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Rotation Periods of Open Cluster Stars, III

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Abstract
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Keywords
Open Cluster Stars, photometric monitoring program, rotation periods

Disciplines
Astrophysics and Astronomy | Other Astrophysics and Astronomy | Stars, Interstellar Medium and the Galaxy

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ABSTRACT. We present the results from a photometric monitoring program of 15 open cluster stars and one weak-lined T Tauri star during late 1993/early 1994. Several slow rotators which are members of the Alpha Persei, Pleiades, and Hyades open clusters have been monitored and period estimates derived. Using all available Pleiades stars with photometric periods together with current X-ray flux measurements, we illustrate the X-ray activity/rotation relation among Pleiades late-G/K dwarfs. The data show a clear break in the rotation–activity relation around $P \sim 6-7$ days—in general accordance with previous results using more heterogeneous samples of G/K stars.

1. INTRODUCTION

In this study we continue our program of photometric monitoring of primarily solar-type cluster stars in order to derive rotation periods and light-curve shapes/amplitudes. Earlier results have been reported in Prosser et al. (1993a; 1993b) (hereafter referred to as Papers I and II) in which periods for generally rapidly rotating stars were determined. Here we have attempted to derive periods for more slowly rotating cluster members; period estimates for 15 cluster stars and 1 weak-lined T Tauri star are presented. The cluster stars observed include stars in the Alpha Persei, Pleiades, and Hyades open clusters.

Period determinations for slow rotations in the Pleiades and Hyades have been provided in previous studies by Van Leeuwen et al. (1987), Radick et al. (1987), and Magnitskii (1987). While spectroscopic observations provide one measure of a star's rotation—$v \sin i$, or the *projected* rotational velocity—photometric monitoring of spotted stars can provide the true stellar rotation period independent of axial projection effects. Photometric monitoring has the additional benefit in that it can provide rotation periods for slow rotators where only upper limits in $v \sin i$ could be determined spectroscopically. The long periods however require a substantial amount of observing, either using a dedicated telescope or the combined monitoring efforts of several observ-

TABLE 1
Observations

Star	N_{obs}	Date/Data Range		Observer
ALPHA PER:				
AP167	42	Jan 94	JD9351-9361	NURO
AP201	40	Nov93-Jan94	JD9297-9361	CfA/NURO
AP212	17	Nov 93	JD9297-9310	CfA
PLEIADES:				
HII 293	67	Nov93-Jan94	JD9297-9361	CfA/Lick/NURO
HII 314	42	Nov 93	JD9297-9327	CfA/Lick
HII 320	44	Nov 93	JD9297-9327	CfA/Lick
HII 357	14	Nov 93	JD9297-9310	CfA
HII1124	52	Nov93-Jan94	JD9308-9361	Lick/NURO
HII2284	64	Nov93-Jan94	JD9297-9361	CfA/Lick/NURO
HII2341	63	Nov93-Jan94	JD9297-9361	CfA/Lick/NURO
HII2548	19	Jan 94	JD9351-9361	NURO
HII3030	38	Nov 93	JD9297-9327	CfA/Lick
HII3063	46	Nov93-Jan94	JD9297-9361	CfA/Lick/NURO
HYADES:				
VA 486	54	Nov93-Jan94	JD9308-9361	NURO/Lick
VA 512	31	Nov92-Mar94	JD8922-9433	CfA/NURO
VA 622	56	Nov93-Jan94	JD9297-9361	CfA/Lick/NURO
FIELD:				
WTT04159 +1716	12	Jan 94	JD9355-9361	NURO

ers at different sites. We have chosen the latter course (Paper I) and report here our results for a sample of predominantly slow rotators. The new rotation periods among Pleiades members enable us to refine the relation between coronal X-ray activity and rotation discussed in Paper II.

