88$	ZETA GEM $\phi=0.78$	ZETA GEM $\phi=0.58$
SI I	14	18	1	0.06	0.07	0.21	0.24	0.44	0.33	0.19
SI II		2	1			0.28	0.66	0.45		0.00
CA I	20	16	3	0.33	0.15	0.30	0.34	0.69	0.66	0.36
SC II	21	4	1	0.01	-0.27	0.41	0.16	0.10	0.35	
TI I	22	10	2	-0.03		0.14	0.33	0.62	0.42	0.26
TI II		4	2			0.30	0.37	0.28		0.17
V I	23	9	5	0.37		0.10	0.28	0.52	0.52	0.38
CR I	24	8	2		0.33	0.02	-0.06	0.28	0.30	0.17
FE I	26	73	24	0.04	-0.01	0.06	0.0	0.28	0.50	0.33
FE II		11	5	0.03	-0.02	0.01	0.18	0.25	0.46	0.33
CO I	27	8	2		0.09	0.56	0.05	0.38	0.45	0.55
NI I	28	23	7	0.16	0.02	0.16	-0.03	0.07	0.34	0.17
ZN I	30	1	1				0.29	-0.04		0.39
Y II	39	1	1			-0.07	0.09	0.30		0.28
LA II	57	4	2	0.32		0.55	0.45	0.59	0.51	
CE II	58	1	1			0.07	0.07			0.20
ND II	60	2	1			0.04	-0.15	0.41		0.20

SPECIES	Z	LINES MAX	LINES MIN	ZETA GEM $\phi=0.17$	X CYG $\phi=0.07$	T MON $\phi=0.92$	T MON $\phi=0.73$	T MON $\phi=0.46$	RS PUP $\phi=0.86$	SV VUL $\phi=0.12$
SI I	14	6	1	0.24	0.60	0.20	0.07	0.10	0.16	0.39
SI II		2	1	0.31	0.82					
CA I	20	9	2	0.45	0.43	0.30	0.23	0.00		0.41
SC II	21	4	1	0.16	0.47	0.43				0.26
TI I	22	13	2	0.21	0.16	0.17	0.33	-0.11	-0.15	0.33
TI II		1	1	0.22	0.39					
V I	23	9	3	0.15	0.17	0.52	0.25		-0.44	0.48
CR I	24	7	1	0.15	0.00	0.05	-0.01		-0.40	0.06
FE I	26	58	27	0.20	0.16	0.23	0.16	-0.03	-0.07	0.25
FE II		11	4	0.22	0.14	0.23	0.16	-0.03	-0.07	0.20
CO I	27	6	3	0.21	0.04		0.39	0.11		
NI I	28	16	6	0.15	-0.05	0.12	0.15	0.00	-0.10	0.01
ZN I	30	1	1	0.19	0.18				0.01	0.01
Y II	39	1	1	0.20	0.21		0.34	0.11	0.18	
LA II	57	3	2	0.46	0.31	0.49	0.51			0.42
CE II	58	1	1	0.22	0.16		0.06	-0.06	-0.16	0.24
ND II	60	3	1	0.26	-0.07		0.06	-0.15	-0.26	0.15

N I lines are moderately strong and an entire multiplet (RMT 1) is available in the same spectral region as the [C I] line. For the analysis we have synthesized the entire region from 8670 to 8745 Å which includes N lines as well as the [C I] line. Typical examples of this synthesis are found in Figure 3. After obtaining the best fit to all N I lines using the N abundance as the free parameter, we computed the unblended equivalent width of N I at 8683.4 Å (see Table 5). The *gf*-values for the total N I synthesis were taken from Lambert (1978).

For the cooler Cepheids T Mon and RS Pup, lines from the CN red system are found in the 8710 Å scan. As CN overlies practically all features in this region, we have added CN to the line list and adopted a somewhat different procedure. We fixed the C abundance by a synthesis lacking CN and then used either CN or N I to obtain the N abundance. The choice of CN or N I was made on the basis of which was stronger and less blended. The computed spectrum was compared to the observed spectrum and, if necessary, the C abundance altered; we iterated until a consistent match was achieved. Then the N I strength was computed and the analysis proceeded as in the other cases.

Oxygen abundances have been computed from the

TABLE 5
EQUIVALENT WIDTHS (mÅ)

STAR	PHASE	C I 8727A	C I 5380A	N I 8683A	O I 6300A	O I 6363A
SU CAS	0.18	19	58	99	23	-
TU CAS	0.06	27	47	114	25	7
DT CYG	0.17	29	69	113	31	9
RT AUR	0.87	28	73	126	16	6
T VUL	0.21	38	57	62	37	15
DELTA CEP	0.22	39	69	80	38	15
	0.29	45	64	77	51	16
X SGR	0.47	62	--	58	--	--
	0.06	28	70	108	28	--
ETA AQL	0.74	46	31	20	64	25
	0.38	34	56	78	25	8
W SGR	0.88	31	70	80	31	9
ZETA GEM	0.78	--	--	--	46	12
	0.58	52	42	59	52	20
	0.17	56	61	74	64	20
X CYG	0.07	43	24	100	57	21
T MON	0.92	34	--	70	--	--
	0.73	70	41	33	105	--
	0.46	53	34	--	114	44
RS PUP	0.86	99	50	51	96	41
SV VUL	0.12	84	94	99	71	27

NOTE: MISSING VALUES ARE DUE TO MISSING INTEGRATIONS, EXTREME BROADENING MAKING MEASUREMENT IMPOSSIBLE, OR UNCERTAINTIES DUE TO NOISE.

[O I] lines at 6300.3 and 6363.7 Å. The 6300.3 Å line had to be handled using a spectrum-synthesis technique thanks to blending with a Sc II line 0.38 Å to the red. The 6363.7 Å line was measured directly. Equivalent widths for the [O I] lines are given in Table 5. Oscillator strengths used were taken from Lambert (1978).

Using the (unblended) equivalent widths given in Table 5, abundances have been derived for models bracketing the proper parameters. The final abundances (Table 6) were derived by interpolation.

The nonvariable supergiants were similarly analyzed. Several of these stars were analyzed previously (Luck 1977, 1978), and those results are quoted in Table 7. The parameters given by Luck (1977) are adopted without modification. For the stars α Aqr, β Aqr, and β Dra, the abundances of C and N have been redetermined using the methods outlined above for Cepheids. Oxygen has not been redetermined because the procedure of Luck (1978) for O is identical to that used here. All parameters and abundances have been derived for δ CMa and γ Cyg as neither star was previously considered by Luck. These values are also given in Table 7.

IV. RESULTS

a) Atmospheric Parameters

Our estimates for the effective temperature, surface gravity, microturbulence (V_T) and macroturbulence (V_M) are given in Table 3. V_M was determined by fitting line profiles of species other than C, N, or O. A Gaussian distribution function was adopted. The internal accuracy is about $\pm$ 200 K for $T_{\rm eff}$, $\pm$ 0.3 dex for log g, and $\pm$ 0.5 km s^{-1} for the turbulent velocities.

