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A STUDY OF CNO ELEMENTS IN BARIUM STARS

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ABSTRACT

Carbon, nitrogen, and oxygen abundances are presented for seven mild barium stars and two classical barium stars. The mild barium stars do not show the carbon enhancement typical of the classical Ba II stars. The CNO abundances of the mild barium and normal G and K giants are identical. An *s*-process enhancement is confirmed for some of the mild barium stars.

The marked division in the abundance patterns and the recent discovery of low-mass comparisons to the classical Ba II stars but not the mild barium stars suggest that the two types of barium stars are unrelated. A possible explanation for the mild barium stars is that the abundance of rare *s*-process elements in the interstellar clouds is not uniform. The mild barium stars were formed in clouds containing an above average abundance of the *s*-process elements but approximately normal abundances of other elements.

Subject headings: nucleosynthesis — stars: abundances — stars: Ba II

I. INTRODUCTION

Barium stars play a key role in our understanding of the early phases of stellar red-giant evolution. Most schemes for increasing the carbon or *s*-process element contents of a stellar atmosphere require a rather advanced stage of red giant evolution (e.g., double-shell source stage) and very high luminosity ($M_v \lesssim -2$; see for instance the discussion of Scalo 1976). The warm temperatures and low ($M_v \sim 0$) luminosities of the barium stars, however, place these stars either on the first ascent of the giant branch or in the post He-core flash phase (Scalo 1976; Pilachowski 1977, and references therein). Most proposals to explain both the early red-giant stage and the exotic chemical compositions of the barium stars have centered on possible anomalous mixing events during the He-core flash. A persistent problem with such proposals (off-center He flashes, for instance) is the necessity to invoke some unknown special conditions in a small fraction of red giants in order to induce such unique nuclear processing and mixing.

Very recently, McClure, Fletcher, and Nemec (1980) have discovered that some, possibly all, classical barium stars are double stars with low mass companions. Böhm-Vitense (1980) has shown further that the companion to the barium star ζ Cap is a white dwarf. It is tempting to conclude from these two studies that membership in a binary system is a prerequisite for formation of a barium star. Smith, Sneden, and Pilachowski (1981) have speculated that the companion of ζ Cap has (during its evolution to a white dwarf) transferred its nuclear processed layers to the envelope of the primary, thereby enriching the primary in both carbon and *s*-process abundances.

Additionally, it has been known for some years that the barium stars do not possess a homogeneous set of spectral characteristics. The classical barium stars were defined as a class of peculiar stars by Bidelman and Keenan (1951). The Ba II stars exhibit generally large overabundances of *s*-process material and discernible strengthenings of the CH, C_2, and CN molecular bands. A second group, called mild or marginal barium stars, possess weaker *s*-process enhancements and few, if any, anomalous molecular band strengths (Eggen 1972; Morgan and Keenan 1973). Pilachowski (1977) has demonstrated that a few mild barium stars have *s*-process enrichments of up to $[s/M] \sim +0.5$.[3] However, Hyland and Mould (1974) have shown that two mild barium stars are simply supergiants whose large microturbulent velocities make the Ba II and Sr II resonance lines anomalously strong, even though those stars possess the solar mix of *s*-process and iron-group elements. The fraction of stars previously classified as mild barium stars which exhibit enriched *s*-process material is unknown. Bond (private communication) has pointed out the existence of some mild barium stars enhanced in the light *s*-process elements (Sr, Y, Zr) but not the heavier ones (Ba, La, Ce, etc.).

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[3] In this study we adopt the standard notation $[X] \equiv \log_{10} (X)_{\rm star} - \log_{10} (X)_{\rm Sun}$. We define the symbols $s \equiv$ the average abundance of available *s*-process elements in a given study, and $M \equiv$ the average abundance of available iron-peak elements.

The McClure, Fletcher, and Nemec (1980) study suggests an additional difference between the classical and mild barium stars. Nine of the eleven observed classical Ba II stars showed a radial velocity variation indicative of binary motion. By contrast, none of the six mild barium stars showed a significant velocity variation. The present study is a spectroscopic comparison of the two groups of barium stars. New analyses for seven mild and two classical barium stars are presented and combined with the recent analyses of the classical barium stars HR 774 (Tomkin and Lambert 1979) and ζ Cap (Smith, Sneden, and Pilachowski 1981). With this data we concentrate on two questions. First, are the reported enhancements of *s*-process elements in the mild barium stars real? Second, if the enhancements are real, to what extent do they correlate with the CNO abundances and carbon isotopic ratios in these stars?

In § II we present the observational material. In § III is a discussion of the model atmosphere derivation and computation of the $[s/M]$ ratio for the program stars. The CNO abundances are derived in § IV, and the overall abundance trends are discussed in § V.

II. OBSERVATIONAL MATERIAL

High-resolution photographic spectra have been used to obtain equivalent widths of iron-peak elements in the program stars. Basic data for the program stars are given in Table 1. Sources of the photographic coudé spectra and equivalent widths are as follows: (1) 56 UMa, ι Cnc, *o* Vir, ζ Cyg; University of Hawaii 2.1 m telescope; Pilachowski (1976). (2) 55 Cam, 58 Leo, *o* Vir, 16 Ser, ζ Cyg; Lick Observatory 3.1 m telescope; present study. (3) HR 2392; Mount Wilson 2.5 m telescope; Burbidge and Burbidge (1957). (4) HR 5058; Cerro Tololo Inter-American Observatory 1.5 m telescope; present study. With the exception of HR 2392, all spectra were obtained with reciprocal dispersions < 10 Å mm^{-1} (red) and < 6 Å mm^{-1} (blue). The corresponding dispersions for HR 2392 were 15 and 10 Å mm^{-1}.

We compared equivalent widths of lines of *o* Vir and ζ Cyg from the Lick and University of Hawaii Observatories, and of HR 5058 from Cerro Tololo and from the study of Danziger (1965). Excellent agreement between the two sets of line data for HR 5058 was found. Small differences ($\lesssim 20\%$) were seen in the comparison of Lick and Hawaii equivalent widths for *o* Vir and ζ Cyg. These differences, which were largest for weak lines, were attributed to differences in continuum placement in the two groups of spectrum tracings. Small correction factors were applied to bring the data sets into average agreement, and mean equivalent widths were computed.

