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ROTATIONAL VELOCITIES OF LOW-MASS STARS IN THE PLEIADES[1]

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ABSTRACT

We have undertaken a spectroscopic rotational velocity survey of over 60 stars fainter than $V = 11$ mag in the Pleiades. Most of those stars have rotational velocities below our detection limit of 10 km s^{-1}, but a significant number (18 stars) have $v \sin i$'s between 25 and 140 km s^{-1}. Based on photometry presented elsewhere, we identify the rapidly rotating stars as heavily spotted, main-sequence stars. Thirteen of the 18 rapid rotators are concentrated to a relatively narrow range of color, $0.95 < V - I < 1.35$. We believe those stars have only recently arrived on the main sequence and that they owe their high rotational velocities to spin up while on their radiative pre–main-sequence evolutionary tracks. The G stars in the cluster should also have spun up via that process. Since all of the stars observed by us with $0.5 < V - I < 0.95$ have projected rotational velocities less than 20 km s^{-1}, the main sequence spin-down time must be short. The significant number of slow rotators ($v \sin i < 10$ km s^{-1}) in the same color range as the rapid rotators argues for a large range in initial angular momentum and/or an age spread of at least 3×10^7 years among low-mass stars in the Pleiades.

Subject headings: clusters: open — stars: evolution — stars: late-type — stars: rotation — stars: variables

I. INTRODUCTION

Measurements of the rotational velocities of young stars are of interest for the light they shed on problems of star formation and early stellar evolution. Recent studies indicate that the division of stars into slow and fast rotators according to mass on the main sequence is present in the pre–main-sequence (PMS) evolutionary phase as well (Vogel and Kuhi 1981; Smith, Beckers, and Barden 1983). From spectroscopic observations of G and K stars in the very young clusters NGC 2264 and Orion Ic, those authors determined that relatively high-mass stars (destined to become A or F type main-sequence stars) have rotational velocities on the order of 50–100 km s^{-1} while on their radiative PMS tracks. Low-mass PMS stars still on convective tracks have rotational velocities at, or below their detection limit.

For older open clusters, little is known about the rotational velocities of low-mass stars. Based upon the limited data available at that time, Skumanich (1972) postulated that rotational velocities of main-sequence field stars decline (t = age). That relation, extrapolated back in time from the Sun, predicts velocities of about 15 km s^{-1} for Pleiades stars of 1.0 $M_{\odot}$, in accord with recent observations (Benz, Mayor, and Mermilliod 1984; Soderblom 1983). Since the rotational velocities of main-sequence, field stars decline further for lower masses (Vaughan *et al.* 1981), main-sequence stars cooler than the Sun might have been predicted to have $v \sin i < 15$ km s^{-1} in the Pleiades.

Given that expectation, the observations of van Leeuwen and Alphenaar (1982*a*, *b*, hereafter together VA) seemed quite surprising because they indicated extremely rapid rotation for some Pleiades K dwarfs. Although Johnson and Mitchell (1958), Robinson and Kraft (1974), and Radick *et al.* (1982) have detected photometric variability in Pleiades stars, only VA obtained enough photometric coverage not only to confirm that variability is common for late-type Pleiades members, but also to derive periods for nearly a dozen stars. The periods obtained by VA for those stars are extraordinarily short, $0.24 < P < 1.22$ days, implying equatorial rotational velocities of up to 170 km s^{-1}. The model for NGC 2264 (in which late-type rapid rotators are believed to be high-mass, PMS stars) cannot be valid for these rapid rotators because both the VA photometry and our own photometry (Stauffer 1984) show that the Pleiades K stars are already on the main sequence.

In order to confirm the reality of the rapid rotations inferred from VA's photometry and to test the ubiquity of that phenomenon, we have conducted a high-resolution spectroscopic survey of late-type stars in the Pleiades. In § II we provide details of our observing procedures and data analysis techniques. The photometric and spectroscopic properties of these stars are compared, and possible origins of the photometric variations are examined in § III. We propose a model to explain the phenomenon in § IV and give some sequences and predictions of our model.

II. DATA ACQUISITION AND ANALYSIS

The stars observed for this program were selected from three sources. The primary list consisted of the twelve stars identified by VA as short-period photometric variables (Table 1). A comparison sample of late G and K stars in the Pleiades was drawn from Johnson and Mitchell's (1958) photometric survey of the cluster. VA and Radick *et al.* (1982) indicated that some of those stars are also variable, suggesting that this sample was likely to contain additional rapid rotators. Finally, a group of moderately late cluster M dwarfs was also observed to see if the rapid rotation

[1] Research reported here used the Multiple Mirror Telescope Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.

TABLE 1

PHOTOMETRIC PERIODS OF PLEIADES K DWARFS FROM VAN LEEUWEN AND ALPHENAAR

Number (1)	$(B-V)$ (2)	Period (3)	Amplitude (4)	Sp. (5)	v_{eq} (6)
34	0.92	1.17	0.05	...	35
625	1.19	0.43	0.12	...	82
686	1.04	0.40	0.10	dK7e	90
879	1.07	0.88	0.07	...	42
882	1.07	0.58	0.12	...	63
1039	1.22	1.22	>0.02	...	28
1124	0.98	0.86	0.07	K0V	46
1332	1.02	1.14	0.05	K5V	38
1531	1.15	0.48	0.13	dK7e	73
1883	1.03	0.24	0.20	K3Ve	170
2034	0.96	0.36	0.07	...	110
3163	1.01	0.43	0.10	...	91

EXPLANATION OF COLUMNS.—Col. (1): Pleiades star numbers from Hertzsprung 1947. Col. (2): $(B-V)$ colors, mostly from Stauffer 1984. The values for 686 and 1531 are from Johnson and Mitchell 1958 but are uncertain because these two stars are embedded in conspicuous nebulosity. Cols. (3) and (4): Photometric period, in days, and amplitude, in magnitudes, from van Leeuwen 1983*a* and van Leeuwen and Alphenaar 1982*a*. Col. (5): Spectral types from Herbig 1962, Wilson 1963, McCarthy 1969, and Soderblom, Jones, and Walker 1983. Col. (6): Equatorial rotational velocity (v_{eq}), predicted from the photometric period by assuming a normal main-sequence color-radius relation.

phenomenon extended to later spectral types. In all, we obtained spectroscopic data for 66 stars of spectral types G(11 stars), K(38 stars), and M(17 stars). All of these stars are high-probability proper motion members of the cluster.

Our high-dispersion spectra of these stars were obtained with the echelle spectrographs (Chaffee 1974) of the Whipple Observatory 1.5 m telescope and the Multiple Mirror Telescope (MMT) on Mount Hopkins, mainly during 1982 October through December. The detectors for both telescope are photon counting intensified Reticons (Latham 1982). At the MMT, integration times ranged from a few minutes for the brightest stars observed ($V \approx 10$ mag) to about 30 minutes for the faintest ($V \approx 16.4$ mag). We observed only the brightest stars at the 1.5 m telescope, and integration times there were about 30 minutes. Such exposure typically resulted in 50–100 counts per pixel at a dispersion of 0.03 Å per pixel and a resolution of 5 pixels FWHM. The finite size of the Reticon array limits our spectral coverage to about 50 Å. For this program, the spectra obtained were centered at either 5200 Å or 6563 Å. Wavelength calibrations were computed from thorium-argon spectra obtained immediately before and after each stellar exposure. Small-scale irregularities in the instrumental response were removed by dividing the data by exposures of an incandescent lamp, observed at the beginning and end of the night. A representative sample of spectra drawn from our survey is shown in Figure 1.