Data on several of the short-period Cepheids were acquired over a time span of several hours, which can be as much as 11% of the period. For these stars we have carefully inspected our results, looking for effects which could result from a rapidly changing temperature or gravity. Such effects would include lines of Fe I or Fe II with similar excitation potential giving different abundances in different wavelength regions (i.e., different times of observation), or variations in line profiles with time. We found no effects in abundances or spectral features which could be attributed to variations in temperature in excess of $\pm$ 200 K. This is interesting since the data of Niva and Schmidt (1979) indicate that the $V-R$ color of TU Cas can change by as much as $0^{\rm m}.1$ in 5 hours. However, the exact color change is sensitive to the phases (both primary and secondary) between which TU Cas is varying. Matching the phases at our times of observation to the Niva and Schmidt data, we conclude that the $V-R$ color of TU Cas changed by $0^{\rm m}.077$ or less during the observations. Using the Bell and Gustafsson (1978) color-temperature calibration, this implies a maximum temperature change of 350 K. Since the $V-R$ color is slightly sensitive to gravity ($\lesssim 0^{\rm m}.01$ variation for a change of 0.75 in log g), the actual change is slightly less. The total possible temperature change is contained within our expected temperature uncertainty, and, hence, it is not really surprising no temperature effects were detected in the data.

The $T_{\rm eff}$ results agree quite well with several previously published spectroscopic analyses; e.g., η Aql by Schmidt (1971), δ Cep by van Paradijs and de Ruiter (1973), and TU Cas by Schmidt (1974). We note that the effective temperatures derived from photometric criteria by Schmidt (1972; see also Schmidt, Rosendhal, and Jewsbury 1974) are systematically hotter by about 500 K than

TABLE 6

CNO ABUNDANCES FOR CEPHEIDS

(LOGARITHMIC ABUNDANCES WITH RESPECT TO H = 12)

STAR	PHASE	C 8727	C 5380	N	O	CNO
SU CAS	0.18	8.12	8.15	8.63	8.61	8.98
TU CAS	0.06	7.95	8.01	9.03	8.25	9.13
DT CYG	0.17	8.30	8.36	8.85	8.76	9.17
RT AUR	0.87	8.35	8.29	8.65	8.51	9.00
T VUL	0.21	8.04	8.18	8.39	8.43	8.80
DELTA CEP	0.22	8.39	8.46	8.66	8.84	9.14
	0.29	8.21	8.32	8.67	8.64	9.03
X SGR	0.47	8.55		8.53		
	0.06	8.44	8.35	8.62	8.94	9.19
ETA AQL	0.74	8.32	8.33	8.52	8.69	9.01
	0.38	8.20	8.32	8.45	8.45	8.86
W SGR	0.88	8.54	8.47	8.19	9.05	9.20
ZETA GEM	0.78				8.66	
	0.58	8.47	8.11:	8.55	8.86	9.14
	0.17	8.38	8.33	8.68	8.80	9.13
X CYG	0.07	7.79	7.91	8.95	8.30	9.06
T MON	0.92	7.90:		8.86:		
	0.73	8.22	8.25	8.57	8.68	9.01
	0.46	8.01	8.21	8.47	8.61	8.91
RS PUP	0.86	8.26	8.38:	8.59	8.54	8.96
SV VUL	0.12	8.51	8.39	8.39	8.84	9.10

NOTE: UNCERTAIN VALUES (:) CAUSED BY EXCEPTIONALLY SEVERE BLENDING DUE TO MACROTURBULENCE OR DECREASED RESOLUTION

T MON NITROGEN ABUNDANCE AT PHASE 0.46 FROM CN

the spectroscopic values. The photometric scheme applied by Pel (1978) provides effective temperatures for η Aql, X Sgr, and W Sgr which are in adequate agreement ($\pm$ 300 K) with our spectroscopic results. Our temperature for the nonvariable Ia supergiant δ CMa ($T_{\rm eff} = 6250$ K) is in good agreement with the temperature ($T_{\rm eff} = 6143$ K) provided by the infrared-flux method (Blackwell, Petford, and Shallis 1980).

The log g values follow the predicted trend: the period-luminosity-color relation suggests that surface gravity decreases with increasing period. The Cepheid gravities span the range covered by nonvariable supergiants of similar spectral type; we do not confirm the result (Schmidt, Rosendhal, and Jewsbury 1974) that Cepheids have a systematically lower surface gravity than the nonvariables. In fact, all of the gravities derived here and in Luck (1977, 1979) are lower than the values given by Schmidt, Rosendhal, and Jewsbury. The probable reason for this is that the effective temperatures used by Schmidt, Rosendhal, and Jewsbury are 500 to 1000 K higher than those used here, and in order to maintain the ionization balance, Schmidt, Rosendhal, and Jewsbury were forced to higher gravities. Pel (1978) has also determined gravities for a number of these stars and obtained mean log g values of 2.14, 1.82, and 1.49 for X Sgr, W Sgr, and η Aql, respectively, with a typical total amplitude of 0.5 dex. These values compare well with our mean values of 1.9, 2.3, and 1.5 for these stars.

b) Metal Abundances

Abundances for Cepheids are given in Table 4. The Fe abundances for the nonvariable supergiants (Table 7) are consistent with results obtained previously for supergiants (Luck and Bond 1980, and references therein). The Cepheid sample has a mean abundance log ϵ(Fe) = 7.58 or 0.08 dex greater than the solar abundance. The nonvariables analysed by Luck (1977) have a mean abundance of 0.14 dex above the solar value.

TABLE 7

NON-VARIABLE SUPERGIANT RESULTS

STAR	EFFECTIVE TEMPERATURE	LOG G	TURBULENCE MICRO	TURBULENCE MACRO	FE	CARBON LUCK 1978	CARBON THIS WORK	NITROGEN LUCK 1978	NITROGEN THIS WORK	OXYGEN LUCK 1978	OXYGEN THIS WORK	NOTE
DELTA CMA	6250	0.60	3.0	16	7.69	----	8.34	----	8.91	----	8.77	A
BETA DRA	5375	1.35	1.9	12	7.80	8.15	8.12	8.68	8.40	8.51	----	B
GAMMA CYG	6100	0.55	3.5	10	7.60	----	8.18	----	8.38	----	8.61	A
BETA AQR	5475	1.30	2.3	10	7.70	8.08	8.15	----	8.47	8.52	----	B
ALPHA AQR	5300	1.40	2.3	10	7.80	8.19	8.22	8.63	8.49	8.60	----	B

NOTES: A) PARAMETERS AND FE ABUNDANCE FROM THIS STUDY
B) PARAMETERS AND FE ABUNDANCE FROM LUCK 1977
MACROTURBULENCE FROM THIS STUDY

The primary sources of uncertainty in these abundances are: (1) line-to-line scatter, and (2) uncertainties in the stellar parameters. The first source of error can be evaluated directly when the abundance is determined from a number of lines ($n \geq 5$). A typical standard deviation about the mean abundance is $\pm$ 0.25 dex. For Fe I, which has numerous lines, this translates into an error in the mean of less than $\pm$0.06 in all cases. For species with fewer than five lines, the errors are more difficult to assess but most probably lie in the range of $\pm$ 0.2 to $\pm$ 0.3 dex.

Table 8 summarizes the dependence of the metal abundance on T_{eff}, log g, microturbulence, and the He mass fraction. The two entries for Fe I and Fe II refer to lines of 50 mÅ and 100 mÅ. The pairs of model atmospheres which were used to construct Table 8 differ by more than the likely uncertainty in the atmospheric parameters. As a result, the entries in the table overstate the probable uncertainties. Moreover, the abundance error arising from parameter changes is not the Gaussian sum of the appropriate values scaled from Table 8. The parameters interact with one another, a change in one generally causing a shift in another, the net effect of which may even be no change in abundance. On the basis of numerical experiments, we estimate the typical parameter-related uncertainties in the abundances to be $\pm$ 0.2 dex.

Analyses of spectra obtained for a Cepheid at different phases provide a check on the accuracy. This comparison strongly implies that the quoted values are accurate at the $\pm$ 0.2 dex level, particularly for those species determined from five or more lines, and especially for the Fe abundances.

