ABUNDANCES IN G DWARF STARS. I. A COMPARISON OF TWO STARS IN THE HYADES WITH THE SUN*

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ABSTRACT

A curve-of-growth analysis has been used to compare abundances in two G dwarfs of the Hyades with those of the sun. The abundances of Na, Mg, Si, Ca, Sc, Ti, Cr, Mn, Fe, and Ni are found to be the same as in the sun within 25 per cent. Ba is overabundant by a factor of 2. The results can be interpreted in either of two ways. If the overabundance of Ba is spurious, then it seems most likely that the enrichment of the interstellar medium between presolar times and the time of formation of the Hyades stars has been negligible. On the other hand, if Ba is indeed overabundant, then the material that has enriched the interstellar medium must have had the solar abundance of the other ten elements studied. By considering the processes discussed by Burbidge, Burbidge, Fowler, and Hoyle (1957) it can be shown that Ba (and other very heavy elements) can be overabundant if the material had been subjected to a temperature of 10^8 degrees but no greater.

I. INTRODUCTION

According to current evolutionary arguments (e.g., Sandage 1957), the stars in the Hyades cluster are said to have an age of about 1 billion years. The determination of the age of meteorites and of the earth by Patterson (1956) indicates that the solar system must be at least 4.55 billion years old, and thus the age of the sun may be a little greater than this—let us say about 5 billion years. This is consistent with studies of the solar interior (Schwarzschild, Howard, and Härm 1957).

If the processes of nuclear genesis of the elements and the distribution of the resulting material into the interstellar medium has been proceeding at a steady and efficient rate between presolar times and the present, there may be a noticeable difference in the abundances of elements heavier than hydrogen between relatively old and young stars. In order to test this hypothesis, we have chosen for study a comparison with the sun of two dwarfs in the Hyades, Nos. 63 and 73, whose colors match those of the sun very closely. Their radial velocity (Wilson 1948), proper motion, proximity to the cluster center, and position in the color-magnitude diagram (Johnson and Heckmann 1956) indicate that they are members and are normal main-sequence stars. Their properties, along with the properties of the sun and of the standard for G2 V stars (Johnson and Morgan 1953), are listed in Table 1.

II. OUTLINE OF PROCEDURE

Preliminary visual comparison of the spectra indicated that no large differences were to be expected. For this reason, the greatest care was taken to minimize both systematic and random errors. The spectra were taken with the coudé spectrograph of the 100-inch telescope, using the 32-inch camera and grating 41B in the second-order, visual, region. The visual region was chosen in order to have a sufficient number of unblended lines in spite of the rather moderate dispersion of 15 A/mm. The projected slit width was 25 μ, which corresponds very closely to the resolution of the 103*a*-D plates. All spectra were

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widened to 0.8 mm. to minimize grain effects and reduce random errors to a minimum. The plates were developed in D-76 for 12 minutes. The 103*a*-D plate gives a wide usable range of wave length from λ 5200 to the atmospheric band at λ 6277. On the more strongly exposed plates it was also possible to measure the magnesium triplet λλ 5167, 5173, 5183, but, because of some blending and the importance of determining the continuum accurately when strong damping wings are present, these measures must be considered to be of lower weight than those of the other lines.

The calibration of density versus intensity was obtained for each plate with the wedge spectrograph in the 100-inch dome. Comparisons with the coudé strips and the wedge spectrograph in the 60-inch dome showed no differences greater than 5 per cent. To obtain solar equivalent widths with the same equipment, five plates of the asteroid Vesta were obtained on the same nights as the Hyades spectra were photographed. As a further check on the consistency of the calibration, it was noted that the equivalent widths from a weak and a strong exposure of Vesta showed no systematic differences.

In the Hyades four plates each of Nos. 63 and 73 were taken. One plate of No. 73 was discarded because of variable fog background. The exposure times for the Hyades stars, which are eighth magnitude, were from 4 to 6 hours in fairly good seeing.

