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THE Ba II STAR ζ CYGNI

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ABSTRACT

A spectral analysis at high dispersion shows that the G8 II star ζ Cygni is a Ba II star showing a relatively small enhancement in the abundance of carbon, strontium, yttrium, barium, lanthanum, and cerium. The possible evolution of such stars is briefly discussed.

I. INTRODUCTION

Although the agreement between observation and theory for the nucleosynthesis of heavy elements by slow neutron capture (*s*-process) is perhaps better established than such agreements for most other elements, it is still desirable to make further observational tests. The theoretical work of Cameron (1955), Burbidge *et al.* (1957), Clayton *et al.* (1961) and Seeger, Fowler, and Clayton (1965) has supplied an apparently adequate basis for understanding the role of slow neutron processes in the building of heavy elements. Observationally, Burbidge and Burbidge (1957), Wallerstein and Greenstein (1964), Warner (1965), and Danziger (1965, 1966) have shown that the occurrence of the *s*-process seems to be favored in K and M giants of both Populations I and II. This work generally involves the detection and detailed study of the most extreme examples of the Ba II type, which are characterized by enhanced lines of ionized barium and an enhanced G band of CH.

We present here the results of an analysis of the bright star ζ Cyg, an inconspicuous example of a Ba II star first brought to our attention by W. P. Bidelman, who pointed out the moderate enhancement of the Ba II line at 4554 Å.

II. OBSERVATIONS

The spectra on which this analysis is based were obtained with the 32-inch camera of the coudé spectrograph of the 100-inch telescope at Mount Wilson. Three spectra in the blue region taken on IIaO plates had a dispersion of 4.5 Å mm^{-1}, and three in the red region on 103aF plates had a dispersion of 6.7 Å mm^{-1}. All spectra and calibration wedges were traced on the digitized microphotometer at Harvard College Observatory. In the reduction procedure a selection of relatively unblended lines was identified, and each tracing was reduced independently with regard to placement of the continuum and measurement of the line strengths. Table 1 contains the final mean values of these measurements. The analysis was then carried out independently by each of the first three authors as a check on the reliability of the method. Some of the results for individual elements depend on very few lines. More certain identification of necessary lines was not possible, probably because the line enhancements are not pronounced in this star.

III. TEMPERATURES AND ABUNDANCES

A differential curve-of-growth analysis was used, the details of which have been given by Danziger (1966). In the present work we have used ε Vir as the standard comparison star, with the line strengths and curve-of-growth abscissae $X_{\odot}'$ published by Cayrel and Cayrel (1963). The curve of growth for ε Vir was obtained by plotting log W/λ against log $X_{\odot}' - \epsilon\Delta\theta$ for the Fe I lines, where ε is the excitation energy. Here $\Delta\theta$ is the value

TABLE 1

LINE STRENGTHS IN ZETA CYGNI

LAMBDA	W(MA)	LOG(W/LAMBDA)
C 1		
4770.00	22.60	-5.32
NA 1		
4497.88	85.30	-4.72
4468.56	114.60	-4.59
4751.82	40.00	-5.07
5682.63	155.00	-4.56
5688.21	225.30	-4.40
5889.95	224.90	-4.42
5895.92	907.20	-3.81
6154.23	110.40	-4.75
6160.75	128.10	-4.68
MG 1		
4702.98	255.10	-4.27
4730.03	113.90	-4.62
5711.09	180.70	-4.50
6318.75	86.10	-4.87
SI 1		
5665.60	93.10	-4.78
5684.52	114.80	-4.69
5690.47	110.60	-4.71
5701.14	75.70	-4.88
5772.26	97.70	-4.77
5793.13	84.20	-4.84
5948.58	147.30	-4.61
6125.03	70.70	-4.94
6131.54	45.80	-5.13
6131.81	68.40	-4.95
6142.50	59.40	-5.01
6145.08	57.30	-5.03
6155.22	78.70	-4.89
6237.34	104.70	-4.78
6243.86	65.00	-4.98
6527.20	71.90	-4.96
6560.68	43.60	-5.18
CA 1		
4425.44	146.90	-4.48
4435.69	216.90	-4.31
4456.61	129.70	-4.54
4507.84	28.90	-5.19
4512.28	57.60	-4.89
4526.94	117.80	-4.58
4578.56	133.60	-4.53
4585.87	204.80	-4.35
4685.27	112.40	-4.62
4847.30	62.80	-4.89
5581.97	164.30	-4.53
5588.76	214.30	-4.42
5590.12	159.60	-4.54
5601.29	221.80	-4.40
5857.45	210.40	-4.44
5867.57	51.60	-5.06

