

WAVE-LENGTHS AND PERIODIC CHANGES OF SPECTRAL TYPE IN THE VARIABLE STAR *l* CARINAE

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ABSTRACT

Cepheid variable l Carinae; periodic variations in wave-lengths and spectral type.—Since the wave-lengths of many lines in stellar spectra change progressively with spectral type it might be expected that in the case of a variable star periodic changes of wave-length might occur. A detailed study of *l* Carinae shows this to be true. The results of measurements of 178 lines between $\lambda\lambda$ 4236 Å and 4495 Å, made on 17 three-prism spectrograms obtained at Lick Observatory, are given in Table I. In general, those lines which vary in wave-length with stellar type vary progressively from light-maximum to light-minimum, shifting by about 0.05 to 0.2 Å. The spectrum may not correspond to a pure type at any phase, but by taking the average of the types indicated by the different lines for each phase, it is found that the mean type varies from F 8 near light-maximum to G 9 near light-minimum. From this change of type a change of color-index may be inferred which agrees with the changes observed or inferred for other Cepheids, showing that color is correlated not only to the hydrogen spectrum, as others have found, but also to the general spectrum. Discrepancies between these results, based on changes of wave-length, and those of Adams and Joy, based on changes of relative intensity and width of lines, are discussed.

Relation of the spectral types of Cepheids to their periods.—By tabulating the available data it is shown (1) that Cepheids are progressively of "later" type as the length of the period of light-variation increases; and (2) that the *range of variation of type* is about one type-interval and is independent of the period.

INTRODUCTION

In my first paper¹ on the determination of wave-lengths in stellar spectra of known types it was found that for many lines the wave-lengths remain substantially the same in all of the spectral types in which these lines are present. For numerous other lines, however, the wave-lengths change progressively² from type to type, so that for any particular line a smooth curve can be drawn through points plotted with $\Delta\lambda$ as ordinates and types as abscissae. In my early experience this was found to hold so rigidly that it was possible to estimate the stellar type—which had not previously been looked up—from the residuals of radial velocity, or of equivalent $\Delta\lambda$,

¹ *Lick Observatory Bulletin*, 4, 90, 1906, and *Astrophysical Journal*, 24, 333, 1906.

² Progressive in the sense of not having discontinuities, but with no restrictions as to direction of change.

for a few of the lines which are subject to the most pronounced changes in position. Subsequently this inversion of the process was employed for developing a method¹ whereby the spectral type can be quantitatively determined from the spectrograms of the star by a direct comparison of the measured wave-lengths with the curves representing the variations in the regular series of types.

At the time when the progressive changes in wave-length as a function of stellar type were discovered, it was pointed out² that similar changes of wave-length which would be progressive with the phase of light-variation might be found in the spectra of individual variable stars. Such periodic changes of wave-length, if found, would offer a quantitative method for the determination of actual changes in spectral type synchronously with the changes in light. The very limited amount of material then available, principally for the star η Aquilae, “. . . showed very strong indications of just such variations in the positions of certain lines. . . .”³ At my suggestion Director Campbell kindly asked Dr. Curtis, then in charge of the Mills Observatory in Chile, to secure for this study series of spectrograms of the fourth-class variable stars l Carinae and κ Pavonis. The present paper discusses the measures of the spectrograms of l Carinae, $\alpha = 9^{\text{h}}42^{\text{m}}$; $\delta = -62^{\circ}3'$ (1900); magnitudes 3.6–5.0; period 35.5 days, which were secured at that time.

PART I. WAVE-LENGTHS FROM 4236 Å to 4495 Å,
OBSERVED WITH THREE PRISMS

Seventeen three-prism spectrograms of l Carinae are available. Three of these (Nos. 299, 311, and 312) were taken with the short (16-inch) camera, and fourteen with the long ($21\frac{1}{4}$ -inch) camera.⁴ $H\gamma$ is central on the plates, and the Fe spark was used as source of light for the comparison spectra. All of the plates were measured

¹ *Astrophysical Journal*, 33, 130, 1911.

² *Ibid.*, 24, 335, 1906.

³ *Lick Observatory Bulletin*, 4, 131, 1907; and *Astrophysical Journal*, 25, 334, 1907, footnote.

⁴ *Publications of the Lick Observatory*, 9, 56, 1907.

by the writer before leaving Mount Hamilton, except Nos. 1149, 1150, and 1201, which were measured by Dr. Olivier, and No. 312, which was measured by Dr. Palmer and the writer. Miss Hobe, Dr. Glancy, and Dr. Merrill assisted in the preliminary reductions. The methods of measurement and reduction employed are similar to those described in *Publications of the Lick Observatory*, 9, and no large errors would be introduced by assuming the system to be the

TABLE I

λ for Radial Velocity	Number of Long-Camera Plates	λ for Radial Velocity	Number of Long-Camera Plates
4245.438.....	8	4379.383.....	7
50.296.....	13	83.720.....	13
50.955.....	13	87.007.....	14
54.502.....	9	91.147.....	14
74.955.....	9	95.255.....	14
88.143.....	14	99.917.....	14
92.304.....	13	4400.615.....	14
93.224.....	6	01.613.....	14
94.277.....	14	04.932.....	13
4306.921.....	14	07.853.....	13
13.043.....	13	08.579.....	8
15.178.....	11	17.863.....	13
18.870.....	14	20.686.....	14
20.975.....	14	27.444.....	14
25.195.....	14	28.715.....	12
28.104.....	14	41.875.....	13
34.075.....	14	42.529.....	14
37.227.....	10	47.915.....	13
39.713.....	4	50.654.....	13
52.018.....	13	59.317.....	14
52.949.....	14	66.749.....	14
71.363.....	14	68.663.....	13
4376.104.....	14	4476.211.....	13

same as for plates with numbers 500+ in that volume. However, in order to define the system more accurately for future use, the stellar wave-lengths employed in the reductions for radial velocity are given in Table I, together with the number of long-camera plates on which these lines were used. Half of these lines are of constant wave-length, both in ι Carinae and in the corresponding types in the stellar series. The remaining lines vary in wave-length. Logically, only the stellar lines of constant wave-length should have been used in defining the system, and the reductions might

TABLE II
OBSERVED WAVE-LENGTHS FOR THE PRINCIPAL LINES WHICH WERE FOUND TO VARY IN *l* CARINAE

λ	ROWLAND												ADAMS INTEN. SUN-SPOTS		LOCKYER ENHANCED			
	λ in Sun	λ in Sun	1209	1201	1200	1212	1220	1150	1150	1079	1090	1098	El.	Spark Arc	IN.	SUN-SPOTS	El.	Spark Arc
4258.4...	.427	.387	.403	.428	.4147	.428	.4147	.428	.4147	.428	.4147	.428	Zr	2-3	0-1		Zr	2-3
4262.0...	.120	.060	.096	.110	.110	.110	.110	.110	.110	.110	.110	.110			4		Zn	1
4268.0...	.985	.009	.044	.057	.057	.057	.057	.057	.057	.057	.057	.057					Cr	5-6
4278.3...	.357	.371	.366	.351	.351	.351	.351	.351	.351	.351	.351	.351						
4288.1...	.102	.127	.163	.170	.170	.170	.170	.170	.170	.170	.170	.170						
4313.0...	.001	.014	.029	.040	.022	.009	.024	.017	.070	.092	.030	.062						
4320.9...	.924	.979	.977	.975	.975	.975	.975	.975	.975	.975	.975	.975						
4331.8...	.853	.827	.840	.815	.844	.844	.868	.824	.795	.811	.795	.802						
4334.0...	.056	.062	.072	.078	.104	.092	.128	.086	.097	.071	.076	.081						
4344.5...	.561	.563	.572	.582	.615	.624	.670	.630	.625	.662	.639	.692						
4352.9...	.954	.958	.926	.943	.971	.921	.940	.969	.940	.959	.955	.920						

have been repeated, a posteriori, for this purpose. However, a detailed examination of the lines of variable wave-length shows that the increases and decreases of wave-length for the various phases of the star pretty closely balance each other, so that no appreciable gain would result in this case from a re-reduction. The details for the wave-lengths of the Fe comparison lines, the dispersion formula, and the correcting curve used with the formula, being the same for my more extensive measures of Southern Mills spectrograms with numbers 500+, more appropriately belong with those results and need not be duplicated here. Other data in regard to the spectrograms are available, if desired by anyone.

The observed wave-lengths (on the Rowland system, defined), obtained from the individual spectrograms, correct relatively to each other within errors of measurement and reduction, are given in Tables II and III, columns 2 to 18. With the exception of the double measures for Plate 312, each tabulated value was derived from a single complete measure, i.e., from two settings of the micrometer thread in the direct and two in the reversed positions of the plate. The arrangement of the spectrograms in a sequence according to phase of velocity and of light variation of the star, as well as the additional columns, are for purposes to be discussed in Part II. The figures directly below the plate numbers¹ in the headings give the phase-interval to the nearest tenth of a day, after maximum of light.² Italics signify that the line is especially poor in appearance. The means in the "remarks" column and footnotes refer to the long-camera plates only, except when it is apparent from the subscript that short-camera plates have also been included. The wave-lengths for the lines in stellar types are taken in part from *Boletín No. 1* of the Córdoba Observatory and in part from unpublished data. As these contain small systematic corrections which may be somewhat altered in a definitive discussion to be made later, they should not be employed at present to derive systematic corrections to the wave-lengths in ι Carinae.