Previous analyses have determined Fe abundances for a number of these Cepheids, and the results are summarized in Table 9. The agreement between the various analyses is astonishing, especially considering the large parameter differences found between this work and the quoted analyses, particularly those of Schmidt and his co-workers. The probable explanation is that the large differences in effective temperature and gravity between these studies offset each other.

c) CNO *Abundances*

Our CNO abundances appear in Tables 6 (Cepheids) and 7 (nonvariables). Although these abundances depend on only a few lines (two each for C and O and about half a dozen for N), a detailed search for possible blends was made so that the abundances should be reliable. When the program line was partially blended, a spectrum synthesis was performed. We suggest that $\pm$ 20% is a fair assessment of the maximum equivalent-width uncertainty.

The sensitivity of CNO abundances to the atmospheric parameters is set out in Table 8 for line strengths appropriate to the various abundance indicators. All of the indicators are gravity sensitive but only N I exhibits a large temperature sensitivity. With the previously stated parameter errors, we estimate that the CNO abundances are uncertain by $\pm$ 0.2 dex.

Our analysis assumes throughout that local thermodynamic equilibrium (LTE) is valid. We note that the strong O I lines near 7770 Å are predicted to show departures from LTE in Cepheid-like atmospheres (Johnson, Milkey, and Ramsey 1974). Although detailed calculations are required, a plausible inference is that similar lines of C I and N I should also show departures from LTE. Several qualitative checks suggest that the departures are small. First, LTE departures in the C I excitation are not apparent in the 5380 Å line because the C abundances derived from the high-excitation C I 5380 Å line and the low-excitation forbidden 8727 Å line agree. The N abundance for several nonvariables and the Cepheid T Mon has been derived from both the N I and the CN lines. The molecular lines should be well represented by LTE so that the agreement between N abundances from the two species suggests that the N I lines are not affected by departures from LTE. The primary reason

TABLE 8

ABUNDANCE SENSITIVITY TO PARAMETER CHANGES

PARAMETER CHANGE	C I 5380A	C I 8727A	N I 8683A	O I 6300A	FE I 6400A	FE I 6400A	FE II 6400A	FE II 6400A
T[1] 5750 → 6000	−0.13	+0.07	−0.27	+0.11	+0.21	+0.24	+0.00	+0.01
G[2] 0.75 → 1.50	+0.23	+0.26	+0.28	+0.27	−0.04	−0.04	+0.27	+0.27
V_T[3] 2.5 → 3.5	−0.08	−0.01	−0.12	−0.03	−0.07	−0.24	−0.08	−0.23
Y[4] 0.3 → 0.5	+0.07	+0.03	+0.13	+0.03	+0.00	+0.01	+0.04	+0.06
LINE STRENGTH (MA)[5]	75	30	90	40	50	100	50	100

MODEL DESCRIPTION : (T_{EFF}/LOG G/Y/V_T)
Y = HELIUM MASS FRACTION
1) (5750/1.50/0.3/2.5) → (6000/1.50/0.3/2.5)
2) (5750/0.75/0.3/2.5) → (5750/1.50/0.3/2.5)
3) (5750/1.50/0.3/2.5) → (5750/1.50/0.3/3.5)
4) (5750/1.50/0.3/2.5) → (5750/1.50/0.5/2.5)
5) EQUIVALENT WIDTH USED TO CALCULATE ABUNDANCE SENSITIVITY TO PARAMETER CHANGES

TABLE 9

IRON ABUNDANCE COMPARISONS

STAR	THIS ANALYSIS	OTHER ANALYSIS	REFERENCE
TU CAS	7.37	7.32	SCHMIDT 1974
RT AUR	7.60	7.30	BAPPU AND RAGHAVAN 1969
DELTA CEP	7.57	7.44	VAN PARADIJS AND DE RUITER 1973
		7.31	HAEFNER 1975
ETA AQL	7.55	7.63	SCHMIDT 1971
X CYG	7.65	7.58	SCHMIDT ET AL 1974
T MON	7.62	7.64	SCHMIDT ET AL 1974

NOTE: ALL VALUES AVERAGED OVER PHASE IF APPROPRIATE

for the apparent lack of LTE departures is probably that our selected lines are weak and formed deep in the atmosphere; the prediction (Johnson, Milkey, and Ramsey 1974) refers to strong lines.

Another check on the CNO abundances, including a test for LTE departures, is their dependence on effective temperature and gravity. When abundance is plotted against $T_{\rm eff}$, no trend is apparent. The abundances derived from forbidden lines may show a trend with respect to gravity. This relation is not strong and could easily be destroyed by slight changes in the gravity or abundance of one or two stars. The magnitude of the changes necessary to destroy any relation is well within the uncertainties of the abundances and the surface gravities.

All abundances for Cepheids and nonvariable supergiants were derived using solar-abundance models from the grid of Gustafsson *et al.* (1975) or computed using the same computer code. Solar composition is a reasonable assumption because the iron-peak elements in these Cepheids show a small range in [Fe/H] from -0.1 to $+0.4$ with a mean value of $+0.1$. The mean total CNO content for the Cepheids is approximately solar. However, the distribution within the CNO elements is radically different in the Cepheids as compared with the Sun. Most Cepheids are deficient in C and O and rich in N. These abundance differences should have a minor effect on the total line blanketing and, hence, on the model atmosphere. The atomic line blanketing from CNO is minimal. Furthermore, molecules containing CNO are not very abundant in these warm stars. We note that the continuum colors derived from the molecular–line-blanketed models of Gustafsson *et al.* (1975) are essentially the same as those derived from the non-molecular–line-blanketed models of Relyea and Kurucz (1978) at the effective temperatures of 5500 K and 6000 K. This agreement confirms the assumption that the exact CNO content is not vital in this temperature range.

V. CEPHEIDS AND THE FIRST DREDGE UP

a) CNO *Abundances after the Dredge Up*

On the main sequence, a zone outside the core is partially processed by the CN cycle, but the temperatures are too low to permit the ON cycle to run. As the star evolves off the main sequence, the temperature of the zone drops and the products of CN cycling are fossilized. When the star becomes a red giant, the convective envelope descends and dredges up these fossils into the atmosphere. Qualitatively, the predicted changes in atmospheric composition are obvious: C is decreased, N is increased, and O remains nearly unchanged (see Iben 1966*a*, *b*, *c* for calculations pertaining to stars of Cepheid masses).

The predictions have been successfully matched to the abundance analyses for some of the lower-luminosity giants with respect to Li (Boesgaard 1970, 1976; Lambert, Dominy, and Sivertsen 1980), Be (Boesgaard and Chesley 1976; Boesgaard, Heacox, and Conti 1977), C, N, and O (Lambert and Ries 1977, 1981), and the ^{12}C/^{13}C ratio (Lambert 1976; Tomkin, Luck, and Lambert 1976). Even when the observations suggest a more severe mixing of processed material, the O abundance is not reduced. The weak G-band stars (Cottrell and Norris 1978; Sneden *et al.* 1978) are an extreme example of considerable atmospheric contamination with CN-cycled, but not ON-cycled, material. The occurrence of ON-cycled material in red-giant atmospheres thus appears to be limited to the more-massive stars or supergiants.

Since the great majority of the Cepheids are predicted to be on a second or third crossing of the instability strip, following the initial crossing to the red-giant branch, our Cepheids should have CNO abundances that reflect the occurrence of the dredge-up phase. We compare the observed CNO abundances with predictions provided by Becker and Iben (1979). The post–dredge-up abundances depend slightly on the stellar mass and the initial composition. The arrows in Figures 4 through 7 show the prediction for a $7\,M_{\odot}$ star of a nearly solar initial composition. The base of the arrow is set at the initial composition, and the tip marks the post–dredge-up composition.