TABLE 1

PROPERTIES OF G DWARF STARS

Star	$B-V$	$U-B$	Sp. Type	References
Sun.	0.63	....	G2 V	Stebbins and Kron (1957)
Hyades No. 73...... (=HD 28344)	.61	0 13	G2	Wilson (1948); Johnson and Knuckles (1955)
Hyades No. 63...... (=HD 28068)	.63	.17	G1	Wilson (1948); Johnson and Knuckles (1955)
G2 V.............. (Standard)	0.64	0.16	G2 V	Johnson and Morgan (1953)

III. REDUCTION

A total of 133 lines was measured on all plates. Of these, 35 were chosen for measurement of equivalent width, and of the remaining lines only the central depth was measured. From those lines whose equivalent width was measured, an empirical relation between equivalent width and central depth was established. It was found that

$$
\begin{aligned}
W &= k_1 (1 - r) && (r > 0.9)\,, \\
W &= k_2 (1 - r)^{1/2} && (0.7 < r < 0.9)\,, \\
W &= k_3 (1 - r)^{2} && (r < 0.7)\,,
\end{aligned}
\qquad (1)
$$

where W is the equivalent width and r is the residual central intensity of a line. The constants k_1, k_2, and k_3 are reduced to a single constant by requiring that relation (1) be continuous at the points $r = 0.9$ and $r = 0.7$. This single plate constant is determined empirically for each plate.

We were very considerably assisted in measuring the microphotometer tracings by Mrs. Mildred S. Matthews and Mrs. Naomi Greenstein. A program for the reduction of displacement readings to residual central intensities and the further reduction to log W/λ by means of relations (1) was prepared for the Datatron 205 at the institute computing center by Mr. Howard Sturgis. It was then necessary only to compute the plate constants and average the values of log W/λ for each star.

Our equivalent widths for the sun and the Hyades stars are listed in Table 2. Also listed in Table 2 are equivalent widths for 85 Pegasi, to be discussed in Paper II.

TABLE 2

$-\log W/\lambda$

Element Line	Multiplet No.	Vesta	No. 63	No. 73	85 Peg
			Na I		
5682.65	6	4 68	4.58	4 65	4.95
5688.22	6	4.68	4.59	4.59	4.80
5889.98	1	3.90	3.82	3.84	3.86
5895.94	1	4.02	3.98	3.97	3.99
6154.24	5	5.31	5.12	5.06	5.30
6160.76	5	5.01	4.96	4.99	5.10
			Mg I		
5167.32	2	3.85	3.92	3 87	3.73
5172.68	2	3.76	3.81	3.76	3 60
5183.60	2	3.66	3.70	3.60	3.50
5528.41	9	4.23	4.19	4.18	4.16
5711.09	8	4.74	4.73	4.71	4.79
			Si I		
5645.66	10	5.09	5.01	5.04	5.28
5665.60	10	5.19	5.11	5.06	5.68
5690.47	10	5.08	5.05	5.02	5.28
5708.44	10	4.80	4.75	4.74	5.04
5772.26	17	5.02	4.90	4.93	5.25
5793.12	9	5.11	5.08	5.07	5.29
5948.58	16	4.86	4.72	4.69	4.85
			Ca I		
5260.37	22	5.15	5.03	5.13	5.23
5581.97	21	4.75	4.67	4.67	4.71
5588.76	21	4.53	4.43	4.41	4.43
5590.13	21	4.79	4.70	4.65	4.74
5601.29	21	4.68	4.61	4.56	4.78
5857.45	47	4.58	4.42	4.43	4.64
6102.72	3	4.52	4.38	4.44	4.50
6122.22	3	4.38	4.31	4.33	4.36
6162.17	3	4.31	4.24	4.26	4.30
6166.44	20	4.95	4.90	4.95	4.96
			Sc II		
5526.82	31	4.89	4.81	4.76	4.90
5657.88	29	4.87	4.82	4.79	5.07
5669.03	29	5.12	5.09	5.11	5.48
			Ti I		
5210.39	4	4.76	4.70	4.72	4.61
5866.45	72	5.19	5.06	5.10	5.20
5965.83	154	5.24	5.09	5.11	5.58
6261.10	104	5.08	5.11	5.23	5.09

