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Rotation Periods of Open Cluster Stars, II

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

Disciplines
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Rotation Periods of Open-Cluster Stars. II.[1]

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ABSTRACT. We present the results from a photometric monitoring program of 21 stars observed during 1992 in the Pleiades and Alpha Persei open clusters. Period determinations for 16 stars are given, 13 of which are the first periods reported for these stars. Brightness variations for an additional five cluster stars are also given. One K dwarf member of the α Per cluster is observed to have a period of rotation of only 4.39 hr, perhaps the shortest period currently known among BY Draconis variables. The individual photometric measurements have been deposited with the NSSDC. Combining current X-ray flux determinations with known photometric periods, we illustrate the X-ray activity/rotation relation among Pleiades K dwarfs based on available data.

1. INTRODUCTION

In our continuing program of photometric monitoring of late F, G, and K dwarfs in open clusters to derive rotation-period and brightness-variation information, we report here the results for observations obtained during 1992. Period estimates for 16 stars are reported, 13 of which represent first-time period determinations. The reader is referred to Prosser et al. (1993, = Paper I) and the references therein for additional information on the observational and theoretical study of spotted stars. Similar programs to determine rotational periods for solar-mass stars in Alpha Persei and the Hyades have been reported by other groups (Radick et al. 1987; O'Dell and Cameron 1993).

Photometric monitoring of stars in young clusters enables rotation periods to be determined independent of projection effects due to axial inclination. Eventually, once a significant sample of periods of solar-type stars in clusters spanning a range of ages has been formed, the photometric periods may be applied towards better understanding the angular momentum evolution occurring in open clusters among solar-type stars. Longer-term monitoring of spotted stars can lead to information regarding the presence of stellar cycles that modulate the amplitude of the star's light curve, or evidence for possible changes over time in the surface starspot distribution. BY Draconis, the prototype dwarf star whose variability is attributed to rotational modulation caused by starspots, is one such example of a target of long-term photometric monitoring (Panov and Ivanova 1993, and references therein). Two stars reported here, H II 1883 and AP 86, already have well-established periods, but were monitored again as part of a longer-term program to monitor changes in the amplitudes of the light curves.

2. OBSERVATIONS AND ANALYSIS

In Table 1 we list the sample of Pleiades and Alpha Persei cluster stars observed, along with the number of observations (N_{obs}), the number of observations rejected during the period analysis (N_{bad}), the date of observation, and observer identification. The sample contains a selection of mostly moderate and fast rotators; stars with large

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TABLE 1
Observations

Star	N_{obs}	N_{bad}	Date/Data Range		Observer
PLEIADES:					
HII 314	87	0	Nov92-Jan93	JD8932-9018	EM/SC
HII 708	88	1	Nov92-Jan93	JD8932-9018	EM/SC
HII 727	85	1	Nov92-Jan93	JD8932-9018	EM/SC
HII2741	8	0	Nov 92	JD8950-8956	NURO
HII2881	20	0	Nov 92	JD8922-8932	CP
ALPHA PER:					
HE373	47	2	Oct 92	JD8901-8905	MDS
HE622	33	3	Oct 92	JD8901-8905	MDS
AP 37	34	0	Nov 92	JD8927-8932	CP
AP 63	26	2	Nov 92	JD8945-8951	NURO
AP 86	23	0	Nov 92	JD8945-8951	NURO
AP117	44	0	Oct-Nov 92	JD8901-8951	NURO/MDS
AP124	100	0	Nov 92	JD8922-8933	CP
AP127	21	1	Oct 92	JD8901-8905	MDS
AP149	33	3	Oct 92	JD8901-8905	MDS
AP226	48	0	Oct 92	JD8901-8905	MDS
AP244	14	0	Oct 92	JD8901-8905	MDS

$v \sin i$'s were predominantly selected due to the limits imposed by available observing time.

Observations by EM/SC were obtained using a photoelectric photometer at the 0.9-m telescope at Serra La Nave, Italy. Observations by "NURO" were obtained by SW/DB/BL/VA/LM using a CCD at the 31-in. telescope of the National Undergraduate Research Observatory in Flagstaff, AZ. SW employed the "apphot" package in IRAF to obtain aperture photometry from the NURO CCD data. CCD observations by MDS were obtained at the Lick Observatory 40-in. telescope and reduced using the IRAF "apphot" package. CCD observations by CP were obtained with the Whipple Observatory 48-in. telescope on Mt. Hopkins, AZ; aperture photometry was derived using the DAOPHOT routines (Stetson 1987) incorporated into the current version of VISTA.

As in Paper I, only observations in V band were obtained for the target stars. 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. Only the relative magnitudes between the variable and comparison stars were used in the period analysis. Additional discussion regarding the techniques of photometric monitoring is given in Paper I. As in Paper I, 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).

