1990AJ.....99.1961F

BARIUM AND IRON ABUNDANCES IN RED GIANTS

J. L. FERNÁNDEZ-VILLACAÑAS, M. REGO, AND M. CORNIDE
Departamento de Astrofísica, Facultad de Ciencias Físicas, Universidad Complutense, 28040 Madrid, Spain
Received 10 August 1989; revised 20 December 1989

ABSTRACT

An intermediate-dispersion abundance analysis has been carried out on a sample of 21 barium and 14 comparison stars. The excess of barium over iron has been used as the most representative indicator of peculiarity. These excesses are higher in the peculiar stars than in the nonpeculiar stars. Particularly interesting is the case of HD 67447, included in the comparison stars, with an excess [Ba/Fe] = 1.61, probably a new barium star. A trend indicating a possible anticorrelation between barium overabundance and metallicity favors the suggestion that the "barium strong" group is older than the "barium weak" one.

I. INTRODUCTION

Barium stars represent an important group within low-mass cool giants and are good examples of the possible performance of the s process, which leads to the formation of heavy elements such as barium and strontium. Observation of elements of this kind in detailed analyses of the stars under study has led, in most cases, to the determination of overabundance of barium and rare earths, as well as Y and Zr.

This kind of giant was first acknowledged as a class by Bidelman and Keenan (1951), who considered the enhancements that the Ba II, Sr II, and some carbon molecules presented. Since then, a series of low-resolution studies has been carried out dealing with the characteristics of these stars. Among them stands out the work by Lü *et al.* (1983), based on the measurement of the Ba II λ 4554 Å line. He classified these stars on the basis of a qualitative index of barium line strength, previously introduced by Warner (1965), in a scale ranging from 1 to 5 on low-dispersion spectrograms. Other works in this field are those by McConnell *et al.* (1972) and Williams (1975). The latter introduced an index, R(Ba), which measures the peculiarity of these stars from narrow-band photometry studies and determines barium abundances using models and spectral synthesis as tools.

Barium stars differ in luminosity class among themselves. The classification according to this parameter is not clear in most cases, making it rather difficult to discern the effects of luminosity from those typical of the internal chemical composition. A similar, though less conspicuous, problem occurs with spectral types, whose determination sometimes varies depending on the source.

Former studies lead us to the cataloging of these stars into several types (mild, marginal, certain, etc.), but the truth is that the existing classifications do not represent a definite characterization, which can be determined only through detailed abundance calculations. So, low-dispersion analyses have given way to high-resolution studies, where the abundance of barium and other elements (including a number of s-process elements) is determined. These results are based on very high-dispersion spectrograms, and for this reason they are applied, to this date, to a rather restricted number of barium stars. From these works we can underline those by Tomkin and Lambert (1983) and Kovacs (1983, 1985). Both sources find enhancements in the s-process elements as well as in the C/O ratio when compared with nonpeculiar stars. Solid-state detectors (Digicon and Reticon) were used in these works, allowing much higher resolution and precision than those obtained in previous studies.

In the present work, an intermediate analysis concerning the aforementioned has been carried out. The spectra have intermediate dispersion so that the resolution is better than that of low-dispersion studies. At the same time, this allows us to include a higher number of stars in lieu of the better quality of high-resolution studies. In this sense, we have approached the analysis of iron and barium abundances for a sample of comparison stars and barium stars. The red part of the optical spectrum has been chosen as the basis for our work; the blanketing effects are not as important there as in the blue spectral region. More importantly, this has been a poorly studied region for these kinds of stars.

II. OBSERVATIONS AND REDUCTION

The sample observed contains 21 barium stars and 14 comparison stars of the same spectral type and luminosity class. Their most important data are listed in Table I. The spectral types range between G7 and M0 and the luminosity classes between III and I. These have been taken from Hoffleit and Jaschek (1982) and Keenan (1983, 1984, 1985). Trigonometric parallaxes are those from Hoffleit and Jaschek (1982). The barium peculiarity indicator is that of Keenan (1983) and Lü *et al.* (1983). It is to be remarked that, except for HR 774 and 56 Peg, the values of the barium indices are low. Tables II(a) and II(b) show the most important photometric data of the sample of stars which have been used in the elaboration of later results. The indices in the Johnson system have been obtained from Hoffleit and Jaschek (1982). DDO photometry has been taken from McClure (1976) and McClure and Forrester (1981).

The observations were carried out with the 1.52 m telescope coudé spectrograph of the Observatorio Astronómico Nacional at Calar Alto (Almería) during two observing periods in 1985 and 1986. 098 and IIIa-F photographic emulsions were used as the detector. The spectra were obtained at a reciprocal dispersion of 21 Å/mm (0.4 Å resolution) in the spectral region 5800–6000 Å, which includes the three Ba II lines analyzed in our work. Exposure times ranged from several minutes for the brightest stars in the sample to 1–2 hr for the faintest.

Calibration was performed with the help of an ETA spectrograph, as well as with comparison star spectra of known energy distribution. The comparison stars selected for that purpose were Vega (α Lyr) and Arcturus (α Boo). The spectra were scanned with a PDS microdensitometer.

Finally, equivalent widths for 16 isolated Fe I lines distributed along the spectrum and three spectral features contain-

 0004-6256/90/061961-10$00.90 © 1990 Am. Astron. Soc.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990AJ.....99.1961F

TABLE I. Basic data. Columns 1 and 2: HD and HR identifications; column 3: star name; column 4: spectral type and luminosity class; column 5: Keenan peculiarity index; columns 6 and 7: right ascension and declination (1950.0); column 8: trigonometric parallax ("); column 9: apparent visual magnitude; column 10: number of observations.

