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STUDIES OF STELLAR ROTATION. V. THE DEPENDENCE OF ROTATION ON AGE AMONG SOLAR-TYPE STARS

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ABSTRACT

The rotational velocities of a large sample of field stars with spectral types between F2 IV, V and G3 IV, V have been obtained from coudé spectrograms of resolution about 6 km/sec. It is shown that the average rotational velocity is higher among those with Ca II emission than among those without. Since there is strong evidence that stars with Ca II emission are younger, on the average, than most solar-type stars, a picture is advanced in which rotation declines with advancing age. It is proposed that magnetically coupled winds, similar to the solar wind, are responsible for this deceleration even after a star takes up residence on the main sequence. The winds are presumably generated only in stars which have subsurface hydrogen convection zones and concomitant chromospheres.

Estimates of rotational velocity among solar-type stars in the Hyades and Pleiades are given which confirm this general picture. It is shown that the mean rotation in the Pleiades is highest of all groups considered and averages about 40 km/sec for stars of mass 1.20 $\mathfrak{M}_\odot$. The time scale for reduction by a factor of 2 of the rotational velocities of Pleiades stars is equal to the age of the Hyades, about 4×10^8 years.

I. INTRODUCTION

The sharp decline in rotational velocities of main-sequence stars later than spectral type F4 V remains one of the most intriguing unexplained phenomena of stellar astronomy. Schatzman (1959, 1962) was the first to point out that the transition between stars with deep envelopes in radiative equilibrium and those with well-developed subsurface convection zones occurred among the early F types. He developed a theory in which magnetic braking produced by the jets or flares associated with active chromospheres was possible only in stars with subsurface hydrogen convection zones. More recently, Brandt (1966) and, independently, Weber and Davis (1967) have given evidence that the solar wind carries a net flux of angular momentum and produces a torque on the Sun sufficient to halve its rotation on a cosmologic time scale, provided it is in uniform rotation. Deutsch (1967), on the other hand, noted that Dicke's (1964) hypothesis of a rapidly rotating solar core surmounted by a slowly rotating convection zone implies a shortening of this time scale by two orders of magnitude. Recent theoretical considerations (Roxburgh 1967; Goldreich and Schubert 1967) have, however, cast doubt on Dicke's (1967) interpretation of his solar oblateness observations, and thus the reduction in the time scale remains for the moment problematical.

Regardless of these considerations, however, a picture has gradually been emerging (cf. Wilson 1966*a*, *b*) in which stars are thought to undergo deceleration, at least of their observable surface layers, as a result of the torque exerted by stellar winds in the presence of magnetic fields. The rate of deceleration depends on the strength of the magnetic field, the initial rotational velocity, the velocity and density of the wind (Weber and Davis 1967), and the length of time over which the process acts. The last factor is controlled by the time a star spends in regions of the H-R diagram where subsurface hydrogen convection zones give rise to concomitant chromospheres and winds. Thus stars destined to become main-sequence objects earlier than F5 lose some angular momentum in their convective stages (Hayashi 1966), but probably support insignificant winds upon main-sequence occupation; these maintain a high proportion of their initial angular momentum. Stars destined to arrive on the main sequence at positions later than F5 lose angular momentum at all evolutionary stages, probably even after taking up main-sequence residence. Theoretical support for this argument is derived from the work of Baker (1963), who showed that the hydrogen convection zone in main-sequence stars diminished rapidly in thickness with increasing luminosity, and essentially cuts off among the early F's.

Wilson (1966*b*) has given evidence that stars with active chromospheres may be usefully defined as those showing Ca II emission on spectrograms of dispersion 10 Å/mm or lower. (By this criterion, the Sun's chromosphere is relatively "inactive," since dispersions of 2 Å/mm or higher are needed to detect the K2 emission.) The picture advanced in the preceding paragraph therefore derives qualitative observational support from Wilson's (1966*a*) finding that, as one passes down the main sequence, slow rotation sets in very abruptly (near F5 V) at a value of $(B - V)$ less than 0.02 mag away from the place where K-line emission first puts in an appearance. It must not be supposed in this argument that all stars later than F5 V show Ca II emission; most objects, in fact, are similar to the Sun in this respect and presumably have chromospheres and winds like those of the Sun. But stars of this spectral type in galactic clusters (Wilson 1963) usually show strong Ca II emission, and Wilson advances the view that chromospheres (and by inference, the winds) decay with advancing age. Since at a given spectral type the stars of the youngest cluster studied by Wilson, viz., the Pleiades, have the strongest emission lines, and the older Hyades, Coma, and Praesepe stars have weaker emission, one can roughly order the strength of emission on a function of the nuclear time scale of the clusters (Wilson 1964, 1966*b*). Among the stars of the field which show it, few have Ca II emission as strong as the stars of the Pleiades (at a fixed spectral type), and most turn out to be rather similar to the Hyades. It should be emphasized, however, that the physical connection between chromospheric activity, as defined by the strength of K2, and the parameters of wind velocity, density, and magnetic-field strength which are needed to compute the rate of rotational deceleration remains obscure, and we are therefore unable to trace the physical process in its early evolutionary stages.

Now, if the sequence of events described above has at least qualitative validity, one may inquire whether any direct observational evidence exists for rotational deceleration among solar-type stars (defined here as stars between F5 V and G3 V). Examination of Wilson's (1966*a*) extensive catalogue of field stars observed for rotation and for Ca II emission at 10 Å/mm dispersion shows that almost no MK class V stars later than F5 can be found that have noticeable rotations; the limiting resolution in $V \sin i$ may be taken as 10–12 km/sec. A definitive answer for stars of the field clearly requires a step upward in resolution. For the Hyades, there fortunately exist rotational velocities at a resolution of 6 km/sec (Kraft 1965) in this range of spectral types, but the comparable Pleiades stars are very faint and Wilson's (1963) plates have a resolution of only about 20 km/sec.

On the basis of comparatively high resolution spectrograms, we will demonstrate in what follows that solar-type stars are rotationally decelerated even after reaching the main sequence, and that this deceleration takes place on a time scale considerably shorter than 10^9 years.

II. OBSERVATIONS OF FIELD STARS

One hundred and thirty-six spectrograms of over one hundred field stars with spectral types between F2 IV, V and G3 IV, V were obtained with the coudé spectrographs at Palomar and Mount Wilson. At the 100-inch telescope, we employed a third-order blue grating giving a dispersion of 5.0 Å/mm with the 32-inch camera, and at the 200-inch we used the usual third-order blue grating and 72-inch camera, a combination yielding a dispersion of 4.5 Å/mm. In both cases the limiting resolution in $V \sin i$ is 6 km/sec. Almost without exception, the stars observed were taken from the list of Strömgren and Perry (1962), and thus the temperature $(b - y)$, surface-gravity (c_1), and line-strength (m_1) indices are known.

Using a spectrocomparator, we estimated rotational velocities visually against similar stars in the Hyades (Kraft 1965) that had been observed earlier with the same spectrographic equipment. The reliability of this method has been amply demonstrated (Kraft 1965, 1967; Anderson, Stoeckly, and Kraft 1966). In effect, the Hyades stars listed in Table 1 are taken as primary standards for rotation. An alternative non-rotational interpretation of the line widths will be discussed later (§ IV).

TABLE 1

HYADES ROTATIONAL VELOCITY STANDARDS

(4.5 and 5.0 Å/mm)

Star No.			$(b-y)$*	Sp†	$V \sin i$‡ (km/sec)
VB	HD	Name			
1	20430	...	0 364	.....	≦ 6
29	27383	55 Tau	352	F8 V	18
31	27406	...	357	G0 V	10
35	27524		.286	F5 V	90
40	27691	...	362	G0 V	8
52	27859	...	.384	G1 V	6
57	27991	70 Tau	.314	F7 V	15
59	28034	...	349	F8 V	≦ 6
62	28033	...	.338	F8 V	≦ 6
65	28205	...	347	F8 V	9
66	28237	...	356	.....	8
77	28394	...	324	F7 V	25
101	29225	...	286	F5 V	40
102	29310	...	384	G1 V	6
105	29419	...	345		≦ 6
113	30311	...	360		7
118	30589	...	.370	...	≦ 6
119	30676	...	356		13
122	30810	...	.351		≦ 6
124	30869	...	0 324	...	25

* Crawford and Perry (1966)
† Morgan and Hiltner (1965)
‡ Kraft (1965).

In Table 2 we list the Strömgren-Perry parameters, rotational-velocity estimates, Ca II emission strength as defined on Wilson's 10 Å/mm plates, and other relevant data for 207 field stars. The values of the surface-gravity index, c_1, are corrected (Strömgren 1966) for the influence of m_1 on c_1, and are denoted by c_1 (corr). Almost all the stars listed in Table 2 had been observed by Wilson (1966*a*) at 10 Å/mm. In a few cases, new 10 Å/mm plates were obtained with exposure suitable for detecting K2. These were matched as closely as possible to the density and background characteristics of Wilson's plates.

