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STELLAR CONVECTION ZONES, CHROMOSPHERES, AND ROTATION

O. C. Wilson
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology

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ABSTRACT

This paper is an attempt to connect the rotations of main-sequence stars with their chromospheric properties and, hence, with the extent of their hydrogen convection zones. It is based on 10 Å/mm spectrograms of 308 stars, with $b - y \geq 0.240$, from the Strömgren-Perry catalogue.

On the zero-age main sequence it is found that rotational velocities of the order of $V \sin i \geq 50$ km/sec set in very abruptly at $b - y = 0.285$, and Kraft's observations show that this is true also in the Hyades. However, similar rotational velocities are found among the field stars at the upper edge of the main-sequence band among spectral types G0–G5, and it is logical to suppose that these objects have evolved from the zero-age line near $b - y = 0.285$. A curve can be drawn in the $(b - y) - c_1$ plane which separates the large from the small rotations, and this curve, therefore, approximates the evolutionary track of stars originating at $b - y = 0.285$ on the zero-age line. This curve, which divides the larger from the smaller angular momenta, applies to the members of spectroscopic binary systems as well as to single stars.

Stars showing emission at H and K have a strong concentration to the zero-age line and extend up the main sequence to $b - y = 0.30$. It cannot be stated definitely that stellar chromospheres terminate near this point, but the evidence indicates that it is quite possible that they do. If so, the close agreement between the onset of larger rotations and the termination of chromospheres is very suggestive of the braking mechanism described by Schatzman. The implication, then, is that deep hydrogen convection ends at $b - y = 0$ 285 on the zero-age line (spectral type F4), and the observations show that the change from deep to shallow convection must occur within a mass range of the order of 5 per cent.

I. INTRODUCTION

One of the older, but still troublesome, problems of astrophysics relates to the rotations of the stars. On the main sequence it has long been known that large rotational velocities are common among the O-, B-, and A-type stars, that these large velocities diminish in proceeding toward cooler objects, and that they virtually disappear somewhere near type F5. The difficulty is not, apparently, to account for the existence of large rotational velocities, which can presumably arise from differential galactic rotation and/or turbulent motions in the prestellar medium, but to explain why they are not found throughout the main sequence. In other words, what is the braking mechanism which is very effective for the later-type stars but much less so for the earlier types? We shall return briefly to this point later.

In recent years there have been a number of observational studies of stellar rotation. Huang (1953), Herbig and Spalding (1955), and Slettebak (1955) have produced extensive lists of rotational velocities for field stars, and Treanor (1960), Abt and Hunter (1962), and Kraft (1965) have made similar studies of the members of clusters and associations. Although many of the field stars were observed with dispersions of the order of 10 Å/mm, the dispersion was considerably less than that for a number of them. Furthermore, in all of these papers except those of Kraft and Treanor, the absolute magnitudes and spectral types were derived solely from spectroscopic observation. As a result, it is impossible to see the detailed form of the rapid decline in rotational velocity, or to locate accurately where it occurs. Both of these items are likely to be of considerable importance in theoretical discussions of braking mechanisms.

A recent paper by Wilson and Skumanich (1964) dealt with spectroscopic observations of 142 stars from the photometric catalogue of Strömgren and Perry (1962), covering the approximate spectral-type range F7–G5, i.e., for $b - y \geq 0.325$. In this work it was noted that several stars of types G0–G5 showed considerable rotational line broadening, and that these stars occurred along the upper edge of the main-sequence band. These objects also gave spectroscopic evidence of higher luminosity than normal for main-sequence stars of the same colors, and it was concluded that they had probably evolved into their present locations from some earlier part of the main sequence not covered by the spectroscopic observations.

It was of interest to the writer to trace the presence of stellar chromospheres, as evidenced by emission at H and K, as far up the zero-age main sequence as possible. The accomplishment of this aim would require a rather limited program of observation of selected zero-age stars having $b - y$ values less than 0.325. But, since the same spectrograms would yield rotational velocities, it was decided to enlarge the observing program by including stars throughout the main-sequence band, extending to $b - y = 0.240$. In this way it was hoped to locate the origin of the rapidly rotating stars mentioned above, and, perhaps, to shed some light on the nature of the decline in rotational velocity among the zero-age stars. The great advantage in proceeding in this way is that the Strömgren-Perry photometry provides the equivalents of spectral types and luminosities, but with much greater accuracy than is attainable from spectroscopic observation. This program has been carried out and the results are described below.

TABLE 1

CALIBRATION OF ROTATION GROUPS

Group	$V \sin i$ (km/sec)	Group	$V \sin i$ (km/sec)
0	≤ 10	3	35–45
0+	10–15	4	45–55
1	15–25	5	>55
2	25–35		

II. THE OBSERVATIONS

a) *Rotational Velocities*

Spectrograms of 10 Å/mm dispersion have now been obtained for a total of 308 stars from the Strömgren-Perry catalogue, for those objects with $b - y \geq 0.240$. This total includes the 142 stars previously discussed by Wilson and Skumanich (1964).

For these spectrograms the projected slit width is about 14 km/sec, which is approximately equal to the resolution of the baked IIa-O emulsion. Hence the minimum line width discernible may be taken as 20 km/sec and the limiting $V \sin i$ as 10 km/sec. Below this value there is no discrimination.

The method of evaluating the rotational velocities was as follows. Starting with any fairly large group of the spectrograms, any convenient plate was selected as a standard and the others were compared with it, one by one, on the comparator. As a result, the plates of the group were readily divided into three subgroups; in one of these the line widths and the resolution of patterns of lines were very similar to those of the standard plate. In the other two subgroups, rotational broadening was distinctly less than the standard in one and distinctly more in the other. The subgroups were then treated in the same fashion and further subdivided. In this manner it was found that the spectrograms could readily be sorted into seven groups within which differences of rotational broadening were fairly small and uncertain, and between which the average differences were distinct. Finally, from spectrograms of the same dispersion of several Hyades stars whose rotational velocities had been previously determined by Kraft (1965), the different rotation groups were calibrated in terms of $V \sin i$. This relationship is shown in Table 1.