Photometric colors were taken from the literature. For the derivation of model temperatures, we used primarily the $(R-I)_K$ broad-band Kron system colors of Eggen (1972) because (a) these near-infrared colors are unaffected by the increased violet opacity of the barium stars, and (b) all but two program stars were observed on the same system, providing internal consistency of the colors. The $(b-y)$ Stromgren intermediate band colors, obtained by Pilachowski (1978) provided a secondary check (see § III). Table 1 contains all photometric data for the program stars.

The University of Texas 2.7 m and 2.1 m telescopes, coudé spectrographs, and Reticon silicon diode arrays (Vogt, Tull, and Kelton 1978) were employed to obtain CNO and *s*-process line data. A standard high-resolution grating was used in the 2.1 m observations, and an echelle grating in the 2.7 m observations. Signal to noise of the

TABLE 1

BASIC DATA

Star	HR	HD	R.A. (1900)	Decl. (1900)	V[a]	$(B-V)$[a]	$(V-R)$[b]	$(V-I)$[b]	$(R-I)_K$[c]	$(b-y)$[f]	Spectral Type
					Mild Barium Stars						
55 Cam	3182	67447	08^{h}02^{m}52^s	+68°46′	5.32	+1.04	...	...	+0.335	0.62	G8 II
ι Cnc	3475	74739	08 40 39	+29 08	4.03	+1.00	+0.75	+1.24	+0.34[d]	0.61	G8 II
58 Leo	4291	95345	10 55 24	+04 09	4.84	+1.17	...	...	+0.40	0.71	K1 III
56 UMa	4392	98839	11 17 20	+44 02	4.97	+1.00	+0.75	+1.21	+0.32[d]	0.61	G8 II
o Vir	4608	104979	12 00 07	+09 17	4.12	+0.98	+0.74	+1.23	+0.35	0.59	G8 III
16 Ser	5802	139195	15 31 41	+10 21	5.26	+0.95	...	...	+0.315	0.57	K0 p
ζ Cyg	8115	202109	21 08 41	+29 49	3.19	+1.00	+0.70	+1.18	+0.335	0.59	G8 II
					Barium Stars						
... .	2392	46407	06 28 06	−11 06	6.27	+1.11	+0.75	+1.23	+0.345	0.66	K0 Ba II
... .	5058	116713	13 20 20	−39 14	5.09	+1.20	...	...	+0.37	0.70	K1 III
... .	774	16458	02 33 21	+81 01	5.78[e]	...	...	...	+0.40	...	K0 p
ζ Cap	8204	204075	21 20 58	−22 51	3.74	+1.00	+0.64	+1.07	+0.30	0.60	G4 Ib Ba II

[a] Blanco *et al.* 1968.
[b] Johnson *et al.* 1966.
[c] Eggen 1972.
[d] Colors from Johnson *et al.* (1966) transformed to the $(R-I)_{Kron}$ system (see Eggen 1972).
[e] Hoffleit 1964.
[f] Pilachowski 1978.

TABLE 2

EQUIVALENT WIDTHS

Star	C_2 5086.4 Å	C_2 5135.6 Å	[O I] 6300.31 Å	[O I] 6363.79 Å	Y II 5087.43 Å	Nd II 5089.83	Nd II 5092.80 Å	Sc II 6300.67 Å	Fe II 6369.46 Å
MILD BARIUM STARS									
55 Cam	34	23	43	13	113	34	64	42	59
ι Cnc	27	16	34	15	108	30	55	31	39
58 Leo	22	30	40	18	83	40	59	30	34
56 UMa	30	22	33	16	103	33	57	29	45
o Vir	29	22	23	11	89	41	63	21	29
16 Ser	36	31	25	11	94	24	45	22	30
ζ Cyg	44	41	28	17	105	28	59	25	40
BARIUM STARS									
HR 2392	122	76	27	...	139	63	83	25	...
HR 5058	150	99	27	18	109	59	72	25	25
HR 774	...	89	33	...	...	...	...	...	...
ζ Cap	101	81	34	22	228	78	114	44	71

scans always exceeded 100, and resolution was about 0.1 Å. Spectral features obtained were: (a) C_2 triplets at 5135 Å and 5086 Å; (b) [O I] lines at 6300 and 6363 Å; (c) CN red system (2 − 0) lines in the 8000 Å region; (d) two Nd II lines and one Y II line near 5086 Å; (e) a Sc II line at 6300 Å and an Fe II feature at 6369 Å. C_2 and [O I] equivalent widths for *o* Vir were taken from Lambert and Ries (1981). Tables 2 and 3 contain all line data obtained from Reticon scans. Other sources for the CN lines, all employing the Texas coudé echelle Reticon system of the 2.7 m telescope, are: 16 Ser and *o* Vir, Tomkin, Luck, and Lambert (1976); HR 2392 and HR 5058, Tomkin and Lambert (1979); ζ Cyg, Tomkin, Lambert, and Luck (1975).

A high-resolution Fourier transform spectroscopy (FTS) (Hall *et al.* 1979) scan of the infrared CO bands was obtained for the program star *o* Vir. The spectrum covered the spectral range of 4100–4900 cm^{-1} at an apodized resolution of 0.135 cm^{-1}.

III. ATMOSPHERE AND METAL ABUNDANCE DETERMINATION

a) *Model Atmospheres*

Since some barium star color indices may be affected by extra molecular absorption, we used the atomic line equivalent widths to define the atmospheric parameters. Species analyzed included the neutral and first ionized stages of Sc, Ti, Cr, and Fe. As usual, only Fe I possessed enough lines over a large range of excitation potential and equivalent width to be used in determining effective temperature and microturbulence. All other species were used to derive the surface gravity.

