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Rotation Periods of Open Cluster Stars. IV.

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Abstract

We present the results from a photometric monitoring program of primarily solar-type open cluster stars obtained during 1994 and 1995. Several members of the α Persei cluster have been monitored and the corresponding relation between coronal x-ray activity and rotation period derived. The relation among mid-G/K type members illustrates both the previously noticed downturn in L_X/L_{bol} at high rotation rates and the sharp decrease in coronal activity at long rotation periods as seen among Pleiades stars. Intensive observation of one slowly rotating G-type member of IC4665 has enabled a period determination of 8−10 days to be made and illustrates the need for (and limitations of) high quality observations.

1. Introduction

As part of a program to obtain rotation period information among solar-type stars in open clusters from photometric monitoring, we present here the results of observations primarily obtained during the 1994 and 1995 observing seasons. Earlier results have been reported in Prosser et al. (1993ab; 1995) and the reader is referred to these earlier papers and the references therein for further discussion on the technique of photometric monitoring for obtaining rotation periods. In this current study we have concentrated on obtaining rotation periods among α Per cluster members not previously observed. Just as the relation between coronal activity and rotation among Pleiades stars could be refined and investigated in Paper III, the large number of α Per stars with rotation period information enables us to study the same relation among members of this slightly younger cluster. Finally, an approximate period has been established for one slowly rotating member of the IC4665 open cluster.

2. Observations and Analysis.

2.1 Alpha Persei

For α Persei, our intent was to obtain a more complete sampling of the rotation properties among solar-type members. By extending the rotation information to longer periods or slower rotators, the rotation-activity relation among α Per members may be better defined.

V-band observations of α Per stars were obtained by both C.P. and K.G.. Observations by C.P. were obtained with the Whipple Observatory 48-in. telescope on Mt. Hopkins, AZ using a CCD camera to obtain relative photometry between target and comparison 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. Observations during both photometric and nonphotometric conditions could be employed in the monitoring, as relative photometry between variable and comparison stars on the same CCD frame was being measured for changes in brightness (see Prosser et al. 1993a). Observations by K.G. were obtained during photometric conditions at Mt. Maidanak (Tashkent) Observatory, Uzbekistan using a 0.48m telescope equipped with a pulse counting FEU-79 photomultiplier tube with a 28″ diaphragm. Exposure times ranged from 20 to 120 seconds. K.G. obtained absolute V (Johnson) photometric magnitudes by observing five standard stars several times each night. K.G.'s observations were reduced using the standard procedures developed by Nikonov (1976). All together, rotational period information was obtained for 35 members of the α Per cluster.

The results of the period analysis among α Per stars are listed in Table 1. Following star name are the approximate V,B−V values, the observed $v \sin i$ and its source reference, the derived period, amplitude, false alarm probability (f) from the periodogram analysis, the number of observations obtained, observer identification, and the dates of observation. As in previous studies, periodogram analysis was performed on either the available relative or absolute V-band photometry using a program which incorporates the method outlined by Horne & Baliunas (1986) and Scargle (1982) for unevenly sampled data. Except for AP121, the individual observations, rather than ensemble averaging, were employed in the period analysis. For AP121, the period estimate is based on 11 nightly mean values distributed over a 13 night period. Periods and amplitudes in Table 1 considered to have greater uncertainties are flagged with a colon. We do not tabulate the individual observations here nor reproduce the light curves for all stars, but will provide this information, including finding charts, upon request. In Figure 1 we provide sample light curves for some relatively slowly rotating stars (AP102, AP114, AP197, AP256) and for some more rapidly rotating stars (AP96, AP122, AP208, AP220). Among the stars listed in Table 1 are some M dwarf members without $v \sin i$ values; these have been observed to show broadened Hα emission features in echelle spectra and were considered to be rapid rotators prior to monitoring.