2. OBSERVATIONS AND ANALYSIS

In Table 1 we list the sample of stars observed. Following the star name are the number of observations (N_{obs}) used in the period determination, the dates of observation, and the observer identification. "CfA" observations were obtained with the Whipple Observatory 48-in. telescope on Mt. Hopkins, AZ by observers B.W./C.P./K.K. "NURO" observations were obtained by A.D./D.B./B.L./S.B./L.M. using the 31-in. telescope of the National Undergraduate Research Observatory in Flagstaff, AZ. "Lick" observations were obtained by M.D.S. at the Lick Observatory 40-in. telescope on Mt. Hamilton, CA. All observations were obtained using a V-band filter (Bessell 1990) with a CCD camera. As only the periods and amplitudes of the target stars are desired, relative photometry between the target star and one or more comparison stars on the CCD frame was obtained from aperture photometry measures using either the IRAF "apphot" package or the DAOPHOT routines (Stetson 1987) in the current version of VISTA. The reader is referred to Paper I where additional discussion regarding the techniques of photometric monitoring is given. Exposure times were set so as to generally attain a count level for the variable and comparison stars which would enable photometric accuracies of 1% or better. Except where noted below, differencing the two comparison stars for each program star confirmed that the photometry had accuracy of this order. As in Papers I and II, periodogram analysis was performed on the relative photometry using a program which incorporates the method outlined by Horne and Baliunas (1986) and Scargle (1982) for unevenly sampled data.

We do not tabulate the individual observations here, but will provide to anyone interested the data and finding charts indicating the variable and comparison stars. The observations have also been submitted to the National Space Science Data Center (NSSDC).

The results of the period analysis for the stars in Table 1 are listed in Table 2. Following the star name are the approximate V, $B-V$ values, the observed $v \sin i$ and its source reference, the derived period, amplitude, and false alarm probability (f) from the periodogram analysis. In those cases where the period is regarded as uncertain it is denoted with a colon. The comparison stars (or primary comparison star) for each target in Table 2 are also given. The comparison stars are designated by Hertzsprung's (1947) H II number for the Pleiades, and Guide Star Catalog number (=GSC; Lasker et al. 1988) for Alpha Per, Hyades, and the weak-lined T Tauri star. The phased light curves for the stars in Table 2 are presented in Fig. 1. Below we briefly discuss some of the more noteworthy stars in Table 2.

2.1 AP 212

In addition to the 6.2:-day period in Table 2, a second period of 1.2 days was indicated in the periodogram analysis of AP 212. The higher false alarm probability of 4.6% associated with the 1.2-day period and the small $v \sin i$ observed for AP 212 lead us to believe that the longer period is more probably correct.

2.2 H II 293, H II 314, and H II 320

As these three Pleiades members lie within a few arcminutes of each other on the sky, relative CCD photometry of all three could be obtained in one observation. The nonmember stars used for comparison were H II 285 and H II 262, with H II 285 as the primary comparison star. For H II 293, the period determinations range from 4.0 to 4.5 days, depending on which combination of observations are used. Analysis of all 67 observations yields a 4.2-day period, the CfA/Lick data alone yield 4.5 days, and the NURO data alone yield 4.0 days. The phased light curve using all observations is shown in Fig. 1. For H II 314, we confirm the 1.5-day period reported in Paper II; additional information on this star is discussed there. H II 320 is a spectroscopic binary (Mermilliod et al. 1992).

2.3 H II 1124

Van Leeuwen et al. (1987) initially reported a 6-day period for H II 1124. When analyzed separately, the Lick and NURO observations in this present study yield periods of 6.5: and 5.9: days, respectively, generally confirming Van Leeuwen et al. results for this low-amplitude star.