Actually, the $V \sin i$ values must form a continuum, and the groups of Table 1 are, to some degree, artificial. Their widths have rather arbitrarily been set equal to their separations in order to avoid any impression of higher accuracy than is really present, and to allow for the fact that there is a considerable range of plate density which enhances the uncertainty for a number of the stars. It is my feeling that to attempt any appreciable increase in precision would very greatly increase the labor involved without yielding any significant change in the over-all picture, and that few, if any, of the stars have been placed in the wrong rotation groups.

A few other comments are in order. The group labeled 0+ is that in which the resolution of very close pairs of faint lines is just noticeably impaired. These effects are rather sensitive to plate density, to emulsion quality, and to minute variations in focus. Moreover, judgment is difficult for objects in which $V \sin i$ is barely above the level of discrimination. Hence it is quite likely that some of the stars in both groups 0 and 0+ should be assigned to the other group. However, as will be seen, most of the 0+ stars are objects in which small rotation is reasonably to be expected and, therefore, it is believed that a majority of the assignments are correct.

Rotation group 5 contains stars with a fairly wide range of rotational velocities, all of which, however, are distinctly larger than those of group 4. In group 5 all of the line patterns which are useful criteria in group 4 have blurred together and the dispersion of 10 Å/mm is too large to permit of accurate line-width estimates. Some of the stars in this group probably have $V \sin i$ values approaching 100 km/sec.

b) H and K Emission Intensities

All of the stars exhibiting H and K emission, including several new ones, have been re-examined and intercompared on the comparator so that the emission intensities have been arranged on a more meaningful scale than in the paper of Wilson and Skumanich (1964).

c) Data

All single stars, except those with H and K emission, are included in Table 2. The various columns are self-explanatory and the $V \sin i$ values corresponding to the rotation groups are to be interpreted according to Table 1. A few of the rotation-group numbers are followed by a colon; these are for a small number of stars observed with an experimental image-tube camera. Since the range of spectrum was limited, the resolution somewhat inferior, and the dispersion larger than for the other stars, no very exact comparison was possible. It is believed, however, that the rotations given for these stars are not seriously in error and, since there are only eight of them in Table 2 and they cannot appreciably modify any of the conclusions, they have been retained.

Table 3 contains rotation and H-K intensity estimates for all single stars showing H-K emissions.

In Table 4 are the results on all known spectroscopic binaries which have been observed. Four stars in this table, not listed as binaries in the *General Catalogue of Stellar Radial Velocities* (Wilson 1953), have been included since their spectra, at 10 Å/mm, show double lines. These new binaries are HD 43358, 60803, 166285, and 221950. Colons following the rotation group numbers again signify image-tube observations.

III. RESULTS

The results of the investigation are shown graphically in several figures. Figure 1 contains the rotational data for all of the observed stars except those known to be spectroscopic binaries; the dashed curve is the zero-age main sequence as defined by Strömgren (1963).

In Figure 2 are shown the rotational velocities for the known spectroscopic binaries included in the observations, and Figure 3 gives the distribution of known spectroscopic

TABLE 2

ROTATIONS OF SINGLE STARS, NO H-K EMISSION

Stromgren No	HD	m_v	$b-y$	m_1	c_1	Rot Group
10	1671	5 2	288	162	566	3
11	2454	6 0	301	134	436	0
13	3229	5 9	306	132	493	0
21	4614	3 6	372	185	275	0
25	5015	4 9	346	193	412	0
30	6210	5 9	356	183	475	2
31	6301	6 1	294	154	471	0+
38	6920	5 7	390	168	410	0
40	7439	5 2	294	130	432	0
41	7476	5 8	283	154	488	0
50	8723	5 3	256	148	485	4
52	8799	5 0	288	148	477	4
56	9562	5 9	395	214	389	0
61	10307	5 1	389	203	338	0
66	11151	5 9	264	181	505	3
73	12235	5 8	388	208	411	0
81	13201	6 4	296	147	403	0
82	13421	5 7	366	170	462	0
83	13456	6 1	266	155	515	0:
84	13555	5 4	308	132	466	0
85	13871	5 8	288	171	498	0+
99	15335	5 9	381	174	353	0
101	15524	5 9	273	166	526	4
105	16176	5 9	320	160	463	1
107	16234	5 7	336	146	380	0
109	16327	6 3	306	170	529	3
110	16399	6 5	281	150	510	0+
112	16647	6 2	268	154	466	1
115	16895	4 2	326	165	373	0
126	18256	5 6	308	153	452	0+
127	18262	6 1	315	164	499	0
129	18404	5 8	277	166	483	1
138	19373	4 2	376	201	376	0
139	19994	5 1	362	192	400	0
140	20193	6 3	247	137	569	0+
143	20395	6 2	257	162	466	0:
148	21019	6 3	436	121	268	0
153	21794	6 4	342	152	418	0
156	22211	6 5	404	180	474	0
193	25570	5 5	250	146	558	3
230	28271	6 5	346	171	497	3
252	29645	5 8	378	190	397	0
253	29859	6 2	344	177	444	0
259	30652	3 3	299	162	413	0+:
278	32923	5 0	415	197	332	0
280	33021	6 3	390	199	338	0
285	33256	5 2	307	129	443	0
288	33608	5 9	295	185	456	0
292	34180	6 1	254	160	531	4:
293	34411	4 8	389	206	363	0
305	35984	6 2	308	150	532	3
306	36066	6 5	376	174	433	0
339	40832	6 2	290	158	487	0+
342	41330	6 1	374	182	334	0
349	43042	5 2	293	163	448	0
351	43318	5 7	313	175	435	0
357	43587	5 8	382	200	331	0
361	45067	5 8	368	162	409	0
363	45504	6 5	342	169	389	0
373	47703	6 3	334	155	376	0
374	48682	5 3	357	185	371	0
375	48737	3 4	288	167	552	4
380	49933	5 8	274	118	469	0:
387	50692	5 8	376	184	306	0
393	51530	6 1	348	134	390	0
397	52711	6 0	374	198	301	0
403	55130	6 4	330	174	380	0
404	55575	5 6	370	173	294	0
410	57006	6 0	338	171	466	0
411	57517	6 5	349	166	375	0
412	57708	6 3	420	235	585	0
425	59380	6 0	320	136	407	0
427	59984	6 0	336	149	334	0
437	61421	0 5	272	167	532	0
447	64235	5 8	257	178	486	1:
453	66011	6 1	356	200	473	0+
456	67228	5 4	408	206	402	0
457	67483	6 3	313	152	514	3
459	67827	6 5	368	194	390	0
469	70110	6 3	384	204	400	0
476	71148	6 3	394	214	317	0
481	71433	6 5	338	163	518	0+
486	72291	6 1	272	136	458	1:
489	72779	6 6	442	200	459	5
497	74243	6 3	290	164	473	1
505	75528	6 3	420	206	386	0
513	76572	6 2	303	135	504	0
534	80441	6 5-6 7	280	138	452	0:
539	81809	5 4	418	182	366	0
542	81997	4 8	296	164	448	1
550	82543	6 2	386	214	587	0
558	83951	6 0	244	162	594	0+
565	84737	5 2	390	203	382	0
572	85380	6 5	368	186	403	0
577	86728	5 6	415	235	385	0
582	87822	6 2	286	165	490	0
586	88986	6 5	396	208	368	0
587	89010	5 9	405	228	364	0
590	89125	5 8	336	140	352	0
592	89389	6 4	366	185	368	0
593	89449	5 0	297	171	459	0+
595	89744	5 9	336	186	450	0
602	90508	6 5	395	182	272	0
604	90839	4 8	341	172	331	0
609	91752	6 3	289	136	476	0
616	93765	6 1	264	132	580	0
620	95128	5 1	392	203	337	0
621	95216	6 4	288	155	436	0
622	95241	6 1	378	170	376	0
643	99028	4 0	267	172	606	0+
644	99285	5 6	254	142	604	2
646	99373	6 3	302	151	501	0
649	99984	5 9	340	148	429	0
650	100180	6 2	367	188	332	0
652	100563	5 8	302	169	419	0+
656	101606	5 7	310	125	400	0
660	102574	6 3	369	204	420	0
662	102634	6 2	325	186	431	0
666	102870	3 8	354	190	412	0
679	106022	6 4	270	153	583	5
681	106516	6 1	317	118	333	0
688	107213	6 3	336	192	451	0
692	107705	6 5	352	190	370	0
699	108722	5 5	289	172	611	5
702	108845	6 2	345	168	415	0
704	108954	6 2	360	181	330	0
706	109358	4 3	385	182	296	0
709 br	110379	3 6	245	147	528	1
709 ft	110380	3 7	245	147	528	2
712	110897	6 0	375	150	280	0
715	111199	6 3	350	164	482	0+
718	111456	5 9	319	158	367	3
727	113022	6 1	288	178	446	1
728	113139	4 9	246	172	576	5
729	113337	6 0	275	167	479	0
731	113848	6 0	269	153	514	2
744	116568	5 8	276	150	46[illegible]	3
748	117176	5 2	452	233	348	0
751	117361	6 3	259	157	642	5
760	119288	6 1	278	146	464	0+
761	119992	6 4	316	154	387	0
764	120066	6 3	404	192	388	0
765	120136	4 5	319	179	439	0
771	121560	6 2	335	154	330	0
773	121682	6 3	260	169	596	0
774	122106	6 3	317	182	484	0+
779	122797	6 3	265	154	508	4
781	124115	6 3	312	175	456	2
783	124570	5 5	343	196	440	0
785	124850	4 2	341	163	448	0