TABLE 2
Period Determinations

Star	V	B−V	$v \sin i$ (km/s)	REF	Period (hrs)	Amp. (mag.)	f	Comparison Star
PLEIADES:								
HII 314	10.56	0.64	38	5	35.5	0.09	6.8×10^{-8}	HII 405
HII 708	10.13	0.62	45	5	25.2:	0.03	2.4×10^{-4}	HII 652
HII 727	9.70	0.55	50	5	28.8	0.04	3.1×10^{-6}	HII 652
HII2741	12.65	1.01	11	6	120:	0.02	8.9×10^{-2}	HII 2697, 2718
HII2881	11.57	0.97	12	7	102	0.04	6.6×10^{-3}	HII 2917, 2921
ALPHA PER:								
HE373	11.50	0.77	140	2	8.0	0.13	7.1×10^{-8}	3315.0532, 3315.1104
HE622	11.63	0.79	61	1	19.3	0.045	7.9×10^{-4}	3320.0777, 3320.0965
AP 37	12.61	0.96	29	1	57.6:	0.03	1.1×10^{-3}	3320.0615, 3320.0737
AP 63	12.29	0.92	161:	4	5.4	0.02	3.2×10^{-3}	3320.1221
AP 86	14.31	1.32	140	1	5.1	0.12-0.13	2.6×10^{-2}	(1.5′ N, 2.4′N:1′W)
AP117	13.05	0.95	83	2	11.3	0.17,0.13	1.6×10^{-7}	3320.1573, 3320.1863
AP124	13.44	1.27[a]	190:	4	4.39	0.08	$\leq 10^{-11}$	3319.1974, 3319.1975
AP127	12.57	0.92	80	3	8.1	0.04	2.2×10^{-3}	3315.2422, 3311.1535
AP149	11.71	1.09[a]	117	3	7.6	0.08	1.4×10^{-5}	3320.0777, 3320.0965
AP226	12.45	1.12[a]	181	3	5.35	0.07	2.7×10^{-7}	3317.1013, 3317.1127
AP244	12.89	1.15[a]	42	3	11.5	0.04	3.9×10^{-2}	3317.0705, 3317.0795

[a] B−V value estimated from $V-I_K$ color.
REF: 1) Stauffer etal. (1985), 2) Stauffer etal. (1989), 3) Prosser (1992), 4) Prosser (1993), 5) Soderblom etal. (1993), 6) Stauffer & Hartmann (1987), 7) Stauffer etal. (1984).

Table 2 lists the results of the period analysis for the stars in Table 1. Following the star name are the approximate V and $B-V$ value, the star's $v \sin i$ value and its source reference, the derived period, amplitude and false-alarm probability (f) from the periodogram analysis. Three of the stars have $f > 1\%$—for AP 86, the derived period is nevertheless correct based on our previous, more extensive monitoring of this star (Paper I, Stauffer et al. 1985;1987), for H II 2741 and AP 244 the periods are unconfirmed and should be taken with caution. We also identify in Table 2 the comparison stars (or primary comparison star) used for each cluster star. The comparison stars are designated by Hertzsprung's (1947) H II number for the Pleiades, and by the *Guide Star Catalog*(=GSC, Lasker et al. 1988) number for α Per. For AP 86, the comparison stars are not in the GSC and approximate offsets from AP 86 are given.

In addition to those stars in Tables 1 and 2 for which periods could be determined, we list in Table 3 some additional stars observed but for which a reliable period could not be determined due to too few observations and/or incomplete phase coverage—only an estimate of the observed brightness variation is given for them. In Figs. 1–17 we present phased light curves for the stars in Table 2. All the Pleiades stars in Table 2 were detected in X rays in a set of long-exposure *ROSAT* pointed observations

TABLE 3
Stars without Periods

Star	N_{obs}	Amp.	Observer
HII 193	29	0.02:	CP
HII 430	11	0.05:	NURO
HII 522	8	0.03	NURO
HII1883	15	0.05-0.06	NURO
AP125	50	0.02	CP

(Stauffer et al. 1993). In α Per, the following stars have been so far detected in a set of *ROSAT* pointed observations for that cluster (Schmitt et al. 1993): HE 622(=AP 19), AP 37, AP 63, AP 117, and AP 149. Below, we briefly discuss some of the more interesting stars listed in Table 2.

H II 314, 708, 727:

A set of late-F/early-G dwarfs with moderate $v \sin i$'s, photometric monitoring of these stars is particularly challenging as their rotational periods were predicted to be on the order of one day. Monitoring over a three-month period was carried out in an attempt to establish reliable periods. The observations can be divided into two time intervals for these three stars: JD 8932–8962 and JD 8996–9018, with the latter time interval containing the majority of observations. Periodogram analysis was carried out on not only the complete data set, but also each of these subintervals individually in case any phase/amplitude shifts were present. These three Pleiades members were observed in sequence with three nonmember comparison stars; the scatter between comparison stars was $\sim \pm 0.01$ mag.

For H II 314, least-squares analysis to fit a period using the complete data set did not yield a well-defined solution. When the 66 observations in the JD 8996–9018 interval were analyzed alone however, a reliable 1.5-day period was derived; the JD 8932–8962 data showed a phase shift with respect to this period. The phased light curve for H II 314 in Fig. 1 shows only the observations from the second time interval. A flat maximum in the light curve is seen, though this could possibly be an artifact of incomplete sampling. H II 314 is also notable because it was observed to undergo very strong flares during *ROSAT* observations of the Pleiades (Caillault et al. 1993) and during far-UV spectroscopic observations on *HST* (Ayres et al. 1993). Soderblom et al. (1993) considered H II 314 to be a possible spectroscopic binary and noted that its Hα emission appeared peculiar, having a sharp core with very broad wings.

For H II 708, periodogram analysis of all observations and just the second time interval alone both yielded a period of ~ 1.05 days and a very low-amplitude light curve. Based on these observations, however, the period from the least-squares analysis is somewhat ill-defined and we regard the derived period as uncertain. The scatter about the phased light curve is of order the same size as the amplitude of the light curve (~ 0.02 mag). It would clearly be advantageous to further monitor this star, although the apparent ~ 1 day period will make this a difficult task. Kraft (1967) finds $v \sin i \simeq 70$ km s^{-1} for H II 708, while Soderblom et al. (1993) derive $v \sin i \simeq 45$ km s^{-1}, which we have adopted here.