In Table 2 we provide some physical characteristics for the α Per stars listed in Table 1. The columns in Table 2 give star name, reddening corrected B−V, the estimated stellar radius in terms of the solar radius ($R_\odot$), the observed period, the corresponding equatorial velocity of the star (v_{eq}), and the observed $v \sin i$. As in previous papers the observed B−V colors have been used to estimate stellar radii using the $(B-V)_o$ vs. $\log(R/R_\odot)$ relation from Allen (1976). A mean reddening of E(B−V)= 0.10 for α Per has been assumed (Prosser 1992, Crawford & Barnes 1974).

Rotation vs. X-ray Activity:

In Papers II & III the relation between rotation period and coronal x-ray activity among Pleiades members was studied using available periods and x-ray luminosities. In Randich et al. (1996, Fig. 10) the relations for Pleiades and for α Per members were compared, although data available among α Per members was limited and restricted to primarily the rapidly rotating stars. To improve upon the relation for α Per stars, we have taken the previous available x-ray/rotation period data (Randich et al., Table 5) and combined it with the new rotation period data of this study and the new periods provided by Allain et al. (1996b, Table 2), together with the ROSAT x-ray survey data in Prosser et al. (1996). In Figure 2 we show the x-ray/rotation period relation for α Per members, segregated by spectral class. The relation among mid-G/K type members illustrates both the downturn in L_X/L_{bol} at high rotation rates that was noted in Randich et al. (1996), and the sharp decrease in coronal activity at long rotation periods as was seen among Pleiades stars (Paper III, Fig. 3).

A few stars in Fig. 2 are worth mentioning. AP114 was reported by Allain et al. to have a period of 1.3 days, however this study has found a period of 4.3 days. A 1.3 day period for AP114 in fact conflicts against its observed $v \sin i < 10$ km/s and the longer period for AP114 has been used in Fig. 2. AP158 appears slightly discordant from the relation followed by other stars with similar periods. While its period is believed to be well determined, its x-ray flux may be slightly underestimated due to rib effects in the ROSAT PSPC observation (Prosser et al. 1996). Another possibility is that AP158 is not a cluster member but rather is an active field star along the line of sight to the α Per cluster. AP225 lies somewhat above the mean L_X/L_{bol} relation for its period; while there were no obvious flare events for AP225, it was observed at a large off-axis distance ($\sim 55'$) and thus its x-ray luminosity may be considered to have a relatively large uncertainty. The two stars with upper limits near $\log P \simeq 1.5$ are AP91 and AP220; AP91 lies on the outskirts of the raster survey approximately $38'$ from the nearest pointing in the survey, while AP220 lies $\sim 54'$ off-axis in one of the deep PSPC pointings in Alpha Per. The upper limits for these stars may not be well-defined due to the relatively large off-axis distances involved and it may be that improved observations of these stars may yield x-ray luminosities and L_X/L_{bol} values which are in better agreement with those for other stars with similar periods in Figure 2. As noted in Paper III, the dependence of stellar activity upon rotation and spectral type has been extensively studied among field stars. As with the Pleiades, the importance of the α Per observations is that they provide a much more homogeneous population of stars in term of age and metallicity for study of the relation between rotation and activity.

2.2 IC 4665

Photometric rotational periods among IC 4665 members have been reported by Prosser (1993) and Allain et al. (1996a). A new variable reported by Prosser (1995), while initially believed not to be a cluster member, actually turns out to be identified with the star P290 (Prosser 1993), which has photometry consistent with cluster membership. If not a cepheid variable, the observed 12.7 day variation for P290 may be due to rotational modulation.

While Allain et al. (1996a) in principle had sufficient time coverage to derive periods up to 10 days for the slowest rotators, they did not detect any period longer than four days. They were unable to conclude on the true rotation rates for the slowest rotating cluster members ($v \sin i \leq 10$ km/s). Considering that the failure to derive periods among the slow rotators might have been due to insufficient phase coverage and signal-to-noise sensitivity in the observational data, new observations were undertaken for one of the slow rotators, P94.