TABLE 2
Period Determinations

Star	V	B−V	$v \sin i$ (km/s)	REF	Period	Amp. (mag.)	f	Comparison Star
ALPHA PER:								
AP167	13.52	1.23[a]	96	2	9.8 hrs	0.10	1.1×10^{-4}	3316.1433
AP201	13.08	1.16[a]	12	1	3.75 d	0.08	4.9×10^{-4}	3320.2175
AP212	13.24	1.09[a]	12	2	6.2: d	0.07	1.3×10^{-2}	3321.2448, 3321.2235
PLEIADES:								
HII 293	10.79	0.70	< 7	3	4-4.5: d	0.02	4.0×10^{-2}	HII 285
HII 314	10.56	0.64	38	3	1.47 d	0.065	1.8×10^{-5}	HII 285
HII 320	11.04	0.88	11	3	4.6: d	0.06	1.6×10^{-3}	HII 285
HII 357	13.32	1.21	< 10	4	3.4: d	0.07:	2.2×10^{-2}	HII 374
HII1124	12.32	0.98	7.5	3	5.9-6.5: d	0.03	1.2×10^{-2}	HII1121,HII1087
HII2284	11.35	0.78	< 7	3	10.1 d	0.02	7.8×10^{-5}	HII2296
HII2341	10.93	0.72	< 7	3	8.2 d	0.02	1.0×10^{-3}	HII2296
HII2548	14.02	1.33	< 10	5	7.5 d	0.06	5.9×10^{-3}	HII2580
HII3030	14.03	1.39	< 10	5	7.4: d	0.04	5.0×10^{-3}	HII3026
HII3063	13.54	1.17	26	3	0.89 d	0.10	2.8×10^{-7}	HII3067
HYADES:								
VA 486	12.05	1.49	< 10	6	2.42 d	0.06	2.1×10^{-4}	1269.1208, 1269.0957
VA 512	14.26	1.53	...	...	8.8 d	0.04	2.1×10^{-3}	1265.0899
VA 622	11.85	1.44	< 10	6	...	...	...	1269.0795, 1269.0771
FIELD:								
WTT04159 +1716	12.28	1.13	68	7	13.3: hrs	0.05:	1.0×10^{-1}	1268.0383

[a] B−V value estimated from V−I_K color.
REF: 1) Prosser (1992), 2) Prosser (1994), 3) Soderblom et al. (1993), 4) Stauffer et al. (1984), 5) Stauffer & Hartmann (1987), 6) Stauffer et al. (1987), 7) Walter et al. (1988)

2.4 H II 2284 and H II 2341

Both H II 2284 and H II 2341 were observed in the same CCD field, with the comparison stars H II 2296 (primary) and H II 2294. The corresponding periods in Table 2 are among the longest periods so far observed among Pleiades stars. For both stars, all available observations were used in the analysis with no significant phase shift evident between datasets by different groups. H II 2294 was unsuitable for use as a comparison star as it was observed to vary by ~0.15 mag over an interval of several days; no period could be derived from the limited data.

2.5 H II 3030 and H II 3063

These two Pleiades members were observed together, along with the comparison stars H II 3026 and H II 3067.

2.6 VA 486, VA 512, and VA 622

Of the three Hyades stars in the present study, VA 622 has been observed to have Hα in absorption while VA 486 and VA 512 have among the strongest Hα emission strengths in their color range (Stauffer et al. 1991). VA 486 and VA 512 were targeted for monitoring since their high activity suggested an improved probability of observing brightness variations related to stellar activity. In the *EINSTEIN* survey of the Hyades (Micela et al. 1988), both VA 486 and VA 512 were detected in X rays, while only an upper limit was derived for VA 622.

VA 486 is a close visual binary with separation ~1″, consequently both components were included in the aperture photometry measures. The NURO and Lick datasets exhibit a phase shift and were analyzed separately: both datasets yield similar periods (NURO: 2.41 days, Lick: 2.43 days) and consistent amplitudes. The light curve for the NURO dataset is shown in Fig. 1.

VA 512 was originally observed in 1992 November by C.P.; a period of 8–10 days was indicated but the analysis was not considered to be conclusive. The analysis with the combined 1994 March NURO observations and November 1992 data yields an 8.8-day period with no significant phase shift apparent between the two datasets. This indicates either that the spot asymmetry responsible for the light curve is very long lived, or simply that the phase agreement between these two epochs is by chance.

