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FLUX MEASUREMENTS AT THE CENTERS OF STELLAR H- AND K-LINES

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ABSTRACT

The coudé scanner of the 100-inch telescope has been used as a two-channel photometer to measure the fluxes at the centers of stellar H- and K-lines, for the purpose of initiating a search for stellar analogues of the solar cycle. From the Strömgren-Perry catalogue 139 stars previously observed at 10 Å mm^{-1} dispersion were selected for this purpose and included most of those in which H-K emission had been seen on the spectrograms. Reasonable agreement between eye-estimated intensities and the photometric results shows that the procedure adopted is suitable for specifying chromospheric activity, but with an accuracy much improved over eye estimates. The probable error of a single measurement of a line is a little less than 2 per cent.

No undoubted variations have been observed during a year's observation. However, the measures are discussed in connection with the Strömgren-Perry photometric parameters $b - y$, m_1, c_1. In this way it is possible to trace in some detail the course of chromospheric evolution as stars begin to move off the zero-age main sequence (ZAMS) toward the giant region. Doublet ratios of the chromospheric components of H and K are one of the by-products of the observations. They show that, in general, the optical thickness of the gas masses involved cannot be very great.

I. INTRODUCTION

The solar cycle of approximately twenty-two-year period has been known for over two centuries. During this time a vast amount of observational data and theoretical speculation relating to the cyclical solar variation has accumulated. Nevertheless, it seems very likely that understanding has been severely hampered because all this material relates to a single star with a fixed set of parameters such as age, mass, and surface temperature. It is a reasonable supposition that if analogous cycles could be detected in other stars with different values of the fundamental stellar parameters, the results would be of considerable value in sharpening the theoretical attack on the whole problem.

The most obvious phenomenon associated with the solar cycle is the periodic rise and fall of the numbers of sunspots. At an average maximum the area occupied by spots is about 1400-millionths of the solar surface, and the corresponding change in luminosity therefore does not exceed about 0.001 mag. Hence the uncovering of analogous stellar cycles by luminosity measurements is not practical. On the other hand, calcium spectroheliograms made with K_2 or H_2 radiation at the centers of the Ca II H- and K-lines differ greatly in appearance between sunspot maxima and minima. At maximum, as compared with minimum, the whole calcium network is notably more intense, and plages are more numerous and brighter. Since all this radiation is concentrated into narrow bands of the order of 0.5 Å width at the centers of the photospheric H and K absorption lines, it is quite reasonable to suppose that suitable measures of the strengths of these chromospheric emissions in stars should provide information on the stellar analogues of the solar cycle. This possibility led to the writer's first interest in stellar chromospheric phenomena about thirty years ago.

Since that time, I have had occasion to look at many spectrograms exhibiting H and K emission in stars of various types and luminosities. In many instances, two or more plates of the same object, taken some years apart, were available. While this material has not been examined with great care, there have been no stars in which rather cursory inspection has suggested variability in the H-K emission lines. If such variability occurs, therefore, it is unlikely to be of large amplitude, or else it has a long period. Judging from my experience, I am inclined to place the upper limit of variability as being of the order of 20 per cent.

From careful visual inspection of low-dispersion spectrograms of five late-type main-sequence stars taken over a five-year period, Popper (1956) was also unable to find any significant H-K variation (with the exception of one flare). An upper limit of the order of 10–20 per cent appears to be a realistic assessment of Popper's results, also. On the other hand, recent measurements by Sheeley (1967) indicate that the solar K_2 may vary by as much as 40 per cent during the sunspot cycle.

If Sheeley's results are correct, and if other stars exhibit similar amplitudes of H-K emission, the observational problem of finding stellar cycles should not be too difficult. However, the experiences of Popper and myself suggest a more pessimistic outlook. Since a considerable number of stars of various kinds should be kept under observation, the technique adopted should not require excessive telescope time per star, but it should at the same time be capable of relatively high accuracy—hopefully of the order of at most 1 per cent. These requirements can be met only by using a photoelectric procedure.

Observations intended ultimately to provide information on variability of stellar chromospheric emission were begun in March 1966 and have been carried on since then as time permitted. The present paper is a progress report on the results of the first year of work (March 1966—April 1967) in a limited region of the main sequence. Little can be said as yet about variability, but the data collected are of a kind not hitherto available and are of interest in other respects.

II. APPARATUS AND PROCEDURES

Details of the equipment and methods employed in the investigation and of the accuracy attained will be found in the Appendix. Very briefly, the observations are made with the coudé scanner of the 100-inch telescope used as a two-channel photometer. Entrance and exit slits are both 1 Å in width, the exit slit is centered accurately on the stellar H- or K-line, and 10^4 counts are made in this channel. Simultaneously, the other channel is counting pulses in two 25 Å lengths of spectrum, separated by about 250 Å, on either side of the H-K region. These two monitor windows are the same for both Ca II lines and also the same for all stars, except for small Doppler shifts nearly always within ± 1 Å. After completing the counts in either H or K, the other line is centered in the exit slit and the procedure repeated.

Because of the nature of the equipment, it was anticipated that spurious variations of an incidental character would be introduced from time to time in the ratio between the two channels, and this has turned out to be true. To correct for these instrumental effects, a standard lamp is observed each afternoon during an observing run. Light from the lamp is injected into the spectrograph through the same small length of entrance slit used for the stars, and counts are made with the exit slit located at the positions of both H and K.

Let N_s and N_m be the pulse counts, corrected for dark current, at the wavelength of one of the Ca II lines for the standard lamp, n_s and n_m the same quantities for a star, and let $R_i = (N_s/N_m)_i$, $r_i = (n_s/n_m)_i$. The subscripts s and m refer to the scan and monitor channels, respectively, i to a particular observing run. For two runs, i and j, we have

$$R_i/R_j = \alpha \,, \quad r_i/r_j = \beta \,. \tag{1}$$

Observation shows that to within a few per cent, on the average,

$$\alpha = \beta \,, \tag{2}$$

or, in other words, the standard lamp provides a good first-order correction of the instrumental variations. The small residual corrections can be obtained by observation of a series of standard stars and will be of importance in ultimately refining the accuracy of the results. These corrections have, however, mostly been ignored in this paper.

From equations (1) and (2), one has, to a good approximation,

$$\frac{r_1}{R_1} = \frac{r_2}{R_2} = \ldots \frac{r_i}{R_i} = \ldots = F . \tag{3}$$

Equation (3) has been applied to all the stellar measures and provides corrected fluxes on an instrumental scale which, while it has no immediate physical interpretation, is the same for all observations, which are therefore comparable.