TABLE 2—*Continued*

Element Line	Multiplet No.	Vesta	No. 63	No. 73	85 Peg
		Ti II			
5336.80.......	69	4.88	4.85	4.85	4.86
		Cr I			
5206.04.......	7	4.31	4.27	4.20	4.26
5221.77.......	193	5.32	5.12	5 33	....
5300.75.......	18	4 86	4.91	4.84	4.93
5304.18.......	225	5.30	5.41	5.26	....
5345.81.......	18	4.61	4.60	4.56	4.63
5348.32.......	18	4.77	4.66	4.69	4.72
5409.79.......	18	4.52	4.50	4.49	4.48
5783.93.......	188	5.17	5.03	5.14	5.38
5787.99.......	188	5.09	5.01	5.07	5.38
		Cr II			
5237.33.......	43	5.04	4.97	4.94	5.38
5305.87.......	24	5.40	5.19	5.20	5.69
5308.43.......	43	5.28	5.18	5.17	....
5334.89.......	43	5.36	5.03	5.19	5.31
		Mn I			
5377.63.......	42	5.01	4.94	4.92	5.36
5394.67.......	1	4.80	4.83	4.90	5.11
5420.36.......	4	4.83	4.74	4.78	5.13
5470.64.......	8	5.01	5.04	5.00	5.29
6013.50.......	27	4.85	4.75	4.78	5.16
6016.64.......	27	4.75	4.68	4.75	5.04
6021.80.......	27	4.76	4.69	4.70	5.06
		Fe I			
5215.19......	553	4.55	4.56	4.43	4.70
5216.28.......	36	4.60	4.55	4.49	4.67
5232.95.......	383	4.16	4.16	4.07	4.25
5253.48.......	553	4.88	4.76	4.80	4.95
5266.56.......	383	4.26	4.26	4.24	4.36
5269.51.......	15	4.01	3.99	3.96	4.01
5281.80.......	383	4.54	4.49	4.41	4.56
5302.31.......	553	4.53	4.49	4.55	4.61
5307.37.......	36	4.77	4.77	4.77	4.82
5322.05.......	112	4.99	4.95	4.92	5.08
5324.19.......	553	4.22	4.24	4.21	4.23
5332.91.......	36	4.65	4.60	4.63	4.70
5339.93.......	553	4.50	4.49	4.47	4.54
5371.49.......	15	4.13	4.10	4.20	4.14
5393.17.......	553	4.53	4.48	4.44	4.56
5397.13.......	15	4.27	4.26	4.27	4.23
5405.78.......	15	4.25	4.19	4.23	4.22
5434.53.......	15	4.41	4.37	4.39	4.34
5497.52.......	15	4.61	4.50	4.49	4.56
5501.48.......	15	4.64	4.58	4.58	4.65
5506.78.......	15	4.65	4.54	4.53	4.56
5532.75.......	783	5.03	4.93	4.96	5.28
5567.40.......	209	4.93	4.88	4.82	5.01
5569.62.......	686	4.57	4.44	4.44	4.57
5572.85.......	686	4.31	4.25	4.29	4.40