¹ The Roman numerals, which refer to the plate-holders, have been omitted in the plate numbers.

² No recent or good early light-curve is available.

TABLE III
SUPPLEMENTARY LIST OF WAVE-LENGTHS OBSERVED IN THE SPECTRUM OF *l* CARINAE

λ in Types	312 2.1	3115 2.6	1120 3.6	1124 6.7	1147 11.6	1149 12.5	1040 17.1	200 17.6	1201 21.0	1200 21.9	1212 23.0	1220 24.0	1150 24.5	311 29.6	1070 30.1	1000 32.2	1008 33.2
4236.079	.061			.968	.904						.884	.944					.909
4239.970		.969	.964					.258									.909
4241.2					.512												
4242.6	.607				.512												
4245.438	.360	.417	.400		.440		.471	.366		.370	.303	.382			.370		
4246.163	100	.154	.160	.141	.148		.142			.132	.132	.139			.147		.103
4246.9	.978		.934														
4247.383		.048	.007		.024					.559		.037					
4250.2	.289	.286	.299	.203	.280	.314			.330	.297	.271	.334	.241	.331	.273	.248	
4250.9	.962	.930	.952	.939	.986	.986			.986	.956	.958	.990	.969	.685	.903	.972	
4254.5	.491	.471	.508	.477	.461					.408	.533	.533		.594	.557		
4256.3	.338																
4266.0		.126	.907	.061	.063		.065			.053	.052	.053		.081	.048		
4267.0	.007	.030	.064	.065	.006				.020	.020	.040	.064		.051	.022	.992	
4268.8			.889	.907	.890				.924	.924	.857	.897		.883			
4271.322	.139																
4271.9	.885																
4273.5			.541														
4274.0	.885	.934	.910	.956	.931			.832		.034	.978	.971		.902	.975		
4275.7	.674	.752	.740	.760	.735					.875	.744	.770		.734	.761		
4276.84		.908	.808	.864	.859					.847	.782	.853					
4277.02	.510	.033	.037	.044	.006		.557			.586	.508	.576		.544			
4279.04					.975						.037						
4282.580	.449	.615	.536	.594	.583												
4283.160		.160	.160	.180	.135									.142	.200		
4284.5	.510				.571												
4285.617		.599	.595	.632	.616												
4287.0	.042																
4287.596					.598												
4290.2	.238																
4292.307	.304	.377	.324	.364	.335	.348			.352	.305	.372	.354	.385	.355	.350	.335	
4293.2	.185				.295					.158	.200	.200		.170	.143	.214	
4294.277	.198	.234	.226	.241	.248	.227	.238	.183	.220	.162	.230	.213	.110	.271	.264	.204	
4295.0			.053		.098					.120	.082	.085		.079			
4296.02	.088		.102		.040	.091			.053	.052	.048	.053	.095	.032			
4296.8		.842	.813											.869	.823		
4298.1	.078	.149	.086		.097				.088	.088	.091	.897		.102	.103		
4304.6	.666										.102	.070		.630	.702		
4306.024	.018	.951	.907	.955	.920	.941	.921		.944	.942	.904	.941	.984	.808	.867	.885	
4308.041	.005	.058	.995														.085

WAVE-LENGTHS IN ι CARINAE

4309.7	725	765	785	805	825	845	865	885	905	925	945	965	985	1005	1025	1045	1065	1085	1105	1125	1145	1165	1185	1205	1225	1245	1265	1285	1305	1325	1345	1365	1385	1405	1425	1445	1465	1485	1505	1525	1545	1565	1585	1605	1625	1645	1665	1685	1705	1725	1745	1765	1785	1805	1825	1845	1865	1885	1905	1925	1945	1965	1985	2005	2025	2045	2065	2085	2105	2125	2145	2165	2185	2205	2225	2245	2265	2285	2305	2325	2345	2365	2385	2405	2425	2445	2465	2485	2505	2525	2545	2565	2585	2605	2625	2645	2665	2685	2705	2725	2745	2765	2785	2805	2825	2845	2865	2885	2905	2925	2945	2965	2985	3005	3025	3045	3065	3085	3105	3125	3145	3165	3185	3205	3225	3245	3265	3285	3305	3325	3345	3365	3385	3405	3425	3445	3465	3485	3505	3525	3545	3565	3585	3605	3625	3645	3665	3685	3705	3725	3745	3765	3785	3805	3825	3845	3865	3885	3905	3925	3945	3965	3985	4005	4025	4045	4065	4085	4105	4125	4145	4165	4185	4205	4225	4245	4265	4285	4305	4325	4345	4365	4385	4405	4425	4445	4465	4485	4505	4525	4545	4565	4585	4605	4625	4645	4665	4685	4705	4725	4745	4765	4785	4805	4825	4845	4865	4885	4905	4925	4945	4965	4985	5005	5025	5045	5065	5085	5105	5125	5145	5165	5185	5205	5225	5245	5265	5285	5305	5325	5345	5365	5385	5405	5425	5445	5465	5485	5505	5525	5545	5565	5585	5605	5625	5645	5665	5685	5705	5725	5745	5765	5785	5805	5825	5845	5865	5885	5905	5925	5945	5965	5985	6005	6025	6045	6065	6085	6105	6125	6145	6165	6185	6205	6225	6245	6265	6285	6305	6325	6345	6365	6385	6405	6425	6445	6465	6485	6505	6525	6545	6565	6585	6605	6625	6645	6665	6685	6705	6725	6745	6765	6785	6805	6825	6845	6865	6885	6905	6925	6945	6965	6985	7005	7025	7045	7065	7085	7105	7125	7145	7165	7185	7205	7225	7245	7265	7285	7305	7325	7345	7365	7385	7405	7425	7445	7465	7485	7505	7525	7545	7565	7585	7605	7625	7645	7665	7685	7705	7725	7745	7765	7785	7805	7825	7845	7865	7885	7905	7925	7945	7965	7985	8005	8025	8045	8065	8085	8105	8125	8145	8165	8185	8205	8225	8245	8265	8285	8305	8325	8345	8365	8385	8405	8425	8445	8465	8485	8505	8525	8545	8565	8585	8605	8625	8645	8665	8685	8705	8725	8745	8765	8785	8805	8825	8845	8865	8885	8905	8925	8945	8965	8985	9005	9025	9045	9065	9085	9105	9125	9145	9165	9185	9205	9225	9245	9265	9285	9305	9325	9345	9365	9385	9405	9425	9445	9465	9485	9505	9525	9545	9565	9585	9605	9625	9645	9665	9685	9705	9725	9745	9765	9785	9805	9825	9845	9865	9885	9905	9925	9945	9965	9985	10005	10025	10045	10065	10085	10105	10125	10145	10165	10185	10205	10225	10245	10265	10285	10305	10325	10345	10365	10385	10405	10425	10445	10465	10485	10505	10525	10545	10565	10585	10605	10625	10645	10665	10685	10705	10725	10745	10765	10785	10805	10825	10845	10865	10885	10905	10925	10945	10965	10985	11005	11025	11045	11065	11085	11105	11125	11145	11165	11185	11205	11225	11245	11265	11285	11305	11325	11345	11365	11385	11405	11425	11445	11465	11485	11505	11525	11545	11565	11585	11605	11625	11645	11665	11685	11705	11725	11745	11765	11785	11805	11825	11845	11865	11885	11905	11925	11945	11965	11985	12005	12025	12045	12065	12085	12105	12125	12145	12165	12185	12205	12225	12245	12265	12285	12305	12325	12345	12365	12385	12405	12425	12445	12465	12485	12505	12525	12545	12565	12585	12605	12625	12645	12665	12685	12705	12725	12745	12765	12785	12805	12825	12845	12865	12885	12905	12925	12945	12965	12985	13005	13025	13045	13065	13085	13105	13125	13145	13165	13185	13205	13225	13245	13265	13285	13305	13325	13345	13365	13385	13405	13425	13445	13465	13485	13505	13525	13545	13565	13585	13605	13625	13645	13665	13685	13705	13725	13745	13765	13785	13805	13825	13845	13865	13885	13905	13925	13945	13965	13985	14005	14025	14045	14065	14085	14105	14125	14145	14165	14185	14205	14225	14245	14265	14285	14305	14325	14345	14365	14385	14405	14425	14445	14465	14485	14505	14525	14545	14565	14585	14605	14625	14645	14665	14685	14705	14725	14745	14765	14785	14805	14825	14845	14865	14885	14905	14925	14945	14965	14985	15005	15025	15045	15065	15085	15105	15125	15145	15165	15185	15205	15225	15245	15265	15285	15305	15325	15345	15365	15385	15405	15425	15445	15465	15485	15505	15525	15545	15565	15585	15605	15625	15645	15665	15685	15705	15725	15745	15765	15785	15805	15825	15845	15865	15885	15905	15925	15945	15965	15985	16005	16025	16045	16065	16085	16105	16125	16145	16165	16185	16205	16225	16245	16265	16285	16305	16325	16345	16365	16385	16405	16425	16445	16465	16485	16505	16525	16545	16565	16585	16605	16625	16645	16665	16685	16705	16725	16745	16765	16785	16805	16825	16845	16865	16885	16905	16925	16945	16965	16985	17005	17025	17045	17065	17085	17105	17125	17145	17165	17185	17205	17225	17245	17265	17285	17305	17325	17345	17365	17385	17405	17425	17445	17465	17485	17505	17525	17545	17565	17585	17605	17625	17645	17665	17685	17705	17725	17745	17765	17785	17805	17825	17845	17865	17885	17905	17925	17945	17965	17985	18005	18025	18045	18065	18085	18105	18125	18145	18165	18185	18205	18225	18245	18265	18285	18305	18325	18345	18365	18385	18405	18425	18445	18465	18485	18505	18525	18545	18565	18585	18605	18625	18645	18665	18685	18705	18725	18745	18765	18785	18805	18825	18845	18865	18885	18905	18925	18945	18965	18985	19005	19025	19045	19065	19085	19105	19125	19145	19165	19185	19205	19225	19245	19265	19285	19305	19325	19345	19365	19385	19405	19425	19445	19465	19485	19505	19525	19545	19565	19585	19605	19625	19645	19665	19685	19705	19725	19745	19765	19785	19805	19825	19845	19865	19885	19905	19925	19945	19965	19985	20005	20025	20045	20065	20085	20105	20125	20145	20165	20185	20205	20225	20245	20265	20285	20305	20325	20345	20365	20385	20405	20425	20445	20465	20485	20505	20525	20545	20565	20585	20605	20625	20645	20665	20685	20705	20725	20745	20765	20785	20805	20825	20845	20865	20885	20905	20925	20945	20965	20985	21005	21025	21045	21065	21085	21105	21125	21145	21165	21185	21205	21225	21245	21265	21285	21305	21325	21345	21365	21385	21405	21425	21445	21465	21485	21505	21525	21545	21565	21585	21605	21625	21645	21665	21685	21705	21725	21745	21765	21785	21805	21825	21845	21865	21885	21905	21925	21945	21965	21985	22005	22025	22045	22065	22085	22105	22125	22145	22165	22185	22205	22225	22245	22265	22285	22305	22325	22345	22365	22385	22405	22425	22445	22465	22485	22505	22525	22545	22565	22585	22605	22625	22645	22665	22685	22705	22725	22745	22765	22785	22805	22825	22845	22865	22885	22905	22925	22945	22965	22985	23005	23025	23045	23065	23085	23105	23125	23145	23165	23185	23205	23225	23245	23265	23285	23305	23325	23345	23365	23385	23405	23425	23445	23465	23485	23505	23525	23545	23565	23585	23605	23625	23645	23665	23685	23705	23725	23745	23765	23785	23805	23825	23845	23865	23885	23905	23925	23945	23965	23985	24005	24025	24045	24065	24085	24105	24125	24145	24165	24185	24205	24225	24245	24265	24285	24305	24325	24345	24365	24385	24405	24425	24445	24465	24485	24505	24525	24545	24565	24585	24605	24625	24645	24665	24685	24705	24725	24745	24765	24785	24805	24825	24845	24865	24885	24905	24925	24945	24965	24985	25005	25025	25045	25065	25085	25105	25125	25145	25165	25185	25205	25225	25245	25265	25285	25305	25325	25345	25365	25385	25405	25425	25445	25465	25485	25505	25525	25545	25565	25585	25605	25625	25645	25665	25685	25705	25725	25745	25765	25785	25805	25825	25845	25865	25885	25905	25925	25945	25965	25985	26005	26025	26045	26
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TABLE III—Continued