A few low-dispersion (1.5 Å resolution) spectra of the program stars were also obtained with the MMT. Those spectra generally covered 3500–4500 Å or 4100–5100 Å at much higher signal-to-noise ratios than the echelle spectra. Our most reliable rotational velocities for the extreme rapid rotators were derived from the 1.5 Å resolution data since the lower signal-to-noise ratio of the echelle spectra precludes measurement of the profiles of weak absorption features in stars with $v \sin i > 80$ km s^{-1}.

Rotational velocities ($v \sin i$'s) and radial velocities (v_{rad}'s) were determined by cross-correlating the program spectra with a template spectrum of a nonrotating star of roughly the same spectral type, in a manner similar to the procedure described by Tonry and Davis (1979). The position of the cross-correlation peak indicates the radial velocity, while the width of the peak indicates the broadening of the spectrum. For the large broadening velocities here (>10 km s^{-1}), we have assumed that rotation dominates all other broadening mechanisms. The error analysis follows the prescription of Tonry and Davis (1979) closely, and the resulting error estimates were checked against stars with known rotational velocities, and with the variation observed in different observations of the same star.

The cross-correlation peak widths were calibrated in terms of $v \sin i$ by the following method. A high quality spectrum of an essentially nonrotating star was convolved with the theoretical broadening function for a uniformly rotating star (Gray 1976). The standard limb darkening law $I = I_0[(1-\epsilon) + \epsilon \cos \theta]$ was adopted with a limb darkening coefficient $\epsilon = 0.6$. The convolution was performed for several rotational velocities, and the resulting theoretically broadened spectra were then cross-correlated with the standard template spectrum. The widths of these cross-correlations were measured to provide the calibration of rotational velocity with peak width.

The misclassification of a double-lined spectroscopic binary (SB2) as a rotationally broadened star is unlikely to occur with the cross-correlation technique. If the line-of-sight difference in radial velocities exceeds the intrinsic breadth of the spectral lines, two correlation peaks are seen. We have identified two SB2's in the Pleiades, H II 173 and H II 1286, in that manner. Binary stars of nearly equal mass with line-of-sight radial velocity differences significantly less than the intrinsic breadth of the spectral lines can have broadened but symmetric correlation peaks. Only a very small fraction of the binary stars in the Pleiades should satisfy those criteria. In a spectroscopic survey of late-type stars in the Hyades obtained with the same instrumentation (Latham and Stefanik 1984), less than 5% of the spectra show broadened correlation peaks that are not obviously asymmetric.

We have tested the cross-correlation procedure in a variety of ways. Perhaps the most stringent tests are provided by measurements of T Tauri stars, for which spectral peculiarities maximize the mismatch between the template and the observed spectra. For the K1 star T Tauri, we find $v \sin i = 19 \pm 1.5$ km s^{-1}, whereas the result of Vogel and Kuhi (1981) is $v \sin i = 18 \pm 5$ km s^{-1}. V410 Tauri has a spectral type of K7 and is a rapid rotator. We measure $v \sin i = 74 \pm 5$ km s^{-1}, whereas Vogel and Kuhi estimate the rotational velocity as 73 ± 15 km s^{-1}. From these comparisons we conclude that our procedure is accurate (given sufficient signal-to-noise ratios) in the range $15 < v \sin i < 80$ km s^{-1}. For the echelle observations of the Pleiades stars, we believe our rotational velocities should have 1 σ errors of approximately 10% for stars with $v \sin i < 50$ km s^{-1}, and 10%–20% for the more rapid rotators. The resolution of the spectroscopic observations prevents measurement of rotational velocities for

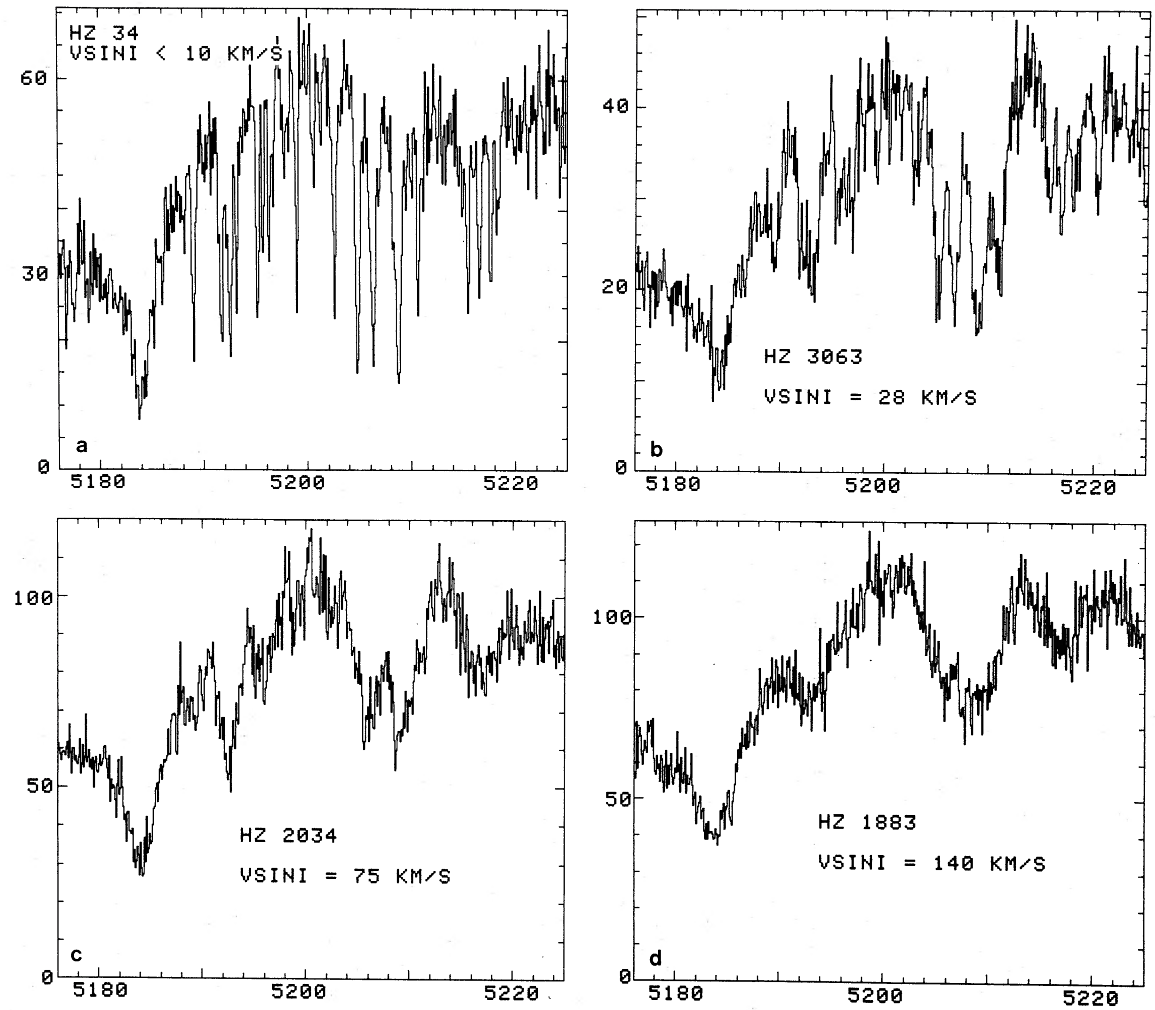

FIG. 1.—Echelle spectra of late-type dwarfs in the Pleiades. Figs. 1*a*–1*d* display a selection of the 5200 Å spectra chosen to cover a wide range of rotational velocities.