Since the K2 emission is projected on a background of nearly zero intensity, considerable overexposure above the level for optimum blackening of the continuum is required to detect it. While it is true that one can (and does) detect weaker emission on 5 Å/mm than on 10 Å/mm plates, the increased exposure time required was judged unwarranted in the light of results shortly to be described. Thus, for present purposes, a star is said to have K2 emission only when it is detectable on plates of dispersion 10 Å/mm. This is

TABLE 2

ROTATIONAL VELOCITIES FOR 207 FIELD STARS WITH $\underline{b} - \underline{y} \geq 0.245$

Name	Strömgren No.	HR	$\underline{b} - \underline{y}$	$\underline{c}_1$ (corr)	Mass Interval* (☉)	$V \sin \underline{i}$ (km/sec)	Observer of $V \sin \underline{i}$†	Emission
....	2	17	0.332	0.410	1.15–1.20	≦ 6	K	....
....	11	107	.301	.463	1.25–1.30	8	K	....
24 η Cas...	21	219	.372	.275	1.10–1.15	≦ 6	K	....
....	25	244	.346	.404	1.15–1.20	≦ 6	K	....
....	31	303	.294	.482	1.30–1.35	12	W	....
37 Cet.....	40	366	.294	.462	1.25–1.30	≦ 10	W	....
38 Cet.....	41	368	.283	.500	1.30–1.35	≦ 10	W	....
....	48	409	.326	.436	1.20–1.25	≦ 6	K	....
....	49	410	.314	.455	1.25–1.30	32	K	....
93 ρ Psc...	50	413	.256	.500	1.35–1.40	65	W‡	....
48 ω And .	52	417	288	.477	1.30–1.35	65	W‡	....
....	61	483	.389	.338	1.00–1.05	≦ 6	K	....
....	65	523	.369	.394	1.10–1.15	≦ 6	K	....
....	66	529	.264	.497	1.30–1.35	40	W	....
....	81	624	.296	.419	1.25-1.30	≦ 10	W	....
17 η Ari ...	84	646	.308	.494	1.25–1.30	9	K	....
20 Ari.....	85	656	.288	.498	1.30–1.35	12	W	....
13 Tri.....	99	720	.381	.378	1.05–1.10	≦ 6	K	....
....	101	728	.273	.529	1.35–1.40	50	W	....
....	105	756	.320	.475	1.25–1.30	20	W	....
....	110	770	.281	.525	1.35–1.40	12	W	....
....	112	783	.268	.478	1.30–1.35	20	W	....
....	113	784	.319	.348	1.20–1.25	≦ 6	K	Yes
13 θ Per...	115	799	.326	.382	1.20–1.25	≦ 6	K	....
46 ρ Ari ...	126	869	.308	.465	1.25–1.30	16	K	....
47 Ari.....	129	878	.277	.486	1.30–1.35	20	W	....
94 Cet.....	139	962	.362	.404	1.15–1.20	7	K	....
50 Per.....	196	1278	.334	.371	1.15–1.20	22	K	Yes
....	204	1321	.410	.287	1.00–1.05	≦ 6	K	Yes
....	205	1322	.367	.323	1.10–1.15	≦ 6	K	Yes
1 π³ Ori ...	259	1543	.299	.419	1.25–1.30	18	K	....
13 Ori.....	280	1662	.390	.349	1.00–1.05	≦ 6	K	....
....	288	1687	.295	.444	1.25–1.30	≦ 10	W	....
....	292	1717	.254	.538	1.35–1.40	50	W	....
15 λ Aur ...	293	1729	.389	.363	1.00–1.05	≦ 6	K	....
111 Tau....	301	1780	.348	.364	1.10–1.15	15	K	Yes
54 χ¹ Ori ..	332	2047	.380	.317	1.05–1.10	6	K	Yes
....	339	2122	.290	.496	1.30–1.35	12	W	....
71 Ori.....	349	2220	.293	.452	1.25–1.30	≦ 10	W	....
....	351	2233	.313	.434	1.25–1.30	≦ 6	K	....
74 Ori.....	355	2241	284	.450	1.30–1.35	17	K	....
....	357	2251	.382	.331	1.00–1.05	≦ 6	K	....
56 ψ⁵ Aur ..	374	2483	.357	.372	1.10–1.15	≦ 6	K	....
31 ξ Gem ..	375	2484	.288	.552	1.35–1.40	67	W‡	....
37 Gem....	387	2569	.376	.319	1.05–1.10	≦ 6	K	....
....	397	2643	.374	.304	1.10–1.15	≦ 6	K	....
....	404	2721	.370	.315	1.10–1.15	≦ 6	K	....
63 Gem....	420	2846	.286	.469	1.30–1.35	40	K	....
22 Lyn.....	421	2849	.308	.411	1.25–1.30	12	K	....
α CMi	437	2943	.272	.534	1.35–1.40	≦ 6	K	....
....	444	3028	.317	.426	1.20–1.25	≦ 6	K	....
....	447	3072	.257	.480	1.35–1.40	20	W	....
18 χ Cnc ...	467	3262	.314	.402	1.20–1.25	≦ 6	K	....
1 Hya......	474	3297	.315	.416	1.20–1.25	35	K	Yes
32 Lyn.....	486	3365	0.272	0.482	1.30–1.35	20	W	....

TABLE 2 -continued

Name	Strömgren No.	HR	b − y	c_1 (corr)	Mass Interval* (☉)	$V \sin i$ (km/sec)	Observer of $V \sin i$†	Emission
3 π^1 UMa . .	490	3391	0.390	0.288	1.05–1.10	5	K	Yes
. . . .	497	3451	.290	.477	1.30–1.35	20	W	. . . .
. . . .	502	3499	.336	.358	1.15–1.20	11	K	Yes
. . . .	509	3538	.411	.341	0.95–1.00	≦ 6	K	Yes
. . . .	517	3579	.286	.499	1.30–1.35	25	K	. . . .
. . . .	526	3625	.377	.314	1.05–1.10	≦ 6	K	Yes
31 τ^1 Hya . .	542	3759	.296	.452	1.25–1.30	29	W‡	. . . .
25 θ UMa . .	545	3775	.314	.477	1.25–1.30	< 15	H	. . . .
19 LMi	574	3928	.300	.460	1.30–1.35	≦ 6	K	. . . .
. . . .	578	3954	.318	.479	1.25–1.30	10	K	. . . .
. . . .	582	3979	.286	.493	1.30–1.35	8	K	. . . .
. . . .	584	4012	.361	.446	1.15–1.20	14	K	Yes
35 Leo.	587	4060	.405	.364	1.00–1.05	≦ 6	K	. . . .
39 Leo.	590	4039	.336	.382	1.15–1.20	≦ 6	K	. . . .
. . . .	592	4051	.366	.375	1.05–1.10	≦ 6	K	. . . .
40 Leo.	593	4054	.297	.459	1.25–1.30	20	K	. . . .
. . . .	595	4067	.336	.450	1.20–1.25	8	K	. . . .
. . . .	599	4084	.265	.477	1.30–1.35	115	H	. . . .
36 UMa A . .	604	4112	.341	.338	1.15–1.20	≦ 6	K	. . . .
35 LMi	609	4150	.289	.501	1.30–1.35	8	K	. . . .
47 UMa. . . .	620	4277	.392	.345	1.00–1.05	≦ 6	K	. . . .
. . . .	621	4281	.288	.448	1.25–1.30	8	K	. . . .
. . . .	622	4285	.378	.402	1.10–1.15	6	K	. . . .
. . . .	634	4345	.392	.314	1.05–1.10	≦ 6	K	. . . .
. . . .	637	4363	.311	.441	1.25–1.30	≦ 6	K	. . . .
. . . .	646	4412	.302	.515	1.30–1.35	≦ 6	K	. . . .
58 UMa. . . .	649	4431	.340	.453	1.20–1.25	≦ 6	K	. . . .
89 Leo	652	4455	.302	.419	1.25–1.30	15	K	. . . .
. . . .	662	4533	.325	.423	1.20–1.25	≦ 6	K	. . . .
β Vir.	666	4540	.354	.413	1.15–1.20	≦ 6	K	. . . .
. . . .	671	4572	.319	.435	1.29–1.25	7	K	. . . .
. . . .	681	4657	.317	.373	1.20–1.25	7	K	. . . .
9 Com	688	4688	.336	.441	1.20–1.25	8	K	. . . .
. . . .	704	4767	.360	.339	1.10–1.15	≦ 6	K	. . . .
β CVn	706	4785	.385	.317	1.05–1.10	≦ 6	K	. . . .
10 CVn	712	4845	.375	.319	1.10–1.15	≦ 6	K	. . . .
. . . .	718	4867	.319	.378	1.20–1.25	35	K	Yes
. . . .	727	4926	.288	.440	1.25–1.30	20	W	. . . .
. . . .	729	4934	.275	.481	1.30–1.35	≦ 6	K	. . . .
39 Com. . . .	731	4946	.269	.529	1.35–1.40	30	W	. . . .
α Com.	733	4968/9	.304	.400	1.25–1.30	25	K	Yes
β Com.	735	4983	.372	.341	1.05–1.10	≦ 6	K	Yes
59 Vir	739	5011	.376	.391	1.10–1.15	≦ 6	K	Yes
66 Vir	744	5050	.276	.482	1.30–1.35	40	W	. . . .
. . . .	759	5148	.346	.346	1.15–1.20	13	K	Yes
. . . .	760	5156	.278	.480	1.30–1.35	12	W	. . . .
. . . .	761	5177	.316	.402	1.20–1.25	9	K	. . . .
τ Boo.	765	5185	.319	.435	1.20–1.25	14	K	. . . .
. . . .	771	5243	.335	.348	1.15–1.20	≦ 6	K	. . . .
. . . .	773	5245	.260	.596	1.40–1.45	8	K	. . . .
. . . .	774	5258	.317	.478	1.25–1.30	12	W	. . . .
. . . .	779	5275	.265	.520	1.35–1.40	50	W	. . . .
. . . .	781	5307	.312	.454	1.25–1.30	30	W	. . . .
14 Boo	783	5323	.343	.430	1.15–1.20	≦ 6	K	. . . .
99 ι Vir . . .	785	5338	.341	.448	1.20–1.25	19	K	. . . .
. . . .	788	5347	.255	.540	1.35–1.40	≦ 6	K	. . . .
18 Boo.	791	5365	.267	.490	1.30–1.35	42	W‡	. . . .
. . . .	796	5387	.261	.495	1.35–1.40	8	K	. . . .
23 θ Boo . . .	798	5404	.334	.434	1.20–1.25	32	K	Yes
. . . .	806	5436	0.285	0.443	1.30–1.35	50	W	. . . .