We predicted abundances for each Fe I line with a trial model atmosphere from the grid of Bell *et al.* (1976) and a line analysis program (Sneden 1973). These abundances were compared to similar ones computed for the same lines in the Sun and in ϵ Vir. The resulting differential abundances of the program stars derived in this manner were largely free of some systematic external errors (e.g., uncertainties in oscillator strengths). These Fe I abundances were then tested to see if there were any correlations with excitation potentials (temperature errors) or equivalent widths (microturbulence errors). Trial stellar atmosphere models were altered until no trends in those two quantities were apparent.

Temperatures and microturbulences derived in this fashion, of course, presume that either (a) the model parameters for the Sun and ϵ Vir are known to high accuracy, or (b) any uncertainties in these standard star parameters introduce no severe errors in the differential quantities when comparing program and standard stars. Ries (1981) contends that the red giant temperature and gravity scales may be in error—see discussion by Lambert and Ries (1981). For ϵ Vir, for instance, a fairly standard model atmosphere [$\equiv (T_{\rm eff}/\log\ g/v_{\rm micro}/$[Fe/H])] is (4970/2.8/2.0/0.0), from Pilachowski (1977). Ries (1981) derived (5300/3.2/0.8/+0.2) for the same star. Some support for a higher temperature scale for late-type stars may be seen in the work of Luck (1977), whose supergiant temperature scale is about 150 K hotter than that determined from previous high-resolution studies. Much of the differences between red giant temperature determinations (130–300 K in this paper) may be attributed to the use of different solar model atmospheres. For instance, at $\log \tau_{\rm ref} = -0.4$, the Bell *et al.* (1976) theoretical solar model shows $T(\tau) = 5610$ K, the Gingerich *et al.* (1971) empirical Harvard-Smithsonian Reference Atmosphere (HSRA) model has $T(\tau) = 5765$ K, and the Holweger and Müller (1974) empirical model has $T(\tau) = 5802$ K (model differences increase toward shallower layers). Clearly, the effective temperature of a star derived differentially with respect to the Sun will depend on the assumed solar model. Since the present study was based on the standards of ϵ Vir and the Sun, no new information may be brought to bear on the red giant temperature scale. Instead, we chose to derive two models for each star: (a) a "low" temperature model determined

TABLE 3

NEW CN (2 – 0) EQUIVALENT WIDTHS

Wavelength	Identification	55 Cam	ι Cnc	58 Leo	56 UMa
	^{12}CN LINES				
7995.65	$R_2(36)$, $R_1(35)$	86	73	...	85
7999.85	$P_1(20)$	62	...	43	50
8000.26	$Q_2(28)$	83	...	62	74
8002.43	$Q_1(27)$	...	87	...	...
8003.21	$P_2(22)$	50	...	38	...
8003.54	$R_1(36)$	53	...	44	...
8003.93	$R_2(37)$	55	...	44	50
8007.47	$P_1(21)$	...	...	48	50
8008.49	$Q_2(29)$	81	74	66	80
8010.08	$Q_1(28)$	78	76	63	75
8011.73	$R_1(37)$	...	...	47	...
8011.93	$P_2(23)$	...	...	46	...
8012.55	$R_2(38)$	56	...	45	59
8015.67	$P_1(22)$	52	45	45	49
8017.02	$Q_2(30)$	72	62	57	68
8018.06	$Q_1(29)$	80	64	67	77
8020.23	$R_1(38)$	55	...	43	...
8021.04	$P_2(24)$	50	...	...	42
8021.48	$R_2(39)$	61	...	41	58
8043.85	$Q_1(32)$	...	...	66	...
8044.39	$Q_2(33)$	94	...	63	86
8051.11	$P_1(26)$	57	...	41	49
8053.06	$Q_1(33)$	76	65	55	73
8057.29	$R_1(42)$	47	39	38	46
8060.70	$P_1(27)$	57	...	49	57
8062.59	$Q_1(34)$	78	72	55	77
8064.10	$Q_2(35)$	85	66	61	75
8420.51	$Q_2(49)(4-2)$	...	49	...	...
8429.96	$Q_2(30)(4-2)$	...	30	...	...
8431.24	$Q_1(29)(4-2)$	...	31	...	...
	^{13}CN LINES				
7997.80	$P_2(16)$	...	3	...	...
8004.7	$Q_2(23)$, $Q_1(21)$, $P_2(17)$	18	5	20	10
8010.45	$Q_1(22)$	7:	...	12:	...
8015.17	$R_1(32)$	5	...	...	4
8019.35	$P_2(19)$	...	...	4:	1:
8048.27	$Q_2(29)$	16	...	14	...
8051.73	$R_1(37)$, $P_2(23)$, $R_2(38)$	...	7	11	8
8058.24	$Q_1(29)$	7:	7:	...	7
8065.03	$Q_2(31)$	...	...	10	6

with the aid of the Bell *et al.* (1976) solar model and the 5000 K ϵ Vir model; (b) a "high" temperature model to be compared with the Holweger and Müller (1974) solar atmosphere and a (5200/3.0/2/0.0) model for ϵ Vir. We show below and in § IV that the basic results of this study are largely unaffected by the temperature scale uncertainty.

We derived gravities with the usual criterion that the average differential abundances of a given element be the same for neutral and ionized lines. Finally, overall average abundances of the iron-peak elements were determined. In computing the final averages, we assigned double weight to the Fe abundances, due to the availability of a large quantity of lines of both ionization states of this element. In Table 4 we list the models and iron-peak metal abundances $[M/H]$ for all stars. Parameters for HR 774 and ζ Cap were obtained from the previously mentioned sources; high temperature models were not derived for these two stars.

Are the model atmosphere parameters correct? External checks may be performed for temperatures and microturbulences. Lambert and Ries (1981) discuss the temperature scale question for their sample of K giant stars; here we check the internal consistency of our derived effective temperatures. In Figure 1 we plot our derived low effective temperatures and $(R-I)_K$ photometric indices, which correlate well. Our low effective temperatures are also in good accord with the empirical $(R-I)_K$ temperature scale shown in Figure 1. This scale was derived from the transformation of Johnson's (1966) temperature versus color index correlation onto the Kron $(R-I)$ scale (see Eggen 1972 for the transformations).

