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 $P\sim6-7$ 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
Astrophysics and Astronomy | Other Astrophysics and Astronomy | Stars, Interstellar Medium and the Galaxy

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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-
2. OBSERVATIONS AND ANALYSIS

In Table 1 we list the sample of stars observed. Following the star name is the number of observations (9_s) used in the period determination, the dates of observation, and the observer identification. "CCD" observations were obtained with the Whipple Observatory 46-in. telescope on Mt. Hopkins, AZ, by observers S.W.C., D.R.C., "NURO" observations were obtained by A.D.O./D.R./L.S./B.A.I. using the 31-in. telescope of the National Underground Research Observatory in Flagstaff, AZ. "Lik" observations were made by M.Z.S. at the Lick Observatory 40-in. telescope on Mt. Hamilton, CA. All observations were obtained using a V-band filter (Brassel 1969) 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 during a session where photometry measures using either the IRAF "aphpix" package or the DAOMATCH routines (Settomasi 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, differing the two comparison stars for each program star confirmed that the photometry had accuracy of this order. As in Papers I and II, photometric analysis was performed on the relative photometry using a program which incorporates the method outlined by Hoyer and Ballew (1986) and Scargle (1982) for unevenly sampled data.

We do not utilize 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 problem of the period analysis for the stars in Table I 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 analysis. In these cases a period error is reported as usual in the case that a period is determined with confidence.

The period analysis of the stars in Table I are listed in Table 2. The V, B - V values, the observed v sin i and its source reference, the derived period, amplitude, and sine wave analysis for the stars in Table 2 are also given.

The comparison stars (primary comparison stars) for each target in Table 2 are also given. The comparison stars are designated by Hertzsprung's (1947) III number for the Phases and Grigelis Star Catalog number (GSC; Luck 1988) for Alpha Per, Hyades, and the weak-lined T Tauri stars. 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 photometric 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 293 and H 314, and H 320

As these three Fovies members lie within a few arc minutes of each other, the sky, relative CCD photometry of all three could be obtained in one observation. The noncomparison stars used for comparison were H 285 and H 262, with H 285 as the primary comparison star. For H 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 CCluch data alone yields 4.5 days, and the NURO data alone yields 4.0 days. The phased light curve using all observations is shown in Fig. 1. For H 314, we confirm the 1.5-day period reported in Paper II; additional information on this star is discussed there. H 320 is a spectroscopic binary (Mumma et al. 1992).

2.3 H 3124

van Leeuwen et al. (1987) initially reported a 6.8-day period for H 3124. When analyzed separately, the LIk and NURO observations in this present study yield periods of 6.5 and 5.9 days, respectively, generally confirming van Leeuwen et al. for this low-amplitude star.
2. OBSERVATIONS AND ANALYSES

In Table 1 we list the sample of stars observed. Following the star name are the number of observations (v) used in the period determination, the dates of the observations, and the observer identification. "O" observations were obtained with the Whipple Observatory 45-in. telescope on Mt. Hopkins, AZ by observers, S.W.C.D.R.K. "N" observations were obtained by A.D.O.d.B./L.S.R.B.A.M. using the 31-in. telescope of the National University Research Observatory in Flagstaff, AZ. "L" observations were obtained by M.D.S. at the Lik Observatory 40-in. telescope on Mt. Hamilton, CA. All observations were obtained using a V-band filter (Brenton 1990) with a CCD camera. As 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 "aperture" package or the DAOMATCH 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 signal-to-noise ratio for the variable and comparison stars which would enable photometric accuracies of 1% or better. Except when noted below, diferencing the two comparison stars for each program star confirmed that the photometry had accuracy of this order. As in Papers I and II, period analysis was performed on the relative photometry using a program which incorporates the method outlined by Huterer and Ballesteros (1988) and Sargiot (1982) for unevenly sampled data.

We do not eliminate the individual observations herein, but will proceed to analyze the data and folding based on 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 relative fold information (if from the periodogram analysis). In those cases wherein the period is regarded as uncertain it is denoted with a color. The comparison stars (primary or secondary) for each target in Table 2 are also given. The comparison stars are designated by Herbig's (1974) if reference for the Phalenes, and Giese Star Catalog number (+GSC; Lohman 1980) for Alpha Per, Hydrae, and the weak-lined T Tauri star. The plotted 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 4.9% associated with the 1.2-day period and the small v sin i observed for AP 212 lead us to the longer period being more probably correct.

2.2 H 3134, H 3144, and H 330

As these three Phalenes 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-observations used for comparison H 285 and H 262, with H 285 as the primary comparison star. For H 3134, the period determinations range from 4.3 to 4.5 days, depending on which combination of observations are used. Analysis of all 57 observations yields a 4.0-day period, the CIa/a data alone yields 4.1 days, and the NUBO data alone yields 4.0 days. The phased light curve using all observations is shown in Fig. 1. For H 3144, we confirm the 1.5-day period reported in Paper II; additional information on this period is discussed below. H 330 is a spectroscopic binary (Mumford et al. 1992).

2.3 H 3124

Vainio Levanen et al. (1987) initially reported a 6.6-day period for H 3124. When analyzed separately, the H 3124 and NUBO observations in this present study yield periods of 6.5 and 5.9 days, respectively, confirming the Vainio Levanen et al. results for this low-amplitude star.