$v \sin i < 10$ km s^{-1}, while for high velocities, the echelle spectral range does not provide enough lines to produce a good correlation. Radial velocities derived via this technique have accuracies of 1–2 km s^{-1} for narrow-lined stars, with progressively larger errors for fainter and/or broader lined stars (see the notes section of Table 2).

For stars with very active chromospheres, absorption lines formed near the top of the photosphere can be filled in by emission, making them appear broad. Vogel and Kuhi (1981) circumvented that problem in their young cluster survey by eliminating from their analysis the spectral lines most strongly affected by emission. We do not believe that chromospheric emission affects our rotational velocities significantly because the Pleiades stars have much weaker emission lines (Hα equivalent widths of only a few angstroms or less). In addition, we have tested for the effect in two ways: (1) Unlike the T Tauri stars (Vogel and Kuhi 1981), we see no decrease in the equivalent width of the Mg I *b* line, even for the most rapidly rotating stars (Fig. 1). The Mg I *b* feature is the metallic line in our spectra that is most sensitive to chromospheric effects. Hα is obviously affected by emission, so we do excise it from our correlations. (2) As noted above, we have been able to accurately measure $v \sin i$ for T Tauri, a star showing conspicuous filling in of the Mg I *b* feature. This demonstrates that the correlation is dominated by other, weaker lines.

As we noted above, several rapid rotators were observed with the MMT spectrograph on the Multiple Mirror Telescope at 1.5 Å resolution. Those spectra were analyzed in the same way as the echelle spectra. Because of the relatively low instrumental resolution, rotational velocities can be derived from these spectra only for the most rapidly rotating Pleiades stars.

For the stars with Hα in emission, rotational velocities can also be estimated from the echelle spectra via Gaussian fits to the emission-line profile. The calibration of emission-line width versus $v \sin i$ was determined by fitting Gaussians to a set of computer-broadened Hα profiles of Gl 285 (= YZ CMi), a bright dMe star with strong Hα emission. Since other mechanisms may contribute to the broadening of Hα, we regard those rotational velocities as upper limits.

Our $v \sin i$'s generally agree well with the recent measure-

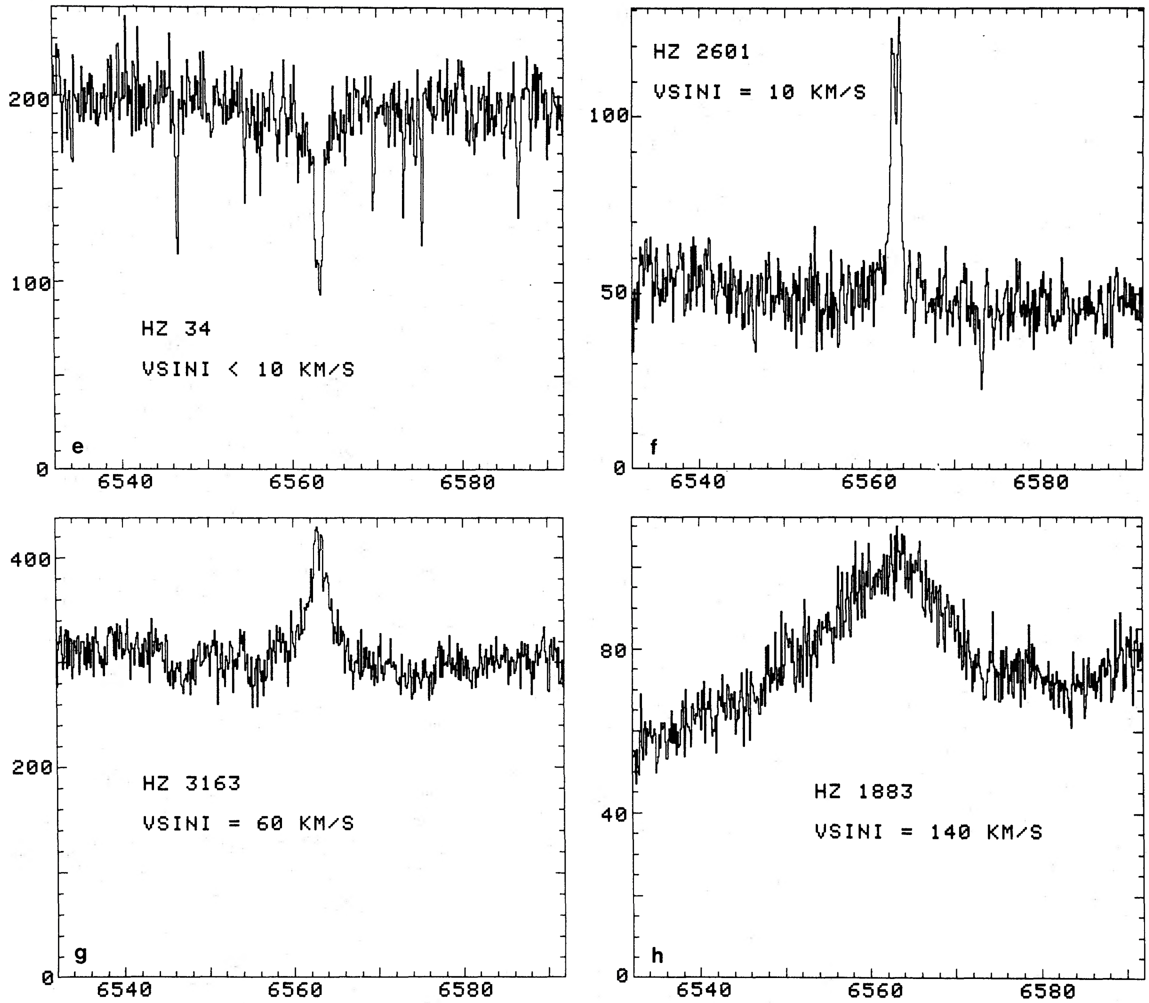

FIG. 1.—*Continued*

ments of Soderblom, Jones, and Walker (1983). However, there are a few stars (H II 34, 97, 357, 879, and 885) for which Soderblom *et al.* determine large $v \sin i$'s, yet our echelle spectra show very narrow lines (Fig. 1), i.e., $v \sin i < 10$ km s^{-1}. We are not certain of the cause of these discrepancies, but our echelle spectra definitely cannot be fit with large $v \sin i$'s for these stars. Those stars for which Soderblom *et al.* could not resolve rotation (i.e., they determine $v \sin i \lesssim 30$ km s^{-1}) are all narrow lined in our echelle spectra. It is possible that the image intensifier spectra used by Soderblom *et al.* exhibit spurious broadening in some cases, but the most rapidly rotating stars were well resolved by them.

III. DISCUSSION

The rotational velocities derived from our spectroscopic survey of the Pleiades are presented in Table 2. Descriptions of the entries are given in the notes to the table. The photometry listed in columns (2) and (3) was taken directly from Stauffer (1984). Approximate absolute magnitudes for the stars can be obtained by subtracting 5.6 mag from the V entries; spectral type estimates can be made by noting the following rough correspondences: $V-I = 0.85$ mag, sp = K0; $V-I = 1.50$ mag, sp = K5; $V-I = 2.00$ mag, sp = M2. Intercomparison of the velocities from the three sources (0.15 Å resolution spectra cross-correlation, 1.5 Å resolution spectra cross-correlation, Hα Gaussian fitting) shows good agreement, with the greatest discrepancy being the Hα width for H II 1883. We discuss that point more fully below.