TABLE 2 - continued

Stromgren No	HD	m_v	b − y	m_1	c_1	Rot Group
788	125111	6 3	255	144	522	0
790	125406	6 2	310	157	533	2
791	125451	5 3	267	162	484	3
795	126053	6 3	402	200	269	0
796	126141	6 2	261	161	488	0
803	127334	6 4	439	250	383	0
806	127821	6 0	285	148	428	4
808	127986	6 4	340	170	486	0
809	128093	6 3	300	131	476	0+
810	128167	4 5	254	135	490	0
811	128332	6 2	340	162	348	0
813	129502	4 0	254	167	530	3
814	130817	6.0	258	139	518	0+
816	130945	5 8	313	169	491	1
819	132254	5 7	338	174	410	0
820	132375	6 0	336	170	428	0
824	133484	6 4	305	161	506	1
825	134044	6 3	353	165	391	0
826	134083	5 0	285	165	449	3
828	136064	5 2	350	177	422	0
829	136202	5 2	352	176	425	0
832	136751	5 9	245	166	643	5
835	137510	6 3	397	214	441	0
841	138525	6 3	348	164	448	0
850	141004	4 4	385	199	354	0
855	142373	4 6	381	151	323	0
856	142860	3 9	320	153	403	0
860	143761	5 4	394	183	322	0
864	147365	5 5	268	168	467	4
870	150012	6 2	276	173	540	2
878	151900	6 3	278	137	506	3
882	153987	6 4	274	154	457	3
887	154905	5 8	318	164	457	2
	154906	5 8	318	164	457	1
891	155646	6 5	330	156	479	0
897	157214	5 4	409	182	309	0
902	157856	6 3	294	154	498	0
912	159332	5 6	328	148	471	0
921	160910	5 6	258	155	541	2
923	161239	5 7	420	223	449	0
927	162826	6 5	352	188	371	0
928	162917	5 8	278	172	458	2
935	164259	4 6	254	154	564	4
938	165567	6 5	323	163	475	0+
941	165908	5 2	361	143	326	0
947	167588	6 5	376	156	357	0
949	168009	6 3	410	206	340	0
951	168151	5 0	281	143	472	0
960	171802	5 4	262	150	524	1
969	173667	4 3	314	150	484	0+
976	175824	5 9	286	162	557	4
977	176095	6 4	307	166	479	0
979	176303	5 4	350	174	455	1
988	178449	5 0	253	144	708	5
989	178476	6 2	288	138	538	4
992	179422	6 3	285	160	468	3
998	181096	6 0	320	147	435	0
1001	182101	6 2	320	125	425	0
1005	182807	6 2	339	168	352	0
1007	182900	5 8	302	169	541	2
1009	184663	6 5	280	144	480	3
1014	185124	5 5	268	176	524	5
1015	185395	4 6	261	158	506	0
1019	186155	5 0	265	202	720	3
1022	186408	6 3	410	214	375	0
1023	186427	6 4	416	226	354	0
1025	186760	6 3	381	182	427	0
1027	187013	5 0	316	155	435	0
1030	187691	5 2	356	188	404	0
1031	187923	6 2	424	190	333	0
1039	190406	5 9	389	197	321	0
1041	191096	6 2	278	155	535	3
1042	191195	5 7	280	156	507	0
1045	192455	5 7	334	186	464	0
1050	192985	5 9	281	164	481	0
1053	194012	6 2	338	162	342	0
1070	197373	6 0	302	140	459	2
1072	198084	4 6	353	197	431	0
1073	198390	6 0	302	146	419	0
1080	199941	6 5	246	155	508	3
1081	199960	6 3	406	209	397	0
1083	200790	6 0	350	170	421	0
1084	201507	6 5	248	160	675	5
1093	203784	6 6	335	159	584	5
1095	203842	6 4	307	172	617	5
1099	204121	6 4	306	157	475	0+
1118	207652	5 3	263	156	545	4
1119	207978	5 6	309	108	439	0
1122	208703	6 2	248	159	523	0+
1123	209149	6 5	298	136	562	3
1133*	210459	4 4	304	177	778	5
1139	210855	5 4	338	174	488	0
1142	211575	6 4	278	172	462	0+
1143	211976	6 2	302	148	409	0
1144	212487	6 2	314	154	486	0
1145	212754	5 8	330	188	417	0
1146	213429	6 2	360	188	328	0
1154	215243	6 4	318	155	432	0
1158	216385	5 3	321	149	433	0
1161	216756	6 0	273	138	530	0
1168	217926	6 3	276	138	625	4
1174	218470	5 8	286	152	495	0
1176	218804	5 8	302	145	442	1
1179	219291	6 4	309	134	549	5
1181	219487	6 5	276	146	468	1
1182	219623	5 6	352	171	396	0
1187	220117	5 8	296	170	489	0+
1189	220657	4 6	390	186	461	4
1191	221356	6 5	350	162	309	0
1198	222451	6 3	272	154	514	2
1202	223421	6 4	277	140	546	5
1205	223552	6 5	258	148	472	5