λ in Types	312 2.1	315 2.6	318 3.6	324 6.7	347 11.6	349 12.5	340 17.1	309 17.6	301 21.0	309 21.9	312 23.0	320 24.0	315 24.5	311 29.6	307 30.1	300 32.2	308 33.2
4367.9.....	.933	.900	.928	.970	.952	.....	.888	.938	.....	.856	.983	.850	.....	.....	.834	.922	.....
4369.9.....	.900	.812	.807	.....	.....	.....	.131	.066	.096	.108	.117	.117	.134	.....	.815	.....	.....
4373.7.....	.700	.....	.....	.068	.....	.....	.388	.385	.....	.302	.373	.402	.....	.115	.121	.093	.....
4376.1.....	.104	.108	.096	.....	.....	.....	.219	.....	.....	.....	.....	.....	.....	.....	.382	.383	.....
4379.3.....	.420	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.209	.....	.....	.....
4382.1.....	.....	.....	.....	.717	.....	.....	.....	.....	.764	.....	.689	.634	.703	.....	.745	.755	.776
4383.721.....	.660	.702	.708	.....	.040	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4385.0.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4385.3.....	.....	.....	.....	.....	.646	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4385.6.....	.....	.....	.....	.963	.646	.....	.962	.041	.975	.909	.953	.902	.917	.938	.900	.979	.....
4387.0.....	.902	.982	.957	.....	.935	.....	.415	.434	.434	.414	.454	.406	.....	.....	.406	.336	.....
4388.0.....	.....	.400	.406	.407	.403	.....	.156	.105	.118	.160	.109	.113	.115	.086	.138	.115	.091
4389.4.....	.450	.129	.100	.110	.148	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4391.14.....	.116	.....	.....	.....	.418	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4393.4.....	.....	.....	.....	.....	.418	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4394.2.....	.197	.300	.214	.200	.217	.....	.191	.287	.....	.190	.188	.185	.....	.200	.166	.218	.203
4396.01.....	.....	.950	.953	.943	.953	.....	.049	.....	.....	.998	.087	.932	.....	.984	.985	.971	.....
4401.613.....	.648	.634	.622	.628	.632	.....	.057	.634	.016	.014	.598	.066	.626	.035	.601	.505	.502
4404.932.....	.942	.922	.950	.958	.958	.....	.....	.....	.907	.900	.901	.923	.811	.023	.947	.928	.991
4406.81.....	.....	.....	.....	.....	.767	.....	.769	.833	.911	.781	.817	.782	.....	.769	.769	.....	.....
4408.579.....	.648	.601	.620	.....	.601	.....	.....	.....	.....	.654	.646	.614	.....	.670	.620	.610	.....
4409.5.....	.....	.558	.548	.....	.533	.....	.....	.....	.....	.575	.525	.526	.....	.595	.510	.525	.....
4411.0.....	.957	.....	.999	.....	.533	.....	.....	.028	.....	.883	.994	.962	.....	.995	.....	.....	.....
4413.7.....	.874	.812	.834	.....	.851	.....	.....	.....	.....	.807	.814	.814	.....	.780	.781	.781	.....
4415.4.....	.443	.....	.456	.....	.....	.....	.....	.....	.....	.375	.374	.371	.....	.301	.410	.452	.....
4418.5.....	.....	.....	.....	.....	.510	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4420.604.....	.789	.758	.730	.726	.695	.....	.710	.718	.677	.680	.676	.671	.634	.....	.670	.718	.682
4422.7.....	.....	.....	.797	.....	.778	.....	.....	.....	.....	.....	.....	.....	.....	.....	.782	.817	.....
4423.0.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4424.3.....	.527	.....	.....	.....	.....	.....	.....	.045	.....	.928	.905	.....	.....	.....	.....	.....	.....
4430.1.....	.....	.....	.....	.....	.162	.....	.....	.342	.....	.361	.360	.327	.....	.257	.417	.....	.....
4430.7.....	.....	.....	.....	.....	.741	.....	.....	.714	.....	.....	.....	.....	.....	.....	.....	.....	.....
4431.5.....	.....	.....	.....	.....	.525	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4433.3.....	.303	.....	.....	.....	.365	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4434.0.....	.043	.....	.....	.....	.020	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4435.4.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4435.7.....	.....	.719	.753	.790	.750	.....	.805	.....	.....	.787	.759	.440	.....	.....	.830	.....	.....
4437.1.....	.....	.....	.....	.....	.152	.....	.102	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4437.9.....	.....	.....	.....	.....	.935	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4442.529.....	.548	.556	.531	.520	.506	.....	.528	.....	.531	.538	.531	.531	.504	.....	.544	.594	.500
4443.2.....	.254	.251	.237	.207	.200	.....	.182	.....	.224	.212	.240	.185	.203	.....	.212	.194	.....
4443.9.....	.975	.935	.949	.998	.966	.....	.977	.....	.139	.060	.052	.059	.181	.....	.066	.048	.....