TABLE 2 -continued

Name	Strömgren No.	HR	b − y	c_1 (corr)	Mass Interval* (☉)	$V \sin i$ (km/sec)	Observer of $V \sin i$†	Emission
....	809	5445	0.300	0.506	1.30–1.35	12	W	....
σ Boo......	810	5447	.254	.515	1.35–1.40	≦ 10	W	....
....	811	5451	.340	.363	1.15–1.20	≦ 6	K	....
107 μ Vir ..	813	5487	.254	.532	1.35–1.40	54	W‡	....
....	814	5529	.258	.519	1.35–1.40	12	W	....
38 Boo	816	5533	.313	.493	1.25–1.30	20	W	....
....	819	5581	.338	.414	1.15–1.20	6	K	....
....	820	5583	.336	.438	1.20–1.25	8	K	....
....	824	5612	.305	.513	1.30–1.35	20	W	....
....	825	5630	.353	.409	1.15–1.20	≦ 6	K	....
45 Boo	826	5634	.285	.453	1.30–1.35	46	W	....
....	828	5691	.350	.429	1.15–1.20	≦ 6	K	....
5 Ser A....	829	5694	.352	.433	1.20–1.25	≦ 6	K	....
27 λ Ser ...	850	5868	.385	.362	1.00–1.05	≦ 6	K	....
1 χ Her....	855	5914	.381	.365	1.05–1.10	≦ 6	K	....
41 γ Ser ...	856	5933	.320	.418	1.20–1.25	7	K	....
15 ρ CrB...	860	5968	395	349	1.00–1.05	≦ 6	K	....
....	864	6091	.268	.468	1.30–1.35	50	W	... .
....	870	6181	.276	.540	1.35–1.40	30	W	....
....	882	6328	.274	467	1.30–1.35	40	W	....
....	884	6349	.374	350	1.05–1.10	≦ 6	K	Yes
21 μ Dra A .	887a	6369	.318	.463	1.25–1.30	30	W	....
21 μ Dra B .	887b	6370	......	......	1.25–1.30	20	W	....
72 Her.....	897	6458	.409	.345	0.95–1.00	≦ 6	K	....
....	902	6489	.294	510	1.35–1.40	8	K	....
....	903	6493	.257	.581	1.35–1.40	50	S	....
....	921	6594	258	.553	1.35–1.40	30	W	....
....	927	6669	.352	.371	1.10–1.15	≦ 6	K	....
....	928	6670	.278	.456	1.30–1.35	25	W	....
....	931	6697	.406	.362	1.00–1.05	≦ 6	K	....
....	938	6764	323	.480	1.25–1.30	12	W	....
99 Her.....	941	6775	.361	363	1.05–1.10	≦ 6	K	....
....	947	6831	.376	393	1.10–1.15	≦ 6	K	....
....	949	6847	.410	.358	1.00–1.05	≦ 6	K	....
36 Dra.....	951	6850	.281	.491	1.30–1.35	8	K	....
....	960	6985	.262	.539	1.35–1.40	20	W	....
....	961	6987	.256	.583	1.35–1.40	67	S	....
110 Her....	969	7061	.314	.500	1.25–1.30	12	K	....
....	977	7163	.307	.483	1.25–1.30	≦ 10	W	....
....	992	7280	.285	.475	1.30–1.35	40	W	....
....	998	7322	.320	.455	1.25–1.30	≦ 6	K	....
....	1001	7354	.320	.461	1.25–1.30	13	K	....
....	1005	7386	.339	.360	1.15–1.20	≦ 6	K	....
....	1009	7438	.280	.498	1.30–1.35	40	W	....
....	1013	7451	.320	.442	1.20–1.25	≦ 6	K	....
42 Aql.....	1014	7460	.268	.520	1.35–1.40	55	W	....
13 θ Cyg...	1015	7469	.261	.514	1.35–1.40	7	K	....
17 Cyg A...	1027	7534	.316	.447	1.25–1.30	9	K	....
54 o Aql ...	1030	7560	.356	.406	1.15–1.20	≦ 6	K	....
15 Sge.....	1039	7672	.389	.333	1.00–1.05	≦ 6	K	....
....	1041	7692	.278	.546	1.35–1.40	40	W	....
....	1042	7697	.280	.517	1.35–1.40	≦ 10	W	....
....	1050	7756	.281	.485	1.30–1.35	≦ 10	W	....
....	1053	7793	.338	.355	1.15–1.20	6	K	....
....	1070	7925	.302	.481	1.30–1.35	30	W	....
15 Del.....	1073	7973	.302	.435	1.25–1.30	≦ 10	W	....
....	1080	8037	.246	.520	1.35–1.40	40	W	....
4 Equ......	1083	8077	.350	.433	1.15–1.20	≦ 6	K	....
....	1099	8205	.306	.487	1.25–1.30	12	W	....
....	1114	8314	0.379	0.317	1.05–1.10	11	K	Yes

TABLE 2 -continued

Name	Strömgren No.	HR	b − y	c_1 (corr)	Mass Interval* (⊙)	$V \sin i$ (km/sec)	Observer of $V \sin i$†	Emission
15 Peg.....	1119	8354	0.309	0.487	1.25–1.30	≦ 6	K	....
....	1122	8376	.248	.530	1.35–1.40	12	W	....
24 ι Peg...	1128	8430	.296	.454	1.25–1.30	7	K	....
....	1142	8507	.278	.462	1.30–1.35	12	W	....
....	1143	8514	.302	.409	1.25–1.30	7	K	....
34 Peg.....	1145	8548	.330	.410	1.15–1.20	7	K	....
....	1146	8581	.360	.332	1.10–1.15	≦ 6	K	....
....	1154	8653	.318	.445	1.20–1.25	≦ 6	K	....
46 ξ Peg...	1155	8665	.330	.429	1.20–1.25	9	K	....
49 σ Peg...	1158	8697	.321	.451	1.20–1.25	≦ 6	K	....
....	1161	8718	.273	.554	1.35–1.40	≦ 10	W	....
51 Peg.....	1163	8729	.416	.364	1.00–1.05	≦ 6	K	....
....	1172	8792	.353	.364	1.10–1.15	7	K	....
5 And......	1174	8805	.286	.510	1.35–1.40	9	K	....
6 And......	1176	8825	.302	.460	1.25–1.30	18	K	....
....	1181	8845	.276	.484	1.30–1.35	20	W	....
....	1182	8853	.352	.408	1.15–1.20	≦ 6	K	....
12 And.....	1187	8885	.296	.489	1.30–1.35	12	W	....
....	1191	8931	.350	.327	1.15–1.20	≦ 6	K	....
17 ι Psc...	1195	8969	.336	.420	1.15–1.20	≦ 6	K	....
....	1198	8977	.272	.526	1.35–1.40	30	W	....
....	1202	9020	.277	.567	1.35–1.40	> 55	W	....
....	1205	9028	.258	.489	1.35–1.40	> 55	W	....
....	1210a	9074	.347	.354	1.10–1.15	7	K	Yes
....	1210b	9075	.347	.354	1.10–1.15	7	K	Yes
85 Peg.....	1213	9088	.431	0.248	0.95–1.00	≦ 6	K	Yes
....	......	3991§	.285	......	1.35–1.40	≧115	H	....
....	......	4251§	.305	......	1.30–1.35	20	H	....
8 α^1 Lib...	......	5530§	.285	......	1.35–1.40	< 20	H	....
31 ε Lib...	......	5723§	.285	......	1.35–1.40	< 20	H	....
31 ψ Dra A.	......	6636§	.285	......	1.35–1.40	15	H	....
16 Cep.....	......	8400§	0.285	......	1.35–1.40	35	H	....

Notes to Table 2

*Mass interval of the Sears' tracks (1967) into which the b − y versus c_1 (corr) vector falls in Figure 1.