For H II 727, separate analysis of all observations and the JD 8996–9018 observations alone both yield a reliable period of ~ 1.2 days. This finding contradicts the much longer ~ 8-day period considered by Van Leeuwen et al. (1987) and is in better agreement with the observed $v \sin i$ for this star. From a smaller number of observations, Van Leeuwen et al. did find evidence for a shorter period of ~ 0.9 days in their data; their secondary peak may be a reflection of the 1.2-day period found here.

H II 2741,2881:

Due to the small number of observations, H II 2741 has the least reliable period determination in Table 2. We have included it however since the available photometry for H II 2741 exhibits the same periodic behavior when compared to either comparison star used, while the difference between comparson stars does not show this effect and shows a scatter of ± 0.01 mag or less. The apparent period is on the order of 5 days. For H II 2881, the derived period of ~ 4.3 days is slightly better defined due to the larger number of observations. The scatter between comparison stars for H II 2881 is ± 0.01 mag.

HE 373, HE 622:

Reliable period determinations for these two stars are particularly useful in that the period and axial inclination information provided by the photometric monitoring may be combined with the Hα-activity observations of Cameron and Woods (1992), enabling a measurement of the radial distribution of absorbing cloud features for these stars. HE 622 (=AP 19) was observed by Cameron and Woods (1992) to have weaker transient features at Hα than HE 373; in accord with the prediction one would make from rotation-activity correlations and the longer rotation period we find for HE 622. For HE 373, there is a strong alias at $P=6.0$ hr in our data, however an 8.0-hr period fit by least-squares to the data yields smaller residuals and a smoother phased light curve.

AP 86:

The scatter between comparison stars for this target was ± 0.02 mag.

AP 117, AP 149:

These two α Per members have had periods previously quoted by O'Dell and Cameron (1993). Although the period determinations here rely on a larger number of observations per star, we derive essentially the same periods and amplitudes quoted by O'Dell and Cameron. The phased light curve for AP 117 (Fig. 11) based on our observations, however, differs noticeably in shape to that reported in O'Dell and Cameron (1993) [the same comparison stars for AP 117 as chosen by O'Dell and Cameron were employed in the present observations]. There is a small difference in the amplitude of variation for AP 117 as observed by MDS (~ 0.13 mag, Oct 92) and NURO (~ 0.17 mag, Nov 92).

AP 124:

The observations of this K4.5 dwarf star reveal a well-defined light curve with a period of only 4.39 hr. To the best of our knowledge, this appears to currently be the shortest observed period for any variable of the BY Dra class. The implied equatorial rotational velocity of ~ 200 km s^{-1} (Table 4) is on the order of one-half of the breakup velocity for such a star (~ 400 km s^{-1}, Sackmann 1970).

TABLE 4
Period Characteristics

Star	B−V$_o$	elev. (mag.)	R/R$_\odot$	Period (hrs)	v_{eq} (km/s)	$v \sin i$ (km/s)	$\sin i$
PLEIADES:							
HII 314	0.60	-	1.04	35.5	36	38	1
HII 708	0.58	0.2	1.05	25.2:	51	45	0.88
HII 727	0.51	0.2	1.12	28.8	47	50	1
HII2741	0.97	-	0.83	120:	8	11	1
HII2881	0.93	0.7	0.84	102	10	12	1
ALPHA PER:							
HE373	0.67	-	1.05	8.0	160	140	0.88
HE622	0.69	-	0.94	19.3	59	61	1
AP37	0.86	-	0.86	57.6:	18	29	1
AP63	0.82	0.2	0.88	5.4	198	161:	0.81
AP86	1.22	-	0.72	5.1	171	140	0.82
AP117	0.85	-	0.87	11.3	94	83	0.88
AP124	1.17[a]	0.4	0.74	4.39	205	190:	0.93
AP127	0.82	-	0.88	8.1	132	80	0.61
AP149	0.75[a]	0.6	0.91	7.6	145	117	0.81
AP226	1.02[a]	-	0.80	5.35	182	181	1
AP244	1.05[a]	-	0.79	11.5	83	42	0.51
				23.1	42	42	1

[a] B−V value estimated from V−I color.

TABLE 5
Pleiades X-ray/Rotation Period Data

Star	Log($\frac{L_x}{L_{bol}}$)	Log(P(hrs))	Spt Type	Notes
HII 34	−4.04	2.20	early K	
HII 314	−3.22	1.55	G1	SB1?
HII 324	−2.83	1.00	K	
HII 625	−2.92	1.01	K0	heavily reddened
HII 686	−2.93	0.98	K7	PhB
HII 708	−3.89	1.40	F9	
HII 727	−3.85	1.46	F9	
HII 739	−3.61	1.81	G0	PhB
HII1124	−3.43	2.16	K1	
HII1136	−3.02	1.10	G8	heavily reddened
HII1332	−3.28	2.30	K4	
HII1531	−3.04	1.06	K7.5	
HII2034	−3.09	1.12	K2.5	
HII2244	−2.82	1.14	K2.5	
HII2741	−3.41	2.08	K	
HII2881	−3.30	2.00	K2	PhB
HII2927	−3.10	0.80	K4	
HII3163	−2.96	1.00	K	

AP 244:

Period analysis for this star yielded as the best period solution an 11.5-hr period *with false-alarm probability of* 4%. There exists however a secondary peak in the periodogram for AP 244 at two times the period of this best solution, corresponding to approximately 23 hr. While the 23-hr period has a much higher false-alarm probability (~34%), the sum of the squares of the residuals between the observations and fitted period is only slightly larger than that for the 11.5-hr period, and the 23-hr period yields an equatorial rotation velocity which is in better agreement with AP 244's $v \sin i$ value (see Table 4)—if the star does indeed have a large inclination angle. We provide in Figs. 16 and 17 the phased light curves corresponding to the 11.5- and 23.1-hr period solutions. The phased light curve for 23 hr shows incomplete coverage in phase space, but this would be expected from observations extending over only a few days.