Direct abundance correlations are shown in Figures 4 and 5. In addition to the Cepheids and the nonvariable supergiants analyzed here, we show the results for the nonvariables analyzed by Luck (1977, 1978). These figures show that the predicted post–dredge-up composition defines one extremity of the marked distribution in CNO abundances. At the other extremity are stars such as X Cyg and TU Cas, with a pronounced C and O deficiency and N enhancement. There is a good correlation between the C and O deficiencies and the N enhancement in all stars. The abundances do not show obvious

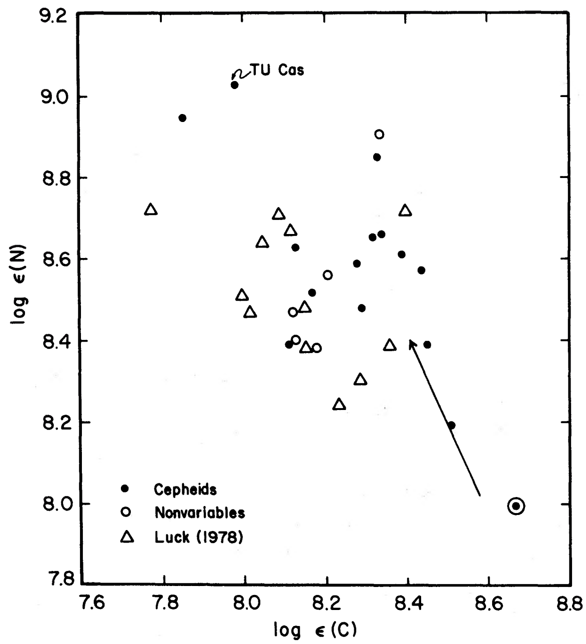

FIG. 4.

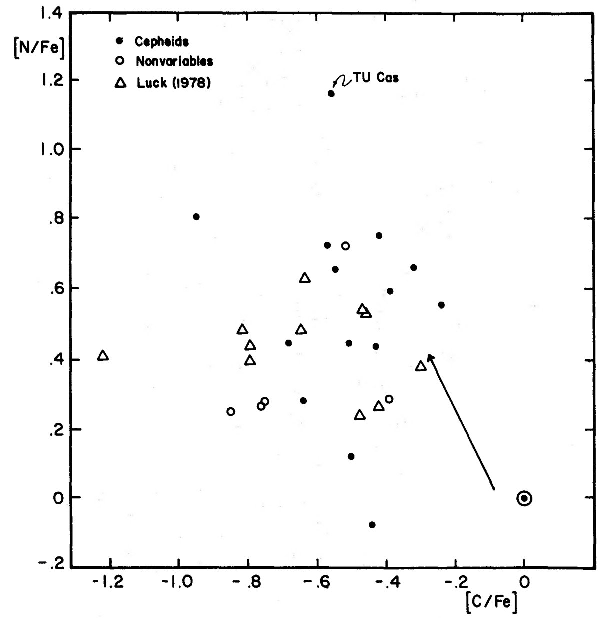

FIG. 6.

FIG. 4.—N and C abundances for Cepheids and nonvariable supergiants. The solar abundances are indicated by the solar symbol. The arrow shows the predicted effect of the red-giant dredge up (see text).

FIG. 6.—Relative N and C abundances for Cepheids and nonvariable supergiants. $[X/\mathrm{Fe}] = \log (X/\mathrm{Fe}) - \log (X/\mathrm{Fe})_{\odot}$. See legend to Fig. 4.

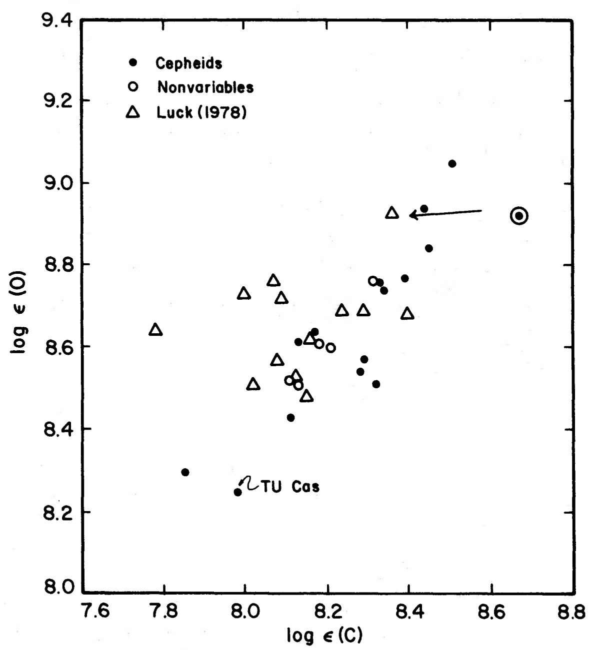

FIG. 5.

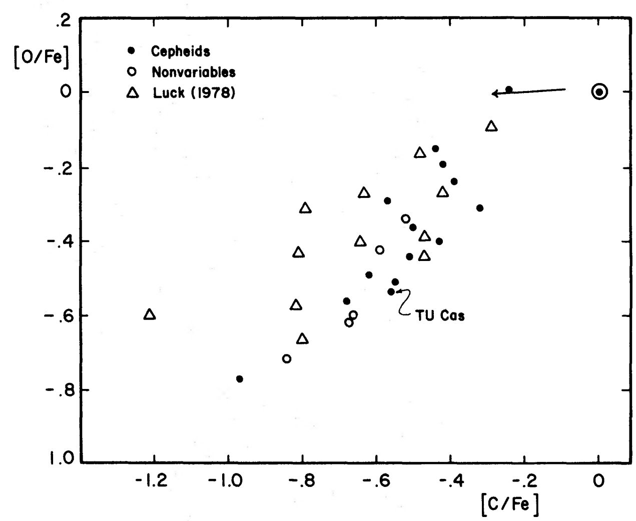

FIG. 7.

FIG. 5.—O and C abundances for Cepheids and nonvariable supergiants. See legend to Fig. 4

FIG. 7.—Relative O and C abundances for Cepheids and nonvariable supergiants. See legend to Fig. 4

trends with the pulsation period or any of the atmospheric parameters. Cepheids and nonvariables show similar abundance distributions.

Since the stars cover a range in metal abundance, we also present Figures 6 and 7, showing comparisons between abundance ratios $[X/\mathrm{Fe}] = \log (X/\mathrm{Fe}) - \log (X/\mathrm{Fe})_{\odot}$. This normalization to the Fe abundance is equivalent, apart from a constant offset, to a normalization to the initial C, N, or O abundance because $[X/\mathrm{Fe}] = 0$ for C, N, and O in main-sequence stars of approximately solar heavy-metal abundance. Figures 6 and 7 are quite similar to their counterparts, Figures 4 and 5. One difference is the lack of a correlation between [N/Fe] and [C/Fe] which would match the apparent $\log \epsilon(\mathrm{N})$ versus $\log \epsilon(\mathrm{C})$ correlation in Figure 4.