†H = Herbig and Spalding (1955)
K = Kraft (present)
W = Wilson (1966a)
S = Slettebak (1955)
W‡ = Mean between Wilson (1966a) and value tabulated by Boyarchuk and Kopylov (1964)

§Six stars for which no Strömgren-Perry (1962) photometry was available. Located in Figure 1 by b − y equivalent to spectral type and c_1 (corr) equal to the mean position between Class IV and Class V.

equivalent to saying that our "emission-line stars" are those with chromospheres considerably more active than the Sun's.

In Figure 1 we plot the individual $b - y$ and c_1 (corr) values for 180 non-emission-line stars of the main sequence with spectral types between F2 and G3, i.e., with $0.225 \leqq b - y \leqq 0.425$. Since $b - y$ measures surface temperature (reddening is negligible since all stars are within 50 pc) and c_1 (corr) measures surface gravity, Figure 1 is equivalent to an H-R diagram, as explained by Strömgren (1963, 1966). The dashed line represents the

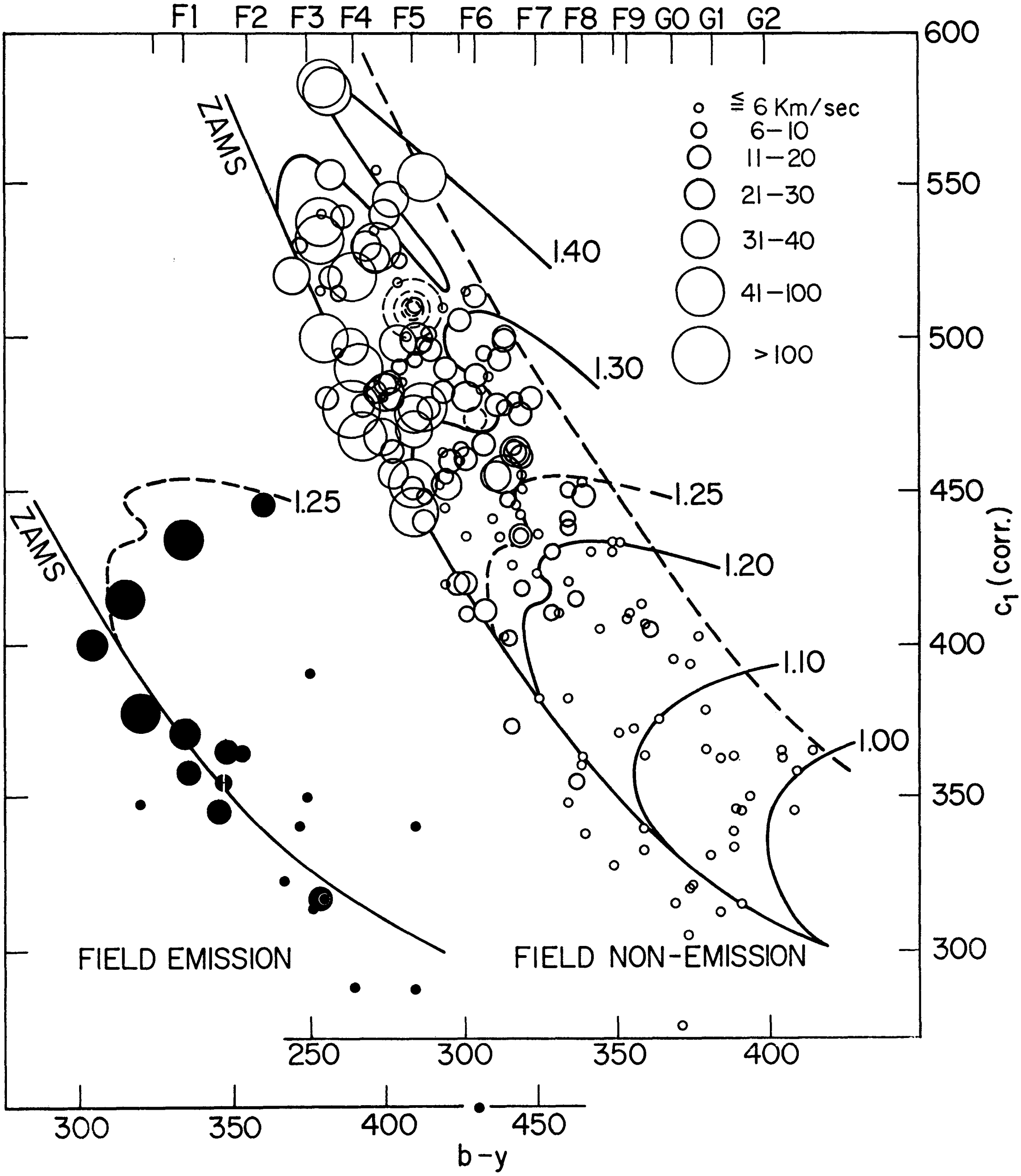

FIG. 1.—Strömgren diagram [$b - y$ versus c_1(corr)] for 207 field stars. Closed and open symbols correspond to stars with and without K2 emission, respectively. The dashed line divides luminosity class IV from V, and the evolutionary tracks are transformed from the calculations by Sears (1967). The dashed circles correspond to the last seven stars of Table 2.

division between class IV and class V stars on the basis of Strömgren's (1963) location of the zero-age main sequence (ZAMS), his relation between M_V and c_1 (corr), and the calibration of M_V with luminosity class given by Keenan (1963). Evolutionary tracks by Sears (1966), transformed to the $b - y$ versus c_1 (corr) plane, are also illustrated. The adoption of Iben's (1967) tracks would produce only slight modifications, and we prefer here to use Sears's results because the grid of masses is finer.

Estimates of $V \sin i$ are indicated by the sizes of the symbols; these are taken from the list by Wilson (1966*a*) for all cases that exceeded his resolution limit, viz., 10 km/sec. The values given in Table 2 were, however, given precedence over those of Wilson for a few common stars, and were naturally adopted for all stars with $V \sin i < 10$ km/sec. The stars plotted as open circles in Figure 1 may therefore be regarded as an entirely random sample of main-sequence objects without K2 emission (as defined above) that lie within 50 pc of the Sun.

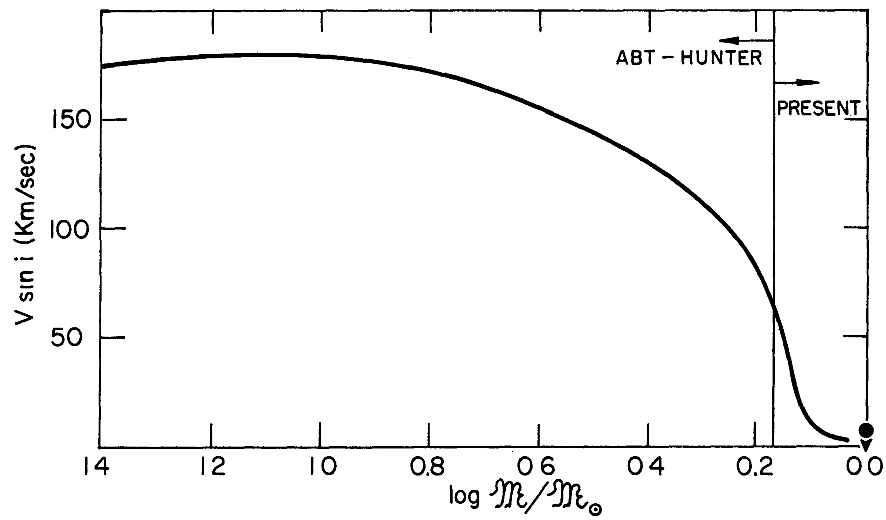

FIG. 2.—$\langle V \sin i\rangle$ as a function of log $(\mathfrak{M}/\mathfrak{M}_\odot)$ for field stars. For log $\mathfrak{M}/\mathfrak{M}_\odot > 0.18$, the curve is adopted from the work of Abt and Hunter (1962). Note the very sharp drop in $\langle V \sin i\rangle$ for masses less than log $\mathfrak{M}/\mathfrak{M}_\odot = 0.20$.

The sharp decline in rotational velocities near spectral type F5 V previously noted by Wilson (1966*a*) is confirmed by the present observational material, and the increased resolution makes the break even more striking. Abt and Hunter (1962) have given the quantity $\langle V \sin i\rangle$ as a function of M_V for field stars brighter than $M_V = +3.0$ (F0 V). Using the mass-luminosity relation given by Harris, Strand, and Worley (1963), we plot the Abt-Hunter data with mass as the independent variable in Figure 2; to their results we attach $\langle V \sin i\rangle$ derived from the data of Figure 1 for stars having $M_V > +3.0$ and no Ca II emission. Inspection of Figure 1 shows that the use of M_V as the independent variable is inappropriate since it is equivalent to striking a mean over c_1 (corr) for a fixed interval in $b - y$. Since the post-ZAMS evolutionary tracks are inclined more or less diagonally across the figure, means struck over c_1 (corr) tend to smooth out the break and valuable physical information is lost.

