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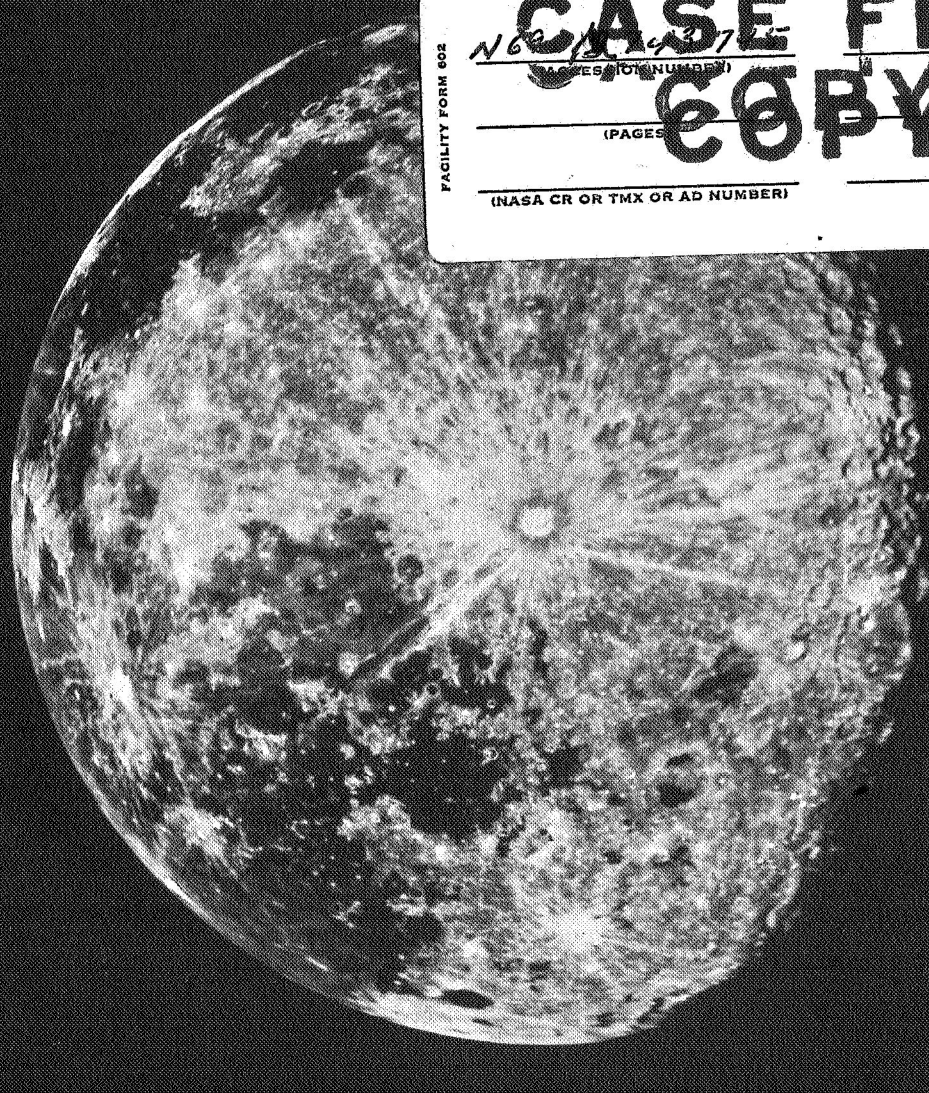
Communications Nos. 112–113



Volume 7 Part 2

THE UNIVERSITY OF ARIZONA

Communications of the LUNAR AND PLANETARY LABORATORY

Communications Nos. 112–113

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1968

Communications of the Lunar and Planetary Laboratory

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Lunar and Planetary Laboratory

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No. 112 UBVRIJKL LIGHT CURVES OF CLASSICAL CEPHEIDS

by W. Z. Wisniewski and H. L. Johnson

April 15, 1968

ABSTRACT

Observations of classical Cepheids are presented. Analyses will be published separately.

We have made multicolor photoelectric observations on the UBVRIJKL system (Johnson, Mitchell, Iriarte and Wisniewski 1966) for 20 classical Cepheid variable stars. For 18 of these stars, the observations extend from the ultraviolet to 2.2μ or 3.4μ in the infrared; for two, the data are limited to the UBVRI filters.

The individual observations are listed in Table 1. This table is divided into two parts; the first, contains the UBVRI data and the second, the JKL data. Since the photometric apparatus was the same as that used on the bright star program, the probable errors listed by Johnson, et al., (1966) also apply to the data of Table 1.

The data of Table 1 are sufficient to define light curves for these stars as wavelengths ranging from the ultraviolet to the infrared. Figures 1–20 show the observed light curves. The UBV data listed by Mitchell, Iriarte, Steinmetz and Johnson (1964) were also plotted, thereby increasing the weights of the UBV curves.

The light curves shown in Figures 1–20 exhibit the well-known shift of phase with wavelength. For example, the times of maximum and minimum light for T Mon shift to later and later phases as one progresses from U to L (from 0.36μ to 3.4μ). On the other hand several stars (SU Cas, DT Cyg and SZ Tau) seem not to show much phase shift. These same three stars are also almost constant in light output at 2.2μ and 3.4μ (K and L magnitudes).

Another group of stars (η Aql, U Aql, W Gem, S Sge and U Sge) exhibit another effect. These stars have secondary "bumps" on the visual light curves; as we proceed to the longer wavelengths these secondary "bumps" become the primary maxima. We suggest that this effect may be related to the phase shifts exhibited by stars with assymetrical light curves; for example, T Mon and X Cyg.

We are preparing, for separate publication, analyses of the data given here in terms of the bolometric light curves and effective temperature curves. The combination of our data with the known radial velocity curves enables us to compute the absolute magnitude for each of these Cepheid variable stars. Our absolute magnitude determinations are entirely empirical and do not depend upon stellar model computations. The results of these analyses will be published in the near future.

This research was supported by the Office of Naval Research.

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Johnson, H. L., Mitchell, R. I., Iriarte, B. and Wiśniewski, W. Z. 1966, *Comm. Lunar and Planet. Lab.*, 4, 99.

Mitchell, R. I., Iriarte, B., Steinmetz, D. and Johnson, H. L. 1964, *Bol. Obs. Tonantzintla y Tacubaya,* 3, 153.

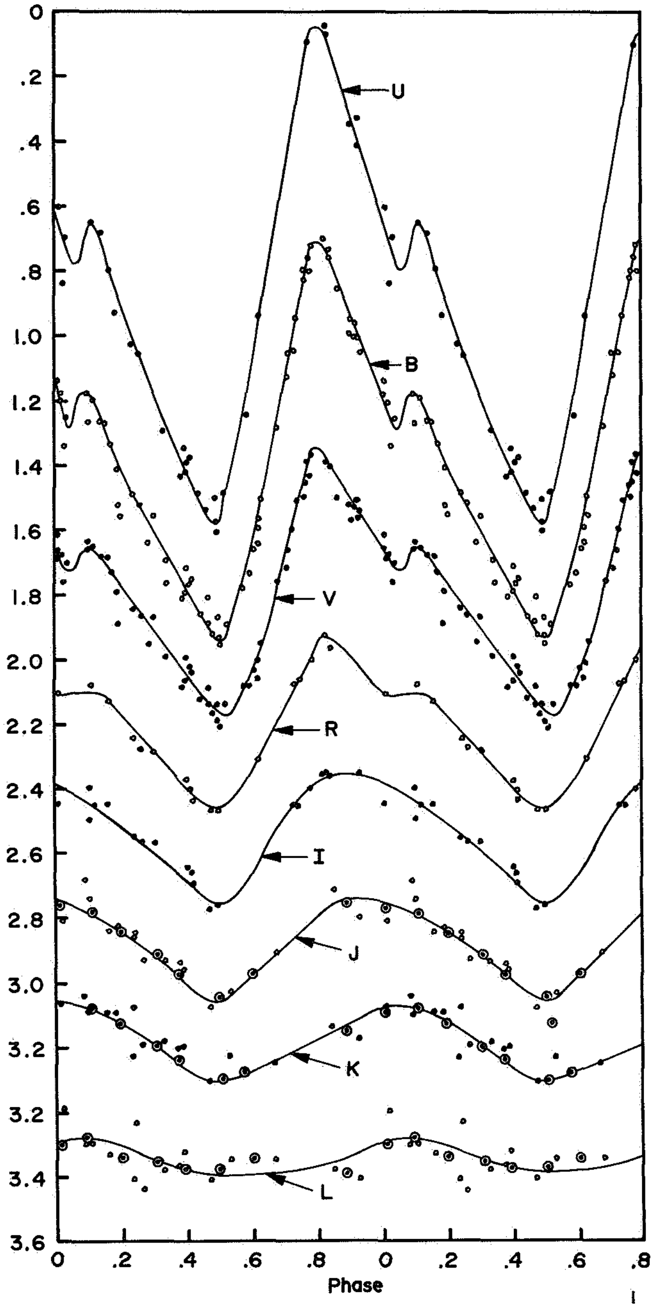

Fig. 1 The light curves for U Aql. Vertical scale gives magnitude differences with arbitrary zero point.

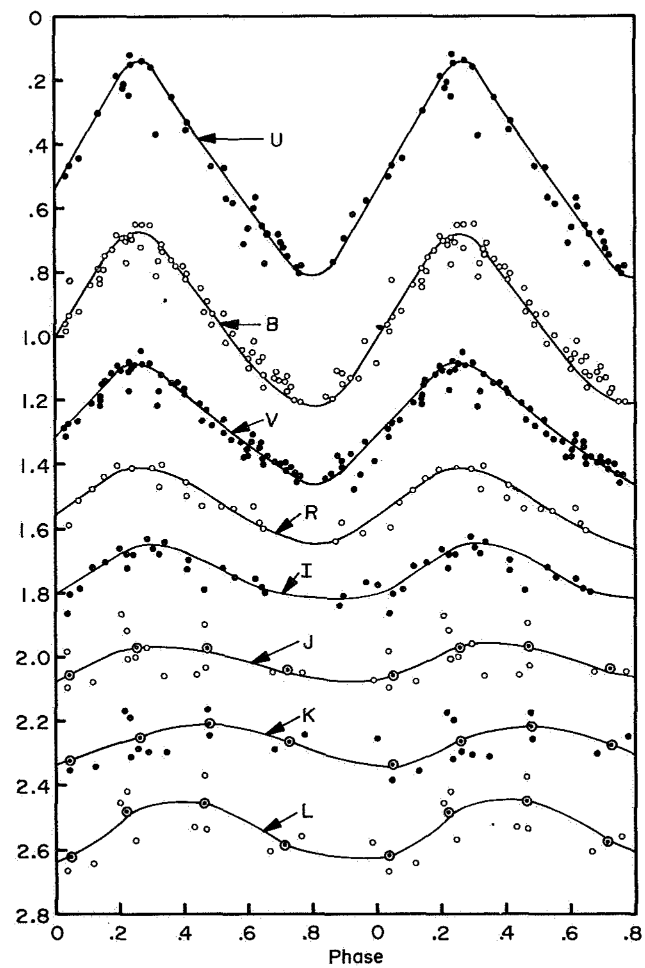

Fig. 2 The light curves for FF Aql.

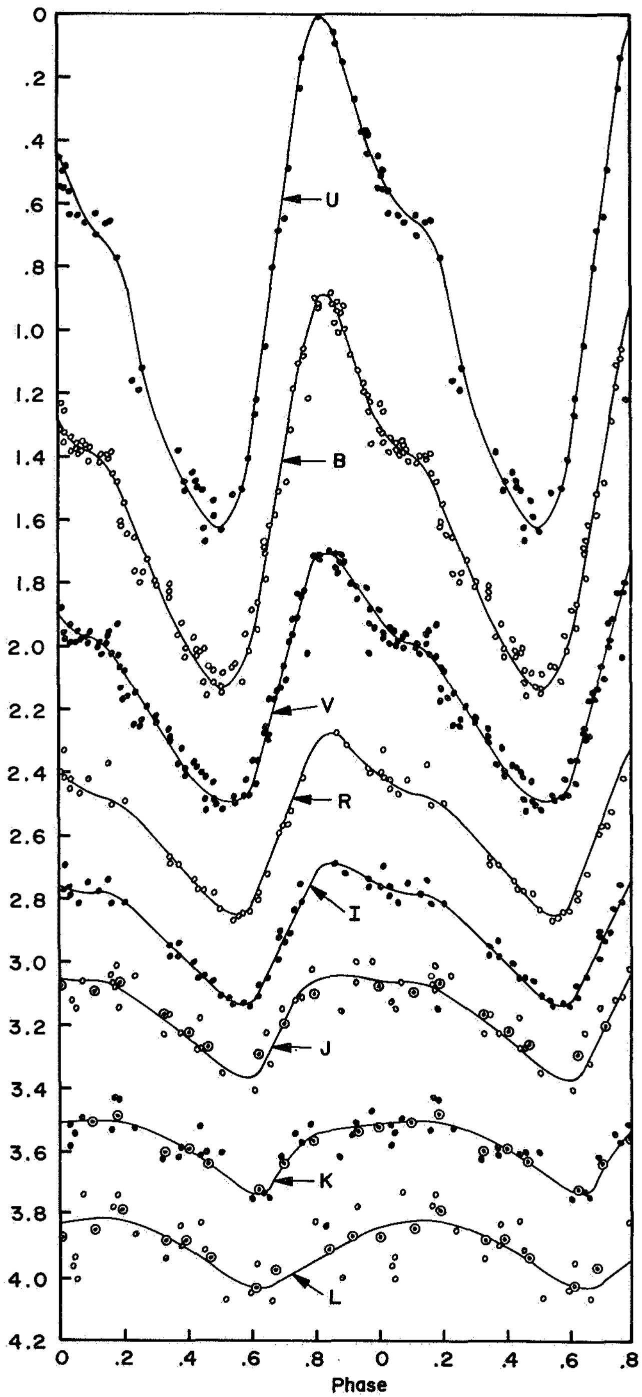

Fig. 3 The light curves for η Aql.

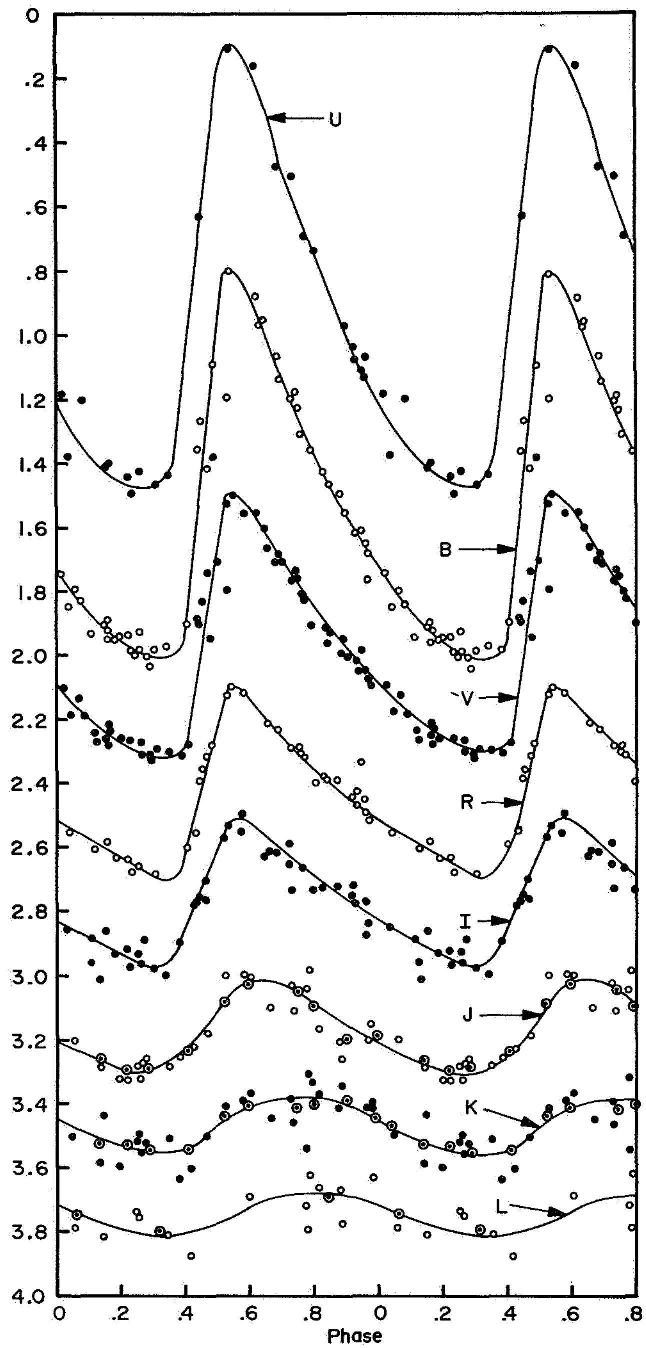

Fig. 4 The light curves for RT Aur.

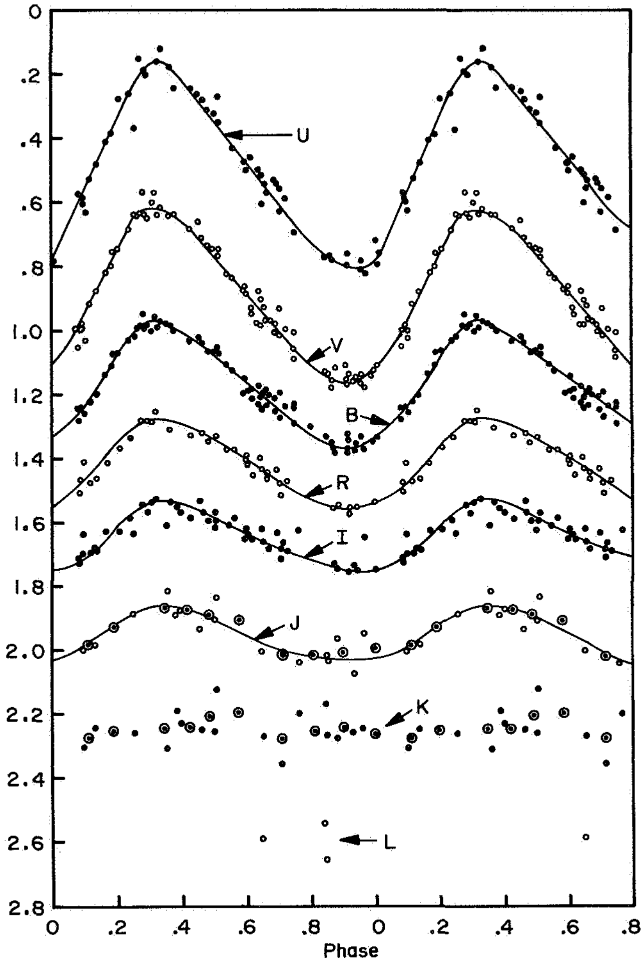

Fig. 5 The light curves for SU Cas.

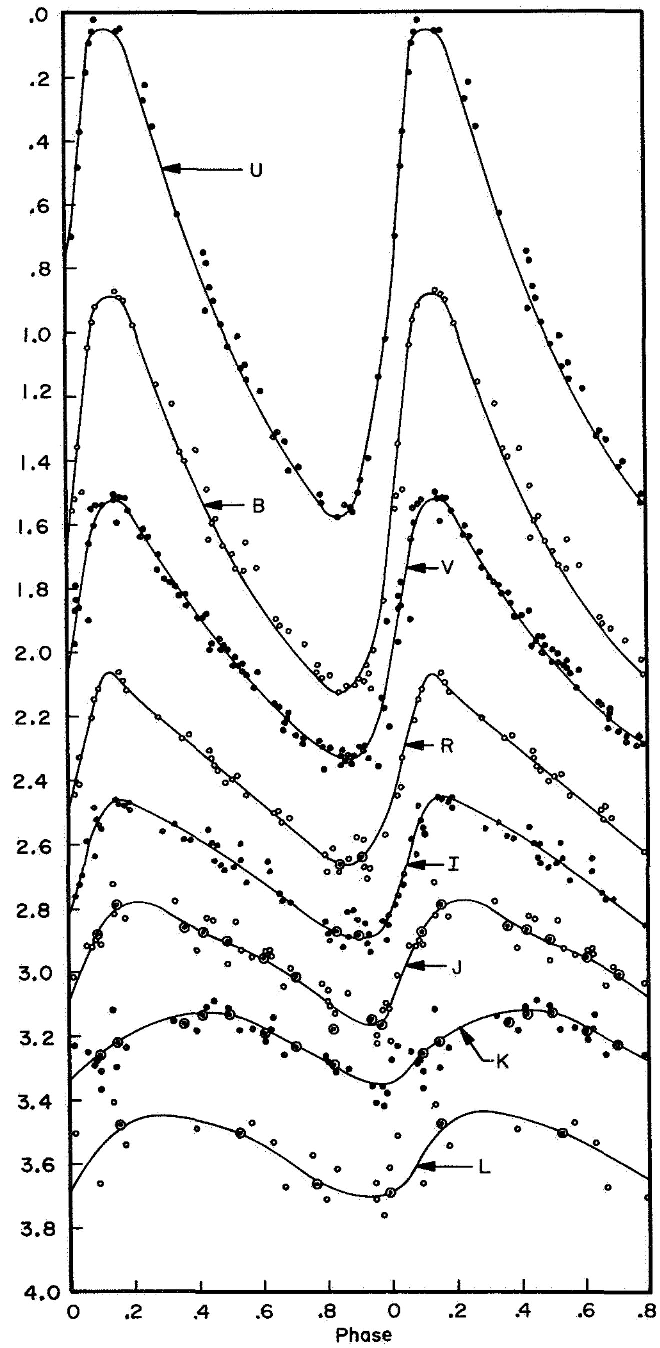

Fig. 6 The light curves for δ Cep.

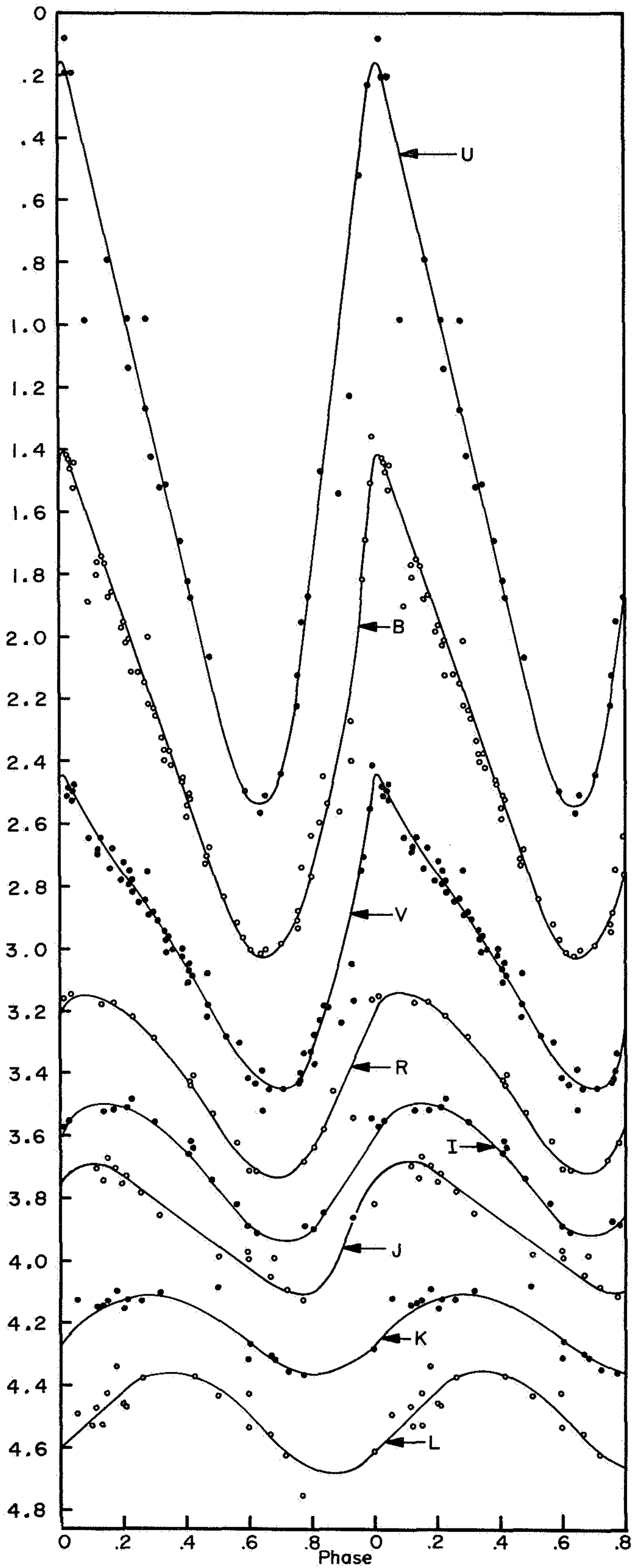

Fig. 7 The light curves for X Cyg.