III. OBSERVATIONS

Since the Sun is the only star known to undergo cyclical variation of the kind under consideration, it is logical to begin the investigation with other main-sequence stars in the general neighborhood of the Sun in the H-R diagram. The observing program was made up of stars from the Strömgren-Perry catalogue (1962) for which I had already obtained 10 Å mm^{-1} spectrograms (Wilson 1966). This procedure has certain advantages: first, the Strömgren-Perry photometry gives information about surface temperature, absolute luminosity, and metallic content; second, the spectrograms provide knowledge of chromospheric emissions visible at 10 Å mm^{-1} and of the stellar rotational velocities. Hence, the observing list contained most of the stars in whose spectra I had observed H and K emission, plus a sample of others scattered randomly through the main-sequence band. Only stars with $v \sin i < 15$ km sec^{-1} were admitted, to avoid significant widening of chromospheric features. Observations have been made of 139 stars selected according to these criteria. The choice of the 1 Å width for both entrance and exit slits conformed to the fact that no chromospheric emissions in the list should exceed about 0.7 Å in width. In this way it was expected that virtually all the chromospheric radiation would be registered, without excessive dilution by residual photospheric light.

This phase of the investigation has three goals: (1) to begin the collection of data which may ultimately lead to the detection and study of stellar analogues of the solar cycle; (2) to establish the validity, or otherwise, of the adopted procedures and to evaluate in a preliminary fashion the over-all accuracy of the measurements; and (3) to explore in a general way chromospheric activity within the limited area of the H-R diagram under discussion.

IV. RESULTS AND DISCUSSION

a) Dependence of Flux on $b - y$

Results of observation are in Table 1, where the first two columns contain, respectively, the HD and Strömgren-Perry catalogue numbers. The columns (3) and (4) are the mean instrumental fluxes for H and K, measured and reduced as described above, and multiplied by 10^4 for convenience. Column (5) gives the number of observations for each star, a single observation being defined as a measure of both H and K. The mean of the H and K fluxes is given in column (6), and the Strömgren-Perry photometric parameters, in units of 0.001 mag., in columns (7), (8), and (9). For all Strömgren-Perry stars previously observed spectroscopically, $c_1 - (b - y)$ and $m_1 - (b - y)$ plots were made and the lower boundaries of the distributions drawn in. From these lower boundaries the quantities Δc_1 and Δm_1 were read off for the stars of Table 1, where they appear in columns (10) and (11). As in the usual convention, luminosity increases with Δc_1, but metallic content decreases with Δm_1. Column (13) contains the Δc_1's corrected for the effect of m_1, following the precept of Strömgren (1963). The remainder of Table 1 will be described later.

Much of the information contained in Table 1 is best shown graphically. Figure 1 is a plot of mean H-K flux against $b - y$, where open circles represent those stars in which emission was seen on 10 Å mm^{-1} spectrograms, and the numbers beside them are eye-

TABLE 1

PHOTOMETRIC DATA

(1) HD	(2) S-P No	(3) F_H	(4) F_K	(5) n	(6) $\frac{1}{2}(F_H+F_K)$	(7) $b-y$	(8) m_1	(9) c_1	(10) Δc_1	(11) Δm_1	(12) $(\Delta c_1)_{corr}$	(13) ΔF_H	(14) ΔF_K	(15) $\Delta F'_K$	(16) $\Delta F'_K/\Delta F_K$	(17) $\frac{1}{2}(\Delta F_H+\Delta F'_K)$	(18) Remarks
2454	11	1822	1470	7	1646	301	134	436	050	035	076	357	317	402	1 126	380	
3229	13	2204	1825	7	2014	306	132	493	115	040	145	739	672	853	1 154	796	
6920	38	1940	1655	6	1798	390	168	410	148	050	186	475	502	638	1 343	556	
7439	40	1685	1324	7	1504	294	130	432	030	040	060					...	
7476	41	1814	1487	7	1650	283	154	488	060	015	070					170	
9562	56	1628	1251	7	1440	395	214	389	130	005	134	163	98	124	0 761	144	
10307	61	1742	1346	7	1544	389	203	338	075	015	086	277	193	245	0 884	261	
12235	73	1823	1479	5	1651	388	208	411	148	007	153	358	326	414	1 156	386	
13201	81	1689	1314	1	1502	296	147	403	000	023	017	...	...	...		...	
13421	82	1470	1153	5	1312	366	170	462	175	035	201	000	000	000		000	
13555	84	1682	1366	4	1524	308	132	466	090	040	120	217	213	270	1 244	244	
15335	99	1527	1195	4	1361	381	174	353	080	037	108	62	42	53	0 855	58	
16234	107	1608	1254	4	1431	336	146	380	053	042	085	143	101	128	0 895	136	