Our initial impression that the CNO abundances reflect the presence of considerable amounts of both CN-cycle and ON-cycle processed material was confirmed by a simple test. Operation of these cycles conserves the CNO nuclei such that the sum of the observed CNO abundances should equal the sum computed from the initial composition. This test is illustrated in Figure 8 for the Cepheids. We assume that the initial CNO abundances may be predicted from the observed Fe abundance. Analyses of main-sequence stars confirm that the abundance of C, N, and O varies in step with the abundance of Fe in stars of near-solar abundance (Clegg, Lambert, and Tomkin 1981). The CNO abundances for the Cepheids correspond to $[\Sigma/\mathrm{Fe}] = [(\mathrm{C} + \mathrm{N} + \mathrm{O})/\mathrm{Fe}] = -0.18$. Conservation of CNO nuclei requires $[\Sigma/\mathrm{Fe}] = 0.0$. The difference between the two values is within the uncertainties of the Cepheid and solar CNO and Fe abundances. Luck (1978) described a similar test for the nonvariable supergiants. A significant depletion of O is not predicted by the standard calculations. The observed O depletion, which is one of the striking results of these abundance analyses, is surely the result of the deposition into the atmosphere of ON-cycle processed material from the interior. This assertion is supported by Figure 8 where the O abundances show a large scatter in the $\log \epsilon(\mathrm{O})$ versus $\log \epsilon(\mathrm{Fe})$ plot, but a smaller scatter and offset from the predicted initial relation in the $\log [\epsilon(\mathrm{C}) + \epsilon(\mathrm{N}) + \epsilon(\mathrm{O})]$ versus $\log \epsilon(\mathrm{Fe})$ plot.

Our conclusion is that the atmospheres on the Cepheids and nonvariable supergiants have been mixed with CN-cycle and ON-cycle processed material beyond the level predicted by the standard calculations.[2] We now discuss several modifications to the standard calculations.

b) *The Initial Composition*

Cepheids evolve from main-sequence B stars. Although peculiar stars are known, the CNO abundances across a sample of B stars are close to the solar values; for example, a recent survey of CNO in B stars (Kane, McKeith, and Dufton 1980) provides mean N and O abundances within 0.15 dex of the solar values. Their C abundance is 0.8 dex below the solar value but they suspect that this low C abundance reflects an error in the adopted f value for the C II 4267 Å doublet. The stellar abundances are confirmed by results for the Orion Nebula (and other H II regions): Peimbert and Torres-Peimbert (1977) obtain CNO abundances for the Orion Nebula which average just 0.18 dex below the solar values. These studies show that the initial composition of the Cepheid progenitors is approximately solar. In particular, there is no evidence that O is deficient in most main-sequence stars. We conclude that the pattern of the CNO abundances in the Cepheids and nonvariable supergiants is not the result of a standard dredge up in a star with an unusual initial composition

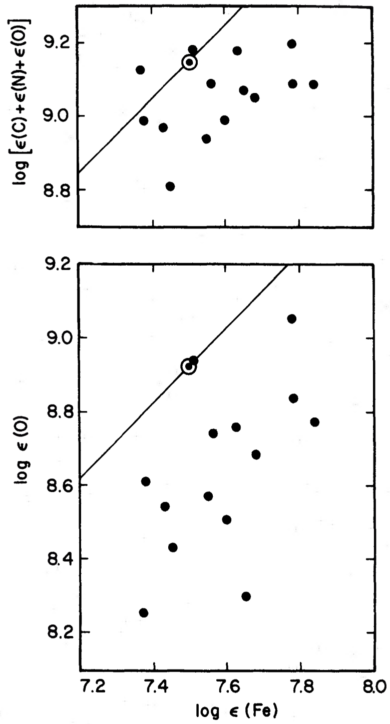

FIG. 8.—The sum of the CNO abundances (*top panel*) and the O abundance (*bottom panel*) versus the Fe abundance of the Cepheids. The solid line passing through the point provided by the solar abundances shows the predicted relations (see text).

c) *Mass Loss*

Mass loss prior to the dredge up has an obvious effect on the CNO abundances: the surface abundances after the dredge up approach more closely the abundances of the CNO-processed material. Inspection of Iben's (1966*a*, *b*, *c*) stellar-structure calculations shows that about 50% of the stellar mass must be removed before the post-dredge-up O abundance at the surface is reduced. This requirement is equivalent to a mean continuous mass-loss rate $dm/dt \gtrsim 2 \times 10^{-7} M_{\odot}\ \mathrm{yr}^{-1}$ for a 10 $M_{\odot}$ star during evolution from the main sequence to the red-giant branch. Observed mass-loss rates for the OB supergiants generally satisfy this limit. Rates for main-sequence stars

[2] A measurement of the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio for T Mon (Loumos, Lambert, and Tomkin 1975) indicated that the atmosphere contained CN-cycle processed material in excess of the standard predictions.

are less well determined but are probably smaller than the requirement. Of course, if the mass loss is limited to the OB supergiant phase, a far higher mass-loss rate must be sustained. There is a possibility that mass loss leads to a cooling of the zone in which the ON cycle runs, and, later, that this O-depleted material is included in the convective envelope. Detailed calculations are needed to predict the effect of a severe mass loss on the CNO abundances in the convectively mixed red giant.

The long-period Cepheid RS Pup is associated with a reflection nebulosity (Westerlund 1961). Havlen (1972) estimates the total nebular mass (dust plus gas) to be approximately $3 M_{\odot}$. Havlen's work shows that the nebulosity is circularly symmetric about RS Pup which indicates, at the very least, that the star has played a major role in the formation of the nebula, and, in fact, that it may be the source. Mass loss is known to occur from some F supergiants at rates which could produce a $3 M_{\odot}$ nebulosity (Lambert, Hinkle, and Hall 1981). Hence, it is possible that the RS Pup nebulosity was formed after the dredge-up phase on the red-giant branch. A Li abundance determination for RS Pup would shed some light upon this process. Mass loss after the dredge up should have little effect on the atmospheric abundances in the Cepheid.[3]

There is one observational argument against the view that severe mass loss is responsible for the CNO abundance anomalies in the supergiants. Lithium is destroyed in all but the outer 1% (by mass) of a star during the main-sequence lifetime. Therefore, if this outer skin is lost, Li will not be observable in the supergiants. However, Luck (1977) has shown that the Li abundance in the supergiants is close to the predicted post–dredge-up value for the case of no mass loss. These supergiants also show an O depletion so that the normal Li abundance implies that the O depletion is not attributable to excessive mass loss. Clearly, this argument presupposes that Li is not produced and convected to the surface.

Masses for Cepheids can be predicted on the basis of their pulsational properties. Comparison of these values with those derived from no–mass-loss evolutionary calculations indicates agreement for most period ranges (Cox 1979, 1980), if reasonable variations in effective temperature and (or) composition are allowed. Further, present evolutionary calculations indicate that loss of more than 10 to 20% of the original mass suppresses the blue loops where Cepheids are found (Lauterborn, Refsdal, and Weigert 1971; Siquig and Sonneborn 1976). Thus, we can effectively eliminate mass loss as the agent responsible for significant amounts of ON-processed material on the surfaces of Cepheids and nonvariable supergiants.

d) *Rotation and Convection*

Giants with a mass $M \sim 2 M_{\odot}$ appear to have CNO abundances close to the predictions for the standard dredge up of CN-processed material (Lambert and Ries 1981); for example, the observed CNO abundances for the Hyades clump giants match the predicted post–dredge-up abundances. The appearance of a marked O deficiency (and a parallel increased C deficiency and N enrichment) in the supergiants would seem to suggest that stellar mass is a critical variable. If it is, it is not a simple dependence because Cepheid CNO abundances show no clear trend with period (i.e., mass). Two factors distinguishing the higher-mass main-sequence stars from the lower-mass stars are: rotational velocity and the nature of the core (convective in high-mass stars and radiative in low-mass stars).

If the rotational velocity is the key parameter, the most rapidly rotating stars presumably evolve to supergiants with the most distorted CNO abundances, and the slower rotators evolve into supergiants with CNO abundances close to the predictions of the standard theory. The G and K giants evolving from the slowly rotating F and G main-sequence stars are expected to have normal abundances. The absence of a correlation between supergiant CNO abundances and the line widths (i.e., an upper limit to the rotational velocity) is not a fatal objection because Kraft (1970) has emphasized that the observed low rotational velocities in giants and supergiants require that angular momentum be transported from the surface layers.