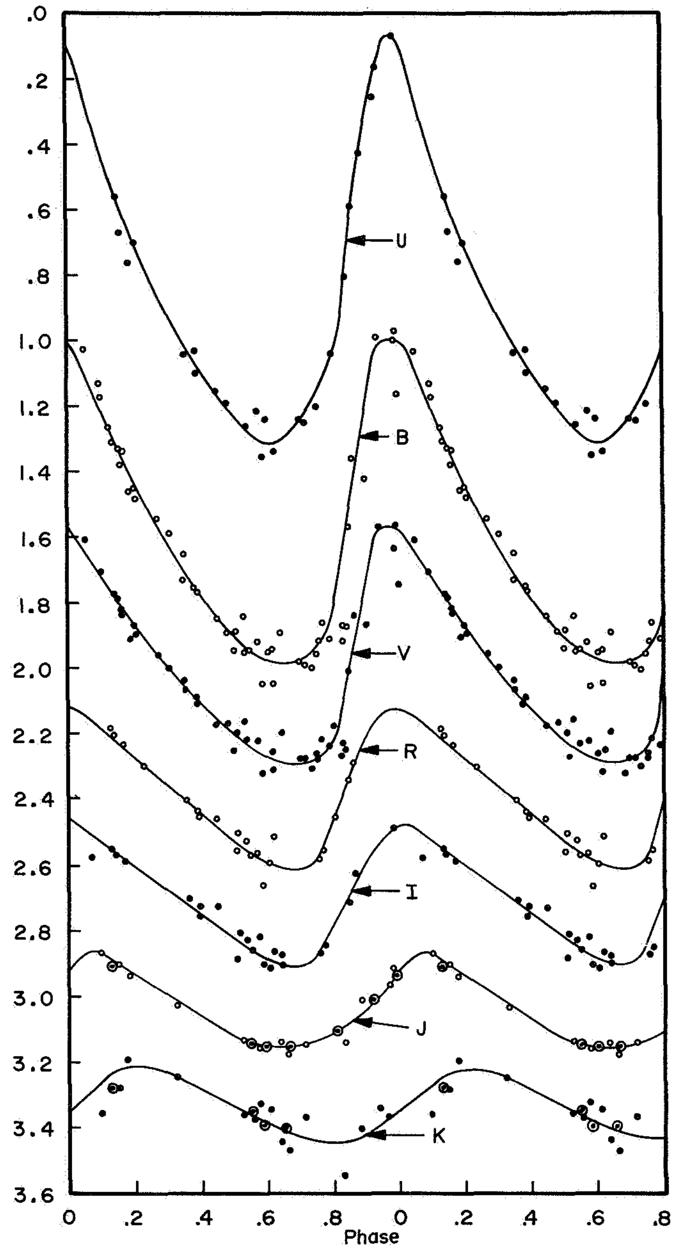

Fig. 8 The light curves for SU Cyg.

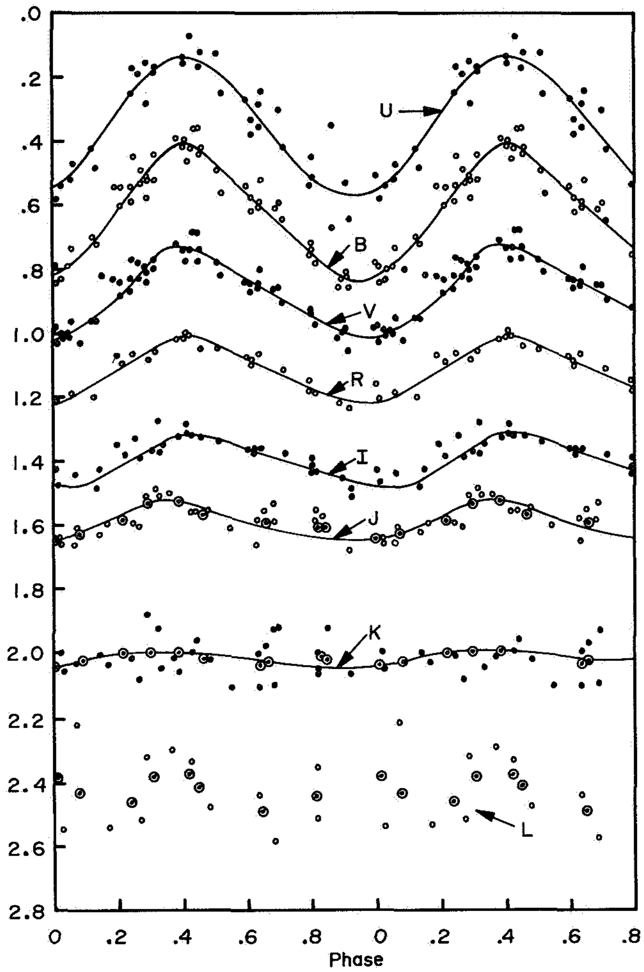

Fig. 9 The light curves for DT Cyg.

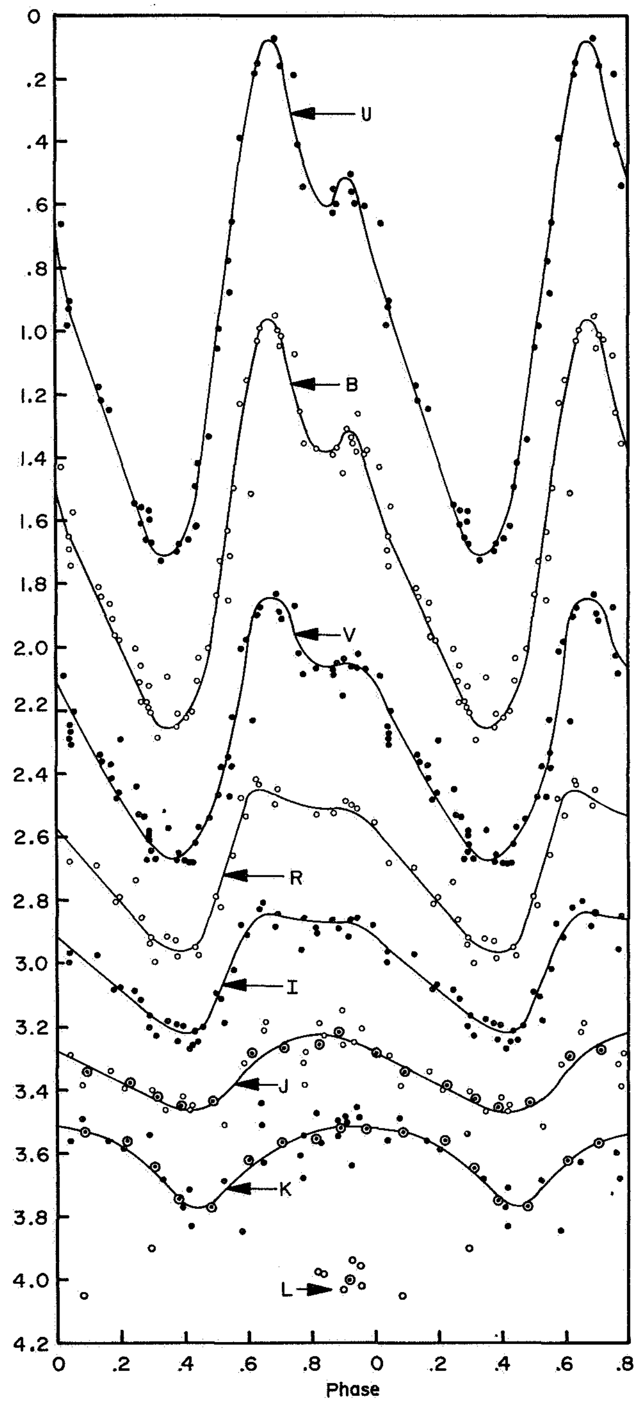

Fig. 10 The light curves for W Gem.

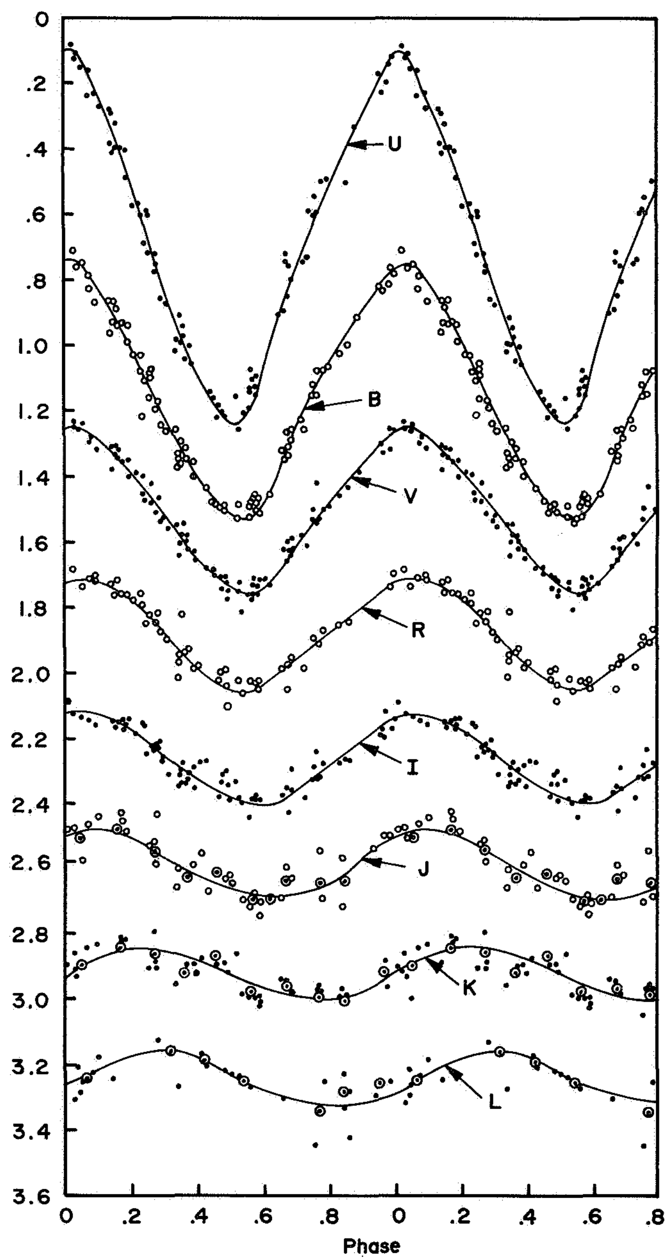

Fig. 11 The light curves for ζ Gem.

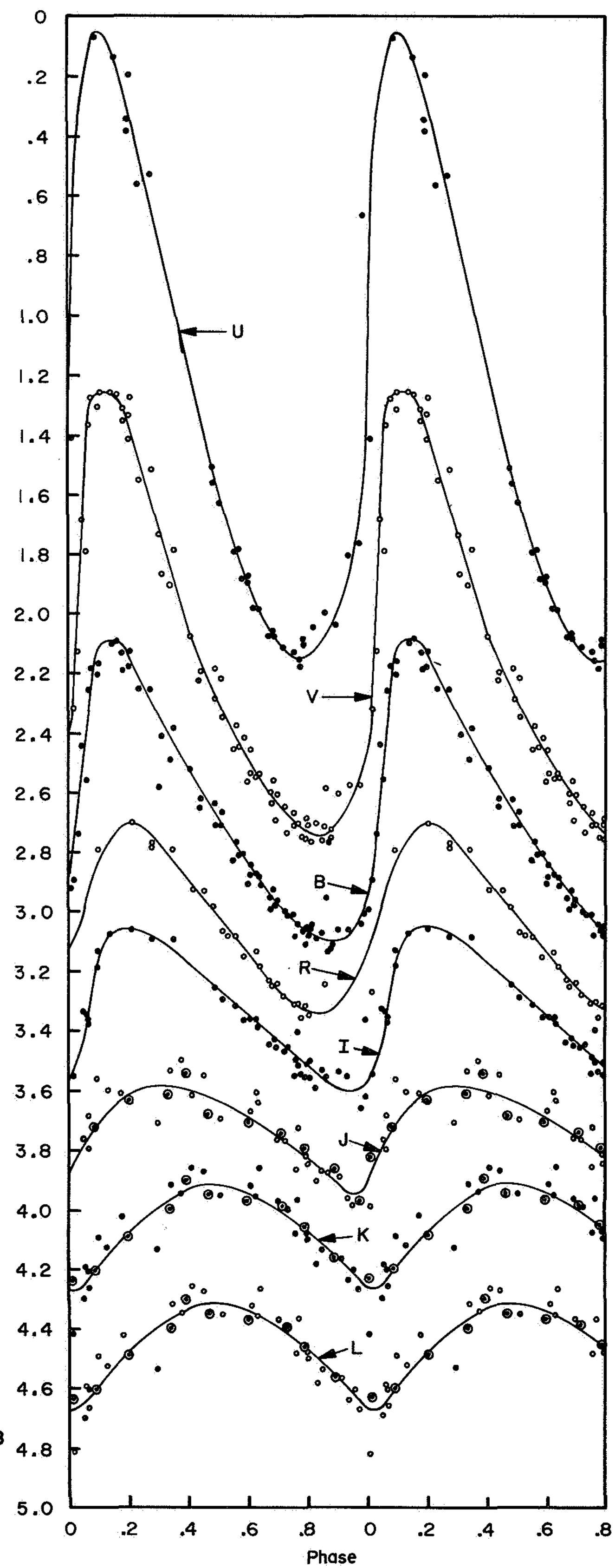

Fig. 12 The light curves for T Mon.

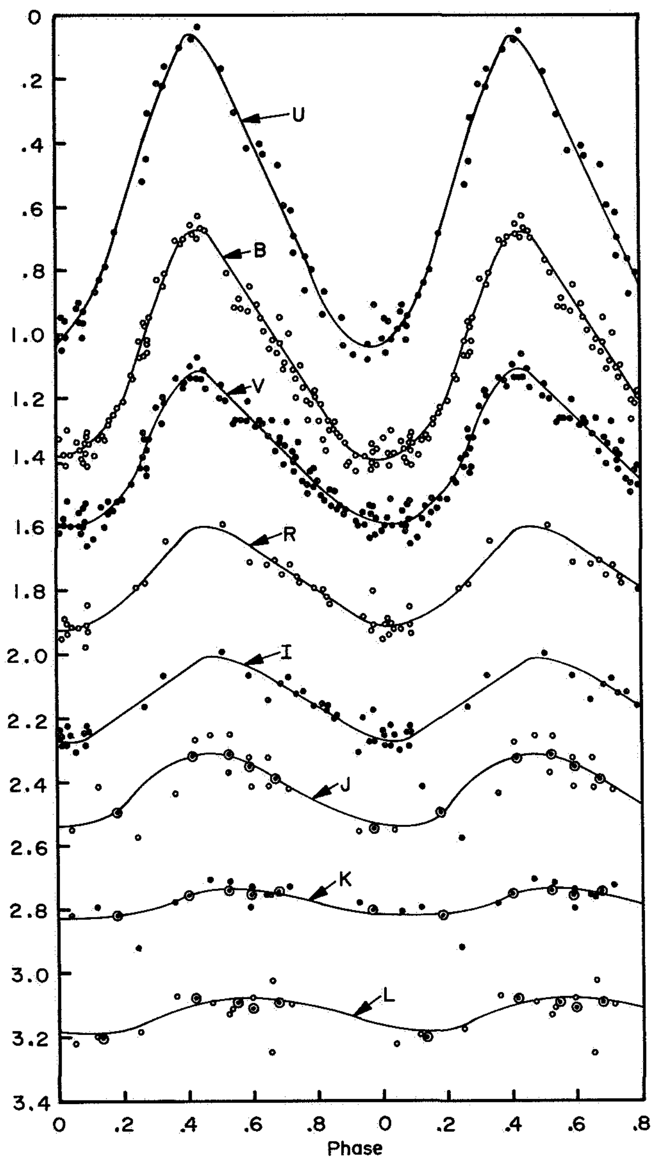

Fig. 13 The light curves for Y Oph.

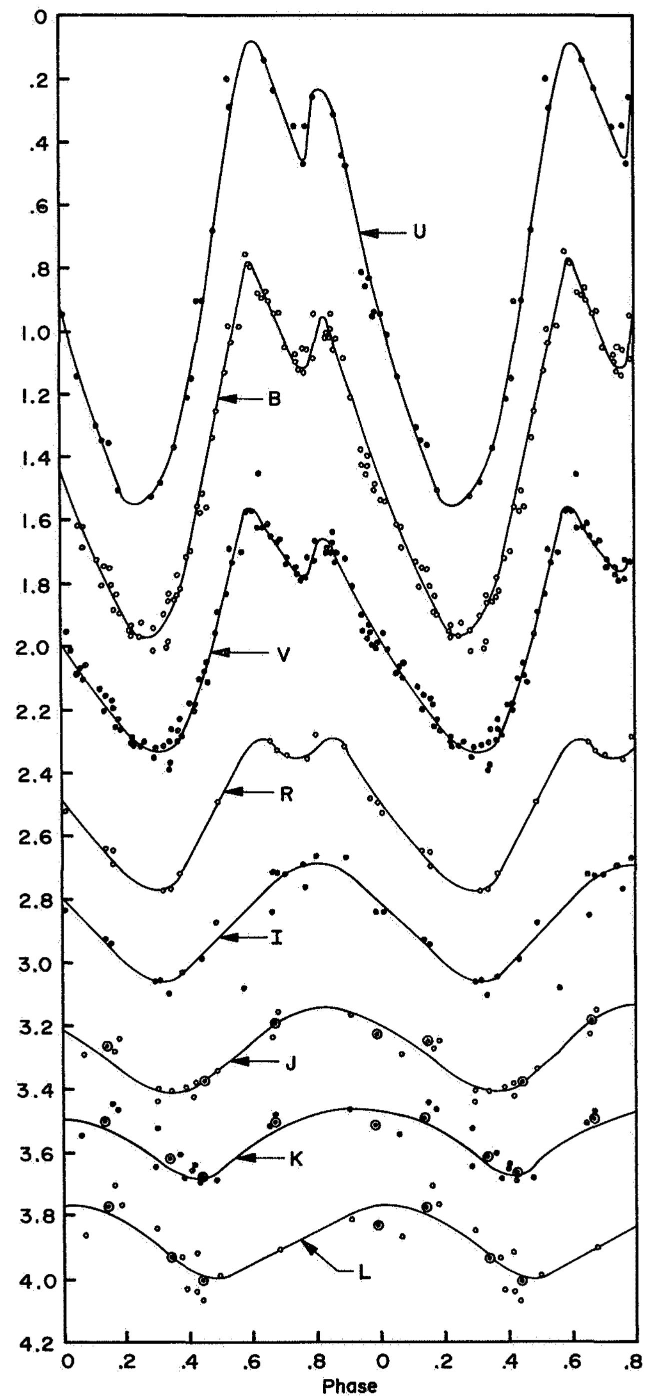

Fig. 14 The light curves for S Sge.

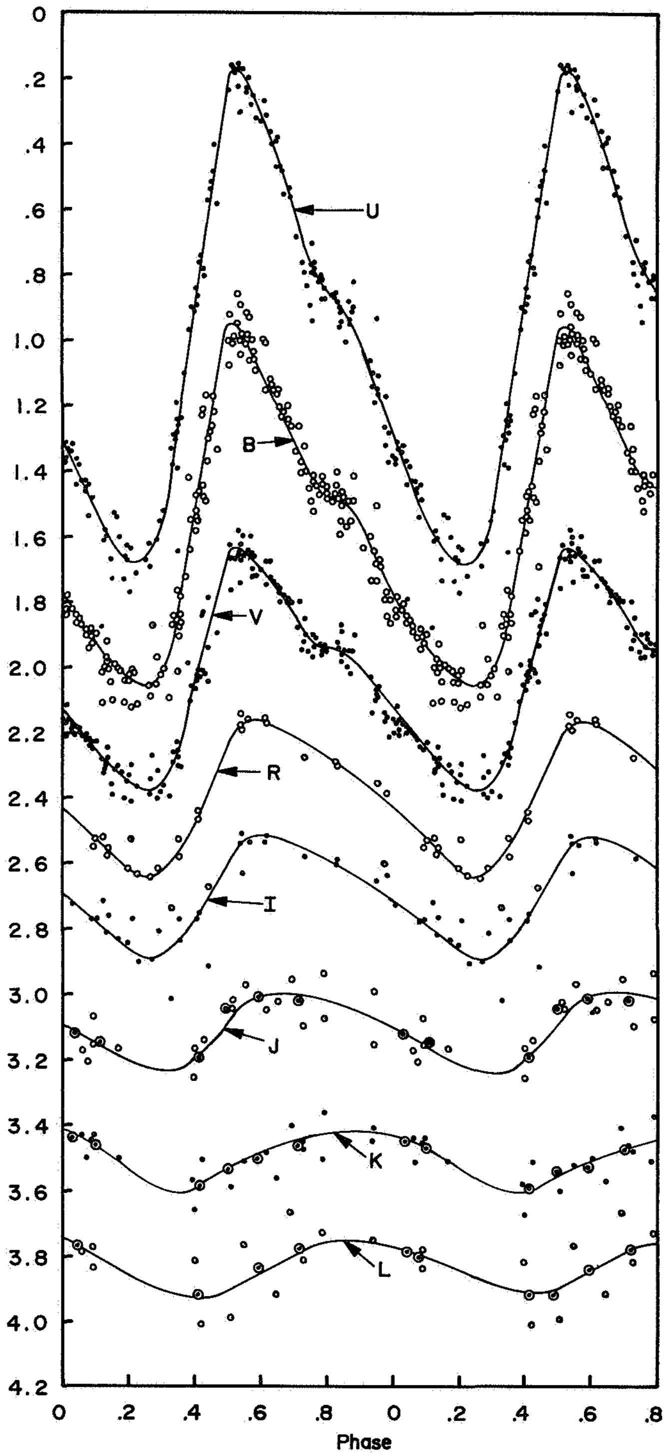

Fig. 15 *The light curves for U Sgr.*

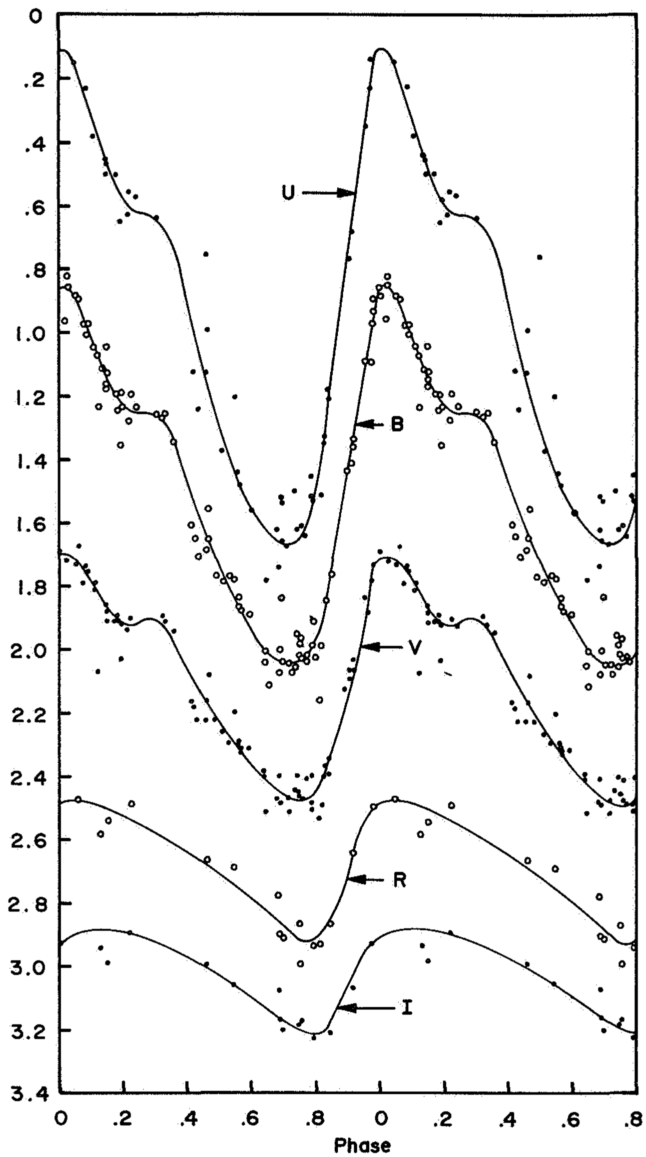

Fig. 16 *The light curves for W Sgr.*

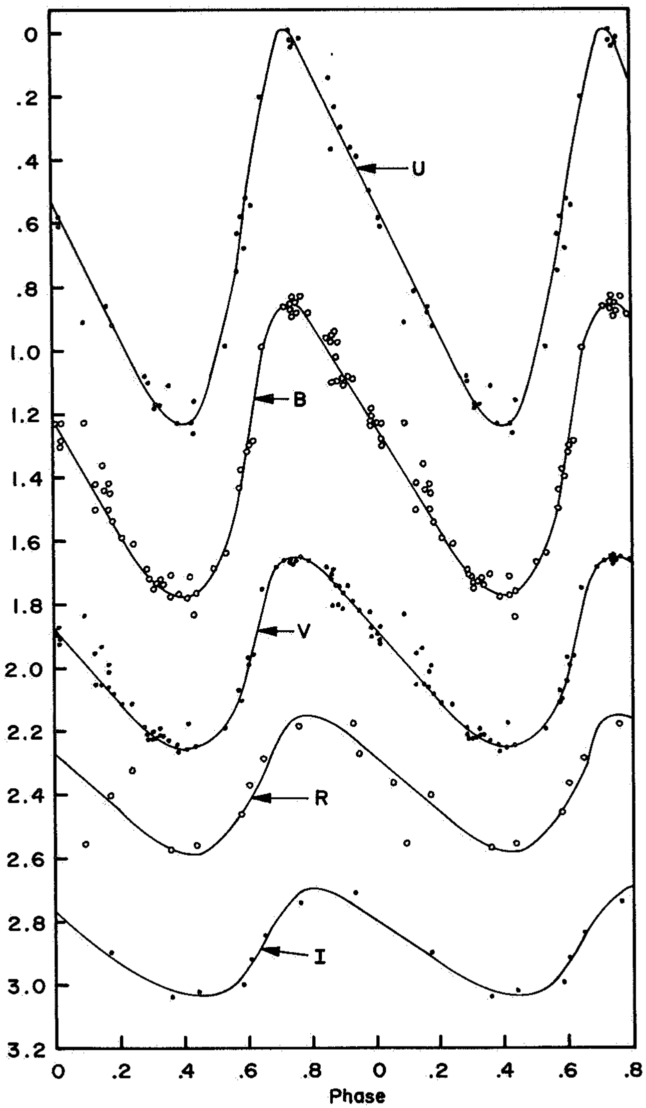

Fig. 17 The light curves for X Sgr.