The sharpness of the break in Figure 1 can best be seen by considering the gradient $\mathcal{G} = [\delta \log \langle\mathcal{J}\rangle]/[\delta \log (\mathfrak{M}/\mathfrak{M}_\odot)]$, where $\langle\mathcal{J}\rangle$ is the mean angular momentum per unit mass of a main-sequence star of mass $\mathfrak{M}$. Elsewhere (Kraft 1967) it has been shown that $\mathcal{G}$ is remarkably constant and has the small value of about 0.6 for stars more massive than 1.5 $\mathfrak{M}_\odot$, provided stars rotate as rigid bodies (physically plausible departures from rigidity do not change this result significantly). But, between $\mathfrak{M}/\mathfrak{M}_\odot = 1.20$ and 1.40,

$\mathcal{G} = 4.5$, nearly an order of magnitude larger. For stars less massive than 1.20 $\mathfrak{M}_\odot$, $\mathcal{G}$ is unknown because the rotational velocities drop below the limit of our resolution.

Returning to Figure 1, we plot also the field emission-line stars, none of which are earlier than F5 V. Wilson (1963, 1966*a*) has argued that these are younger than their non-emission-line counterparts because (1) the former lie closer to the ZAMS, on the average, than the latter, and (2) the emission-line strengths of the former are similar to those of stars in galactic clusters which average 10 to 100 times younger than typical

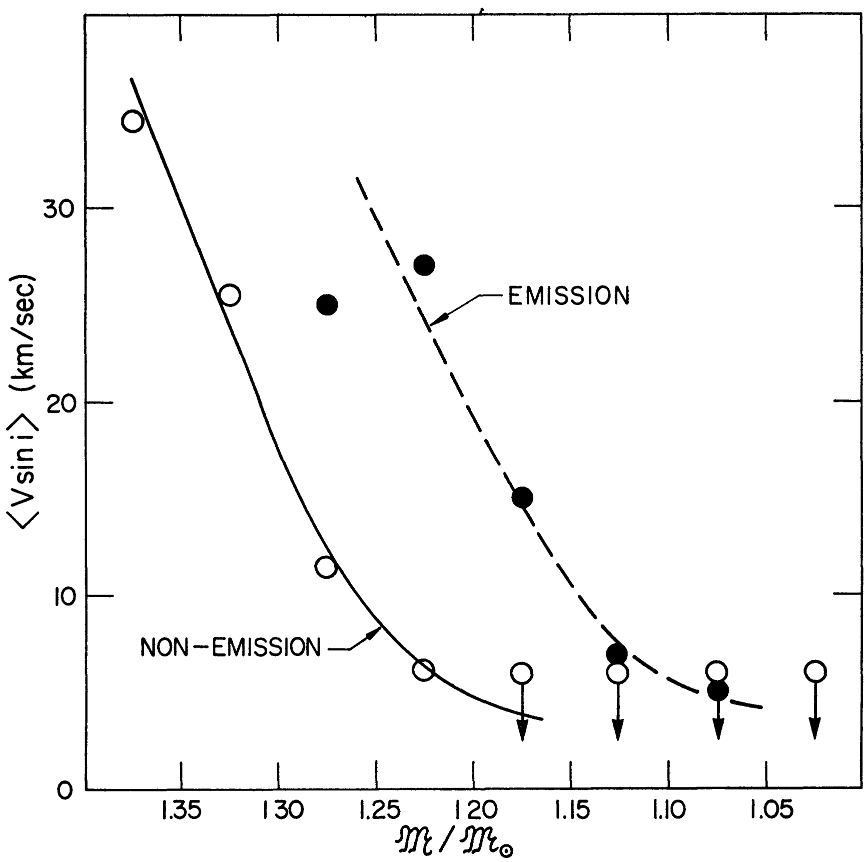

FIG. 3.—$\langle V \sin i \rangle$ as a function of ($\mathfrak{M}/\mathfrak{M}_\odot$) for emission-line and non-emission-line field stars later than F2 V. Arrows indicate that the rotational velocity is less than the resolution limit, viz., 6 km/sec. The mean points have weights depending on the number of stars involved, and the curves are drawn accordingly.

stars of the field. (Only about 5 per cent of field stars per unit volume of space have Ca II emission.) Inspection of Figure 1 yields directly the principal result of this investigation: *for stars less massive than* $\mathfrak{M}/\mathfrak{M}_\odot = 1.25$, *the largest rotational velocities are associated with the stars having active chromospheres.* This is illustrated also in Figure 3, where we plot $\langle V \sin i \rangle$ as a function of mass for the emission-line and non-emission-line stars. Since the stars with K2 lie, on the average, closer to the ZAMS than those without, a correction to Figure 3 is required to allow for the mean difference in radius between the two kinds of stars. For rigid-body rotation this amounts to about a 20 per cent increase in $\langle V \sin i \rangle$ for the stars without K2, but this does not change the leading result. Thus in the mass range 1.15–1.30 $\mathfrak{M}_\odot$, stars with active chromospheres have rotational velocities about three times larger than those without.

This difference is illustrated somewhat differently in Figure 4, where percentage frequency is plotted as a function of $V \sin i$ for the two groups of stars. The frequency function, especially for the non-emission-line stars, is strikingly non-Maxwellian in the sense that too many stars are found in the interval $0 \leqq V \sin i \leqq 6$ km/sec.

The material at hand strongly suggests that the earlier picture advanced by Wilson (1966*a*) is indeed correct; viz., that with declining mass on the main sequence, stars suddenly develop subsurface hydrogen convection zones which generate stellar chromospheres accompanied by winds, that the winds couple a stellar magnetic field producing

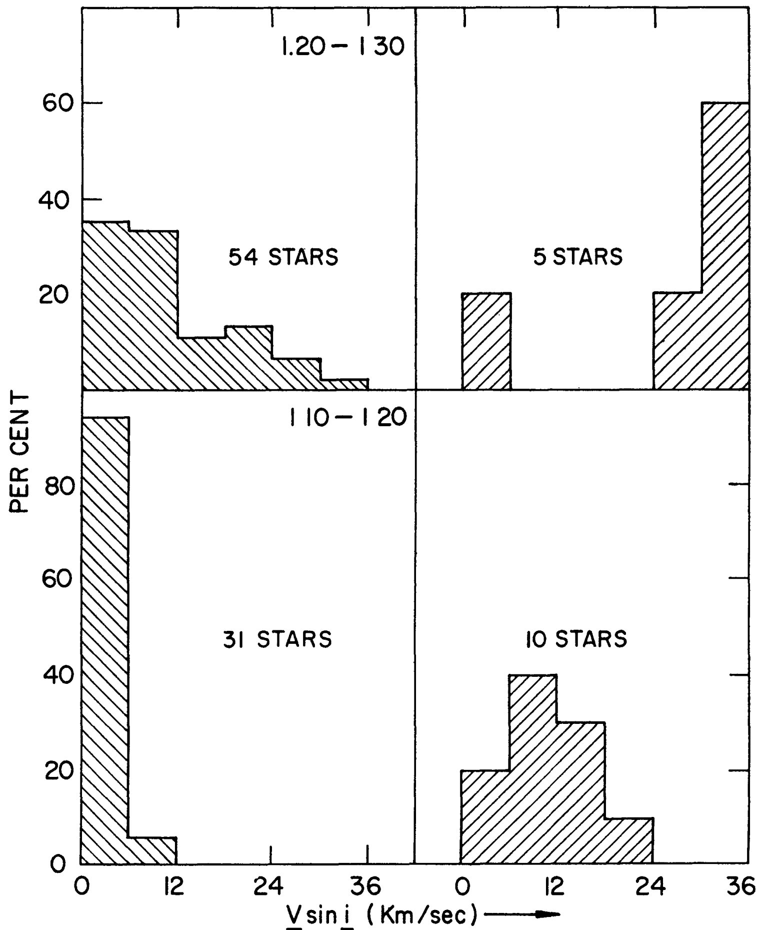

FIG. 4.—Frequency of stars with given rotational velocity in two mass intervals. The emission-line (*right panels*) and non-emission-line (*left panels*) stars have widely differing frequency functions.

torque on the star, and thus over a very short mass interval, main-sequence stars show a marked decline in rotational velocity. What is new in the present observations is that the time scale for this deceleration is of the order of the age of *active* stellar chromospheres—a number considerably smaller than 10^9 years (Wilson 1964). Since the field stars represent a mixture of stars of different ages, however, we cannot give a precise value for this time scale, and we return to this question in § III, where the stars of galactic clusters are discussed.

Passing down the main sequence toward mass 1 $\mathfrak{M}_\odot$, we see that even among emission-line stars the rotational velocities decline and drop under the limit of resolution near G0 V. We might expect this to be the case if the deceleration process were no more than simply proportional to the time a star spends in regions of the H-R diagram where hydrogen convection zones play a role in the internal structure. Thus a star of mass 1 $\mathfrak{M}_\odot$

spends about 50 per cent more time in the Hayashi phases than one of mass 1.15 $\mathfrak{M}_\odot$ and, therefore, conceivably arrives on the main sequence with a more advanced deceleration.