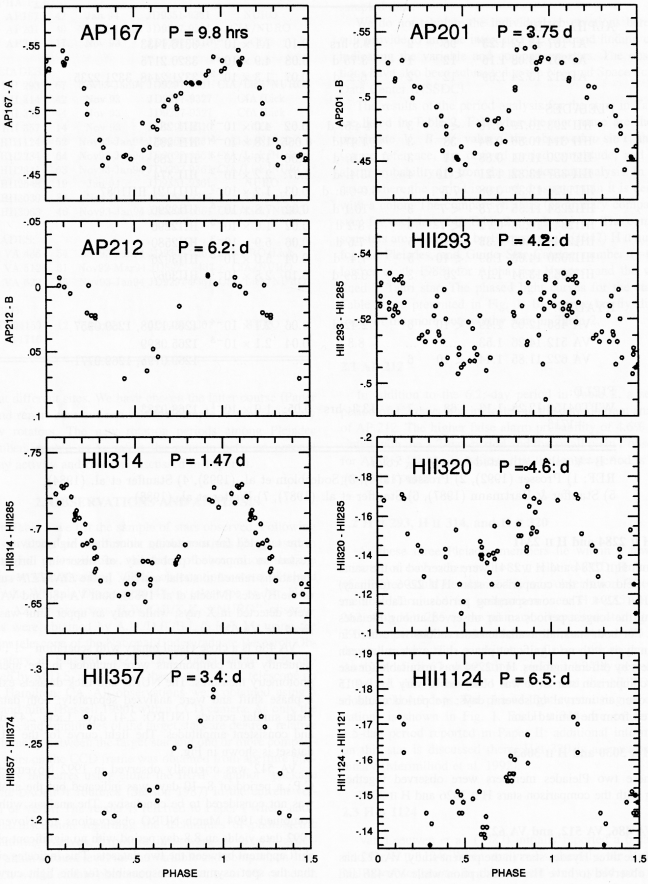

FIG. 1—Phased *V*-band light curves for those stars with period determinations in Table 2.

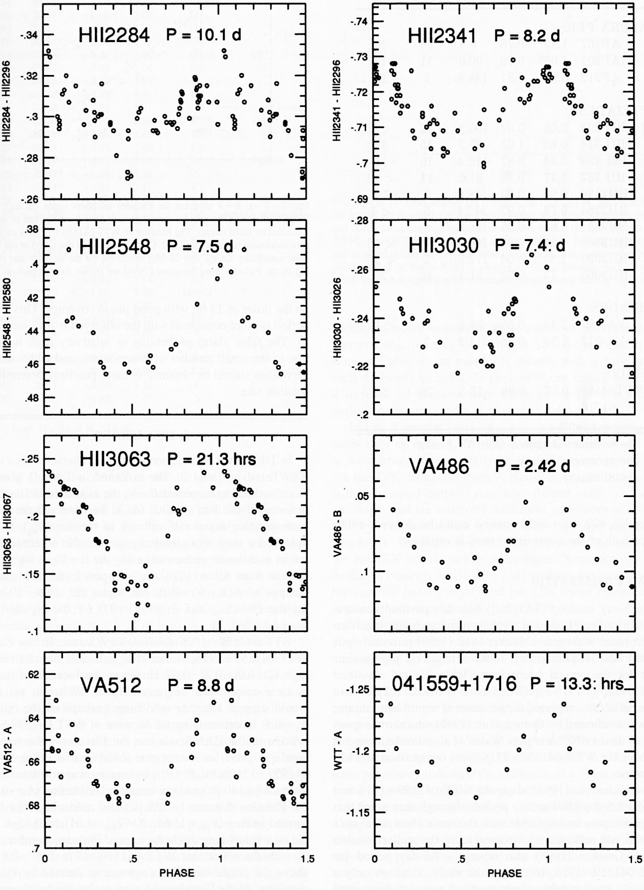

FIG. 1—(Continued)