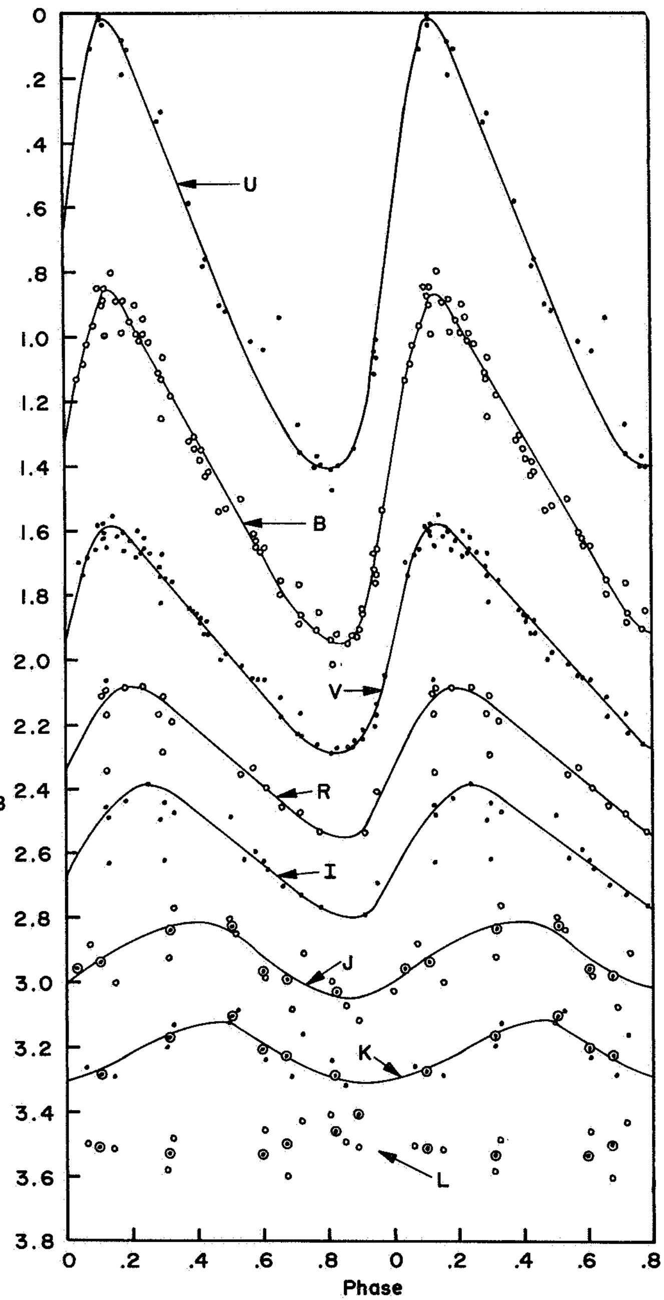

Fig. 18 The light curves for Y Sgr.

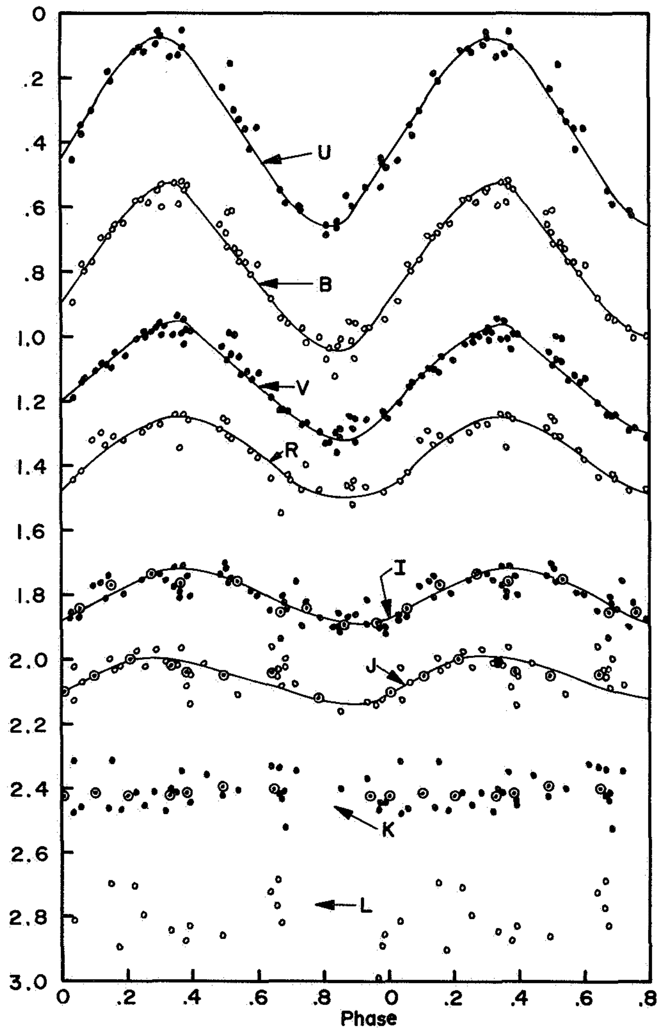

Fig. 19 The light curves for SZ Tau.

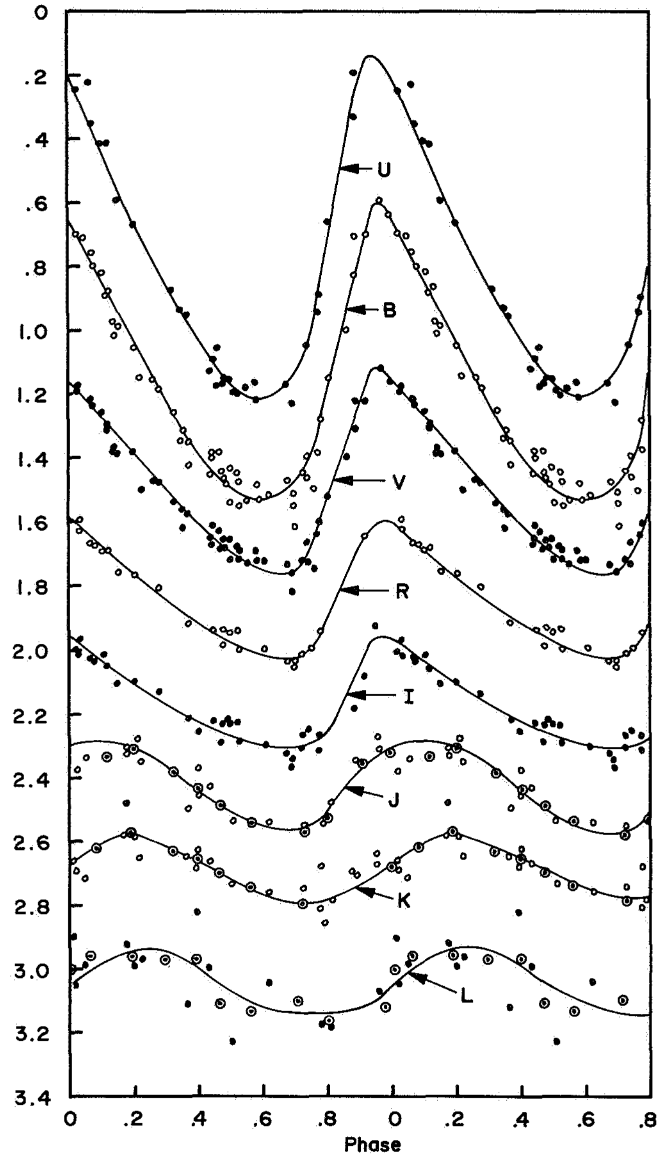

Fig. 20 The light curves for T Vul.

TABLE 1A

UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	
		U AQL			
8658.6819	6.209	7.140		5.462	4.850
8674.6014	6.314	7.337		5.500	4.844
8675.6604	6.385	7.465		5.530	4.852
8676.6531	6.570	7.755		5.678	4.963
8679.6402	6.299	7.245		5.469	4.848
8930.9055	6.839	8.070	9.002	5.869	5.156
8932.8651	6.131	6.998	7.593	5.399	4.799
9028.6748	6.742	7.949	8.878	5.832	5.090
9035.6406	6.719	7.960	8.887	5.801	5.055
9038.6497	6.102	6.956	7.563	5.362	4.757
9040.6079	6.353	7.392	8.146	5.500	4.849
9041.6180	6.563	7.714	8.554	5.672	4.959
9042.6246	6.696	7.911	8.844	5.770	5.039
9045.6161	6.092	6.933	7.538	5.337	4.749
9066.5975	6.055	6.901		5.324	4.756
9068.5827	6.332	7.363		5.466	4.786
9069.5654	6.544	7.682	8.520	5.638	4.948
9281.9046	6.784	8.006		5.858	5.163
9377.6500	6.355	7.466		5.500	4.889
		FF AQL			
7592.6268	5.228	5.898	6.413		
8658.6745	5.484	6.319		4.804	4.296
8659.6973	5.476	6.309		4.821	4.337
8670.6167	5.275	5.969		4.675	4.179
8678.6268	5.309	6.037		4.680	4.222
9000.7069	5.251	5.992		4.646	4.204

JD2430000+	V	B	U	R	I
		FF AQL			
9028.6638	5.284	6.017	6.554	4.707	4.228
9029.6093	5.414	6.215	6.769	4.737	4.258
9035.6264	5.432	6.212	6.780	4.813	4.268
9037.6249	5.284	6.003	6.532	4.664	4.199
9038.6398	5.447	6.276	6.855	4.785	4.287
9040.5978	5.366	6.120	6.641	4.718	4.289
9041.5968	5.188	5.847	6.350	4.614	4.161
9042.6010	5.361	6.129	6.676	4.736	4.221
9045.6055	5.194	5.882	6.389	4.613	4.165
9066.5908	5.501	6.311		4.784	4.310
9068.5770	5.218	5.919		4.595	4.139
9069.5591	5.423	6.189	6.782	4.740	4.250
9281.8972	5.374	6.134	6.666	4.798	4.305
9376.6646	5.204	5.896		4.617	4.183
9377.6422	5.367	6.121		4.733	4.292
		ETA AQL			
8209.8687	3.616	4.412	4.871	3.092	2.634
8496.9658	3.727	4.459	4.940	3.103	2.664
8506.9990	4.177	5.171	5.885	3.395	2.883
8515.9797	4.233	5.143	5.769	3.504	3.012
8517.9670	3.542	4.194	4.652	3.014	2.620
8518.9789	3.789	4.585	5.129	3.123	2.691
8522.9687	4.274	5.222	5.903	3.540	3.039
8526.9639	3.766	4.603	5.160	3.077	2.641
8536.9699	4.278	5.267	6.017	3.571	3.036
8655.6994	3.756	4.575		3.123	2.652

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		ETA AQL			
8658.7072	4.294	5.330		3.534	3.007
8670.6227	3.824	4.657		3.204	2.714
8681.6113	3.876	4.641		3.268	2.829
8699.5909	3.882	4.750		3.196	2.713
8712.5934	3.762	4.527	5.051	3.119	2.672
8724.5963	3.934	4.718	5.184	3.295	2.825
8910.9235	4.096	4.990	5.551	3.427	2.949
8930.9173	4.225	5.232	5.999	3.475	2.952
8931.8919	4.282	5.317	6.001	3.547	3.029
8932.8867	3.903	4.685	5.143	3.270	2.841
9028.6986	3.787	4.593	5.135	3.172	2.715
9031.6825	4.236	5.283	6.042	3.484	2.961
9035.6659	3.734	4.538	5.060	3.153	2.658
9038.6687	4.215	5.211	6.007	3.473	2.943
9040.6247	3.783	4.519	4.992	3.224	2.809
9041.6380	3.508	4.114	4.555	2.980	2.588
9042.6447	3.684	4.433	4.952	3.104	2.659
9045.6350	4.173	5.180	5.948	3.446	2.905
9066.6104	4.090	5.048		3.373	2.850
9068.5948	4.160	5.063	5.714	3.476	2.972
9069.5795	3.644	4.288	4.739	3.123	2.715
9281.9181	4.067	5.012		3.390	2.879
9377.6637	3.942	4.718		3.295	2.895
		RT AUR			
7668.7426	5.513	6.212	6.640	4.974	4.555
8108.6994	5.496	6.216	6.677	4.924	4.525

JD2430000+	V	B	U	R	I
		RT AUR			
8367.8963	5.331	5.869	6.225	4.858	4.552
8368.7729	5.181	5.665	6.069	4.728	4.415
8369.7750	5.548	6.267	6.750	4.941	4.543
8370.7686	5.764	6.542	7.041	5.136	4.726
8408.8685	5.402	5.961	6.247	4.884	4.573
8410.8084	5.563	6.231	6.612	4.980	4.578
8468.6707				4.777	
8469.6837				4.788	
8658.9837	5.031	5.410		4.627	4.374
8676.9376	5.804	6.575	7.034	5.200	4.802
8679.9793	5.714	6.497		5.083	4.667
8682.9863	5.556	6.279		4.957	4.574
8723.9125	5.492	6.213	6.711	4.833	4.557
9037.9928	5.769	6.556		5.135	4.734
9041.9010	5.790	6.590	7.090	5.179	4.774
9045.8966	5.791	6.587	7.067	5.185	4.782
9067.0111	5.597	6.360		5.018	4.636
9098.9560	5.001	5.408	5.709	4.600	4.332
9100.8293	5.684	6.453	6.972	5.052	4.659
9148.6948	5.497	6.170		4.887	4.527
9148.8872	5.551	6.250		4.978	4.580
9150.7660	5.388	5.945	6.282	4.921	4.598
9151.6763	5.209	5.697			
9151.8503	5.268	5.813		4.786	4.455
9154.6134	5.241	5.723		4.814	4.506
9159.5902	5.411	6.037		4.896	4.535
9159.7156	5.467	6.053		4.887	4.509

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		RT AUR			
9173.6665	5.059	5.456		4.622	4.358
9174.6128	5.414	6.059		4.879	4.528
9175.6856	5.772	6.581		5.104	4.691
9177.6800	5.164	5.622		4.711	4.430
9178.6649	6.343	7.148		5.579	4.869
9468.9180	5.327	5.908	6.286	4.814	4.471
		SU CAS			
7592.7799	6.040	6.786	7.293	5.316	4.834
7597.7843	5.986	6.723	7.236		
8367.6409	5.995	6.681	7.171	5.309	4.847
8367.7442	6.007	6.706	7.215	5.335	4.859
8368.6558	6.037	6.732	7.236	5.368	4.885
8369.6007	6.005	6.698	7.212	5.308	4.826
8370.6416	6.008	6.682	7.183	5.365	4.886
8371.5817	5.983	6.729	7.160	5.355	4.847
8408.6634	5.977	6.681	7.199	5.299	4.819
8410.7360	5.991	6.729	7.246	5.415	4.906
8658.8733	6.145	6.929	7.420	5.438	4.946
8674.7998	5.938	6.623	7.111	5.315	4.827
8680.8546	5.784	6.436		5.184	4.744
8682.8851	5.756	6.373		5.153	4.724
8700.7914	5.865	6.544	7.021	5.237	4.769
8720.6548	6.050	6.806	7.238	5.337	4.830
9004.9639	5.902	6.626		5.274	4.808
9028.9927	6.167	6.981		5.460	4.929
9031.7725	5.786	6.451	6.899	5.185	4.770

JD2430000+	V	B	U	R	I
		SU CAS			
9035.8059	5.784	6.440	6.880	5.207	4.738
9036.7865	6.160	6.976	7.478	5.456	4.924
9037.8815	5.831	6.485	6.943	5.231	4.787
9038.8309	6.181	6.966	7.491	5.465	4.955
9041.8546	5.835	6.511	6.979	5.226	4.768
9042.7274	6.173	6.958	7.463	5.471	4.954
9045.7875	5.864	6.534	7.011	5.248	4.790
9045.9346	5.924	6.639	7.130	5.276	4.786
9066.6829	5.869	6.547	6.978	5.267	4.822
9068.6999	5.830	6.483	6.962	5.226	4.780
9069.6397	6.034	6.796	7.289	5.375	4.882
9098.7681	6.031	6.768	7.268	5.365	4.877
9099.5872	6.040	6.802	7.279	5.407	4.922
9100.5889	5.944	6.662		5.299	4.821
9100.8023	6.071	6.815	7.326	5.379	4.878
9154.6046	5.803	6.402		5.186	4.735
9159.6148	6.182	6.920		5.450	4.940
9159.7329	6.174	6.957		5.452	4.945
9173.6595	6.077	6.853		5.376	4.912
		DEL CEP			
7592.7544	4.327	5.204	5.851	3.580	3.145
8368.5873	3.958	4.670	5.196	3.362	2.971
8369.5924	4.161	4.986	5.625	3.482	3.053
8370.6230	4.356	5.236	5.877	3.686	3.239
8371.5731	4.004	4.652	5.088	3.451	3.068
8408.5811	4.338	5.190	5.817	3.595	3.155

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		DEL CEP			
8410.5580	3.691	4.257	4.655	3.204	2.865
8655.7872	4.183	4.936	5.420	3.571	3.167
8677.7534	3.655	4.136	4.498	3.209	2.895
8679.7104	3.877	4.581		3.309	2.905
8699.6627	3.521	3.967		3.075	2.780
8722.7145	3.973	4.688	5.156	3.360	2.911
8724.5809	4.372	5.277		3.691	3.211
8931.9296	3.987	4.744	5.234	3.335	2.956
8939.9428	4.340	5.220	5.758	3.668	3.245
9004.8617	3.973	4.612	5.002	3.426	3.039
9028.7674	3.991	4.762	5.272	3.412	2.986
9031.7304	3.865	4.453	4.833	3.331	3.006
9035.7694	4.296	5.175	5.812	3.640	3.161
9036.7625	4.197	4.953	5.444	3.567	3.153
9037.8003	3.516	3.982	4.356	3.092	2.786
9038.8064	3.824	4.467	4.932	3.269	2.888
9041.8197	4.313	5.179	5.768	3.674	3.223
9042.7142	3.600	4.060	4.397	3.152	2.844
9045.7989	4.170	5.013	5.615	3.530	3.085
9066.6752	4.058	4.839	5.408	3.451	3.028
9068.6651	4.322	5.140	5.772	3.628	3.190
9069.6164	3.540	4.010	4.362	3.116	2.818
9098.6612	4.038	4.786	5.339	3.389	2.981
9099.5943	4.196	5.030	5.642	3.520	3.092
9100.5823	4.347	5.233	5.882	3.649	3.198
9148.5866	4.299	5.167		3.621	3.172
9150.5828	3.518	3.989		3.124	2.799

JD2430000+	V	B	U	R	I
		DEL CEP			
9151.5804	3.824	4.493		3.267	2.893
9154.5697	4.324	5.172		3.711	3.246
9159.5829	4.342	5.203		3.661	3.204
9377.8025	4.016	4.831		3.388	2.959
		X CYG			
8224.8599	6.449	7.560	8.424	5.644	5.063
8555.8999	6.047	7.039		5.278	4.717
8655.7359	6.181	7.307		5.320	4.676
8658.7384	6.469	7.835		5.524	4.854
8678.6542	6.837	8.302		5.815	5.111
8681.6250	6.676	7.925		5.740	5.094
9028.7435	5.950	6.806	7.428	5.265	4.743
9031.6999	6.078	7.154	7.989	5.276	4.716
9035.7137	6.448	7.798	9.022	5.539	4.815
9038.6985	6.816	8.261	9.694	5.813	5.088
9041.6568	6.738	8.028	9.151	5.785	5.088
9042.6946	6.581	7.740	8.668	5.684	5.047
9066.6360	6.286	7.525	8.618	5.386	4.753
9068.6099	6.484	7.810	9.075	5.503	4.833
9069.5940	6.573	7.972	9.268	5.630	4.937
		SU CYG			
8655.6922	7.119	7.761		6.554	6.146
8658.6951	7.137	7.844		6.570	6.158
8681.6058	7.098	7.785		6.504	6.104
8931.8811	7.226	7.951	8.255	6.633	6.203
8932.8768	6.914	7.467	7.703	6.340	6.012