16673	113	2147	1759	3	1953	319	174	348	000	005	004	682	606	770	1 129	726	E
18256	126	1837	1510	9	1674	308	153	452	080	020	095	372	357	453	1 218	412	
18262	127	1546	1230	2	1388	315	164	499	139	015	150	81	77	98	1 210	90	
19994	139	1733	1379	9	1556	362	192	400	108	010	116	268	226	287	1 071	278	
20193	140	2416	2082	7	2249	247	137	569	060	035	086	....	....	....	. ...	329	
25998	196	2805	2450	8	2628	334	180	373	042	007	047	1340	1297	1647	1 229	1494	E
26913	204	4060	3742	6	3901	410	260	287	038	000	038	2595	2589	3288	1 267	2942	E
26923	205	2950	2631	6	2790	367	190	318	032	015	043	1485	1478	1877	1 264	1681	E
29645	252	1551	1213	7	1382	378	190	397	125	020	140	86	60	76	0 884	81	
29859	253	1439	1123	4	1282	344	177	444	127	015	138	000	000	000	. ...	000	
32923	278	1667	1340	5	1504	415	197	332	084	032	108	202	187	237	1 173	220	
33021	280	1592	1256	2	1424	390	199	338	073	017	086	127	103	131	1 031	129	
33256	285	1627	1275	5	1451	307	129	443	070	045	104	162	122	155	0 957	158	
33608	288	2226	1858	4	2042	295	185	456	055	000	055	...	...	...	. ...	...	
34411	293	1672	1305	5	1488	389	206	363	097	010	105	207	152	193	0 932	200	
35296	301	3036	2661	8	2848	348	169	352	042	025	061	1571	1508	1915	1 219	1743	E
39587	332	3075	2779	10	2927	380	193	307	035	020	050	1610	1626	2065	1 283	1838	E
41330	342	1634	1269	2	1452	374	182	334	056	025	075	169	116	147	0 870	158	
43042	349	1728	1421	6	1574	293	163	448	040	007	045	...	...	...		...	
43318	351	1476	1154	2	1315	313	175	435	070	000	070	000	000	000	. ...	000	
43587	357	1866	1421	2	1644	382	200	331	061	012	070	401	268	340	0 848	370	
45067	361	1536	1184	2	1360	368	162	409	125	045	159	71	31	39	0 549	55	
45504	363	1569	1228	2	1398	342	169	389	070	022	086	104	75	95	0 913	100	
47703	373	1563	1266	4	1410	334	155	376	045	032	069	98	113	144	1 469	121	
48682	374	1712	1345	2	1528	357	185	371	074	015	085	247	192	244	0 988	246	
49933	380	2266	1883	8	2074	274	118	469	025	050	063	...	...	...	. ...	514	
50692	387	1777	1401	2	1589	376	184	306	030	025	048	312	248	315	1 009	314	
51530	393	1512	1204	1	1358	348	134	390	080	060	125	...	...	...	. ...	...	
52711	397	1760	1396	2	1578	374	198	301	022	010	030	295	243	309	1 047	302	
55130	403	1644	1326	5	1485	330	174	380	043	010	051	179	173	220	1 229	200	
59380	425	1754	1389	1	1572	320	136	407	057	045	091					...	
61421	437	1752	1424	8	1588	272	167	532	085	002	086					000	
66011	453	1698	1401	4	1550	356	200	473	180	000	180	233	248	315	1 352	274	
67228	456	1626	1272	2	1449	408	206	402	150	020	165	161	119	151	0 938	156	
67827	459	1440	1145	2	1292	368	194	390	105	010	113	000	000	000	. ...	000	
75332	502	2794	2468	7	2631	336	184	362	035	005	039	1329	1315	1670	1 256	1500	E
75528	505	1659	1307	3	1483	420	206	386	140	025	159	194	154	196	1 010	195	
76151	509	2865	2427	5	2646	411	237	341	092	000	092	1400	1274	1618	1 156	1509	E
76572	513	1498	1195	5	1346	303	135	504	120	035	146	000	000	000	. ...	000	
78366	526	2463	2157	7	2310	377	198	311	036	010	044	998	1004	1275	1 278	1136	E
81809	539	2046	1665	5	1856	418	182	366	122	050	160	581	512	650	1 119	616	
82543	550	1588	1313	3	1450	386	214	587	320	000	320	123	160	203	1 650	163	
86728	577	1708	1356	6	1532	415	235	385	138	000	138	243	203	258	1 062	250	
87822	582	1848	1507	3	1678	286	165	490	070	005	074	...	...	....	. ...	238	
88737	584	2387	2022	9	2204	361	184	440	148	017	161	922	869	1104	1 197	1013	E
88986	586	1644	1296	2	1470	396	208	368	110	012	119	179	143	182	1 017	180	
89010	587	1628	1269	5	1448	405	228	364	115	000	115	163	116	147	0 902	155	
89125	590	1762	1391	3	1576	336	140	352	025	050	063	297	238	302	1 017	300	
89744	595	1441	1122	3	1282	336	186	450	120	000	120	000	000	000		000	
91752	609	1690	1332	2	1511	289	136	476	065	035	091					091	
93765	616	2329	1943	2	2136	264	132	580	110	037	138	...	...	...	. ...	466	
95128	620	1638	1308	5	1473	392	203	337	075	015	086	173	155	197	1 139	185	
95216	621	2060	1674	2	1867	288	155	436	020	015	031	...	...	...		447	
95241	622	1458	1104	1	1281	378	170	376	101	040	131	000	000	000	. ...	000	
97334	634	3342	3003	6	3172	392	210	311	050	007	055	1877	1850	2350	1 252	2114	E
99373	646	1606	1268	3	1437	302	151	501	115	020	130	141	115	146	1 035	144	
100180	650	1856	1523	1	1690	367	188	332	047	015	059						
100563	652	2072	1707	3	1890	302	169	419	035	000	035	607	554	704	1 160	656	
101606	656	1605	1229	3	1417	310	125	400	030	050	068	140	76	96	0 686	118	
102870	666	1686	1340	8	1513	354	190	412	112	007	117	221	187	237	1 072	229	
106516	681	2145	1765	5	1955	317	118	333	000	060	045	680	612	777	1 143	728	
107213	688	1428	1148	5	1288	336	192	451	125	000	125	000	000	000		000	