Meridional circulation currents are often cited as a possible link between rotation and large-scale CNO processing. Although the physics of meridional currents in rotating stars is far from being fully understood, it seems clear that a molecular-weight gradient (μ-gradient) will suppress the currents (Mestel 1953, 1957). Since little H is consumed in a CN-processed zone, there is no μ gradient, and, hence, meridional currents could mix a greater portion of the envelope through this region. Meridional circulation will probably lead to turbulence in the radiative zone outside the H-burning shell (Kobayashi 1980). As a consequence of the resulting turbulent diffusion, envelope material may be circulated through and processed in the deeper hotter layers. The effects of the additional CN-processing might be reflected in the surface composition of the rapidly rotating main-sequence star (Paczyński 1973) and should certainly appear at the surface after the first dredge up. In order to explain the Cepheids and nonvariable supergiants, additional ON-cycle processing must occur. The interior calculations show that sufficient H is burned in an O-depleted zone for there to be a modest μ-gradient across the zone. This gradient may prevent the meridional currents from penetrating the latter zone (Dearborn and Eggleton 1977; Sweigart and Mengel 1979). In the rotating star, the meridional circulation might reduce the μ-gradient by continuous replenishment of H from the envelope. A detailed calculation for a rapidly rotating star along the evolutionary track from formation to red giant is now needed.

A convective core exists in those main-sequence stars in which the CNO cycle is responsible for the luminosity ($M \gtrsim 1.5 M_{\odot}$). Recently, Roxburgh (1978) and Cloutman (1978) have suggested that the standard stellar-structure calculations have underestimated the size of the

[3] The composition of the red giant on the asymptotic giant branch after the second dredge up will be affected by the mass loss.

core. Cloutman and Whitaker (1980) used a simplified statistical model of convective turbulence and followed the evolution of a 15 $M_\odot$ star. Their calculations show that the convective core extended about 3 $M_\odot$ beyond the size predicted by standard models. Unfortunately, the calculations were not run to predict the surface abundance changes at the dredge up on the red-giant branch. We may point to two possible effects. First, the size of the envelope containing material with the original composition is reduced by the core extension. The CN-cycle processed material participating in the dredge up is just outside the core. With a reduced envelope mass, the surface abundances are more severely influenced by the dredge up. Second, it may be possible for the convective envelope of the red giant to grow down to the outer part of the extended core and dredge up ON-cycled material. These two possibilities should be examined.

If the convective core is the origin of the O deficiency observed in evolved massive stars, it is not at all clear why the CNO abundances show no trend with stellar mass. We speculate that rotation may be a second parameter. The combination of the convective core and a high rotational velocity is proposed as the key to the CNO abundances in the Cepheids and nonvariable supergiants.

VI. HELIUM-ENRICHED CEPHEIDS

Recent theoretical work has led to a suggestion that the atmospheres of certain Cepheids must be helium enriched. If the helium abundance is increased above the normal Population I value, pulsation theory is able to account for the observed period ratios of double-mode Cepheids, and to predict a stellar mass for these and the bump Cepheids that is consistent with the mass derived from the mass-luminosity relation provided by standard stellar-evolution calculations (Cox *et al.* 1977; Cox, King, and Hodson 1978; Cox, Hodson, and King 1979; Cox 1979). These proposals have been coupled with a model invoking a stellar wind which preferentially removes H from the atmosphere leaving a He-enriched atmosphere and outer envelope (Cox, Michaud, and Hodson 1978).

The observed CNO abundances lead to the unavoidable conclusion that the atmosphere of a Cepheid (and a nonvariable supergiant) contains a considerable proportion of CN-cycled and ON-cycled material. These cycles convert H to He, and, therefore, the Cepheid must be He enriched. Through a simple model of the mixing processes, we may obtain an estimate of the He enrichment.

The conclusion that the He enrichment is appreciable in some Cepheids follows from the observed depletion of O. To deplete O via the ON-cycle in a time shorter than the age of the Cepheid (principally, the main-sequence lifetime) requires exposure to a temperature $T_6 \gtrsim 25$ where $T_6 = T/10^6$ K. We assume a density $\rho \sim 5$ g cm^{-3} typical of the H-burning shell in the main-sequence star (Iben 1966*a*, *b*, *c*). The CN-cycle will reach equilibrium very quickly with N/C ~ 80 at $T_6 = 25$ (Caughlan and Fowler 1962); N/C runs from 118 to 61 over the interval $T_6 = 20$ to 30. Since the material mixed into the atmosphere from the H-burning shell is poor in C, the observed C abundance is a measure of the relative masses of primordial (unprocessed) and processed material. The observed O abundance and the relative masses provide the O abundance in the processed material. The O depletion leads to an estimate of the number of protons consumed and, hence, the number of He nuclei produced. Finally, this latter estimate and the relative masses are combined to provide the He abundance in the atmosphere. We illustrate this procedure for the double-mode Cepheid TU Cas which is the most O-deficient star of our sample.

We adopt a simple model consisting of an inner processed zone of mass M_p and an envelope of mass M_e with the original composition. After mixing, the abundance ratio A/B is

$$\frac{A}{B} = \frac{M_e A_e + M_p A_p}{M_e B_e + M_p B_p}, \tag{1}$$

where A and B refer to the number density of species A and B, and subscripts p and e refer to the processed zone and envelope, respectively.

For TU Cas and other stars showing a significant O-depletion, we assume $C_p \ll C_e$. The CNO cycle conserves nuclei such that $N_p = C + N + O - O_p$ when $N_p \gg C_p$. Straightforward manipulation of the N/C and O/C abundance ratios from equation (1) gives

$$\frac{M_p}{M_e} = \frac{\left(\frac{N + O}{C} - \frac{N_e + O_e}{C_e}\right)}{\left(\frac{C_e + N_e + O_e}{C_e}\right)}, \tag{2}$$

and

$$\frac{O_p}{O_e} = \left(\frac{O}{C} - \frac{O_e}{C_e}\right)\frac{M_e}{M_p} \times \frac{C_e}{O_e}. \tag{3}$$

The results for TU Cas are $M_p/M_e = 4$ and $O_p/O_e = 0.01$. Note that although other ratios (for example, C/Fe and O/Fe) give different numerical results, the conclusion is clearly that $O_p/O_e \ll 1$ for TU Cas. This is demanded by the result that the O depletion is quite similar to the C depletion. Moreover, the result $O_p/O_e \ll 1$ is not sensitive to the adoption of a two-zone model. In the real star, we might expect mixing to involve three zones: the envelope, a CN-cycled zone, and an ON-cycled zone. The parameters of this three-zone model cannot be fully defined because the number of unknown variables exceeds the number of observed abundances for elements affected by the mixing. However, the inclusion of the CN-cycled zone with a normal O abundance can only reinforce the conclusion that $O_p/O_e \ll 1$. A consideration of the effects of the uncertainties in the observed abundances suggests that they set a more serious constraint on the conclusion; for example, if the observed O/C ratio is doubled in equation (3), O_p/O_e is increased to $O_p/O_e \sim 0.3$.