*Sharp off-center cores in H and K Interstellar?

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TABLE 3

SINGLE STARS WITH H-K EMISSION COMPONENTS

Strömgren No	HD	m_v	$b-y$	m_1	c_1	Rot Group	H-K Int
113 ..	16773	5 9	319	174	348	0	1
196	25998	5 6	334	180	373	0+	1
204	26913	7 2	410	260	287	0	3
205	26923	6 5	367	190	318	0	2
301	35296	5 1	348	169	352	0+	3
332	39587	4 6	380	193	307	0	2
490	72905	5 7	390	206	282	0	3
502	75332	6 2	336	184	362	0	2
509	76151	6 0	411	237	341	0	2
526	78366	6 0	377	198	311	0	1
584	88737	6 1	361	184	440	0	1
634	97334	6 3	392	210	311	0	2
718	111456	5 9	319	158	367	3	1
720	111812	5 1	437	195	407	4	2:*
733 .	114378	5 2	304	152	386	1	1
735 .	114710	4 3	372	193	336	0	1
739 .	115383	5 2	376	191	383	0	3
759 .	119124	6 3	346	166	334	0	2
798	126660	4 1	334	156	418	1	1
884	154417	5 9	374	174	329	0	2
1114	206860	6 1	379	190	305	0	3
1210	224635	6 6-6 6	347	176	348	0	1
1213	224930	5 8	431	190	203	0	1

* The emission is broad and the intensity given is likely to be an underestimate.

TABLE 4

OBSERVATIONS OF SPECTROSCOPIC BINARIES

Strömgren No.	HD	m_v	$b-y$	m_1	c_1	Rot. Group	H-K Int	Remarks
32	6397	5 6	276	149	508	0	0	2 sp.
62.	10308	6 3	306	154	463	0+	0	2 sp.
87	13974	5 1	386	191	254	0	1	
104	15814	6 1	354	196	349	0	1	
108	16246	6 6	267	161	485	3:	0	
353	43358	6 3	301	139	478	0	0	2 sp.
417	58551	6 4	324	123	356	0:	0	
420	58728	5 3	286	166	466	2:	0	
432	60803	5 9	373	193	382	0	0	2 sp.
452	65626	6 5	405	198	394	0+	3*	
528	79028	5 2	386	182	375	0	0	
770	121370	2 8	378	206	474	0	0	
874	150680	3 0	415	207	408	0	0	
899	157482	5 7	442	205	460	0+	2	2 sp.
920	160365	6 3	382	151	573	5	0	
929	163151	6 3	291	172	543	5	0	
945	166285	5 7	305	164	452	0	0	2 sp.
961	171834	5 4	256	144	564	4	0	
1092	203454	6 5	349	181	319	0+	1	
1128	210027	4 0	296	159	446	0:	0	
1138	210763	6 4	312	178	487	0+	0	2 sp
1183 .	219877	5 7	254	172	521	4:	0	
1193	221950	5 6	304	121	389	0	0	2 sp.
1201	223346	6 4	308	128	478	0+	0	

* Emission is from fainter component of system

binaries among the Strömgren-Perry stars with $b - y \geq 0.240$. In Figure 3, eight binaries with $c_1 > 0.7$ and $0.30 < b - y < 0.39$ have been omitted. Data on the binaries is from the *General Catalogue of Radial Velocities* (Wilson 1953), and the four newly discovered ones mentioned above have been included. In both of these figures the dashed curve is again Strömgren's zero-age main sequence, and the solid curve is the boundary between the large and small rotations in the $(b - y) - c_1$ plane as determined from Figure 1.

Figure 4 shows the rotational velocities in the Hyades. These are taken from recent work by Kraft (1965) and have been plotted using the same symbols as in Figures 1 and 2.

Intensities of H-K emission in all single stars whose spectra exhibit these features are given in Figure 5, in which the solid and dashed curves are the same as in Figures 2 and 3.