LAMBDA	W(MA)	LOG(W/LAMBDA)
6102.72	210.80	-4.46
6122.22	291.20	-4.32
6161.29	135.70	-4.66
6162.17	307.10	-4.30
6166.44	130.30	-4.68
6169.06	151.90	-4.61
6169.56	182.50	-4.53
6439.07	218.40	-4.47
6449.81	161.30	-4.60
6455.60	106.40	-4.78
6464.70	56.30	-5.06
6471.66	171.90	-4.58
6493.78	168.50	-4.59
6499.65	143.00	-4.66
6508.74	31.10	-5.32
6572.78	114.10	-4.76
SC 1		
6210.68	57.30	-5.03
6305.67	63.10	-5.00
SC 2		
5640.97	107.70	-4.72
5657.87	153.50	-4.57
5667.16	103.20	-4.74
5669.03	127.30	-4.65
5684.19	102.20	-4.75
6245.63	116.40	-4.73
6279.76	104.40	-4.78
6300.70	18.40	-5.53
6309.90	51.10	-5.09
6320.85	35.50	-5.25
TI 1		
4449.14	128.30	-4.54
4453.31	122.20	-4.56
4453.71	93.00	-4.68
4465.81	83.90	-4.73
4503.76	27.60	-5.21
4512.73	149.20	-4.48
4518.02	124.90	-4.56
4534.78	153.40	-4.47
4548.76	133.70	-4.53
4555.49	137.40	-4.52
4562.64	62.80	-4.86
4617.27	107.00	-4.64
4623.10	124.30	-4.57
4639.94	88.50	-4.72
4645.19	109.60	-4.63
4656.47	137.30	-4.53
4675.12	85.70	-4.74
4681.91	126.20	-4.57
4693.67	84.30	-4.75
4715.30	74.10	-4.80
4722.60	65.50	-4.86
4742.32	28.40	-5.22

LAMBDA	W(MA)	LOG(W/LAMBDA)
4742.79	79.10	-4.78
4747.68	21.50	-5.34
4758.12	85.60	-4.74
4759.27	81.70	-4.77
4769.78	35.00	-5.13
4778.26	37.00	-5.11
4781.72	61.80	-4.89
4805.43	63.20	-4.88
4820.41	90.70	-4.73
4840.87	122.10	-4.60
5662.15	72.20	-4.89
5866.45	140.70	-4.62
5899.30	118.60	-4.70
5903.32	48.10	-5.09
5922.11	94.90	-4.80
5937.81	72.00	-4.92
5953.16	115.10	-4.71
5965.83	98.90	-4.78
5978.34	88.20	-4.83
6064.63	49.30	-5.09
6091.18	71.10	-4.93
6121.02	22.00	-5.44
6126.22	110.00	-4.75
6258.10	127.90	-4.69
6258.71	198.10	-4.50
6261.10	138.10	-4.66
6312.24	36.30	-5.24
6336.10	35.40	-5.25
6554.23	69.60	-4.97
TI 2		
4411.94	125.60	-4.55
4417.72	155.70	-4.45
4443.80	202.30	-4.34
4468.49	253.40	-4.25
4470.86	120.70	-4.57
4501.27	239.80	-4.27
4544.01	112.80	-4.61
4563.76	227.30	-4.30
4568.31	85.00	-4.73
4571.97	218.00	-4.32
4583.44	85.10	-4.73
4589.96	166.20	-4.44
4636.34	77.70	-4.78
4657.21	103.60	-4.65
4708.66	102.90	-4.66
4719.52	51.30	-4.96
6559.58	55.10	-5.08
V 1		
4444.21	131.20	-4.53
4524.22	28.70	-5.20
4577.17	152.60	-4.48
4594.10	153.60	-4.48
4635.18	46.90	-4.99
4730.39	31.70	-5.17