HD	HR	Name	Sp.T.	Ba	R.A.	DEC.	PAR.	m_V	N
Ba stars									
5395	265	ν^2 Cas	G8.5 IIIb	0.3	0 53 40	58 54 41	0.051	4.66	3
13520	643	60 And	K3.5 III	0.5	2 10 04	43 59 53		4.84	2
13611	649	65 Cet	G6 II-III	0.3	2 10 20	8 36 47	0.022	4.37	3
16458	774		G8p	3.0	2 40 25	81 14 22	0.013	5.76	1
30834	1551	2 Aur	K2.5 IIIb	0.4	4 49 16	36 37 14		4.77	2
39003	2012	32 Aur	G9.5 III	0.2	5 48 01	39 08 10	0.017	3.97	2
43232	2227	γ Mon	K1.5 III	0.3	6 12 25	-6 15 29	0.013	3.97	2
59294	2864	6 CMi	K1+ III	0.4	7 27 00	12 06 41	0.029	4.53	3
69267	3249	β Cnc	K4 III	0.5	8 13 48	9 20 27	0.012	3.52	4
74739	3475	ι Cnc	G7.5 IIIa	0.1	8 43 40	28 56 39	0.017	4.20	3
82308	3773	λ Leo	K4.5 III	0.3	9 28 52	23 11 22	0.020	4.31	2
83618	3845	ι Hya	K2.5 III-IIIb	0.3	9 37 18	-0 54 53	0.026	3.89	3
95345	4291	58 Leo	K1 III	1 *	10 57 58	3 53 10	0.007	4.83	2
95578	4299	61 Leo	M0 III	0.2	10 59 17	-2 12 55	0.032	4.74	1
98262	4377	ν UMa	K3- III	0.3	11 15 46	33 22 02	0.020	3.70	3
98839	4392	56 UMa	G7.5 IIIa	0.3	11 21 50	43 45 26	0.002	5.10	1
119228	5154	83 UMa	M2 IIIab	1.0	13 38 50	54 56 03	0.014	4.66	1
133208	5602	β Boo	G8 IIIa	0.4	15 00 04	40 35 13	0.037	3.49	1
202109	8115	64 Cyg	G8 III-IIIa	0.6	21 10 48	30 01 15	0.027	3.40	1
206778	8308	ε Peg	K2 Ib	1 *	21 41 44	9 38 42	0.006	2.38	1
218356	8796	56 Peg	G8 Ib	2 *	23 04 40	25 11 53	0.006	4.77	1
Comparison stars									
3627	165	δ And	K3 III		0 36 39	30 35 16	0.028	3.27	1
12533	603	57 And	K3- IIb		2 00 50	42 05 31	0.013	2.26	2
27371	1346	γ Tau	K0- IIIab		4 16 56	15 30 29	0.028	3.65	1
28305	1409	ε Tau	G9.5 III		4 25 42	19 04 16	0.020	3.53	1
29139	1457	α Tau	K5+ III		4 33 03	16 24 38	0.054	0.85	7
62345	2985	κ Gem	G8 IIIa		7 41 26	24 31 10	0.026	3.57	1
67447	3182		G7+ II		8 07 52	68 37 26	0.021	5.50	2
76294	3547	16 Hya	G9 II-III		8 52 45	6 08 13	0.035	3.11	1
77912	3612		G7 Ib-II		9 03 21	38 39 12	0.021	4.70	2
124897	5340	α Boo	K1+ III		14 13 23	19 26 31	0.097	-0.04	2
129312	5480	31 Boo	G7+ III		14 39 11	8 22 28	0.011	4.86	1
163770	6695	θ Her	K1 IIa		17 54 32	37 15 22	0.002	3.86	1
205435	8252	ρ Cyg	G8 III		21 32 06	45 22 12	0.002	4.02	1
210807	8468	24 Cep	G7 II-III		22 08 51	72 05 41	0.017	4.79	1

(*) barium peculiarity taken from Lü et al. (1983)

ing Ba II lines were measured for the 35 stars in the sample. These are given in Tables III(a)–III(e). The Ba II λ 5853.68 Å line appears blended with the Fe I λλ 5852.22 and 5855.08 Å lines. The Ba II λ 6141.72 Å seems to be blended with a Fe I line, though, in this case the Ba II line is the main contributor to the blend. The third spectral feature contains both the Ba II λ 6496.90 Å and the Fe I λ 6496.47 Å lines. Line wavelengths were taken from Moore *et al.* (1966).

III. ANALYSIS: THE SPECTRAL SYNTHESIS

Due to the resolution of our spectra, the Ba II lines appeared to be blended, mainly with Fe I lines. To solve this problem the whole area of the blend was measured, and with the help of a spectral synthesis program the barium abundance could be derived once the iron abundance was known.

The spectral synthesis (see Cornide and Rego 1985 for details) was performed taking as the starting point the choice of a model atmosphere from the grid calculated by Gustafsson and his colleagues (kindly provided by Dr. Gustafsson in a private communication). No interpolation was carried out among different models because the uncertainties introduced in the measuring of the equivalent widths were higher than the fluctuations resulting from assigning two or more close models. Therefore, each star was assigned the model whose parameters were the closest to those previously calculated by the different methods described below. Hydrostatic equilibrium and ionization equations were solved in the usual way, taking into account the line-transfer equation in the LTE hypothesis in order to obtain equivalent widths for a set of different values of abundance.

Since barium stars belong to the old disk population (McClure 1984), it seems reasonable that their metallicities would not be very different from the solar abundance. Therefore, that value was generally adopted for our sample of barium and comparison stars; only for those stars with previously published metallicities was that parameter modified in the sense of assigning lower values than in the solar case. This was done according to the following criterion: if the iron abundance from Morel *et al.* (1976) and Williams (1975) was negative for a certain star, the Gustafsson models with metallicity − 0.25 dex with respect to the solar case were used.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990AJ.....99.1961F

The calculation of a spectral synthesis requires reliable values of the excitation potentials and oscillator strengths. After a comparative study of observed stars whose equivalent widths were previously known, better agreement in equivalent widths was found if we used the excitation potentials and log *gf* values from Gurtovenko and Kostik (1982) for the Fe I lines.

On the other hand, excitation potentials from Moore *et al.* (1966) were taken for the Ba II lines. The log *gf* values used were those that reproduced the equivalent widths of the Ba II lines for the solar spectrum (Moore *et al.* 1966) when performing our spectral synthesis using the solar model (Kurucz 1979).

The spectral line synthesis was carried out point by point with a regular step of 0.01 Å. Only classical damping was considered, though the possible fluctuations in that parameter had a negligible effect compared with the equivalent widths uncertainties. The macroturbulent velocity was not important in the synthesis, as line profiles were of no interest.

Different equivalent widths obtained from different abundance values enabled the determination of the abundance for each spectral line; finally, the value of the abundance for each element was taken as the average of the individual results for each line.