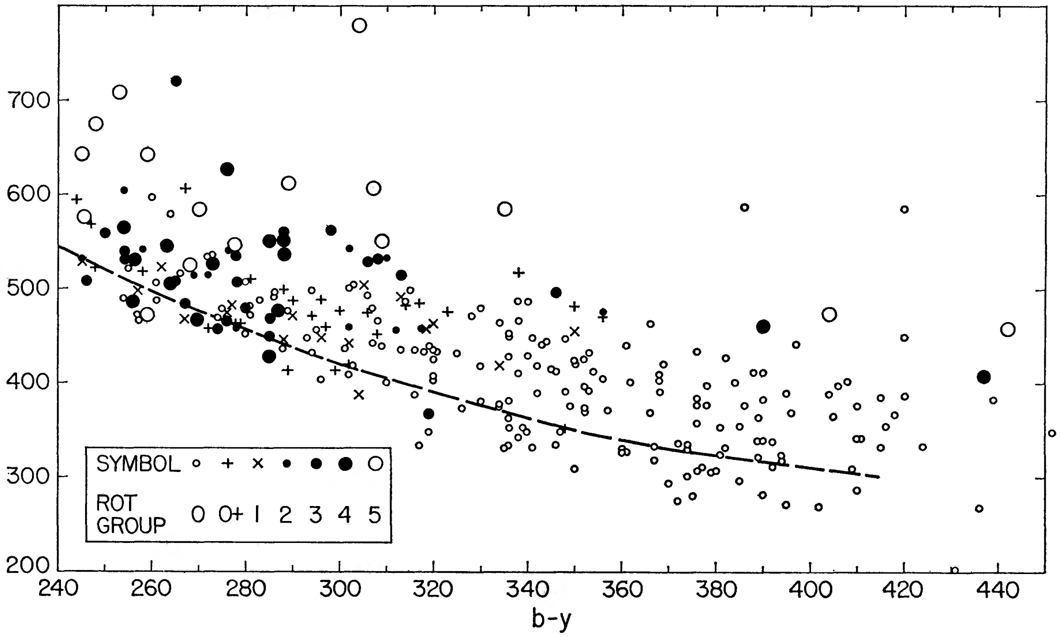

FIG. 1.—Axial rotations of all single stars in $[(b - y), c_1]$ — plane. Dashed curve is zero-age main sequence.

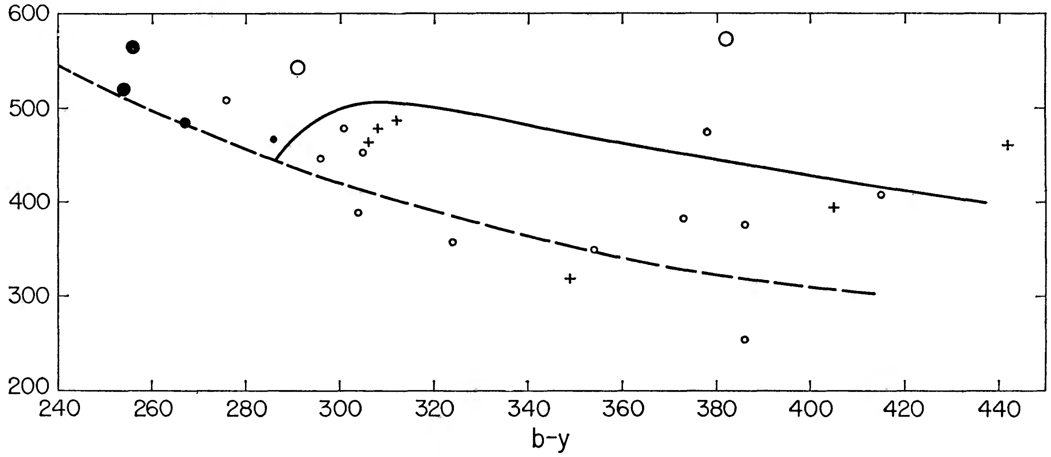

FIG. 2.—Rotational velocities for spectroscopic binaries. Dashed curve is zero-age main sequence. Solid curve is boundary between large and small rotations of Fig. 1.

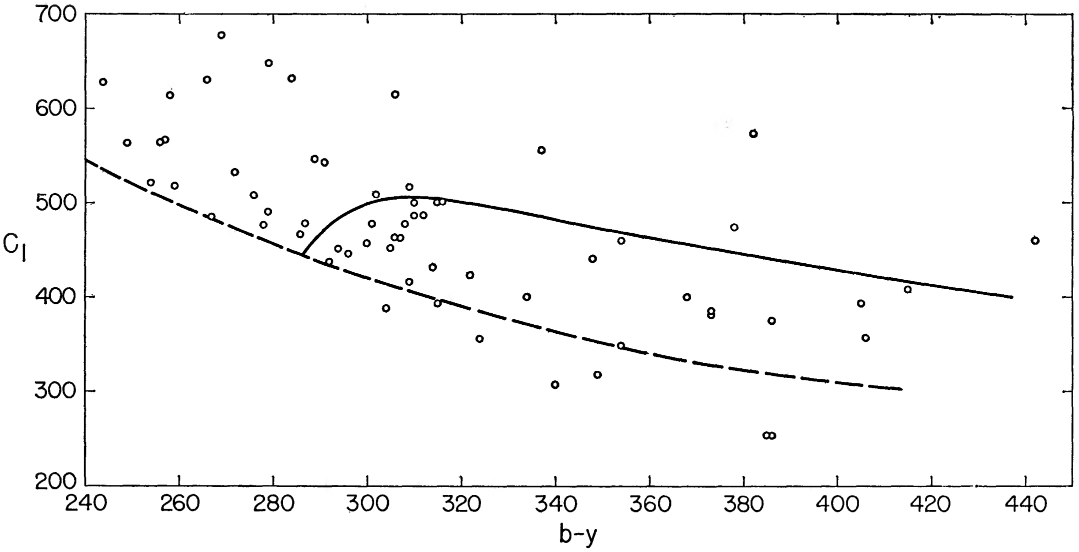

FIG. 3.—Distribution of known spectroscopic binaries among Strömgren-Perry stars with $b - y \geq 0.240$. Curves same as in Fig. 2.