TABLE 1 -continued

(1) HD	(2) S-P No.	(3) F_H	(4) F_K	(5) n	(6) $\frac{1}{2}(F_H+F_K)$	(7) $b-y$	(8) m_1	(9) c_1	(10) Δc_1	(11) Δm_1	(12) $(\Delta c_1)_{corr}$	(13) ΔF_H	(14) ΔF_K	(15) $\Delta F'_K$	(16) $\Delta F'_K/\Delta F_H$	(17) $\frac{1}{2}(\Delta F_H+\Delta F_K)$	(18) Remarks
107705	692	1760	1386	6	1573	352	190	370	065	007	070	295	233	296	1 003	296	
109358	706	1722	1374	2	1548	385	182	296	030	030	052	257	221	281	1 093	269	
110897	712	1656	1332	5	1494	375	150	280	000	060	045	191	179	227	1 188	209	
111199	715	1945	1588	1	1766	350	164	482	175	032	199	...	...	....	...	....	
114378	733	2443	2104	9	2274	304	152	386	002	020	017	978	951	1208	1 235	1093	E
114710	735	2079	1761	8	1920	372	193	336	058	015	069	614	608	772	1 257	693	E
115383	739	3244	2845	8	3044	376	191	383	107	010	115	1779	1692	2149	1 208	1964	E
117176	748	1602	1286	6	1444	452	233	348	120	020	135	137	133	169	1 234	153	
119288	760	1899	1537	7	1718	278	146	464	025	025	044	...	...	...		208	
120066	764	1483	1188	4	1336	404	192	388	136	032	160	000	000	000		000	
120136	765	1967	1601	3	1784	319	179	439	088	000	088	502	448	569	1 133	536	
121560	771	1614	1288	4	1451	335	154	330	000	035	026	149	135	171	1 148	160	
121682	773	2110	1778	4	1944	260	169	596	120	000	120	...	...	...		224	
124570	783	1470	1139	6	1304	343	196	440	125	000	125	000	000	000	...	000	
124850	785	2241	1848	4	2044	341	163	448	128	030	150	776	695	883	1 138	830	
125111	788	2604	2224	2	2414	255	144	522	030	025	049	...	...	...	...	614	
126053	795	1873	1477	3	1675	402	200	269	015	022	031	408	324	411	1 007	410	
126141	796	2052	1714	4	1883	261	161	488	015	010	023					183	
127334	803	1909	1499	1	1704	439	250	383		000							
127986	808	(1737)	(1436)	2		340	170	486									
128167	810	2109	1695	3	1902	254	135	490	000	035	026					102	
130817	814	1876	1567	6	1722	258	139	518	035	030	057					000	
132375	820	(1618)	(1258)	3	....	336	170	428	...	...	...	...	....	...	...	...	
134044	825	1668	1322	5	1495	353	165	391	090	032	114	203	169	215	1 059	209	
136202	829	1550	1227	7	1388	352	176	425	122	020	141	85	74	94	1 106	90	
137510	835	1845	1406	1	1626	397	214	441	181	006	185	...	...	...		...	
138525	841	1469	1097	1	1283	348	164	448	138	030	160	000	000	000	...	000	
141004	850	1800	1446	6	1623	385	199	354	086	015	097	335	293	372	1 110	354	
142373	855	1544	1210	10	1377	381	151	323	052	060	097	79	57	72	0 911	76	
142860	856	1682	1322	6	1502	320	153	403	053	025	072	217	169	215	0 991	216	
143761	860	1599	1252	10	1426	394	183	322	062	035	088	134	99	126	0 940	130	
154417	884	2584	2244	8	2414	374	174	329	050	035	076	1119	1091	1386	1 239	1252	E
155646	891	1536	1220	2	1378	330	156	479	142	030	164	71	67	85	1 198	77	
157214	897	1677	1306	7	1492	409	182	309	060	045	094	212	153	194	0 915	203	
157856	902	1965	1568	2	1766	294	154	498	095	015	106						
159332	912	1479	1171	7	1325	328	148	471	132	035	158	000	000	000	...	000	
161239	923	1554	1199	5	1376	420	223	449	205	010	213	89	46	58	0 652	74	
162826	927	1549	1185	1	1367	352	188	371	066	010	074	...	...	...	...	...	
165908	941	1629	1259	8	1444	361	143	326	032	060	077	164	106	135	0 823	150	
167588	947	1566	1238	8	1402	376	156	357	080	055	121	101	85	108	1 069	104	
176095	977	1901	1547	8	1724	307	166	479	100	007	105	436	394	500	1 147	468	
182101	1001	2162	1798	8	1980	320	125	425	075	055	116	697	645	819	1 175	758	
182807	1005	1635	1292	8	1464	339	168	352	028	022	044	170	139	176	1 035	173	
187013	1027	1568	1248	8	1408	316	155	435	078	025	097	103	95	121	1 175	112	
187691	1030	1602	1253	8	1428	356	188	404	107	010	115	137	100	127	0 927	132	
187923	1031	1633	1296	7	1464	424	190	333	093	045	127	168	143	182	1 083	175	
190406	1039	2256	1903	9	2080	389	197	321	056	017	069	791	750	952	1 204	872	E
194012	1053	2026	1692	6	1859	338	169	342	018	020	033	561	539	684	1 219	622	
198390	1073	1638	1305	7	1472	302	146	419	035	025	054	173	152	193	1 116	183	
199960	1081	1777	1381	7	1579	406	209	397	147	015	158	312	228	290	0 929	301	
200790	1083	1604	1264	6	1434	350	170	421	113	025	132	139	111	141	1 014	140	
206860	1114	3289	2992	9	3140	379	190	305	033	020	048	1824	1839	2336	1 281	2080	E
207978	1119	1608	1260	8	1434	309	108	439	065	065	114	143	107	136	0 951	140	
208703	1122	2548	2163	8	2356	248	159	523	015	010	023	...	..	...	...	456	
211976	1143	1585	1240	7	1412	302	148	409	020	022	036	120	87	110	0 917	115	
212487	1144	1470	1149	7	1310	314	154	486	127	022	143	000	000	000	...	000	
212754	1145	1500	1187	8	1344	330	188	417	080	000	080	35	34	43	1 228	39	
215243	1154	1559	1243	7	1401	318	155	432	077	025	096	94	90	114	1 213	104	
216385	1158	1510	1185	8	1348	321	149	433	085	032	109	45	32	41	0 911	43	
216756	1161	1943	1629	7	1786	273	138	530	080	030	102					226	
221356..	1191	1707	1348	7	1528	350	162	309	000	035	026	242	195	247	1 021	244	
224635E	1210E	2279	1852	1	2066	347	176	348	035	017	048	814	699	888	1 091	851	E
224635W	1210W	2168	1845	1	2006	347	176	348	035	017	048	703	692	879	1 250	791	E
224930	1213	1988	1630	7	1809	431	190	203	000	050	038	523	477	606	1 159	564	E

estimated emission intensities (Wilson 1966). With due regard for their lower accuracy, it is evident that the estimates have, for the most part, placed the stars in the proper order of their chromospheric emission strengths. Conversely, this general agreement may also be considered evidence that the adopted procedure is a successful method of measuring the degree of chromospheric activity.

Points representing other stars overlap somewhat with those for which Ca II emission was previously seen, and they extend down to a lower boundary which is quite sharply defined. Stars occupying positions on the lower boundary are those with minimum chromospheric emission, but it is not clear whether the minimum is zero or whether it involves some small residual chromospheric activity. If the latter is true, it would appear

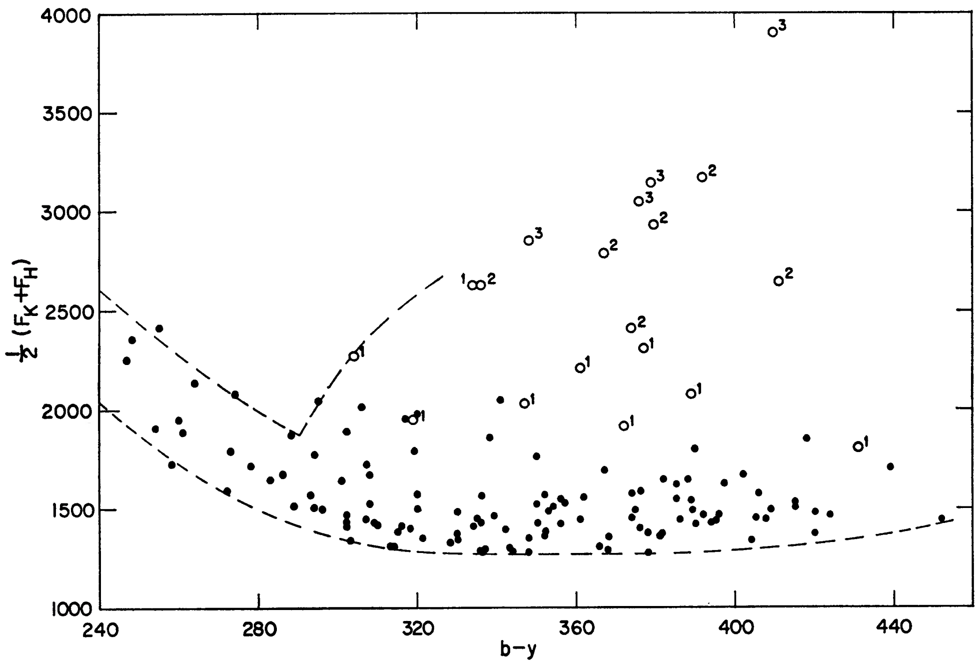

FIG. 1.—Mean instrumental H-K flux plotted against $b - y$ for all stars. Open circles are stars for which emission was seen on 10 Å mm^{-1} plates, and numbers beside them are eye-estimated emission intensities.

that the residual chromospheric radiation is surprisingly constant in amount. It should be mentioned here that the probable errors of nearly all the plotted points are of the order of their diameters (see Appendix, *d*).

The lower boundary in Figure 1 is horizontal for $0.31 < (b - y) < 0.40$ but rises on the left and, to a lesser degree, on the right. The rise on the left is presumably due to the weakening and narrowing of the photospheric H and K absorption lines as the surface temperature increases, so that more and more of the inner wings of the lines are included in the 1 Å band width. It is likely, however, that the slower rise toward the right has a different cause. One must remember that the monitor windows include a number of metallic lines and that the flux through these windows is an integration of all the features within them. The metallic lines strengthen toward lower surface temperature, thus producing a reduction in the monitor flux and a corresponding apparent increase in the central H-K intensities. Both effects just mentioned are either negligible or cancel each other in the central portion of Figure 1.