PART II. CHANGES OF SPECTRAL TYPE IN l CARINAE

My early measures and reductions, in 1908, showed quite clearly changes of spectral type from maximum to minimum light. This change of type is at once evident by comparing under a microscope a plate taken near maximum with one taken near minimum. Unfortunately the spectrograms are not at hand, so that I shall have to be content with reproducing some of my notes from such a comparison made rather hastily in 1908:

The absorption is greater at light-minimum. The spectrum has a somewhat knotted appearance, giving the impression of the presence of bright lines. Probably on account of the increased absorption this appearance becomes more prominent at minimum. A direct comparison of plates 1115 II and 1220 IV, at 2.6 and 24.0 days respectively after maximum, shows:

- 4351 stronger at minimum.
- 4352.9 stronger at minimum.
- 4358.9 widened toward the violet and stronger at minimum.
- 4376.1 faint at maximum; strong at minimum.
- 4404.9 stronger and widened at minimum—thus resembling late type.
- 4408.5 becomes very much stronger at minimum. Compare appearance with 4409.5.
- 4413.7 good and sharp at maximum; becomes somewhat weaker and fuzzy at minimum.
- 4422.0 widens toward violet at minimum; violet edge fuzzy at minimum.
- 4325.6 red edge fuzzy at maximum; line broad, strong, and sharp at minimum; very marked.
- 4437.9 broad and fairly strong at minimum; at maximum very faint.
- 4445.7 strong and sharp at minimum; very faint (not measurable) at maximum.
- 4471.0 has edge toward red fuzzy at maximum; sharp at minimum; very decided difference.
- 4481.4 Mg and Ti much weaker at minimum.
- 4482.3 much stronger at minimum.
- 4490 much stronger at minimum.

The last line is a blend of 4489.91 Fe 4, in sun-spots 6, and 4490.25 Mn-Fe 3 N, in spots 3-4. These notes are especially interesting when compared with the data for the same lines in Tables II and III, most of which were subsequently obtained and which they supplement as far as they go. The changes of intensities from near light-maximum (type F9.4) to near minimum

(type G8.6)¹ run parallel with the changes from sun (type G) to sun-spots (type K). Note also, for example, that 4445.7, marked "very faint (not measurable) at maximum," later received no measures near maximum.

Although the wave-lengths resulting from my early reductions were at the time compared for type with my first curves of variation in the stellar series, publication of the results was delayed because this comparison lacked the quantitative accuracy which was readily foreseen to be possible. The improvement of the curves for the stellar types and my method for determining stellar types² resulted largely from a desire to determine accurately the changes of spectral type in variable stars in a way which would be strictly quantitative and be as free as possible from the personal element. The results given below for ι Carinae still do not represent the greatest accuracy attainable by these methods, for the reason that the measures are not all by one observer, and, from the experience gained, a somewhat improved list of lines could be selected for measurement. I hope that observers with adequate instrumental equipment may extend this work to other variables and to other regions of the spectrum, as we may confidently expect very profitable results. If desired, I would gladly suggest a suitable list of lines to anyone who wishes to take up a similar study. The dispersion of three prisms should be employed in order to have the scale sufficiently large. The effects noted below were first looked for on the one-prism spectrograms of Y Ophiuchi and T Vulpeculae, but the dispersion was inadequate. For best results all the different factors entering into the problem, such as slit-width, general intensities of exposure, development, etc., should be maintained as constant as possible. Except for very short light-periods, the exposure time may more safely be varied than the slit-width to allow for the changing intensities of the light. For the present, in order to avoid certain systematic effects, discussed in a report to the Solar Conference in 1913, the curves of variation of wave-length upon which determinations of type are to be based

¹ See Table IV, Plates 1115 and 1220.

² *Astrophysical Journal*, 33, 130, 1911.

Lines of Varying Wave-Lengths
 Spectrograms arranged according to phase of light variation
 Continuous lines for *l* Carinae; dashed lines for types