LAMBDA	W(MA)	LOG(W/LAMBDA)
4831.64	84.00	-4.76
4832.43	77.90	-4.79
4864.74	107.30	-4.66
4875.46	104.90	-4.67
5670.83	83.70	-4.83
5727.02	144.20	-4.60
5727.66	62.90	-4.96
5737.04	67.30	-4.93
6039.69	79.00	-4.88
6081.42	78.30	-4.89
6090.18	118.00	-4.71
6111.62	58.90	-5.02
6119.50	86.30	-4.85
6135.36	71.20	-4.94
6150.13	75.30	-4.91
6199.20	86.90	-4.85
6216.37	141.70	-4.64
6224.51	51.10	-5.09
6233.19	47.80	-5.12
6242.80	75.80	-4.92
6243.11	139.70	-4.65
6256.91	38.40	-5.21
6266.32	31.60	-5.30
6274.67	70.90	-4.95
6285.18	69.10	-4.96
6292.86	96.30	-4.82
6296.52	81.70	-4.89
6452.35	27.70	-5.37
6504.16	61.30	-5.03
6531.44	28.40	-5.36
CR 1		
4475.34	56.00	-4.90
4492.31	48.90	-4.96
4511.90	107.70	-4.62
4535.15	65.50	-4.84
4540.72	133.90	-4.53
4542.07	65.30	-4.84
4545.96	168.50	-4.43
4591.39	143.10	-4.51
4604.58	95.00	-4.69
4616.14	149.70	-4.49
4622.76	62.40	-4.87
4626.19	130.60	-4.55
4637.18	67.90	-4.83
4646.17	165.60	-4.45
4651.29	158.70	-4.47
4652.16	167.50	-4.44
4693.95	74.80	-4.80
4695.15	52.90	-4.95
4697.06	94.20	-4.70
4700.61	58.40	-4.91
4708.04	98.40	-4.68
4718.43	114.20	-4.62
4724.42	108.20	-4.64
4730.71	75.50	-4.80

TABLE 1, CONTINUED

LAMBDA	W(MA)	LOG(W/LAMBDA)
CR 1		
4737.35	109.70	-4.64
4756.11	99.70	-4.68
4764.29	45.40	-5.02
4767.86	36.10	-5.12
4789.35	122.30	-4.59
4790.34	40.50	-5.07
4801.03	88.80	-4.73
4829.38	132.90	-4.56
4836.86	38.60	-5.10
5712.78	63.90	-4.95
5783.11	77.20	-4.87
5783.93	112.90	-4.71
5787.99	102.30	-4.75
6330.10	83.00	-4.88
6537.92	15.20	-5.63
CR 2		
4558.66	152.50	-4.48
4588.22	129.80	-4.55
4592.09	91.90	-4.70
4616.64	82.30	-4.75
4634.11	133.00	-4.54
4671.42	48.00	-4.99
4848.24	91.10	-4.73
6013.50	179.00	-4.53
6016.64	181.50	-4.52
6021.80	170.70	-4.55
MN 1		
4453.01	98.60	-4.65
4470.14	93.90	-4.68
4502.22	110.80	-4.61
4671.69	41.60	-5.05
4709.72	120.00	-4.59
4739.11	110.40	-4.63
4754.04	168.10	-4.45
4761.53	134.50	-4.55
4762.38	159.40	-4.48
4765.86	121.20	-4.59
4766.43	147.70	-4.51
4783.42	199.10	-4.38
4826.90	43.20	-5.05
FE 1		
4478.04	69.40	-4.81
4481.62	94.30	-4.68
4502.59	67.50	-4.82
4504.84	123.10	-4.56
4516.27	116.00	-4.59
4523.40	89.10	-4.71
4525.88	63.80	-4.85
4536.51	65.90	-4.84
4541.95	41.60	-5.04
4547.85	33.40	-5.13
4551.67	69.10	-4.82
4554.47	98.60	-4.66
4556.94	73.90	-4.79

LAMBDA	W(MA)	LOG(W/LAMBDA)
4566.52	91.30	-4.70
4571.45	55.40	-4.92
4572.85	66.80	-4.84
4574.24	102.00	-4.65
4575.80	66.70	-4.84
4579.34	93.40	-4.69
4579.83	84.20	-4.74
4587.13	107.70	-4.63
4595.36	177.50	-4.41
4596.43	69.40	-4.82
4598.12	137.10	-4.53
4598.73	54.80	-4.92
4602.01	139.80	-4.52
4602.94	215.20	-4.33
4603.34	62.30	-4.87
4604.23	57.60	-4.90
4614.22	85.20	-4.73
4619.29	127.40	-4.56
4625.05	156.70	-4.47
4630.13	145.60	-4.50
4633.76	71.10	-4.81
4635.62	54.60	-4.93
4635.85	95.00	-4.69
4637.51	127.70	-4.56
4641.22	70.70	-4.82
4642.62	41.40	-5.05
4643.47	118.10	-4.59
4647.44	179.60	-4.41
4657.60	72.50	-4.81
4658.29	50.60	-4.96
4661.54	65.20	-4.85
4661.98	111.00	-4.62
4672.83	62.90	-4.87
4677.57	47.20	-5.00
4678.85	133.90	-4.54
4679.23	94.30	-4.70
4682.58	70.80	-4.82
4683.57	106.00	-4.65
4690.15	82.90	-4.75
4690.37	73.40	-4.81
4700.17	113.90	-4.62
4701.05	121.60	-4.59
4704.96	106.00	-4.65
4707.28	158.50	-4.47
4707.49	101.80	-4.67
4728.56	156.00	-4.48
4729.03	67.00	-4.85
4733.60	190.30	-4.40
4734.10	111.30	-4.63
4735.85	106.70	-4.65
4736.78	220.40	-4.33
4737.63	93.00	-4.71
4741.53	127.00	-4.57
4745.81	138.90	-4.53
4749.93	70.30	-4.83
4757.58	101.30	-4.67
4765.49	158.10	-4.48
4772.82	140.90	-4.53