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		SU CYG			
9028.6890	7.165	7.814	8.095	6.586	6.169
9031.6728	7.122	7.848	8.159	6.523	6.129
9035.6550	7.126	7.821	8.116	6.563	6.113
9038.6596	6.971	7.631	7.938	6.401	6.003
9040.6175	6.745	7.260	7.488	6.284	5.919
9041.6293	6.662	7.167	7.449	6.183	5.853
9042.6346	6.990	7.655	7.929	6.437	6.029
9045.6260	6.734	7.279	7.563	6.230	5.883
9066.6039	7.153	7.843		6.511	6.162
9068.5885	6.677	7.201		6.194	5.859
9069.5732	7.009	7.665	8.000	6.451	6.052
9100.5489	7.074	7.745	8.050	6.458	6.029
9281.9125	7.163	7.851		6.593	6.219
9377.6574	7.149	7.844		6.557	6.184
		DT CYG			
8367.5879	5.960	6.557	6.942	5.434	5.117
8368.5787	5.661	6.134	6.475	5.250	4.974
8369.5760	5.802	6.346	6.737	5.298	4.968
8370.6080	5.862	6.402	6.722	5.398	5.086
8371.5626	5.681	6.194	6.426	5.245	4.942
8655.7499	5.744	6.247		5.288	4.983
8658.7580	5.674	6.159		5.212	4.926
8671.7442	5.771	6.321	6.675	5.293	4.970
8674.7451	5.873	6.481		5.383	5.036
8677.7323	5.876	6.490		5.401	5.067
8678.6657	5.621	6.091		5.216	4.927
9004.8495	5.905	6.530		5.421	5.049
9028.7547	5.675	6.141	6.468	5.242	4.928
9029.6199	5.841	6.416	6.749	5.335	5.015
9031.7213	5.752	6.306	6.654	5.265	4.969
9035.7407	5.668	6.147	6.468	5.259	4.927
9038.6297	5.645	6.115	6.435	5.197	4.888
9041.6071	5.739	6.241	6.570	5.270	4.967
9042.6149	5.885	6.479	6.805	5.360	5.032
9042.7627	5.861	6.437	6.771	5.387	5.042
9066.6501	5.745	6.276	6.629	5.288	4.978
9068.6258	5.636	6.097	6.453	5.209	4.916
9069.6100	5.830	6.439	6.811	5.378	5.038
9099.5797	5.832	6.453	6.835	5.347	5.000
9100.5763	5.733	6.238		5.267	4.950
9375.7663	5.742	6.280	6.585	5.281	4.976
		W GEM			
7597.8595	6.767	7.673	8.305		
8108.7063	7.077	8.022	8.684	6.316	5.708
8367.9069	7.232	8.359	9.257	6.352	5.719
8368.7806	7.375	8.509	9.392	6.427	5.796
8369.7819	7.173	8.132	8.756	6.286	5.696
8370.7769	6.598	7.330	7.882	5.914	5.427
8408.8747	7.269	8.333	9.115	6.474	5.847
8410.8171	6.527	7.244	7.778	5.993	5.485
8468.6756				6.049	5.483
8469.6773				6.191	5.576

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		W GEM			
8658.9893	7.004	8.041		6.176	5.593
8674.0277	6.761	7.671	8.294	6.009	5.460
8676.9463	7.365	8.586		6.496	5.833
8680.9553	6.763	7.670		6.024	5.490
8723.9315	7.147	8.303	9.248	6.236	5.683
9038.0023	6.759	7.650		5.995	5.459
9041.9947	7.318	8.400	9.187	6.447	5.820
9042.9506	6.921	7.790	8.353	6.152	5.620
9045.9054	6.747	7.653	8.260	6.016	5.468
9067.0170	6.680	7.453		6.029	5.509
9098.9643	6.573	7.295	7.853	5.927	5.429
9100.8361	6.775	7.685	8.324	6.020	5.463
9148.6076	6.733	7.605		5.980	5.439
9151.6586	7.310	8.484		6.432	5.799
9154.8581	6.587	7.349		5.949	5.443
9159.5985	7.343	8.499		6.416	5.769
9174.5937	7.175	8.263		6.298	5.677
9174.6323	7.165	8.274		6.293	5.676
9175.8476	7.272	8.390		6.414	5.781
9177.6875	6.709	7.523	8.090	5.973	5.474
9468.9452	7.356	8.512	9.374	6.479	5.843
		ZET GEM			
8080.7593	3.672	4.379	4.815	3.094	2.745
8108.7136	3.935	4.750	5.283	3.289	2.885
8113.6326	3.855	4.677	5.301	3.189	2.761
8142.6444	3.715	4.462	4.930	3.102	2.755

JD2430000+	V	B	U	R	I
		ZET GEM			
8143.6327	3.802	4.586	5.189	3.159	2.738
8147.6229	4.136	5.075	5.827	3.448	3.007
8367.9144	3.866	4.765	5.450	3.215	2.807
8368.7934	4.014	4.939	5.735	3.320	2.890
8369.7884	4.137	5.102	5.931	3.380	2.924
8369.8951	4.107	5.082	5.898	3.372	2.894
8370.7835	4.138	5.074	5.830	3.426	2.986
8371.8949	4.030	4.932	5.417	3.449	3.023
8376.9809	3.758	4.526	5.095	3.155	2.772
8378.9056	3.992	4.941	5.672	3.338	2.896
8379.9302	4.113	5.107	5.917	3.424	2.977
8380.9785	4.118	5.064	5.772	3.445	3.007
8381.8637	4.026	4.915	5.602	3.387	2.974
8397.8254	3.798	4.624	5.267	3.154	2.753
8431.7905	4.123	5.053	5.799	3.429	2.987
8441.8147	4.179	5.088	5.842		
8443.8127	3.884	4.672	5.244	3.313	2.926
8449.7746	4.005	4.940	5.692	3.367	2.938
8461.7298	4.123	5.085	5.854	3.419	2.982
8469.6901	3.958	4.856	5.571	3.297	2.910
8480.6503	4.054	4.997	5.757	3.383	2.950
8481.6745	4.172		6.128	3.488	3.060
8482.6394	4.118	5.060	5.796	3.424	2.983
8483.6307	3.992	4.852	5.456	3.350	2.957
8498.6163	3.745	4.528	5.095	3.114	2.749
8499.6307	3.877	4.757	5.415	3.218	2.828
8509.6412	3.871	4.702	5.387	3.249	2.849

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		ZET GEM			
8510.6310	4.043	4.968	5.715	3.413	2.944
8658.9956	3.707	4.418	4.872	3.147	2.793
8671.0208	3.780	4.554	5.082	3.126	2.746
8675.0154	4.216	5.213	5.958	3.458	2.998
8676.9584	4.014	4.856	5.445	3.389	2.984
8678.0174	3.860	4.619		3.254	2.877
8679.9853	3.632	4.307	4.783	3.080	2.729
8699.8893	3.660	4.360	4.840	3.136	2.781
8723.9389	3.946	4.903	5.696	3.217	2.876
9038.0094	3.937	4.837	5.556	3.272	2.846
9041.9104	3.995	4.857	5.441	3.378	2.960
9042.9733	3.901	4.670	5.199	3.267	2.878
9045.9242	3.696	4.423	4.935	3.110	2.743
9067.0235	3.736	4.524	5.110	3.156	2.769
9098.9710	3.929	4.839	5.554	3.279	2.857
9129.9113	4.008	4.928	5.682	3.345	2.914
9148.8413	3.790	4.622	5.274	3.177	2.785
9151.7265	4.150	5.108	5.916	3.438	2.990
9159.6697	3.912	4.788	5.473	3.245	2.837
9174.6198	3.906	4.712	5.289	3.313	2.928
9175.7333	3.835	4.591	5.204	3.241	2.865
9177.6957	3.642	4.347	4.851	3.136	2.735
		T MON			
8108.6928	5.705	6.603	7.204	4.993	4.492
8367.8854	6.423	7.854	9.189	5.449	4.734
8368.7660	6.500	7.942	9.247	5.466	4.750

JD2430000+	V	B	U	R	I
		T MON			
8369.7682	6.581	8.004	9.260	5.491	4.783
8370.7597	6.550	7.983	9.236	5.516	4.815
8408.8598	5.626	6.568	7.332	4.907	4.364
8410.8007	5.757	6.816	7.665	4.977	4.389
8468.6659				5.122	4.505
8469.6885				5.134	4.499
8674.0204	6.394	7.614	8.549	5.470	4.851
8682.9807	5.883	7.081		4.992	4.392
8723.8714	6.454	7.878	9.130	5.442	4.854
9037.9503	6.133	7.482	8.645	5.186	4.556
9041.9846	6.383	7.828	9.125	5.384	4.688
9042.9297	6.449	7.896	9.206	5.430	4.747
9045.8878	6.567	8.045	9.315	5.552	4.847
9067.0046	6.263	7.671	8.925	5.286	4.622
9151.6998	6.459	7.900	9.210	5.445	4.756
9154.6203	6.579	8.003		5.547	4.866
9159.6618	6.504	7.780	8.805	5.561	4.928
9173.7886	6.212	7.641	8.763	5.267	4.593
9207.6478	6.539	7.999	9.288	5.507	4.819
9391.9840	6.307	7.712	9.020	5.350	4.665
9392.9952	6.376	7.843	9.115	5.337	4.666
9470.9422	6.164	7.514			
		Y OPH			
8510.9334	6.401	7.873	9.110	5.116	4.151
8518.9611	5.962	7.264	8.263	4.796	3.892

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		Y OPH			
8522.9370	6.186	7.599	8.784	4.959	4.017
8526.9259	6.342	7.872	9.128	5.009	4.068
8528.9382	6.385	7.863	9.065	5.045	4.120
8658.6415	6.068	7.520		4.904	3.992
8674.5898	6.011	7.351		4.911	3.961
8676.6075	6.076	7.500		4.922	3.965
8680.5731	6.359	7.882		5.080	4.098
8937.7937	6.367	7.904	9.168	5.129	4.167
8938.7725	6.393	7.911	9.152	5.136	4.177
8939.7929	6.380	7.873	9.109	5.148	4.177
9014.6245	5.916	7.178			
9018.6211	6.128	7.532		4.947	3.998
9019.6119	6.138	7.598		4.968	4.015
9025.6028	6.348	7.841		5.127	4.144
9028.5984	6.106	7.465		4.984	4.063
9029.5990	6.009	7.309	8.319	4.845	3.961
9037.6136	6.221	7.693	8.892	4.988	4.056
9038.6203	6.296	7.777		5.041	4.095
9040.5873	6.342	7.846	9.125	5.114	4.167
9041.5864	6.321	7.799	9.053	5.105	4.124
9042.5909	6.343	7.810	9.036	5.112	4.144
9175.0232	6.308	7.824		5.007	4.056
9238.8901	6.082	7.414	8.398		
9246.9052	6.373	7.875	9.043	5.091	4.184
9280.8805	6.420	7.824	9.109	5.150	4.138
9281.8801	6.353	7.835	9.075	5.120	4.202
9377.6031	6.122	7.547		4.917	4.039

JD2430000+	V	B	U	R	I
		S SGE			
8567.9187	5.885	6.910		5.186	
8658.7133	5.691	6.591		4.992	4.533
8678.6477	5.932	6.880		5.217	4.735
9028.7082	5.854	6.849	7.647	5.138	4.627
9031.6912	5.589	6.362		4.986	4.567
9035.6917	5.635	6.501	7.132	4.982	4.471
9038.6778	6.013	7.006	7.774	5.272	4.756
9041.6475	5.372	6.045	6.528	4.820	4.417
9042.6546	5.363	6.055	6.554	4.779	4.362
9045.6440	5.868	6.857	7.655	5.146	4.641
9066.6160	5.350	6.003		4.795	4.416
9068.6019	5.422	6.184	6.745	4.800	4.361
9069.5869	5.653	6.640	7.245	5.017	4.532
9100.5617	5.423	6.156		4.835	4.417
9281.9236	6.008	6.940		5.263	4.801
9377.6723	5.421	6.158		4.849	4.462
		U SGR			
8224.7839	6.724	7.838	8.591	5.839	5.169
8510.9520	6.652	7.758	8.579	5.699	4.987
8522.9600	6.375	7.298	7.967	5.562	4.934
8526.9563	6.996	8.307	9.337	5.925	5.172
8527.9563	7.000	8.311	9.345	5.925	5.176
8528.9530	6.363	7.301	7.933		
8553.8769	7.048	8.342	9.368	6.013	5.247
8559.9323	6.929	8.199		5.948	5.170
8655.6464	7.020	8.270		6.015	5.208

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		U SGR			
8658.6479	6.551	7.626		5.675	4.980
8669.6075	6.975	8.205	9.088	5.980	5.238
8677.5895	6.374	7.300		5.580	4.941
8906.9058	6.323	7.266	7.870	5.553	4.911
8908.8810	6.627	7.745	8.566	5.705	5.004
8910.9126	6.975	8.272	9.281	5.979	5.216
8931.8025	7.067	8.401	9.413	6.033	5.302
9000.6893	6.745	7.799		6.077	5.314
8937.8286	6.982	8.404	9.573	5.927	5.114
8938.8073	7.088	8.383	9.388	6.043	5.296
8939.8034	6.732	7.849	8.567	5.842	5.148
8940.7938	6.345	7.283	7.895	5.561	4.940
9014.6370	6.458	7.374			
9018.6558	6.931	8.195		5.926	5.168
9025.6229	6.947	8.219		5.953	5.162
9246.9409	6.768	7.805	8.637	5.753	5.051
9250.9233	6.438	7.344	7.999	5.592	5.032
9264.9378	6.376	7.304	8.008	5.568	4.915
9280.8961	6.811	7.930	8.872	5.785	5.036
9377.6281	7.095	8.388		6.135	5.417
		W SGR			
8161.9372	5.008	5.989	6.723	4.173	3.674
8192.8496	5.070	6.035	6.714	4.390	3.866
8205.8050	4.761	5.648	6.229	4.063	3.595
8518.9701	5.084	6.035	6.757	4.303	3.806
8522.9499	4.505	5.191	5.657	3.885	3.495

JD2430000+	V	B	U	R	I
		W SGR			
8526.9405	5.055	6.013	6.720	4.260	3.788
8527.4583	5.135	6.156	6.990	4.328	3.838
8655.6306		5.831		4.300	3.770
8671.6038	4.996	5.905	6.558	4.331	3.843
8937.8053	4.904	5.764	6.314	4.268	3.809
8938.7835	4.386	4.974	5.331	3.891	3.531
9000.6709	4.677	5.238		3.979	3.542
9246.9245	4.798	5.770	6.305	4.086	3.659
9264.9196	4.660	5.336	5.781	4.041	3.671
9281.8668	4.451	5.049	5.570	3.946	3.491
		X SGR			
8186.8551	4.843	5.764	6.364	4.059	3.517
8225.7898	4.500	5.235	5.695	3.876	
8517.9541	4.356	4.987	5.401	3.785	3.341
8522.9254	4.827	5.707	6.310	4.067	3.541
8526.9174	4.394	5.089	5.564	3.674	3.214
8553.8437	4.247	4.832	5.216	3.684	3.239
8940.7794	4.418	5.152	5.589	3.772	3.312
9246.9145	4.567	5.317	5.724	3.867	3.423
9264.9076	4.610	5.418	6.078	3.901	3.398
9281.8550	4.700	5.375	5.881	3.960	3.495
9376.6049	4.436	5.229	6.108	4.059	3.622
		Y SGR			
8510.9430	5.403	6.086	6.582	4.787	4.340
8518.9893	5.859	6.816	7.514	5.031	4.495

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		Y SGR			
8526.9487	5.935	6.864	7.510	5.109	4.599
8528.9470	5.473	6.266	6.804	4.813	4.346
8553.8530	5.864	6.851	7.540	5.095	4.550
8655.6366	5.422	6.145		4.780	4.286
8682.5798	6.049	7.048		5.236	4.693
8937.8161	5.376	6.061	6.509	4.810	4.360
8938.7946	5.518	6.317	6.832	4.866	4.398
9018.6417	5.389	6.051		4.806	4.360
9025.6135	5.559	6.382		4.889	4.377
9246.9327	5.917	6.959		5.156	4.609
9264.9293	6.237	7.054	7.902	5.230	4.670
9280.8893	5.819	6.706		5.052	4.520
9281.8877	5.968	6.970	7.775	5.174	4.631
9376.6429	5.450	6.199		4.866	4.389
9377.6198	5.626	6.453		4.988	4.525
		SZ TAU			
7592.8938	6.654	7.607	8.218	5.801	5.222
7594.0033	6.505	7.365	7.899	5.719	5.169
7594.8342	6.384	7.187	7.725	5.744	5.195
7595.8181	6.622	7.543	8.145	5.946	5.329
7597.8041	6.364	7.132	7.672		
8367.6915	6.701	7.625	8.258	5.885	5.310
8367.8597	6.640	7.553	8.195	5.843	5.258
8368.6743	6.447	7.255	7.811	5.710	5.165
8369.7611	6.463	7.282	7.830	5.651	5.104
8370.7495	6.713	7.635	8.283		

JD2430000+	V	B	U	R	I
		SZ TAU			
8408.7139	6.635	7.556	8.164	5.862	5.264
8410.7450	6.383	7.211	7.755	5.719	5.145
8469.6007				5.666	
8680.9496	6.335	7.123		5.638	5.113
8681.8847	6.578	7.485		5.836	5.252
8720.7431	6.628	7.549	8.065	5.880	5.318
9004.9885	6.379	7.183		5.674	5.125
9029.0023	6.712	7.669		5.924	5.292
9037.9406	6.666	7.575	8.208	5.876	5.294
9038.8753	6.597	7.494	8.056	5.846	5.263
9041.8766	6.632	7.539	8.135	5.876	5.294
9042.8577	6.389	7.138	7.654	5.671	5.129
9045.8444	6.382	7.176	7.706	5.695	5.149
9068.9302	6.524	7.403	8.013	5.752	5.185
9098.7845	6.538	7.379	7.943	5.818	5.234
9099.7502	6.419	7.119	7.651	5.646	5.111
9100.7552	6.618	7.555	8.187	5.824	5.244
9148.5950	6.676	7.610		5.867	5.285
9148.7443	6.647	7.575		5.863	5.287
9151.5963	6.686	7.620		5.896	5.295
9154.5906	6.685	7.600		5.877	5.269
9154.7730	6.677	7.610	8.240	5.899	5.297
9159.6218	6.374	7.137		5.657	5.136
9173.6508	6.751	7.649		5.884	5.299
9174.5797	6.487	7.293		5.737	5.207
9174.7538	6.457	7.251		5.722	5.189
9175.6699	6.425	7.256		5.687	5.137

TABLE 1A UBVRI CEPHEID MAGNITUDES

JD2430000+	V	B	U	R	I
		SZ TAU			
9175.7457	6.381	7.215		5.662	5.115
9177.6701	6.478	7.289		5.694	5.156
9392.9839	6.449	7.326		5.704	5.153
9468.8229	6.505	7.376	7.948	5.776	5.200
		T VUL			
8367.5777	5.985	6.741	7.268	5.386	4.986
8368.5712	6.072	6.818	7.338	5.448	5.056
8370.6005	5.688	6.282	6.691	5.155	4.805
8371.5549	5.871	6.647	7.051	5.315	4.913
8658.7462	5.595	6.188		5.087	4.751
8671.6882	5.475			4.995	4.669
8678.6597	6.023	6.812		5.397	4.998
8681.6380	5.778	6.483		5.202	4.831

JD2430000+	V	B	U	R	I
		T VUL			
8711.5966	5.493	5.993	6.345	5.022	4.715
8720.6446	5.514	6.053	6.323	5.063	4.730
8930.9437	5.955	6.763	7.261	5.337	4.931
8931.9028	6.050	6.845	7.332	5.437	5.040
9028.7321	5.989	6.771	7.295	5.396	4.984
9031.7102	5.683	6.352	6.769	5.158	4.800
9035.7276	5.555	6.117	6.509	5.089	4.715
9038.7088	5.904	6.581	6.994	5.346	4.964
9041.6797	5.914	6.681	7.191	5.338	4.924
9042.7037	6.035	6.768	7.266	5.434	5.023
9066.6429	5.537	6.097	6.450	5.068	4.732
9068.6182	5.976	6.736	7.290	5.329	4.921
9069.6037	5.962	6.697	7.144	5.396	4.952
9099.5728	5.957	6.728	7.250	5.345	4.926
9100.5705	6.020	6.745		5.412	5.003

TABLE 1B →
(I)JKL CEPHEID MAGNITUDES

U AQL

JD2430000+	I	J	K	L
8558.9134			4.060	
8640.7446		4.425	3.785	
8674.6673		4.405	3.758	3.592
8675.6679		4.439	3.783	3.726
8694.5708		4.308	3.826	3.774
9041.6612		4.523	3.886	3.833
9061.5864		4.338	3.784	3.694
9062.5744		4.444	3.771	3.638
9063.5659		4.553	3.891	3.718
9064.5849		4.625	3.921	3.747
9072.5876		4.507	3.940	3.744
9273.8910		4.531	3.875	3.777
9274.8930		4.669	3.998	3.803
9391.6343		4.281	3.733	3.777
9392.6317		4.458	3.925	3.804
9393.6438		4.536	3.893	3.767
9425.6213	4.751	4.397	3.863	3.808

FF AQL

JD2430000+	I	J	K	L
8320.6069	4.365	3.993	3.575	
8339.5961	4.132	3.874	3.492	
8558.9086		3.959	3.490	
8669.7056		3.979	3.543	3.443
8674.6570		3.906	3.506	3.216
8676.6587		3.949	3.480	3.403
8693.6376		3.931	3.440	3.331
9061.5744		3.945	3.430	3.359
9062.5649		3.970	3.449	3.371
9063.5535		3.768	3.363	3.249
9072.5727		3.817	3.388	3.275
9273.8856		3.900	3.482	3.364
9386.6196		3.795	3.355	3.168
9393.6363		3.880	3.522	3.460

ETA AQL

JD2430000+	I	J	K	L
8301.6618	2.655	2.411	1.969	
8494.9656	2.803	2.448	2.022	
8497.0069		2.299	1.874	
8521.9722	2.951	2.568	1.999	
8523.9773	2.735	2.422	1.943	
8558.9339		2.707	2.143	1.954
8564.8931		2.473	1.921	1.822
8669.6788		2.420	1.981	1.935
8669.7280		2.447	1.942	2.005
8670.6390		2.310	1.831	1.734
8671.7247		2.523	2.022	1.934
8675.6995		2.457	2.013	2.002
8694.5840		2.648	2.201	2.065
9035.6343		2.423	1.915	1.958
9036.5885		2.367	1.932	1.768
9038.6010		2.569	2.008	1.916
9061.6463		2.620	2.141	2.071
9062.6081		2.320	1.915	1.818
9063.5981		2.298	1.908	1.768
9064.6084		2.358	1.896	1.730
9072.6070		2.446	1.835	1.780
9273.9115		2.340	1.927	1.848

ETA AQL

JD2430000+	I	J	K	L
9274.9144		2.467	2.009	1.829
9391.6713		2.527	2.128	2.040
9393.6762		2.367	1.945	1.838
9425.6410	2.836	2.526	1.987	1.893

RT AUR

JD2430000+	I	J	K	L
8339.9878	4.679	4.398	3.909	
8368.9258	4.392	4.229	3.882	
8370.9382	4.765	4.470	4.047	
8378.8221	4.699	4.450	4.130	
8379.8659	4.417	4.299	3.942	
8392.8312	4.818	4.481	4.081	
8396.7753		4.522	4.093	
8397.7844	4.569	4.380	3.997	
8398.7735	4.531	4.308	3.959	
8400.7883	4.690	4.458	4.025	
8431.7587	4.297	4.191	3.885	
8482.6141	4.735	4.525	4.035	
8739.9766		4.481	4.014	3.835
8740.9866		4.192	3.909	
8771.7779		4.178	3.802	3.890
9060.9738		4.479	4.004	3.905
9061.9030		4.205	3.862	3.787
9062.9350		4.405	3.909	3.865
9063.9466		4.454	3.931	3.910
9140.8533		4.233	4.039	3.817
9184.6745		4.640	4.103	4.040
9185.6337		4.175	3.831	3.719
9185.7326		4.364	3.863	3.761
9227.6561		4.396	3.995	3.886
9424.9489	4.700	4.350	3.905	3.731
9425.9892	4.728	4.518	3.990	3.850
9448.9695		4.426	4.009	3.977
9461.8835		4.458	3.840	3.770