In the ON cycle, two protons are consumed in converting ^{16}O to ^{14}N. At the inferred high temperatures

($T_6 \gtrsim 25$), the CN cycle operates simultaneously and consumes many more protons. We use Caughlan's (1965) calculations to infer the total consumption of protons. The initial stellar material has about 700 protons for every CNO nucleus. For a gas consisting initially of equal parts of C and O, Caughlan's results show that the consumption of 700 protons reduces the O abundance to $O_p/O_e \sim 0.1$ at $T_6 = 20$ and 0.01 at $T_6 = 50$. Since results for a gas consisting initially of pure O are quite similar, we do not expect the O_p/O_e ratios to be very different for a gas with an initial solar composition. The conclusion is clear: the processed material with $O_p/O_e \sim 0.01$ mixed into the envelope of TU Cas is H depleted and He rich. If we assume that H is fully depleted in the processed material, the mass ratio M_p/M_e corresponds to a mass fraction $Y \sim 0.8$ for the current envelope of TU Cas. Even if $O_p/O_e \sim 0.3$ is adopted, the current He abundance must be high: $Y \sim 0.4$ according to the analysis based upon Caughlan's results. A more modest He enrichment is estimated for the average Cepheid. Several of the Cepheids with no detectable O depletion should have an essentially normal He abundance.

The effect of the He enrichment on the stellar envelope and, in particular, on the derived abundances must be considered. This is because an increase in the He mass fraction implies a decrease in the H mass fraction, and, hence, a modification of the (metal/H) ratios with respect to their primordial values. The larger number of Cepheids and nonvariable supergiants with only modest O deficiencies have He mass fractions of ~ 0.35. This means that the number density of H in the envelope has been decreased by only about 0.04 dex. Such a decrease will obviously have no significant effect on our analysis. For TU Cas and X Cyg the situation is less clear, particularly if the He mass fractions are as high as 0.8. In this case, the H number densities must be decreased by factor of 2 from their primordial values, leading to an increase of 0.3 dex in the (metal/H) ratios over the lifetime of the star. We must emphasize that our derived abundances are correct, particularly for the stars with only moderate O deficiencies, to within the limits of the analysis. This is because H continues to dominate the opacities even at high He mass fractions. An effect caused by the high He mass fraction will be slight alterations in the model atmospheres. The effects of this are minor, as can be seen from Table 8. We note that the values given in Table 8 reflect only the alterations in the atmosphere due to additional He, not any changes due to the decrease in H. To allow for the latter effect, a constant shift of + 0.1 dex must be added to all uncertainties due to variation in the He mass fractions.

Direct spectroscopic detection of He in a Cepheid atmosphere is nearly impossible. The indirect effects of a high He abundance on the atmospheric structure and spectrum appear to be small and almost indistinguishable from effects attributable to microturbulence and surface gravity (Sonneborn, Kuzma, and Collins 1979; Böhm-Vitense 1979). Calculations show that stars of Cepheid mass evolving back to the blue from the red-giant branch may reach a surface temperature as high as 14,000 K. These stars might be used to derive the He abundance. When our understanding of the chromospheres of late-type supergiants is more advanced, it may be possible to use the ultraviolet emission lines to derive the He abundance. It is possible that the mixing is so severe that the surface composition of some main-sequence stars is affected.[4]

Cox, Hodson, and King (1979) predict $Y = 0.65$ for double-mode Cepheids such as TU Cas. They found that a He enrichment above the Population I value of $Y \sim 0.26$ was necessary to explain the period ratio. This enhanced He mass fraction is confined in their model to the outer 10^{-3} (by mass) of the star. The high value of Y in this region then establishes a large composition gradient which alters the pulsational properties of the star. The predicted value of Y does overlap the range of our inferred He abundances for TU Cas, but our result, since it is produced by mixing, will not support any gradient within the star. Since the Cox, Hodson, and King mechanism is totally dependent upon the existence of the gradient, our finding of a high He mass fraction in TU Cas does not resolve the problem of the period ratios.

Pulsational properties of homogenous models are not particularly sensitive to composition, even for large variations in the He content (Carson and Stothers 1976; Becker, Iben, and Tuggle 1977). For this reason, our abundance results will not have a significant effect on the theoretical period-luminosity (PL) relationship. Nor is there any evidence in the observed PL relationships of any effect which could be ascribed to composition (Iben and Tuggle 1975).

The position of the instability strip is relatively insensitive to the He content. Changing Y from 0.28 to 0.38 alters the blue-edge temperature by less than 100 K (Iben and Tuggle 1975). The calculations also indicate that going to an even larger He mass fraction would have diminishingly small effects. Therefore, these abundance results cannot be used to rectify the positions of the theoretical and observed blue edges of the instability strip. Further, since the bulk of the Cepheids and the nonvariable supergiants have comparable CNO abundances, and hence, He content, there is no way to use these data to account for the presence of nonvariable stars in the instability strip.

VII. CONCLUDING REMARKS

Our CNO abundance analysis shows that the level of CNO-cycled material in the atmospheres of effectively all supergiants exceeds the predictions of the standard stellar-evolution calculations. In particular, the observed reduction of O through the ON-cycle is not predicted by the calculations. On the other hand, observations and predictions for lower-mass giants are in reasonable

[4] The possible blue straggler (star C in the list given by Arp, Sandage, and Stevens 1959 which appears to be separated by 1 mag from the main-sequence turnoff) in NGC 129, which contains the Cepheid DL Cas, has a high He abundance $n(\mathrm{He})/n(\mathrm{H}) = 0.165$ (Schmidt 1978). Extensive mixing and a resultant prolongation of the main-sequence lifetime has been suggested to account for the blue stragglers (Wheeler 1979).

accord. Observational and theoretical efforts need to be continued in order to locate the origin of the additional processing and mixing in supergiants. We noted the potential importance of the convective core in massive stars. We have tentatively suggested that the high rotational velocities found on the upper main sequence may induce meridional circulation currents which sponsor wholesale processing of the stellar envelope. The consequences of exposing the supergiant envelope (perhaps a mass fraction of 30 to 40% of the star) to severe CNO processing impact many areas of stellar evolution and nucleosynthesis as well as the chemical evolution of the galaxy.

The CNO anomalies most certainly imply a significant He enrichment throughout supergiant and Cepheid envelopes. This enrichment will have no first-order effect upon the pulsational properties of these stars, and hence, will not give ready answers to the problems of discrepant mass estimates for double-mode Cepheids, the position of the instability strip, or the existence of nonvariable stars in the instability strip. These problems may become tractable when these results have been incorporated into our understanding of stellar evolution, and as a result, more realistic evolutionary models become available.

We thank Drs. T. G. Barnes, H. E. Bond, and A. S. Endal for helpful discussions, Dr. J. Tomkin for assistance at the telescope, and J. F. Dominy and C. Luck for their help in reducing the data. We are indebted to Drs. B. Gustafsson, R. A. Bell, and A. Nordlund for their cooperation in converting the MARCS code to run at Louisiana State University. Dr. K. Eriksson was instrumental in the implementation of the code. Computer time was provided by the Louisiana State University Network Computer Center. This research was supported in part at Louisiana State University by the National Science Foundation (grant AST 78-25538), and at the University of Texas by the National Science Foundation (grant AST 79-22014) and the Robert A. Welch Foundation.