In connection with this point, a small sample of stars near G0 V, with and without emission lines, was observed at very high resolution, mostly with the 100-inch coudé spectrograph. These are listed in Table 3. A grating and camera combination was employed that yielded a dispersion of 2.4 Å/mm and effective resolution of about 3 km/sec. The sample is small because the high resolution required is very wasteful of telescope time. Histograms of frequency as a function of rotational velocity for the two groups are plotted in Figure 5 and show that the higher rotations, i.e., those around 5–7 km/sec, are found only in the emission-line group. Not too much weight can be assigned to this,

TABLE 3

ROTATIONAL VELOCITIES FOR STARS NEAR SPECTRAL TYPE G0 V
(Observed at 2.4 Å/mm)

Star	Strömgren No	Emission	$(b-y)$	$V \sin i$ (km/sec)	Plate No
Sun	..	No	.. ... .	$\leqq 3$	Ce 18613
HR 483.	61	No	0 389	$\leqq 3$	Ce 18516
HR 1322	205	Yes	367	3–5	Ce 18566
15 λ Aur	293	No	.389	$\leqq 3$	Ce 18568
χ^1 Ori.	332	Yes	.380	5–7	Ce 18517, Pa 7776*
37 Gem .	387	No	376	$\leqq 3$	Ce 18609
π^1 UMa.	490	Yes	390	3–5	Pa 7780*
HR 3625	526	Yes	377	$\leqq 3$	Ce 18610
47 UMa	620	No	392	$\leqq 3$	Ce 18611b
β CVn	706	No	385	$\leqq 3$	Ce 18611a
β Com . .	735	Yes	.372	3–5	Ce 18612
15 Sge	1039	No	389	3–5	Ce 18567
51 Peg .	1163	No	0 416	$\leqq 3$	Ce 18565

* Palomar plate IIa-D, 3 3 Å/mm with 144-inch camera

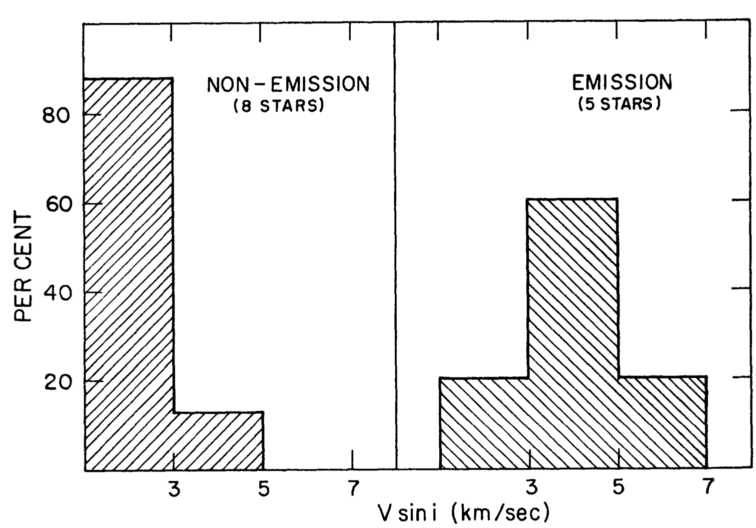

FIG. 5.—Frequency of stars near G0 V with given rotational velocity Individual stars are listed in Table 3.

however, because of the smallness of the sample and because the line widths are down to the level at which turbulence contributes a large fraction of the broadening. This point will be discussed more fully in § IV.

III. OBSERVATIONS OF STARS IN GALACTIC CLUSTERS

Rotational velocity estimates for solar-type stars in the Hyades, based on the plates of resolution 6 km/sec mentioned in § I, have already been reported (Kraft 1965); most of these are listed in Table 1. The corresponding Pleiades stars are listed in Table 4. We have tried to photograph all stars down to G0 V ($m_{pg} \sim 10.7$) at a dispersion of at least 9 or 10 Å/mm if the widths could not be resolved on the plates taken by Wilson at

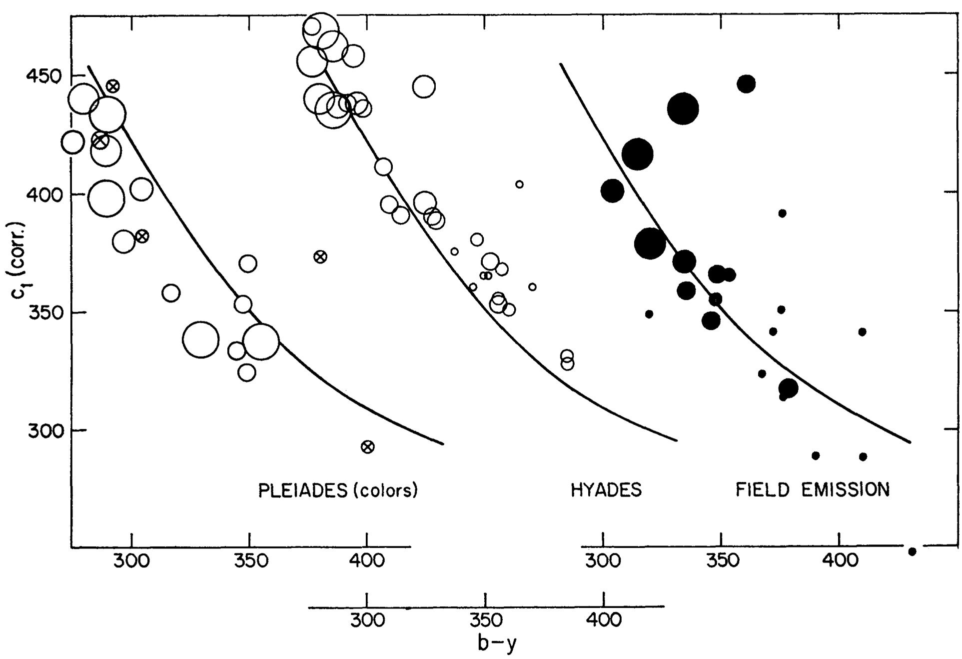

FIG. 6.—Strömgren diagram for field emission-line stars, Hyades, and Pleiades. All stars are located by observed values of $b - y$ and c_1 (corr). Small crossed circles have $V \sin i \leqq 20$ km/sec.

18 Å/mm. However, the exposure times required with the coudé spectrograph at Palomar run around 4 hours, and at Mount Wilson, 8 hours. It has not been possible to cover all stars in this way, but we believe the sample is adequate to derive the leading result.

The rotational velocities of solar-type emission-line field stars, the Hyades, and the Pleiades are compared in a Strömgren diagram in Figure 6. The photometry is that by Crawford and Perry (1966, 1967). Corrections for reddening are required for the Pleiades in both $b - y$ and c_1 (corr). This has been accomplished using the trajectories of Strömgren (1966) and the relation between $b - y$ and β valid for the Hyades (Crawford and Perry 1966). It should be noted that the procedure leads to unexplained small discrepancies between the mean diagram of both the Pleiades and the Hyades and the location of the ZAMS. It is not within the scope of the present investigation to discuss these discrepancies; their effect on the results is, in any case, minor.

Because Strömgren-Crawford photometry is not available for all Pleiades stars of interest, we have also used spectral classification and the relationship between c_1 (corr) and $b - y$ defined by the ZAMS to illustrate the way in which rotation varies with position on the main sequence. The rotational velocities along the Pleiades main sequence are plotted with color and spectral type as the independent variable in Figure 7;

TABLE 4

ROTATIONAL VELOCITY ESTIMATES, PHOTOMETRIC PARAMETERS, AND SPECTRAL TYPES FOR PLEIADES STARS WITH $(b-y)^{\circ} \geq 0.275$