2.4 H 2284 and H 2341

Both H 2284 and H 2041 were observed in the same CCD field, with the comparison stars H 2286 (primary) and H 2244. The corresponding periods in Table 2 are among the longest periods so far observed among Phalenes stars. For both stars, all available observations were used in the analysis with no significant phase shift evident between datasets by different groups. H 2284 was unsuitable for use as a comparison star as it was observed to vary by 0.15 mag over an interval of several years; no period could be derived from the limited data.

The light curves for the H 330 and H 2341 datasets are shown in Figs. 2 and 3. H 3124 was originally observed in November 1992 by C.P., a period of 8.10 days was indicated but the analysis was not considered to be conclusive. The accuracy with the combined 1994 March NUBO observations and November 1992 data yields an 8.6-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 alignment between these two epochs is by chance.
Fig. 1.—Phased V-band light curves for these stars with period determinations in Table 2.
Fig. 1—Phased V-band light curves for these 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_s), the observed period, the corresponding equatorial velocity of the star (v_p), and the observed r_s. For simplicity we use the observed B - V colors to estimate stellar radii using the B - V vs log [R/R_☉] relation from Allen (1976) and the observed r_s for the Pleiades and B - V corrected for the Hyades have been assumed.

WTT4159 = 1716 Evolutionary Status. In the case of WTT4159 = 1716, Walter et al. estimate minimum reddening: A_v = 0.04 ± 0.02. 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 WTT4159 = 1716 relative to the ZAMS, we use the Pleiades main sequence (age ~ 70 Myr) as a surrogate ZAMS as in Paper I. WTT4159 = 1716 (B - V) photometry was corrected for its distance (~140 pc) and not estimated reddening (A_v = 0.5) to the Pleiades distance (~125 pc) and reddening. The transformed values (V_m = 11.65, B_v = 10.81) were then plotted on a color-magnitude diagram of Pleiades members (Fig. 3) with the result that WTT4159 = 1716 lies ~0.8 mag above the single star main sequence as defined by Pleiades members. As the Pleiades age, stars are on the main sequence in this region of the color-magnitude diagram. Whether this

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### Table 4

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<th>Star</th>
<th>Log(A_v)</th>
<th>Log (A_v)</th>
<th>Log(V_m)</th>
<th>Log(B_v)</th>
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### Table 3

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<th>r_s (Sun)</th>
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Note: Additional notes indicating those cases of photometric or spectrophotometric binaries (i.e., PB II or III). 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 determined from photometric monitoring.

In Fig. 3 we plot log(A_v)/log(V_m) vs log P/10 for those Pleiades stars in Table 4. The late-Fourth-Gyr-M member 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-Fourth-Gyr-M stars have thinner outer convective envelopes and are relatively inefficient generators of coronal activity compared to late-type stars having larger convective envelopes. The early-G dwarf HD 314 is not deviant from the late-GK dwarfs in Fig. 3; in higher X-ray activity may be due to binarity. At G4, H is 2.541, perhaps less intermediate between the late-Fourth-Gyr-M and late-GK dwarf categories; it is plotted with the late-Gyr 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(l_x)/log(A_v) from the very rapid rotators (P < 10 days) to slower rotators with periods ~6 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, Martell and Catala (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 Fourth-Gyr-M dwarfs in comparison to late-GK dwarfs. The Pleiades observations presented here provide a much more homogenous 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
### Table 3

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<th>Star B-V</th>
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<th>(\epsilon_{\text{rec}})</th>
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### Table 4

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#### 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 \(\epsilon\) vs. 4. We use the observed B-V colors to estimate stellar radii using the B-V vs. \(\log R_{\odot}\) relation from Allen (1976), as in Paper I and II. Mean reddening of \(E(B-V)\) is \(0.30\) for Alpha Per, \(E(B-V)\) is \(0.04\) for the Pleiades, and \(E(B-V)\) is \(0.00\) for the Hyades have been assumed.

WTT 041559 + 1716 Evolutionary Stage. In the case of WTT 041559 + 1716, Walter et al. estimate minimal reddening of \(E(B-V)\) \(=0.00\) to \(0.20\). However, the location of the star in their color-color diagram (Fig. 5, Walter et al. 1988) would suggest a larger reddening, perhaps on the order of \(E(B-V)\) \(=0.50\). The locations of WTT 041559 + 1716 relative to the ZAMS, we use the Pleiades main sequence age \(\sim 70\) Myr as a surrogate ZAMS as in Paper I. WTT 041559 + 1716 B-V photometry was corrected for its distance \((140 \pm 40)\) pc and not estimated reddening \((\sim 0.5)\) to the Pleiades distance \((125 \pm 4)\) pc and reddening. The transformed values \(V_{\text{eq}}=11.65, R_{\odot}=1.01\) were then plotted in 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...
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 \(-4 \leq \log(L_\gamma/L_{bol}) \leq -4.5\) 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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servations. Franklin and Marshall and Gettysburg College
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B. Zamkoff. Support for the Lick observations by M.D.S.
was provided by NSF Grant No. AST-90-16521 (to B.
Jones). This study was supported by NASA Grant No.
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