REFERENCES

Abt, H. A., and Levy, S. G. 1974, *Ap. J.* (*Letters*), **188**, L75.
Arp, H., Sandage, A., and Stephens, C. 1959, *Ap. J.*, **130**, 80.
Bappu, M. K. V., and Raghavan, N. 1969, *M.N.R.A.S.*, **142**, 295.
Barnes, T. G., Dominy, J. F., Evans, D. S., Kelton, P. W., Parsons, S. B., and Stover, R. J. 1977, *M.N.R.A.S.*, **178**, 661.
Becker, S. A., and Iben, I., Jr. 1979, *Ap. J.*, **232**, 831.
Becker, S. A., Iben, I., Jr., and Tuggle, R. S. 1977, *Ap. J.*, **218**, 633.
Bell, R. A., and Gustafsson, B. 1978, *Astr. Ap. Suppl.* **34**, 229.
Blackwell, D. E., Petford, A. D., and Shallis, M. J. 1980, *Astr. Ap.*, **82**, 249.
Boesgaard, A. M. 1970, *Ap. Letters*, **5**, 145.
———. 1976, *Pub. A.S.P.*, **88**, 353.
Boesgaard, A. M., and Chesley, S. E. 1976, *Ap. J.*, **210**, 475.
Boesgaard, A. M., Heacox, W. D., and Conti, P. S. 1977, *Ap. J.*, **214**, 124.
Böhm-Vitense, E. 1979, *Ap. J.*, **234**, 521.
Carson, T. R., and Stothers, R. 1976, *Ap. J.*, **204**, 461.
Caughlan, G. R. 1965, *Ap. J.*, **141**, 688.
Caughlan, G. R., and Fowler, W. A. 1962, *Ap. J.*, **136**, 453.
Clegg, R. E. S., Lambert, D. L., and Tomkin, J. 1981, in preparation.
Cloutman, L. B. 1978, *Bull. AAS*, **10**, 400.
Cloutman, L. D., and Whitaker, R. W. 1980, *Ap. J.*, **237**, 900.
Cottrell, P. L., and Norris, J. 1978, *Ap. J.*, **221**, 893.
Cox, A. N. 1979, *Ap. J.*, **229**, 212.
———. 1980, *Ann. Rev. Astr. Ap.*, **18**, 15.
Cox, A. N., Deupree, R. G., King, D. S., and Hodson, S. W. 1977, *Ap. J.* (*Letters*), **214**, L127,
Cox, A. N., Hodson, S. W., and King, D. S. 1979, *Ap. J.* (*Letters*), **230**, L109.
Cox, A. N., King, D. S., and Hodson, S. W. 1978, *Ap. J.*, **224**, 607.
Cox, A. N., Michaud, G., and Hodson, S. W. 1978, *Ap. J.*, **222**, 621.
Dearborn, D. S. P., and Eggleton, P. P. 1977, *Ap. J.*, **213**, 177.
Fernie, J. D., and Hube, J. O. 1968, *A.J.*, **73**, 492.
Gustafsson, B. 1979, private communication.
Gustafsson, B., Bell, R. A., Ericksson, K., and Nordlund, Å. 1975, *Astr. Ap.*, **42**, 407.
Haefner, R. 1975, *Astr. Ap.*, **45**, 287.
Havlen, R. J. 1972, *Astr. Ap.*, **16**, 252.
Hoffleit, D. 1964, *Catalogue of Bright Stars* (3d ed.; New Haven: Yale University Observatory).
Holweger, H., and Müller, E. A. 1974, *Solar Phys.*, **39**, 19.
Iben, I., Jr. 1966*a*, *Ap. J.*, **143**, 483.
———. 1966*b*, *Ap. J.*, **143**, 505.
———. 1966*c*, *Ap. J.*, **143**, 516.
Iben, I., Jr., and Tuggle, R. S. 1975, *Ap. J.*, **197**, 39.
Johnson, H. R., Milkey, R. L., and Ramsey, L. W. 1974, *Ap. J.*, **187**, 147.
Kane, L., McKeith, C. D., and Dufton, P. L. 1980, *Astr. Ap.*, **84**, 115.
Keller, C. F., and Mutschlecner, J. P. 1970, *Ap. J.*, **161**, 217.
Kobayashi, M. 1980, *Pub. Astr. Soc. Japan*, **32**, 147.
Kraft, R. P. 1970, in *Spectroscopic Astrophysics*, ed. G. H. Herbig (Berkeley: University of California Press), p. 385.
Lambert, D. L. 1976, *Mem. Soc. Roy. Sci. Liège*, ser. 6, **9**, 405.
———. 1978, *M.N.R.A.S.*, **182**, 249.
Lambert, D. L., Dominy, J. F., and Sivertsen, S. 1980, *Ap. J.*, **235**, 114.
Lambert, D. L., Hinkle, K. H., and Hall, D. N. B. 1981, *Ap. J.*, submitted.
Lambert, D. L., and Luck, R. E. 1978, *M.N.R.A.S.*, **183**, 79.
Lambert, D. L., and Ries, L. M. 1977, *Ap. J.*, **217**, 508.
———. 1981, *Ap. J.*, submitted.
Lauterborn, D., Refsdal, S., and Weigert, A. 1971, *Astr. Ap.*, **10**, 97.
Loumos, G. L., Lambert, D. L., and Tomkin, J. 1975, *Pub. A.S.P.*, **87**, 859.
Luck, R. E. 1977, *Ap. J.*, **212**, 743.
———. 1978, *Ap. J.*, **219**, 148.
———. 1979, *Ap. J.*, **232**, 797.
Luck, R. E., and Bond, H. E. 1980, *Ap. J.*, **241**, 218.
Mestel, L. 1953, *M.N.R.A.S.*, **113**, 716.
———. 1957, *Ap. J.*, **126**, 550.
Moore, C. E., Minnaert, M. G. J., and Houtgast, J., 1966, *The Solar Spectrum from* 2935 Å *to* 8770 Å *NBS Monog.*, no. 61 (Washington, D.C.: USGPO).
Niva, G. D., and Schmidt, E. G. 1979, *Ap. J.*, **234**, 245.
Paczyński, B. 1973, *Acta Astr.*, **23**, 191.
Peimbert, M., and Torres-Peimbert, S. 1977, *M.N.R.A.S.*, **179**, 217.
Pel, J. W. 1978, *Astr. Ap.*, **62**, 75.
Relyea, L. J., and Kurucz, R. L. 1978, *Ap. J. Suppl.*, **37**, 45.
Ross, J. E., and Aller, L. H. 1976, *Science*, **191**, 1223.
Roxburgh, I. W. 1978, *Astr. Ap.*, **65**, 281.
Schmidt, E. G. 1971, *Ap. J.*, **170**, 109.
———. 1972, *Ap. J.*, **174**, 605.
———. 1974, *M.N.R.A.S.*, **167**, 613.
———. 1978, *Ap. J.*, **219**, 543.
Schmidt, E. G., Rosendhal, J. D., and Jewsbury, C. P. 1974, *Ap. J.*, **189**, 293.
Siquig, R. A., and Sonneborn, G. 1976, *Bull. AAS*, **8**, 320.
Smith, M. A., Testerman, L., and Evans, J. C. 1976, *Ap. J.*, **207**, 308.
Sneden, C. 1973, Ph.D. thesis, University of Texas.
Sneden, C., Lambert, D. L., Tomkin, J., and Peterson, R. 1978, *Ap. J.*, **222**, 585.
Sonneborn, G., Kuzma, T. J., and Collins, G. W., II. 1979, *Ap. J.*, **232**, 807.

Sweigart, A. V., and Mengel, J. G. 1979, *Ap. J.*, **229**, 624.
Tomkin, J., and Lambert, D. L. 1978, *Ap. J.*, **223**, 937.
Tomkin, J., Luck, R. E., and Lambert, D. L. 1976, *Ap. J.*, **210**, 694.
van Paradijs, J., and de Ruiter, H. 1973, *Astr. Ap.*, **24**, 317.
Vogt, S. S., Tull, R. G., and Kelton, P. K. 1978, *Appl. Optics*, **17**, 574.
Westerlund, B. 1961, *Pub. A.S.P.*, **73**, 72.
Wheeler, J. C. 1979, *Ap. J.*, **234**, 569.

DAVID L. LAMBERT: Department of Astronomy, University of Texas, Austin, TX 78712

R. EARLE LUCK: Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803