H II	$(b-y)^{\circ}$*	c_1°*	m_1°*	$V \sin i$ (km/sec)	Sp (Hydrogen)	Sp (Metals)	Sp (Mean)	Sp (Hβ Photo.)	Sp Mendoza (1956)	Rad. Vel. (km/sec)
25....	0.289	0.418	0.164	40	F5 V	F6 V	F6 V	F5 V	F8	+ 2.0
164....	.304	.402	.149	30	F5.5 V	F6 V	F6 V	F6 V	......	+ 5.0
233....	.287	.422	.168	≦ 20	F6 V	F4 V	F5 V	F5 V	......	+ 0.2
405....	.349	.371	.180	15	F7.5 V	F8 V	F8 V	F9 V	F9 V	+ 3.4
530....	.252	.513	.163	≦ 12	F5 V	F3 V	F3 V	F3 V	F5	+ 4.4
627....	.297	.380	.167	25	F7 V	F7 V	F7 V	F6 V	......	+ 2.2
708....	.355	.337	.197	70	F7 V:	F8 V	F7 V	F9 V	......	− 0.6
727....	.329	.338:	.155	45	F6.5 V	F8 V	F7.5 V	F7 V	F9 V	+ 3.2
739....	.400	.293	.195	≦ 12	G0 V	G1 V	G1 V	G1 V	G1	+ 4.8 var?
745....	.259	.419	.162	65	F3 V	F4.5 V	F4 V	F4 V	F5 V	+ 4.7
923....	.....	.....	.....	12:	F9 V	G0 V	G0 V	......	......	+ 3.6 var?
948....	.380	.373	.195	≦ 12	F8 V	G0 V	F8.5 V	G1 V	G0 ?	− 7.2 var?
1101....	.....	.....	.....	30	F9 V	F9 V	F9.5 V	......	......	+ 1.8
1122....	.272	.407	.168	28	F4 V	F6 V	F5.5 V	F4.5	F4 V	+ 2.3
1132....	.280	.440	.175	40	F5 V	F6 V	F5 V	F5 V	......	+ 2.7
1139....	.274	.422	.166	30	F4 V	F5 V	F5 V	F4.5 V	F8	+ 3.1
1200....	.292	.446	.151	≦ 20	F6 V	F6 V	F6 V	F5.5 V	......	+ 2.6
1309....	.289	.398	.152	85	......	......	......	F5 V	F6 V	+ 1.1
1338....	.273	.487	.164	110	......	......	......	F4 V	......	......
1392....	.....	.....	.....	≦ 20	G0 V	F9 V	F9 V	......	......	+ 3.9
1613....	.317	.357	.182	18	F5 V	F6 V	F6 V	F6.5 V	F8 V	+ 3.5
1726....	.304	.382	.177	≦ 12	F6.5 V	F6.5 V	F7 V	F6 V	F6 V	+ 4.2
1766....	.253	.448	.....	20	F3 V	F5 V	F5 V	F3.5 V	F4 V	+ 5.1
1797....	.349	.323	.....	15	F8 V	G1 V	G0 V	F9 V	......	+ 3.7
1856....	.344:	.333	.....	12	F7 V	F7 V	F7 V	F8.5 V	......	+ 4.0
1912....	.290	.433	.156	75	......	......	......	F5 V	......	......
1924....	.....	.....	.....	≦ 20	F8 V	F9 V	F9 V	......	......	+ 2.1
2172....	.....	.....	.....	≦ 20	......	F9.5 V	F9 V	......	......	−12.4
2345....	.277	.484	.150	130	......	......	......	F4.5 V	F3 V	......
2500....	.....	.....	.....	30	......	G0.5 V	F9.5 V	......	......	+10.4
2506....	.347	.....	.198	20	F8 V	G0 V	F8 V	F8.5 V	......	+ 2.1
3031....	0.254	0.597	0.138	230	......	......	......	F3.5 V	F2 V	......
3179....	.....	.....	.....	≦ 20	F9 V	G0 V	G0 V	......	......	+ 5.3

*Colors from Crawford and Perry (1967). $E(b-y)$ obtained from standard Hyades relation between β and $b-y$ (Crawford and Perry 1966).

the spectral types are given also in Table 4. The types are derived from comparison with spectrograms of similar stars in the Hyades that were classified by Morgan and Hiltner (1965). We note that the spectral types derived from ratios of ionized and metallic lines and the appearance of the G band are consistently about one spectral subclass later than those derived from ratios involving hydrogen (H13) and metals. We are therefore not entirely convinced that photometric methods based on the strength of Hβ give unambiguously the reddening and the temperature of the star, but whether or not this is true, it has little effect on the interpretation of the rotational velocities in the present investigation.

Comparison of Figures 6 and 7 with Figure 1 shows immediately that, for stars less massive than 1.25 $\mathfrak{M}_\odot$, the rotational velocities of Pleiades stars are the largest, those of Hyades stars and field emission-line stars are comparable and somewhat smaller, and

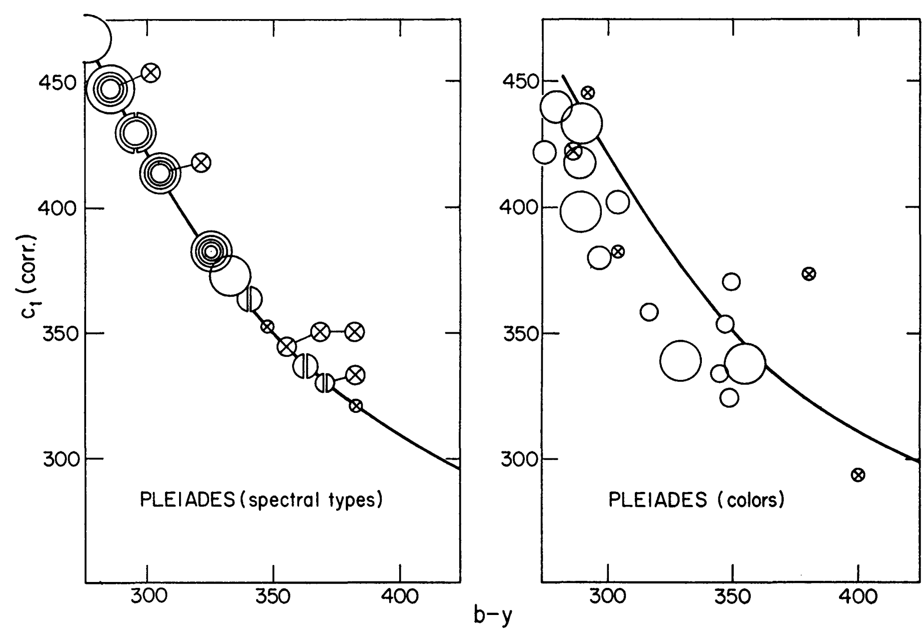

FIG. 7.—Same as Fig. 6 for the Pleiades, but with stars in the left panel located by the $b - y$ equivalent of spectral type and with c_1 (corr) derived from fitting to the ZAMS.

those of the field stars without emission are the smallest of all. If we may make the assumption that physical properties of cluster stars are in all respects, including rotation, entirely characteristic of stars in their youthful period of main-sequence occupation, we interpret the diagrams as showing deceleration of solar-type stars, probably as a result of the existence of stellar winds. The mean rotational velocities as a function of mass are shown in Figure 8. In Table 5 we give $\langle V \rangle$ as a function of cluster age (on the nuclear time scale; cf. Iben 1965, 1966*a*, *b*) for a star of mass 1.20 $\mathfrak{M}_\odot$, on the assumption of a random orientation of rotational axes (Kraft 1967).

From the data of Table 5 we conclude that the time for reduction by one-half of the rotation of Pleiades stars of mass near 1.20 $\mathfrak{M}_\odot$ is about the age of the Hyades, viz., 4×10^8 years (cf. Auman 1965). Though this number is somewhat sensitive to the hydrogen/helium ratio, we can safely conclude that the deceleration time for solar-type stars is at least one order of magnitude shorter than the nuclear time.

IV. DISCUSSION

The similarity of the internal properties of stellar configurations at masses 1.00 and 1.20 $\mathfrak{M}_\odot$ would lead one to expect that the former must likewise undergo rotational deceleration, but an extrapolation of the Pleiades curve of Figure 8 suggests that the deceleration progresses more rapidly for the lower masses at a fixed age. Thus, after an elapsed time of only 3×10^7 years (the nuclear age of the Pleiades), a star of mass 1.20 $\mathfrak{M}_\odot$ has had the rotation of at least its observable surface layers reduced to 40 km/sec, but a star typical of the Sun would have been reduced to about 10 km/sec—a value not greatly different from G0 V field dwarfs with K emission, such as χ^1 Ori. If these stars had undergone no more braking action than is characteristic of a Pleiades star of mass 1.5 $\mathfrak{M}_\odot$ just above the break of Figure 1, and if, as suggested earlier (Kraft 1967), the angular-momentum density $J/\mathfrak{M}$ goes as slowly as $\mathfrak{M}^{0\ 57}$ for stars of the main sequence above the break, we would have expected the solar-type stars to rotate with velocities near 75 km/sec if the relation were extrapolated below the break. The angular-momentum density would then have been about 1.2×10^{17} cm^2 sec^{-1} for solar-type stars at age 3×10^7 years.

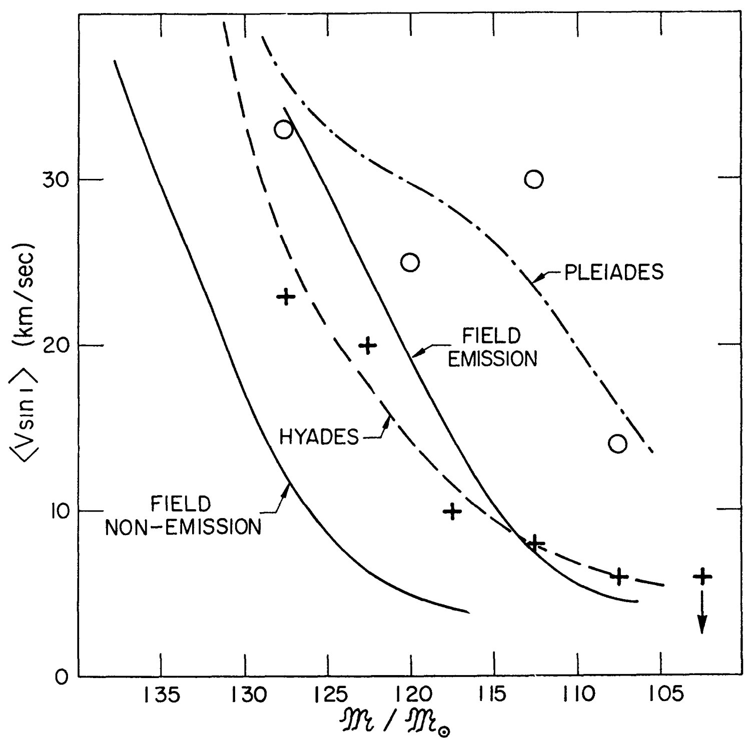

FIG. 8.—$\langle V \sin i \rangle$ as a function of ($\mathfrak{M}/\mathfrak{M}_\odot$) for field and cluster stars. Crosses and open circles correspond, respectively, to mean values for the Hyades and Pleiades.