LAMBDA	W(MA)	LOG(W/LAMBDA)
4779.44	83.60	-4.76
4785.96	46.70	-5.01
4786.81	128.40	-4.57
4787.84	84.30	-4.75
4788.76	104.40	-4.66
4789.65	131.30	-4.56
4793.95	25.40	-5.28
4794.35	36.70	-5.12
4798.27	72.80	-4.82
4799.41	79.90	-4.78
4800.14	48.50	-5.00
4800.65	116.30	-4.62
4802.53	28.80	-5.22
4802.88	87.60	-4.74
4804.53	60.40	-4.90
4808.16	67.90	-4.85
4809.94	40.60	-5.07
4813.11	49.70	-4.99
4815.24	43.10	-5.05
4835.86	95.00	-4.71
4839.09	39.50	-5.09
4839.55	100.40	-4.68
4844.02	95.40	-4.71
4845.66	75.40	-4.81
4848.90	90.30	-4.73
4859.75	193.30	-4.40
4863.65	106.50	-4.66
4871.32	224.80	-4.34
4873.76	33.20	-5.17
4874.36	47.40	-5.01
5567.40	164.60	-4.53
5569.63	215.30	-4.41
5572.85	286.90	-4.29
5576.10	184.00	-4.48
5586.76	295.00	-4.28
5618.65	102.50	-4.74
5619.60	123.50	-4.66
5620.53	119.20	-4.67
5624.55	217.90	-4.41
5633.97	125.60	-4.65
5635.85	75.10	-4.88
5638.27	123.90	-4.66
5641.46	126.60	-4.65
5650.71	75.60	-4.87
5655.51	138.60	-4.61
5679.02	109.50	-4.71
5701.55	181.60	-4.50
5705.48	85.00	-4.83
5717.85	135.30	-4.63
5731.77	121.20	-4.67
5741.86	70.60	-4.91
5752.04	107.40	-4.73
5762.43	118.10	-4.69
5762.99	211.60	-4.44
5775.09	116.00	-4.70
5778.47	82.40	-4.85
5793.93	87.10	-4.82
5798.19	129.20	-4.65

LAMBDA	W(MA)	LOG(W/LAMBDA)
5806.73	100.60	-4.76
5809.25	114.80	-4.70
5814.80	53.90	-5.03
5816.36	151.70	-4.58
5848.09	87.70	-4.82
5852.19	81.60	-4.86
5855.13	42.30	-5.14
5856.08	78.70	-4.87
5859.61	136.40	-4.63
5862.36	139.90	-4.62
5873.21	67.60	-4.94
5883.84	166.60	-4.55
5905.67	99.60	-4.77
5909.99	119.60	-4.69
5916.25	152.10	-4.59
5927.80	74.40	-4.90
5929.70	83.00	-4.85
5930.17	147.10	-4.61
5934.66	138.20	-4.63
5943.58	56.90	-5.02
5949.35	116.30	-4.71
5952.75	120.60	-4.69
5956.70	161.60	-4.57
5975.36	97.60	-4.79
5976.80	172.20	-4.54
5983.70	126.90	-4.67
5984.81	157.70	-4.58
5987.06	145.00	-4.62
6003.03	153.70	-4.59
6005.53	92.00	-4.81
6007.96	121.60	-4.69
6008.58	153.60	-4.59
6024.07	168.10	-4.55
6027.06	128.70	-4.67
6055.99	127.00	-4.68
6062.89	99.60	-4.78
6065.49	231.30	-4.42
6078.50	143.00	-4.63
6079.02	88.00	-4.84
6082.72	116.80	-4.72
6089.57	114.30	-4.73
6093.66	66.00	-4.97
6094.42	41.30	-5.17
6096.69	75.30	-4.91
6100.26	42.40	-5.16
6102.18	124.50	-4.69
6105.15	37.30	-5.21
6120.25	46.60	-5.12
6127.91	116.80	-4.72
6136.62	238.90	-4.41
6137.00	164.40	-4.57
6137.70	257.50	-4.38
6151.62	130.00	-4.68
6157.73	144.10	-4.63
6159.41	137.40	-5.22
6165.37	100.50	-4.79
6173.34	164.70	-4.57
6180.22	149.30	-4.62