CTIO 0.9m CCD V-band photometry of P94 was obtained during May 1995; 43 observations were obtained over a 13 day interval. When compared to constant comparison stars, the relative photometry of P94 exhibited cyclic variation on the order of 10 days, with an amplitude of $\sim 0.02 - 0.03$ mag. In Figure 3, we show this cyclic variation for three different assumptions. The top diagram shows the phased light curve using all data points to derive a period of 8.1 days. The middle plot shows the 8.5 day periodicity found if one averages each night's observations; resulting in 11 mean datapoints. Finally, the bottom diagram shows the phased light curve for P94 if one assumes a slightly longer period of 10.0 days as visually suggested from the data. There is little to discriminate between these phased light curves, implying that the error in the period fitting may be on the order of 20%. In fact there is only about 1 km/s difference in the corresponding equatorial velocities for periods of 8.5 and 10.0 days. P94 however clearly exhibits rotational modulation on an 8-10 day timescale and it is likely that other slow rotators in the cluster may show similar behavior given sufficient observations.

We note that the moderately rotating cluster member P100 ($v \sin i = 21$ km/s) was also contained within the same CCD field as P94. P100's light curve exhibited an amplitude of 0.15 magnitudes and a period of 2.37 days, in good agreement with the results of Allain et al. (1996a).

3. Summary

The present study has provided rotational period information for over 30 α Persei cluster members, significantly increasing the number of cluster members with rotation information and helping to obtain a more complete sampling among solar-type stars and to extend the rotation information to longer period, slower rotators. The rotation-coronal activity relation among α Persei members has been constructed; the mid-G/K type stars show a decrease in L_X/L_{bol} at periods ≥ 10 days similar to that seen among Pleiades members.

In IC 4665, the slow rotator P94 has been intensively observed and shown to exhibit rotational brightness variations with a period on the order of 8–10 days, illustrating the need for high quality data with sufficient phase coverage for deriving rotational periods for slowly rotating stars.

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Figure Captions

Fig. 1. Sample phased light curves for some relatively rapidly and slowly rotating α Per members. The AP102/AP197 light curves are based on V-band photoelectric photometry by KG, while the remaining light curves are based on relative CCD photometry by CP employing nearby comparison stars on the frame.

Fig. 2. $\log(L_X/L_{bol})$ vs. the logarithm of the rotation period (in hours) for α Per stars. Points connected by a line represent stars with multiple period determinations.

Fig. 3. Photometric light curve for P94 in IC4665 for three cases: a) 8.1 day period found using all datapoints, b) 8.5 day period found using the night average observations, and c) 10 day period as suggested from the original, unphased data. All three plots illustrate relative photometry between P94 and a nearby comparison star 'A'.

