Rotation Periods of Open Cluster Stars, III

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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.

Keywords
Open Cluster Stars, photometric monitoring program, rotation periods

Disciplines
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Rotation Periods of Open-Cluster Stars. III.

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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-
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 core 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), used in the period determination, the dates of observation, and the observer identification. "C" observations were obtained with the Whipple Observatory 48-in. telescope on Mt. Hopkins, AZ, by observers O.W.C.K.D.R. "N" observations were obtained by A.D.O.D.R.B.S.L.R.A.M. using the 31-in. telescope of the National Observatory Research Observatory in Flagstaff, AZ. "L" observations were obtained by M.B.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 measurements using either the IRAF "aphot" package or the UKSTU routines (Stackel 1967) in the current version of VISTA. The reader is referred to Paper I where additional discussions on the techniques of photometric monitoring is given. Exposure times were set so as to generally attain a signal level for the variable and comparison stars which would enable photometric accuracies of 1% or better. Except where noted below, differing the two comparison stars for each program star confirmed that the photometry had accuracy of this order. As in Paper I and II, photometric analysis was performed on the relative photometry using a program which incorporates the method outlined by Huntre and Boksen (1984) and Scargle (1982) for unevenly sampled data.

We do not eliminate the individual observations here, but will proceed 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 sine wave alignment probability (R) from the periodogram analysis. In these cases where the period is regarded as uncertain it is denoted with a colon. The comparison stars (primary comparison star for each target in Table 2 are also given. The comparison stars are designated by Hertzsprung's [1947] HR number for the Pleiades, and Goff 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 1.8 days was indicated in the periodogram analysis of AP 212. The higher false alarm probability of 4.6% is associated with the 1.2-day peak and the small v sin i observed for AP 212 lead to us the conjecture that the longer period is more probably correct.

2.2 HR 293, HR 314, and HR 320

As these three Pleiades members lie within a few arcseconds 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 HR 285 and HR 262, with HR 285 as the primary comparison star. For HR 262, 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 CCA/Lick data alone yield 4.5 days, and the NUBO data alone yield 4.0 days. The phased light curve using all observations is shown in Fig. 1. For HR 314, we confirm the 1.5-day period reported in Paper II; additional information on this star is discussed there. HR 320 is a spectroscopic binary (Marshall et al. 1992).

2.3 HR 324

Van Loewen et al. (1987) initially reported a 4.8-day period for HR 324. When analyzed separately, the Lick and NUBO observations in this present study yield periods of 6.5 and 5.4 days, respectively, confirming Van Loewen et al. results for this low-amplitude star.

2.4 HR 2284 and HR 2341

Both HR 2284 and HR 2341 were observed in the same CCD field, with the comparison stars HR 2296 (primary) and HR 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. If HR 2294 was unstable for use as a comparison star as it was observed to vary by ~0.15 mag over an interval of seven days; no period could be derived from the limited data.

2.5 HR 3063 and HR 3067

These two Pleiades members were observed together, along with the comparison stars HR 3062 and HR 3067.

2.6 Vd 486, Vd 512, and Vd 622

Of the three Hyades stars in the present study, Vd 486 has been observed to have Hg in absorption while Vd 686 and Vd 512 have among the strongest H reflexion strengths in their color range (Stauffer et al. 1981). Vd 486 and Vd 512 were targeted for monitoring since their high activity suggested an improved probability of observing brightness variations related to stellar activity. The K I survey of the Hyades (Miszalska et al, 1988), both Vd 486 and Vd 512 were detected in X-rays, while only an upper limit was derived for Vd 622. Vd 486 is a close visual binary with separation = 1", consequently both components were included in the aperture photometry measurements. The NUBO and Lick datasets exhibit a phase shift and were analyzed separately; both datasets yield similar periods (NUBO: 2.41 days, Lick: 2.43 days) and consistent amplitudes. The light curve for the NUBO dataset is shown in Fig. 1.
2. OBSERVATIONS AND ANALYSIS

In Table 1 we list the sample of stars observed. Following the star name are the number of observations (Nₕₖ) used in the period determination, the dates of observation, and the observer identification. "CIA" observations were obtained with the Whipple Observatory 48-in. telescope on Mt. Hopkins, AZ, by observers G.W. C.G.R. "NUBO" observations were obtained by A.D.O.B.R.S.R.B.M. using the 31-in. telescope of the National Observatory. Observations by M.J.O.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 measurements using either the IRAF "affine" package or the _ASTROS 平台 routines (Stetson 1987) in the current version of the IRAF.

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 signal-to-noise ratio of 10 for the variable and comparison stars which would enable photometric accuracies of 1% or better. Except when noted below, differing the two comparison stars for each program star confirmed that the photometry had accuracy of this order. As in Paper I and II, photometric analysis was performed on the relative photometry using a program which incorporates the method outlined by Noyes and Ballester (1980) and Stetson (1982) for unevenly sampled data.

We do not tabulate for the individual observations, 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 Science Data Center (NSDC).