SU CAS

JD2430000+	I	J	K	L
8323.7783	4.897	4.594	4.198	
8323.8424	4.881	4.576	4.143	
8339.8759	4.808	4.406	4.203	
8343.8297	4.754	4.474	4.084	
8377.6057	4.867	4.610	4.251	
8378.6612	4.839	4.478	4.158	
8379.6509	4.822	4.630	4.093	
8395.5822	4.933	4.665	4.155	
8396.6114	4.732	4.527	4.145	
8397.5879	4.848	4.538	4.140	
8398.6431	4.797	4.421	4.017	
8400.5911	4.811	4.499	4.152	
8430.5729	4.941	4.555	4.167	
8431.5795	4.767	4.468	4.123	
8669.8854		4.590	4.167	3.983
8693.6708		4.622	4.163	4.049
8771.6360		4.615	4.066	3.935

DEL CEP

JD2430000+	I	J	K	L
8298.7316	2.823	2.643	2.187	
8315.7095	2.963	2.737	2.316	

DEL CEP

JD2430000+	I	J	K	L
8315.7769	2.990	2.734	2.283	
8316.6708	3.155	2.838	2.362	
8316.7385	3.192	2.857	2.375	
8317.6758	3.201	2.919	2.523	
8317.7359	3.141	2.922	2.481	
8320.6477		2.732	2.277	
8323.6380	2.849	2.702	2.375	
8323.6879	2.856	2.717	2.466	
8339.6656	2.947	2.718	2.393	
8377.5957	2.765	2.620	2.398	
8378.5924	2.853	2.583	2.237	
8379.5877	2.902	2.639	2.236	
8395.5718	2.964	2.770	2.209	
8396.6036	3.053	2.793	2.317	
8397.5809	3.123	2.868	2.401	
8398.5921	2.899	2.719	2.351	
8400.5734	2.866	2.631	2.214	
8638.8298		2.928	2.411	2.312
8669.6715		2.756	2.282	2.169
8741.6434		2.899	2.469	2.460
8747.6220		2.694	2.409	2.360
9061.7424		2.749	2.240	2.230
9062.6637		2.898	2.382	2.410
9063.6800		3.023	2.376	2.307
9064.6563		2.630	2.343	2.239
9072.6734		2.846	2.366	2.373
9385.7720		2.813	2.328	2.204
9390.7904		3.000	2.441	2.366
9424.6858	2.927	2.668	2.338	2.267

X CYG

JD2430000+	I	J	K	L
8558.9398		4.456	3.697	
8646.8088		4.596	3.919	
8671.7390		4.352	3.753	3.659
8676.6914		4.588	3.686	3.633
8694.5938		4.575	3.913	3.626
9038.7372		4.597	3.864	3.731
9040.7021		4.694	3.953	3.822
9061.6680		4.421	3.883	3.809
9062.6298		4.181	3.723	3.690
9063.6429		4.303	3.741	3.670
9064.6260		4.301	3.691	3.537
9072.6458		4.656	3.902	3.758
9385.7140		4.729	3.962	3.955
9391.6990		4.340	3.739	3.726
9393.6944		4.383	3.726	3.573
9424.6542		4.272	3.730	3.627
9425.6566	4.706	4.324	3.727	3.664

SU CYG

JD2430000+	I	J	K	L
8320.6186	6.172	5.848	5.440	
8558.9286			5.346	
8671.7152		5.698	5.340	5.322
8674.7046		5.850	5.367	5.111
8675.6891		5.672	5.368	
9035.6009		5.833	5.371	5.334
9040.6874		5.717	5.407	5.353
9061.6266		5.735	5.246	5.292
9062.5843		5.862	5.327	
9063.5785		5.848	5.546	
9064.5969		5.570	5.361	
9072.5955		5.645	5.196	
9273.9033		5.837	5.359	5.131
9391.6540		5.610	5.281	5.239
9393.6600		5.885	5.473	5.452
9425.6314	5.785	5.620	5.359	5.320

DT CYG

JD2430000+	I	J	K	L
8340.6457	5.023	4.825	4.393	
8343.6182	4.950	4.707	4.447	
8377.5883	5.089	4.876	4.458	
8378.5852	4.878	4.683	4.317	
8556.8773		4.752	4.372	
8556.9648		4.729	4.315	
8557.9150		4.807	4.422	4.119
8564.8453		4.769	4.319	
8638.8156		4.757	4.357	
8640.8280		4.788	4.405	
8669.7465		4.894	4.457	
8674.7455		4.782	4.443	4.417
8676.7918		4.856	4.500	4.347
8725.6079		4.789	4.425	4.440
8738.6087		4.700	4.411	4.194
8741.5648		4.803	4.501	
9061.6947		4.780	4.396	4.351
9062.6561		4.842	4.391	
9063.6691		4.755	4.388	4.235
9064.6469		4.749	4.397	4.255
9072.6617		4.856	4.445	4.445
9385.7356		4.703	4.272	4.219
9391.7315		4.784	4.496	4.485
9393.7166		4.748	4.417	4.382
9425.6838	4.987	4.802	4.481	4.419

W GEM

JD2430000+	I	J	K	L
8368.9403	5.798	5.322	4.860	
8370.9534	5.404	5.103	4.606	
8377.8760	5.784	5.403	4.781	
8378.8291	5.347	5.104	4.536	
8379.8743	5.459	5.279	4.776	
8392.8439	5.863	5.359	4.808	
8396.7818	5.519		4.600	
8397.8005	5.563	5.189	4.657	
8398.7797	5.894	5.236	4.653	
8400.7952	5.858	5.347	4.925	
8482.6536	5.569	5.212	4.698	
8483.6691	5.489	5.037	4.645	
8692.9448		5.360	4.782	5.957
8771.7905		5.298	4.637	4.400
9060.9841		5.126	4.665	4.479
9061.9282		5.102	4.582	4.522
9062.9452		5.282	4.587	4.552
9063.9558		5.292	4.680	
9140.8635		5.146	4.736	4.440
9185.6431		5.209	4.942	

W GEM

JD2430000+	I	J	K	L
9227.6650		5.151	4.594	4.536
9391.9673		5.079	4.726	
9392.9622		5.170	4.642	
9424.9392	5.498	5.085	4.568	4.476
9425.9980	5.491		4.547	4.461

ZET GEM

JD2430000+	I	J	K	L
8315.9850	2.744	2.427	2.007	
8316.0243	2.742	2.451	2.023	
8316.9714	2.835	2.516	2.038	
8317.0089	2.817	2.576	1.991	
8317.9688	2.935	2.637	2.104	
8318.0047	2.925	2.645	2.092	
8323.9943	2.775	2.550	2.149	
8324.0213	2.796	2.518	2.150	
8339.9957	2.995	2.693	2.181	
8369.9408	2.903	2.628	2.090	
8370.9809	2.982	2.701	2.206	
8427.7765	2.755	2.482	2.017	
8431.7674	2.980	2.683	2.192	
8476.7744	2.686	2.480	2.097	
8480.6207	2.888	2.587	2.090	
8481.6629	2.941	2.624	2.115	
8482.6369	2.981	2.745	2.221	
8483.6173	2.891	2.633	2.183	
8493.6179	2.948	2.592	2.141	
8494.6303	2.836	2.545	2.150	
8496.6733	2.718	2.503	2.080	
8499.6014		2.526	2.103	
8502.6192	3.040	2.716	2.193	
8505.6383	2.865	2.616	2.189	
8669.9720		2.575	2.128	2.086
8670.9810		2.560	2.086	2.040
8739.9608		2.539	2.028	2.089
8740.9992		2.510	2.108	2.009
8771.7990		2.465	2.042	2.028
8773.8767		2.570	2.085	1.921
9036.0168		2.443	2.030	1.971
9060.9943		2.694	2.186	2.062
9061.9477		2.687	2.138	2.097
9062.9533		2.702	2.241	2.237
9063.9623		2.642	2.149	2.076
9140.8735		2.662		1.998
9185.6523		2.567	2.164	2.018
9197.7443		2.477	2.056	2.107
9227.6715		2.502	2.160	2.049
9424.9578	2.872	2.550	2.068	1.964
9426.0066	2.930	2.642	2.058	2.031
9448.9877		2.688	2.171	2.044
9461.8899		2.573	2.199	2.052

T MON

JD2430000+	I	J	K	L
8323.9793	4.676	4.294	3.762	
8324.0146	4.650	4.181	3.700	
8368.9097	4.761	4.263	3.492	
8369.9562	4.704	4.222	3.469	
8370.9112	4.811	4.347	3.597	

T MON

JD2430000+	I	J	K	L
8377.8585	4.641	4.263	3.695	
8378.8146	4.437	4.058	3.588	
8379.8573	4.371	4.100	3.621	
8392.8184	4.662	4.168	3.423	
8396.7695	4.853	4.360	3.580	
8397.7733	4.857	4.315	3.587	
8398.7681	4.892	4.398	3.680	
8400.7809	4.844	4.387	3.668	
8431.7503	4.638	4.293	3.794	
8482.6236	4.852	4.457	3.735	
8483.6451	4.964	4.443	3.769	
8727.7924		4.480	3.914	3.851
8771.7690		4.136	3.362	3.184
9060.9626		4.030	3.417	3.364
9061.8903		3.995	3.443	3.324
9062.9266		4.109	3.361	3.230
9063.9380		4.040	3.371	3.318
9140.8397		4.204	3.633	3.458
9185.6210		4.478	3.702	3.718
9227.6445		4.193	3.449	3.306
9392.9523		4.107	3.458	3.327
9394.9570		4.258	3.473	3.356
9425.9784	4.839		3.634	3.439
9461.8766		4.103	3.518	3.440

Y OPH

JD2430000+	I	J	K	L
8320.5834	4.203	3.557	2.685	
8565.8297		3.582	2.821	2.583
8670.5926		3.439	2.679	2.469
8674.5856		3.422	2.698	2.477
8675.5930		3.422	2.663	2.424
8676.6106		3.430	2.634	2.395
9041.5812		3.556	2.729	2.623
9270.8512		3.282	2.651	
9272.8018		3.261	2.617	2.510
9273.8544		3.330	2.646	2.483
9274.8279		3.329	2.655	2.654
9385.5681		3.419	2.697	2.597
9391.5858		3.263	2.612	2.488
9392.5850		3.376	2.663	2.525

S SGE

JD2430000+	I	J	K	L
8317.6449	4.753	4.419	3.733	
8320.6296	4.542	4.211	3.719	
8670.6514		4.358	3.863	3.836
8674.7281		4.144	3.675	3.607
8693.6287		4.262	3.653	3.498
9061.6556		4.272	3.756	3.658
9062.6200		4.223	3.676	3.560
9063.6070		4.387	3.853	3.640
9064.6139		4.405	3.854	3.709
9072.6198		4.386	3.819	3.732
9273.9241		4.373	3.893	3.829
9391.6795		4.365	3.903	3.863
9393.6842		4.133	3.691	3.699
9425.6477	4.572	4.320	3.897	3.787

U SGR

JD2430000+	I	J	K	L
8317.6193	5.232	4.667	3.998	
8320.5954	4.920	4.544	3.981	
8557.8656		4.575	3.991	
8558.8727		4.650	3.939	3.390
8640.7060		4.706	3.999	
8667.5952		4.671	3.929	3.895
8670.6240		4.543		
8674.5956		4.657	3.935	3.936
8676.6231		4.754	4.160	
9256.8799		4.642	3.998	4.112
9258.9403		4.597	3.965	3.917
9272.8349		4.428	3.855	3.828
9273.8656		4.491	3.901	3.851
9274.8590		4.568	3.947	3.882
9298.8741		4.519	4.056	4.017
9385.6065		4.519	4.083	4.091
9391.6044		4.667	4.069	3.921
9392.6029		4.468	4.004	3.871
9393.6028		4.450	3.896	3.763

W SGR

JD2430000+	I	J	K	L
8670.6038		3.515	2.844	2.805
9270.8629		3.505	2.984	2.881
9272.8198		3.343	3.001	2.966
9273.8493		3.130	2.835	2.699
9274.8411		3.157	2.609	2.604
9274.8469		3.139	2.759	2.719
9391.5783		3.187	2.700	2.590
9393.5862		3.497	3.098	3.053

X SGR

JD2430000+	I	J	K	L
9270.8576		2.978	2.528	2.418
9272.8112		3.159	2.665	2.630
9273.8441		3.147	2.634	2.566
9386.5563		3.123	2.651	2.727
9391.5707		2.903	2.424	2.355
9392.5716		3.154	2.616	2.547
9393.5799		3.363	2.765	2.825

Y SGR

JD2430000+	I	J	K	L
8339.5872	4.387			
8557.8550		4.123	3.602	3.682
8564.8333		4.049	3.491	
8694.6081		4.228		
9270.8690		4.200	3.644	3.507
9272.8280		4.206	3.694	3.617
9273.8602		3.969	3.531	3.584
9274.8522		4.006	3.528	
9385.5953		4.287	3.696	3.702
9386.5994		4.270	3.723	3.591
9391.5943		4.113	3.566	3.529
9392.5937		4.324	3.813	3.610
9393.5949		4.084	3.666	3.601
9425.5802	4.529	4.179	3.641	3.555

SZ TAU

JD2430000+	I	J	K	L
8323.8918	5.211	4.930	4.265	
8343.8809	5.134	4.770	4.312	
8377.7290	5.257	4.826	4.216	
8378.7552	5.186	4.763	4.244	
8379.7380	5.205	4.825	4.303	
8396.6967	5.270	4.876	4.352	
8397.7430	5.205	4.939	4.343	
8398.6602	5.218	4.796	4.418	
8400.6519	5.149	4.809	4.368	
8430.6737	5.247	4.960	4.297	
8431.5977	5.134	4.796	4.354	
8480.6035	5.154	4.873	4.239	
8482.6039	5.172	4.821	4.310	
8674.9419		4.811		3.991
8727.7808		4.773	4.309	4.106
8769.7089		4.905	4.300	
8771.6463		4.837	4.207	4.092
9041.8690		4.901	4.338	4.252
9045.8543		4.824	4.352	4.192
9060.9197		4.929	4.373	4.209
9061.8476		4.807	4.298	4.239
9062.9185		4.887	4.324	4.213
9063.8461		4.938	4.374	4.395
9140.6975		4.887		4.272
9185.5979		4.760	4.229	4.122
9185.6595		4.832	4.317	4.167
9391.9300		4.822	4.365	4.294
9392.9290		4.840	4.316	4.253
9424.9229	5.081	4.856	4.235	4.078
9425.9343	5.300	4.926	4.338	4.285
9461.8664		4.848	4.335	4.223

T VUL

JD2430000+	I	J	K	L
8320.6402	4.882	4.542	4.195	
8340.6327	4.954	4.568	4.176	
8377.5734	4.960	4.745	4.242	
8378.5764	4.622	4.471	4.138	
8379.5718		4.505	3.978	
8395.5550	5.013	4.878	4.307	
8671.7583		4.538	4.216	4.086
8673.7882		4.726	4.230	4.324
8694.6251		4.472	4.082	4.081
9040.6751		4.545	4.142	4.068
9061.6798		4.513	4.176	4.170
9062.6483		4.520	4.079	4.022
9063.6590		4.649	4.128	3.912
9064.6379		4.733	4.254	4.139
9072.6539		4.624	4.162	4.092
9385.7252			4.165	4.002
9391.7216		4.695	4.142	4.216
9393.7082		4.678	4.281	4.277
9424.6641		4.733	4.357	4.268
9425.6738	4.707	4.574	4.190	4.150

No. 113 STELLAR SPECTROSCOPY, 1.2μ TO 2.6μ

by H. L. JOHNSON, I. COLEMAN, R. I. MITCHELL
AND D. L. STEINMETZ

Aug. 8, 1968

ABSTRACT

We have made infrared spectroscopic observations of 21 stars, using a rapid-scanning Michelson interferometer. The range of wavelength is from 1.2 μ (8200 cm^{-1}) to 2.6 μ (3900 cm^{-1}), and the resolution is 8 cm^{-1}. All spectra have been corrected for atmospheric extinction, mostly by the method of equal-altitude photometric transfers from standard objects. The atmospheric transmission corrections are based upon a Lunar spectrum obtained from the NASA Convair 990 Jet Aircraft, at an altitude of 41,500 feet. The corrected ground-obtained spectrum of α Ori was checked by an aircraft spectrum of the same star, showing that the extinction corrections are valid.

Only four stars, all Mira variable stars, showed significant amounts of steam absorption in their spectra. There exists a correlation of this absorption with long-wavelength (9–14 μ) infrared excess for giant stars, but not for supergiants.

1. Introduction

Observation of infrared stellar and planetary spectra has been one of the major programs at the Lunar and Planetary Laboratory. Up to this time, most of these spectroscopic observations were made by Kuiper (1962a, 1962b, 1963, 1964), who used a single channel spectrometer.

It is possible, however, to make the observational procedure much more efficient by observing all of the spectral elements simultaneously, as is done in the visual spectral region where photographic plates record an entire spectrum. A similar procedure could, perhaps, be used in the infrared spectral region but it would require several hundred, or a thousand, separate detectors to be placed in the focal plane of a spectrograph. A different method was suggested by Felgett (1951), who showed that, under the special condition that the detector noise output is not signal-dependent, a Michelson interferometer has the ability to make very efficient simultaneous observations of all the individual spectral elements. The special condition, above, is met in the infrared spectral region.

2. The Instrumentation

All of the spectra that are discussed and presented in this article were made using a Michelson interferometer constructed for us by Block Associates of Cambridge, Massachusetts. This interferometer is similar to the one described by Mertz (1965a); it differs in that it contains two interferometer "cubes" whose moving mirrors are coupled mechanically. The "signal cube" is used for the stellar spectra and has two unrefrigerated PbS detectors arranged as described by Mertz. The "reference cube" has two optical inputs: one, a broad-band white light whose interferogram is used to establish the zero-point of the signal interferogram from the other cube; the other, a nearly monochromatic helium line at 1.0833 μ. The monochromatic line produces a sine-wave interferogram whose amplitude is nearly independent of the positions of the moving mirrors, but whose "zero-crossings" are used to determine the scale of the signal interferogram. Thus, in this interferometer design, the mirror motion need not be exactly uniform or linear, since the mirror position is at all times known from the helium reference line. Furthermore, all frequencies (or wavelengths) in the final spectrum are directly related to that of the helium line.

The interferometer uses the rapid scan technique of Mertz; the scan time is 2 seconds, so that all electrical signal frequencies are between 200 and 500 Hz. It is, of course, necessary to add together many scans (interferograms) of the fainter objects in order to obtain spectra with a satisfactory signal-to-noise ratio. This summation is performed by a "co-adder," also supplied by Block Associates.

The interferometer mirrors move a distance of approximately 0.6 mm, thus causing a change in path length of about 1.2 mm. The final spectra have a resolution of approximately 8 cm^{-1}.

Unfortunately, the reference cube drifts slightly with respect to the signal cube, making it impossible to "co-add" interferograms for more than 10 or 15 minutes. We overcame this problem by sending a relatively broad-band "green light" (at about 0.55 μ) through the signal cube; comparison of the resulting interferogram with those from the reference cube allows us to compensate for the drift. Thus, the interferometer has four outputs: The stellar signal interferogram, the "green light" fringe, the "white light" fringe from the reference cube, and the monochromatic signal from the 1.0833 μ helium reference line. These four outputs must be combined to produce the corrected signal interferogram, with known zero-point and scale.

At the telescope, the data consisting of the four outputs of the interferometer are recorded on a Consolidated Electrodynamics Model 5-752-7 seven-track tape recorder. In order to increase the signal-to-noise ratio of the tape recorder, the signal interferogram is recorded on three tracks, connected in parallel. These recordings are subsequently played back by a similar machine in the laboratory, and co-added. The tapes are played back at eight times the recording speed, so as to reduce the time spent co-adding.

3. *Data Reduction*

The Fourier transformation of the co-added interferograms, and the subsequent phase correction, follow the procedures outlined by Mertz (1965b, 1967), with minor modifications. Since the sample points are controlled by the zero-crossings of the interferogram of the helium reference line, no corrections for non-uniform sampling are needed. We found it necessary to correct the interferograms for non-linearity of the electronics (actually, the non-linearity of the magnetic tape) before the computation of the spectra. All computations were made by an IBM 1130 computer system; this machine includes a plotter which drew the spectra we publish here.

The fact that the sample points are controlled by the zeroes of the helium reference line's interferogram means that we know the wavelength (or frequency) of each point in the computed spectrum. It is, therefore, quite convenient to combine spectra or to take the ratio of one spectrum (point by point) to another. We can, therefore, treat our data as multicolor photometry (2000-filter photometry!) and make corrections for atmospheric extinction and reductions to a standard system by the usual photometric procedures. We have not yet established a standard photometric system based upon the interferometer data (although we do plan to do so), but all of the spectra we publish here have been corrected for atmospheric extinction.

Our correction of the computed spectra for atmospheric extinction was made possible by lunar observations that were made from an altitude of 41,500 feet. These observations were made with a 12-inch telescope in the NASA Convair 990 Flying Observatory. The same interferometer was used, so that the airplane data are strictly comparable with the data obtained from the ground. The airplane setup and procedures have been described by Kuiper and Forbes (1968) and Kuiper, Forbes and Mitchell (1968). Since our atmospheric extinction corrections are based upon a lunar spectrum obtained at an altitude of 41,500 feet, our corrected spectra still contain the atmospheric absorption features due to the atmosphere above this altitude. We have not yet worked out the corrections from the airplane altitude to outside the atmosphere; all of the corrected spectra published herein are, therefore, corrected to 41,500 feet. As will be seen, this incomplete correction removes most of the atmospheric absorptions; it even makes possible significant observations through the water vapor absorption bands near 1.4 μ and 1.8 μ.

4. *Atmospheric Extinction*

The first spectrum we exhibit is that of the Moon from 41,500 feet; this spectrum is shown in Figure

1. Figures 2 and 3 show ground-based lunar spectra on a relatively dry night at the Catalina Observatory; the air-masses are 1.2 and 1.9, respectively. Division of the spectra of Figures 2 and 3 by that of Figure 1 yielded the atmospheric-transmission spectra shown in Figures 4 and 5. A stellar observation taken at the same air mass as the ground-based lunar observations may be corrected for atmospheric extinction by dividing the stellar spectrum by the atmospheric-transmission spectrum. Alternatively, standard photometric procedure, which involves the computation of an extinction coefficient at each wavelength, can be used to correct stellar data that have no equal-altitude lunar comparison.

It is our plan to set up on a satisfactory basis the photometric correction of our spectra. This must involve, of course, the taking of observations by standard photometric procedures, so that the data needed for the corrections are available. On only one of the nights (March 14, 1968) upon which our present data were taken were good photometric procedures of observation used. The corrected spectra from this night show what the technique is capable of doing; the data from other nights have been corrected as well as possible, using equal-altitude transfers from either the Moon, or stars calibrated from data taken on the good photometric night.

The quality of our correction for atmospheric extinction may be assessed by comparison of Figures 6, 7 and 8. Figure 6 shows the spectrum of α Ori, as observed from the ground on the night (March 14) on which satisfactory photometric data were obtained; Figure 7 shows the spectrum of α Ori, corrected for atmospheric extinction, (the computer program lifts the pen when the atmospheric transmission is less than 20%; this explains the discontinuous line in Figure 7). Figure 8 shows the spectrum of α Ori as actually observed from the airplane by Kuiper, Forbes, and Mitchell.

Since the aircraft observatory has only a 12-inch telescope (compared to a 60-inch on the ground), the signal-to-noise ratio of the high-altitude α Ori spectrum is comparatively poor. Nevertheless, it serves to confirm our correction of the ground-obtained spectrum; compare the spectra of Figures 7 and 8.