TABLE 1
Alpha Persei Period Determinations

Star	V	B−V	$v \sin i$ (km/s)	REF	Period (days)	Period (hrs)	Amp. (mag.)	f	N(obs)	Observer	Date/Data Range	
HE373	11.50	0.77	140	1	0.33	8.0	0.10	2.8×10^{-4}	35	KG	Sep94	JD9604-9625
HE601	11.43	0.73	15	1	3.6:	86.4:	0.09	6.1×10^{-4}	28	KG	Dec95	JD0045-0096
AP 25	12.25	0.88	12	1	3.7	88.8	0.02-0.03	1.3×10^{-4}	44	CP	Dec94	JD9695-9708
AP 28	13.09	1.05	12	1	3.47	83.3	0.15	1.1×10^{-4}	35	CP	Oct95	JD9995-0008
AP 33	12.92	1.02	<10	1	6.4	153.6	0.02-0.03	2.8×10^{-2}	32	CP	Oct95	JD9995-0008
AP 37	12.61	0.96	29	1	2.45:	58.8:	0.06	6.9×10^{-4}	54	CP	Nov94	JD9671-9673
AP 41	12.03	0.85	10	1	4.74	113.8	0.04	1.4×10^{-5}	41	CP	Dec94	JD9695-9708
AP 72	12.78	0.99	<10	1	5.1:	122.4:	0.06	1.6×10^{-1}	33	KG	Dec95	JD9952-0096
AP 75	13.82	1.27	11	1	2.79	67.0	0.07	1.4×10^{-4}	34	CP	Oct95	JD9995-0008
AP 96	14.55	1.52	...	...	0.346	8.3	0.08	1.1×10^{-8}	54	CP	Nov94	JD9661-9672
AP 97	12.08	0.87	<10	1	4.8:	115.2:	0.03	2.4×10^{-2}	33	KG	Dec95	JD9952-0096
AP102	11.96	0.80	11	1	4.3	103.2	0.05	1.9×10^{-1}	30	KG	Aug/Dec94	JD9579-9696
AP108	12.92	1.03	14	1	3.85	92.4	0.05	1.5×10^{-7}	43	CP	Dec94	JD9695-9708
AP109	15.84	1.53	...	...	0.25	6.0	0.07	1.5×10^{-3}	31	CP	Nov94	JD9670-9673
AP110	12.27	0.92	<10	1	5.1	122.4	0.04	3.8×10^{-6}	44	CP	Dec94	JD9695-9708
AP112	13.68	1.15	13	1	2.67	64.1	0.08	4.0×10^{-6}	38	CP	Oct95	JD9995-0008
AP114	13.40	1.07	<10	1	4.32	103.7	0.13	3.5×10^{-5}	31	CP	Oct95	JD9995-0008
AP118	12.06	0.81	160	1	0.324	7.78	0.09	6.1×10^{-6}	35	KG	Sep/Dec94	JD9604-9696
AP119	12.57	0.89	12	2	3.1:	74.4:	0.07	2.3×10^{-1}	32	KG	Dec95	JD9953-0096
AP120	15.18	...	...	...	0.30:	7.2:	0.05	4.0×10^{-7}	112	CP	Oct95	JD9995-0002
AP121	11.89	0.79	7	3	10.7:	256.8:	0.02	1.7×10^{-1}	35	CP	Oct95	JD9995-0008
AP122	15.18	...	142	4	0.231	5.55	0.08	1.5×10^{-14}	109	CP	Nov/Dec94	JD9670-9708
AP158	11.93	0.85	13-15	2,3	3.25	78.0	0.05	1.2×10^{-7}	43	CP/KG	Aug/Dec94	JD9579-9708
AP189	13.05	0.94	92	3	0.629	15.1	0.10	4.0×10^{-9}	51	CP	Nov94	JD9661-9673
AP193	12.28	...	64	2	0.744	17.85	0.09	4.4×10^{-5}	31	KG	Sep/Dec94	JD9604-9696
AP196	12.51	...	12	2	4.54	109.0	0.05	1.1×10^{-1}	29	KG	Aug/Dec94	JD9579-9696
AP197	12.31	1.00	12	2	5.55	133.2	0.05	1.4×10^{-2}	25	KG	Aug/Dec94	JD9580-9696
AP199	12.10	0.98	23	2	1.8:	43.2:	0.09	4.3×10^{-5}	33	KG	Sep/Dec94	JD9604-9696
AP205	15.20	...	...	...	0.264	6.33	0.10	2.2×10^{-3}	104	CP	Oct95	JD9995-0002
AP208	15.54	...	...	...	0.325	7.81	0.17	3.6×10^{-12}	73	CP	Oct95	JD9997-0002
AP211	15.07	...	...	...	0.288	6.9	0.10	1.2×10^{-2}	16	CP	Nov94	JD9670-9673
AP220	12.68	...	20	2	1.3	31.2	0.03	7.9×10^{-3}	18	CP	Dec95	JD0059-0061
AP247	13.20	...	20	2	2.5	60.0	0.09	1.0×10^{-5}	66	CP	Oct95	JD9995-0008
AP256	11.79	0.81	10	2	5.87	140.9	0.04	5.9×10^{-5}	34	CP	Oct95	JD9995-0008
AP257	13.00	...	11	3	4.83	115.9	0.05	9.7×10^{-4}	34	CP	Oct95	JD9995-0008