TABLE 4

MODELS AND CNO ABUNDANCES

Star	Model $T_{eff}/\log g/\zeta_t$	$[M/H]$	log C	log N	log O	$^{12}C/^{13}C$	log C/O	log C/N
			MILD BARIUM STARS					
55 Cam	4830/2.25/2.5	−0.37	8.24	8.20	8.85	18	−0.59	+0.04
	5000/2.40/2.5	−0.28	8.38	8.45	9.06	18	−0.68	−0.07
ι Cnc	4850/2.00/2.7	+0.2	8.1:	8.2:	8.6:	20	−0.5:	−0.1:
58 Leo	4500/1.50/2.0	−0.29	8.13	7.71	8.57	13	−0.44	+0.42
	4800/2.50/2.3	+0.19	8.48	8.19	9.04	13	−0.56	+0.29
56 UMa	4800/2.25/3.0	+0.01	8.16	8.28	8.68	32	−0.52	−0.12
	5000/2.60/3.0	+0.10	8.27	8.47	8.90	32	−0.63	−0.20
o Vir	4900/2.60/2.0	−0.28	8.30	7.85	8.77	14	−0.47	+0.45
	5100/2.70/2.0	+0.07	8.33	8.02	8.83	14	−0.50	+0.31
16 Ser	5000/3.00/2.3	−0.03	8.47	8.18	8.94	25	−0.47	+0.29
	5250/3.40/2.6	+0.00	8.60	8.37	9.16	25	−0.56	+0.33
ζ Cyg	4870/2.50/2.0	+0.08	8.39	8.39	8.81	20	−0.42	+0.00
	5000/2.80/2.2	+0.06	8.49	8.57	8.96	20	−0.47	−0.08
			BARIUM STARS					
HR 2392	4900/2.40/2.0	+0.02	8.61	8.07	8.82	21	−0.21	+0.54
	5100/2.70/2.0	+0.03	8.68	8.32	8.90	21	−0.22	+0.36
HR 5058	4750/2.25/3.5	+0.03	8.65	8.22	8.77	20	−0.13	+0.43
	5000/3.00/3.0	+0.27	8.90	8.52	9.11	20	−0.21	+0.38
HR 774	4500/2.00/2.25	−0.32	8.60	8.31	8.72	23	−0.12	+0.29
ζ Cap	5200/1.60/3.50	−0.15	8.57	8.13	8.56	>40	+0.01	+0.44

The correlation of spectroscopic temperatures with $(b-y)$ demonstrates that this Stromgren color in a mild barium star is a good temperature index. A shift in the Bell and Gustafsson (1978) temperature scale by about +150 K brings the spectroscopic and photometric $(b-y)$ temperature scales into accord. Also, Figure 1 clearly shows a separation in $(b-y)$ between the mild and classical barium stars of the same effective temperatures. The redder colors of the classical barium stars are attributable to extra molecular absorption due to C_2 and CH in the 4800 Å spectral region (Bond and Neff 1969; Pilachowski 1978).

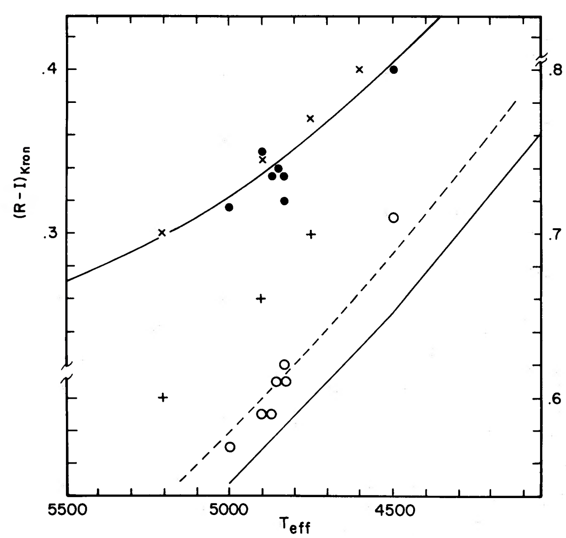

FIG. 1.—Spectroscopic effective temperatures as functions of stellar colors. In the $T_{eff}-(R-I)_{Kron}$ correlation, filled circles represent mild barium stars and crosses represent classical barium stars. The curve is the Johnson (1966) calibration (see text). In the $T_{eff}-(b-y)$ correlation, open circles are mild barium stars while plus signs are classical barium stars. The solid curve is the Bell and Gustafsson (1978) calibration, and the dashed curve is that calibration displaced by +150 K.

An indirect test of microturbulent velocities came from the Reticon low-noise spectra. Ries (1981) derived stellar model atmosphere parameters (from photographic data) for a number of K giant stars and derived CNO abundances from low-noise spectra of the same spectral regions as we employed in the present study. From her spectra we measured full widths at half-maximum (FWHM) of weak unblended iron-peak lines for 20 normal K giants. The natural line widths were always greater than the instrumental widths, and, after subtraction of the instrumental widths, an excellent correlation was found between measured line widths and the corresponding microturbulences as derived by Ries (line widths were of course numerically larger due principally to the presence of macroturbulence). We derived a (linear) empirical line width-microturbulence relation and applied this relation to line widths measured on the barium star scans. Good correlation was found between microturbulences derived from Reticon scan line widths and those from curve-of-growth analyses; typical differences of 0.5 km s^{-1} were seen, with no trend to higher values from either data set. From this check, and from the knowledge that most transitions of interest for this study are relatively weak (Tables 2 and 3), we conclude that microturbulence uncertainties are small and do not affect our basic results.