5. *The Stellar Spectra*

The spectra of Figures 7 and 8 indicate that the amount of water-vapor absorption in the α Ori spectrum is very small. Note, especially, that the aircraft spectrum (Figure 8) shows no lines stronger than

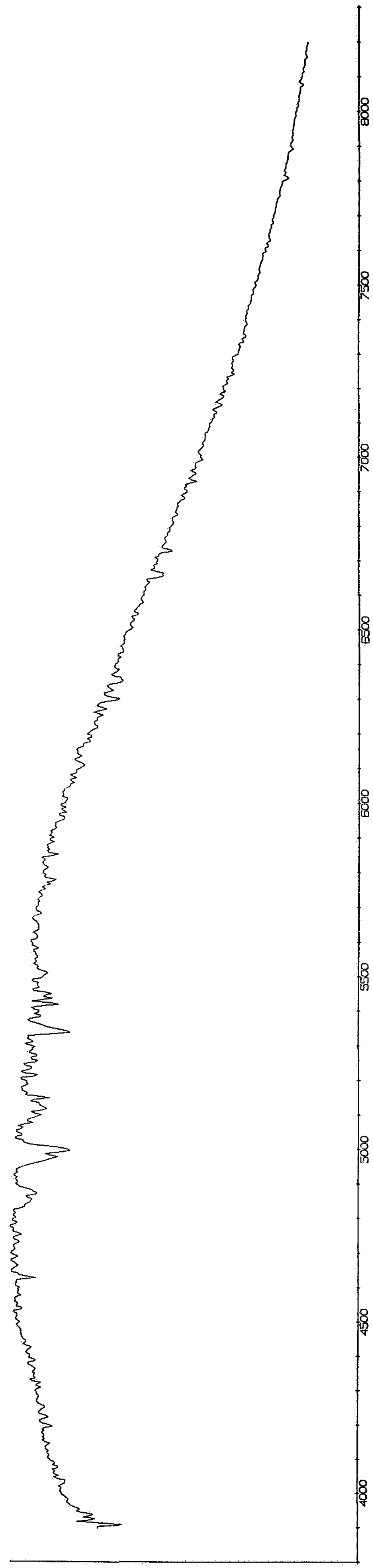

Fig. 1 The spectrum of the Moon from the NASA Convair 990 Jet Aircraft, at 41,500 feet.

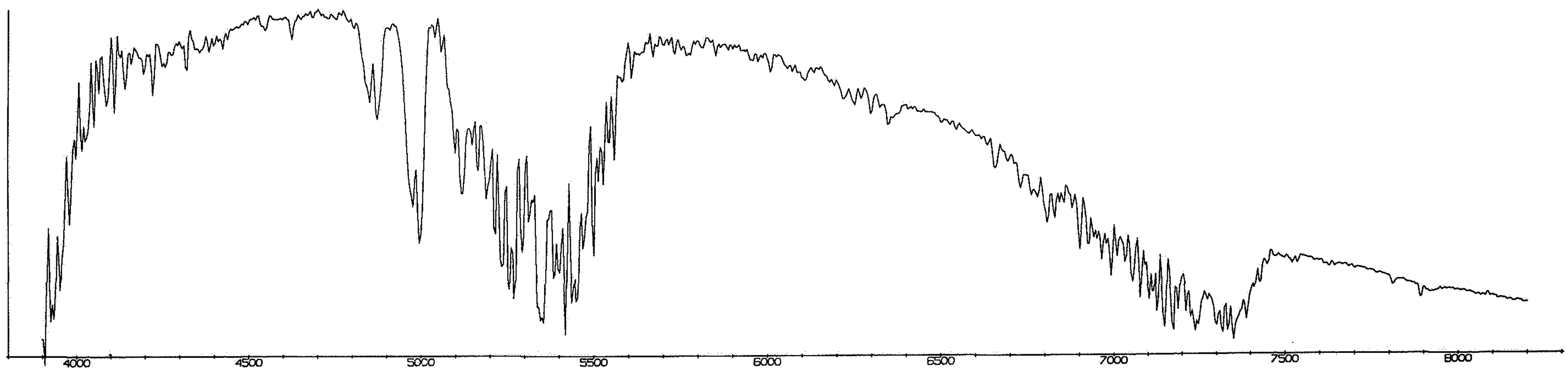

Fig. 2 The spectrum of the Moon from the Catalina Observatory. The air mass is 1. 2.

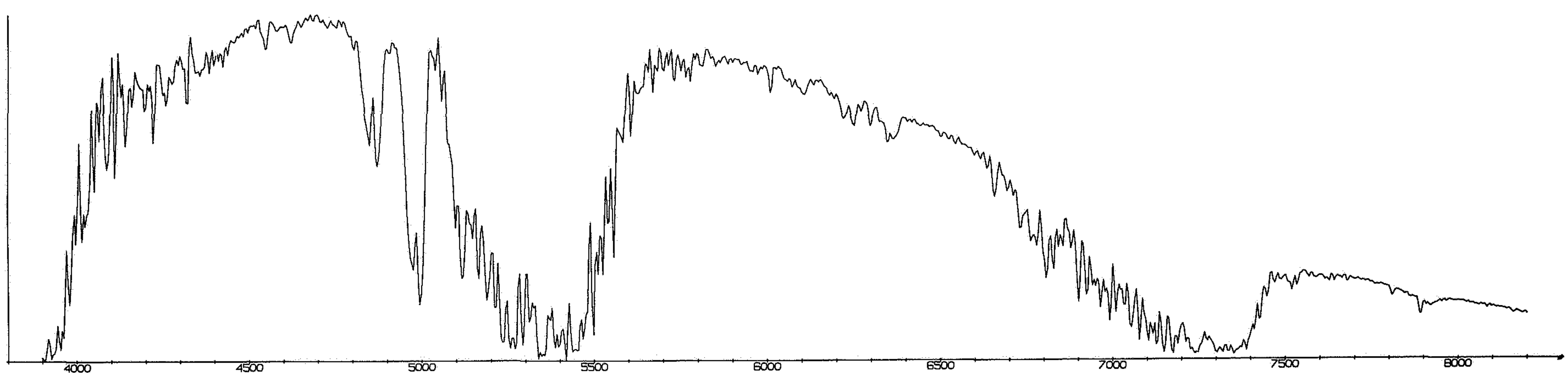

Fig. 3 The spectrum of the Moon from the Catalina Observatory. The air mass is 1.9.

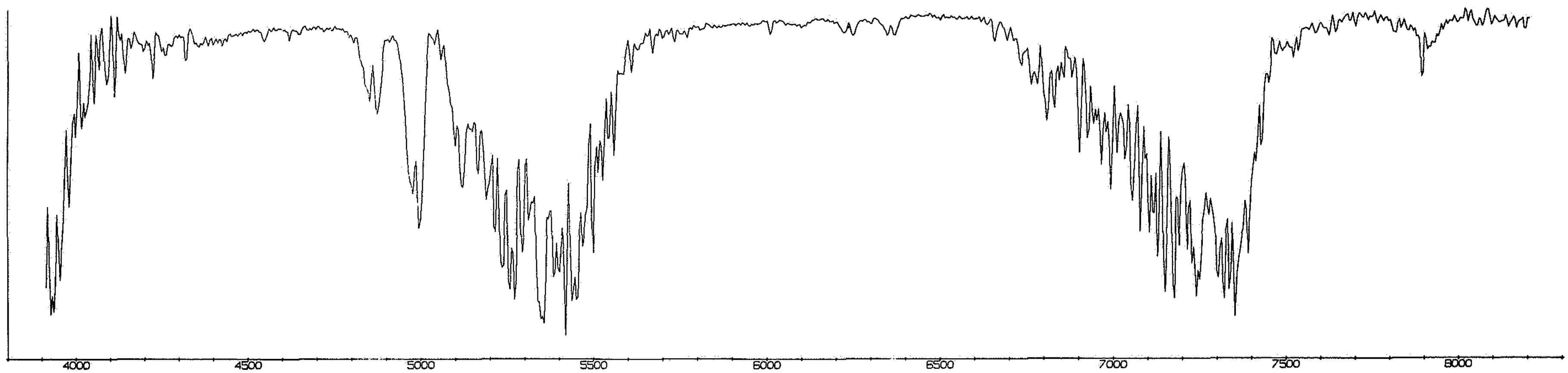

Fig. 4 The atmospheric transmission from the spectra of Figures 1 and 2.

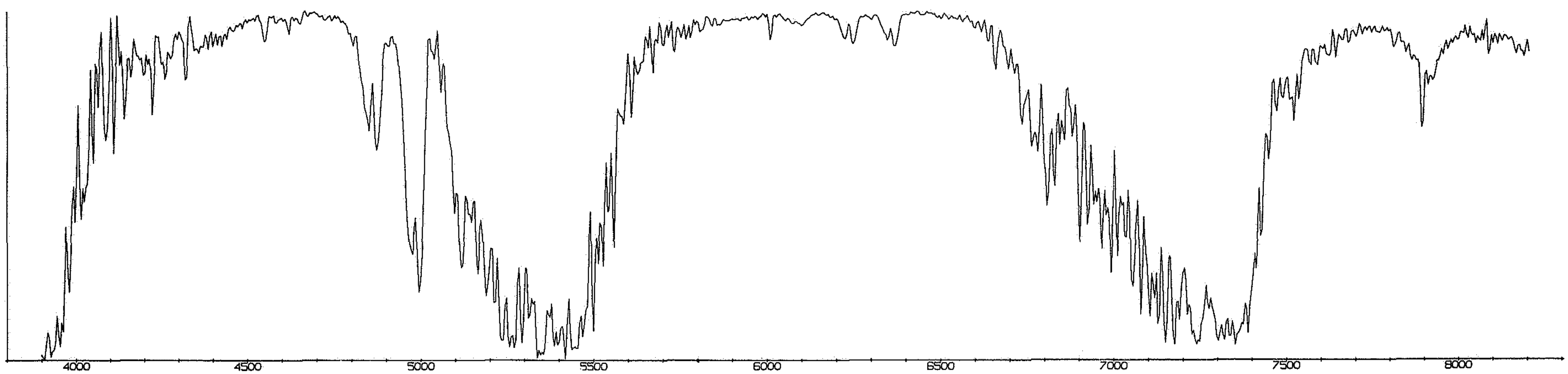

Fig. 5 The atmospheric transmission from the spectra of Figures 1 and 3.

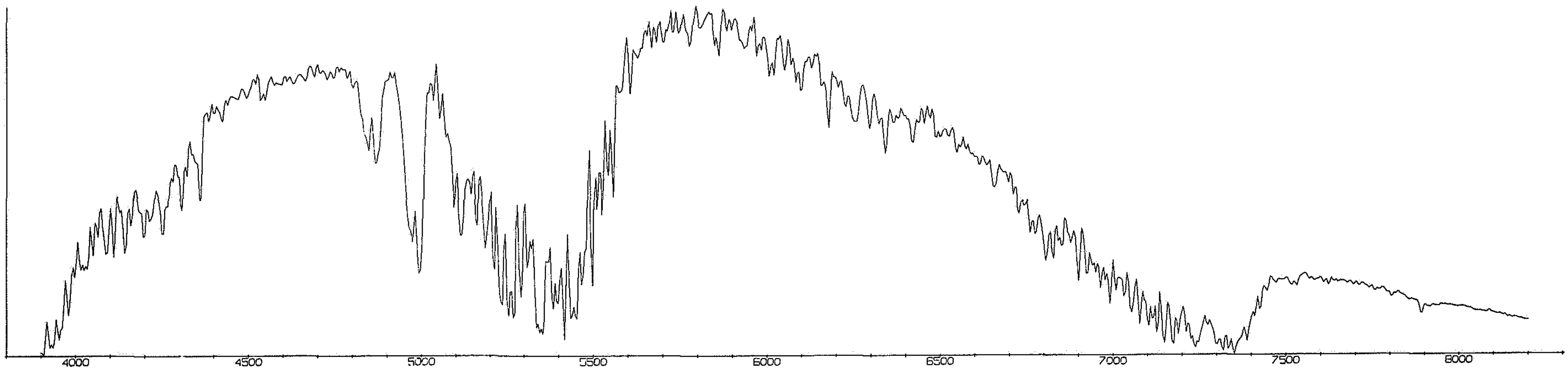

Fig. 6 The spectrum of α Ori from the Catalina Observatory, without correction for atmospheric extinction

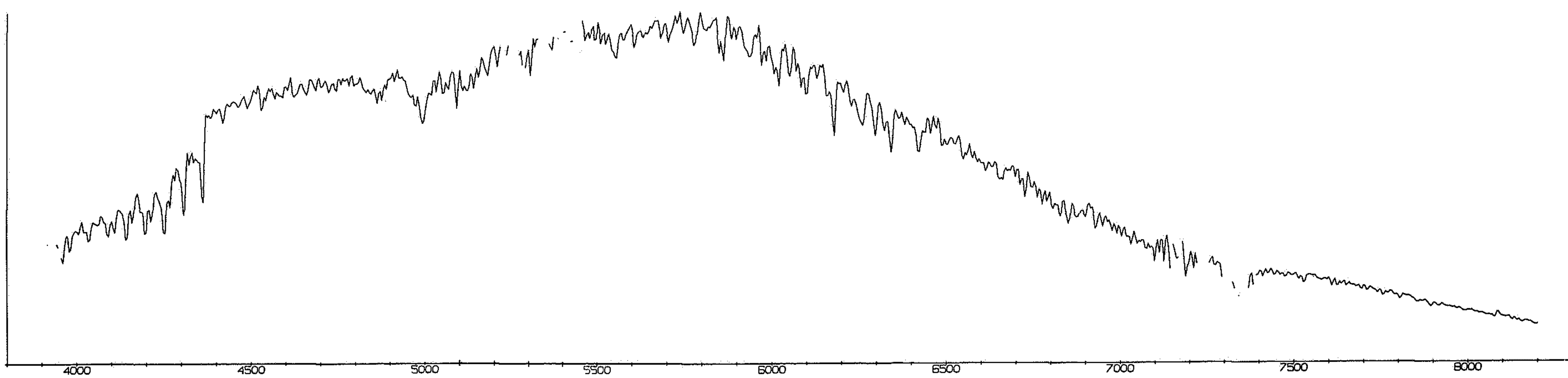

Fig. 7 The corrected spectrum of α Ori; M2 Iab. Dry night. Good equal-altitude transfer on March 14.

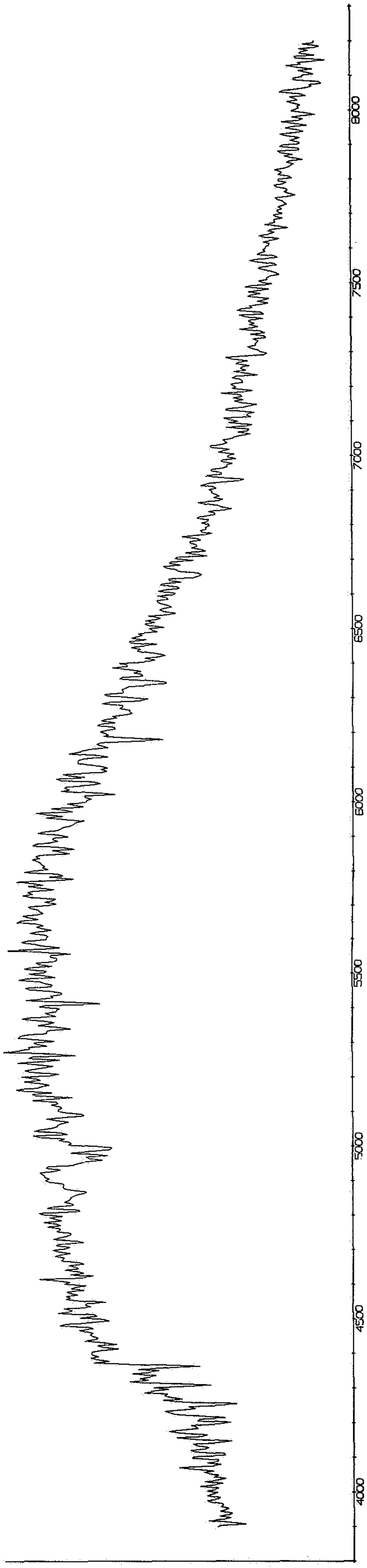

Fig. 8 The spectrum of α Ori from the NASA Convair 990 Jet Aircraft.

the noise level, in the regions of the 1.4 μ (7000 cm^{-1}) and 1.9 μ (5300 cm^{-1} bands.

As shown by Auman (1967), the opacity of steam (hot water-vapor) in the 3850 cm^{-1} (2.6 μ) region is several times as great as at 5300 cm^{-1} and 7000 cm^{-1}. Therefore, the use of the 3850 cm^{-1} band results in a more sensitive test for stellar steam. Although Figure 8 does not so indicate, our interferometer operates down to, and below, 3300 cm^{-1}, the practical limit of the present unrefrigerated PbS detectors. The aircraft spectra do cover this important spectral region; the spectrum of α Ori and the comparison lunar spectrum taken from the same altitude are shown in Figures 9 and 10, for the range from 3500 cm^{-1} to 4300 cm^{-1}. This lunar spectrum is not the one shown in Figure 1, but is another one taken during the flights when α Ori was observed; the two objects were separated in the sky by only a few degrees at the time of observation and the absorption due to the atmosphere above the aircraft should be very nearly equal in the spectra of Figures 9 and 10.

It is evident that the amount of water-vapor absorption at 3850 cm^{-1} in the α Ori spectrum is practically identical to that in the comparison lunar spectrum. These spectra show conclusively that there is no appreciable steam absorption in the spectrum of α Ori, a result contrary to that obtained by Woolf, Schwarzschild and Rose (1964) from the balloon observatory, Stratoscope II, but in agreement with that of Kuiper (1962b). (Could a water-vapor atmosphere carried up by the balloon be the cause of the Stratoscope II results?)

The CO bands in the spectral range from 3900 cm^{-1} to 4300 cm^{-1} show clearly in Figures 6, 7 and 8, although the higher noise level in Figure 8 obscures the weaker details and distorts the line shapes. Note that the correction for atmospheric extinction that is contained in the spectrum of Figure 7 removes the interfering water-vapor bands and allows a clearer picture to be obtained of these CO bands. These bands were observed by Kuiper (1964, Fig. 22) with a resolution of about 5000 showing the rotational structure. They also show in the α Ori spectrum given by McCammon, Münch and Neugebauer (1967). Their spectra, however, have lower resolution and are not corrected for atmospheric extinction.

We have observed 21 stars, including α Ori, whose infrared spectra have been corrected for atmospheric extinction. These stars are listed in Table 1, along with their spectral types and the numbers

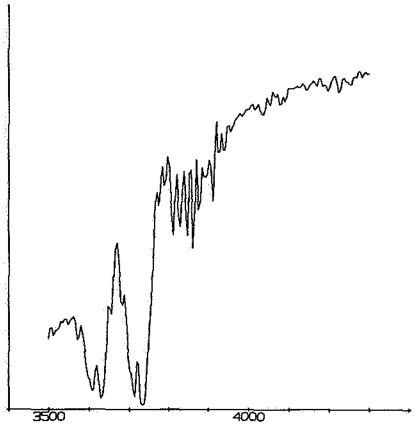

Fig. 9 The spectrum, 3500 cm^{-1} to 4300 cm^{-1}, of the Moon from the NASA Convair 990.

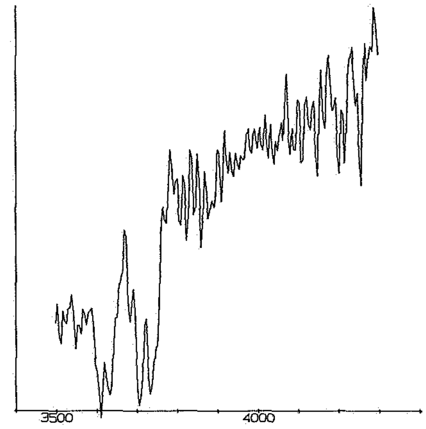

Fig. 10 The spectrum, 3500 cm^{-1} to 4300 cm^{-1}, of α Ori from the NASA Convair 990.

of the Figures in which their spectra appear. In addition, the lunar spectrum of Figure 1 (except for the general trend of the continuum) may also be considered to represent that of the Sun, whose spectral type is G2 V. Most of these spectra have been corrected for atmospheric transmission by the method of photometric equal-altitude transfers. Some, however, had no satisfactory equal-altitude comparisons; these were corrected for atmospheric extinction as well as possible, using transmission curves derived for other nights. This compensation cannot be expected to be satisfactory except in spectral regions where the water-vapor absorption is always relatively small; we have, therefore, blanked out regions where the water-vapor absorption is high. The captions for the Figures describe the method of extinction correction (equal-altitude, or not) and indicate the quality of the night.

Two spectra of α Boo are shown in Figures 11 and 12; the first is uncorrected, while the second is corrected for atmospheric extinction. Note that in Figure 12, as in Figure 7, the spectrum is discontinuous in the regions of strong atmospheric water-vapor absorption; this is caused by the fact that the computer program lifts the pen when the atmospheric transmission is less than 20 percent. Note the clarity with which the CO bands around 3900-4300 cm^{-1} can be seen in the corrected spectrum. The CO bands in the α Boo spectrum are weaker than those in α Ori, but there are more of them, extending toward smaller wave-numbers. This fact is not readily apparent in the uncorrected spectra.

The strengths of these CO bands increase with advancing spectral type; among the giant stars, they are strongest in the Mira stars. Their strengths also increase with stellar luminosity; compare δ Oph (M1 III), α Ori (M2 Iab) and μ Cep (M2 Ia). The CO bands in the spectrum of μ Cep are fully as strong as those in the Mira spectra. Numerous other features show changes with spectral type. For example, there are band structures at about 6380 and 6470 cm^{-1} which become stronger in the later spectral types, but do not become stronger with higher luminosity (at M2). There is an emission feature at about 4616 cm^{-1}, which appears in some spectra, but not in others. In most cases, the presence or absence of this feature has been confirmed by other spectra taken on other nights; for example, we have several spectra of R Hya, all of which show this

TABLE 1
CATALOGUE OF OBSERVATIONS

STAR	SPECTRAL TYPE	FIGURE
Sun (Moon)	G2 V	1
α Boo	K2 IIIp	11, 12
α Hya	K4 III	13
α Tau	K5 III	14
γ Dra	K5 III	15
β And	M0 III	16
δ Oph	M1 III	17
η Gem	M3 III	18
δ^2 Lyr	M4 II	19
ρ Per	M4 II-III	20
R Lyr	M5 III	21
α Her	M5 Ib-II	22
o Cet	M5e (max)	23
R Hya	M6e	24
R Leo	M8e	25
χ Cyg	Mpe, S	26
α Ori	M1-M2 Iab	6, 7, 8
α Sco	M1-M2 Iab	27
μ Cep	M2 Ia	28
U U Aur	C5, 3	29
Y CVn	C5, 4	30
U Hya	C7, 3	31

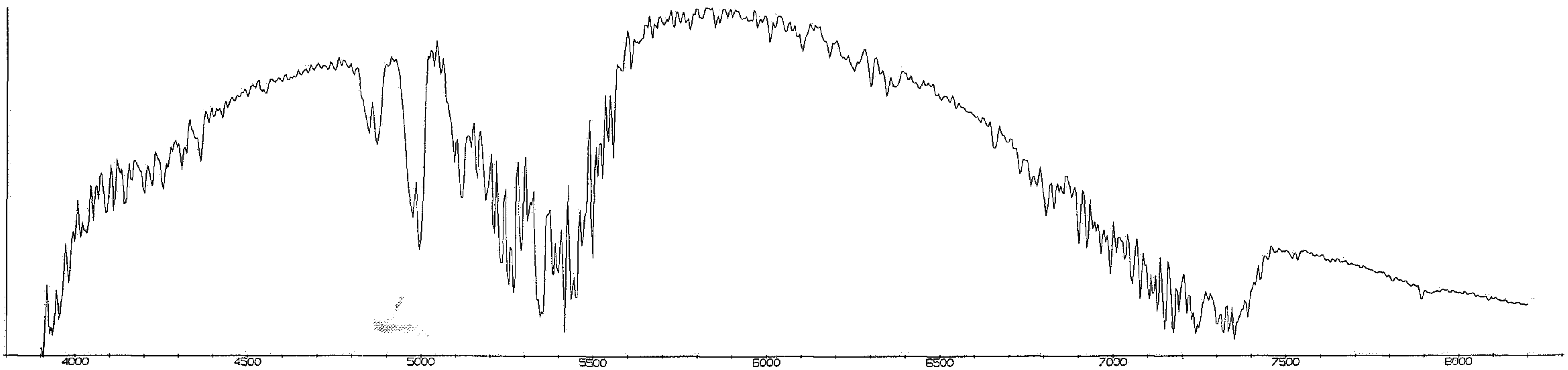

Fig. 11 The spectrum of α Boo from the Catalina Observatory, without correction for atmospheric extinction.