REF: 1) Stauffer et al. (1985,1989), 2) Prosser (1992), 3) Prosser (1994), 4) Prosser (1996, priv. comm)

TABLE 2
Alpha Per Stars: Physical Characteristics

Star	$(B-V)_o$	$R/R_\odot$	Spt	Period (days)	(hrs)	v_{eq} (km/s)	$v \sin i$ (km/s)
HE373	0.67	0.96	early-G	0.33	8.0	145	140
HE601	0.63	1.00	early-G	3.6:	86.4:	14	15
AP 25	0.78	0.90	late-G	3.7	88.8	12	12
AP 28	0.95	0.83	early-K	3.47	83.3	12	12
AP 33	0.92	0.83	~K0	6.4	153.6	6.5	<10
AP 37	0.86	0.86	~K0	2.45:	58.8:	18:	29
AP 41	0.75	0.91	late-G	4.74	113.8	10	10
AP 72	0.89	0.85	~K0	5.1:	122.4:	8	<10
AP 75	1.17	0.74	K7.3	2.79	67.0	13	11
AP 96	1.42	0.64	M0	0.346	8.3	94	
AP 97	0.77	0.91	late-G	4.8:	115.2:	10	<10
AP102	0.70	0.93	~G5	4.3	103.2	11	11
AP108	0.93	0.83	~K0	3.85	92.4	11	14
AP109	1.43	0.64	M1	0.25	6.0	130	
AP110	0.82	0.88	late-G	5.1	122.4	9	<10
AP112	1.05	0.79	K7.1	2.67	64.1	15	13
AP114	0.97	0.81	early-K	4.32	103.7	9.5	<10
AP118	0.71	0.93	~G5	0.324	7.78	145	160
AP119	0.79	0.90	late-G	3.1:	74.4:	15	12
AP120	1.50[a]	0.54	M2.0	0.30:	7.2:	91	
AP121	0.69	0.93	~G5	10.7:	256.8:	4	7
AP122	1.41[a]	0.65	M1	0.231	5.55	142	142
AP158	0.75	0.91	late-G	3.25	78.0	14	13-15
AP189	0.84	0.87	late-G	0.629	15.1	70	92
AP193	0.79[a]	0.90	late-G	0.744	17.85	61	64
AP196	0.84[a]	0.87	late-G	4.54	109.0	10	12
AP197	0.90	0.85	K4	5.55	133.2	8	12
AP199	0.88	0.85	K4	1.8:	43.2:	24	23
AP205	1.42[a]	0.64	M0.8	0.264	6.33	123	
AP208	1.47[a]	0.60	M1.3	0.325	7.81	93	
AP211	1.39[a]	0.66	M0	0.288	6.9	116	
AP220	0.86[a]	0.86	~K0	1.3	31.2	33	20
AP247	0.99[a]	0.81	K4.5	2.5	60.0	16	20
AP256	0.71	0.92	~G5	5.87	140.9	8	10
AP257	0.91[a]	0.84	K4.3	4.83	115.9	9	11