No independent checks for gravities and metal abundances are possible. We note, however, that our metal abundance trends show good correlation with the results of other workers.

b) *s-Process Enhancements*

Most previous *s*-process studies in barium stars have been carried out with photographic spectra, and the transitions employed either (a) were saturated in the barium star, or (b) were extremely weak in the comparison stars. This situation has led to doubts about the magnitude of the enhancements (see the discussion in § I). We derived an independent measure of *s*-process abundances using several metal lines which appear on the Reticon spectra of Ries (1981) and those of this study. On our spectra, three *s*-process element lines are suitable indicators: 5087.43 Å (Y II, 1.07 eV excitation potential); 5089.83 Å (Nd II, 0.20 eV) and 5092.80 Å (Nd II, 0.37 eV). Iron-peak element lines chosen for comparison were 6300.67 Å (Sc II, 1.51 eV) and 6369.46 Å (Fe II, 2.89 eV). Scandium, although not officially an iron-peak element, correlates well with the iron-peak elements in these stars (Warner 1965; Helfer and Wallerstein 1968; Pilachowski 1977). Equivalent-width measures for these lines in the program stars are given in Table 2; similar measures were obtained by us for nine K giants of Ries (1981). As previously indicated, a large number of iron-peak ionized lines were measured on photographic spectra of the program stars. For the present computations of *s*-process enhancements, we limited our search for iron-peak lines to those available on Reticon spectra, to provide comparison lines measured in a consistent way and from identical data as those of *s*-process elements.

Abundances were deduced by interpolation in a grid of theoretical model atmosphere curves-of-growth. Averages were computed for the three *s*-process lines and the two iron-peak lines, which gave directly the *s*-process enhancements $[s/M]$. Oscillator strength uncertainties were eliminated in the following process. First, solar oscillator strengths of the lines were computed, using the equivalent widths measured directly from the Liège solar atlas (Delbouille, Neven, and Roland 1973) and the theoretical line predictions of the Holweger and Müller (1974) solar atmosphere. With these oscillator strengths the $[s/M]$ ratios of the nine normal K giants were derived. The average ratio $\langle [s/M] \rangle = -0.06$, was very close to solar. Finally, program star abundances were calculated and normalized to a defined scale $[s/M]_{\rm K\ giant} \equiv 0.0$. Since (a) all lines except λ5087 are weak in the program stars, (b) all lines are from singly ionized species, (all these elements are nearly totally ionized in the line forming regions of the atmospheres), and (c) all lines except λ6369 are of similar excitation potential, the derived $[s/M]$ ratios were largely free of atmosphere parameter uncertainties. Equivalent width uncertainties and errors which result from uncertainties in curve-of-growth parameters contributed about ± 0.25 dex uncertainty in the abundances from each line employed in this analysis. The line selection criteria mentioned above brought the total $[s/M]$ uncertainty to about ± 0.15 dex.

The $[s/M]$ ratios for the barium stars are tabulated in Table 5, along with *s*-process indicators from other workers. The values of $[s/M]_{\rm other}$ were computed from straight means of all available *s*-process and iron-peak element abundances given in the cited sources. The ratio as derived here versus that from other workers is plotted in Figure 2; K-giant ratios are taken from Helfer and Wallerstein (1968) and Griffin (1976). The correlation between our ratio and the other, heterogeneous sets of

TABLE 5

s-PROCESS INDICATORS

Star	$[Ba/Fe]_{\rm Williams}$[a]	Ba Index[b]	$[s/M]_{\rm Pilachowski}$[d]	$[s/M]_{\rm others}$	$[s/M]_{\rm this\ study}$
		MILD BARIUM STARS			
55 Cam	+1.20	...	...	...	+0.01
ι Cnc	+0.44	0.1:	+0.16	...	+0.1
58 Leo	+0.42	...	...	...	+0.23
56 UMa	+0.31	0.3:	+0.25	...	−0.04
ο Vir	+0.84	1	+0.57	+0.87[i]	+0.61
16 Ser	+0.64	0.7, 1[c]	...	+0.33[e]	+0.38
ζ Cyg	+0.58	0.65	+0.31	+0.28[f]	+0.17
		BARIUM STARS			
2392	...	3[c]	...	1.02[g]	+0.83
5058	...	3[c]	...	0.77[f]	+0.59
774	+1.29	3[c]	+0.80	1.26[j], 0.54[k]	...
				0.54[m]	...
ζ Cap	...	2[c]	...	0.90	+0.78

[a] Williams 1975.
[b] Keenan and Wilson 1977.
[c] Warner 1965.
[d] Pilachowski 1977.
[e] Helfer and Wallerstein 1968.
[f] Chromey *et al.* 1969.
[g] Burbidge and Burbidge 1957.
[h] Danziger 1965.
[i] Williams 1972.
[j] Tomkin and Lambert 1979.
[k] Cowley 1968.
[m] Nishimura 1967.

TABLE 6

ABUNDANCES OF STELLAR CLASSES

Abundance	Sun[a]	K giants[b]	Mild Barium Stars	Classical Barium Stars
C	8.67	8.35	8.34	8.65
N	7.99	8.26	8.24	8.25
O	8.92	8.87	8.86	8.77
$^{12}C/^{13}C$	89	19	20	~25
$[s/M]$	≡0.00	≡0.00	+0.21	+0.73

[a] Lambert 1978.
[b] Lambert and Ries 1981.

data is excellent. Since our ratio should be internally consistent for all stars, it will be the basic *s*-process indicator for most of the rest of this paper.

Tables 5 and 6 and Figure 2 may be used to illustrate two additional points. First, the $[s/M]$ values for the three stellar groups are: +0.00 for K giants (by definition here); +0.21 for mild barium stars; +0.73 for the classical barium stars. Therefore, while the average *s*-process enhancements are clearly much less in the mild barium stars than in the classical ones, the enhancements are not negligible. On average, the classification-dispersion spectra used to identify mild barium stars apparently do show real abundance effects. Second, although some fraction of the mild barium stars have no appreciable *s*-process enhancements, another group (16 Ser, *o* Vir) show substantial (~0.4–0.6) effects. Our sample of stars is too small to discover what fraction of mild barium stars are very overabundant in *s*-process material. Also, the small systematic trend of

$$[s/M]_{\text{this study}} \approx [s/M]_{\text{others}} - 0.15$$

is insignificant, given the present small sample of stars and the stated abundance uncertainties of previous *s*-process abundance determinations.