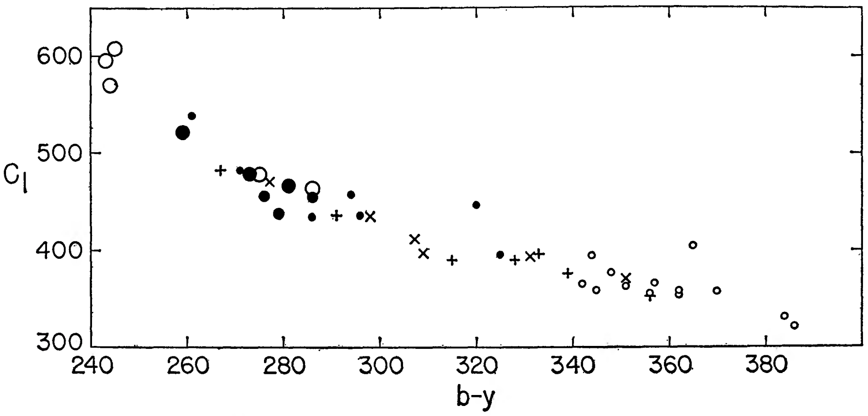

FIG. 4.—Axial rotations in Hyades (Kraft)

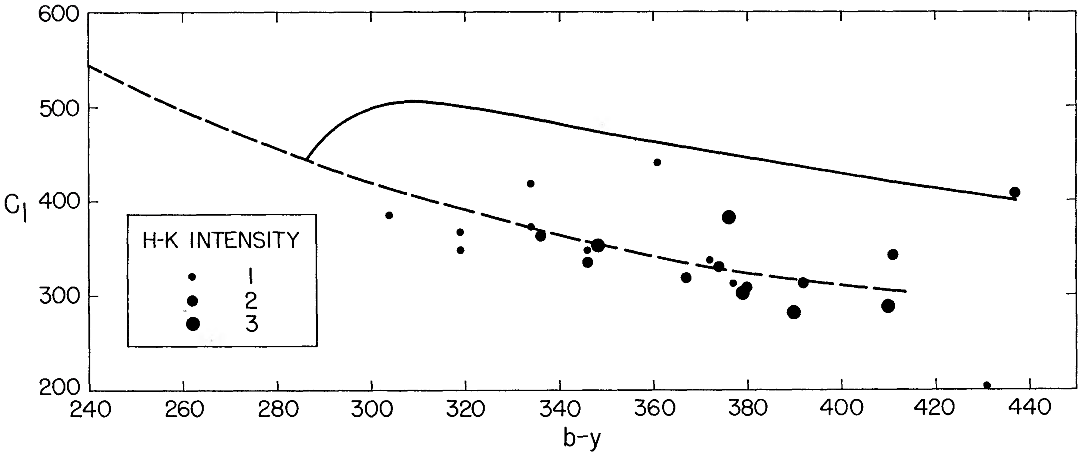

FIG. 5.—Single stars with H-K emission. Curves same as in Fig. 2

IV. DISCUSSION

a) Stellar Rotation

The first question relates to Figure 1: Where have the rotating stars on the right-hand side originated? The most logical answer is that they have come from the nearest point on the zero-age main sequence where similar rotational velocities are found, i.e., at $b - y \approx 0.285$. With the relationship between $b - y$ and spectral type given by Strömgren (1963), this point corresponds to spectral type F4. The natural interpretation of the distribution of the larger rotations in Figure 1 is, therefore, that stars, beginning on the zero-age main sequence, follow evolutionary trajectories which carry their representative points upward and to the right in the diagram. Note that the stars of small rotation, just to the right of the larger rotational velocities near $b - y = 0.285$, also have a distribution in the plot which is consistent with this interpretation. If this picture of affairs is correct, then the solid curve in Figures 2, 3, and 5, which forms the boundary between the larger and smaller rotations of Figure 1, must represent approximately the evolutionary track for stars originating close to $b - y = 0.285$ on the zero-age main sequence.

The relationship between Δc_1, as measured from the zero-age line, and ΔM_V is given by Strömgren (1963). A G2 star on the boundary line between large and small rotations would have $\Delta c_1 \sim 0.1$ and $\Delta M_V \sim 1.6$. This information, together with the revised stellar temperature scale of Harris (1963), leads to the result that the radius of a zero-age F4 star must increase by a factor of about 1.6 in evolving to G2. This factor is much too small to reduce the observed rotational velocities at zero-age F4 to small rotations (≤ 10 km/sec) at evolved G2, although one would expect a noticeable decrease. However, it must be recalled that aspect effects can play a large role in observations of stellar rotation when the number of objects concerned is small, as it is here both at zero-age F4 and evolved G2, and that no statistical comparison of rotation velocities is possible with the limited information available. Note that, although the smaller rotational velocities to the right of $b - y = 0.285$ also show a distribution extending upward and to the right, they do not continue to as large values of $b - y$ as do the larger rotations. A natural explanation is that these smaller rotational velocities are more quickly reduced below the discrimination level of the spectrograms by the increasing stellar radius. It seems reasonably safe to conclude that the observed rotations at zero-age F4 and evolved G2 are not incompatible with the notion that the solid curve in Figures 2, 3, and 5 represents approximately an evolutionary track.

Kelsall and Strömgren (1965) have made evolutionary calculations for models with $\log \mathfrak{M} = 0.25$ and larger. It is not difficult to transform their results, at least approximately, into tracks in the $(b - y) - c_1$ plane, and in Figure 6 is shown their curve for a $\log \mathfrak{M} = 0.25$ star with $X = 0.70$, $Y = 0.28$, $Z = 0.02$. The general form of the evolutionary track is rather similar to that of the boundary between larger and smaller rotations derived from Figure 1. Unfortunately, the computations do not extend down to masses of F4 stars ($\log \mathfrak{M} \sim 0.12$), but Strömgren (1963) states that for $\log \mathfrak{M} = 0.20$ the evolutionary changes in luminosity and effective temperature are small during hydrogen burning. If this is indeed the case, then the curved line of Figures 2, 3, and 5 is not an evolutionary track, and the existence of the rotating stars on the right-hand side of Figure 1 is hard to interpret.

In any event, the boundary between large and small rotations for single stars seems to apply also for members of binary systems. In Figure 2, all of the larger rotational velocities are found above and to the left of the solid curve, which was determined from the observations of the single objects. Also, in Figure 3, the density of points is noticeably higher to the left of $b - y \approx 0.31$ than it is to the right of this value. Hence the solid curved line of Figures 2, 3, and 5 marks, in the $(b - y) - c_1$ plane, a separation between larger and smaller values of angular momentum, whether the angular momentum resides in single stars, in the members of binary systems, or in the orbital motion of stellar pairs.

In the case of angular momentum of orbital motion, however, the separation into two regions is much less sharply defined than for the angular momentum of individual stars.