There is clearly an excellent correlation between rapid rotaton (large $v \sin i$) and short photometric period; some of these Pleiades K dwarfs indeed rotate at extraordinary rates. We have computed equatorial rotational velocities from the photometric periods (Table 1) by assuming a normal main-sequence color-radius relation. These predicted velocities are compared to our spectroscopic $v \sin i$'s in Figure 2. Note that for a random distribution of rotation axes, $\langle (v \sin i)/v \rangle = \pi/4$ (Chandrasekhar and Münch 1950). For those variables with periods less than $0^{\mathrm{d}}.8$ ($v > 50$ km s^{-1}), the predicted and observed values agree well.

However, for five stars with $P > 0^{\mathrm{d}}.8$, we measure $v \sin i < 10$ km s^{-1}. This discrepancy is significant; these upper limits to $v \sin i$ are well determined for such sharp-lined stars, and it is very unlikely that all five stars would have small inclination angles. These longer photometric periods

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TABLE 2

ROTATIONAL VELOCITIES OF LOW-MASS PLEIADES DWARFS

Star	V	$V-I$	$v \sin i$ Ech.	$v \sin i$ Hα	$v \sin i$ MMT	Hα	v_{rad}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
34	11.96	0.78	<10			abs.	5.6
97	12.65	1.06	<10			...	7.4
133	14.30	1.56	19			...	5.9
134	...	...		40[a]		em.	...
173	10.89	0.70	10:[b]			...	...
189	13.96	1.46	<10			...	6.8
296	11.45	0.72	17			...	6.7
324	12.99	1.10	>50	90		em.	2 d
347	14.00	1.77		65[a]		em.	...
357	13.32	1.34	<10			em.	4.0d
451	13.43	1.25	<10			em.	5.2
571	11.26	0.71	<10			...	29.0
625	12.69	1.27	>50			abs.	17 e
636	12.40	0.93	<10			abs.	4.9
676	13.64	1.34	<10			f.i.	6.6d
686	13.52	1.32	>50	150		em.	14 e
738	12.30	1.29	>60			n.f.	...
739	9.57	0.51	16[c]			...	6.2
793	14.27	1.59	<10			...	8.5
799	13.66	1.39	<10			...	6.1
879	12.79	1.01	<10			...	4.1
882	12.95	1.14	>60	80		em.	2 e
885	12.08	1.02	<10			...	7.0
1039	12.96	1.26	10			...	4.5
1061	14.21	1.65	<10			...	5.9
1100	12.25	1.22	<10			f.i.	5.4
1124	12.32	0.88	<10			...	5.1
1173	15.10	1.90	<10			em.	4.3d
1275	11.45	0.67	10			abs.	3.6d
1286	15.35	2.33	b			em.	...
1298	12.33	0.89	10			abs.	7.4d
1305	13.52	1.25	>90		120±22	em.	...
1321	15.22	2.24	17			em.	4.1d

Star	V	$V-I$	$v \sin i$ Ech.	$v \sin i$ Hα	$v \sin i$ MMT	Hα	v_{rad}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1332	12.53	0.91	<10			...	6.7
1348	12.70	1.19	<10			...	5.2
1355	14.02	1.72	<10			...	8.2
1454	12.86	1.05	<10			abs.	6.2
1531	13.58	1.29	50	50		em.	7 e
1553	12.49	1.16	12			...	5.7
1653	13.50	1.32		30[a]		em.	...
1776	10.94	0.58	<10			...	5.5
1883	12.66	1.04	>100	335	140±15	em.	11 e
2034	12.65	0.96	>60		75±25	n.f.	4 e
2126	11.71	0.71	<10			...	6.1
2244	12.58	0.99	50	45		em.	8 e
2278	10.94	0.74	<10			abs.	5.5
2311	11.35	0.65	<10			abs.	5.3
2407	12.19	0.82	<10			...	14.2
2588	13.36	1.20	<10			em.	6.5
2601	15.01	2.19	10			em.	3.5d
2602	15.49	2.32	<15			em.	3.9d
2741	12.65	0.94	10			...	7.7
2870	12.51	0.92	<10			...	8.8
2881	11.57	0.91	12			...	6.3
2984	12.41	0.88	<10			...	8.4
3019	13.53	1.27	<10			...	8.5
3063	13.54	1.30	28			...	4.3d
3163	12.77	1.04	60	65		em.	3 e
A 28	16.20	2.57	>30	45		em.	1.0d
B 173	15.16	2.05	>50	55		em.	1 e
MT 41	15.43	2.17	<12			em.	4.1d
MT 61	15.27	2.28	<10			em.	4.9d
T 40	16.37	2.53	<15			em.	3.4d
T 42B	15.42	2.04	15:			em.	6.4d
T 69	16.15	2.31	>50	60		em.	8 e
T 86	15.44	2.28	<10			em.	6.9d

EXPLANATION OF COLUMNS.—Col. (1): Pleiades star designation. The numbers are from Hertzsprung 1947; "A" means an Asiago flare star, "B" means a Byurakan Observatory flare star, "MT" means a McCarthy and Treanor star, and "T" is a Tonantzintla star (see Stauffer 1983). Cols. (2) and (3): Photometry from Stauffer 1983. Cols. (4)–(6): $v \sin i$'s (km s^{-1}) from the present study. The columns contain results from cross-correlation of echelle spectra, the breadth of Hα emission, and cross-correlation of MMT spectrograph data (1.5 Å resolution), respectively, as explained in the text. Notes to entries in these columns have the following meanings: [a] Spectrum noisy, $v \sin i$ uncertain; [b] Double-lined spectroscopic binary (SB2); and [c] Large difference in spectral type between the program star and the cross-correlation template; $v \sin i$ suspect. Col. (7): Remarks on the Hα feature: f.i. means the absorption line is partially filled in by emission, n.f. means that the spectrum is featurless at Hα—the emission may be very broad. Col. (8): Radial velocity (km s^{-1}) from our cross-correlations. If no note appears, the error is 1–2 km s^{-1}; d means an error of 2–4 km s^{-1}; and e means an error of 5–10 km s^{-1}. No radial velocity is given for very broad-lined stars or for the SB2's.

may be spurious for two reasons. First, VA have observed at the European Southern Observatory, in Chile, where the minimum zenith distance for the Pleiades is 54° (1.70 air mass). Thus the Pleiades can only be observed for a few hours each night. If $P < 0^{d}.5$, a significant portion of the light curve can be sampled in a single night, but for longer periods only a fraction of the light curve can be seen. Aliasing effects may be important in such cases. Second, the five stars with $P > 0^{d}.8$ all have small photometric amplitudes, $\Delta V \approx 0.05$ mag. Such small amplitudes ensure that no intrinsic variation will be detected reliably in a single night's observation. Van Leeuwen (1983*b*) has indicated that periods longer than 6 days are possible for H II numbers 34, 879, 1124, and 1332, although the shorter periods generally result in less scatter. These stars should be carefully reexamined from northern latitudes.

a) *The Distribution of Rotational Velocities*

A histogram of the rotational velocity results is shown in Figure 3. The velocities shown are those obtained from the cross-correlation technique, with lower limits denoted by cross-hatching. Two features of that histogram are evident: the strong concentration of nonrotating stars with $v \sin i < 10$ km s^{-1} and the relatively flat distribution of rotating stars with projected rotational velocities extending to more than 100 km s^{-1}. Seven of the stars with $v \sin i > 25$ km s^{-1} were predicted to be rapid rotators by VA. We have identified an additional 11 Pleiades stars having $v \sin i > 25$ km s^{-1} with our spectroscopic program. We predict that those stars are also short-period photometric variables.