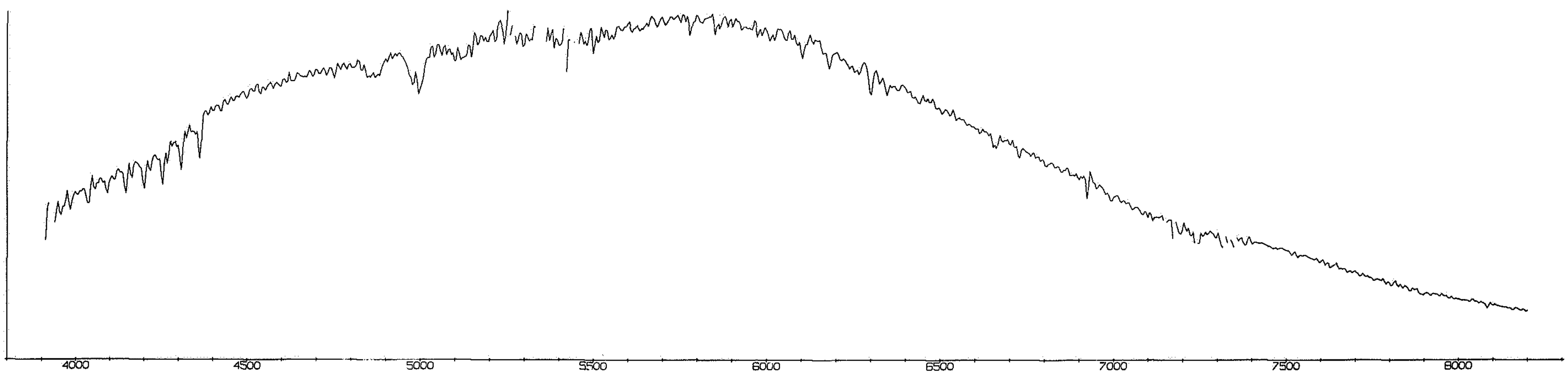

Fig. 12 The corrected spectrum of α Boo; K2 IIIp. Dry night. Good equal-altitude transfer on March 14.

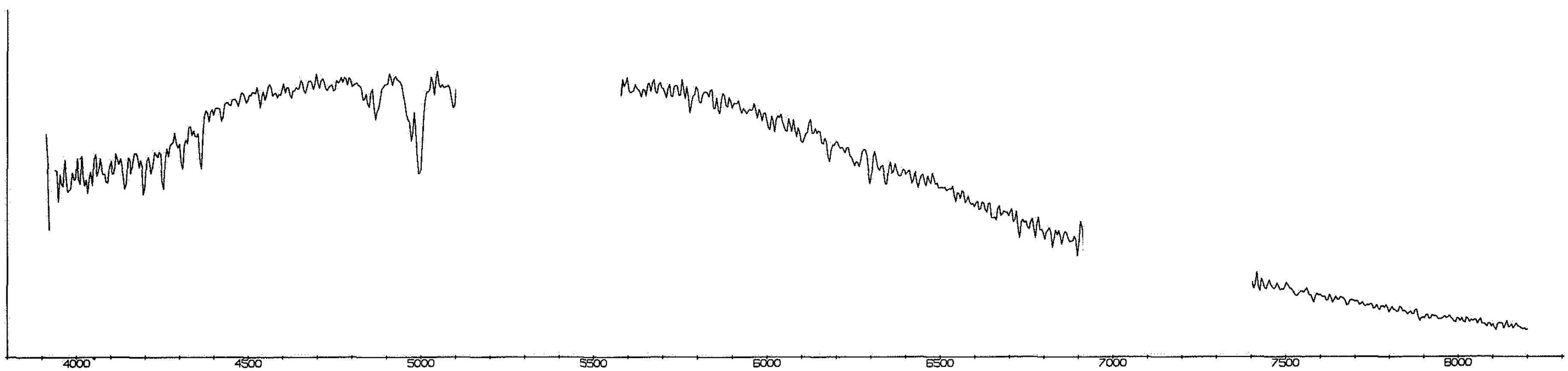

Fig. 13 The corrected spectrum of α Hya, K4 III. Not equal-altitude transfer. CO_2 seems somewhat undercorrected, but water-vapor satisfactory. No 4616 cm^{-1} peak is evident.

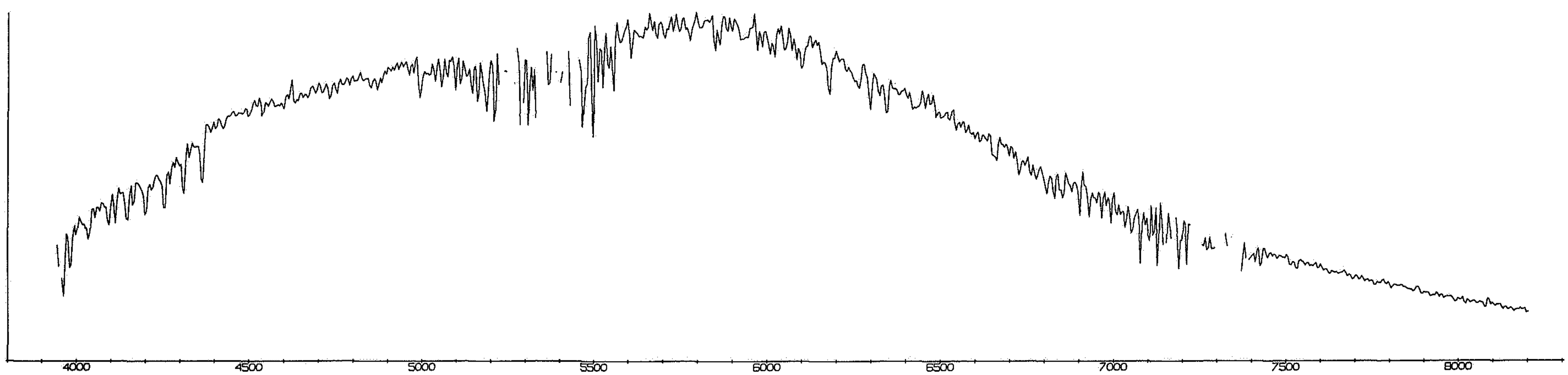

Fig. 14 The corrected spectrum of α Tau, K5 III. Dry night, good equal-altitude transfer on March 14. CO_2 is somewhat overcorrected, but H_2O is nevertheless undercorrected, with line structure present. The spectrum was taken on the same night as those of α Ori and α Boo (Figure 7 and 12) and the correction should be of similar quality.

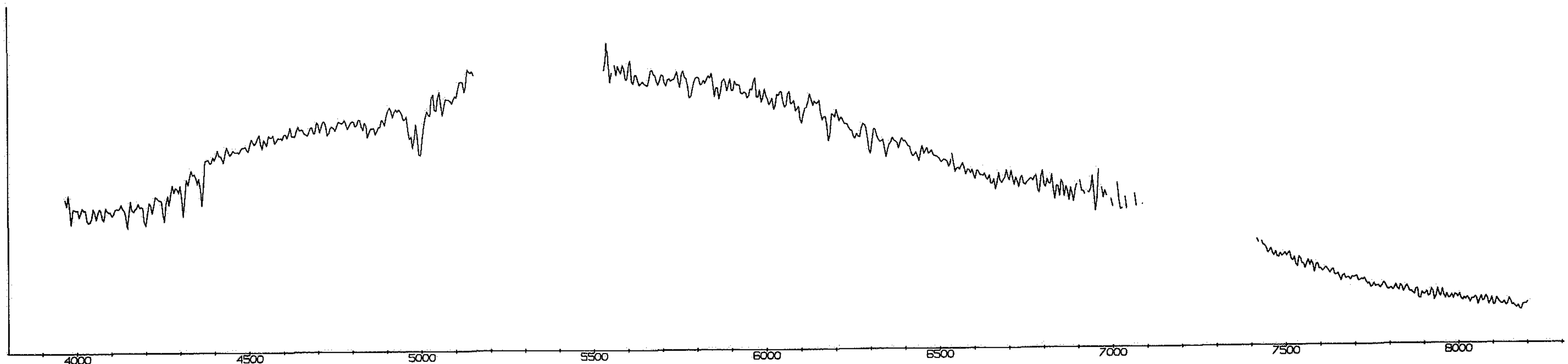

Fig. 15 The corrected spectrum of γ Dra, K5 III. Damp night, but good equal-altitude transfer. Even though this night was much damper than March 14, the line structure showing in α Tau (Figure 14) around 5100, 5500 and 7000 cm^{-1} is not evident.

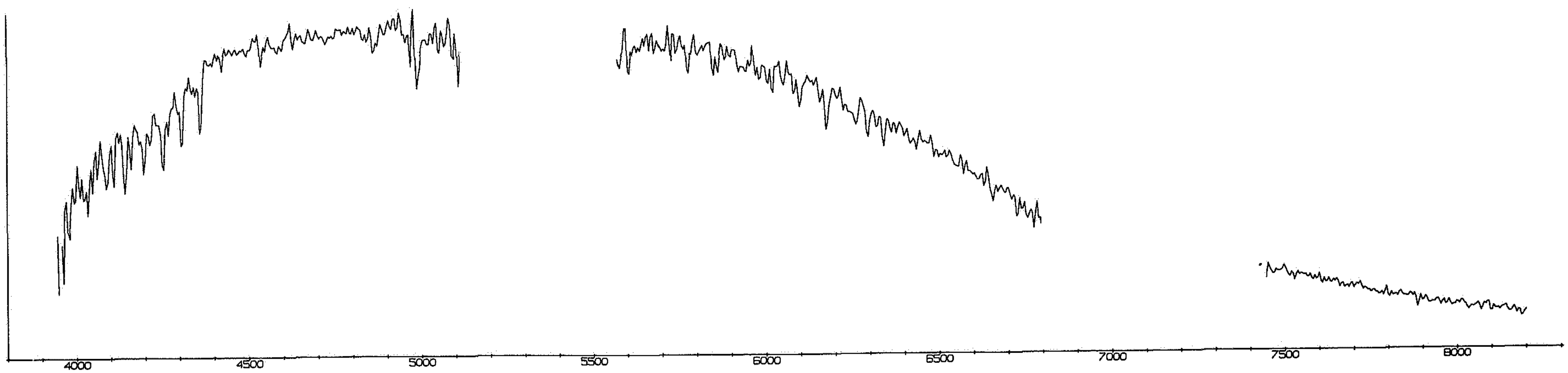

Fig. 16 The corrected spectrum of β And, MO III. Not equal-altitude transfer.

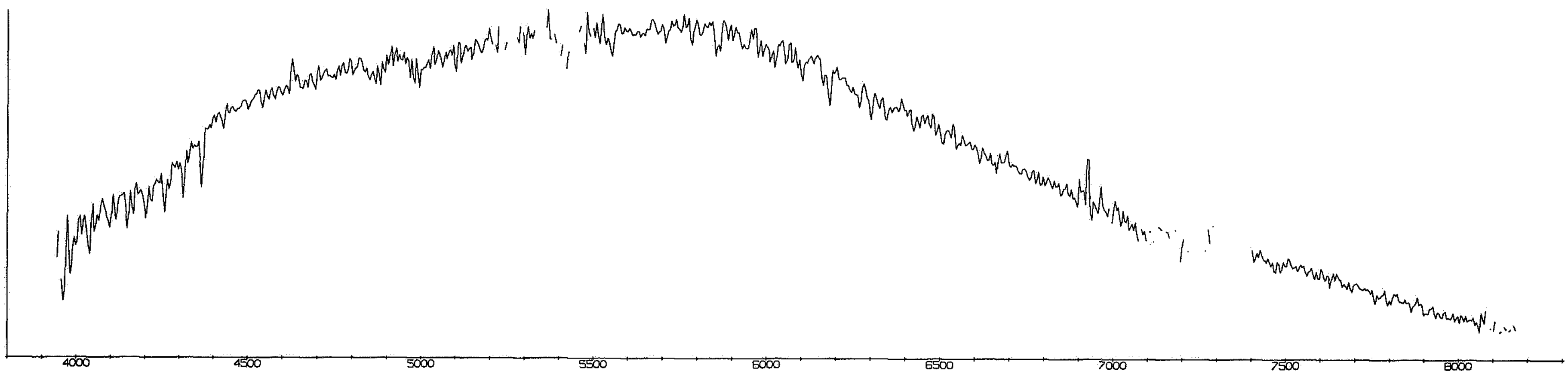

Fig. 17 The corrected spectrum of δ Oph, M1 III. Dry night, good equal-altitude transfer.

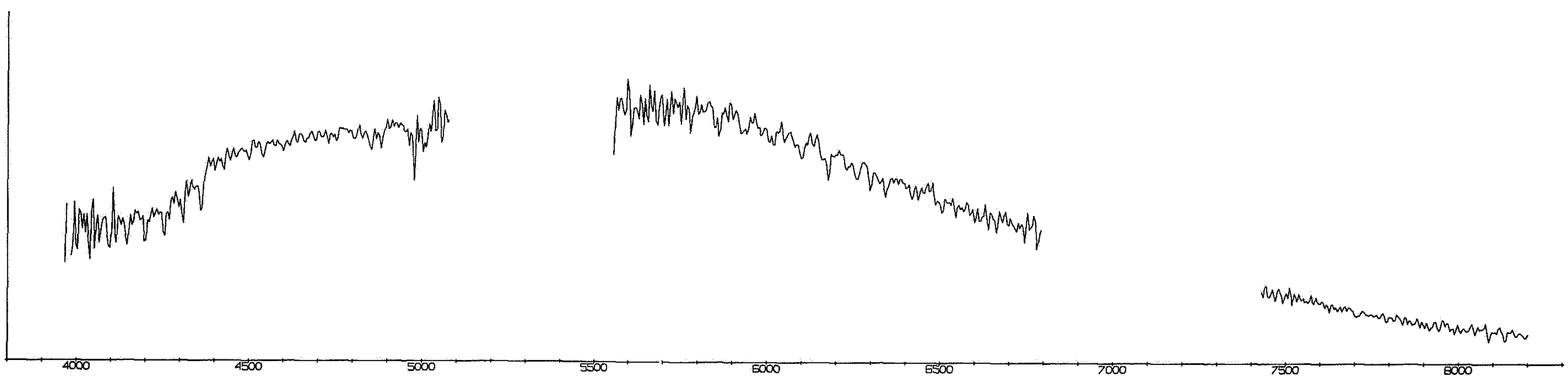

Fig. 18 The corrected spectrum of η Gem, M3 III. Not equal-altitude transfer. CO_2 and, probably, H_2O are overcorrected.

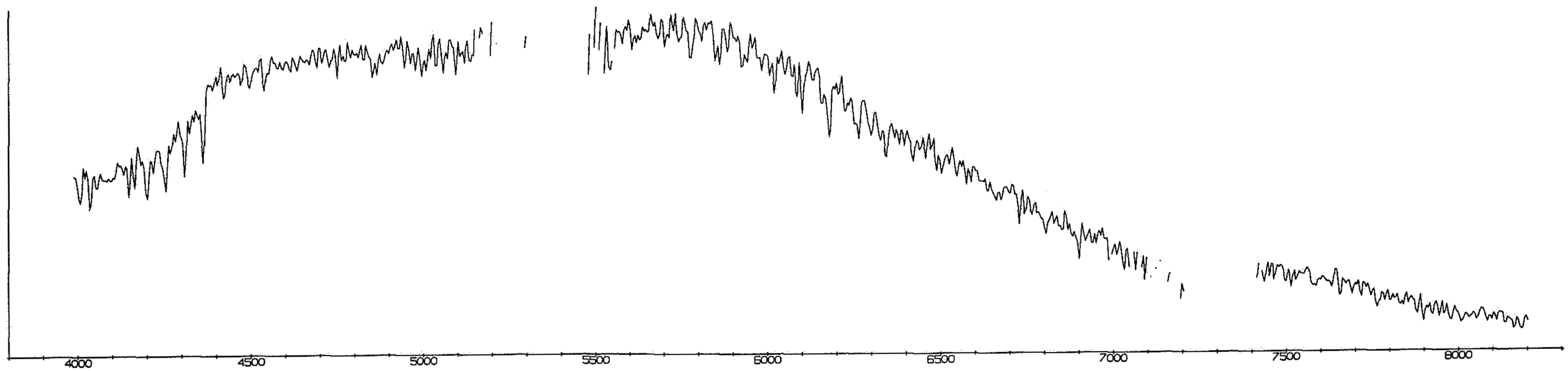

Fig. 19 The corrected spectrum of δ^2 Lyr, M4 II. Good equal-altitude transfers on two nights. No 4616 peak on either spectrum.

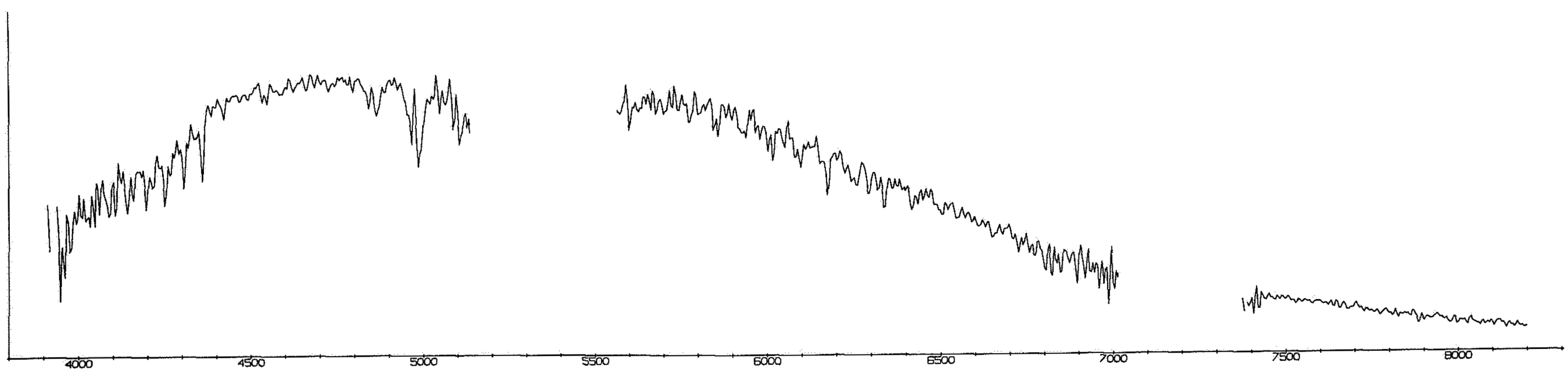

Fig. 20 The corrected spectrum of ρ Per, M4 II-III. Not equal-altitude transfer. CO_2 slightly undercorrected, possibly also H_2O.

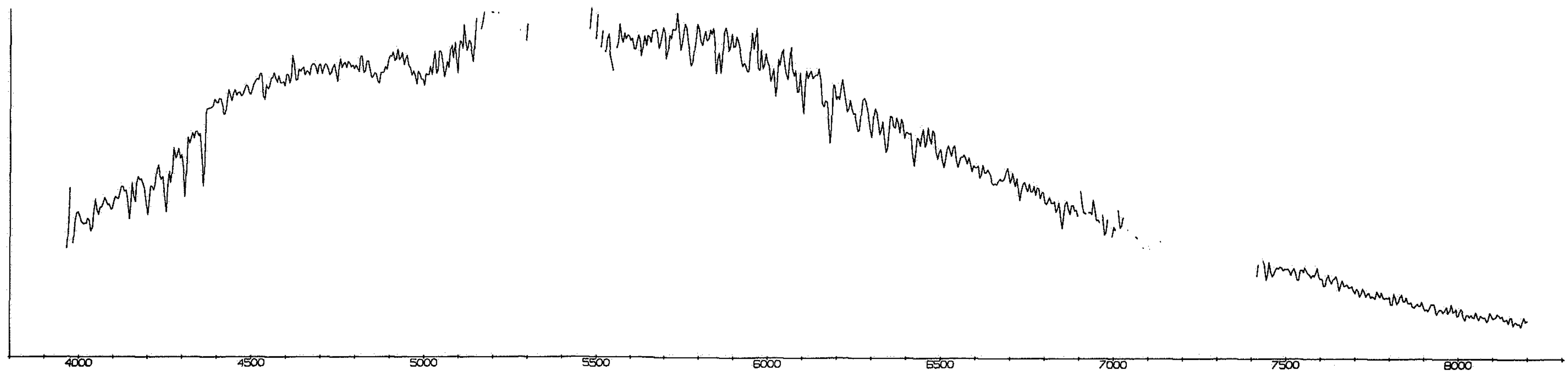

Fig. 21 The corrected spectrum of R Lyr, M5 III. Good equal-altitude transfers on two nights. CO_2 a little overcorrected. 4616 peak on both spectra.

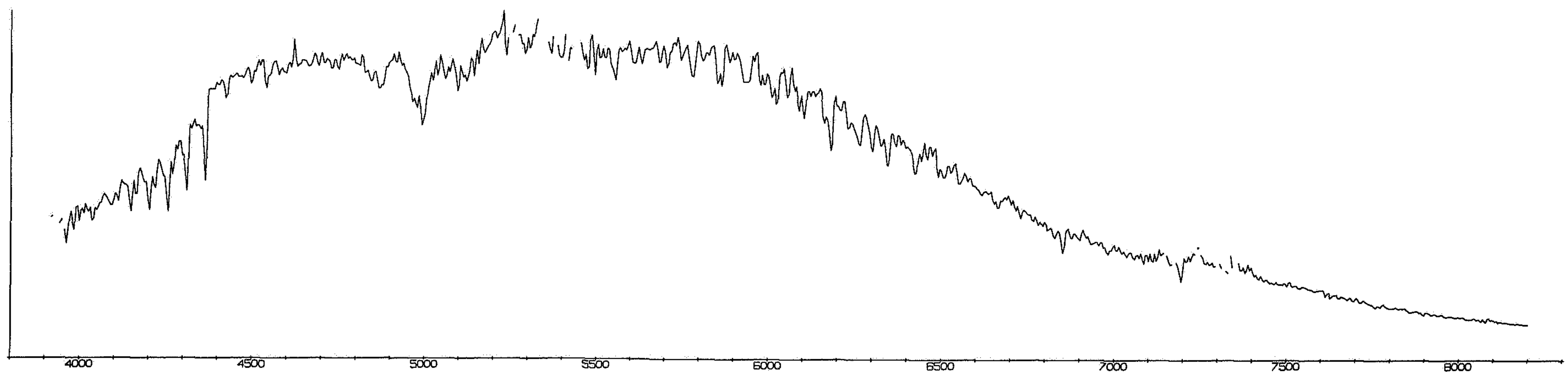

Fig. 22 The corrected spectrum of α Her, M5 Ib-II. Dry night, good equal-altitude transfer on March 14.

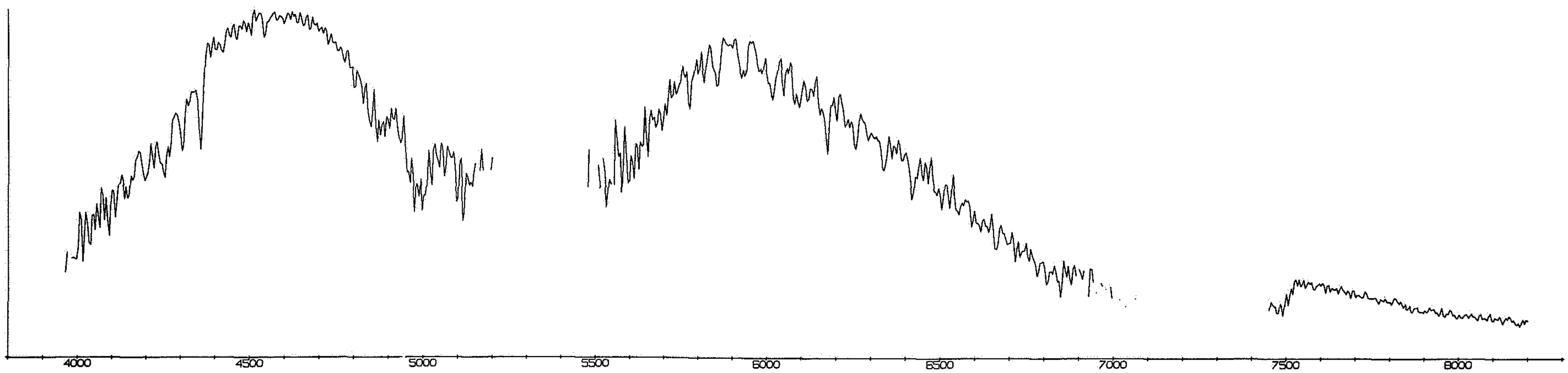

Fig. 23 The corrected spectrum of *o* Cet, M5e (max). Equal-altitude transfer on damp night. The presence of large stellar steam absorptions is evident.