The upper boundary decreases from the left until $b - y \approx 0.290$, where it suddenly rises. This rise might properly be termed the "chromospheric bulge" and must mark the onset of strong chromospheric emission. Its location agrees closely with a previous determination and with the place where large stellar rotation terminates (Wilson 1966). With this interpretation, stars to the left of $b - y = 0.290$ do not have strong chromospheric emissions. Weak emissions can and do occur in this region, however, as evidenced by the fact that they have been observed at high dispersion in the spectrum of Procyon (Kraft and Edmonds 1959). This star lies on the lower boundary of the distribution of points with $b - y < 0.290$.

Figure 1 is the basis of the remaining entries of Table 1. The means of F_{H} and F_{K} were computed for the thirteen lowermost stars of Figure 1, lying between $b - y = 0.300$ and $b - y = 0.404$, and it is assumed that these means represent the residual photospheric fluxes for stars in this $b - y$ range, essentially undisturbed by chromospheric emissions. Quantities ΔF_{H} and ΔF_{K} for other stars with $b - y > 0.300$ were then obtained by subtracting these means from their measured fluxes and are entered in columns (13) and (14). It is thus implicitly assumed that the differential fluxes, ΔF_{H} and ΔF_{K}, are the chromospheric contributions to the total fluxes in the H- and K-lines. In column (15), $\Delta F'_{\mathrm{K}}$ is found by multiplying ΔF_{K} by a factor to be described later, and the significance of columns (16) and (17) is obvious. In the remarks (col. [18]), an E signifies that H-K emission was seen on 10 Å mm^{-1} spectrograms.

For $b - y < 0.290$, the measured flux is a fairly rapidly varying function of $b - y$. Entries in column (17) for stars in this region were obtained by subtracting from the measures the appropriate value on the lower boundary shown in Figure 1.

b) Stars with $b - y < 0.290$

For $b - y < 0.290$ the vertical scatter represents a range of about 30 per cent in the H-K flux, and the question arises whether this is due to chromospheric effects. When the ΔF's for these stars are plotted against Δm_1, or against $(\Delta c_1)_{\mathrm{corr}}$, there are no apparent trends in either case, and both plots appear to show only random scatter. It is possible that the vertical width of the distribution in this region is due in part to an intrinsic scatter among the relatively weak chromospheric emissions in these stars. A test could be made by taking well-exposed high-dispersion spectrograms of some of these objects near the upper boundary to see if they show stronger emission than does Procyon.

If the mean H-K fluxes are plotted, rather than the $\Delta F'$s, a curious result is obtained, as shown in Figure 2. In Figure 2, *a*, where the fluxes are plotted against Δm_1, there is no correlation. But in Figure 2, *b*, where the abscissae are $(\Delta c_1)_{\mathrm{corr}}$, the stars appear to divide into two groups, the lower of which shows a remarkably tight correlation between the two parameters in the sense that flux diminishes with $(\Delta c_1)_{\mathrm{corr}}$. The upper group, averaging about 30 per cent higher in H-K flux, shows a similar relationship (the dashed lines in Fig. 2, *b*, are parallel) but a much looser correlation. By picking out corresponding points in Figures 2, *a*, and 2, *b*, it is easily verified that the lack of correlation with Δm_1 holds within the two groups as well as for the whole collection of points. Metallic content, therefore, cannot be responsible for the character of Figure 2, *b*.

However, the sense of the correlation in Figure 2, *b*, could be accounted for by variation of the photospheric H-K absorption lines with luminosity. In these stars the Sr II line, 4077, increases in strength with absolute magnitude, and the Ca II lines should behave similarly. For given $b - y$, therefore, the H-K absorption lines should strengthen with increasing Δc, thus leading to an apparent variation of central flux with luminosity, as shown in Figure 2, *b*.

The bifurcation in Figure 2, *b*, could be due to a considerable difference in calcium abundance between the two groups of stars. Since the m_1 values for the two groups are much the same, this would imply that the abundance of calcium varies independently of that of the other metals, unless the m_1's are seriously perturbed by microturbulence. In any event, it is worth noting that the upper group in Figure 2, *b*, may represent the later-type analogues of the Am stars.

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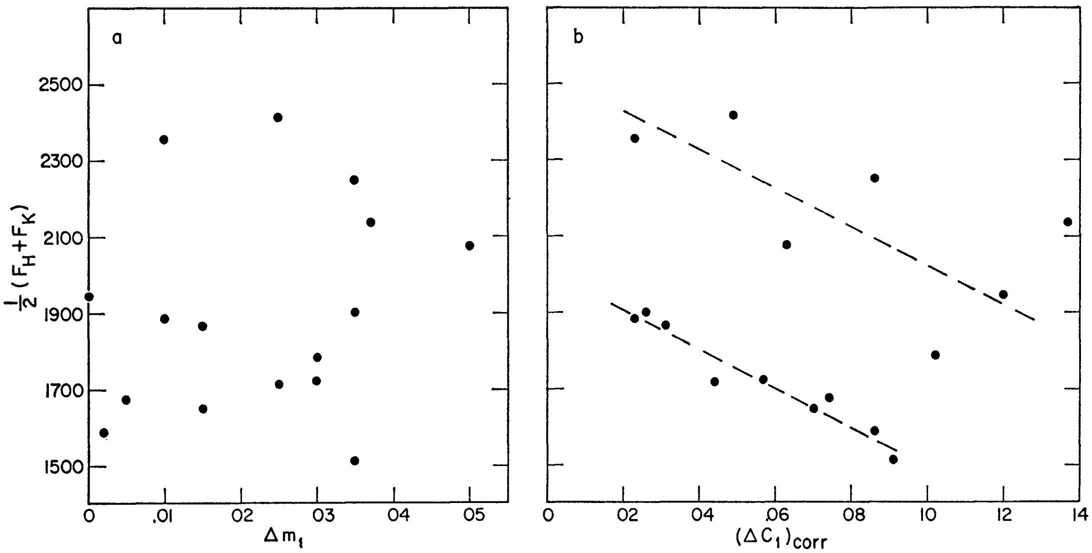

FIG. 2.—For stars with $b - y \leq 0.29$. (*a*) Mean H-K flux plotted against Δm_1. (*b*) Mean H-K flux plotted against $(\Delta c_1)_{corr}$.