The histogram of rotational velocities for these Pleiades stars closely resembles that for G–K stars in NGC 2264

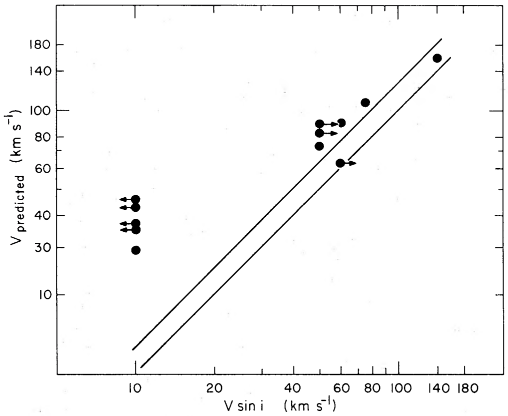

FIG. 2.—Observed $v \sin i$ versus predicted rotational velocity for van Leeuwen and Alphenaar's photometric variables. The two lines are for $v \sin i = v_{pred}$ and $v \sin i = (\pi/4) * v_{pred}$. Arrows indicate that only rotational velocity limits were derived from the cross-correlation technique. Note that for one of the stars shown as a lower limit (H II 882, $v \sin i > 60$ km s^{-1}), the width of the Hα emission line places an upper limit on the rotational velocity of 80 km s^{-1}.

(Vogel and Kuhi 1981). The stars in NGC 2264 are still well above the main sequence, and Vogel and Kuhi explained the high-velocity tail of their distribution by noting that the rapid rotators would arrive on the main sequence as A–F stars ($M > 1.5\ M_{\odot}$). Since stars in that mass range typically have main-sequence rotational velocities of the order of 200 km s^{-1}, high rotational velocities during their pre-main-sequence phase of evolution were expected. The low-mass stars in NGC 2264 generally have low $v \sin i$'s. At the age of NGC 2264 ($\sim 3 \times 10^6$ years; Cohen and Kuhi 1979), the rapid rotators are on radiative tracks, while the slow rotators are fully convective. This distinction, which was emphasized by Vogel and Kuhi, is important for the Pleiades stars as well, as we discuss below.

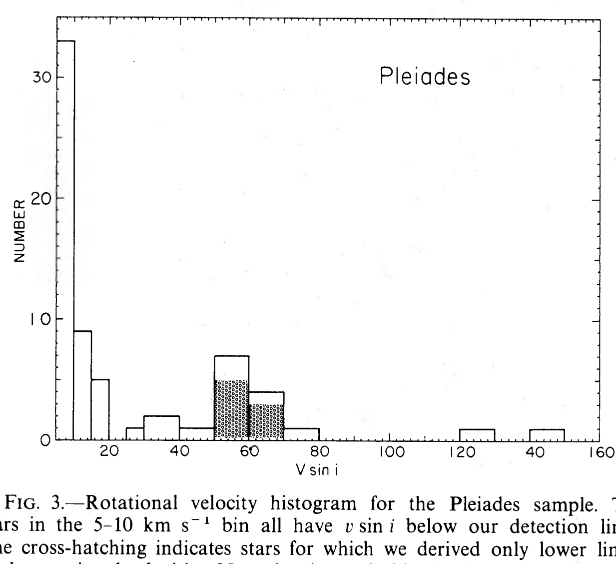

FIG. 3.—Rotational velocity histogram for the Pleiades sample. The stars in the 5–10 km s^{-1} bin all have $v \sin i$ below our detection limit. The cross-hatching indicates stars for which we derived only lower limits to the rotational velocities. Note the change in bin size from 5 to 10 km s^{-1} at $v = 30$ km s^{-1}.

b) *Rapid Rotators in the Color-Magnitude Diagram*

The identification of late-type rapid rotators as high-mass, pre-main-sequence stars is unlikely to be valid for the Pleiades simply because it is much older than NGC 2264 ($\tau_{\rm Pleiades} \approx 7 \times 10^7$ years; Patenaude 1978). Stars with $M > 1\ M_{\odot}$ in the Pleiades are certainly already on the main sequence with spectral types earlier than G2. We can directly test the evolutionary state of the stars observed spectroscopically by examining the photometry of Stauffer (1983). Figure 4 shows a V versus $V-I$ color magnitude diagram for the cluster, where stars with $v \sin i$ greater than and less than 25 km s^{-1} appear as different symbols. Most of the rapid rotators are on the main sequence. The few rapid rotators that lie above the main sequence are probably binaries (the fraction of stars lying clearly above the main sequence is the same for the fast and slow rotators). Since the rapid rotators and the slow rotators have the same approximate mass ($M \approx 0.75\ M_{\odot}$), another explanation must be sought for their different rotational velocities.

Several other facets of Figure 4 are worthy of comment. Most of the rapid rotators are concentrated in a small color range, $0.95 < V-I < 1.35$ mag, where half of the stars observed spectroscopically have $v \sin i > 25$ km s^{-1}. In part that result is due to the VA photometric survey being limited to stars in roughly that color range. However, even if all of the 11 remaining Pleiades members in that color range are narrow lined, the fraction that are rapid rotators would still exceed 35%. Outside that color range, the fraction of stars with $v \sin i > 25$ km s^{-1} is 0 for 19 (0%) for $V-I < 0.95$ mag and 5 for 21 (24%) for $V-I > 1.35$ mag. Rapid rotation turns on sharply at spectral type K2 and may become less prevalent among the late K and early M type cluster members.

We emphasize that the above statements can be inverted: even for $0.95 < V-I < 1.35$ mag, approximately half of the stars have $v \sin i < 10$ km s^{-1}. Rapid rotation is common, but far from universal, in that color range for Pleiades members. We note that none of the 35 Hyades stars with $0.95 < V-I < 1.35$ mag observed by Latham and Stefanik (1984) have $v \sin i > 10$ km s^{-1}. If those Hyades stars passed through a rapid rotation phase comparable to that observed for the Pleiades stars, their loss of angular momentum must be very rapid, much faster than predicted by the $t^{-1/2}$ relation.

c) *The Source of the Photometric Variations*

Figure 5 shows the $B-V$ versus $V-I$ diagram for late-type stars in the Pleiades. The diamonds are stars identified as photometric binaries in Stauffer (1984) on the basis of their location in the V versus $V-I$ color-magnitude diagram. Those binaries are displayed toward the bottom right of the diagram simply because they are composite systems: $(B-V)$ is sensitive to the hotter component while $(V-I)$ reflects the cooler component, and thus the stars are blue in $B-V$ for their $V-I$.

The rapid rotators (denoted by "+" symbols) are generally not photometric binaries, but their colors may be similarly affected if the variations are due to spots. Such spots, if unevenly distributed in longitude, will produce photometric variations as rotation changes the fraction of the visible