TABLE 3
Physical Characteristics

Star	$B-V_0$	$R/R_\odot$	Period (hrs)	v_{eq} (km/s)	$v \sin i$ (km/s)
ALPHA PER:					
AP167	1.13[a]	0.76	9.8	94	96
AP201	1.06[a]	0.79	90.0	11	12
AP212	0.99[a]	0.81	148.8:	7	12
PLEIADES:					
HII 293	0.66	0.97	100.8:	12	< 7
HII 314	0.60	1.03	35.3	35	38
HII 320[b]	0.84	0.87	110.4:	10	11
HII 357	1.17	0.75	81.6:	11	< 10
HII1124	0.94	0.83	148.8:	7	7.5
HII2284	0.74	0.92	242.4	5	< 7
HII2341	0.68	0.95	196.8	6	< 7
HII2548	1.29	0.69	180.0	5	< 10
HII3030	1.35	0.66	177.6:	5	< 10
HII3063	1.13	0.76	21.3	43	26
HYADES:					
VA 486[c]	1.49	0.55	58.1	11	< 10
VA 512	1.53	0.48	211.2	3	...
FIELD:					
WTT04159 +1716	0.97	0.86	13.3:	78	68

[a] B−V value estimated from V−I color.
[b] spectroscopic binary.
[c] visual binary.

For VA 622, no reliable period could be derived; either one or both of the comparison stars is variable.

2.7 WTT 041559+1716

An X-ray source ("TAP 26") near this position was discovered by Feigelson et al. (1987), using archival data from the *Einstein Observatory*. Walter et al. (1988) provided optical and near-IR photometry, found a relatively high $v \sin i$ value for the optical counterpart (Table 2), and classified WTT 041559+1716 (=HBC 376) as a naked T Tauri star. Walter et al. also reported the presence of significant lithium; this was confirmed by Gomez et al. (1992) who show a spectrum of the Li 6707 Å region. Walter et al. estimate an age of ~4 Myr for WTT 041559+1716 from comparison to PMS isochrones.

Bouvier et al. (1993) observed WTT 041559+1716 and found a 2.5-day photometric period, although they noted that this period was incompatible with the star's observed $v \sin i$ and did not consider it as representing the stellar rotation period. Grankin (1993) also reports a 2.5-day period for WTT 041559+1716. In the present study, although only a relatively small number of observations over a 6-day period could be obtained, the new data appear to indicate a period on the order of 13 hr, with good phase coverage. This shorter period is more consistent with the observed $v \sin i$ (see Table 3). The false alarm probability is relatively high however, due to the small number of observations and additional observations should be obtained to more precisely determine its rotation rate.

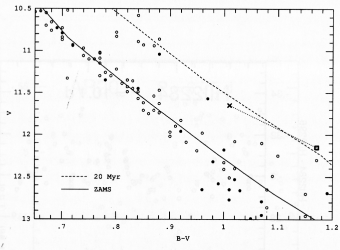

FIG. 2—V vs. $B-V$ diagram for Pleiades members (open circles). Those Pleiades members for which rotation periods have been derived to date are indicated by filled circles. The location of WTT 041559+1716 is shown for zero reddening (open square) and A_V=0.5 (cross), as discussed in the text. A solar metallicity ZAMS and 20-Myr isochrone for the distance and reddening of the Pleiades from Swenson (1994) are shown for comparison.

3. DISCUSSION

In Table 3 we provide some physical characteristics of the stars listed in Table 2. The columns in Table 3 give star name, reddening corrected $B-V$, the estimated stellar radius in terms of the Sun's radius ($R_\odot$), the observed period, the corresponding equatorial velocity of the star (v_{eq}), and the observed $v \sin i$. For simplicity we use the observed $B-V$ colors to estimate stellar radii using the $B-V_0$ vs log $(R/R_\odot)$ relation from Allen (1976), as in Papers I and II. Mean reddenings of $E(B-V)$=0.10 for Alpha Per, $E(B-V)$=0.04 for the Pleiades, and $E(B-V)$=0.0 for the Hyades have been assumed.