TABLE 2—*Continued*

Element Line	Multiplet No.	Vesta	No. 63	No. 73	85 Peg
			Fe I		
5576.10	686	4.69	4.62	4.60	4.69
5584.77.......	782	5.13	5.10	4.99	5.37
5586.73.......	686	4.32	4.24	4.26	4.35
5615.65.......	686	4.19	4.14	4.14	4.31
5809.25.......	982	5.13	5.01	5.03	5.49
5852.23.......	1178	5.37	5.13	5.29	5.70
5855.09.......	1179	5.72	5.35	5.36	....
5859.60.......	1181	4.89	4.84	4.89	5.28
5862.37.......	1180	4.85	4.76	4.76	5.08
5873.22.......	1087	5.61	5.23	5.37	....
5883.84.......	982	4.95	4.88	4.85	4.98
5916.25.......	170	5.03	5.01	5.00	5.19
5927.80.......	1175	5.24	5.07	5.00	5.37
5934.66.......	982	4.91	4.81	4.81	5.07
5956.70.......	14	5.05	5.03	5.04	5.30
5983.69.......	1175	4.93	4.84	4.78	5.15
5984.83.......	1260	4.84	4.77	4.68	4.98
5987.08.......	1260	4.98	4.87	4.78	5.16
6024.07.......	1178	4.74	4.59	4.66	4.80
6065.49.......	207	4.66	4.59	4.61	4.71
6082.72.......	64	5.29	4.98	5.15	5.48
6137.71.......	207	4.59	4.48	4.53	4.67
6151.62.......	62	5.13	5.05	5.01	5.27
6173.34.......	62	4.98	4.97	4.95	5.10
6200.32.......	207	4.87	4.88	4.85	4.98
6213.44.......	62	4.86	4.88	4.81	4.92
6219.29.......	62	4.81	4.80	4.81	4.95
6240.66.......	62	5.10	5.07	5.08	5.35
6252.56.......	169	4.72	4.68	4.72	4.82
6254.26.......	111	4.72	4.71	4.67	4.85
6265.14.......	62	4.89	4.83	4.89	4.98
			Fe II		
5197.57.......	49	4.81	4.76	4.64	4.98
5234.63.......	49	4.81	4.68	4.60	4.95
5316.70.......	{48, 49}	4.46	4.48	4.37	4.66
5325.56.......	49	5.02	5.10	4.95	5.26
5337.73.......	48	5.27	5.16	5.16	5.53
5362.87.......	48	4.77	4.71	4.57	4.91
5991.38.......	46	5.17	5.10	5.03	5.50
6149.24.......	74	5.29	4.99	4.96	5.32
6238.38.......	74	5.22	5.10	5.10	5.34
6247.56.......	74	5.06	5.02	5.00	5.32
			Ni I		
5578.73.......	47	5.01	5.00	4.98	5.24
5754.68.......	68	4.81	4.78	4.83	5.02
5805.22.......	234	5.14	5.05	5.11	5.39
5892.88.......	68	4.81	4.72	4.76	4.85
6108.12.......	45	5.03	4.94	5.00	5.06
6175.38.......	217	5.14	5.04	5.02	....
6176.82.......	228	5.01	4.84	4.87	5.17
6224.00.......	228	5.29	5.25	5.28	5.46
			Ba II		
5853.68.......	2	5.08	4.91	4.85	5.24
6141.72.......	2	5.29	4.99	4.96	5.32

A comparison of our solar equivalent widths with those tabulated by Allen (1934) shows a systematic difference, in that ours are too strong by 12 per cent. Miss Bell (1951) found a difference of 17 per cent between her work with the Utrecht Atlas and Allen's tabulation. Considering our relatively small dispersion, the fact that our solar equivalent widths fall between Allen's and Miss Bell's indicates a satisfactory calibration for our plates.

IV. CURVES OF GROWTH

Because of the similarity between the Hyades stars and the sun, it was decided to use a curve-of-growth analysis. It is to be expected that any differences in atmospheric structure will appear only as second-order effects when the spectral type and absolute magnitude of two stars are so similar. The small scatter in the curves of growth serves to justify this procedure. Since we wish to derive differences between the Hyades stars and the sun, we have used our equivalent widths for Vesta to derive values of log η_c from the curve of growth for the sun as given by Goldberg and Pierce (Aller 1953). Sample curves of growth are shown in Figures 1 and 2.