3. DISCUSSION

In Table 4 we provide some physical characteristics of the stars listed in Table 2. The columns in Table 4 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}), the observed $v \sin i$, and estimated inclination angle for the star's axis of rotation. The approximate displacement above the cluster main sequence is also given for those stars which appear significantly elevated. The displacement evident for some stars introduces some uncertainty in an attempt to convert the observed rotational periods to *rotational velocities*. The uncertainty arises because an estimate of the stellar radius depends on assumptions made regarding the cause of this observed displacement. Possible reasons for such displacements include (see also the discussion in Paper I): (a) binarity, (b) spots, (c) rapid rotation,[1] and (d) enhanced reddening. As in Paper I, for simplicity we use the observed $B-V$ colors of both the elevated and nonelevated stars to estimate stellar radii using the $B-V_0$ vs. $\log(R/R_\odot)$ relation from Allen (1976). Mean reddenings of $E(B-V)=0.10$ for α Per and $E(B-V)=0.04$ for the Pleiades have been assumed. The rotational velocities are useful for determining the correlation between rotation and chromospheric/coronal activity, free from uncertainties introduced by $\sin i$ corrections (see below and, e.g., Duncan et al. 1984), while the inclination angles are useful for interpreting the Hα transient absorption features observed in some of these stars (Cameron and Woods 1992).

Finally, we provide an initial look at applying the photometric period information among Pleiades members to the relation between X-ray activity and rotation. In Table 5 we provide a listing of all those Pleiades members with known photometric periods and X-ray flux measures from Stauffer et al. (1993). Photometric and spectroscopic binaries among the stars in Table 5 have been noted with "PhB" or "SB," respectively. The stars in Table 5 are mostly K dwarfs, with a few late-F/early-G dwarfs included. These data are plotted in Fig. 18 to compare $\log(L_x/L_{bol})$ to log(Period). From Fig. 18, we see that the L_x/L_{bol} ratios for the three stars of earliest spectral type (H II 708, 727, 739) lie noticeably below the L_x/L_{bol} val-

[1]This displacement might arise by analogy with predictions for stars with radiative envelopes—Sweet and Roy (1953)—though no similar calculations have been made for rapidly rotating stars with outer convective envelopes to our knowledge.

ues of the other Pleiades members. In Fig. 19, we plot $\log(L_x/L_{bol})$ vs. $B-V_0$ from Stauffer et al. (1993, Table 7) for known Pleiades members, with those stars from Table 5 indicated. Earlier than ~G0, L_x/L_{bol} decreases rapidly with decreasing $B-V$. This provides the explanation for why H II 708, 727, and 739 appear discrepant in Fig. 18—at the same rotation period, these relatively early-type stars (with quite thin outer convective envelopes) are relatively inefficient generators of coronal activity compared to the other, later-type stars in Table 5. The one early-G dwarf (H II 1136) not deviant from the K dwarfs may have a higher X-ray activity due to binarity, as noted in Table 5, or perhaps it has a later spectral type than as cataloged.

Looking at the K dwarfs alone in Fig. 18, one sees that rapid ($P\sim 10$ hr) rotators have about twice the level of X-ray activity than slower ($P\sim 100$ hr) rotating stars. Among slowly rotating ($v \sin i < 10$ km s^{-1}) late-type Pleiades dwarfs, a steep drop off in X-ray flux has been observed (Staufferet al. 1993); thus, one would predict a corresponding drop in X-ray activity at long rotation periods (beyond ~100 hr, or ~4 days). The long-period regime of Fig. 18 is less well-defined however due to both the fewer number of stars with periods and the more uncertain X-ray fluxes for the two slowest rotators (H II 34, 1332). H II 1332 was identified in the *ROSAT* PSPC images as part of a blended X-ray source lying about 25′ off-axis and consisting of two other Pleiades stars (H II 1298, 1321). While attempts were made to carefully deblend these X-ray sources, the computed X-ray flux for H II 1332 is necessarily somewhat uncertain. H II 34 was identified as an X-ray source about 20′ off-axis in one of the *ROSAT* PSPC fields. The X-ray source lies uncomfortably close to the inner ring mask of the PSPC frame and is likely shadowed to some extent by the mask, resulting in a more uncertain X-ray flux for that reason. The functional form of the dependence of L_x/L_{bol} on $v \sin i$ for $v \sin i < 10$ km s^{-1} was poorly defined due to the presence of many $v \sin i$ upper limits among the slowly rotating Pleiades stars (Stauffer et al. 1993). We are continuing to address this problem by obtaining rotational periods for a sample of the Pleiades slow rotators.