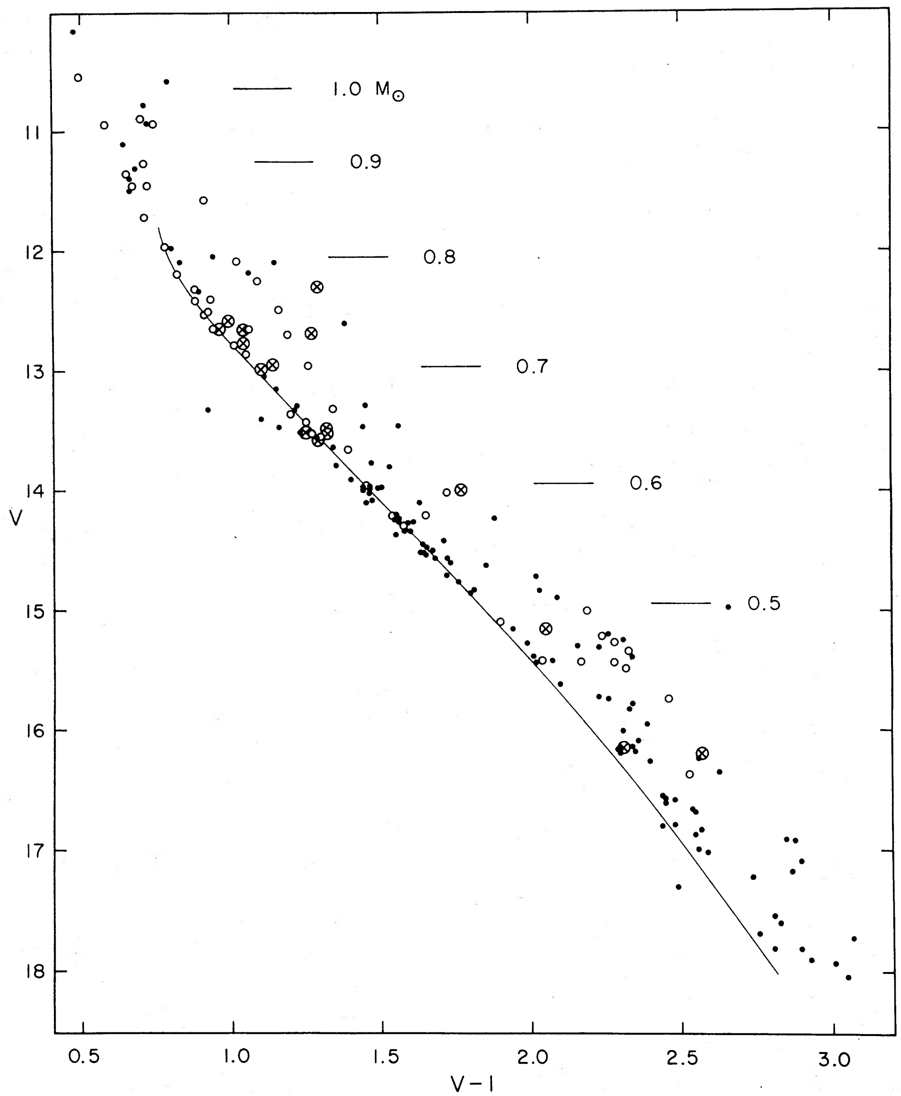

FIG. 4.—V versus $(V-I)$ color-magnitude diagram for the entire photometric sample of Stauffer (1983). Filled dots are stars for which no echelle spectra were obtained; small open dots are stars with $v \sin i < 25$ km s^{-1}; $\otimes$ symbols denote the stars with $v \sin i > 25$ km s^{-1}. The mass points shown were derived from the zero-age main-sequence models of Copeland, Jensen, and Jorgensen (1970).

stellar hemisphere that is affected. Spot models have been applied successfully to the BY Draconis and RS Canum Venaticorum variables to explain similar photometric variations. Stars so affected will have composite colors because the photosphere includes regions of more than one temperature; hence, the displacement of the rapid rotators in Figure 5. That displacement, if interpreted as being due to only two characteristic temperatures, implies that the photospheres and spots typically differ by at least 700 K.

A few stars in the composite region of Figure 5 are not designated as either binaries or rapid rotators. We do not have spectra for those stars, so they could be additional rapid rotators. The binary stars in Figure 5 were identified from their location in a color-magnitude diagram. Since the color-color diagram is more sensitive to low-mass secondaries, the unidentified stars in the composite region could also be binary systems with $0.4 < M/M_\odot < 0.6$. The candidate rapid rotator/binary stars are H II 559, H II 883, H II 915, H II 1532, H II 2927, and T73.

If the color properties of the rapid rotators are due to star spots, other indications of stellar activity should be present as well. Flare star observations provide one such activity index. Due primarily to the efforts of the staffs of Tonantzintla and Byurakan observatories, extensive data exist on flare stars in the Pleiades. The most recent compendium of that data (Haro, Chavira, and Gonzalez 1982) shows a striking correlation between flare activity and rapid rotation. This can be seen by comparing Figure 4 to Figure 6 of Stauffer (1984). Stauffer's Figure 6 shows the same color-magnitude diagram, but with the flare stars emphasized. The onset of flare activity is at exactly the same color that rapid rotation first appears, $(V-I) = 0.95$ mag. This connection is not so clear-cut when individual stars are considered. For $0.95 < V - I < 1.35$ mag, nine of 12 rapid

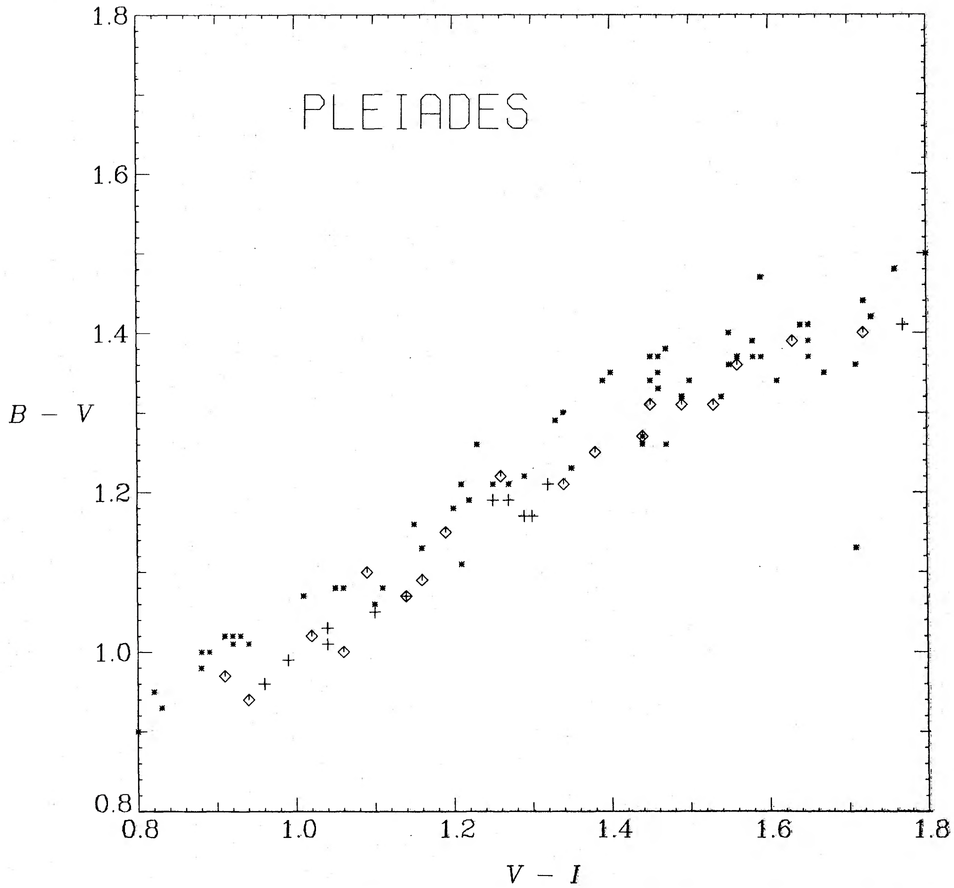

FIG. 5.—$(B-V)$ versus $(V-I)$ diagram for the Pleiades photometric sample. Diamond symbols are photometric binaries; + symbols are rapid rotators. The remaining stars either have $v \sin i < 25$ km s^{-1} or have not yet been observed spectroscopically.

rotators are flare stars, but so are eight of the 10 stars with $v \sin i < 10$ km s^{-1}. Thus flaring does not appear to be intimately connected with rapid rotation on a star-to-star basis, although the similar turn-on points suggest there is at least some connection.