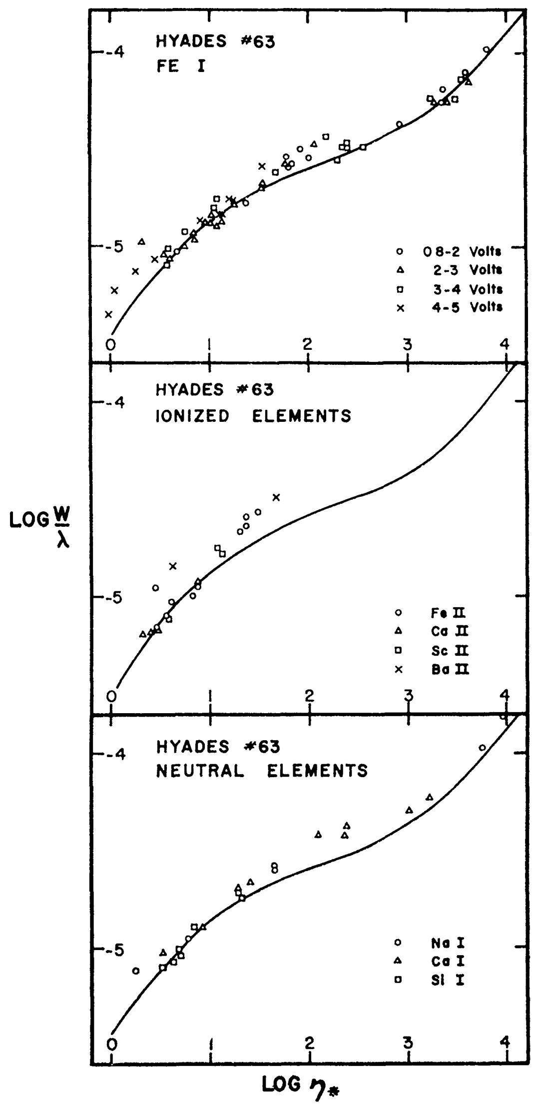

FIG. 1.—Curves of growth for Hyades No. 63. The solid line is the curve of growth for the sun by Goldberg and Pierce (Aller 1953).

From the curves of growth we obtain the differences in the atmospheric parameters as compared with the sun. The neutral iron lines are used for the excitation temperature. The vertical shift yields the difference in the velocity parameter. The horizontal shift of ionized iron and chromium with respect to neutral iron and chromium, respectively, determines the state of ionization. We have weighted the determination from the iron lines by twice that for chromium, since more lines of ionized iron were available. Using the assumption that the difference in ionization temperature equals the difference in excitation temperature, we compute the electron pressure. With the difference in electron pressure and temperature, we compute the difference in opacity. We thus have sufficient data to use the horizontal shift in the curve of growth to determine the difference in abundance of neutral iron which is converted by knowledge of the state of ionization to the total abundance of iron. For the other elements the horizontal shift in the curve of growth relative to iron, combined with the known state of ionization, yields the abundances relative to iron.

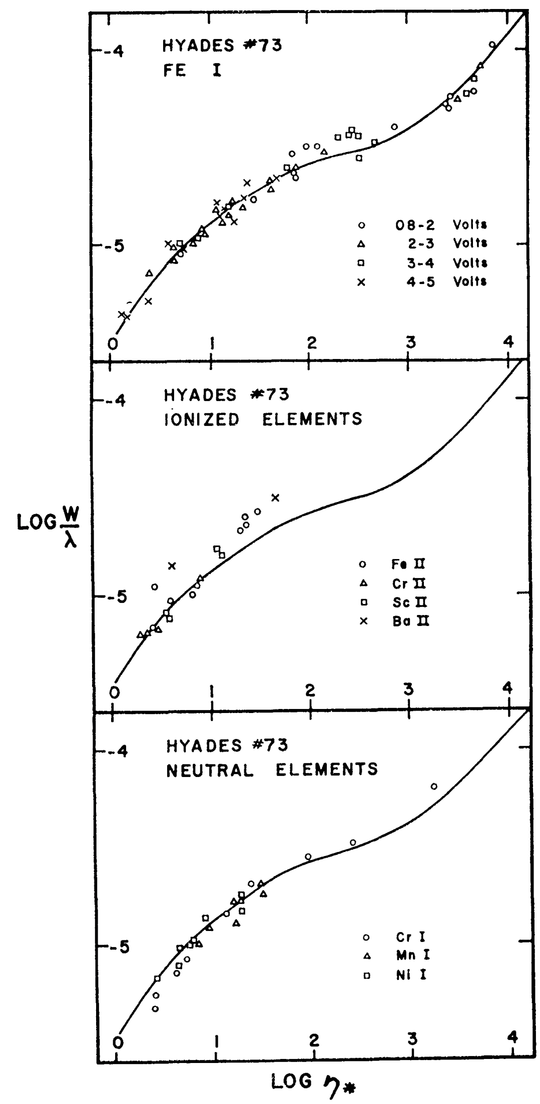

FIG. 2.—Curves of growth for Hyades No. 73. The solid line is the curve of growth for the sun by Goldberg and Pierce (Aller 1953).

V. RESULTS

As noted above, we are deriving only differences with respect to the sun, so our results are independent of uncertainties inherent in studies of the solar atmosphere. It is necessary only that the solar lines in question be correctly identified and that the effects of stratification in the Hyades be similar to those in the sun.