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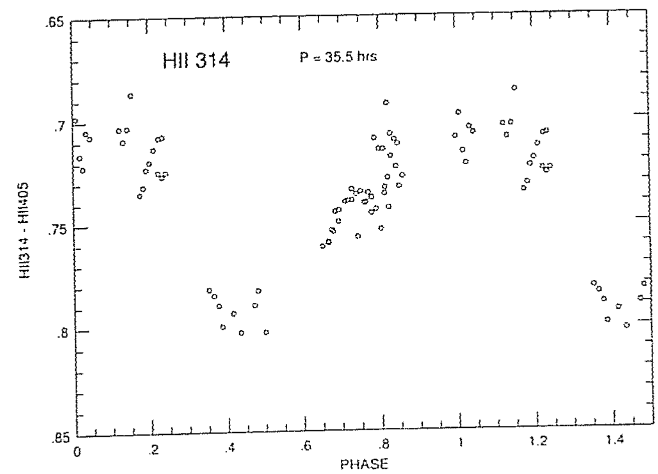

FIG. 1—Differential *V*-band photometry for H II 314.

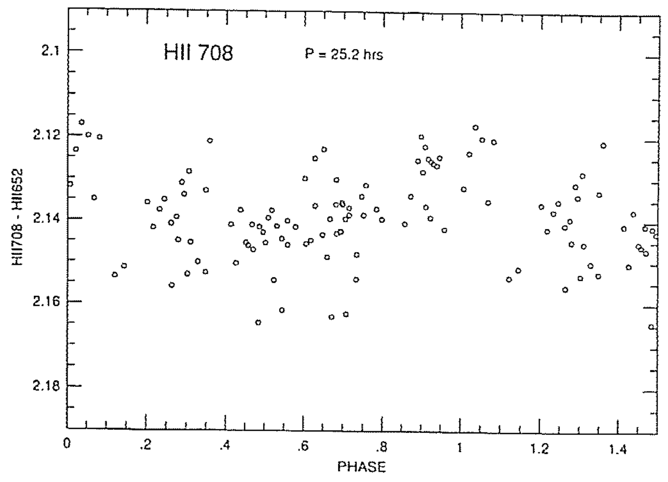

FIG. 2—As for Fig. 1, except for H II 708.

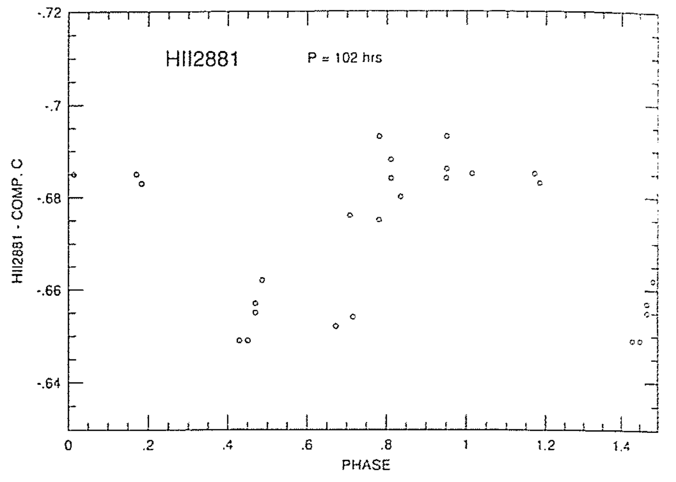

FIG. 5—As for Fig. 1, except for H II 2881.

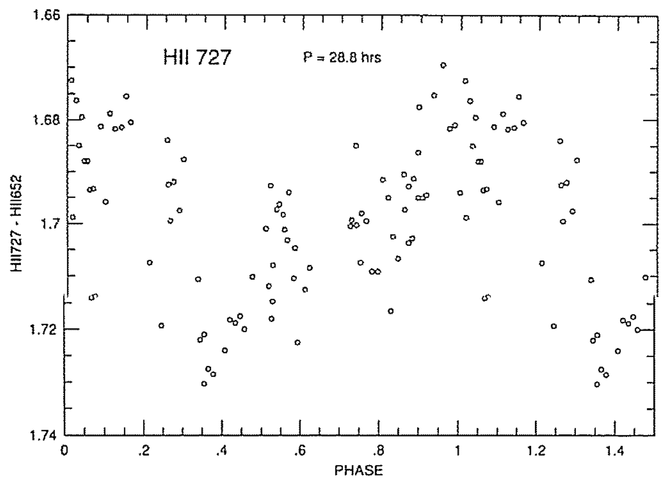

FIG. 3—As for Fig. 1, except for H II 727.

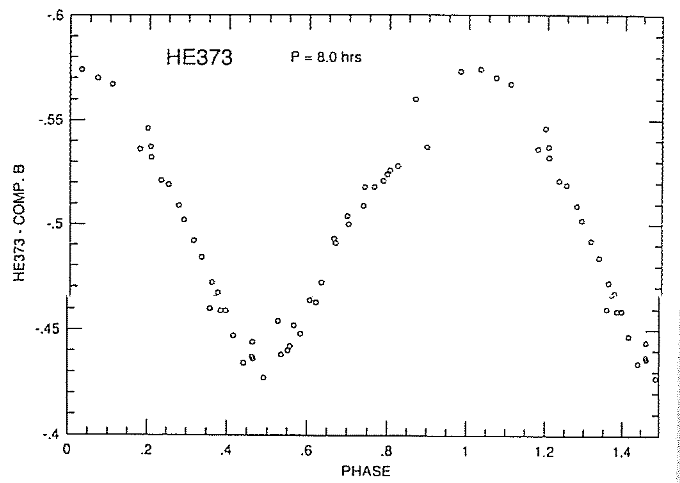

FIG. 6—As for Fig. 1, except for HE 373.