The spectral synthesis program is able to reproduce the range of equivalent widths studied, even those higher than 200 mÅ; this has been checked comparing the results from the program with those from the literature on HR 774, (Tomkin and Lambert 1983) and Arcturus (Griffin 1968).

The remaining parameters affecting both the model atmosphere and the spectral lines studied, e.g., effective temperature, surface gravity, and microturbulent velocity, had a decisive importance in the equivalent width synthesis, so their determination needs to be discussed in more detail. The results for these three parameters are listed in Table IV.

a) Effective Temperature

The effective temperatures of the sample stars were calculated by the different calibrations with photometric indices. For this purpose, the color excess $E(B-V)$ needed to be determined. This was carried out on most stars by means of the method described by Janes (1977), which consists of an iterative process that converges to a fixed color excess value $E(B-V)$, with an error less than 0.03 mag, allowing us to achieve the intrinsic indices $(B-V)_0$, $C(45-48)_0$, $C(42-45)_0$, and $C(41-42)_0$. For those stars for which we could not apply this method, the one described by Janes and McClure (1975) was used.

TABLE II(a). Johnson colors.

HD	Name	U-B	B-V	V-R	V-I	V-J	V-K	V-L
Barium stars								
5395	ν^2 Cas	1.66	0.96	0.77	1.27			
13520	60 And	3.22	1.48					
13611	65 Cet	1.49	0.88	0.67	1.16	1.51	2.06	
16458		1.30						
30834	2 Aur	2.99	1.41	1.09	1.87			
39003	32 Aur	2.23	1.14	0.82	1.38	1.79	2.46	
43232	γ Mon	2.73	1.31	0.97	1.61	2.13	2.91	
59294	6 CMi	2.66	1.29	0.90	1.54			
69267	β Cnc	3.25	1.48	1.12	1.90	2.44	3.37	3.52
74739	ι Cnc	1.81	1.03	0.75	1.24	1.56	2.14	
82308	λ Leo	3.43	1.54	1.23	2.13	2.71	3.69	3.84
83618	ι Hya	2.77	1.32	0.99	1.66	2.18	3.01	3.16
95345	58 Leo	2.28	1.16					
95578	61 Leo	3.54	1.62	1.33	2.29	2.90	3.92	4.08
98262	ν UMa	2.95	1.40	1.06	1.76	2.31	3.18	3.33
98839	56 UMa	1.78	0.98	0.75	1.21	1.64	2.21	
119228	83 UMa	3.59	1.63	1.40	2.52	3.19	4.25	4.43
133208	β Boo	1.68	0.97	0.65	1.09	1.57	2.16	
202109	Zeta Cyg	1.75	0.99	0.70	1.18	1.55	2.11	2.22
206778	ε Peg	3.22	1.52	1.05	1.81	2.36	3.20	
218356	56 Peg	2.50	1.35	0.97	1.65			
Comparison stars								
3627	δ And	2.76	1.28	0.92	1.58	2.04	2.80	2.98
12533	57 And	2.13	1.21	0.94	1.62	2.08	2.91	2.98
27371	γ Tau	1.81	0.99					
28305	ε Tau	1.88	1.01	0.73	1.23	1.60	2.21	
29139	α Tau	3.46	1.54	1.23	2.17	2.70	3.67	3.86
62345	κ Gem	1.62	0.92	0.71	1.16	1.55	2.11	
67447		1.85	1.04					
76294	16 Hya	1.82	1.00	0.71	1.20	1.62	2.23	2.31
77912		1.85	1.04	0.75	1.24			
124897	α Boo	2.51	1.23	0.97	1.62	2.13	2.95	3.09
129312	31 Boo	1.76	1.00					
163770	θ Her	2.81	1.35	0.90	1.53	2.04	2.84	
205435	ρ Cyg	1.45	0.89	0.71	1.21	1.47	2.05	2.14
210807	24 Cep	1.53	0.92	0.69	1.17			

© American Astronomical Society • Provided by the NASA Astrophysics Data System

TABLE II(b). DDO colors.

HD	Name	C(45–48)	C(42–45)	C(41–42)
Barium stars				
5395	ν^2 Cas	1.195	0.851	0.109
13520	60 And	1.368	1.253	0.243
13611	65 Cet			
16458		1.341	1.033	0.455
30834	2 Aur	1.317	1.101	0.257
39003	32 Aur	1.234	0.938	0.292
43232	γ Mon	1.304	1.027	0.314
59294	6 CMi	1.292	1.022	0.326
69267	β Cnc	1.373	1.263	0.254
74739	ι Cnc	1.174	0.808	0.216
82308	λ Leo			
83618	ι Hya	1.298	1.110	0.261
95345	58 Leo	1.224	0.958	0.229
95578	61 Leo			
98262	ν UMa	1.333	1.135	0.274
98839	56 UMa	1.177	0.800	0.246
119228	86 UMa			
133208	β Boo	1.147	0.779	0.193
202109	Zeta Cyg	1.197	0.836	0.294
206778	ε Peg	1.384	1.097	0.353
218356	56 Peg			
Comparison stars				
3627	δ And	1.301	1.118	0.336
12533	57 And			
27371	γ Tau	1.158	0.805	0.264
28305	ε Tau	1.185	0.838	0.292
29139	α Tau			
62345	κ Gem	1.165	0.805	0.200
67447		1.178	0.790	0.249
76294	16 Hya	1.177	0.822	0.237
77912		1.187	0.805	0.246
124897	α Boo	1.265	1.018	0.195
129312	31 Boo	1.187	0.810	0.242
163770	θ Her	1.319	0.988	0.421
205435	ρ Cyg	1.146	0.776	0.132
210807	24 Cep	1.155	0.757	0.182

TABLE III(a). Equivalent widths. Column 1: wavelength (Å); column 2: excitation potential (EV); column 3: oscillator strength; columns 4–10: equivalent width (mÅ).