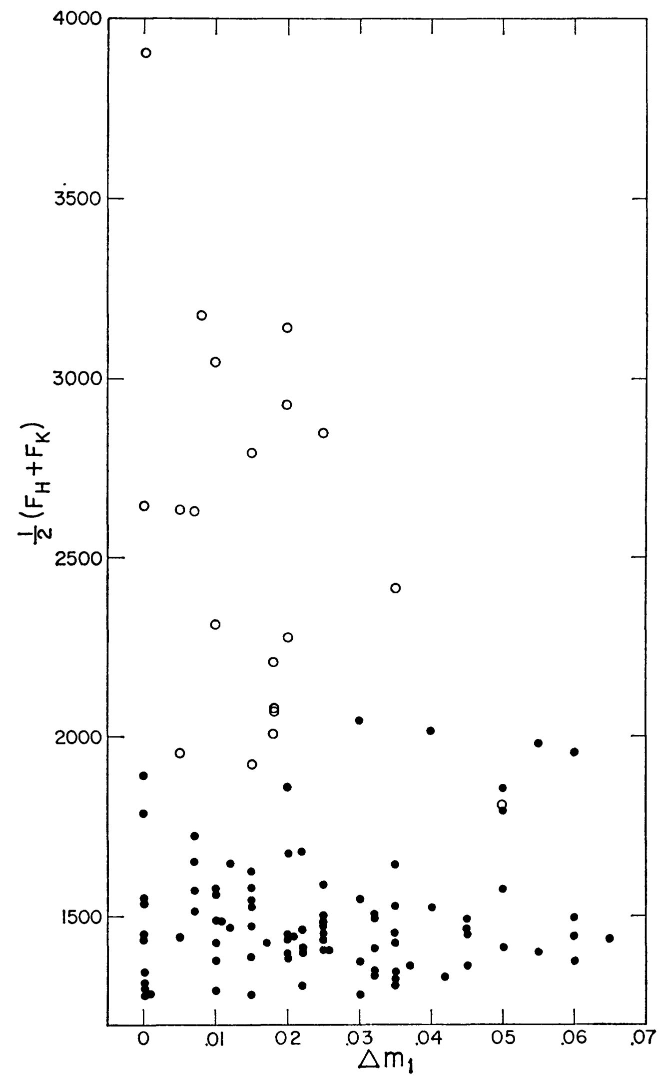

FIG. 3*a*.—Mean H-K flux versus Δm_1 for stars with $b - y \geq 0.30$

c) *Stars with* $b - y > 0.300$

For these stars, the differential fluxes are obtained by subtracting the same quantities from the measured fluxes for all objects. Hence it is immaterial whether diagrams are constructed from the fluxes themselves or from the differentials. Figure 3*a* is a plot of mean H-K flux against Δm_1. It is evident that the strong emissions nearly all occur in stars with smaller Δm_1. To some extent, this effect must merely reflect the fact that there are more stars with small Δm_1, i.e., with nearly solar metal content, than with large Δm_1. A major part of the effect is probably real, however, and presumably indicates that in the solar neighborhood the younger stars tend to have larger metal contents than the older ones. This is because in Figure 3*b* the emission-line stars have small Δc_1 also. In the band of points at the bottom of the diagram, no trend is discernible. The vertical width of this band, some 300 flux units or so, therefore represents a real intrinsic spread of chromospheric emission common to all Δm_1 values. The density of points is higher in the left-hand half of the band for the reason noted above.

A plot of mean H-K flux against $(\Delta c_1)_{corr}$ is shown in Figure 3*b*. If two or three points are ignored, the bulk of the distribution resembles a hook, with a long shank containing the strong emission objects on the left, a band at the bottom with a slight but definite

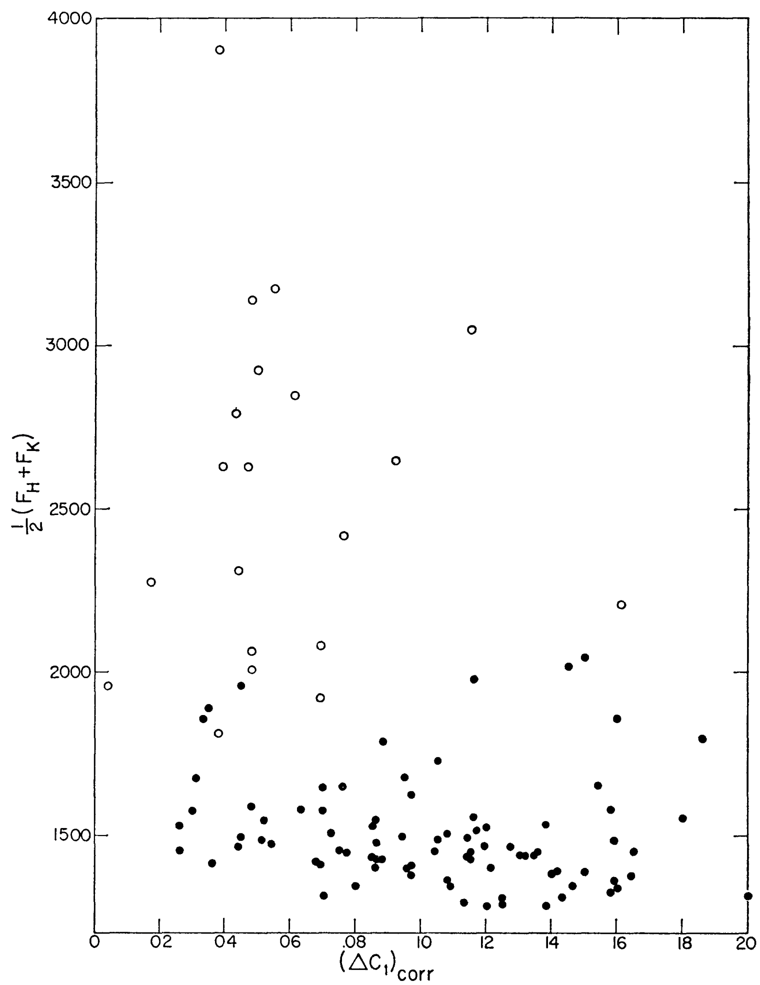

FIG. 3*b*.—Mean H-K flux versus $(\Delta c_1)_{corr}$ for stars with $b - y \geq 0.30$

downward slope to the right, and a rise on the right-hand side. Unlike Δm_1, $(\Delta c_1)_{corr}$ varies with time for each star; Figure 3*b* must therefore contain information on the secular changes in chromospheric emission for stars in this part of the H-R plane. The chromospheric evolution suggested by Figure 3*b* is this: A star arrives in equilibrium on the main sequence with strong chromospheric emission such that its representative point lies somewhere in the left-hand vertical portion of the figure. With the passage of time, the representative point descends until it lies within the band at the bottom. The trajectory of a point during this initial descent is vertical. The precise value of the flux at which the point comes to rest within the lower band must depend upon parameters outside the framework in which we are working. Figure 3*a* shows, for instance, that it does not depend on metal content. Conceivably, this residual flux may be a function of the ratio of rotational energy to magnetic energy stored in the star upon arrival at equilibrium on the zero-age main sequence.