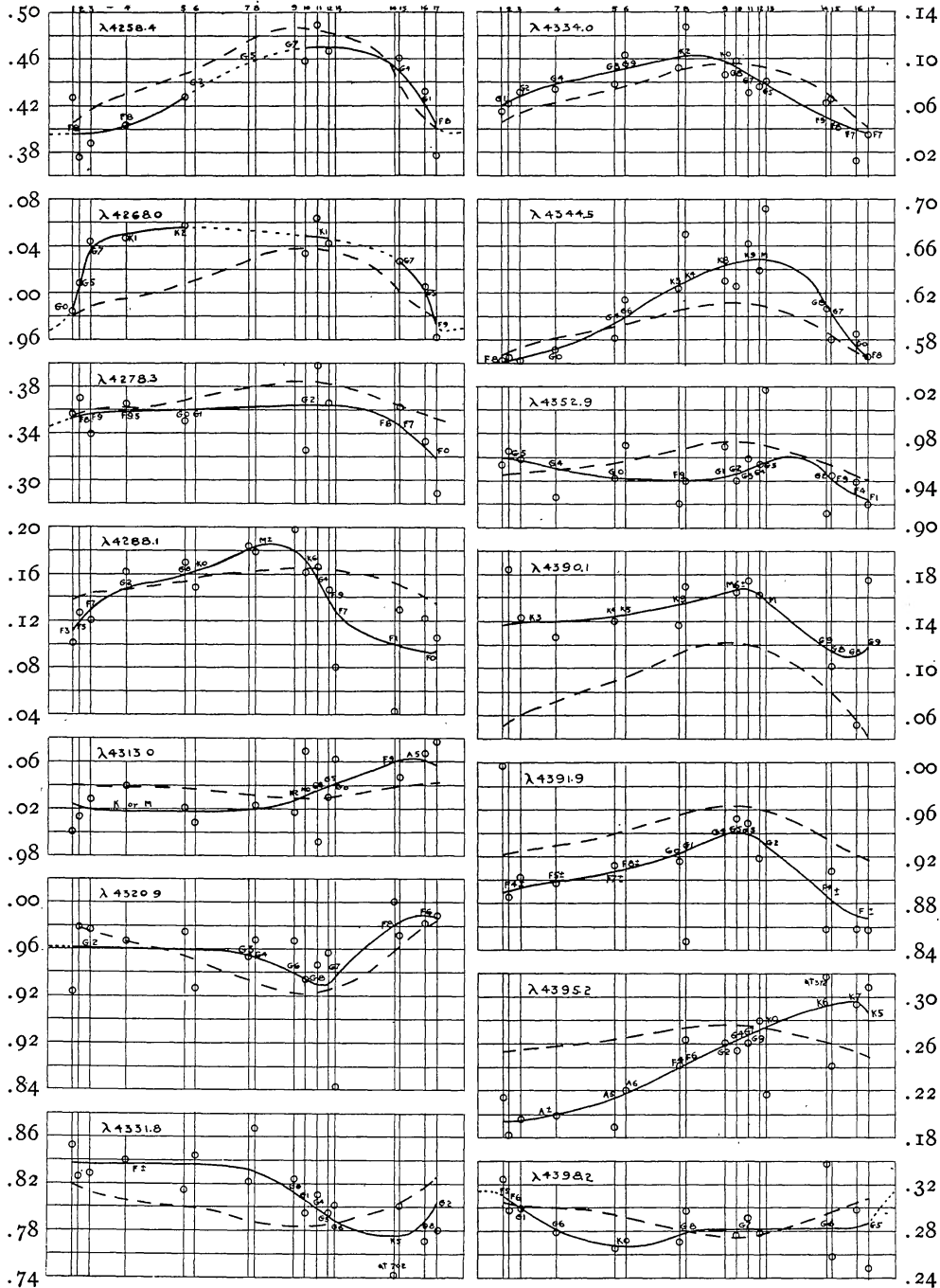


FIG. 1

Lines of Varying Wave-Lengths—Continued

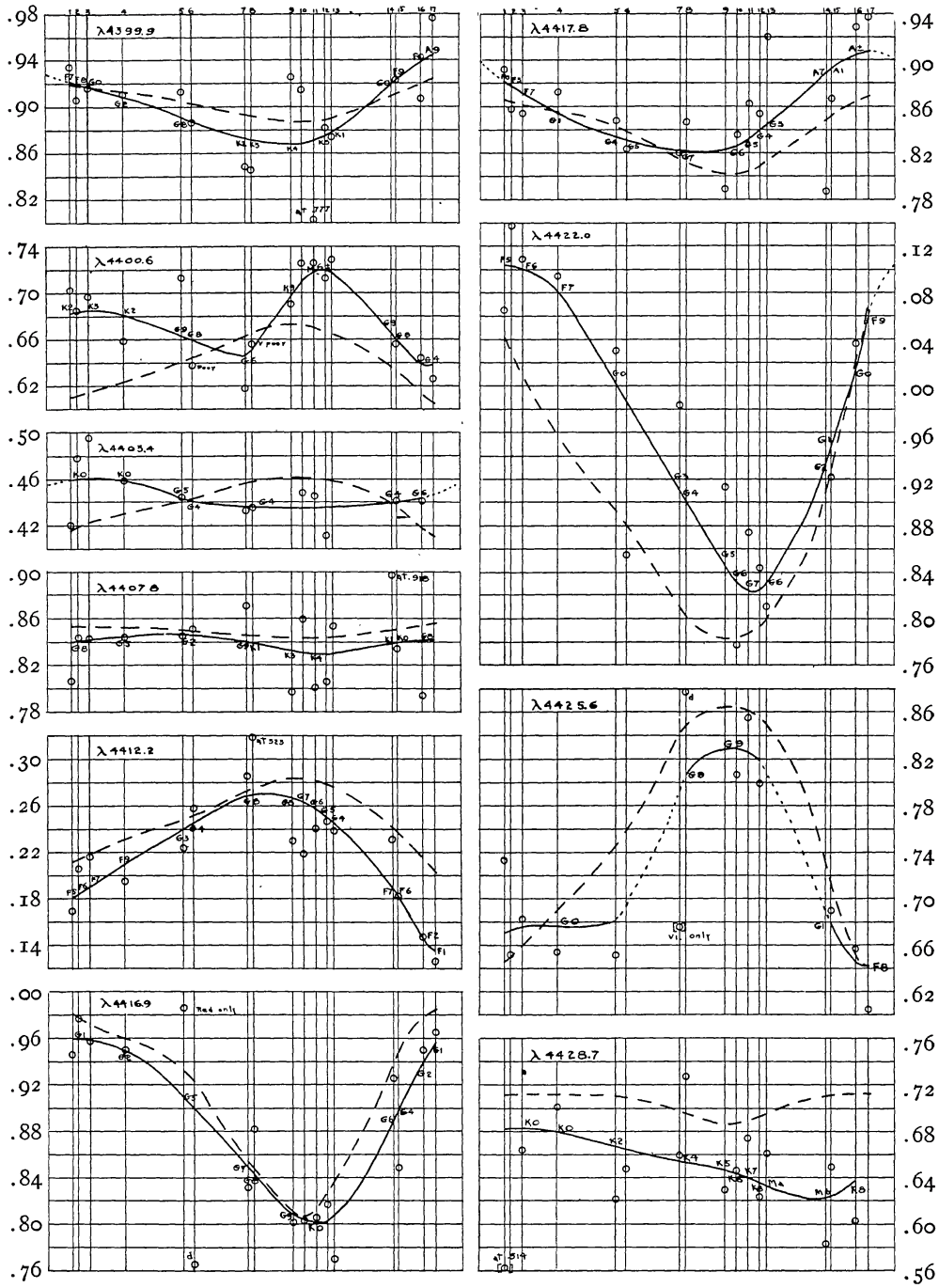
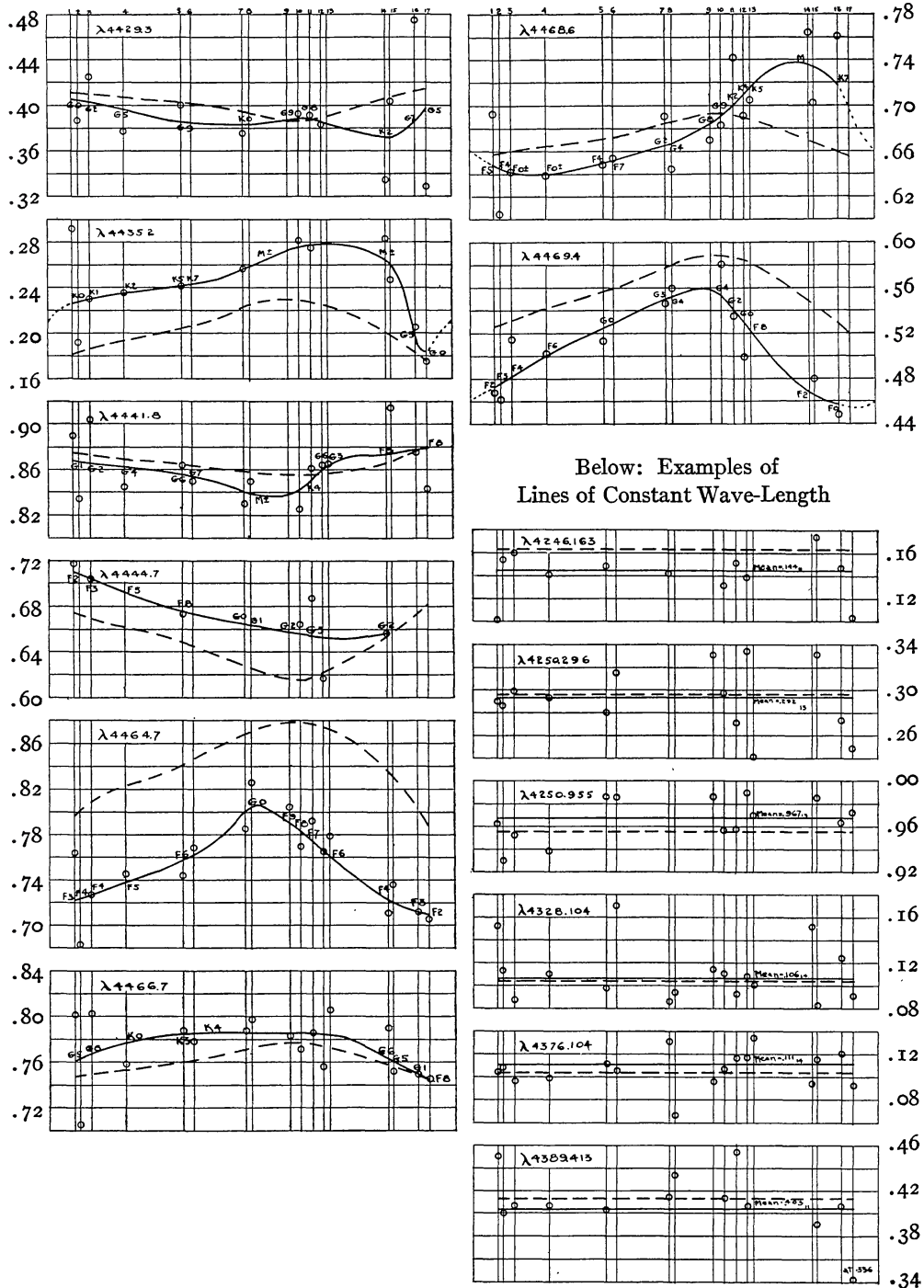


FIG. 1—Continued

Lines of Varying Wave-Lengths—Continued



Below: Examples of Lines of Constant Wave-Length

FIG. 1—Continued

should be determined from plates taken with the same instrumental equipment which was used to obtain the plates for the star under consideration.

The wave-lengths in Tables II and III furnish the data for a quantitative determination of the spectral type of ι Carinae corresponding to each spectrogram. The individual lines give separate determinations of type by comparison of the observed wave-lengths with the curves of variation found for the lines in the general series of stellar types. With but two exceptions only curves published in *Boletin No. 1* of the Córdoba Observatory (1911) were used. The results of this comparison are collected in

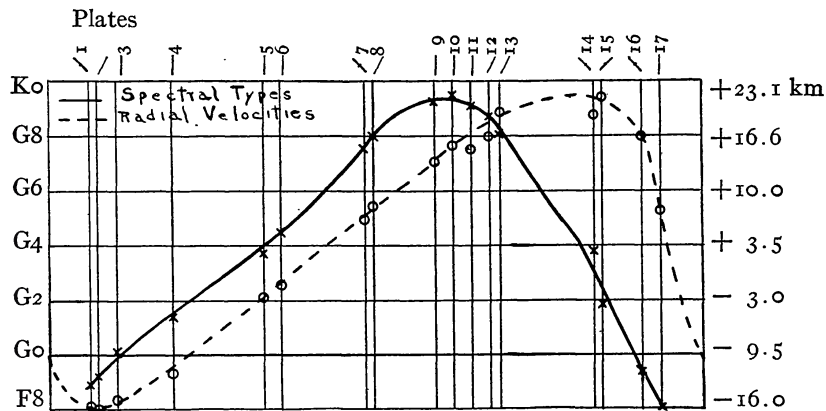


FIG. 2.—Simultaneous variations of spectral type and of radial velocity in ι Carinae.

Tables IV and V, which are self-explanatory, and in the figures. The weights in the third column of Table IV were formed according to (a) the range of variation of wave-length from types F to K in the stellar types, and (b) the definiteness of the curve showing the change of wave-length with change of phase in ι Carinae, taking into account also the number of observations upon which the curve is based. The means at the bottom of Table IV, which may be regarded as fairly representing the actual changes of type in this star, are compared in Figure 2 with the simultaneous changes of radial velocity. The curves for spectral type and for radial velocity in the figure synchronize with each other about as closely as other variations in Cepheids have been found to synchronize with each other.