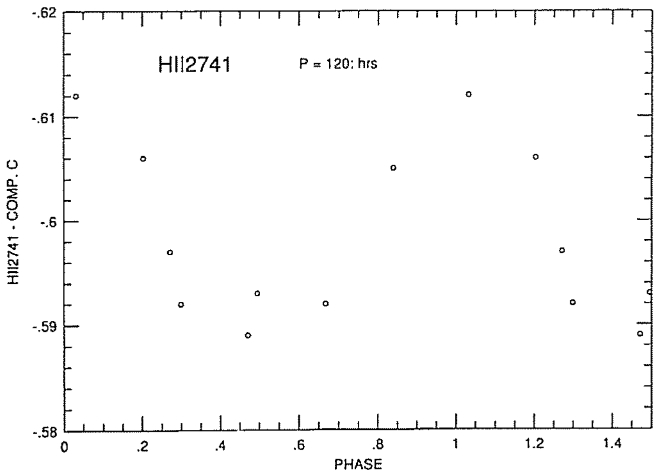

FIG. 4—As for Fig. 1, except for H II 2741.

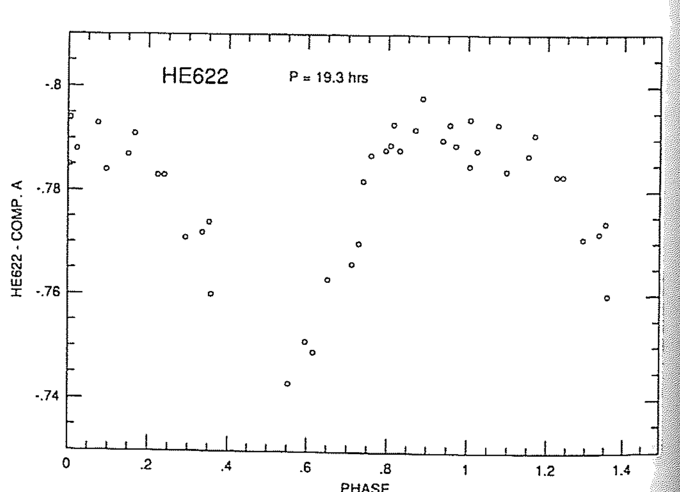

FIG. 7—As for Fig. 1, except for HE 622.

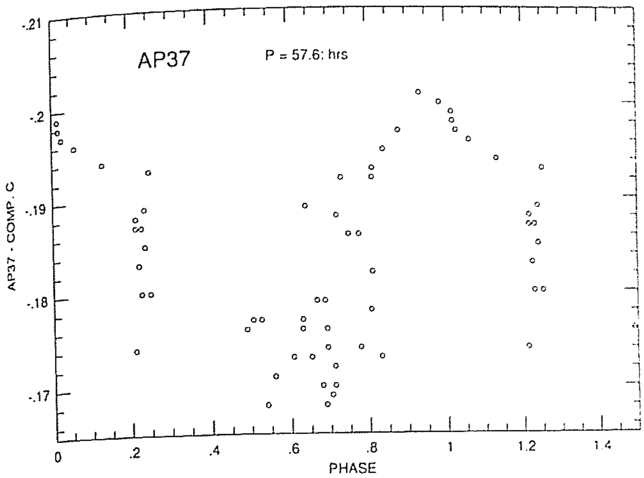

FIG. 8—As for Fig. 1, except for AP 37.

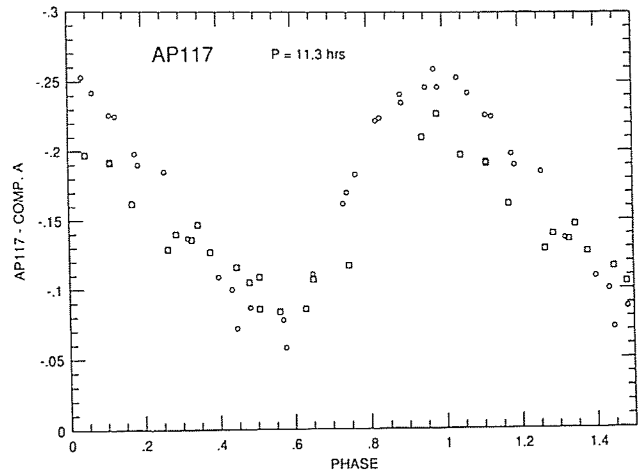

FIG. 11—As for Fig. 1, except for AP 117. Observations by NURO are plotted as open circles, while those by MDS are shown as squares.

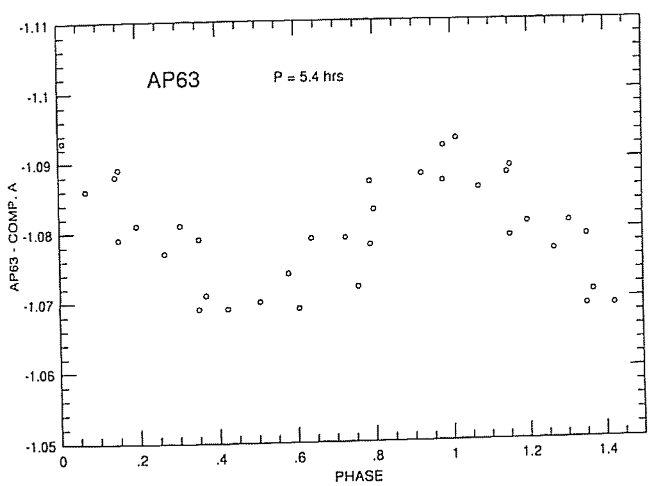

FIG. 9—As for Fig. 1, except for AP 63.