			HD 5395 ν^2Cas	HD 13520 60 And	HD 13611 65 Cet	HD 16458	HD 30834 2 Aur	HD 39003 32 Aur	HD 43232 γ Mon
Fe I lines									
5809.22	3.88	−1.74		86				85	72
5862.37	4.55	−0.36		93		97	42	117	70
5905.68	4.65	−0.87					100	138	97
5916.26	2.45	−2.97	120	173		42	208	256	190
5934.67	3.93	−1.17	89	192	191	131	226	185	325
6003.02	3.88	−0.96		110	123				276
6065.49	2.61	−1.60	159	193	190	175	223		206
6157.73	4.07	−1.37							
6173.34	2.22	−2.95				148	129		127
6200.32	2.61	−2.39		312					332
6213.44	2.22	−2.67	112	239			164		216
6219.29	2.20	−2.44	247	230			165		
6252.57	2.40	−1.64	235	183	160	213	202	155	213
6393.61	2.43	−1.65	161	339	173	308	281		305
6411.66	3.65	−0.47	124	170	185	111	193		102
6421.36	2.28	−2.04	240	142		125	192	187	105
Ba II lines									
5853.69	0.60	−1.30		171	191	192		172	178
6141.73	0.70	−0.40	167	335	228		226		294
6496.91	0.60	−0.70	249	305		229	272	277	329

1990AJ.....99.1961F

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990AJ.....99.1961F

TABLE III(b). Equivalent widths (continued).

			HD 59294 6 CMi	HD 69267 β Cnc	HD 74739 ι Cnc	HD 82308 λ Leo	HD 83618 ι Hya	HD 95345 58 Leo	HD 95578 61 Leo
Fe I lines									
5809.22	3.88	-1.74	95						
5862.37	4.55	-0.36	161	133	94	133	125		167
5905.68	4.65	-0.87	96	121		84			
5916.26	2.45	-2.97	149	156	91	154	149	80	134
5934.67	3.93	-1.17	101	247	150	213	175	152	203
6003.02	3.88	-0.96	128	132	149	154	119	145	
6065.49	2.61	-1.60	179	157		279	211	210	197
6157.73	4.07	-1.37	148	92			131		
6173.34	2.22	-2.95	118	124			97		
6200.32	2.61	-2.39	259				236	178	
6213.44	2.22	-2.67	295	190	186	226	157	286	
6219.29	2.20	-2.44	146			141	159		
6252.57	2.40	-1.64	169	230	186		205		
6393.61	2.43	-1.65	353	299	249	274	247	228	
6411.66	3.65	-0.47		125	212	108	173	240	133
6421.36	2.28	-2.04		159		211	116	141	
Ba II lines									
5853.69	0.60	-1.30		249		186	139		
6141.73	0.70	-0.40	270	324	254	205	276	320	219
6496.91	0.60	-0.70	225	297	258	249		393	241

TABLE III(c). Equivalent widths (continued).

			HD 98262 ν UMa	HD 98839 56 UMa	HD 119228 83 UMa	HD 133208 β Boo	HD 202109 Zeta Cyg	HD 206778 ε Peg	HD 218356 56 Peg
Fe I lines									
5809.22	3.88	-1.74	102		143		62	141	74
5862.37	4.55	-0.36		138	224			109	
5905.68	4.65	-0.87					41	108	
5916.26	2.45	-2.97	166	119			89	248	125
5934.67	3.93	-1.17	218	237	219		118	384	128
6003.02	3.88	-0.96	137	135		90	57	187	
6065.49	2.61	-1.60	235	209	128	127	133	355	205
6157.73	4.07	-1.37	108					115	203
6173.34	2.22	-2.95	122			199	77	133	65
6200.32	2.61	-2.39	337					347	389
6213.44	2.22	-2.67			222	180	130	263	152
6219.29	2.20	-2.44	189		149			271	
6252.57	2.40	-1.64	276				175	259	155
6393.61	2.43	-1.65	271	240	211	228	330	296	221
6411.66	3.65	-0.47	122	151		107	104	119	164
6421.36	2.28	-2.04	131	210		116	140	164	
Ba II lines									
5853.69	0.60	-1.30	212	259	219		117		226
6141.73	0.70	-0.40	231		232	201	201	287	283
6496.91	0.60	-0.70	250			254		299	

TABLE III(d). Equivalent widths (continued).

			HD 3627 δ And	HD 12533 57 And	HD 27371 γ Tau	HD 28305 ε Tau	HD 29139 α Tau	HD 62345 κ Gem	HD 67447
Fe I lines									
5809.22	3.88	-1.74		71			51		
5862.37	4.55	-0.36	93	103		64	114		
5905.68	4.65	-0.87		87		115	68		219
5916.26	2.45	-2.97	146	175	84	192	116	63	
5934.67	3.93	-1.17		180	116	111	160	136	
6003.02	3.88	-0.96	78	116			123	67	
6065.49	2.61	-1.60	190	143	134	203	199		
6157.73	4.07	-1.37	68	121			80	85	163
6173.34	2.22	-2.95	125	98			93	72	
6200.32	2.61	-2.39	332	282	371		233		
6213.44	2.22	-2.67		374	149		130		
6219.29	2.20	-2.44		258	159		153		
6252.57	2.40	-1.64	97	165	111		164	138	127
6393.61	2.43	-1.65	174	233	195	212	224	204	277
6411.66	3.65	-0.47	130	94	112	151	106		139
6421.36	2.28	-2.04	132	121		131	116		191
Ba II lines									
5853.69	0.60	-1.30				103			197
6141.73	0.70	-0.40	110	200	274		154	202	301
6496.91	0.60	-0.70		233	264	264	233		390

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990AJ.....99.1961F

TABLE III(e). Equivalent widths (continued).

			HD 76294 16 Hya	HD 77912	HD 124897 α Boo	HD 129312 31 Boo	HD 163770 θ Her	HD 205435 ρ Cyg	HD 210807 24 Cep
Fe I lines									
5809.22	3.88	-1.74	90	174	111	88			
5862.37	4.55	-0.36		124	50	178	76		
5905.68	4.65	-0.87	57		82				
5916.26	2.45	-2.97		171	111	263	190	138	
5934.67	3.93	-1.17	88		165		222		71
6003.02	3.88	-0.96	114	138		112	157		120
6065.49	2.61	-1.60	124		121		213		
6157.73	4.07	-1.37	136	66					
6173.34	2.22	-2.95	30		77			124	
6200.32	2.61	-2.39	302		187		199		
6213.44	2.22	-2.67				164	208	111	
6219.29	2.20	-2.44			115				
6252.57	2.40	-1.64	250	159	160	128	231	212	228
6393.61	2.43	-1.65	226	205	205	190		232	
6411.66	3.65	-0.47	111						169
6421.36	2.28	-2.04	163	76	122	129	144		180
Ba II lines									
5853.69	0.60	-1.30	121	237	109	187	237		
6141.73	0.70	-0.40			188	214	395	194	
6496.91	0.60	-0.70			293				236

TABLE IV. Physical parameters of the barium and comparison stars. T_{eff}: effective temperature; log *g*: surface gravity; MICRO: microturbulent velocity (km/s).