TABLE IV
THE TYPES INDICATED BY THE INDIVIDUAL LINES FOR EACH SPECTROGRAM OF ι CARINAE

λ	No. of Obs.	Weight	312 I	1115 2	1120 3	1124 4	1147 5	1149 6	1040 7	299 8	1201 9	1209 10	1212 11	1220 12	1150 13	311 14	1079 15	1090 16	1098 17
4258.4	11	.50	F8	F8	F8	F8	G1.5	G2	G5	G5.5	G7	G7.5	G7.5	G7.5	G5	G4	G1	F8	
480.0	11	.50	G0	G5	G5	G4	G0	G0	K1.5	K1.5	K1	K1	K1	K1	F8	G7	G3	F0	
78.3	11	.34	F3	F8	F9	F9.5	G0	G1	G1	G2	G2	G2	G2	G1	F1	F7	F0	F0	
88.1	17	.45	F3	F5	F7	(K or M)	G8	Ko	M =	M =	M =	K6	G8	G0	F9	A5	A5	F0	
4313.0	15	.0																	
20.0	17	.45	G2	G2	G2	(F =)	G2	G3	G3	G4	G0	G0	G0	G0	G2	K5	F6	G2.5	
31.8	17	.0																	
34.0	17	.50	G1	G1	G2.5	G4	G7.5	G0	K2	K2	K0	K0	K0	Mb =	G5	F7	F7	F7	
44.5	17	.50	F8	F8	F8	F9.5	G4	G6	K3	K4.5	K8	K8.5	K8.5	Mb =	G5	G7	F7	F7	
52.9	17	.38	G5	G5	G5	G4	G0	G0	F9	F9	G1	G1	G1	G4	G2	F0	F4	F1	
90.1	12	.38	K3	K3	K3	F5 =	K4	F8 =	K9	Ma	G4.5	G4.5	G4.5	G2	G2	G6	G6	G6	
91.9	14	.30	F4 =	F4 =	F4 =	A =	F7 =	F4 =	Go	Go	G2	G2	G2	G2	G2	G6	G6	G6	
95.2	17	.34	F5	F6	F6	A =	Ko	Ko	F6	F6	G8	G8	G8	G7	G6	G6	G6	G6	
98.2	14	.38	F7	F7.5	F7.5	G0	G0	G0	K2	K3	K3.5	K3.5	K3.5	G7	G7	G9	G9	G9	
99.9	16	.42	K2.5	K2.5	K3	K3	G9	G8	G5.5	G5.5	K0	K0	K0	Mb =	F4 =	F4 =	F4 =	F =	
4400.0	16	.29	Ko	Ko	Ko	G9.5	G5	G3.5	G3.5	G3.5	K3.5	K3.5	K3.5	G3.5	G4	G4	G4	G4	
03.4	12	.40	Ko	Ko	Ko	G9.5	G2	G2	G8	G8	K3	K3	K3	G3.5	G4	G4	G4	G4	
07.8	15	.16	F5	F6	F7	F9	G3	G4	G9	G8	G8	G7	G6	K3.5	F7	F6	F2	F1	
12.2	17	.50	F5	F6	F7	G2	G5	G5	G7.5	G8	G9	G9.5	G9.5	G5	A7	G4.5	G4.5	G4.5	
16.9	17	.45	F0	F1	F1	G1	G2	G2	G7.5	G7.5	G7	G6	G6	G4	G7	G6.5	G6.5	G6.5	
17.8	17	.45	F0	F3	F6	G1	G4.5	G5	G7	G7	G7	G6	G6	G4	G7	G6.5	G6.5	G6.5	
22.0	14	.50	F5	F5	F6	F7	Go	Go	G3	G3.5	G5	G6	G7	G6	G1	G1.5	G1.5	G1.5	
25.6	14	.33	F6	F6	F6	Go	Go	Go	G3	G3.5	G5	G6	G7	G6	G1	G1.5	G1.5	G1.5	
28.7	14	.27	Ko =	Ko =	Ko	Ko.5	K2	K2.5	K3.5	K4	K5	K7	K8	Ma	G3	Mb	K8	F9	
29.3	12	.27	Go	Go	Go	G1.5	G9	G9	G9.5	G9.5	G9	G8	G8	G8	Mb	K2	K2	Go	
35.2	12	.45	Ko	Ko	Ko	K2	K5	M =	M =	M =	M =	M =	M =	M =	M =	M =	M =	M =	
41.8	15	.16	F2.5	F2.5	F2.5	F4	F8	F8.5	F9.5	F9.5	G2	G2	G2	G3	F8.5	F8.5	F8.5	F8.5	
44.7	7	.41	F2.5	F2.5	F2.5	F4	F6	F6	Go	Go	G2	G2	G2	G3	G2	G2	G2	G2	
64.7	17	.50	F3.5	F3.5	F3.5	F4	F6	F6	F9.5	F9.5	G1	G1	G1	G3	F4	F3.5	F3.5	F3.5	
66.7	17	.38	G5	G5	G7.5	Ko	K3	K4	K4	K4	K4	K4	K4	K4	K4	K4	K4	K4	
68.6	16	.38	F5	F4	Fo =	Fo =	F4	F7	G2	G4	G8	G9	K2	K4	Mb	Mo	K7	Ko =	
69.4	12	.50	F6	F3	F4	F6	F9.5	Go.5	G3	G4	G4	G4	G4	G4	F2	F1.5	Fo	Fo	
72.9	14	.41	F6	F6	F6	F7	G1	G1	G5	G5	K4	K5	K6	K6	K3 =	G7 =	G6 =	F9	
Weighted means			F9.0	F9.4	Go.2	G1.5	G3.7	G4.4	G7.5	G8.1	Go.3	Go.4	Go.0	G8.6	G3.8	G1.8	F9.5	F8.0	
Sum of weights			12.2	12.2	12.2	12.2	12.2	12.0	12.0	12.0	12.2	12.2	12.2	12.2	12.0	12.0	12.0	12.2	
Probable error for the mean			± 0.9	± 0.9	± 0.9	± 0.9	± 0.8	± 0.8	± 0.8	± 0.8	± 0.8	± 0.8	± 0.8	± 0.8	± 1.1	± 1.1	± 1.1	± 1.0	
Probable error of an observation of weight 1			± 3.1	± 3.0	± 3.0	± 2.9	± 2.7	± 2.7	± 2.8	± 2.7	± 2.7	± 2.7	± 2.7	± 2.9	± 3.1	± 3.9	± 3.8	± 3.4	

NOTES

λ 4313.0 Partly indeterminate—range from F to K only .020 A.
 4331.8 Partly indeterminate.
 4390.1 Questionable whether this line should be used here.
 4391.9 Partly extrapolated. Weight too high?
 4403.4 Direction of variation seems opposite to that in types.
 λ 4422.0 Compared with unpublished curve.
 4428.7 Curve systematically too low by .03A =.
 4435.2 Curve systematically too high.
 4441.8 Compared with unpublished curve.
 4472.9 1149, 1040, 299, 311, 1079, and 1090 have weight 0.16.

NOTE.—In Table IV, the seventeen vertical columns show a range of types one and three-fourths times as great as the horizontal lines. On account of the preliminary status of the method some lines were included in the determinations of type for which slight changes of wave-length correspond to large changes of type. The inevitable result is that not only will moderate accidental errors of measurement increase both the horizontal and the vertical ranges greatly, but small bodily displacements of wave-length for such a line in the spectrum of the star will shift the corresponding changes of type to a very different level, directly affecting the range in the vertical columns. To illustrate: One line may show a range of variation from, let us say, A to G while another line may indicate variations between G and K or M, the variations for the two lines synchronizing with each other and with the light- and velocity-variations of the star. For these reasons the probable errors accompanying Table IV, which were computed from the vertical ranges actually listed, do not represent the limit of accuracy which is inherent in the method. The means at the bottom of the columns may nevertheless be regarded as representing fairly well the actual changes of type of the star, because the errors referred to above, which are systematic for individual lines, partake of the nature of accidental errors for purposes of the means.

In order that the reader may not carry away the erroneous impression that an enormous amount of time will be involved in practical applications of the method employed above for the determination of spectral type, it may be well to call attention to the fact that the method is still in the preliminary stages of development. The aim has been to include as large a number of lines as the nature of the spectra and other limitations would permit, for the simple reason that the behavior of all lines was unknown and could not be safely determined by inference. As was pointed out in the article, a considerable amount of exploratory work is still urgently needed. Eventually measurement for type will be restricted to a very limited list of most suitable lines, probably not more than from eight to twelve per plate in addition to those used for radial velocity.

TABLE V

ADDITIONAL LINES GIVEN AS VARIABLE IN *Córdoba Observatory Boletín No. 1*

- λ 4254.5 Partly indeterminate and partly discordant.
 4267.1 Curve for stellar types is too weak—only six observations.
 4274.9 Unsatisfactory. Not entirely accordant, nor is it especially discordant.
 4293.2 Too few observations in ι Carinae.
 4314.3 Partly in accord in ι Carinae, but the small range, together with the oscillations in stellar types, render this line unsuited for determinations of spectral type.

- 4315.1 Wave-lengths in *l* Carinae are nearly all above the highest parts of the curve for stellar types. This is one of the few lines which seem to be discordant.
- 4318.8 Partly accordant and partly indeterminate. The range of variation is apparently greater in *l* Carinae than in stellar types.
- 4321.9 Partly indeterminate—range from G to K₂ is only .016 Å.
- 4325.1 Wave-length changes by approximately the same amount as in types G to K, but the curve for types is systematically higher by .035 Å±.
- 4325.9 More or less accordant, aside from being systematically higher by .035 Å±.
- 4340.6 H γ . One measure for Plate 1212 corresponds to type K₂.
- 4351.1 Weakly determined both in types and in *l* Carinae.
- 4352.0 Not suitable for this purpose with present data—variation only .011 Å from F to K.
- 4354.7 Data weak in *l* Carinae and in types.
- 4359.8 More or less indeterminate in types F to K except with a large number of observations.
- 4362.2 Data weak.
- 4394.2 In types later than G the measured line is a blend of λ .225 with two weak companions to the violet. The former gradually becomes weaker and the latter stronger. In *l* Carinae the faint companions were not included in the measures, as is indicated by a note for measure on Plate 1220.
- 4427.4 Omitted because too much of results had to be extrapolated.
- 4443.9 The measure sometimes includes the companion to the red, λ 4444.385. The displacement toward the red in the later types and in *l* Carinae near light-minimum may be largely due to personality in the settings on close pairs; the companion at λ .385 is then moderately strong, whereas it is quite weak in early types and in *l* Carinae near maximum light. With the additional data which I have for stellar spectra taken with several different dispersions, it should be possible to separate the personality effects from the true displacements.
- 4459.3 Not suited for this purpose, because in stellar types the variation of the wave-length is confined almost entirely to types earlier than G.