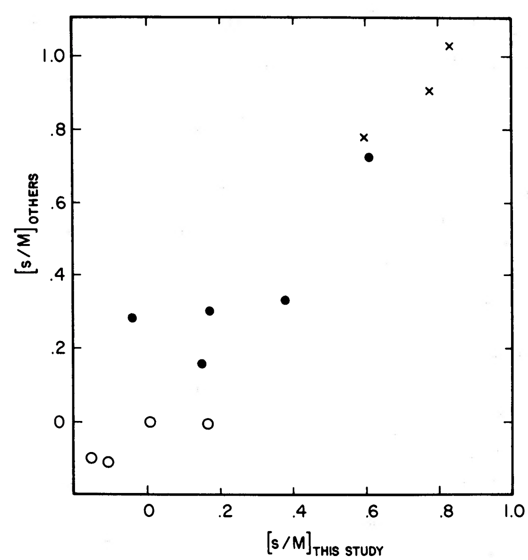

FIG. 2.—The correlation of *s*-process to metal ratios derived in this study and from other investigators. Filled circles represent mild barium stars, crosses represent classical barium stars, and open circles represent the ordinary K giants analyzed by Lambert and Ries (1981).

IV. CNO ABUNDANCES

Carbon, nitrogen, and oxygen abundances were derived in all program stars, using the same transitions and generally the same atomic and molecular line data as those given by Lambert and Ries (1977, 1981). Here we limit our discussion to some points of interest to the present study.

Carbon and oxygen abundances were solved for simultaneously and iteratively, since CO molecular association severely depletes the free carbon and moderately affects the oxygen. Generally the procedure was straightforward, but several interations were needed for those stars in which C/O approaches unity. Also, full account was taken of the desaturating effect of the spread in wavelength of the members of each C_2 triplet. The triplet was treated as a single line only when saturation effects were small, that is, for blend equivalent widths less than about 20 mÅ. For stronger triplets, the blend was synthesized explicitly using a standard spectrum synthesis program (Sneden 1973).

The nitrogen abundance rested on individual lines of the CN red system. The usual warning must be given that the dissociation energy of CN is still uncertain (see the discussion of Lambert 1978). Also, most lines of the CN red system used here belong to the (2–0) band. The oscillator strength for this band was determined by Arnold and Nicholls (1972) to be $f_{(2-0)} = 7.71 \times 10^{-4}$, while Duric, Erman, and Larsson (1978) derive $f_{(2-0)} = 1.4 \times 10^{-3}$. Attempts to predict the (2–0) band in the Sun (line measures from the Liège atlas of Delbouille, Neven, and Roland (1973); the Holweger and Müller (1974) solar atmosphere; Lambert (1978) abundances) suggest that if $D_0(\text{CN}) = 7.65$ eV, then $f_{(2-0)} = 1.1 \times 10^{-3}$. This solar $f_{(2-0)}$ oscillator strength has been adopted for the present work. While these uncertainties indicate potentially substantial errors in nitrogen abundances derived from a CN analysis, note that the concern of this paper is a comparison among barium stars and normal K giants. Adoption of a consistent set of CN parameters permits such a comparison free of an overall scaling error. Finally, since mostly (2–0) CN lines were used in the $^{12}C/^{13}C$ analysis, saturation effects in the relatively strong ^{12}CN lines (see Table 3) limit the accuracy attained for this ratio. We estimate the

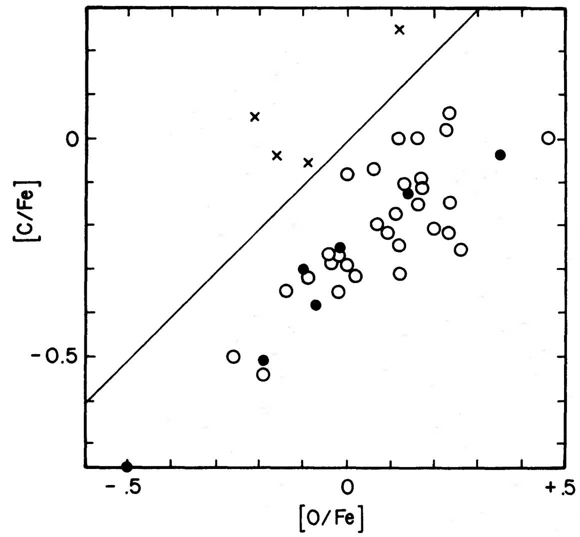

FIG. 3.—Carbon and oxygen abundances referred to the iron peak abundances in the program stars. All symbols are as in Fig. 2. The solid line represents the solar ratio of C/O. Note the clear separation between the classical barium stars and the other groups.

carbon isotope ratio error to be ± 5 (as low as ± 2 in cases where CN $(4-0)$ lines were available).

The CNO abundances are given in Table 4. We chose to derive abundances for both low and high effective temperature models. For ι Cnc, only one abundance set is presented because the atomic line equivalent widths possessed a large scatter and the [O I] features were weak and broad, and hence their equivalent widths were subject to large measurement and continuous placement errors. It is evident from Table 4 that while absolute abundances may change by large factors between the two models, the ratios C/N and especially C/O are relatively insensitive to model choices. Model computations indicate that the CNO features employed in this analysis are formed at reasonably deep ($\tau \sim 0.4$) atmosphere levels in the program stars. Therefore, uncertainties in the outer layers of the model atmospheres do not influence the derived CNO abundance ratios. Of course, model uncertainties have no appreciable effects on derived values of $^{12}C/^{13}C$. In Figure 3 we show the carbon and oxygen abundances for our sample of barium stars and the sample of K giants analyzed by Lambert and Ries (1981). A clear separation between the classical and mild barium stars may be seen: the classical barium stars exhibit log (C/O) ≈ -0.12, while the mild barium stars have log (C/O) ≈ -0.52, a ratio nearly identical to the average log (C/O) ratio of normal K giants (Lambert and Ries 1981). This result is in accord with the apparent lack of anomalies in the molecular bands in the moderate-resolution spectra of mild barium stars.

The infrared CO spectrum of o Vir affords a check on the carbon abundance for this star. The first overtone bands were synthesized with the models and abundances of o Vir listed in Table 4 (see Smith, Sneden, and Pilachowski 1981 for details of CO synthesis regions and line parameters). The CO features were matched very well (within 0.1 dex) with the abundances derived from C_2 and [O I] lines. In early K giants in which C < O, the CO features are most sensitive to carbon abundance variations, therefore the CO synthesis in o Vir confirms the carbon abundance derived from the C_2 features.