TABLE 5

$\langle V \rangle$ AS A FUNCTION OF AGE FOR STARS OF MASS $\mathfrak{M}/\mathfrak{M}_\odot = 1.20$

Kind of Star	Approximate Nuclear Age (years)	$\langle V \rangle$ (km/sec)
Field non-emission	5×10^8–5×10^9	6
Field emission	Probably mostly similar to Hyades	25
Hyades	4×10^8	18 5
Pleiades	3×10^7	39

The preceding discussion ignores the angular momentum tied up in the solar system, the density of which is 1.5×10^{17} cm^2 sec^{-1} (Allen 1963); the original solar nebula could therefore have contained an angular momentum of at least 5×10^{50} gm cm^2 sec^{-1}. Very roughly half of this went into the planets, and the other half was retained by the early Sun. On the assumption that this bifurcation occurred before the solar nebula occupied the position of classical T Tauri variables in the H-R diagram, as is probable from Hoyle's (1960) theory, we imagine that, at first, the wind along with flare activity must have acted to decelerate the entire Sun, since stars are totally convective in the Hayashi stages. But after main-sequence occupation, the Sun would have retained only a narrow outer convective region extending down 10–15 per cent of the radius. If the winds were capable of carrying away about half the angular momentum of the whole Sun during the late Hayashi phases, the amount remaining would approximately agree with that required by Dicke's (1967) observation of the solar oblateness. Since the Hayashi contraction times and the nuclear age for the Pleiades are very nearly equal for solar-type stars, this would imply that the time scale for the last stage in the deceleration process is of order 10^8 years, as derived in the preceding section. Though the deceleration time for the entire Sun is about $5–7 \times 10^9$ years (Brandt 1966; Weber and Davis 1967), it is wrong to conclude that the present work actually supports in any way the Dicke result, since the strengths of the winds and of the magnetic fields in solar-type stars of Pleiades age are completely unknown. It should be noted, finally, that the above picture of the history of the solar rotation is offered only as a *plausible* sequence of events based on the observations reported in this paper; in particular, we cannot derive exact numbers for the rotational velocity at various stages if we start from a value of $J/\mathfrak{M}$ that represents a statistical mean with a half-width of a factor of 2.

We conclude this paper with an attempt to answer the following criticism. If the strength of Ca II emission is in some sense a measure of the activity of stellar convection zones, and if the photospheric turbulent velocities in some way also reflect this activity, might not one expect a larger turbulence in the photospheres of stars with K emission than in those without? And, if this is true, how does one know that the wide lines of the stars with K emission are not a result of a very large contribution of macroturbulence? Indeed, perhaps rotation is totally irrelevant to the interpretation of the profiles. In its effect on the line profiles, one cannot distinguish rotation from radial macroturbulence with rms velocity $\sigma = \frac{2}{3}$ ($V \sin i$) (Abt 1957). This alternative interpretation would imply macroturbulent motions in Pleiades stars of mass 1.20 $\mathfrak{M}_\odot$ of about 25 km/sec.

This hypothesis seems implausible for at least two reasons. First, Bonsack and Culver (1966) have shown that the turbulent velocities associated with the photospheres of late-type stars are essentially proportional to the widths of the K2 emission. A turbulent velocity of 25 km/sec is appropriate to supergiants which have K2 emission widths of around 200 km/sec. Yet the widths of the emission lines in the dwarfs considered in this paper are no wider than would be expected for their luminosities (cf. Wilson and Bappu 1957), plus a broadening corresponding to photospheric line widths. This is exactly what would be expected if the source of the broadening were rotation.

A second argument is more convincing. Unless the spectrum of turbulence is widely different in the emission- and non-emission-line stars, one would expect—on the turbulence hypothesis—that the *micro*turbulent velocities ought to differ by an amount similar to the macroturbulent velocities, viz., a factor of about 5. The microturbulence is measured by the line intensities of saturated lines, i.e., by the flat portion of the curve of growth. We have compared the line intensities of saturated lines in two stars with K emission and four without. These are listed in Table 6; the two stars with K emission have (formal) rotational broadening of 11 and 22 km/sec, and the balance have very sharp lines. To minimize difficulties in locating the continuum, a crucial operation in this test, 100-inch coudé plates were obtained in the yellow on baked IIaD emulsions at a dispersion of 6.7 Å/mm.

Experience shows (cf. Greenstein 1948; Gunn and Kraft 1963) that for stars of spectral type intermediate F all the metals are essentially singly ionized. If we choose stars in a limited range of $b - y$, c_1, and m_1, the strengths of saturated lines of ionized metals such as Ti II, Fe II, Sc II, and Cr II will be, to a high degree of approximation, independent of the degree of ionization and excitation. The equivalent widths of such lines, in fact, satisfy the relation $W \propto (\mathrm{Fe/H})^{0\ 25} V^{0\ 75}$ (Conti and Deutsch 1966). To answer with the necessary precision the question raised in the preceding paragraph, one need only compare the intensities of saturated lines of ionized metals. Only sixteen unblended lines could be found in the region λλ5125–5700; the mean W's of these averaged over the two stars with K emission is taken as standard. For each line in each of the other stars, we find the quantity $\Delta W = W(st) - W(*)$. Therefore, ΔW is positive if the lines are weaker than in the two stars with K emission. We normalize ΔW and define a quantity $\langle \Delta W/W \rangle$ for each of the four non-emission-line stars; the sign convention for this quantity is the same as that of ΔW. In Figure 9 we plot $\langle \Delta W/W \rangle$ as a function of Δm_1, which measures line strength in the Strömgren photometric system. The straight lines of Figure 9 have the slopes required by the Conti-Deutsch (1967) calculations for the

TABLE 6

STARS OBSERVED ON IIa-D PLATES FOR STRENGTHS OF IONIZED METALLIC LINES

Star			$b-y$	c_1 (corr)	Emission	$\langle \Delta W/W \rangle$ (per cent)	Δm_1	$V \sin i$ (km/sec)
Name	Strömgren No.	HR						
50 Per	196	1278	0.334	0 371	Yes	0.0*	−0.003	22
. . . .	502	3499	336	358	Yes	0 0*	− .006	11
13 θ Per	115	799	326	382	No	−10 1	+ .010	≦ 6
39 Leo	590	4039	336	382	No	+ 4.8	+ .039	≦ 6
. . . .	771	5243	.335	348	No	+10 0	+ .024	≦ 6
. . . .	1053	7793	0.338	0 355	No	+ 3 8	+0.018	6

* Mean taken zero by definition.

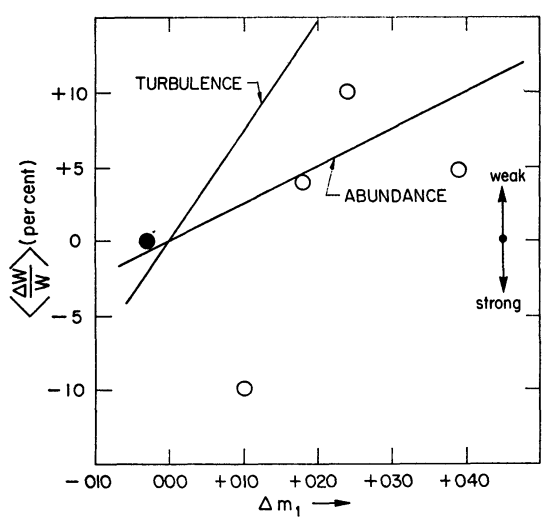

FIG. 9.—$\langle \Delta W/W \rangle$ as a function of Δm_1. The lines have slopes corresponding to the Conti-Deutsch theory, but their locations are arbitrary.

contrary cases of line weakening by changes in turbulence or abundance separately. The material at hand is not sufficient to make a distinction between these cases, but it shows, nevertheless, that the stars without K emission have line strengths within 10 per cent of those that do. This implies a range of ± 15 per cent in microturbulence. It does not seem very reasonable that so small a range in microturbulence should be accompanied by changes of a factor of 5 in macroturbulence. We conclude, therefore, that the widths of lines in stars with K emission are, in fact, a result of rotation.

I am indebted to Drs. R. L. Sears and D. L. Crawford for communicating results in advance of publication, and to Miss Sylvia Burd and Mr. Malcolm Riley for measuring the radial velocities of Pleiades stars. Much of the inspiration for inaugurating this work was derived from the "Sun among the Stars" Conference held in Riverside, California, April, 1966. The author is indebted to the officers of the Carnegie Institution for making this conference possible.

Added March 28, 1967.—After this article had been prepared for publication, we received a paper (*Ap. J.*, **147**, 1188, 1967) by P. Demarque and R. Roeder supporting the earlier unpublished results of N. Baker, viz., that the depth of the hydrogen convection zone in main-sequence stars goes abruptly to zero somewhere in the spectral-type range F2–F6, the exact point depending on the ratio of mixing length to scale height.

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