Another item of considerable interest in Figure 1 is the sudden appearance of $V \sin i$ values of the order of 50 km/sec on the zero-age line at $b - y \approx 0.285$. These occur with surprising abruptness; in fact, the transition from $V \sin i \leq 10$ km/sec to the larger values takes place in a range of $b - y$ not much in excess of 0.02. The only reasonable conclusion is that the sudden change in rotational velocities is dependent in some manner upon the difference in mass corresponding to a range of order 0.02 in $b - y$. We can make a rough estimate of the magnitude of this mass difference from the data of Table 5, where the first two columns are from Strömgren (1963) and the third is from Allen (1955).

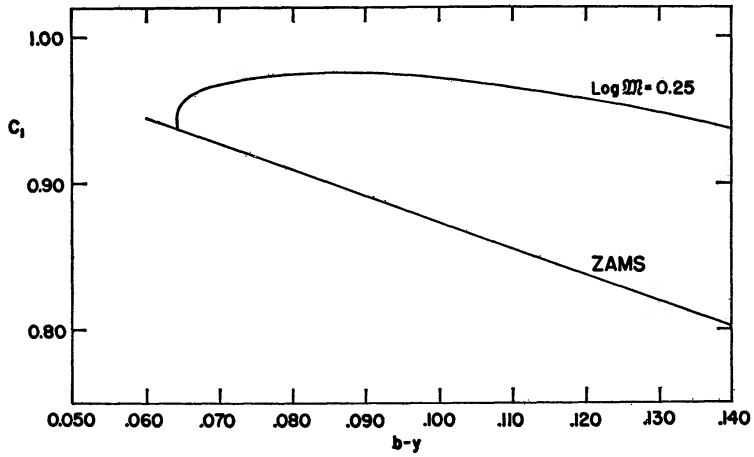

FIG. 6.—Evolutionary track for log $\mathfrak{M} = 0.25$, $X = 0.70$, $Y = 0.28$, $Z = 0.02$ (Kelsall and Strömgren).

TABLE 5

SPECTRAL TYPES, COLORS, AND MASSES

Spectral Type	$b-y$	log $\mathfrak{M}$	$\mathfrak{M}$
F0............	0 20	0 19	1 55
F5....	0 30	0 10	1.26

Using a simple linear interpolation, we find that the mass changes by a little over 4 per cent for an increment of 0.02 in $b - y$. It must be concluded, therefore, that for stars whose masses are close to 1.3 $M_\odot$, the braking mechanism must depend strongly on the mass.

At this point, Figure 1 should be compared with Figure 4, in which Kraft's (1965) values of $V \sin i$ for Hyades stars have been plotted with the same symbols. It is evident that the larger axial rotations in the Hyades set in at precisely the same $b - y$ as they do for the field stars. The transition region in the Hyades appears to cover about twice as large a range of $b - y$, however, but this may be due, in part, to the fact that Kraft's rotational velocities were obtained with spectrograms of twice the dispersion used for the field stars, and his discrimination of small rotations is therefore superior.

Strömgren (1963) finds, in the range $0.050 < b - y < 0.225$, that the fast rotators have distinctly smaller m_1 values than do the slow rotators, where m_1 is the metallic index. In Table 6 are given some data concerning m_1 for the observed stars between $b - y = 0.240$ and $b - y = 0.290$. The mean value of m_1 for the two groups of smallest rotation is compared with that for the two groups of largest rotation, and it is seen that there is no significant difference between them. Whatever the cause for the m_1 differences between slow and fast rotators farther up the main sequence, it is not effective in the spectral-type range F2–F4.

V. STELLAR CHROMOSPHERES AND HYDROGEN CONVECTION ZONES

We turn now to consideration of stellar chromospheres. From the standpoint of observation, there seems no doubt that the presence of visible emission cores in the Ca II H- and K-lines is an indicator of chromospheric activity. Moreover, since the solar H-K emissions are well below the limit of detectability in integrated sunlight at a dispersion of 10 Å/mm, it may be concluded that a star of solar type whose spectrum exhibits these features at the same dispersion has a decidedly more active chromosphere than that of the Sun. If the star is of earlier spectral type than the Sun, its chromosphere must have still more emissivity to render the H-K reversals visible, since these lines compete, in effect, with the intensity in the neighboring continuum. The earlier the spectral type, the more potent a chromosphere must be in order to be detected at any given dispersion.

The consensus of all recent theoretical work is that a chromosphere owes its existence and excitation to mechanical energy supplied by an underlying hydrogen convection zone. However, there is good evidence that another factor, tentatively identified as the surface magnetic field, plays a major role in chromospheric excitation. It appears that chromospheres decrease in activity with time for main-sequence stars for which there is no reason to postulate any secular change in the hydrogen convection zone, and, as a result, it has been suggested that stellar magnetic fields decay from the epoch of arrival on the main sequence (Wilson 1963). Therefore, in seeking to use observable chromospheric activity as an indicator of the presence of a strong hydrogen convection zone, it is necessary to work with stars on the zero-age main sequence. By so doing it should be possible, in principle, to proceed upward along the zero-age main sequence and to determine by observation where chromospheres, and hence strong convection zones, terminate. This was one of the major aims of the present investigation.

TABLE 6

MEAN m_1 VALUES, $0.240 \leq b - y \leq 0.290$

Rot. Group	No. of Stars	Mean m_1
0, 0+...	31	0 153
4, 5	22	0 156

Single stars which show H-K emission are plotted in Figure 5, where the concentration of these features along the zero-age line is very noticeable. In fact, this concentration is one of the items of evidence supporting the conclusion that chromospheric activity diminishes with age among main-sequence stars (Wilson and Skumanich 1964). The recent observations have added a few more examples, which now extend almost to $b - y = 0.30$. Of interest here is the question whether strong chromospheres really terminate near this point or whether the H-K emissions vanish simply because the adjacent continuum becomes too intense. It is impossible to give a categorical answer, even though reference to Figure 1 shows that a considerable number of stars of small rotation have been observed along the zero-age line to the left of $b - y = 0.30$. The data of Table 7 shed some light on the problem; the first two columns are from Strömgren (1963), the third from Harris (1963), and the corresponding black-body emissivities at λ 4000 Å are in the fourth. One sees that the intrinsic intensity in the continuum near H and K is about 36 per cent stronger at $b - y = 0.25$ than at 0.30. For half the range, i.e., at $b - y = 0.275$, the increment in continuum intensity should be about half as great, or about 18 per cent. I am of the opinion, though I cannot prove, that strong chromospheric emissions should be detectable at least up to $b - y = 0.275$.