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

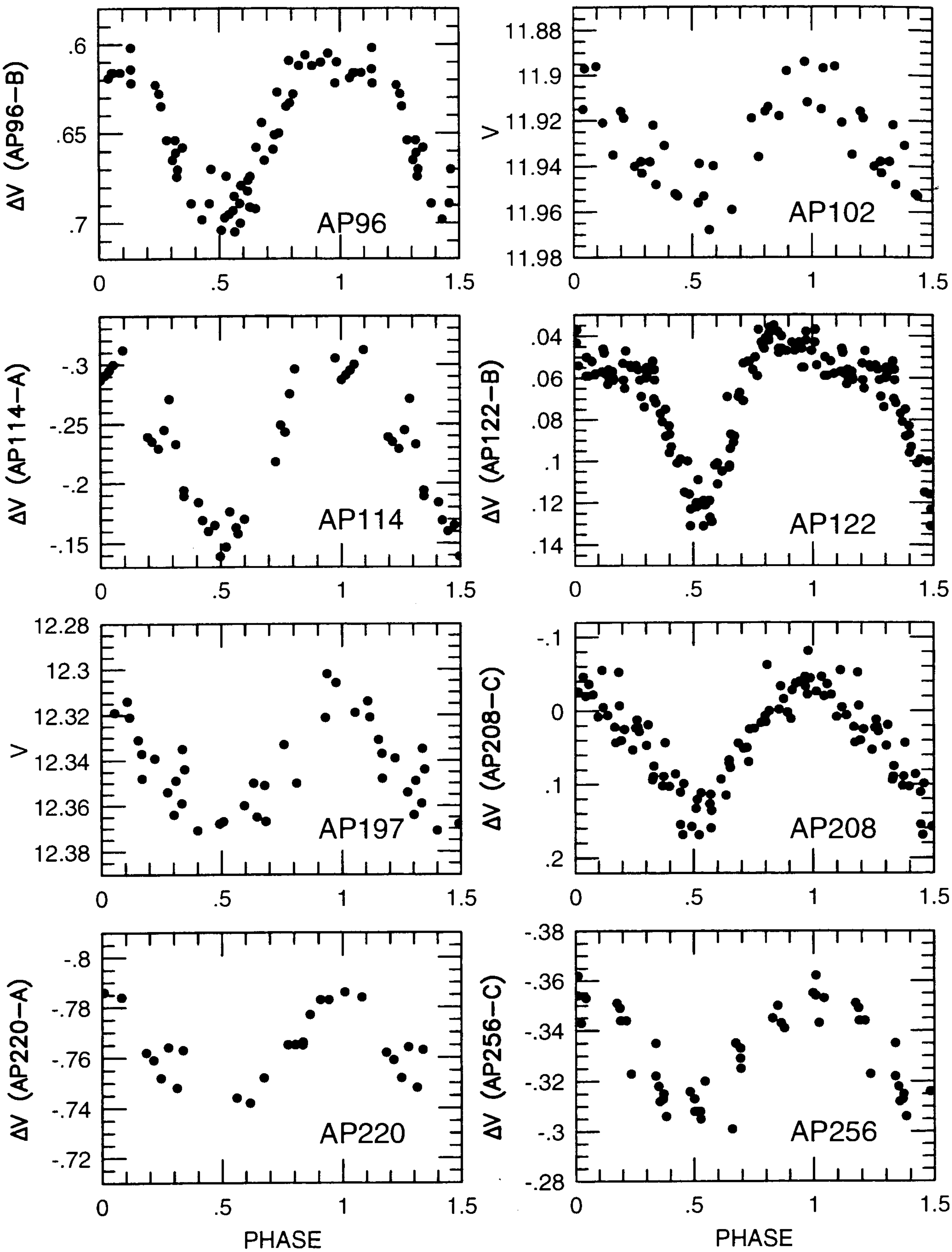
ΔV (AP96−B)
AP96
V
AP102
ΔV (AP114−A)
AP114
ΔV (AP122−B)
AP122
V
AP197
ΔV (AP208−C)
AP208
ΔV (AP220−A)
AP220
ΔV (AP256−C)
AP256
PHASE
PHASE