V. DISCUSSION

Our CNO analyses clearly show that the mild and classical barium stars may be distinguished by their carbon abundances. The mild barium stars are indistinguishable from normal G and K giants when CNO abundances are compared. Classical barium stars have a marked overabundance of carbon relative to the G and K giants. These results are apparent from Figure 4*a* and Table 6. Although the present sample is small, it would appear that the mild and classical barium stars form two

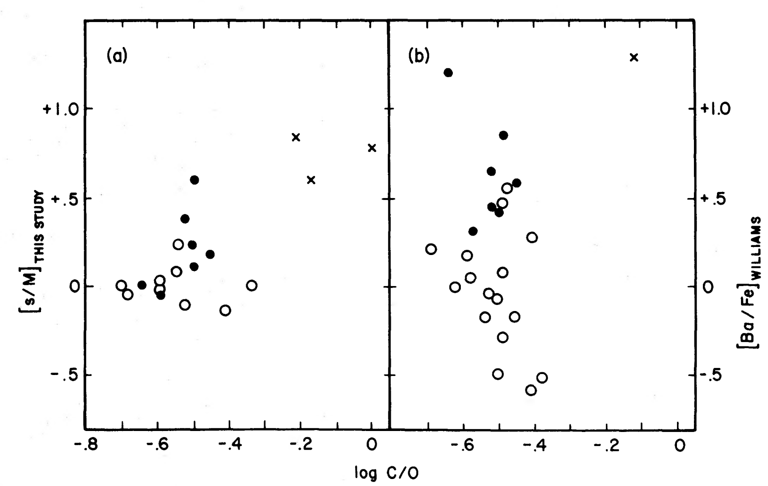

FIG. 4.—The derived C/O ratios versus two *s*-process indicators. All symbols are as in Fig. 2. In (*a*) the *s*-process indicator is the [*s*/*M*] ratio derived in § III, and in (*b*) the indicator is the photometric [Ba/Fe] ratio of Williams (1975). A smaller number of stars are shown in this figure than in Fig. 3 because of the lack of Reticon spectra at 5086 Å (necessary for the derivation of [*s*/*M*] ratios) or the lack of a Williams (1975) photometric [Ba/Fe] index for some stars.

distinct classes; i.e., none of the mild barium stars show a carbon overabundance intermediate between that of the barium stars and the normal G and K giants.

Williams (1975) reported photometric [Ba/Fe] ratios for the majority of our stars. He measured the line absorptions in the 6140.5–6143.6 Å region relative to those in the 6067–6077 Å and 6202–6212 Å regions. The first region contains the 6141.7 Ba II line, while the latter two are free of *s*-process features. Williams demonstrated that the ratio of the line absorptions in the two regions could be translated into [Ba/H] and [Fe/H] abundances. In Figure 4*b* we show the correlation between the derived C/O ratios and the Williams [Ba/Fe] ratio. Again, [Ba/Fe] is independent of the C/O ratio in K giants, but the range of *s*-process abundances is far greater for the photometric data than for our [*s*/*M*] values. The cause of this larger spread may be attributed to either (a) random large errors in the photometric [Ba/Fe] indices, or (b) systematic errors in the indices which are correlated with stellar parameters. Williams (1975) shows that the indices are fairly insensitive to temperature uncertainties and makes an approximate correction for luminosity effects by assuming larger microturbulent velocities for supergiant stars than for giant stars. We show in Figure 5 that some trend of higher values for more luminous stars still exists in the Williams (1975) data. Hyland and Mould (1974) suggests that much of this apparent trend is not due to real abundance effects. In Figure 5, however, we have isolated with different symbols only those stars appearing in Figure 4*b* (not all stars in Fig. 4*b* have measured K-line absolute magnitudes). Little trend with absolute magnitude is seen for the [Ba/Fe] indices of this subset of stars. The large spread of photometric [Ba/Fe] relative to spectroscopic [*s*/*M*] seen in Figure 4 may therefore be attributed to random photometric and

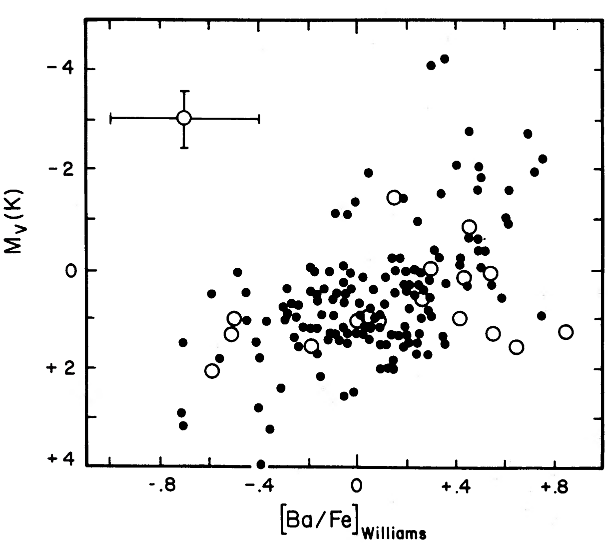

FIG. 5.—The correlation of stellar absolute visual magnitude (Wilson 1976) and the photometric [Ba/Fe] ratios of Williams (1975). In this figure, open circles are the stars from Fig. 4*b* which have measured K-line magnitudes, and filled circles are all other stars common to the lists of Wilson (1976) and Williams (1975).

analysis errors (e.g., choice of T_{eff}, log g, ...). It would be of interest to carry out a spectroscopic abundance analysis of extreme cases in Williams's (1975) list to confirm other suspected cases of anomalous (high and low) *s*-process abundances.