Next follows a slow and rather small decline in chromospheric flux as the star evolves away from the ZAMS, so that the minimum observed H-K fluxes occur among the moderately evolved stars. Finally, for $(\Delta c_1)_{corr}$ in the vicinity of 0.14–0.18, the flux begins to rise again. A reasonable interpretation of this rise is that it marks the beginning of the rejuvenation of surface magnetic fields, which must be postulated to account for the universal presence of chromospheric emission in the giant region of the H-R plane, starting at spectral type G0.

d) *Doublet Ratio for Chromospheric Emission*

The ratio of the emission strengths of the H and K chromospheric components is of importance in fixing the physical circumstances under which the emission occurs, in particular the optical thickness of the gas masses involved. Table 1 contains information on this topic, which we now evaluate for stars with $b - y \geq 0.300$.

It is necessary first to decide on the true relative values of flux units at the wavelengths of the H- and K-lines. For the thirteen stars lying on the lower boundary of Figure 1, the means of the F_K and F_H are 1153 and 1465, respectively, and, since fifty-three observations contribute to these numbers, they should be firmly established. We assume that these are the residual fluxes in the photospheric absorption lines of the stars under consideration. These lines are very strong and heavily saturated; one would expect, therefore, that the ratio of the fluxes in their central regions should not differ greatly from unity. The measured ratio is, however, $F_H/F_K = 1465/1153 = 1.27$, and it must be supposed, therefore, that most of the difference between this number and unity has been introduced in the instrumentation. That this is indeed the case is borne out by the ratio measured for the standard lamp, which is always very close to $F_H/F_K = 1.22$. For a color temperature of 2800° K, this ratio should be 1.07. Unfortunately, the standard lamp cannot be compared directly to the stars for two reasons. In the first place, light from the lamp passes through an additional filter before entering the spectrograph, and this could introduce some, though probably not much, change in the measured ratio. The more fundamental reason is that the lamp provides a true continuous spectrum, whereas the stars do not. During stellar observation, the monitor channel does not measure the true stellar background because the monitor windows contain many absorption lines and, consequently, register fewer quanta than they would if the lines could be removed while the effective temperature of the star remained constant. Just as an example, typical values for the monitor counts, for 10^4 in the scan channel, are 127000 for the K-line and 100000 for H. Then $F_H = 10^4/10^5$ and $F_K = 10^4/1.27 \times 10^5$, which lead to $F_H/F_K = 1.27$. Suppose that about 20 per cent more light would be received in the monitor channel if there were no stellar absorption lines. The monitor counts would then be 1.20×10^5 and 1.47×10^5 for H and K, respectively, and F_H/F_K would be 1.22.

I do not see how the existing data can be used to evaluate accurately the flux ratio, F_H/F_K, for the residual photospheric light in the H- and K-lines. On the other hand, the above arguments show that it is quite reasonable to assume this ratio to be unity and that, in fact, it is probably close to this value. Accordingly, the ΔF_K of column (14) of Table 1 have been multiplied by 1.27 to yield the $\Delta F'_K$ of column (15). In this way the instrumental effects have been largely eliminated, and the ΔF_H of column (13) should be in very nearly the same units as the $\Delta F'_K$ of column (15). Finally, the ratios $\Delta F'_K/\Delta F_H$ are in column (16), and the mean of the differential fluxes are in column (17).

The stars in Table 1 with $(b - y) \geq 0.300$ and for which there are three or more observations have been divided into four groups according to their values of $\frac{1}{2}(\Delta F_H + \Delta F'_K)$. This quantity has the ranges 0–200, 201–400, 401–800, and >801 for the four groups. Means of $\Delta F'_K/\Delta F_H$ and of $\frac{1}{2}(\Delta F_H + \Delta F'_K)$ were formed and are plotted in Figure 4, where the numbers beside each point are the numbers of stars included in the means.

The simplest interpretation of Figure 4 is this: Weak chromospheric emission is produced in gas masses of moderate, though not extreme, optical thickness, but as the total emission increases, the optical thickness diminishes until, for the stronger lines, it is sufficiently small for the doublet ratio in Ca II to be approximately 1.25. It is of course

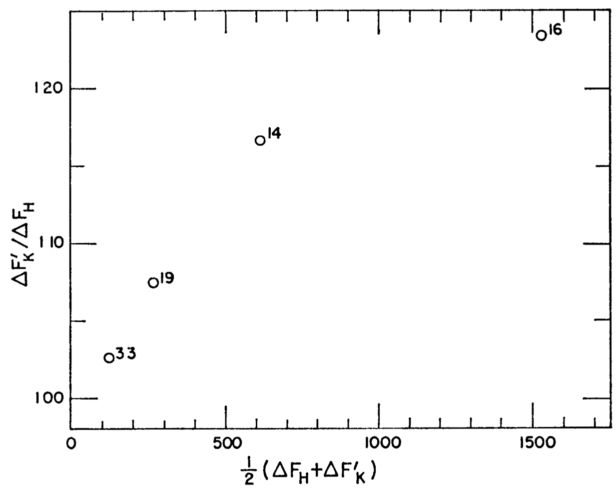

FIG. 4.—Mean chromospheric flux versus mean doublet ratio for groups of stars with $b - y \geq 0.30$ and three or more observations Numbers beside points are numbers of stars included in means.

quite possible that this interpretation is oversimplified and that the conditions of emission are complicated to a degree sufficient to render it invalid. Nevertheless, future theoretical investigations should, to be successful, provide a natural explanation for the results shown in Figure 4.

Finally, as to variability of chromospheric emission, the only statement which can be made is that during the first year of this program there has been no certain evidence of change in any of the observed stars. On the other hand, the time-base line is less than a year for many of them, and there is hope that the accuracy of observation can be improved. It is my intention to continue these observations, concentrating mostly on the stars with stronger chromospheric emissions, for an indefinite period in the future until variations of undoubted reality are found, or until it becomes clear that the technique is inadequate for the purpose.

In this connection a few words concerning the necessary accuracy are in order. Returning to Figure 1, the mean H-K flux for the stars on the lower boundary is about 1300 units, and this represents the constant non-variable portion of the flux for all stars. For stars in the middle of the lower band, the mean flux is about 1500 units. One per cent accuracy in the measurements of the total flux in these objects, therefore, represents 7.5 per cent precision in the measurement of the chromospheric component, which is much less favorable. About all that can be said is that the accuracy should be as great as possible, and that the higher it is, the brighter the prospect of successfully pushing the search for chromospheric variability toward the lower boundary of the distribution in Figure 1.

My thanks are due to J. B. Oke and E. W. Dennison for the design and construction of the scanner, and to the latter and his associates for prompt and efficient aid in overcoming occasional electronic difficulties. A. H. Vaughan, Jr., helpfully provided instruction in the operation of the equipment at the beginning of the program. The antiquated nature of the 100-inch telescope makes work of the kind described here physically exhausting for both the observer and the night assistant, especially when, as was frequently the case, thirty to forty stars were observed in the course of a night's work. Therefore, sincere thanks are offered to E. Hancock, A. Olmsted, H. Schaefer, and B. Traxler, who provided patient and efficient assistance at the telescope. Lastly, the tedious task of reducing the observations has been performed with great care by M. R. Riley, and Miss Louise Lowen provided invaluable assistance at the Computing Center.