TABLE 1, CONTINUED

LAMBDA	W(MA)	LOG(W/LAMBDA)
FE 1		
6191.56	285.60	-4.34
6219.29	187.10	-4.52
6230.73	287.40	-4.34
6232.66	164.80	-4.58
6240.66	127.90	-4.69
6246.33	189.20	-4.52
6252.56	226.90	-4.44
6253.82	51.90	-5.08
6265.14	196.00	-4.50
6270.24	135.30	-4.67
6271.29	69.50	-4.96
6280.63	186.50	-4.53
6290.97	116.20	-4.73
6293.92	49.90	-5.10
6297.80	165.30	-4.58
6301.52	144.30	-4.64
6302.51	165.60	-4.58
6311.51	97.10	-4.81
6315.81	96.90	-4.81
6318.02	216.80	-4.46
6322.69	163.80	-4.59
6330.86	60.20	-5.02
6335.34	190.70	-4.52
6336.84	180.70	-4.54
6344.13	158.80	-4.60
6355.04	184.70	-4.54
6358.69	194.40	-4.51
6364.38	92.30	-4.84
6380.75	113.90	-4.75
6392.43	62.20	-5.01
6393.61	229.30	-4.45
6396.39	44.00	-5.16
6400.01	219.00	-4.47
6400.33	171.80	-4.57
6408.03	155.50	-4.61
6411.66	173.10	-4.57
6419.98	134.10	-4.68
6430.85	209.10	-4.49
6456.87	37.20	-5.24
6469.21	110.80	-4.77
6475.63	167.10	-4.59
6481.88	140.40	-4.66
6494.52	69.60	-4.97
6494.99	239.30	-4.43
6495.78	134.20	-4.68
6496.46	91.20	-4.85
6498.95	128.40	-4.70
6518.38	108.80	-4.78
6533.97	94.30	-4.84
6546.25	180.50	-4.56
6551.68	46.20	-5.15
6569.26	128.50	-4.71
6574.24	110.20	-4.78
6575.02	128.80	-4.71
FE 2		
4491.40	115.40	-4.59

LAMBDA	W(MA)	LOG(W/LAMBDA)
4508.28	129.90	-4.54
4520.23	121.50	-4.57
4555.89	132.50	-4.54
4576.33	120.10	-4.58
4582.84	102.30	-4.65
4656.97	54.90	-4.93
4731.44	117.30	-4.61
4833.21	33.90	-5.15
5991.38	72.40	-4.92
6084.11	62.10	-4.99
6149.24	68.30	-4.95
6238.38	89.80	-4.84
6247.56	95.90	-4.81
6369.45	42.00	-5.18
6416.91	73.20	-4.94
6432.65	74.90	-4.93
6456.38	91.70	-4.85
6516.05	101.80	-4.81
CO 1		
4478.32	36.40	-5.09
4588.69	58.10	-4.90
4693.19	73.60	-4.80
4749.68	91.30	-4.72
4754.36	30.00	-5.20
4768.07	31.70	-5.18
4781.43	38.10	-5.10
4792.86	62.10	-4.89
4813.48	75.30	-4.81
4867.87	117.50	-4.62
5915.55	67.00	-4.95
6093.14	68.30	-4.95
6116.99	36.60	-5.22
6189.01	68.20	-4.96
6282.64	113.30	-4.74
6450.23	181.70	-4.55
NI 1		
4470.48	126.80	-4.55
4506.30	41.90	-5.03
4513.00	44.90	-5.00
4553.18	96.50	-4.67
4604.99	160.00	-4.46
4606.23	150.20	-4.49
4648.66	103.80	-4.65
4675.64	56.10	-4.92
4686.22	113.90	-4.61
4701.54	89.20	-4.72
4703.81	106.40	-4.65
4729.29	43.40	-5.04
4731.81	77.30	-4.79
4732.47	76.10	-4.79
4752.43	114.80	-4.62
4756.52	125.60	-4.58
4807.00	85.40	-4.75
4814.62	34.60	-5.14
4829.03	95.80	-4.70
4831.18	92.00	-4.72