The Figures 1, in which the observed wave-lengths on individual spectrograms are represented by circles, give three things for each line: (a) the curve showing the variation of wave-length in *l* Carinae with change in phase of velocity and variation of the light; (b) the spectral type for each plate obtained by comparing the wave-length taken from the curve in (a) with the curve for the stellar series;

and (c) that portion of the curve for the stellar series which corresponds to the means of the types for the individual spectrograms of ι Carinae, i.e., from F9 to G9.4 and back to F8.

The two curves in the graphs generally rise or fall together toward light-minimum, even when widely separated by systematic differences, thus illustrating how the individual lines show the progressive change of the star to the so-called later types. Note especially the lines with a large range of variation, such as 4412.2, 4416.9, 4422.0, 4425.6, 4464.7, and 4469.4. For only one line, 4403.4, the main tendencies of the two curves indicate opposite directions of change of wave-length. Minor or secondary deviations between the two curves are to be expected, first, because the present data are not ideal in every way, as explained above, and second, because of the fair possibility—and even perhaps probability—that the changes of type with changes of phase in the light and variations of velocity do not coincide in every detail with the corresponding stellar types as classified at present, and, moreover, may not always repeat themselves exactly in different periods. Also in the variable star where the surface conditions—i.e., in the comparatively shallow layer in which all of the light that reaches us originates—are undergoing constant and apparently violent changes, it would seem that a considerable overlapping of the distinguishing characteristics of types almost certainly takes place. An exact correspondence would perhaps be more surprising than the presence of moderate differences.

An interesting comparison is to follow in detail (for the components of lines) the changes of intensity from sun to sun-spots and from spark to arc and to compare these with the observed changes of wave-length in the series of stellar types and in ι Carinae. The last five columns in Table II aid in showing the remarkable extent to which all of these changes run parallel. Some of these have been collected in Table VI in order to bring out, in a way in which verbal description cannot, how some of the shifts are produced by a weakening of an enhanced component as the star approaches light-minimum, while other shifts are due to a marked strengthening of arc or of sun-spot lines. “Str” stands for a strengthening and “wk” for a weakening of the component.

TABLE VI

λ_{ROWLAND}	SUN	SUN SPOTS	SPARK	ARC	NEAR MINIMUM		
					Violet Comp.	Red Comp.	Shift of Blend in Star
a) Enhanced Lines or Weakened in Spots							
4261.891.....	2						
.086.....	1}						
.142.....	1}	0	Cr 5-6	0		wk	to violet
4314.248.....	Sc 3	2			wk		to red
.381.....	1						
.479.....	Ti 1						
.673.....	ON						
4320.661.....	0}						
.756.....	00}	1-2					
.907.....	Sc 3	3					
.119.....	2	1	Ti 3	1		wk	to violet
4371.3.....					wk		to red
4395.201.....	Ti 3	2	Ti 9	5	wk		to red
4399.776.....	Ni 0						
.935.....	Ti, Cr 3	2	Ti 7	3		wk	to violet
4412.092.....	1	0			wk		to red
4416.636.....	V 0	1:1					
.811.....	0ON						
.985.....	2	1				wk	to violet
4469.316.....	Ti 1	0-1			wk		to red
.441.....	0000						
.545.....	Fe 4	4					
4472.884.....	Fe 1}						
.967.....	Mn 0}	2					
.096.....	Ni? 0	00				wk	to violet
b) Spot Lines or Arc Lines							
4258.219.....	IN	0-1					
.477.....	Fe 2	4				str	to red
4265.832.....	Ti 0	0-1			str		to violet
.081.....	Mn 2	2-3					
4278.308.....	0						
.390.....	Fe-Ti 3	3-4				str	to red
4288.038.....	Ti 2						
.149.....	Ni 1		Ru 1	1			
.310.....	Ti, Fe 1	2				str	to red
4321.813.....	Ti 0	1			str		to violet
.961.....	Fe 2						
.204.....	ON						
4344.451.....	Ti 2	n.c.	Ti 3	1			
.670.....	Cr 4	6				str	to red
4351.000.....	Ti 1	n.c.	Ti 2	0			
.216.....	Cr 3	5				str	*
4371.144.....	Zr 1}						
.221.....	1}	1-2	Zr 3	1			
.320.....	00						
.442.....	Cr 2	3-4				str	to red

* To red in late types.

TABLE VI—Continued

λ_{ROWLAND}	SUN	SUN SPOTS	SPARK	ARC	NEAR MINIMUM		
					Violet Comp.	Red Comp.	Shift of Blend in Star
b) Spot Lines or Arc Lines							
4389.801.....	Mn, Ni? 0	.....	.....	.....	.....	.....	.....
.930.....	00	.....	.....	.....	.....	.....	.....
.034.....	00	.....	.....	.....	.....	.....	.....
.149.....	V 2	4	.....	.....	.....	str	to red
4395.201.....	Ti 3	2	Ti 9	5	.....	.....	.....
.413.....	V, Zr 2	3	.....	.....	.....	str	to red
4400.343.....	Zr OND?	.....	.....	.....	.....	.....	.....
.555.....	Sc 3	3-4	.....	.....	.....	.....	.....
.738.....	V 1	3	.....	.....	.....	str	to red
4407.810.....	V 2	8	.....	.....	.....	str†	to violet
.871.....	Fe 4	.....	.....	.....	.....	.....	.....
4412.092.....	1	0	.....	.....	.....	.....	.....
.297.....	V 00	.....	.....	.....	.....	.....	.....
.415.....	Cr 0	1:0	Mo 2	0	.....	str	to red
4416.636.....	V 0	1:1	.....	.....	.....	str	to violet
.811.....	00N	.....	.....	.....	.....	.....	.....
.985.....	2	1	.....	.....	.....	.....	.....
4421.733.....	V 0	1:1	.....	.....	.....	str	to violet
.928.....	Ti 00	0	Ti 3	2	.....	.....	.....
.104.....	1	00-0	.....	.....	.....	.....	.....
.226.....	0	.....	.....	.....	.....	.....	.....
4464.617.....	Ti? 2	n.c.	Ti 3	1	.....	.....	.....
.844.....	Mn 2	.....	.....	.....	.....	.....	.....
.938.....	Fe 1	3-4	.....	.....	.....	str	to red

† Probably V is strengthened relatively more than Fe.

For numerous lines where the observed changes are clearly in the direction accordant with changes from sun to sun-spots, no application could be made to the determination of type because of inadequate data in stellar types. Nevertheless these lines also serve to confirm the fact that changes occur in the spectrum of ι Carinae which are in many ways similar to consecutive changes of spectral type.

PART III

Recently Adams and Joy¹ have noted a marked distinction in the spectral types of Cepheids as obtained from the hydrogen lines alone or from the general spectrum. For nine stars they find in the mean a spectrum of F1 at maximum and F7 at minimum of light, based on the hydrogen lines alone. From the general

¹ *Proceedings of the National Academy of Sciences*, 4, 129-132, 1918.

spectrum they obtain for the same stars F9 at maximum and G0 at minimum. The mean variation of type indicated by the hydrogen lines is 0.6 of the interval between F and G, whereas the general spectrum shows a variation of only 0.1. That is, according to Adams and Joy, the general spectrum shows very little change of type during the period of light-variation. These observers note, however, in addition to the changes in the hydrogen lines, certain other differences in the spectra of Cepheids at maximum and minimum, the three most important of which, also previously observed, are: (1) a shift of the maximum of the continuous spectrum toward shorter wave-lengths at maximum of light; (2) a general, slight widening of the spectral lines at minimum; (3) an increase in the intensity of the so-called "enhanced" lines at maximum. The first of these can influence the positions of the lines only indirectly and in a minor way, and need not be especially dwelt upon here. The second and third will be referred to again later.

The main result of Adams and Joy, namely, that the indications of changes of spectral type in the Cepheids are confined chiefly to the hydrogen lines, appears to be completely at variance with my observed changes of spectral type in *l* Carinae, as determined from the general spectrum and given in detail above. In view of these contradictory results it may be well to discuss the data in Part II in somewhat greater detail, with special reference to their bearing upon this question.

The methods employed in Part II for the determinations of spectral type are essentially different from those employed by Adams, Shapley, and Joy. The latter are based upon differential relative changes in the intensities and widths of lines, partly estimated and partly measured. The former were intentionally freed as much as possible from qualitative estimations by placing the entire weight in the determinations of type upon the measured positions of the lines. Each of these methods has its limitations as well as its advantages, and I am inclined to the view that the best results will be attained by combining the two methods. To me it seems quite unsafe to neglect the measured positions of the lines, as these furnish the best means of identifying with a fair degree of certainty the components involved in observed changes of intensity and width.