WTT 041559+1716 Evolutionary Status. In the case of WTT 041559+1716, Walter et al. estimate minimal reddening: A_V=0.0(+0.2/−0.0). However, the location of the star in their color–color diagram (Fig. 5, Walter et al. 1988) would suggest a higher reddening, perhaps on the order of A_V≃0.5. In determining the location of WTT 041559+1716 relative to the ZAMS, we use the Pleiades main sequence (age ~70 Myr) as a surrogate ZAMS as in Paper I. WTT 041559+1716's (V,$B-V$) photometry was corrected for its distance (~140 pc) and our estimated reddening (A_V~0.5) to the Pleiades distance (~125 pc) and reddening. The transformed values (V_{ple}≃11.65, $B-V_{ple}$≃1.01) were then plotted on a color–magnitude diagram of Pleiades members (Fig. 2) with the result that WTT 041559+1716 lies ~0.8 mag above the single-star main sequence as defined by Pleiades members. At the Pleiades age, stars are on the main sequence in this region of the color–magnitude diagram. Whether this

TABLE 4
Pleiades X-Ray/Rotation Period Data

Star	LogL_x	Log($\frac{L_x}{L_{bol}}$)	Log(P(hrs))	Spt Type	Notes
HII 34	28.98	−4.04	2.20	early K	
HII 152	< 29.31[a]	< −4.17	2.00	G1	
HII 293	29.13	−4.29	2.01	G1	
HII 296	29.93[a]	−3.31	1.78	G8	
HII 314	30.28	−3.22	1.55	G1	SB1?
HII 320	29.90	−3.47	2.04	G5	SB
HII 324	29.85	−2.83	1.00	K	
HII 357	29.28[a]	−3.38	1.91	K6	
HII 625	30.19	−2.92	1.01	K0	heavily reddened
HII 686	29.75	−2.93	0.98	K7	PhB
HII 708	29.78	−3.89	1.40	F9	
HII 727	29.98	−3.85	1.46	F9	
HII 739	30.29	−3.61	1.81	G0	PhB
HII 879	< 29.47[a]	< −3.30	2.25	K	
HII 882	29.64[a]	−3.06	1.14	K3	
HII1124	29.47	−3.43	2.16	K1	
HII1136	30.14	−3.02	1.10	G8	heavily reddened
HII1332	29.22[a]	−3.63	2.30	K4	
HII1531	29.56	−3.04	1.06	K7	
HII1883	29.67[a]	−3.15	0.75	K2	
HII2034	29.67	−3.09	1.12	K3	
HII2244	29.99	−2.82	1.14	K3	
HII2284	< 28.79	< −4.42	2.38	late-G	
HII2341	< 28.85	< −4.52	2.29	G4	
HII2548	28.98	−3.52	2.26	K7	
HII2741	29.38	−3.41	2.08	K	
HII2881	29.90	−3.30	2.00	K2	PhB
HII2927	29.34	−3.10	0.80	K4	
HII3030	< 28.77	< −3.77	2.25	K7	
HII3063	29.61	−2.93	1.33	K	
HII3163	29.78	−2.96	1.00	K	

[a] logLx from Micela et al. (1994).

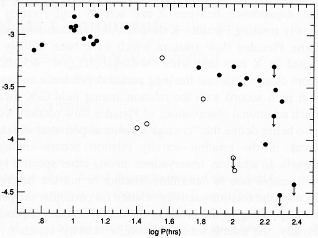

FIG. 3—Plot of X-ray activity [in terms of $\log(L_x/L_{\rm bol})$] vs. the logarithm of the period (in hours) for those Pleiades stars with known rotation periods and X-ray measurements reported in Stauffer et al. (1994) or Micela et al. (1994). Stars in Table 4 are plotted as open circles for spectral types F9–G1 and as filled circles for G4–K9. When only the K dwarfs are considered, a general trend of lower X-ray activity with longer rotation period is indicated, with what appears to be a dramatic drop in X-ray flux for $\log P \geq 2.2$.

elevation above the ZAMS is due to binarity or to WTT 041559+1716 being in the pre-main-sequence phase of evolution and still evolving to the ZAMS, is difficult to ascertain. This comparison to the Pleiades would indicate that WTT 041559+1716 is significantly older than the 4-Myr estimate by Walter et al.—its age could approach that of the Pleiades since Pleiades members exist which have similar elevations above the single-star cluster sequence. Comparison of WTT 041559+1716's position in Fig. 2 to theoretical isochrones suggests that it is at least as old as 20 Myr. In Table 3 we have used WTT 041559+1716's observed $B-V$ to find $R/R_{\odot}=0.86$ and $v_{\rm eq}=78$ km/s. If one instead chooses to assume that the star is still evolving to the ZAMS, then correcting the stellar radius to its pre-main-sequence value [case (3), Paper II], one finds $R/R_{\odot}\simeq 1.2$ and $v_{\rm eq}=110$ km/s.