The results of the period analysis for the stars in Table 1 are found 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 sine-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 (primary comparison star for each target in Table 2) are also given. The comparison stars are designated by Hertzsprung's (1947) If number for the Pleiades, and Grise Star Catalog numbers (GSC; Labek et al. 1988) for Alpha Per, Hydrae, 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 4.8% associated with the 1.2-day period and the small v sin i observed for AP 212 lead us to the longer period is more probably correct.

2.2 H η 298, H η 314, and H η 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 non-comparison stars used for comparison were H η 298 and H η 262, with H η 285 as the primary comparison star. For H η 298, 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 CIA/Lick data alone yield 4.5 days, and the NUBO data alone yield 4.0 days. The phased light curve using all observations is shown in Fig. 1. For H η 314, we confirm the 1.5-day period reported in Paper II; additional information on this star is discussed there. H η 320 is a spectroscopic binary (Mamajek et al. 1992).

2.3 H η 312

Van Leeuwen et al. (1987) initially reported a 6.6-day period for H η 312. After analyzing separately, the Lick and NUBO observations in this present study yield periods of 6.5 and 5.5 days, respectively, confirming Van Leeuwen et al. results for this low-amplitude star.

2.4 H η 2284 and H η 2341

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

2.5 H η 3030 and H η 3063

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

2.6 H η 486, H η 512, and H η 622

Of the three Hayades stars in the present study, H η 486 has been observed to have Hα in absorption while H η 486 and H η 512 have among the strongest Hα emission strengths in their color range (Stauffer et al. 1991). H η 486 and H η 512 were targeted for monitoring since their high activity suggested an improved probability of obtaining brightness variations related to stellar activity. The ZELLEN survey of the Hayades (Muzerolle et al., 1998), both H η 486 and H η 512 were detected in X-rays, while only an upper limit was derived for H η 622. H η 486 is a close visual binary with separation ~1", consequently both components were included in the aperture photometry measurements. The NUBO and Lick datasets exhibit a phase shift and were analyzed separately; both datasets yield similar periods (NUBO: 2.41 days, Lick: 2.43 days) and consistent amplitudes. The light curve for the NUBO dataset is shown in Fig. 1. H η 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 NUBO 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 period between these two epochs is by chance.
Fig. 1—Phase-V band light curves for those stars with period determinations in Table 2.

Fig. 1—(Continued)
Fig. 1—Phase V light curves for those stars with period determinations in Table 2.
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 ($V_\text{eq}$) and the observed $V$-band magnitude. For simplicity we use the observed $B-V$ colors to estimate stellar radii using the $B-V$ vs. log (R/\text{R}_\odot)$ relation from Allen (1976), as in Papers I and II. Mean reddening of $(E(B-V)=0.08)$ for Alpha Per, $(E(B-V)=0.04)$ for the Pleiades, and $(E(B-V)=0.90)$ for the Hyades have been assumed.

Table 4 gives $X$-ray luminosities in the 0.3–2 keV range for stars with X-ray observations. 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 ($V_\text{eq}$) and the observed $V$-band magnitude. For simplicity we use the observed $B-V$ colors to estimate stellar radii using the $B-V$ vs. log (R/\text{R}_\odot)$ relation from Allen (1976), as in Papers I and II. Mean reddening of $(E(B-V)=0.08)$ for Alpha Per, $(E(B-V)=0.04)$ for the Pleiades, and $(E(B-V)=0.90)$ for the Hyades have been assumed.

Table 5 gives the rotation periods for stars with available rotation periods. The columns in Table 5 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 ($V_\text{eq}$) and the observed $V$-band magnitude. For simplicity we use the observed $B-V$ colors to estimate stellar radii using the $B-V$ vs. log (R/\text{R}_\odot)$ relation from Allen (1976), as in Papers I and II. Mean reddening of $(E(B-V)=0.08)$ for Alpha Per, $(E(B-V)=0.04)$ for the Pleiades, and $(E(B-V)=0.90)$ for the Hyades have been assumed.