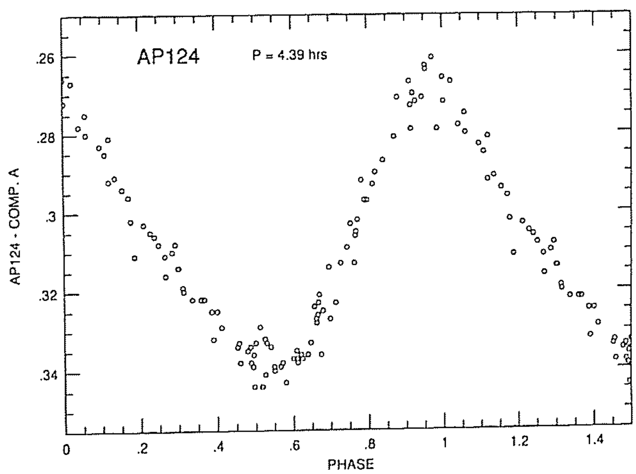

FIG. 12—As for Fig. 1, except for AP 124.

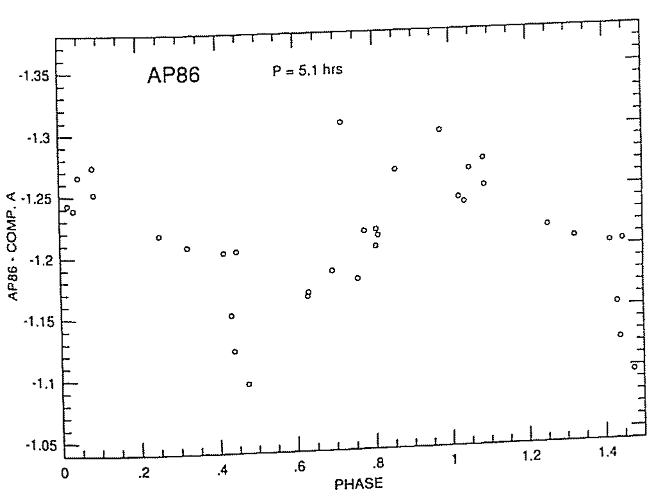

FIG. 10—As for Fig. 1, except for AP 86.

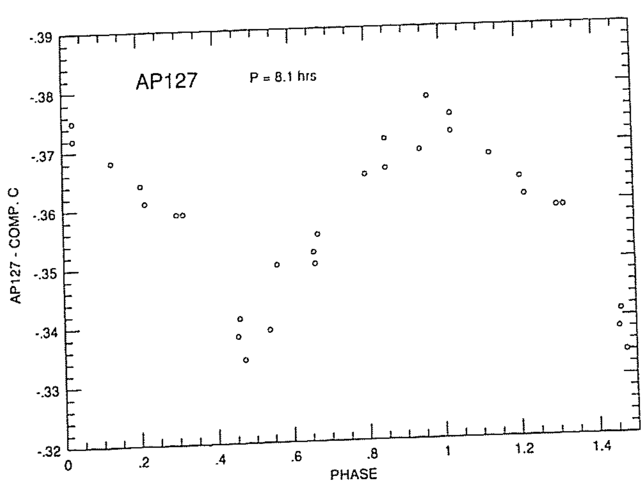

FIG. 13—As for Fig. 1, except for AP 127.

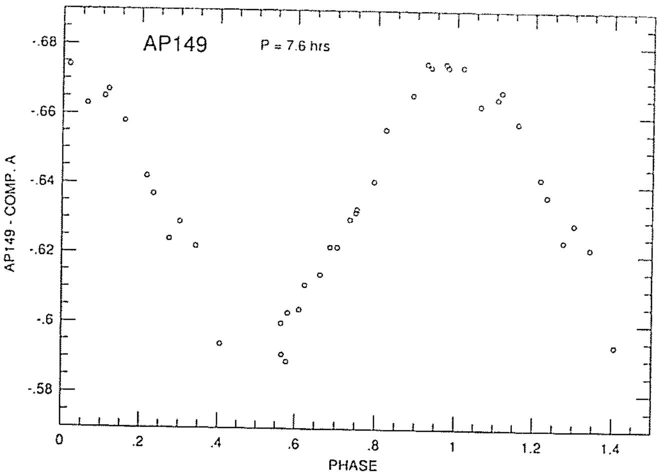

FIG. 14—As for Fig. 1, except for AP 149.

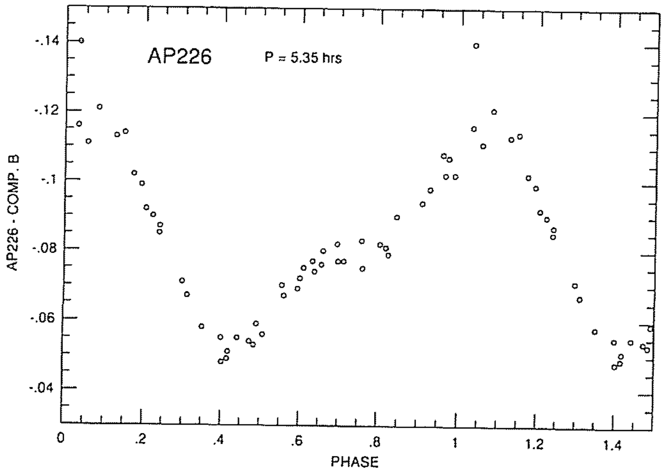

FIG. 15—As for Fig. 1, except for AP 226.