As, unfortunately, the ι Carinae spectrograms are in Santiago, they cannot be referred to at this time with the special aim of directly bridging the gap between the general spectrum and the hydrogen spectrum. My notes state that "in κ Pavonis and ι Carinae (F5 and G types) the $H\gamma$ region looks very fuzzy and diffuse, $H\gamma$ being v v broad"; and they also contain the suggestion to "see if $H\gamma$ gets narrower and sharper toward light-minimum" than at maximum. This suggestion was not followed up because of other demands upon my time. Evidently the failure to measure $H\gamma$ on sixteen of the seventeen spectrograms is attributable to poor quality of the line, possibly in part due also to interference of close neighboring lines and to underexposure of the $H\gamma$ region on some of the spectrograms.

The lines observed, given in Tables II and III, belong to and are among the most characteristic and important lines in the general spectrum. Their measured positions identify them, on the whole I believe without any serious outstanding uncertainties, with corresponding lines in the spectra of the sun and of sun-spots, and these in turn have been identified with corresponding lines in stellar spectra. The lines having constant wave-lengths in the stellar types also have constant wave-lengths in ι Carinae. The lines which vary progressively during the period of variation of light (Table IV), and upon which the changes of spectral type are based, are among the most important lines showing progressive changes of wave-length in the series of stellar types. Among the identified components of these lines are Cr, Fe, Mn, Sc, Ti, and V, elements of which the spectral lines exhibit marked and progressive changes of intensity in types A to M.

Nor are the observed changes in ι Carinae covered by the general widening of spectral lines at minimum and by the increased intensity of the "enhanced" lines at maximum, effects (b) and (c) referred to by Adams and Joy. Table II shows numerous lines for which the position of the blend is progressively shifted in ι Carinae from maximum to minimum light and in stars from early to late types, in the direction indicated by the changes in the intensities of the components from sun to sun-spots. Note, for example, the lines 4266.0, 4296.0, 4320.9, 4416.9, and 4422.0, for which both the shift indicated by sun-spot data and the observed shift in ι Carinae

and in the later stellar types are to the violet; and the lines 4278.3, 4288.1, 4390.1, 4391.9, 4412.2, and 4469.4, for which the indicated and observed displacements are to the red. For most of these lines no enhanced components are involved. Several lines, 4292.3, 4298.1, 4391.1, and 4408.5, for which the sun-spot data indicate balanced changes for the intensities of the components, have practically constant wave-lengths in stellar types. Some lines, like 4334.0, show clearly accordant variations in *l* Carinae and in types, with no spot data given. Perhaps corresponding changes will be found in spot spectra. The wholly or partly discordant lines are few. Thus, for 4277.6 the observed displacement is toward the violet both in types and in *l* Carinae, contrary to the expected shift. For 4420.6 a slight shift toward the red might possibly be expected; the observed shift in the variable star is to the violet; in types the data are weak. Such apparent discordances may later be removed in part by additional data from spots and Cepheids. On the whole, the agreement between the expected or inferred and the observed changes of wave-length of the blends is remarkably close.

The "general slight widening of the spectral lines at minimum," additional effect (2) of Adams and Joy (above), seems also brought out in my notes of 1908, reproduced in Part II—unless I misconstrue the intent of these observers. Can the greater part of the apparent widening be explained as a widening of blends due to a considerable increase in intensity of one or more of the components rather than as a genuine widening of single lines? As in later types, so also in *l* Carinae toward minimum of light, the selective absorption increases, many more components being strengthened than weakened, with the result that numerous blends are apparently widened and a small number perhaps narrowed. This, however, does not explain all increases in width, as, for example, for 4468.6, which is apparently a single line in the sun.

My data also contain partial evidence bearing upon Adams and Joy's effect (3)—"an increase in the intensity of the so-called enhanced lines at maximum"—which seems in part confirmatory and in part suggests the changed statement "a greater relative intensity of the so-called 'enhanced' lines in *l* Carinae than in the corresponding types in the stellar series." For the former state-

ment the two curves in Figures 1 for the lines having enhanced components should diverge more and more as maximum of light is approached, the relative shift in ι Carinae being in the direction of the enhanced component of the blend. This seems actually to occur for one or two lines (see 4395.2). For other lines (see 4464.7) the two curves remain parallel throughout their entire length, the systematic displacement between them being in the direction required for greater strength of the enhanced component in the variable star than in the corresponding stellar types. However, the evidence is not clear-cut either way. And, besides, for several lines for which the two curves are parallel and separated no enhanced components are given.

As one of the results of the foregoing investigation it is possible to outline roughly an extensive field of research which can profitably be followed. In order to be able to distinguish the characteristics shared by all Cepheids from those peculiar to individual stars, the spectra of a number of Cepheids should be studied in greater detail. The digressions from a strictly parallel behavior of the lines in Cepheids and in the series of stellar types may lead to results more interesting and far-reaching than the accordances. Also the emissions, the "knotted appearance" referred to in my notes, deserve further study. It may be to the point to recall that the one fact which more than any other led to serious questioning of the binary-star explanation for Cepheids was the discovery of the apparent relation between the light- and the velocity-variations. With dispersions equal to and greater than that of the three-prism Mills spectrographs, it should be possible to follow the simultaneous changes of the lines for the different elements through the cycle of changes of light and velocity.¹ Such results for a number of Cepheids would provide the necessary data for correlating any effects found with such factors as (1) the length of the period; (2) the limiting types between which the variations take place; (3) and (4) the types and the range of variation indicated by the different classes of lines (i.e., spark, arc, spot, etc.), and by the lines of individual elements or groups of elements; and (5) more

¹ The data in Part I are not sufficiently complete to permit of doing this in ample detail for ι Carinae.

exact relationships of the curves representing variations of visual light, photographic light, velocity, color-index, and type.

Thus even the meager data at present available seem sufficient to establish a relation with the length of the period of light-variation. This seems to have been observed by Campbell¹ and later by Shapley² to apply to Cepheids as well as to the general list of variable stars as found, I believe, first at Harvard. However, the exact relationship noted below seems not to have been brought out. Table VII, taken in part from Shapley³ and Seares and Shapley,⁴ with *l* Carinae added, shows a fairly definite progression of the Cepheids toward "later" types, see columns "Shapley" and "Albrecht," with increasing length of the period. This effect seems more clearly and definitely shown in the means of groups of two or three consecutive stars, as given at the bottom of the table. Apparently it is much more strongly marked for very short periods and diminishes to slight changes for periods greater than five days. The poorly marked, slow increase in the length of the period with spectral type, found by Campbell, is thus readily accounted for by the poor representation of very short periods in Campbell's tables. The effect seems absent for the hydrogen spectrum in Adams and Joy's list of nine stars (*loc. cit.*) and to be indicated only slightly in their results from the general spectrum. Here also its apparent absence or small value seems to lie in part in the small number of stars used and in part in the absence from their list of stars with very short periods.

In Table VII my types for *l* Carinae should perhaps be somewhat reduced to make them strictly comparable with the types found by Shapley, due to the presence of a second effect, namely, that the hydrogen lines yield somewhat "earlier" types than the general spectrum. This second effect, which is apparently shown in the tables of Adams and Joy (*loc. cit.*) and somewhat strengthened by my results from the general spectrum of *l* Carinae, seems to

¹ *Lick Observatory Bulletin*, 6, 51, 1910.

² *Astrophysical Journal*, 40, 451, 1914, and *Contributions of the Mount Wilson Observatory*, No. 92.

³ *Ibid.*, 44, 274, 1916, and *Contributions of the Mount Wilson Observatory*, No. 124.

⁴ *Ibid.*, 48, 238, 1918, and *Contributions of the Mount Wilson Observatory*, No. 159.

have its source in the relatively greater strength of the hydrogen lines than of the lines of the general spectrum. In this connection it may be well to bear in mind also, as pointed out above, that the changes in the spectra of Cepheids are more complex than can be accounted for by pure and complete changes of type.

The range through which the type varies in Cepheids (see last column of Table VII) seems to be independent of the period, and to be nearly constant, averaging a little less than one type-interval (10.0 tenths).

Seares and Shapley (*loc. cit.*) have pointed out that the color changes in Cepheids inferred from the hydrogen spectrum (from the relation that the change in color equals 0.4 change in spectrum) agree with the color changes observed photometrically for these stars. On the other hand, the changes of color inferred from the general spectrum are nearly zero and thus discordant. These results are reproduced in my Table VII, columns 3, 4, 5, and 6. It should be noted that the change in color-index, inferred from my observed change of type in *l* Carinae from the general spectrum, is closely of the same magnitude as the changes of color-index obtained for the other Cepheids, both photometrically and inferred from the changes in the hydrogen spectrum. Very weak results for changes of type in η Aquilae, from measures of the general spectrum made by Campbell and Wright for other purposes, give an inferred change of color-index of 0.4. Thus my results seem to show practically the same correlation between the color of Cepheids and the general spectrum as was found for the hydrogen spectrum.

The foregoing investigation, begun a dozen years ago, has been interrupted a number of times. Aside from the part of the work completed at the Lick Observatory, portions of the final reductions were made at the Córdoba and University of Michigan observatories. The definitive discussion and preparation of the manuscript for the printer should be accredited to the Department of Meridian Astrometry of the Carnegie Institution of Washington (Albany). It is a great pleasure to acknowledge my indebtedness to these observatories for the time allowed toward this problem.

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