Other abundances in the CNO group shed little further light on the barium stars. In Figure 6 we have plotted the C/N and $^{12}C/^{13}C$ ratios versus the *s*-process abundances. The $^{12}C/^{13}C$ ratios appear to have identical ranges in the K giants, mild barium stars, and classical barium stars. The C/N ratios of the classical barium stars are well correlated with their [*s*/*M*] ratios (see Fig. 6*a*) due merely to the carbon enhancements of these stars (Table 6). It is interesting to note (based on only four stars) that in spite of the large overabundances of carbon in the classical barium stars, log (N) appears little different than in K giants, and the $^{12}C/^{13}C$ ratio may be higher than in the normal stars. Following a similar suggestion by Tomkin and Lambert (1979), we speculate that whatever phenomenon is responsible for the injection of fresh carbon into the atmosphere of barium stars has little CNO-cycle hydrogen burning associated with it. Warner (1965) suggested that all classical barium stars have $^{12}C/^{13}C \gtrsim 20$. A systematic search in the barium stars for anomalous $^{12}C/^{13}C$ ratios could provide a definitive test for the role of the CNO cycle in the formation of these stars. An exception to these trends is HR 4474, in which Lambert and Tomkin find $^{12}C/^{13}C = 13$. A complete abundance study of this star should be conducted.

The C/N ratios in the mild barium stars do exhibit a slight, positive correlation with [*s*/*M*]. Our data are too few to state conclusively that this trend exists; it is necessary first to identify more cases of real, large ($\gtrsim +0.3$) overabundances of the *s*-process elements in the mild barium stars. We stress once more that the trend in C/N exhibited in Figure 6*a* is independent of uncertainties in CN parameters, since all stars have been analyzed in an identical fashion.

The differing CNO abundances suggest different origins for the mild and classical barium stars. An overabundance of *s*-process matrial and simultaneous carbon overabundance indicate an exposure to the neutron sources for the *s*-process (the $^{13}C(\alpha, n)^{16}O$ and/or the $^{22}Ne(\alpha, n)^{25}Mg$ reactions) which occur during helium burning. Iben and Truran (1978) show how thermal pulses in a double-shell star can lead to surface enhancements of material exposed to the ^{22}Ne reaction. The main problem with an identification of this theoretical scenario with the classical barium stars is that the observed luminosities are far short of the required theoretical luminosity (see Scalo 1976 or Iben and Truran 1978 for discussions of this point). The discovery of McClure, Fletcher, and Nemec (1980) and Böhm-Vitense (1980) that the classical barium stars have a low mass companion has led Smith, Sneden, and Pilachowski (1981) to speculate that binary mass transfer from the former primary (which had undergone thermal pulsing) is sufficient to enrich the barium star atmospheres in ^{12}C and *s*-process material. How would the progenitors of the barium stars appear before the companions became white

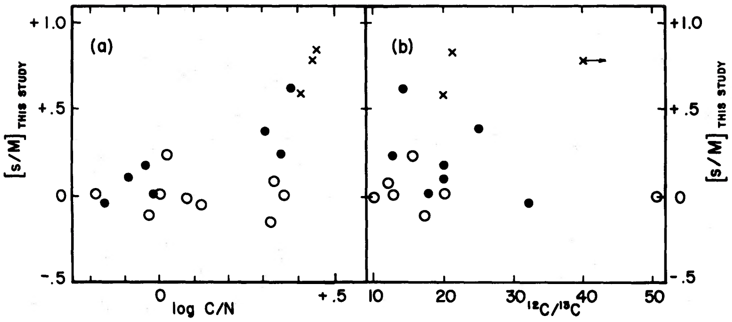

FIG. 6.—The [s/M] ratios plotted vs. the (a) C/N and (b) $^{12}C/^{13}C$ ratios. All symbols are as in Fig. 2.

dwarfs? If ordinary mass loss is involved, the system probably would be a very luminous carbon star (N type?) with a main sequence or subgiant undetected companion. If the mass transfer came from very deep layers in the former primary at the planetary nebula stage, the system probably would not have appeared at all anomalous before the planetary nebula occurred.

A more prosaic origin appears probable for the mild barium stars. We speculate that the mild barium stars are normal G and K giants. Such giants must show the spread in the [s/Fe] abundance that exists in the interstellar clouds. The stars which enriched the interstellar medium that formed the mild barium stars may have included some of the thermally pulsing high-mass stars discussed by Iben and Truran (1978). These stars may have returned to the interstellar medium some increased carbon and s-process elements. Since the cosmic abundances of the heavy elements are so low compared to the CNO group, the enhancements may not have affected the total carbon but produced large star-to-star variations in the s-process.

If this speculation is correct, main-sequence stars and subgiants should show a corresponding spread in the [s/Fe] abundance ratio for a given feature. Butcher (1972) showed that $[s/M] = 0$ to high accuracy in 18 disk stars. However, MacConnell, Frye, and Upgren (1972) found that the number of mild barium stars is about $\frac{1}{2}\%$ of the total G and K giant population. If we presume primordial abundance variations for the mild barium stars, then a random sample of dwarf stars ought to show s-process variations in roughly the same fraction. The sample of 18 stars in Butcher's (1972) study is therefore too small to test this hypothesis.

Wallerstein (1962) examined 21 solar-type dwarf stars and concluded that there existed marginal evidence that [Ba/Fe] was greater than zero in a few stars. Enhancements of up to about +0.4 dex were found, but Wallerstein cautioned that the errors in the derived barium abundances were large. Wallerstein (1962) also noted that [Ba/Fe] ≥ 0 in all stars. However Williams (1975) suggests that s-process deficient stars exist (see Fig. 5 of the present paper). If confirmed cases of stars with $[s/M] < 0$ are found, the case for a cosmic scatter in s-process abundances will be strengthened. Since there are no known mechanisms for s-process depletions in normal stages of stellar evolution, s-process underabundances would most easily be attributed zero-age abundance differences. Brown (1981, in preparation) is performing a systematic search of the Zr/Ti ratios in many of Williams's (1975) stars. The data for that study are low-noise scans of very weak atomic lines; the accuracy of this work should be much higher than previous studies.

VI. SUMMARY

A high-resolution study of CNO and s-process abundances has been performed for seven mild barium stars and two classical barium stars. Mild barium stars are not carbon enriched. The s-process enhancements of the mild barium stars are less than those of the classical barium stars, but these enhancements are real. The classical barium stars apparently result from mass transfer with a binary. The mild barium stars probably reflect scatter in the primordial abundances of s-process material in the Galaxy.

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