Another indication of stellar activity available to us is the presence and strength of Hα emission. The bluest star for which we detect Hα in emission is H II 2244, with $V - I = 0.99$ mag, again, essentially the same turn-on point. For $0.95 < V - I < 1.35$ mag, eight of 11 (72%) of the rapid rotators have Hα clearly in emission versus only two of six of the stars with $v \sin i < 10$ km s^{-1}. Thus, for this color range, the presence of quiescent emission lines apparently correlates with rapid rotation somewhat better than flaring activity. For $V - I > 1.35$ mag, essentially all Pleiades stars have Hα in emission, while relatively few stars have $v \sin i > 25$ km s^{-1}. We assume that chromospheric activity is still connected to rotation, but for these fainter, more convective stars, a lower rotational velocity suffices to produce detectable Hα emission.

The slowly rotating Pleiades stars with Hα in emission uniformly have FWHM(Hα) ≈ 50 km s^{-1}, essentially the same as for dMe stars in the field (Worden, Schneeberger, and Giampapa 1981). For the rapid rotators, we have already noted that the Hα width correlates well with $v \sin i$, except for H II 686 and H II 1883. For those two stars, the projected rotational velocities inferred from the Hα emission width are much larger than the equatorial velocities inferred from the photometric periods. Therefore, rotation cannot be the only broadening mechanism for Hα. Two possible means for producing a broader emission profile in those stars would be through emission from a disk, as for FK Comae stars, or through a combination of wind expansion and/or turbulent broadening, as for T Tauri stars (De Campli 1981; Hartmann, Edwards, and Avrett 1982). Because the emission line profiles are symmetric and nearly Gaussian for those two stars, we prefer the latter explanation. H II 686 and H II 1883 are two of the three shortest period variables found by VA so it is plausible that they would show the broadening effect most strongly. What is not clear is whether the other Hα widths are unaffected (the wind turns on at some critical velocity) or if they are simply affected to a smaller degree.

IV. THE NATURE AND ORIGIN OF THE RAPID ROTATORS

VA have argued that the photometric variations of the K dwarfs result from ellipsoidal deformation due to rapid rotation, rather than starspots. In such a model, the photometric period would be equal to one-half the rotational period. The velocities predicted from the photometric periods would, therefore, be half as large as previously estimated in order to construct Figure 2. The spectroscopic data contradict that model since the observed *projected* velocities for the seven shortest period veriables would be larger than their "true" rotational velocities. The spectroscopically estimated $v \sin i$'s require that the photometric periods approximately equal the rotational periods. The starspot model predicts such an equality. If the photometric variations are caused by star spots, we can also explain the colors of the rapid rotators, as well as connections between rotation and Hα emission. Van Leeuwen (1983*a*) now also appears to favor a starspot model for the rapid rotators.

If we identify the source of the photometric variability as due to star spots, it is still necessary to explain the high rotational velocities. One means whereby low-mass stars can become rapid rotators is through synchronous rotation in a close binary. For the majority of the rapid rotators, that hypothesis is almost certainly incompatible with our data. Most pertinently, the mean radial velocity and velocity dispersion of the stars with $v \sin i > 25$ km s^{-1} in Table 2 is $\langle v \rangle = 6.3$ km s^{-1}, $\sigma = 5.1$ km s^{-1}. Those same quantities for the slowly rotating stars in the cluster (excluding stars with *d* and *e* quality velocities and H II 571 which has a radial velocity more than 5 σ from the cluster mean) are $\langle v \rangle = 6.6$ km s^{-1} and $\sigma = 1.8$ km s^{-1}. The velocity dispersions are in both cases consistent with our predicted measurement errors, since the rapid rotators generally have quality class *e* radial velocities (see the notes section to Table 2). If synchronism were required, the short periods observed by VA would imply velocity amplitudes for binary orbits of 100 to 200 km s^{-1}, clearly inconsistent with the observed radial velocities. As noted earlier, the rapid rotators also are generally not photometric binaries. Finally, the spun-up binary model provides no explanation for why most of the rapid rotators are concentrated in a relatively narrow spectral type range.

Another easily dismissed hypothesis is that the rapid rotators are, somehow, much younger than the average Pleiades star—young enough so that their rotational velocities predicted from the $t^{-1/2}$ law (Skumanich 1972; Soderblom 1983) are >50 km s^{-1}. If the stars were that young (an age $\sim 6 \times 10^6$ is required), they would still lie unambigously above the main sequence. The photometry precludes this.

a) *A Model for the Rapid Rotators*

One of the most peculiar aspects of the rapid rotation problem is that it is generally confined to the K stars. The G and M stars that we have observed are generally slowly rotating. We would like to develop a theory which reproduces this distribution of rotation with spectral type in a natural way.

We suggest that the mechanism which most easily accounts for the concentration of rapid rotators among the K stars is spin-up during radiative track contraction. Stars with masses $>0.5\ M_\odot$ are expected to evolve down Hayashi tracks until a radiative core begins to develop. At this point, the star moves leftward in the H-R diagram until it is quite close to the ZAMS. During this phase, the moment of inertia of the star decreases substantially as a result of the decrease in radius and the increasing concentration of mass in the central core. If this evolutionary phase is sufficiently rapid, the decrease in the moment of inertia can exceed any angular momentum loss that may result from magnetic braking, and the star will spin up.

From the evolutionary calculations of VandenBerg *et al.* (1983), we estimate that K stars of 0.75 $M_\odot$ are about 7×10^7 years old when they complete their radiative track contraction. This is the same age derived from the turnoff of the upper main sequence in the Pleiades (Patenaude 1978). On the other hand, stars of 1.0 $M_\odot$ reach the end of their radiative tracks at an age of about 3×10^7 years (Iben 1965). If the G stars in the Pleiades have ages $\sim 7 \times 10^7$ years, they have had 4×10^7 years to spin down from the effects of magnetic braking in the absence of any appreciable change in moment of inertia. Thus the age of the Pleiades inferred from the main-sequence turnoff is consistent with the idea that low-mass stars spin up considerably on their radiative tracks, and that the G stars have had time to spin down, but the K stars have not.

The theoretical evolutionary calculations for stars with $M < 0.45\ M_\odot$ indicate that these stars are fully convective all the way to the ZAMS (VandenBerg *et al.* 1983). Since these stars do not develop radiative cores, we would expect to see few or no rapid rotators among the Pleiades M stars. We do find a lower frequency of rapidly rotating stars among the M dwarfs observed; however, three M stars in our echelle sample are rapid rotators. The mean projected rotational velocity for those stars is not very high ($\langle v \sin i \rangle \approx$ 50 km s^{-1}), and we believe those stars may have either formed with greater than average angular momentum or have been spun up by binary companions.

Can the decrease in the star's moment of inertia quantitatively account for the observed spin-up? In order to derive that estimate, we have used the 0.75 $M_\odot$ evolutionary tracks of VandenBerg *et al.* (1983) and have assumed that core contraction starts at a point on the Hayashi track where the stellar luminosity equals the ZAMS luminosity. During radiative core development, the radius decreases by a factor ~ 1.5. In addition, the star becomes more centrally condensed. We have estimated the size of the latter effect by assuming that the star has a moment of inertia comparable to a polytrope with the same ratio of central density to average density. The tabulation of VandenBerg *et al.* (1983) shows that the main sequence density ratio is $\log \rho_c/\bar{\rho} = 1.42$. We adopt a polytrope of $n = 2.5$ to represent this stage (for which $\log \rho_c/\bar{\rho} = 1.37$). Since the initial model is assumed to be completely convective, the appropriate polytropic index at that stage is $n = 1.5$. Combining the change in internal structure with the decrease in radius, we estimate a total reduction in the moment of inertia ($\propto R^2$) of a factor of 4.4. If the star rotates as a rigid body, and if the magnetic braking is not too efficient, the equatorial velocity ($\propto R_*$) may increase by a factor of almost 3.