HD	Name	Teff	log g	MICRO
Barium stars				
5395	ν^2Cas	4800	2.2	1.0
13520	60 And	3900	1.6	1.8
13611	65 Cet	5100	2.0	1.3
16458		4500	1.4	1.9
30834	2 Aur	4100	1.6	2.0
39003	32 Aur	4600	2.0	1.8
43232	γ Mon	4400	1.6	1.2
59294	6 CMi	4400	1.8	1.6
69267	β Cnc	3900	1.6	1.0
74739	ι Cnc	4900	2.2	1.6
82308	λ Leo	3900	1.6	1.8
83618	ι Hya	4200	1.8	1.1
95345	58 Leo	4500	2.2	2.3
95578	61 Leo	3700	1.4	1.6
98262	ν UMa	4100	1.6	1.5
98839	56 UMa	4900	2.0	1.6
119228	83 UMa	3600	1.6	1.8
133208	β Boo	4900	2.8	1.5
202109	Zeta Cyg	4900	2.0	1.4
206778	ε Peg	4400	1.2	2.3
218356	56 Peg	5100	1.2	1.7
Comparison stars				
3627	δ And	4200	2.0	1.2
12533	57 And	4300	1.4	1.6
27371	γ Tau	4800	2.6	1.3
28305	ε Tau	4800	2.2	2.1
29139	α Tau	3800	1.8	1.0
62345	κ Gem	4900	2.4	1.1
67447		5000	2.0	1.0
76294	16 Hya	4900	2.2	1.2
77912		5000	2.0	1.1
124897	α Boo	4300	2.0	1.5
129312	31 Boo	4800	1.8	1.3
163770	θ Her	4700	1.4	1.6
205435	ρ Cyg	4900	2.8	2.3
210807	24 Cep	5000	2.2	2.6

Lü and Sawyer (1979) have obtained spectral energy distributions for some barium stars which exhibit a conspicuous absorption feature near 4100 Å due to the Bond–Neff depression. For wavelengths greater than 4200 Å this effect is not appreciable. Therefore, the DDO bands $m_{42}-m_{48}$ and the E$(B-V)$, computed using the method of Janes (1975), are substantially free of such an effect. In any case, the uncertainties produced by a possible influence of the Bond–Neff depression will be less than the errors of the temperature calibration T_{eff} vs $(B-V)$.

As other photometric calibrations were performed, we were to determine the color excesses corresponding to the photometric indices used for that purpose. This was carried out by using the interstellar reddening curve from Savage and Mathis (1979) and comparing the results with those obtained from Johnson (1966) using the Van de Hulst curve No. 15.

The calibrations used were those from Ridgway *et al.* (1980), with the intrinsic index $(V-K)_0$; Böhm-Vitense (1981), with the $(B-V)_0$ index for giant and supergiant stars with solar metallicity (the uncertainties are 250 K); and Johnson (1968), using the relations among effective temperature and photometric indices $U-V, B-V, V-R, V-I, V-J, V-K$, and $V-L$ and spectral type versus effective temperature.

Finally, we adopted the mean value from the aforementioned calibrations as the effective temperature of each star.

b) Surface Gravity

Log *g* values were obtained from Janes and McClure (1975) using DDO photometry indices C(45–48) and C(42–45), which were previously corrected for extinction as explained above. The results agreed with those from Morel *et al.* (1976) and Williams (1975) for stars having the same luminosity class.

As our sample contains mainly weak barium stars, the differences in the DDO indices resulting from peculiarity do not exceed the error inherent in the Janes and McClure cali-

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990AJ.....99.1961F

bration of log *g*. This can be checked taking into account the mean magnitude differences of Lü and Sawyer (1979) for the DDO bands between standard and barium stars. For the strongest barium star in the sample, HR 774, with a Warner index of 3, the mean differences in the DDO indices lead us to an error of 0.2 in log *g*, which is no larger than that resulting from the calibration.

c) Microturbulent Velocity

The microturbulent velocity was determined using the set of Fe I lines listed in Tables III(a)–III(b), with the Zeta Cap empirical curve of growth for Fe I (Tech 1971).

IV. RESULTS AND DISCUSSION

Once all of the previous parameters were fixed and model atmospheres assigned for each individual star, the above procedures were followed to carry out spectral synthesis, leading to the determination of iron and barium abundances. The results concerning the abundance of the whole sample of stars are shown in Table V, where a distinction between the comparison and peculiar barium stars has been made. As the number of lines on which the abundance determinations were based is not high enough, we adopted the confidence limit given by the Student's t distribution as the abundance error; when the number of lines was two, the minimum and maximum values were taken. The results concerning iron and barium abundances, as well as the confidence limits, are shown in Fig. 1.

In Fig. 2 the iron abundances obtained in this paper have been plotted versus those from Morel *et al.* (1976) and Williams (1975) for the stars in common. The values range from [Fe/H] = −1.00 for HD 5395 (while Williams gives −0.75) to [Fe/H] = 0.55 for α Boo (while Williams gives 0.25); the latter is based on the synthesis of only a single Fe I line.

In addition, Pilachowski (1977) gives [Fe/H] = −0.50 for HR 774 while our value is [Fe/H] = −0.36, [Fe/H] = −0.20 for β Cnc while ours is [Fe/H] = −0.07, and [Fe/H] = −0.10 for Zeta Cyg compared with our value of [Fe/H] = −0.17. Cowley (1968) gives [Fe/H] = −0.18 for HR 774 while the value

TABLE V. Iron and barium abundances. Column 1: HD number; column 2: star name; columns 3–5: iron abundance, confidence limit, and number of Fe I lines; columns 6–8: barium abundance, confidence limit, and number of Ba II lines; column 9: barium-over-iron excess.