LAMBDA	W(MA)	LOG(W/LAMBDA)
4852.56	83.50	-4.76
4857.38	104.80	-4.67
4866.28	119.60	-4.61
4873.27	71.90	-4.83
4873.44	78.60	-4.79
4874.81	49.90	-4.99
5578.73	143.50	-4.59
5593.74	90.50	-4.79
5614.79	83.20	-4.83
5641.88	58.70	-4.98
5682.20	103.80	-4.74
5748.34	109.30	-4.72
5754.68	184.20	-4.49
5805.23	78.60	-4.87
5831.62	67.50	-4.94
5847.01	90.90	-4.81
6007.31	79.80	-4.88
6086.29	79.30	-4.89
6108.12	157.50	-4.59
6111.06	66.30	-4.96
6116.18	142.60	-4.63
6128.99	94.20	-4.81
6130.17	50.30	-5.09
6175.42	76.80	-4.91
6176.81	115.90	-4.73
6177.26	67.20	-4.96
6186.74	69.30	-4.95
6191.19	187.70	-4.52
6204.64	50.50	-5.09
6223.99	67.90	-4.96
6230.12	78.90	-4.90
6259.62	41.70	-5.18
6314.65	148.40	-4.63
6322.17	48.60	-5.11
6327.60	111.90	-4.75
6360.80	54.80	-5.06
6366.48	88.20	-4.86
6378.26	71.70	-4.95
6414.60	44.00	-5.16
6482.81	109.10	-4.77
6532.89	60.30	-5.03
ZN 1		
4722.16	109.70	-4.63
4810.53	96.20	-4.70
6362.35	61.00	-5.02
SR 1		
4607.33	129.90	-4.55
Y 1		
4643.69	69.70	-4.82
6435.02	42.50	-5.18
ZR 1		
4575.52	79.30	-4.76
4772.32	35.90	-5.12
4805.88	13.80	-5.54

LAMBDA	W(MA)	LOG(W/LAMBDA)
4828.05	22.00	-5.34
6127.49	34.40	-5.25
6134.58	59.50	-5.01
6143.23	45.00	-5.14
ZR 2		
4485.44	53.00	-4.93
4613.95	99.80	-4.66
BA 2		
4554.03	445.20	-4.01
5853.69	217.70	-4.43
6141.72	324.50	-4.28
6496.90	242.70	-4.43
LA 2		
4559.28	32.80	-5.14
4662.51	64.80	-4.86
4716.44	34.80	-5.13
4804.04	38.50	-5.10
6262.30	65.10	-4.98
6320.39	64.50	-4.99
6390.48	49.50	-5.11
6399.04	16.80	-5.58
CE 2		
4508.08	36.70	-5.09
4562.36	90.80	-4.70
4572.28	95.10	-4.68
4582.50	80.70	-4.75
4628.16	92.80	-4.70
4725.09	31.30	-5.18
4773.94	47.60	-5.00
6043.39	35.60	-5.23
PR 2		
4510.16	67.10	-4.83
ND 2		
4446.39	69.30	-4.81
4703.58	46.80	-5.00
4811.34	55.90	-4.93
SM 2		
4467.34	64.30	-4.84
4499.48	32.30	-5.14
4519.63	56.60	-4.90
4523.91	60.00	-4.88
4537.95	59.20	-4.88
4566.21	58.70	-4.89
4591.85	30.20	-5.18
4642.24	66.80	-4.84
4676.91	50.30	-4.97
4719.84	48.20	-4.99
GD 2		
4483.33	20.20	-5.35
4639.00	42.70	-5.04

of θ_{exc} (ε Vir) − $\theta_{exc}(\odot)$ that minimizes the scatter in the curve of growth; $\theta_{exc} = 5040/T_{exc}$, where T_{exc} is the excitation temperature. From the Wrubel (1949) curve of best fit we obtained values of log η_0(ε Vir) for all lines, as well as the microturbulent velocity v for ε Vir, which is the same for both blue and red spectral regions.