APPENDIX

a) Coudé Scanner

Since the coudé scanner has not been described in detail in the literature, it is necessary, in the interest of clarity, to indicate here a few of its essential features.

The optical portion of the apparatus is mounted on the plate base of the 9-foot camera and consists of two parts. The first part provides two windows, about 25 Å wide and separated by about 250 Å, which intercept two 25 Å sections of the stellar spectrum. Light from these two regions is combined optically and fed into a refrigerated photomultiplier which, with its associated electronics, forms the monitor channel. The second, or scanning, section is more complicated. A prism is mounted so that one end can be moved up or down along a portion of the spectrum between the two monitor bands, while the other end projects the spectrum onto a scanning slit behind which is a second refrigerated photomultiplier. The prism is rotated by a lever arm actuated by a micrometer screw, which is in turn driven by a stepping motor. Attached to the stepping motor is a digital shaft encoder that provides a readout of the prism position at the observing station. One readout unit corresponds to approximately 0.011 Å in the spectrum. As long as the connection between the encoder and the stepping motor is unchanged, setting a given fixed wavelength to a specified readout insures that the same range of wavelengths will always appear accurately in the monitor windows.

The electronic part of the equipment counts photon pulses in both channels to any desired preset total in either one. When this total is reached, the count ceases and the results, including the HD number of the star and the scan-prism readout, are printed on tape. No means of recording the integration time is provided; therefore, a small manually operated electric clock is used to obtain these intervals which are needed to correct the pulse counts for dark current. Dark currents are found from 20 to 30 samplings of 100-sec intervals in both channels during a run, and the mean values are then used in all reductions.

The most suitable photomultipliers available to me when this work was initiated were an ITT FW 130 for the scan channel and an RCA 7102 for the monitor, with S20 and S1 cathodes, respectively. Since the S1 has strong red sensitivity, filters are required to remove unwanted first-order radiation. Corning 9788 filters are used for this purpose. One is placed inside the spectrograph in the monitor beam, a second is in front of the entrance slit during all measurements, and a third is mounted in front of the aperture in the standard-lamp box. Calculation indicates that effects of red radiation should be reduced to less than 1 per cent of the total in both channels for all observations.

b) Wavelength Calibration

An accurate wavelength calibration, essential for the work under discussion, is obtained by scanning the Fe I 3930 Å line produced in a hollow cathode tube. At the beginning of each run this line is located and the grating adjusted until the line center is within about 20 readout units of a standard value. As noted above, this procedure insures that the same wavelength intervals always appear within the monitor windows, to an accuracy of the order of 0.2 Å.

The position of $\lambda 3930$ is determinable to about 0.02 Å by recording a scan on a Brown recorder. Once $\lambda 3930$ has been located, the scale of the apparatus yields the readouts for undisplaced H- and K-lines. Computer-plotted curves, available for all stars on the program, permit the Doppler correction, in readout units, to be read to the nearest unit for every day of the year. For any given star and date these corrections, added to the undisplaced H and K values, allow the scanning slit to be placed accurately at the centers of the star's H- and K-lines. A correction curve includes, of course, the catalogue value of the star's radial velocity as well as the component of the Earth's motion. Since all stars on the program are relatively bright and have radial velocities of qualities *a* or *b* in Wilson's *Catalogue* (1953), the setting error due to uncertainty in the radial velocity should seldom exceed 0.04–0.05 Å.

Every effort is made to keep the wavelength errors to within 0.05 Å, and in any event less than 0.1 Å. Unfortunately, the equipment is subject to wavelength drifts whose origin is not fully understood, but which are probably of thermal origin since they appear to depend on the temperature difference between the inside and outside of the spectrograph. Consequently, it is necessary to check the wavelength at least three or four times nightly, and, under the most unfavorable circumstances, an hourly check is made. The seriousness of this drift was not appreciated until the work was well along, and some of the earlier measures are probably somewhat reduced in accuracy owing to uncorrected wavelength shifts.

c) Standard Lamp

Because the scanner is an accessory of a spectrograph used by many individuals for a variety of purposes, the photomultipliers are mounted at the beginning of each run and disassembled again at the end. As a result, small mechanical shifts can, and do, introduce spurious differences between the two channels. To correct for these, a standard lamp is observed each afternoon during an observing run. A series of ten counts, to a total of 10^5 each in the scan channel, are made at the wavelengths of the H- and K-lines, thus insuring negligible statistical error. The importance of using a standard lamp is shown by the fact that the lamp readings have exhibited a range of nearly ± 9 per cent thus far.

The lamp is mounted in a small wooden box with an aperture in one end which is directed down the spectrograph axis toward the slit. A ground glass and filter are placed over the aperture. Directly over the slit is a second ground glass and a mask that leaves uncovered about 2 mm of slit length centered on the point where star images are held during stellar observations. In this way the same areas on the cathodes should be illuminated by the lamp as by the stars. Radiation from the lamp overfills the collimator, but tests have shown the effects of this excess light to be insignificant.

The lamp itself is a GE Type 1960 consisting of a coiled tungsten filament inside a small quartz envelope. Iodine vapor inside the bulb inhibits deposition of metal on the inner surface of the envelope. Nominal operating voltage is 11.0 V, but 10.8 V have been used to insure long life. Current is supplied by a modified Technipower M 10.8–12.0 A power supply which, by actual measurement, has maintained voltage constant to about 0.005 V during the period of use.

Results from the standard lamp have not been as satisfactory as hoped. Lamp readings during a run usually are constant to within 1 or 2 per cent, but they occasionally show a range as great as 4 per cent. The reason for these variations is unknown. In any case, the star observations have been reduced using the lamp factors, as explained in the text. Observations for each night have been reduced with the lamp factors from the preceding afternoon, but unless the consistency of the lamp readings can be improved, it is evident that numerous observations of standard stars will be required to achieve the ultimate in over-all precision consistent with the statistical uncertainty.

d) *Accuracy*

One great advantage of the pulse-counting technique is that the number of counts provides a basic statistical limit to the precision of the observations, to which the observational error must be made to approach as closely as possible. In the present instance, the number of counts in the monitor channel exceeds those in the scan channel by factors of the order of 5 to 12, and, therefore, even though the dark current is twice as large in the monitor channel, the over-all statistical error may be considered to be that due to 10^4 counts in the scan channel. For 10^4 counts, the standard deviation is 1 per cent, and the probable error of an observation, due to statistics alone, is 0.7 per cent.

Probable errors have been computed, after correction by the standard-lamp factors, for thirteen stars for which six or more observations were available. The probable errors of a single observation of one line range from 0.6 to 3.2 per cent, with mean values of 1.9 and 1.8 per cent for H and K, respectively. This result is perhaps not too disappointing, but there is plenty of room for improvement, since these probable errors are nearly three times larger than those of purely statistical origin. Since it is not known what accuracy is needed to produce incontrovertible evidence of stellar cycles, every effort will be made to improve the accuracy and to approach the statistical error more closely.

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