The statistics involved here may also be helpful. For $0.275 \leq b - y \leq 0.300$ twelve stars of small rotation lying close to the zero-age main sequence have been observed, but none shows H-K emission. On the other hand, three out of eleven such stars with $0.300 \leq b - y \leq 0.325$ do have H-K reversals. Thus it may well be that strong chromospheres cease to exist in the region of $b - y$ just below 0.30, but a definite statement to this effect is not possible on the available evidence.

It is quite unfortunate that the termination of chromospheres, if it occurs, comes just at, or near, the effective temperature where the difficulty of detecting the chromospheric emissions is becoming severe. It is possible that examination of H and K with high dispersion in a limited number of zero-age stars in this neighborhood may be helpful. If not, the solution may have to await the possibility of observation with an extraterrestrial spectrograph in order to see if there is any fairly sudden change in chromospheric properties near $b - y = 0.30$.

TABLE 7

BLACK-BODY EMISSIONS AT λ 4000 Å

Sp. Type	$b-y$	T_e	$\log J_{4000}$
F2	0 25	6930	3 308
F5	0 30	6540	3 175

VI. CONCLUSIONS

It is necessary now to see whether the foregoing material can be put together into a reasonable picture. To this end we adopt the view that the rotating stars on the right-hand side of Figure 1 have arrived at their present locations by evolutionary processes from an origin on the zero-age main sequence near $b - y = 0.285$. If so, the ages of these objects must be well in excess of 10^9 years, judging from the Kelsall-Strömgren (1965) computations for more massive stars. The observations show that during this lengthy period the rotational velocities of these stars have been preserved; hence, if they have ever undergone any large loss of angular momentum, it must have occurred prior to arrival on the main sequence.

From Figure 1 again, the distribution of points for those stars in rotation groups 0+, 1, and 2, near $b - y = 0.30$, suggests that these smaller rotations have also been preserved during residence at the zero-age location. But these stars, differing only slightly in mass from those with higher rotations just to their left in the diagram, must certainly have lost angular momentum at some time, and the question is when. It could be, of course, that these objects lost most of their angular momentum during a pre-main-sequence stage, but this is not the only possibility.

The alternative is to suppose that these stars have lost a major part of their angular momentum after arrival on the main sequence, but that the braking mechanism is such that it becomes less and less effective as the rotational velocity diminishes, and that it therefore requires much longer to reduce $V \sin i$ from 20 to 10 km/sec than to reduce it from 50 to 20 km/sec. This alternative, together with the distinct possibility that strong hydrogen convection terminates near $b - y = 0.30$, is highly suggestive of the braking mechanism proposed recently by Schatzman (1962). Moreover, if, as is probable, the field stars dealt with here are on the average older than the Hyades, the greater width of the transition zone of intermediate $V \sin i$ in the Hyades (Fig. 4 versus Fig. 1) is accounted for quite naturally. Also, limited evidence indicates that rotational velocities in this region are larger in the Pleiades than in the Hyades (Wilson 1963); therefore the transition zone in the Pleiades may be even wider than in the Hyades. If this picture is essentially the correct one, it implies that the transition from deep to shallow hydrogen convection occurs very close to spectral type F4, and that the change from one regime to the other takes place within a mass range that is probably considerably less than 10 per cent.

Thus zero-age stars with $b - y < 0.285$ are presumed to have at most only weak chromospheric activity because of the ineffectiveness of their hydrogen convection zones, while those with $b - y > 0.285$ that do not show chromospheric activity at the dispersion used are presumed to be old enough to have suffered a major decay of their magnetic fields. But then one might expect that a star originating on the zero-age main sequence at $b - y = 0.285$, and following an evolutionary trajectory upward and to the right in Figure 1, would soon arrive at a lower surface temperature and that strong hydrogen convection would then set in. Therefore, if other conditions, such as adequate magnetic fields, are suitable, observable chromospheres should be common along and above the right-hand part of the curved solid line of Figure 5. It is clear that this is not so; in fact, only two objects in Figure 5 are close to the solid curve. One of these objects (No. 720 in the Strömgren-Perry catalogue) is a rotating star and the other is not. Some of the stars along the top of the main-sequence band are rotating with sufficient speed so that weak emissions of intensity 1, which would be clearly visible in a non-rotating star, could be rendered invisible by rotational smearing, but there are others for which this explanation cannot apply. I can think of no good reason for this dearth of chromospheric activity along the upper edge of the main-sequence band. In any case, this result is probably not serious for the general arguments given here, since it is known that chromospheric activity is virtually universal among giants and supergiants of types G0 and later (Wilson and Bappu 1957), and many of these stars must have originated on the main sequence at earlier spectral types than F4. Clearly, sooner or later, such objects acquire convection zones and chromospheres.

In considering the distribution of known spectroscopic binaries (see Fig. 3), it must be acknowledged at the outset that these results may well be seriously affected by selection effects and observational weaknesses that cannot be evaluated. For instance, many of the stars to the left of and above the solid curve have rotationally broadened lines, and the reduced accuracy of measurement for these objects might lead to the erroneous classification of some of them as spectroscopic binaries. On the other hand, while spectroscopic binaries are known among the dK and dM stars, they seem to be rather rare in this part of the main sequence. Therefore, it is also possible that there is a real and fairly steep decline in the frequency of close pairs down the main sequence, and that Figure 3 exhibits a portion of this decline.

We know (from, e.g., Slettebak 1955) that the observed rotations of main-sequence stars attain a maximum in the middle-B types and then decline in proceeding toward cooler objects. It is conceivable that this distribution of angular momentum with mass represents also that of the protostars from which the observed main-sequence stars originated. In each range of mass there is presumably a range of initial angular momenta, so that the fraction of protostars unable to attain the main sequence before being disrupted by fission might roughly parallel the observed angular momenta of those objects which do attain it. If this suggestion has any physical merit, it might be able to explain why the frequency of spectroscopic binaries declines with mass, provided these objects arise through fission.

The results of this paper clearly illustrate the great value of the Strömgren-Perry photometry for astrophysical studies of various kinds. I wish to thank Professor Bengt Strömgren for advance copies of the catalogue and of the Kelsall-Strömgren model calculations.

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