This procedure was followed in establishing a curve of growth for ζ Cyg. In this case log W/λ for ζ Cyg was plotted against log η_0(ε Vir) − $\epsilon\Delta\theta_{exc}$, where $\Delta\theta_{exc}$ is θ_{exc} (ε Vir) − θ_{exc} (ζ Cyg). Here the best value of $\Delta\theta_{exc} = -0.04$ was obtained by the method of least squares for all Fe I and Ti I lines. Since the value $\Delta\theta_{eff} = -0.04$ was obtained from Eggen's (1955) $(P - V)$ measure converted to $(B - V)$ for ε Vir, the Yale *Catalogue of Bright Stars* value for ζ Cyg, and Johnson's (1966) relation between $(B - V)$ and T_{eff},

TABLE 2

CURVE-OF-GROWTH PARAMETERS

Parameter	Value	Parameter	Value
$\Delta\theta$	−0 04	$V_{\zeta\ Cyg}$	2.7
log $a_{\zeta\ Cyg}$ . .	−3.0	$V_{\epsilon\ Vir}$ . .	2.2
log $a_{\epsilon\ Vir}$.	−3 0	Δ log κ .	−0 19
Δ log P_e .	−0 23		

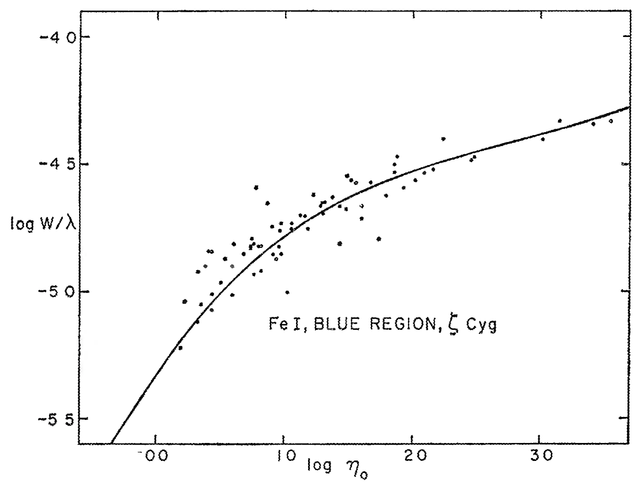

FIG. 1.—Curve of growth for the Fe I lines in the blue spectral region of ζ Cyg. Solid line represents the Wrubel curve of best fit.

this temperature difference has been employed throughout. We assumed $\Delta\theta_{exc} = \Delta\theta_{eff} = \Delta\theta_{ion}$. Parameters from the Wrubel curves of best fit are given in Table 2. The typical curves of growth are shown in Figures 1 and 2.

When lines measured in ζ Cyg were not available in the list for ε Vir, a secondary list given by Wallerstein and Greenstein (1964) was used. In some cases (log η_0)-values for the Sun (Utrecht equivalent widths and Goldberg-Pierce curve of growth) were used, after corrections for the difference in excitation, ionization, and continuous opacity were applied by comparing lines common to the Sun and ε Vir.

A combination of the expression for log η_0 and the Boltzmann and Saha equations for ε Vir and ζ Cyg results in the following relation:

$$[\eta_{0_{i+1,j}}/\eta_{0_{i,k}}] = -[P_e] + \tfrac{5}{2}[T_{ion}]$$
$$- [\theta_{ion}(\zeta\ Cyg) - \theta_{ion}(\epsilon\ Vir)](\chi_i + \epsilon_{i+1,j} - \epsilon_{i,k}) ,$$

where the quantities in square brackets indicate the difference between the logarithms of those quantities for ζ Cyg and ϵ Vir. Here i and $i+1$ indicate ionization levels, and j and k are excitation levels. P_e is the electron pressure, $T_{\rm ion}$ the ionization temperature, and χ_i the ionization potential of state i. Assuming $\Delta\theta_{\rm exc} = \Delta\theta_{\rm ion}$, we calculated $\Delta \log P_e$ by using all possible line pairs of neutral and ionized iron and titanium.

Under the reasonable assumption that the continuous opacity is due to H^-, we obtain the difference $\Delta \log \kappa (=\Delta[\log P_e f(T)])$ between these quantities in the two stars, as given in Table 2.

An expression for $N_{\rm el}/N_{\rm H}$, the abundance of any element relative to hydrogen, is given by the following relation:

$$[N_{\rm el}/N_{\rm H}] = [\eta_0] - [q] + \epsilon\Delta\theta_{\rm exc} + [\kappa v B] ,$$

where q represents the fraction of the total number of atoms of the element in the ionization stage being considered, and B is the partition function for that same ionization stage.