The observations of Vogel and Kuhi (1981) indicate that most low-mass T Tauri stars have $v \sin i < 35$ km s^{-1}. The stars they observed were somewhat more luminous, and hence at an earlier evolutionary phase than the initial point of the sequence described above. It seems reasonable to suppose that the K dwarfs were rotating at 20–30 km s^{-1} at the start of radiative core development. In that case, it appears possible to produce stars rotating at 60–90 km s^{-1} at the end of contraction. This encompasses much, but not all, of the observed range of rotation.

Relatively little angular momentum loss by means of magnetic braking during the radiative track PMS phase can be tolerated in this picture; otherwise, the spin-up is small. We find it encouraging that a relatively large spin-up has, in fact, been predicted for solar mass stars by Endal and Sofia (1981). Those authors have considered the rotational history of the PMS Sun, adopting plausible angular momentum loss rates from the theory of Belcher and MacGregor (1976). Their calculations indicate that it is possible for a solar type star to spin up significantly during its radiative track contraction, and to spin down rapidly at the conclusion of this phase. However, the results are suggestive rather than conclusive, given the uncertainties in magnetic braking.

Another problem with this picture is that it implies that angular momentum loss cannot prevent spin-up of K stars on time scales of several times 10^7 years, while G stars spin down on time scales $< 3 \times 10^7$ years. Endal and Sofia (1981) suggest an escape from this difficulty. In their models, the convective envelope is rapidly braked, but not the radiative core. That is, the effective moment of inertia is reduced because the entire star does not need to be spun down. If rapid radiative track contraction produces rapid rotation, the constraints on this spin-up and subsequent spindown suggest that the cores of young main-sequence stars may be rotating appreciably faster than their envelopes.

Even if one eliminates all magnetic braking during spin-up, it seems difficult with this picture to produce the stars rotating > 100 km s^{-1}. It may be necessary to postulate a significant spread in the initial angular momenta of the Pleiades K stars. In this connection, it is interesting to note that one low-mass T Tauri star in the Taurus cloud, V410 Tau, is rotating at 75 km s^{-1}, based on results from Vogel and Kuhi (1981) and our own spectra. Rydgren and Vrba (1983) have shown that this K7 star exhibits photometric variations with a period of $1\overset{d}{.}92$, which they attribute to the rotational modulation caused by starspots. Combining this period with the rotational velocity leads to a minimum radius $\sim 3\ R_{\odot}$, in agreement with the luminosity derived by Cohen and Kuhi (1979). This object is probably a low-mass star well above the main sequence, and it is tempting to speculate that such an object might later evolve into an extremely rapid rotating star like H II 1883.

As noted previously, the rapid rotators coexist with an approximately equal number of stars of the same spectral type that have rotational velocities below our detection limit. The lack of Hα emission in most of the latter group suggests that they are, in fact, intrinsically slowly rotating stars. This result may partially be the result of a spread in the initial angular momenta of the K stars. It seems more likely that the coexistence of the slowly rotating stars with the extreme rapid rotators is due to a spread in ages of those stars. The slow rotators formed earlier in time, enabling them to spin down by the present time. The apparent rapid spin-down of the G stars in the cluster and the prediction of the Endal and Sofia model indicate that the spread in age is $> 2\text{–}3 \times 10^7$ years.

Duncan and Jones (1983) have recently found other evidence for an age spread among late-type Pleiades stars. Those authors have measured lithium abundances in G and K stars in the Pleiades and Hyades clusters. They have interpreted the large range of lithium abundances for the Pleiades stars as evidence of a spread in age. The faintest star in their survey has $V \approx 12.6$ mag, so there is only a small overlap between their sample and ours. There is a good correlation between Li abundance and rotational velocity for the stars in common, however. We have divided the overlap stars into low- and high-lithium abundance sets according to their position in Figure 5 of Duncan and Jones (1983). The former group (H II 1100, 1275, 1776, 2278, 2311, and 2741) all have $v \sin i < 10$ km s^{-1}; for the latter group (H II 173, 296, 571, 739, 885, 2126, 2244, and 2881) four of eight have $v \sin i > 10$ km s^{-1}. That correlation qualitatively confirms the Li abundance spread observed by Duncan and Jones. Whether those stars differ in age or in initial angular momentum cannot yet be determined.

b) *Consequences of the Model*

While the model of rotational acceleration during radiative core contraction is attractive, there are problems in understanding the very large rotational velocities of some stars in combination with the low velocities of others. If this model is correct, several consequences follow. First, a more thorough study of rotation on the lower main sequence of the Pleiades should reveal more rapid rotators in the $1.3 < V-I < 2.0$ mag color range $(0.5 < M/M_{\odot} < 0.7)$. The maximum rotational velocity of the rapid rotators should decrease with decreasing mass, in response to the decreasing amount of time spent on radiative track contraction. Also, there should be few rapid rotators below 0.45 $M_{\odot}$. Because of their faintness, these low-mass Pleiades stars are difficult to observe, but valuable clues to their PMS evolution may be revealed.

Second, other young clusters should show this same phenomenon—we see no reason for the Pleiades to be unique. The point on a cluster's main sequence where this phenomenon first appears should be very sensitive to the cluster's age. In particular, we expect to see rapidly rotating G stars in a cluster slightly younger than the Pleiades.

V. CONCLUSIONS

We have shown that most of the short-period photometric variables discovered by van Leeuwen and Alphenaar are indeed rapidly rotating stars, with projected rotational velocities greater than 50 km s^{-1}. H II 1883 is the most extreme case, with a projected rotational velocity of 140 km s^{-1}. Some of the longest period variables found by VA may be spurious since the ratios of their projected rotational velocities to their predicted velocities are systematically much lower than for the shorter period variables. In total, we have measured rotational velocities greater than 25 km s^{-1} for 18 K and M dwarfs in the Pleiades. Most of the rapid rotators are concentrated in a narrow color (spectral type) range $0.95 < V-I < 1.35$ mag (K2–K6). For $V-I < 0.95$ mag, we find no stars with $v \sin i > 20$ km s^{-1}, while for $V-I > 1.35$ mag there are a few stars with moderate rotational velocities ($v \sin i \approx 40$ km s^{-1}), but the fraction of stars that are rapidly rotating appears less than for the 0.95–1.35 mag color range.

The rapid rotators appear generally to be single, main-sequence stars. Their observed rotational velocities are contradictory to the suggestion that the light variations are due to ellipsoidal structure of stars spinning near breakup. The alternative hypothesis that the rapid rotators are spotted stars is consistent with those rotational velocities and the position of the stars in the color-color and color-magnitude diagrams. That conclusion is supported by the near coincidence of the turn-on points for rapid rotation, flare activity, and Hα emission at $V-I \approx 0.97$ mag.

The spectral type distribution of the rapid rotators is most easily explained by the idea that these stars have spun up during radiative track contraction. In that picture, the G stars in the cluster were rapid rotators and they have already spun down; the mid-K stars have recently arrived on the main sequence. The turn-on point for rapid rotation is then a sensitive age indicator for low-mass stars in open clusters. The color range over which rapid rotation occurs and the rotational velocity distribution in that color range may eventually allow us to constrain the range of initial angular momentum, the time spread of star formation, and the precise dependence of $\dot{J}$ on J.

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