Figure 1

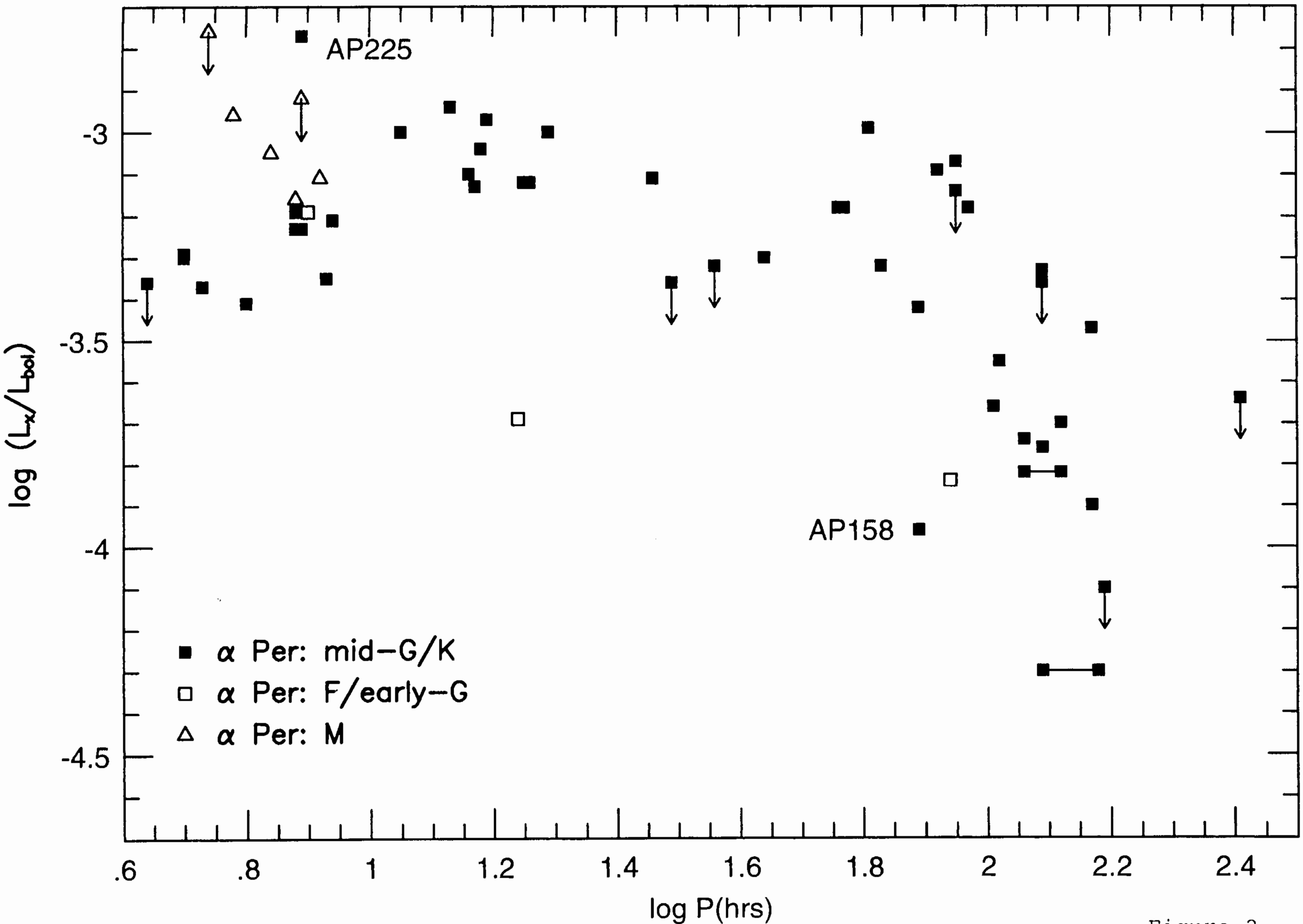
AP225
AP158
α Per: mid-G/K
α Per: F/early-G
α Per: M
-3
-3.5
-4
-4.5
log (L_x/L_{bol})
.6
.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
log P(hrs)