HD	Name	[Fe/H]	C.L.	N.	[Ba/H]	C.L.	N.	[Ba/Fe]
Barium stars								
5395	ν^2 Cas	-1.00	0.10	2	1.00	0.20	2	2.00
13520	60 And	0.30		1	0.88		1	0.58
13611	65 Cet	-0.01	0.05	2	0.30	0.20	2	0.31
16458		-0.36	0.07	6	0.60	0.10	2	0.96
30834	2 Aur	-0.05	0.31	3	0.69		1	0.74
39003	32 Aur	-0.12		1	-0.10		1	0.02
43232	γ Mon	0.04	0.36	6	0.75	0.05	2	0.71
59294	6 CMi	0.12	0.27	4	1.10		1	0.98
69267	β Cnc	-0.05	0.29	5	0.77	0.72	3	0.82
74739	ι Cnc	-0.07	0.13	6	0.37	0.21	2	0.44
82308	λ Leo	0.05	0.15	5	0.97	0.08	2	0.92
83618	ι Hya	0.05	0.23	5	0.80		1	0.75
95345	58 Leo	-0.18	0.22	6	0.75	0.05	2	0.93
95578	61 Leo	-0.23	0.04	2	0.27		1	0.50
98262	ν UMa	-0.02	0.16	5	0.25	0.05	2	0.27
98839	56 UMa	0.23	0.15	6	0.56		1	0.33
119228	83 UMa	0.30		1	0.30		1	0.00
133208	β Boo	0.55		1	0.81	0.10	2	0.26
202109	Zeta Cyg	-0.17	0.31	5	0.40		1	0.57
206778	ε Peg	0.04	0.22	6	0.60		1	0.56
218356	56 Peg	-0.15	0.43	3	0.94	0.02	2	1.09
Comparison stars								
3627	δ And	0.46		1	-0.69		1	-1.15
12533	57 And	0.09	0.50	5	0.20		1	0.11
27371	γ Tau	0.09	0.15	4	0.60		1	0.51
28305	ε Tau	-0.04	0.12	2	0.44		1	0.48
29139	α Tau	-0.17	0.14	7	-0.06	0.01	2	0.11
62345	κ Gem	0.23	0.06	2	0.69		1	0.46
67447		-0.30		1	1.31	0.25	3	1.61
76294	16 Hya	-0.21	0.40	3	-0.19		1	0.02
77912		0.38	0.26	3	1.31		1	0.93
124897	α Boo	-0.69	0.10	5	-0.40		1	0.29
129312	31 Boo	-0.44		1	0.70		1	1.14
163770	θ Her	0.25	0.40	4	1.30		1	1.05
205435	ρ Cyg	-0.05	0.25	2	0.56		1	0.61
210807	24 Cep	-0.14		1	0.20		1	0.34

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990AJ.....99.1961F

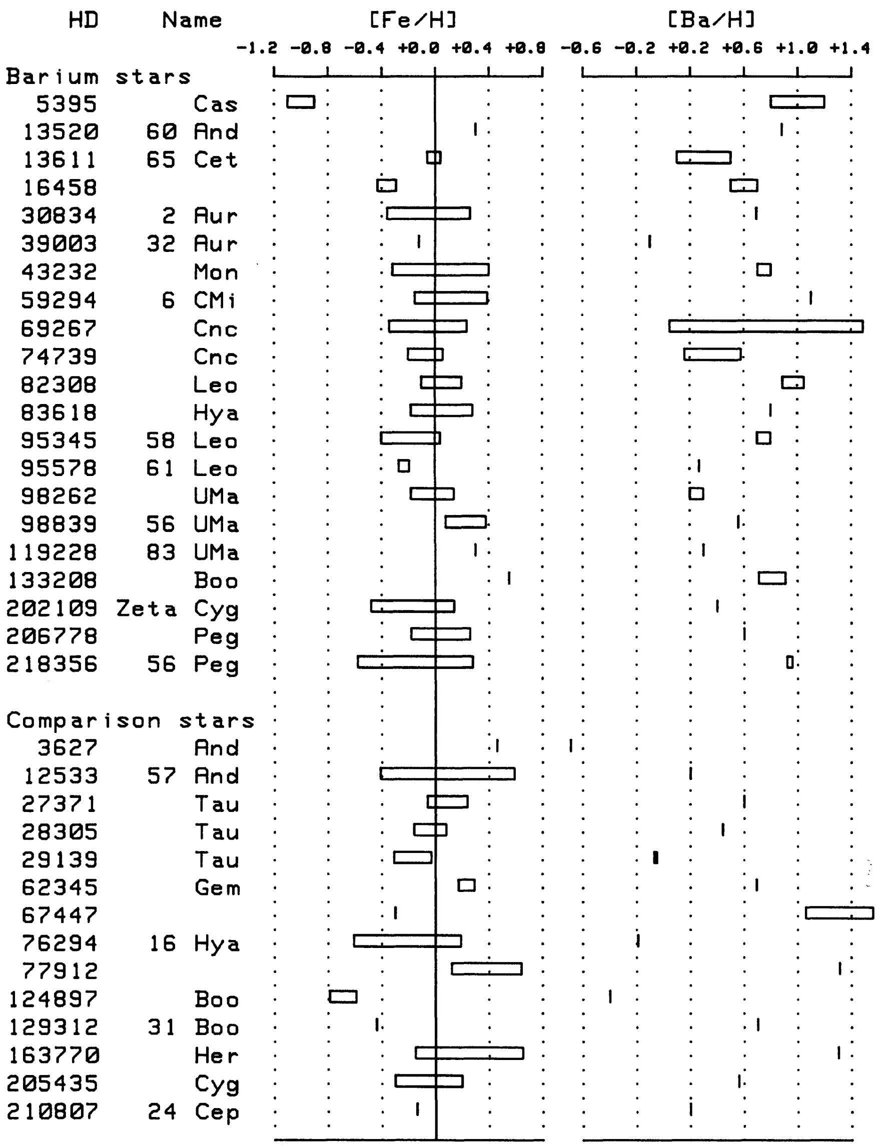

FIG. 1. Iron and barium abundances for the sample of barium and comparison stars. Confidence limits are shown when possible.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990AJ.....99.1961F