Additional notes indicating those cases of photometric or spectroscopic binaries (i.e., PB or SB). As in Paper II, the stars in Table 4 are mostly K dwarfs with a few late-B 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(1/L$_\odot$) vs. log(1/P) for those Pleiades stars in Table 4. The late-F to early-K dwarfs are shown in yellow, labeled "Pleiades." The F to early-G dwarfs are shown in red, labeled "Hyades." The K to early-M dwarfs are shown in black, labeled "Trumpler II." The late-M dwarfs are shown in blue, labeled "Taurus." The open circles indicate late-F to early-K dwarfs, the filled circles indicate F to early-G dwarfs, the filled squares indicate K to early-M dwarfs, and the filled triangles indicate late-M dwarfs. The open diamonds indicate late-F to early-K dwarfs, the filled diamonds indicate F to early-G dwarfs, the filled rhombi indicate K to early-M dwarfs, and the filled triangles indicate late-M dwarfs. The open squares indicate late-F to early-K dwarfs, the filled squares indicate F to early-G dwarfs, the filled rhombi indicate K to early-M dwarfs, and the filled triangles indicate late-M dwarfs. The open triangles indicate late-F to early-K dwarfs, the filled triangles indicate F to early-G dwarfs, the filled rhombi indicate K to early-M dwarfs, and the filled triangles indicate late-M dwarfs. The open circles indicate late-F to early-K dwarfs, the filled circles indicate F to early-G dwarfs, the filled squares indicate K to early-M dwarfs, and the filled triangles indicate late-M dwarfs. The open diamonds indicate late-F to early-K dwarfs, the filled diamonds indicate F to early-G dwarfs, the filled rhombi indicate K to early-M dwarfs, and the filled triangles indicate late-M dwarfs. The open squares indicate late-F to early-K dwarfs, the filled squares indicate F to early-G dwarfs, the filled rhombi indicate K to early-M dwarfs, and the filled triangles indicate late-M dwarfs. The open triangles indicate late-F to early-K dwarfs, the filled triangles indicate F to early-G dwarfs, the filled rhombi indicate K to early-M dwarfs, and the filled triangles indicate late-M dwarfs. The open circles indicate late-F to early-K dwarfs, the filled circles indicate F to early-G dwarfs, the filled squares indicate K to early-M dwarfs, and the filled triangles indicate late-M dwarfs.
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 (Rₜₜ), the observed period, the corresponding equatorial velocity of the star (vₑₚ) and the observed vₑₚ. For simplicity we use the observed B−V colors to estimate stellar radii using the B−V vs. log (Rₑₚ/Rₜₜ) relations from Allen (1976), as in Papers I and II. Mean reddening 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.

WTT04159+1716 Evolutionary Status. In the case of WTT04159+1716, Walter et al. estimate minimal reddening: Aᵥ=0.00±0.20. 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 Aᵥ=0.5. In determining the location of WTT04159+1716 relative to the ZAMS, we use the Pleiades main sequence (age ~70 Myr) as a surrogate ZAMS as in Paper I. WTT04159+1716’s (B−V)−y′ photometry was corrected for its distance (140 pc) and not estimated reddening (Aᵥ=0.5) to the Pleiades distance (~125 pc) and reddening. The transformed values (Vₚₚ/11.65, B−Vₚₚ/1.01) were then plotted on a color−magnitude diagram of Pleiades members (Fig. 3) with the result that WTT04159+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

elaboration above the ZAMS is due to binarity or to WTT04159+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 WTT04159+1716 is significantly older than the 4−Myr estimate by Walter et al. ~300 Myr ago only because of the single−star cluster sequence. Comparison of WTT04159+1716’s position in Fig. 2 to theoretical isochrones suggests that it is at least 100 Myr younger than the Hyades and at least 300 Myr younger than the Pleiades. In Table 3 we have used WTT04159+1716’s observed B−V to find Rₑₚ/Rₜₜ=0.86 and vₑₚ=29 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 Rₑₚ/Rₜₜ=1.2 and vₑₚ=116 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 Miska 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 Jₚ₋ₐ and log(Jₚ₋ₐ)/data are from Stauffer et al. or from Miska et al. where indicated. Observed or estimated spectral types are given, along with additional notes indicating those cases of photometric or spectrophotometric binaries (i.e., PB or SB). As in Paper II, the stars in Table 4 are mostly K dwarfs with a few late−F and early−G dwarfs included. To the best of our knowledge, Table 4 includes all Pleiades stars which currently have rotation data determined from photometric monitoring.

In Fig. 3 we plot log(Jₚ₋ₐ)/data vs. log Pₚ for those Pleiades stars in Table 4. The late−F/early−G M stars are seen to have lower X−ray activity levels for a given period than the late−GK dwarf members. A plausible explanation for this is that the late−F/early−G stars have faster non−coronal envelopes and are relatively inefficient generators of coronal activity compared to late−type stars having larger convective envelopes. The early−G dwarf H 314 is not detected from the late−GK dwarfs in Fig. 3, in higher−X−ray activity may be due to binarity. A category III might lie intermediate between the late−F/early−G and late−GK dwarf categories; it is plotted with the late−GK group in Fig. 3.

The rotation−activity relationship shown in Fig. 3 for Pleiades K dwarfs illustrates what is perhaps a gradual trend of decreasing log(Jₚ₋ₐ)/data from the very rapid rotators (P < 10 days) to slower rotators with periods ~6−8 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 1984) and references therein, Marci and Catalina (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 1984; Walter et al. 1985), along with the lower X−ray activity levels in late−GK dwarfs in comparison to late−GK dwarfs. The Pleiades observations present here provide a much more homogeneous population of stars in terms of age and metallicity for study of the relation between rotation and activity.
rotation periods in Fig. 3 prevent meaningful calibration of the dependence between X-ray activity and rotation for slowly rotating Pleaides K dwarfs. Additional monitoring of those Pleaides 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 Pleaides 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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