Rotation vs X-ray Activity. In Paper II an initial study of the relation between rotation period and coronal X-ray activity among Pleiades members was performed using available periods and X-ray luminosities from Stauffer et al. (1994). We can now refine this relationship using the additional period determinations in Table 2 and the recent Pleiades X-ray study by Micela et al. (1994) which provides X-ray luminosities for some stars not covered by the Stauffer et al. survey. In Table 4 we give a synopsis of the Pleiades X-ray/rotation-period data, where the log L_x and $\log(L_x/L_{\rm bol})$ data are from Stauffer et al. or from Micela et al. where indicated. Observed or estimated spectral types are given, along with additional notes indicating those cases of photometric or spectroscopic binaries (i.e., PhB or SB). As in Paper II, the stars in Table 4 are mostly K dwarfs with a few late-F/early-G dwarfs included. To the best of our knowledge, Table 4 includes all Pleiades stars which currently have rotation periods determined from photometric monitoring.

In Fig. 3 we plot $\log(L_x/L_{\rm bol})$ vs. $\log P$(hr) for those Pleiades stars in Table 4. The late-F/early-G members are seen to have lower X-ray activity levels for a given period than the late-G/K dwarf members. A plausible explanation for this is that the late-F/early-G stars have thinner outer convective envelopes and are relatively inefficient generators of coronal activity compared to later-type stars having larger convective envelopes. The early-G-dwarf H II 314 is not deviant from the late-G/K dwarfs in Fig. 3; its higher X-ray activity may be due to binarity. At G4, H II 2341 perhaps lies intermediate between the late-F/early-G and late-G/K dwarf categories; it is plotted with the late-G/K group in Fig. 3.

The rotation–activity relation shown in Fig. 3 for Pleiades K dwarfs illustrates what is perhaps a gradual trend of decreasing $\log(L_x/L_{\rm bol})$ from the very rapid rotators ($P\sim 10$ hr) to slower rotators with periods ~6.5 days, at which point there appears to be a dramatic drop in X-ray flux as one continues to longer periods. The dependence of stellar activity upon rotation and spectral type has been extensively studied among field stars [Vilhu (1984a) and references therein, Marilli and Catalano (1984)]. Observations of field G/K stars have previously indicated the existence of a break or change in the dependence between X-ray activity and rotation occurring for periods around 10 days (Vilhu 1984b; Walter 1982), along with the lower X-ray activity levels among F/early-G dwarfs in comparison to late-G/K dwarfs. The Pleiades observations presented here provide a much more homogeneous population of stars in terms of age and metallicity for study of the relation between rotation and activity.

The upper limits in X-ray activity encountered at long rotation periods in Fig. 3 prevent meaningful calibration of the dependence between X-ray activity and rotation for slowly rotating Pleiades K dwarfs. Additional monitoring of those Pleiades slow rotators which have been reliably detected in X rays and with $-4 \leq \log(L_x/L_{bol}) \leq -4.5$ should more clearly illustrate the long period dependence and check if it is in accord with the relation among field G/K dwarfs. Such additional observations of Pleiades slow rotators would also better define the "critical" rotational period at which the break in the rotation–activity relation occurs among K dwarfs. In addition, observations among other spectral types will enable one to determine whether or not the functional form of the rotation–activity relation (in particular the period corresponding to the break in the curve) is mass dependent. Finally, the establishment of similar activity–rotation relations for stars in other clusters will enable one to see if similar relations hold at other ages for stars within narrow spectral-type/mass intervals.

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