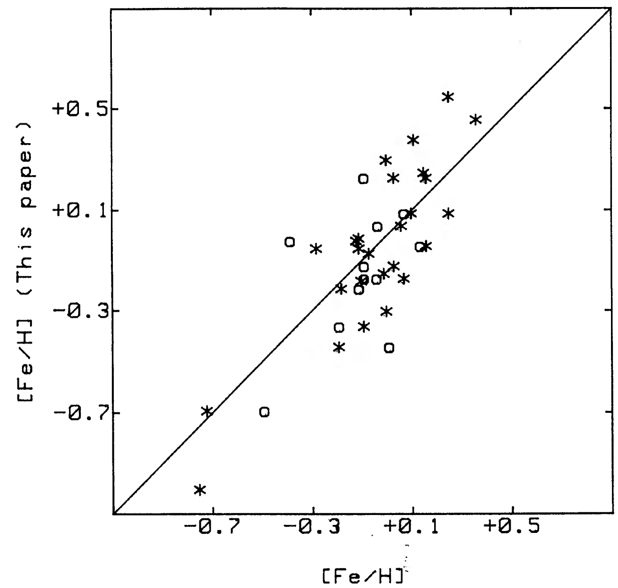

FIG. 2. Iron abundances from Morel *et al.* (1976) (O) and Williams (1975) (*), vs the values in this paper.

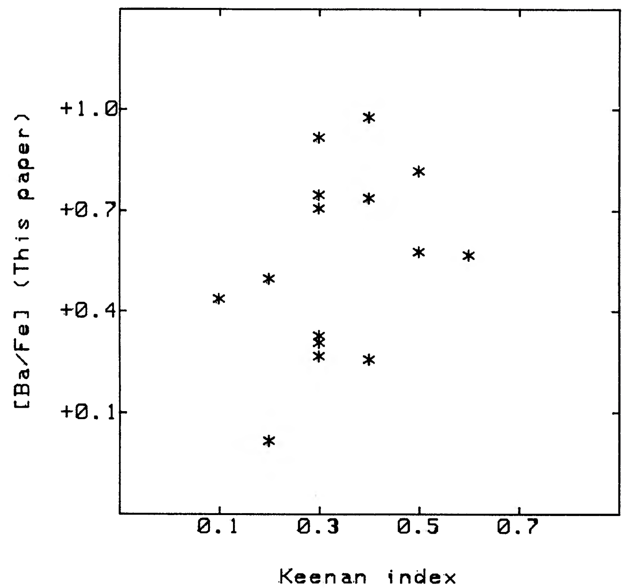

FIG. 4. Barium-over-iron excess vs Keenan barium indicator for the sample of barium stars studied.

from Tomkin and Lambert (1983) is [Fe/H] = − 0.43.

The barium abundances from this paper have been plotted versus the ones from Williams (1975) (Fig. 3). The barium group has barium abundances higher than the solar value; 6 CMi is an outstanding case, with [Ba/H] = 1.1, although this result is based on only one Fe I line. The exception is 32 Aur, with [Ba/H] = − 0.10. The comparison stars have barium abundances distributed around the solar value, with [Ba/H] = − 0.69 for Delta And as the lowest one. Extreme cases are HD 67447 and HD 77912, each with barium abundances [Ba/H] = 1.31, higher than any of the barium stars.

Pilachowski (1977) gives a value of [Ba/H] = 1.0 for HR 774, while the abundance from Tomkin and Lambert (1983) is [Ba/H] = 0.82, that from Cowley (1968) is [Ba/H] = 0.80 and our result is [Ba/H] = 0.60. Zeta Cyg and β Cnc have barium abundances [Ba/H] = 0.30 and 0.20, respectively, while our results are [Ba/H] = 0.40 and 0.37.

We have used the excess of barium over iron, [Ba/Fe], as the most representative indicator of peculiarity. These values, shown in Table V, should be compared with the Keenan index (Fig. 4); that there is no correlation may be due to the dependence of the Keenan indicator on the temperature and

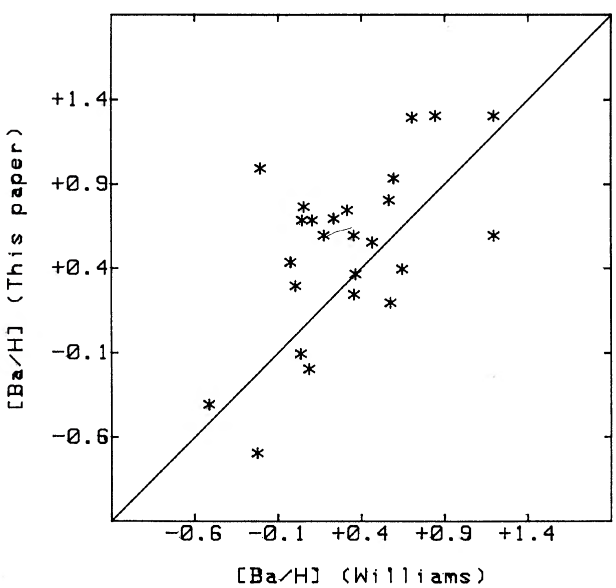

FIG. 3. Barium abundances from Williams (1975) vs the values in this paper.

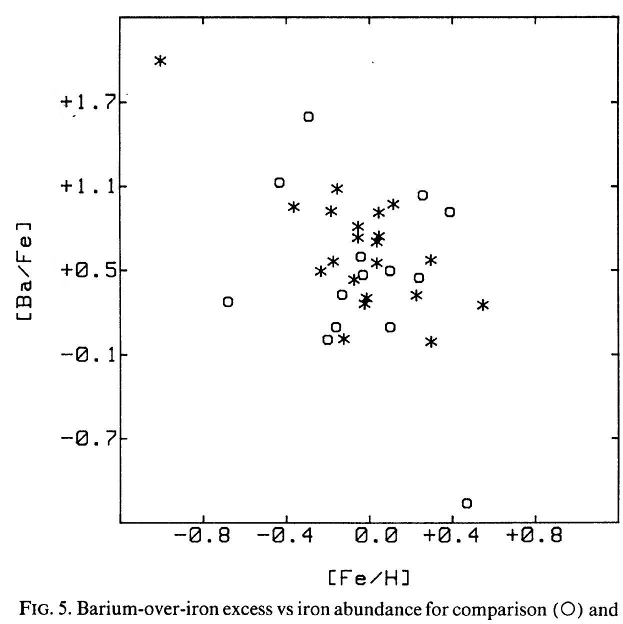

FIG. 5. Barium-over-iron excess vs iron abundance for comparison (O) and barium (*) stars.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990AJ.....99.1961F

surface gravity.