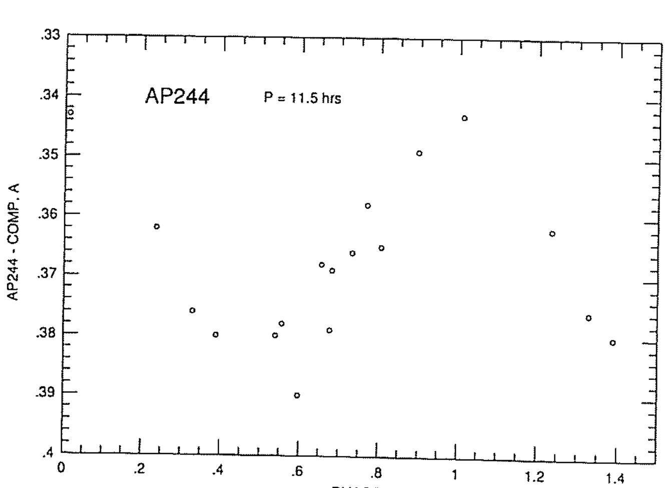

FIG. 16—As for Fig. 1, except for AP 244. A period of 11.5 hr has been used.

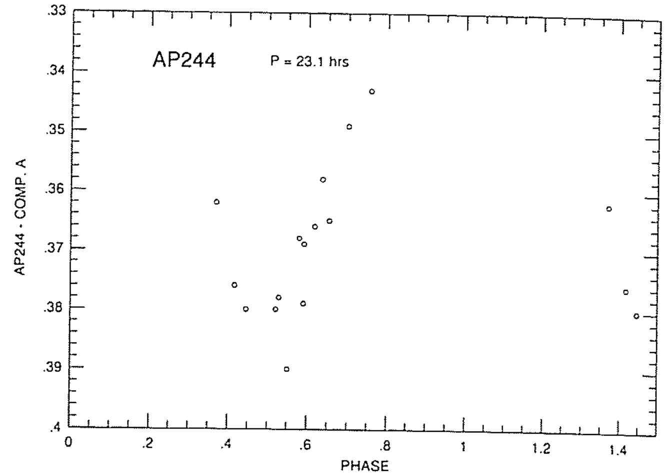

FIG. 17—The same observations for AP 244 as in Fig. 16, only now phased with a 23.1-hr period.

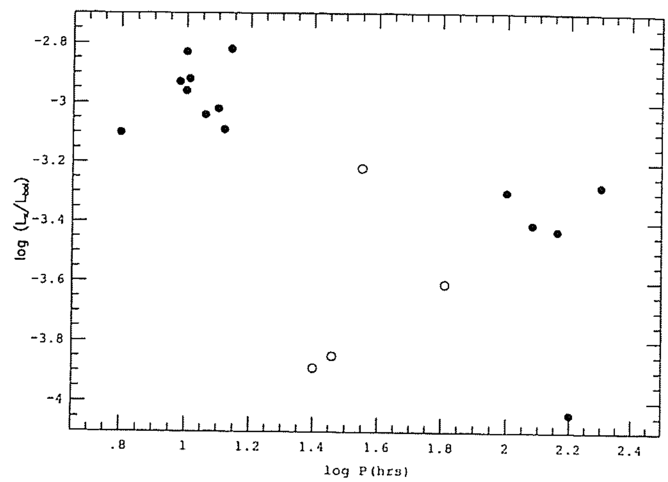

FIG. 18—Plot of X-ray activity [in terms of $\log(L_x/L_{bol})$] vs. the logarithm of the period (in hours) for those Pleiades stars with known rotation periods and X-ray measurements reported in Stauffer et al. (1993). Stars in Table 5 are plotted as open circles for spectral types F9–G1 and as filled circles for G8–K9. When only the K dwarfs are considered, a general trend of lower X-ray activity with longer rotation period is indicated by the data.

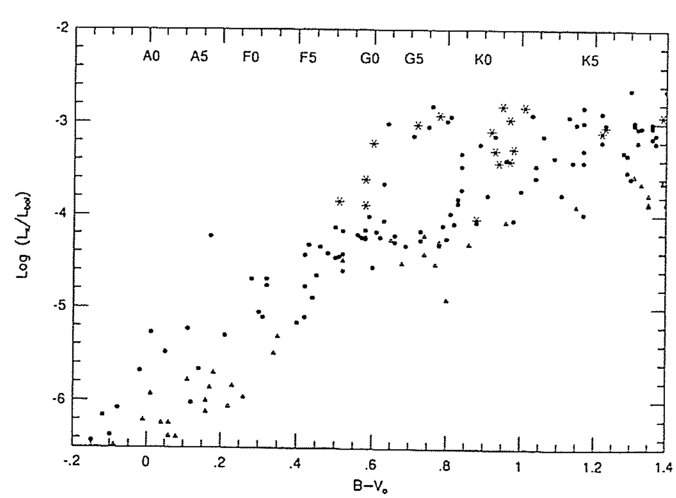

FIG. 19—Illustration of the dependence of X-ray activity on reddening-corrected $B-V$ color (or spectral type), using the Pleiades *ROSAT* observations reported in Stauffer et al. (1993). Upper limits in $\log(L_x/L_{bol})$ are shown as triangles. Stars from Table 5 are plotted as asterisks.