Figure 2

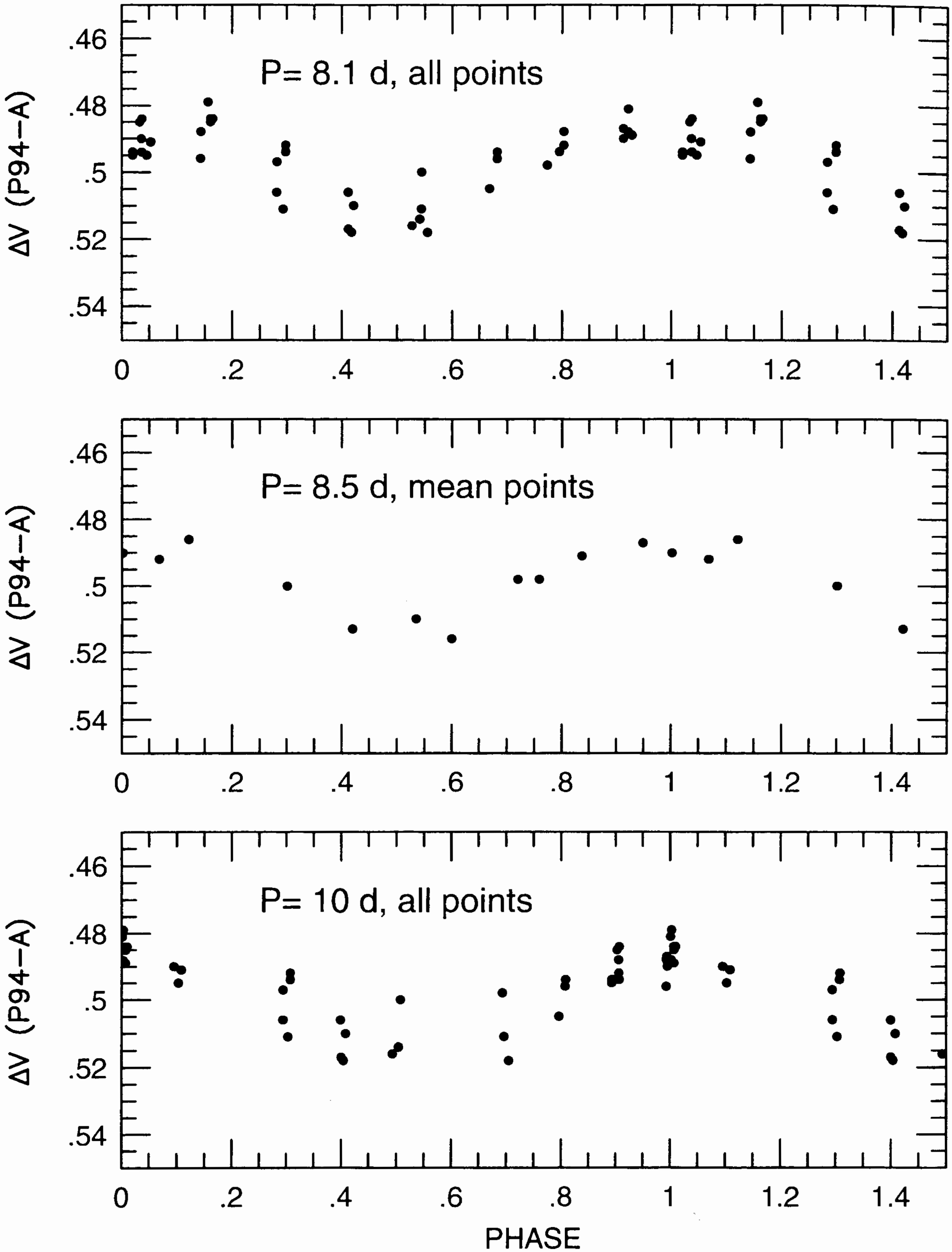
P= 8.1 d, all points
ΔV (P94−A)
.46
.48
.5
.52
.54
0
.2
.4
.6
.8
1
1.2
1.4
P= 8.5 d, mean points
ΔV (P94−A)
.46
.48
.5
.52
.54
0
.2
.4
.6
.8
1
1.2
1.4
P= 10 d, all points
ΔV (P94−A)
.46
.48
.5
.52
.54
0
.2
.4
.6
.8
1
1.2
1.4
PHASE

Figure 3