The small scatter in the curves of growth permits accurate determinations of the atmospheric parameters. The largest source of error is the determination of the state of ionization from the shift of the ionized lines with respect to the neutral lines. In No. 63 the maximum error in log P_e is ± 0.10, while in No. 73, where the ionized iron lines scatter more, it is ± 0.20. The differences in the atmospheric parameters are listed in Table 3. Instead of listing probable errors, we list the *maximum error* the data will allow.

In Table 4 are listed the abundances of eleven elements relative to the sun. Again we list *maximum errors*, which range from ± 25 to ± 60 per cent.

We conclude that the abundances of ten elements studied (i.e., excluding barium) are the same in the Hyades as in the sun within 25 per cent. Barium seems to be overabundant by a factor of 2. Although this depends upon only two lines, one of which is slightly blended, both lines are strong in both stars, and we believe the overabundance to be real.

TABLE 3

DIFFERENCES OF ATMOSPHERIC PARAMETERS OF HYADES STARS FROM THE SUN

	No. 63	Maximum Errors	No. 73	Maximum Errors
$\Delta\theta_{exc}$	−0.025	0.025	−0.05	0.025
Δ log V	+ .08	.05	+ .10	.05
Δ log P_e	+ .10	.10	+ .25	.20
Δ log $K(H^-)$	+0.05	.10	+0.13	.20
Δ log a	0	0.10	0	0.10

TABLE 4

LOGARITHMIC ABUNDANCE DIFFERENCES IN THE HYADES RELATIVE TO THE SUN

Element	No. 63 Abundance Difference	Max. Error	No. 73 Abundance Difference	Max. Error	Mean Difference of Hyades
Na	+0.04	0.10	−0.11	0.10	−0.03
Mg	− .15	.15	.00	.20	− .07
Si	+ .01	.10	+ .04	.10	+ .02
Ca	+ .10	.10	+ .09	.10	+ .09
Sc II	.00	.10	+ .05	.15	+ .02
Ti	+ .08	.15	+ .18	.20	
Ti II	− .04	.20	− .03	.20	+ .05
Cr	.00	.15	+ .02	.10	+ .04
Cr II	+ .12	.10	+ .01	.10	
Mn	+ .04	.10	+ .01	.10	+ .02
Fe	+ .01	.10	+ .13	.10	+ .06
Fe II	− .03	.10	+ .13	.10	
Ni	+ .06	.10	+ .10	.10	+ .08
Ba II	+0.30	0.20	+0.42	0.20	+0.36

VI. DISCUSSION

We conclude from the results given above that there has been little or no heavy-element enrichment of the interstellar medium since the time of formation of the sun. Aller, Elste, and Jugaku have reached the same conclusion from a study of the abundances of the light-elements in the B0 star τ Scorpii (1957). Either the rate of star formation is now drastically less than it was in presolar times, or the matter processed in stars and later discharged into the interstellar medium has the solar abundance of elements heavier than sodium, with the possible exception of some of the heaviest elements, such as barium. This second possibility means that those stars have not used either the α-process or the e-process to any appreciable extent, but the overabundance of barium would indicate that some s-process acting on the iron peak elements has taken place (Burbidge, Burbidge, Fowler, and Hoyle, 1957). To get a source of neutrons requires reactions such as $C^{13}(\alpha, n)O^{16}$ which require a temperature of 10^8 degrees. The absence of an overabundance of either calcium or magnesium indicates that the α-process had not been active and thus the temperature never reached 10^9 degrees. The normal abundance of sodium, which is produced by the reaction $Ne^{22}(p, \gamma)Na^{23}$, further reduces the maximum possible temperature to 2×10^8 degrees. Thus we can say that, if appreciable material has been added to the interstellar medium since the sun condensed, then, when this material was in stars, it was subject to temperatures as great as 10^8 degrees but no higher.

This overabundance of barium suggests that a study of the late-type giants in the Hyades at the highest dispersion available might reveal other abundance anomalies among the very heavy elements, particularly the rare earths.

We have had several valuable discussions with Dr. J. L. Greenstein during the course of this work. The skill and experience of Mr. E. Hancock with the 100-inch telescope and coudé spectrograph were of great assistance in obtaining the spectrograms.

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