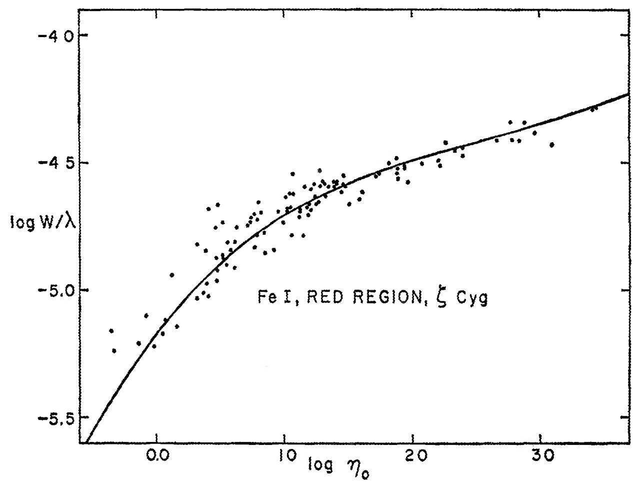

FIG. 2.—Curve of growth for the Fe I lines in the red spectral region of ζ Cyg. Solid line represents the Wrubel curve of best fit.

We present the final abundances in Table 3. Results for separate ionization stages are given, together with errors that mostly represent estimates of maximum systematic uncertainties.

IV. DISCUSSION

Inspection of Table 3 reveals that ζ Cyg has most of the characteristics of Ba II stars. It has apparent overabundances of carbon, as well as most of the heavy elements produced by the s-process, in particular, strontium, yttrium, barium, lanthanum, and cerium. However, the enhancement of s-process material is less pronounced here than in previously known stars of the type. In fact some of the elements produced by the s-process, particularly those heavier than barium, are not significantly overabundant, perhaps because the few available lines do not permit great accuracy. On the other hand, if we retain the concept of slow neutron processes in stars, this lack of enhancement may reflect a complicated history of neutron exposure and mixing. A review of these possibilities is given by Clayton (1968). With a spectral type G8 II and a trigonometric parallax of 0".021, ζ Cyg appears to lie near the middle of the mass range 1–4 $M_\odot$, and its position therefore lies within a similar range proposed by Warner (1965) for the phenomenon of the Ba II star.

There is some evidence suggesting that this enhancement of heavy elements has its origin, not in the G and K giant phase, but earlier in the main-sequence phase of these stars. For example, Danziger (1966) has pointed out earlier that the abundance results for 63 Tau obtained by Van't Veer-Menneret (1963) are in qualitative and perhaps even quantitative agreement with the concept of an extensive exposure of iron-peak elements to slow neutrons in this Am star. Presumably other Am stars share similar properties. More recently the work of Kohl (1964), Strom, Gingerich, and Strom (1966) and Conti and Strom (1968) indicates there may be many stars near A0 that are characterized by enhancements in the *s*-process elements. It is just these stars of approximately 2 $M_\odot$ that eventually evolve into the region of the Ba II stars. If this possibility is accepted, we can also assert that such enhancements are not surface phenomena since all evolutionary models of giant stars of 2 $M_\odot$ show deep outer convection zones and therefore considerable mixing. This conjecture does not provide any insight into the possible physical details of the enhancements of heavy elements in A stars, but it suggests that

TABLE 3

ABUNDANCES IN ζ CYG

Element	Logarithmic Abundance		Element	Logarithmic Abundance	
C I	+0.4	±0.4	Fe II	−0.1	±0.2
Na I	−0.2	±0.2	Co I	−0.2	±0.2
Mg I	0.0	±0.3	Ni I	−0.1	±0.2
Si I	0.0	±0.2	Zn I	0.0	±0.3
Ca I	−0.1	±0.2	Sr I	+0.3	±0.3
Sc I	+0.1	±0.4	Y I	+0.2	±0.3
Sc II	+0 1	±0.2	Zr I	+0.2	±0.2
Ti I	−0 2	±0.2	Zr II	+0.1	±0.3
Ti II	−0.2	±0.2	Ba II	+0.8	±0.3
V I	−0.1	±0.2	La II	+0.2	±0.3
Cr I	−0.2	±0 2	Ce II	+0.2	±0.2
Cr II	0 0	±0.2	Nd II	−0.2	±0.4
Mn I	−0.2	±0.2	Sm II	0.0	±0.3
Fe I	−0.1	±0.2	Ge II	−0 2	±0.4

the cause be sought in the possible peculiarities of structure of main-sequence A stars rather than of G and K giants. The reason that F giant stars with these peculiarities are not found may be that few F giant stars in general are found in the solar neighborhood because of relatively rapid evolution through the region of F giant stars.

What seems clear, however, is that the phenomenon of the Ba II star is not a discrete and discontinuous one. This work suggests that there is a continuous range of properties of the Ba II stars from the normal G and K giants to the most exaggerated examples of Ba II stars so far detected.

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