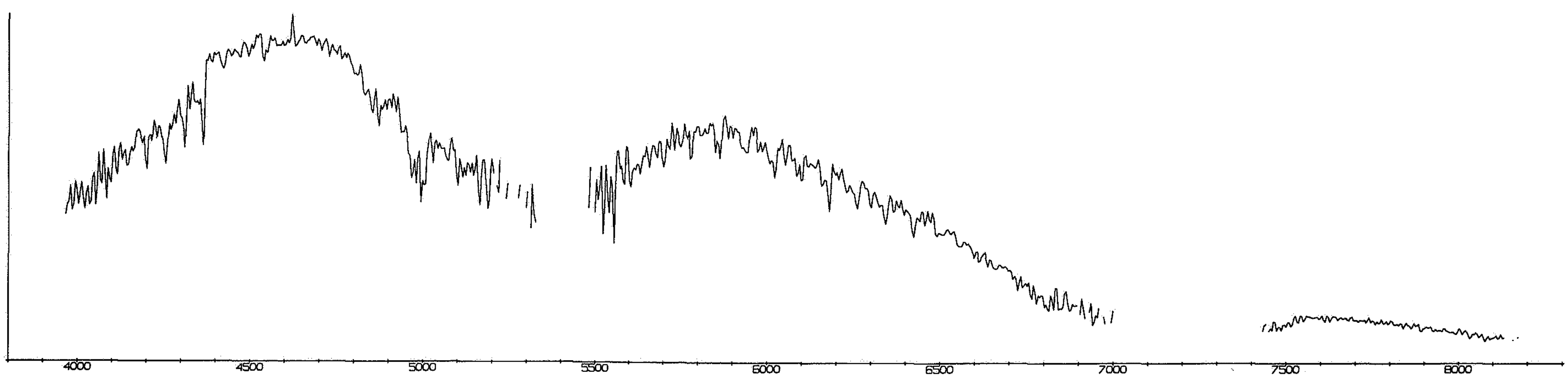

Fig. 24 The corrected spectrum of R Hya, M6e. Equal-altitude transfer on dry night. Steam absorption less than in *o* Cet. The 4616 cm^{-1} emission peak (Brackett γ) appears in all our spectra of this star.

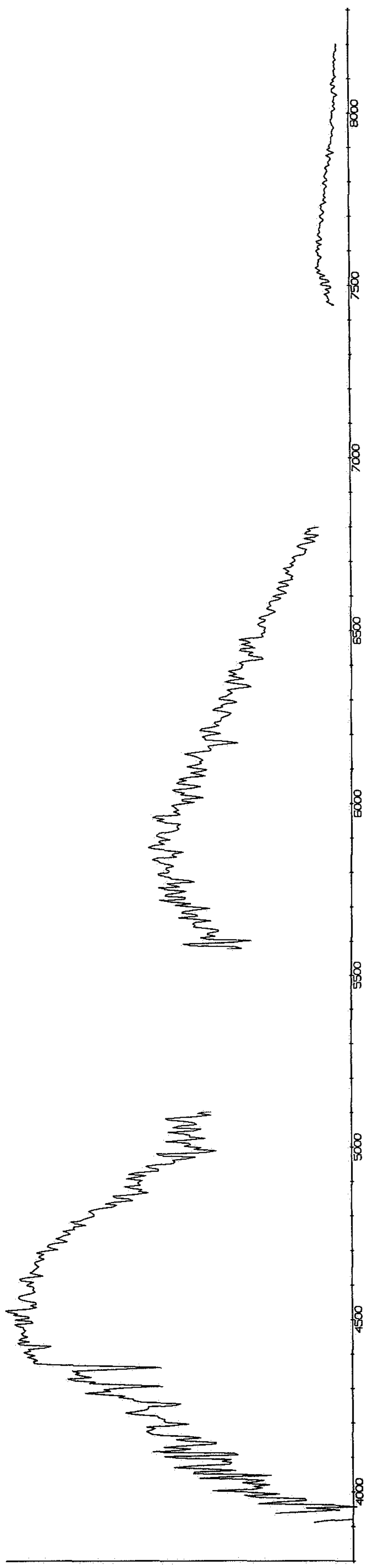

Fig. 25 The corrected spectrum of R Leo, M8e. Not equal-altitude transfer. Steam absorption is like in *o* Cet, stronger than in R Hya. The 4616 cm^{-1} emission appears in another spectrum of this star.

emission feature, while the duplicate spectra of *o* Cet do not show it. One spectrum of R Leo shows this emission feature, the other (Figure 25) does not. An absorption feature appears at this point in the lunar spectra, Figures 1, 2 and 3. This feature is apparently Brackett γ.

There is another series of CO bands beginning at 6420 cm^{-1} and extending downward to 5700 cm^{-1}. Altogether, ten bands of this series are clearly visible in the spectrum of χ Cyg (Fig. 21); they are less clearly visible in the spectra of the M4-M5 stars and the other Mira stars.

As we would expect from the spectral type of α Boo, Figure 12 shows no significant steam absorption in the spectrum of this star. Unexpected was the virtual absence of steam from all of the observed stars, except for the four Mira stars, χ Cyg, *o* Cet, R Hya and R Leo. α Tau exhibits lines around 5300 and 7000 cm^{-1} which could be attributed to steam, unless the correction for atmospheric extinction is faulty; α Sco shows some evidence of absorption at these wavelengths, but the star was observed at an air mass of 2.0, and the extinction correction probably is imperfect. A second specrum of α Sco was obtained on another night, when another equal-altitude transfer to the Moon was made. This spectrum is deficient at the high-frequency end, probably because of a mal-adjustment of the interferometer, but it serves to confirm the spectrum of Figure 27. We see no reason to believe that α Sco has a higher steam content than does α Ori. The 4616 cm^{-1} peak is confirmed by this spectrum.

The spectra of the four Mira stars show large absorptions due to stellar steam, a fact that was first shown for Mira (*o* Cet) by Kuiper (1962b, 1964). The infrared spectra of *o* Cet, R Hya and R Leo appear to be quite similar, except for the amount of steam absorption. χ Cyg not only has less steam absorption than do the other three Miras, but its spectrum differs in other respects. Note particularly that the steam absorptions in the Mira-star spectra differ greatly in character from the water-vapor absorptions in our atmosphere (Figure 4 and 5); this was first pointed out by Kuiper (1962b), who attributed the extra width to "hot" (steam) bands that are not appreciably excited at the temperature of the Earth's atmosphere. The wings of the steam bands extend well into the atmospheric transmission "windows" where the extinction corrections are small. Thus, determinations of the amount of stellar steam absorption from our spectra should be accurate. The difference between the o Cet spectrum and those of R Lyr and α Her cannot be due to the extinction correction.

This segregation of the Mira stars from other stars, on the basis of their large steam absorptions, was previously unknown, although Kuiper's (1962b, 1964) data suggested it. It has generally been assumed that steam absorption would increase with advancing spectral type and that stars at M5, such as R Lyr and α Her, would surely exhibit the effects. The difference between these two M5 giants and o Cet (which was observed near maximum light when its spectral type is about M5) is spectacular.

Our findings that the M4-M5 giants and the supergiants α Ori, α Sco and μ Cep have little or no stellar steam absorption is contrary to those of Woolf, Schwarzschild and Rose (1964) and Danielson, Woolf and Gaustad (1965), who observed from the balloon observatory, Stratoscope II. Their low-resolution spectra were interpreted as indicating steam absorptions in α Ori 10 to 20 percent of those in o Cet, while the μ Cep absorptions were 33 percent of those o Cet. Clearly, such absorptions in α Ori and μ Cep are not indicated by our spectra; as we discussed in the second paragraph of this section, the aircraft spectrum of α Ori offers no evidence for significant stellar steam absorptions.

The spectra of the three carbon stars, U U Aur, Y CVn and U Hya (Figures 29, 30 and 31), show, as expected, that the steam absorption bands in these stars are weak. These late carbon stars show no evidence of steam absorptions like those of the Mira stars (Figures 23, 24 and 25). Note the peaked appearance of the carbon-star spectra at about 5700 cm^{-1}; steam absorption in Miras shifts their peak to 5900–6000 cm^{-1}. These differences are not due to the atmospheric extinction correction, since the corrections are small in these regions (see Figures 4 and 5). McCammon, Münch and Neugebauer (1967) have already commented upon other features of the spectrum of Y CVn, including the sharp drop at 5660 cm^{-1}. This feature also appears in the spectra of U U Aur and U Hya. We suggest that the absorption is due to C_2, in accord with the laboratory spectra of Ballik and Ramsey (1963). Note the inverse correlation of this feature with the strength of the CO bands at 3900–4300 cm^{-1}. These stars show many features that do not appear in the K and M stars; furthermore, they differ rather strongly among themselves.

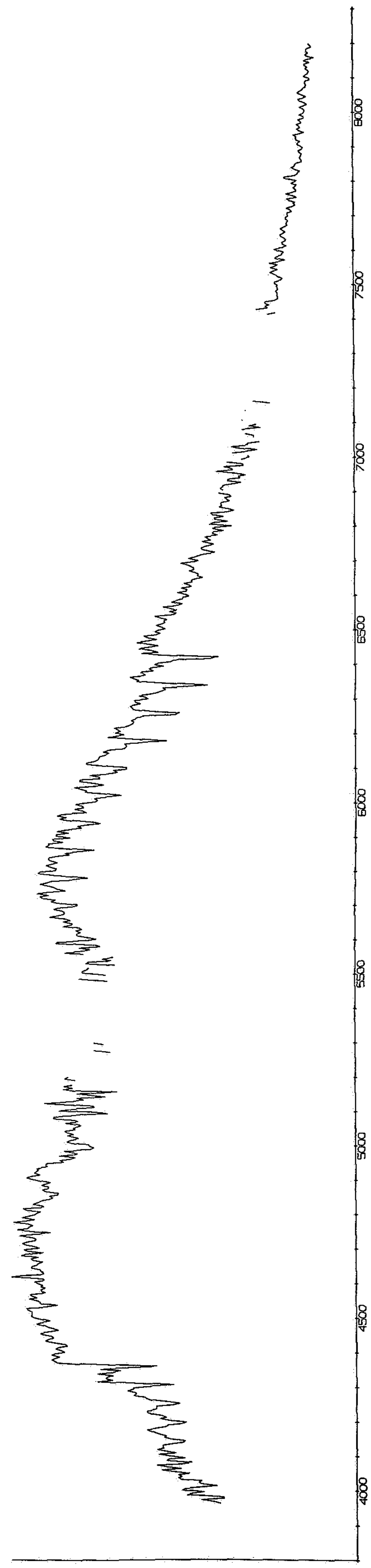

Fig. 26 The corrected spectrum of χ Cyg, Mpe, S. Good equal-altitude transfers on two nights. Steam absorption smaller than in R Hya, but quite definite. The 4616 cm^{-1} emission appears here, and also in another spectrum.

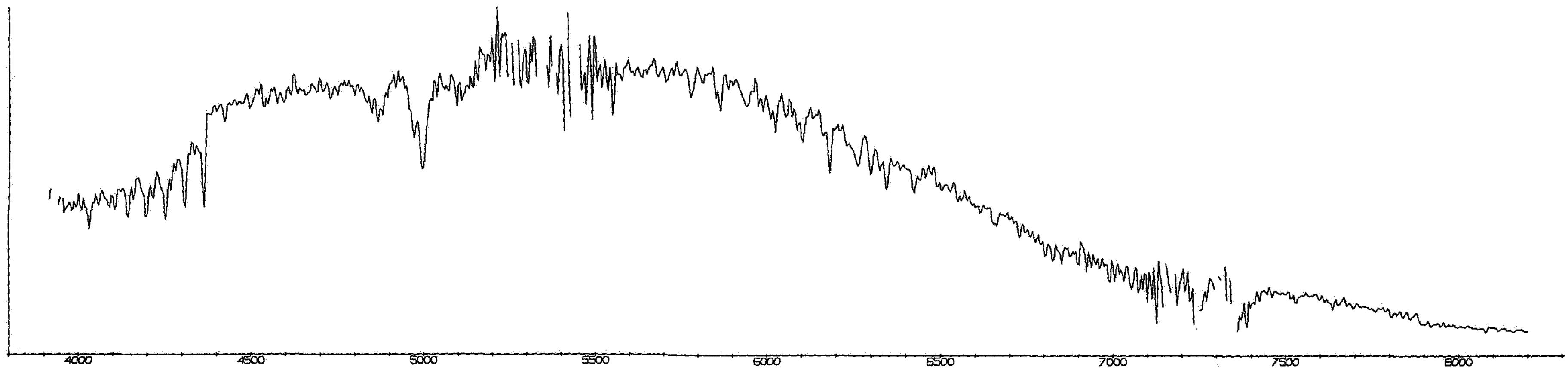

Fig. 27 The corrected spectrum of α Sco, M2 Iab. Dry night, equal-altitude transfer on March 14. CO_2 is undercorrected, probably also H_2O. Air mass = 2.0. Another spectrum, also from equal-altitude transfer, confirms low steam absorption.

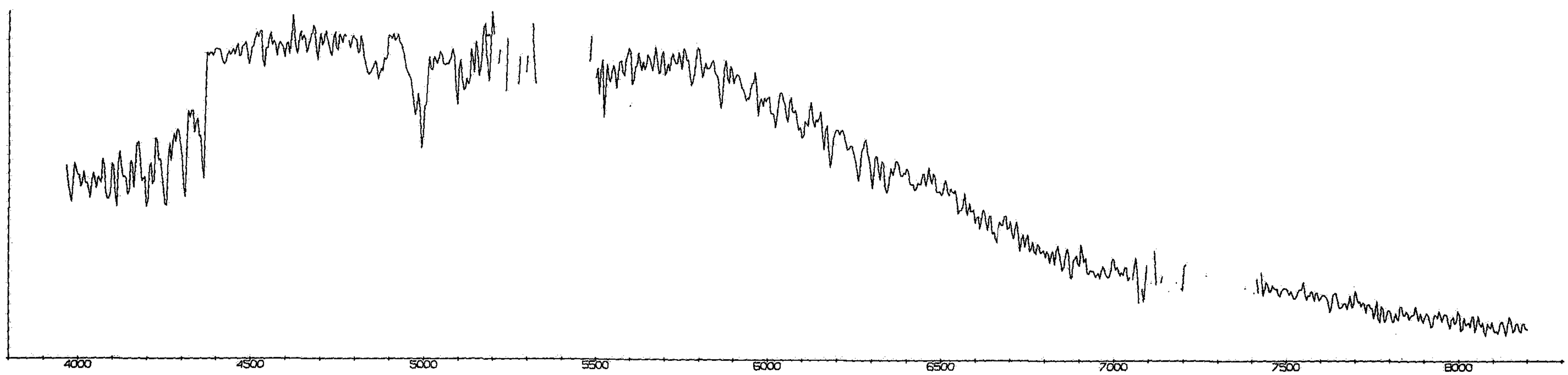

Fig. 28 The corrected spectrum of μ Cep, M2 Ia. Equal-altitude transfer on night of moderate water-vapor absorption. The spectrum shows no steam absorption, even though the CO_2 band strengths suggest undercorrection. A second spectrum confirms this one.

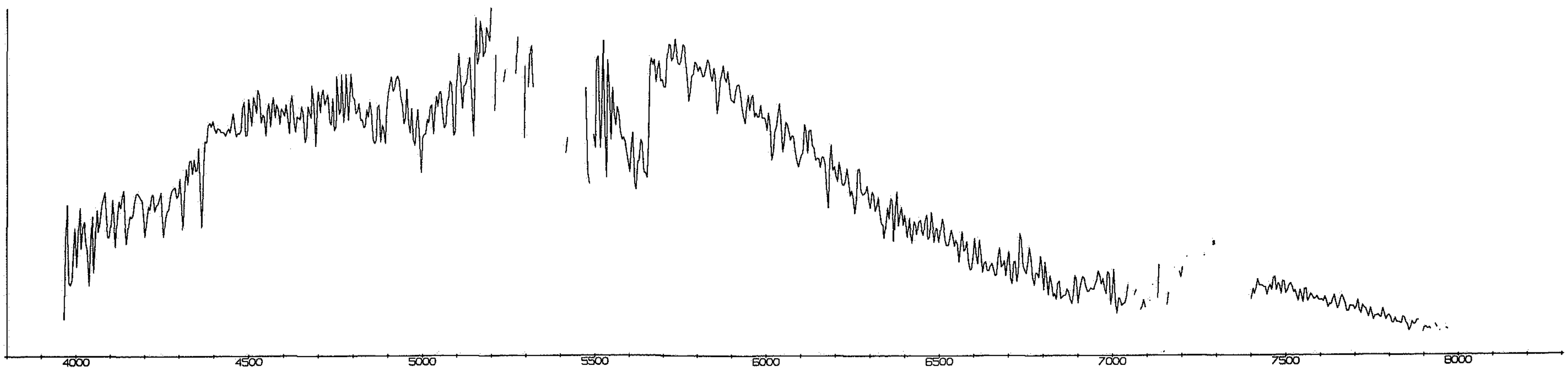

Fig. 29 The corrected spectrum of UU Aur, C5, 3. Equal-altitude transfer on moderately damp night.

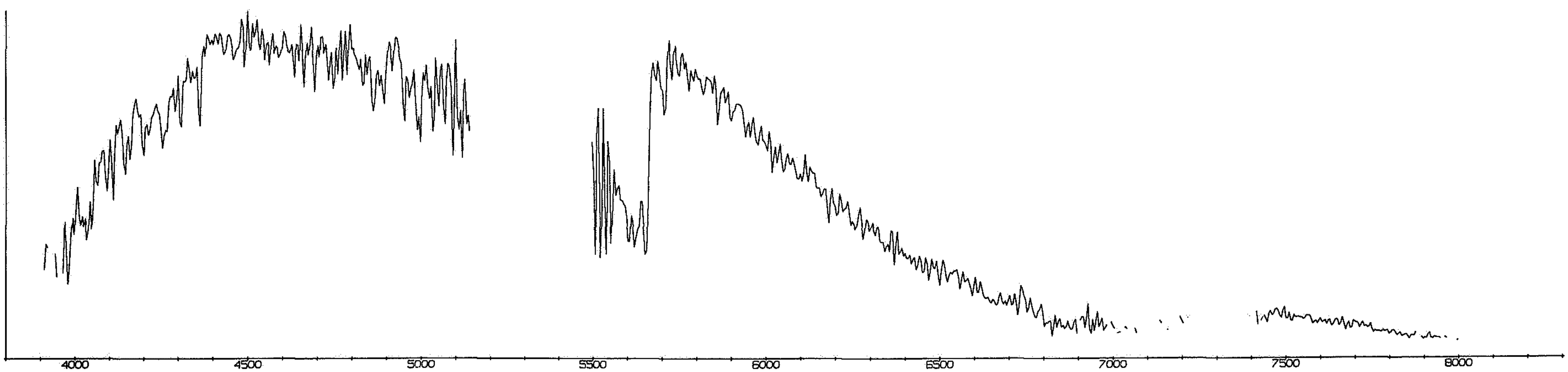

Fig. 30 The corrected spectrum of Y CVn, C5, 4. Dry night, but not equal-altitude transfer.

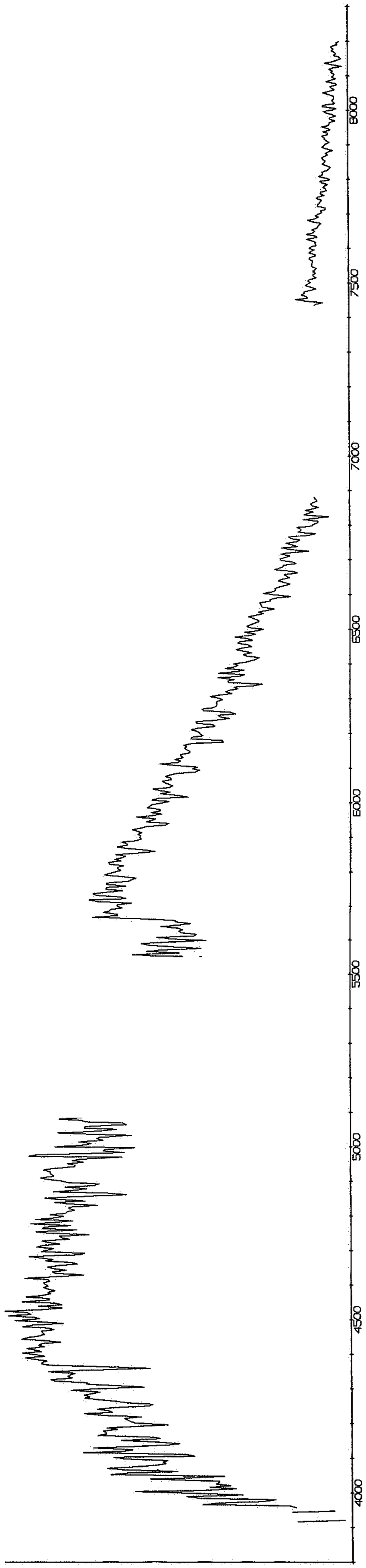

Fig. 31 The corrected spectrum of U Hya, C7, 3. Not equal-altitude transfer.

6. Conclusion

We have given here infrared spectra of 21 stars, corrected for atmospheric extinction to 41,500 feet. All spectra were derived from data taken with a rapid-scanning Michelson interferometer. Some stars show evidence of stellar steam absorption in their spectra; others do not. There is no evidence of steam in the spectra of α Her or R Lyr, even though their spectral type is M5; o Cet near maximum light, with a spectral type also about M5, has strong steam absorption. We also note that χ Cyg has smaller steam absorptions than does o Cet (and R Hya and R Leo).

There is some correlation between the strength of the steam bands in our spectra and the strength of the 9–12 μ excess emission found by Gillett, Low and Stein (1968). For example, α Her has no steam, and has no 9–12 μ excess; o Cet has strong steam absorptions, and strong 9–12 μ emission. χ Cyg is intermediate in both attributes. The same point can be made by reference to the K-N (2.2 μ–10.2 μ) colors, as shown in Table 2. The first group of stars in the table has K-N averaging around zero; the second group (the Mira stars) has K-N $\sim$ + 1.0. On the other hand, the third group of stars shows that the correlation does not exist for the early-M supergiants, which also have large excesses both in K-N (Johnson 1967) and from the data of Gillette, Low and Stein.

It seems quite possible to explain the observed infrared excesses exhibited by both the supergiants and the Mira stars as radiation from large circumstellar clouds surrounding the stars. Such clouds are already known to exist for some of these stars (Deutsch 1960). Why the steam is associated only with the Mira stars, remains to be explained.

TABLE 2
K-N COLORS OF STARS

STAR	SPECTRAL TYPE	K-N	H_2O PRESENT
α Boo	K2 IIIp	−0.10	No
α Tau	K5 III	+0.15	?
γ Dra	K5 III	+0.10	No
δ^2 Lyr	M4 II	−0.05	No
R Lyr	M5 III	+0.06	No
α Her	M5 Ib-II	−0.08	No
χ Cyg	S7, 1e	+1.2:	Yes
o Cet	MSe (max)	+0.9	Yes
R Hya	M6e	+0.9	Yes
α Ori	M2 Iab	+0.77	No
α Sco	M2 Iab	+0.42	No
μ Cep	M2 Ia	+1.62	No

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