There is not a definite difference in [Ba/Fe] between the barium and the comparison stars in the sample studied because the barium stars selected are not very peculiar. In this sense, there are comparison stars with barium-over-iron excess higher than those corresponding to barium stars. Among them, HD 67447 stands out, with [Ba/Fe] = 1.61, perhaps a new barium star. On the other hand, Delta And, with [Ba/Fe] = − 1.15, represents the least peculiar star in the sample. The star showing the highest barium-over-iron excess, [Ba/Fe] = 2.00, is υ^2 Cas, which has a barium abundance [Ba/H] = 1.00. This is in the opposite sense to the value given by Williams (1975), [Ba/H] = − 0.20, for a peculiar star with a Warner index of 2.

In Fig. 5 we have plotted the barium-over-iron excess [Ba/Fe] vs iron abundance, trying to confirm the correlation pointed out by Kovacs (1985), in the sense that the lower the iron content, the more overabundant barium appears to be relative to iron. If this is so, "barium strong" stars would be older than "barium weak" ones, in agreement with Catchpole *et al.* (1977), who found a higher velocity dispersion for the "barium strong" group. Unfortunately, most of the stars in our sample exhibit an iron content in the range $-0.5 \leqslant$ [Fe/H] $\leqslant 0.5$; only in one case is this value roughly − 1.0, giving rise to a significant lack of data in the $-1.0 \leqslant$ [Fe/H] $\leqslant -0.5$ range. Therefore, very little can be predicted about the existence of an anticorrelation. However, if our data and those of Kovacs (1985) are plotted together, a general trend can be observed. If such an anticorrelation is even doubtful, the differences in velocity dispersion between both groups could be explained by assuming the hypothesis that these stars are all members of binary systems. Concerning this, McClure (1983) has studied the variations in radial velocities, finding them lower for the "barium weak" group, which would indicate that these systems are bound in orbits with larger radii than those belonging to the "strong" group. In this way, the transfer of heavy elements from one member of the binary system to the other would be smaller for the "barium weak" group (Böhm-Vitense *et al.* 1984), leading to a lower barium overabundance.

REFERENCES

Bidelman, W. P., and Keenan, P. C. (1951). Astrophys. J. **114**, 473.

Böhm-Vitense, E. (1981). Annu. Rev. Astron. Astrophys. **19**, 314.

Bohm-Vitense, E., Nemec, J., and Proffitt, C. (1984). Astrophys. J. **278**, 726.

Catchpole, R. M., Robertson, B. S. C., and Warren, P. R. (1977). Mon. Not. R. Astron. Soc. **181**, 391.

Cornide, M., and Rego, M. (1985). Astrophys. Space Sci. **105**, 55.

Cowley, C. R. (1968). Astrophys. J. **153**, 169.

Griffin, R. F. (1968). *A Photometric Atlas of the Spectrum of Arcturus* (Cambridge Philosophical Society, Cambridge, England).

Gustafsson, B. (1984). Private communication.

Gurtovenko, E. A., and Kostik, R. I. (1982). Astron. Astrophys. Suppl. **47**, 193.

Hoffleit, D., and Jaschek, C. (1982). *Catalogue of Bright Stars* (Yale University, New Haven).

Janes, K. A., and McClure, R. D. (1975). Dudley Obs. Rep. **9**, 99.

Janes, K. A. (1977). Publ. Astron. Soc. Pac. **89**, 576.

Johnson, H. L. (1966). Annu. Rev. Astron. Astrophys. **4**, 193.

Johnson, H. L. (1968). in *Stars and Stellar Systems*, edited by B. M. Middlehurst and L. H. Aller (University of Chicago, Chicago), Vol. VII, p. 167.

Keenan, P. C. (1983). Centre de Donnés Stellaires Bull. **24**, 19.

Keenan, P. C. (1984). News. Chem. Peculiar Late-Type Stars **1**, 5.

Keenan, P. C. (1985). CDS Bull. **29**, 25.

Kovacs, N. (1983). Astron. Astrophys. **124**, 63.

Kovacs, N. (1985). Astron. Astrophys. **150**, 232.

Kurucz, R. L. (1979). Astrophys. J. Suppl. **40**, 1.

Lü, P. K., Dawson, D. W., Upgren, A. R., and Weis, E. W. (1983). Astrophys. J. Suppl. **52**, 169.

Lü, P. K., and Sawyer, D. (1979). Astrophys. J. **231**, 144.

McClure, R. D. (1976). Astron. J. **81**, 182.

McClure, R. D., and Forrester, W. T. (1981). Publ. Dominion Astrophys. Obs. **XV**, No. 14.

McClure, R. D. (1983). Astrophys. J. **268**, 264.

McClure, R. D. (1984). Publ. Astron. Soc. Pac. **96**, 117.

McConnell, D. J., Frye, R. L., and Upgren, A. R. (1972). Astron. J. **77**, 384.

Moore, C. E., Minnaert, M. G. J., and Houtgast, J. (1966). *The Solar Spectrum* 2935 *A to* 8770 *A*, NBS Monograph No. **61** (U. S. Government Printing Office, Washington, DC).

Morel, M., Bentolila, C., Cayrel, G., and Hauck, B. (1976). In *Abundance Effects in Classification*, IAU Symposium No. **72**, edited by B. Hauck and P. C. Keenan (Reidel, Dordrecht).

Pilachowski, C. A. (1977). Astron. Astrophys. **54**, 465.

Ridgway, S. T., Joyce, R. R., White, N. M., and Wing, R. F. (1980). Astrophys. J. **235**, 126.

Savage, B. D., and Mathis, J. S. (1979). Annu. Rev. Astron. Astrophys. **17**, 73.

Tech, J. L. (1971). *A High-Dispersion Spectral Analysis of the Ba II Star HD* 204075, NBS Monograph No. **119**, (NBS, Washington, DC).

Tomkin, J., and Lambert, D. L. (1983). Astrophys. J **273**, 722.

Warner, B. (1965). Mon. Not. R. Astron. Soc. **129**, 263.

Williams, P. M. (1975). Mon. Not. R. Astron. Soc. **170**, 343.

© American Astronomical Society • Provided by the NASA Astrophysics Data System