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THE ACTIVITY, VARIABILITY, AND ROTATION OF LOWER MAIN-SEQUENCE MEMBERS OF THE COMA STAR CLUSTER

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ABSTRACT

High-precision, differential, Strömgren b, y photometric observations of nine members of the Coma star cluster, spectral types F3 V to K0 V, were made at Lowell Observatory between 1984 and 1987. We found that four G-type stars in this sample were all variable on both seasonal and year-to-year time scales, and the single K-type star also showed hints of variability. In contrast, four F-type stars were not detectably variable on either time scale. The variable stars tended to become slightly bluer as they brightened. The low-level photometric variability of Coma stars appears to resemble closely that observed among similar stars in the Hyades cluster. We also measured rotation periods for the four G-type stars from modulation present in our photometric data. The rotation periods of these stars and similar stars in the Hyades are comparable. The fact that the Coma and Hyades clusters are essentially indistinguishable in terms of their activity, variability, and rotational characteristics presents difficulties for claims that the photometric "Hyades anomaly" is a consequence of stellar activity.
Subject headings: clusters: open — photometry — stars: rotation — stars: variables

I. INTRODUCTION

For decades, the nearby open cluster in the constellation Coma Berenices has been consigned largely to supporting roles on a stage dominated by more conspicuous players such as the Hyades and the Pleiades. Among its few center-stage appearances is the paper by Trumpler (1938), who studied the proper motions, radial velocities, photographic and visual photometry, color indices, and spectral types of stars in the vicinity of the Coma cluster and produced a membership list that has remained an important foundation for subsequent work. The Coma cluster is, admittedly, poor in stars. Trumpler identified only 43 likely members, and that list of candidates has grown but little over the intervening 50 years. Most of the cluster's members are either A- or F-type dwarfs. Its main sequence also includes a handful of G- and early K-type stars, and three or four red dwarfs (DeLuca and Weis 1981). It has no upper main-sequence members earlier than spectral type A0. There are no late-type giants, although most authors do identify two evolving stars as members. The cluster's poverty, however, is by no means exceptional. Indeed, Trumpler characterized Coma as "a typical representative of [the] most numerous class of clusters," a class of sparse, loosely bound systems whose lack of low-mass members, he suggested, may be a consequence of cluster evaporation.

Early UBV photoelectric photometry (Johnson and Knuckles 1955; also Mendoza 1963) revealed that F- and early G-type Coma stars show an ultraviolet excess of 0.035–0.050 mag relative to similar stars in the Hyades cluster. This excess was attributed to unequal line blanketing arising from an assumed difference in the mean chemical compositions of the two clusters. This explanation has successfully weathered the test of time. The mean metallicity of Coma, measured spectroscopically, is only about two-thirds that of the Hyades (e.g., Boesgaard 1989). Coma stars are, in fact, somewhat metal-poor ([Fe/H] = −0.065, or 86%) relative to the Sun, as well.

Twenty years ago, Crawford and Barnes (1969) discovered that F- and early G-type main-sequence stars in the Hyades cluster systematically show a Strömgren c_1 surface-gravity index excess of ~0.04 mag relative to similar stars in the Coma cluster and the field. This "Hyades anomaly" remains one of the enduring riddles of stellar photometry (e.g., Dobson 1989). It has generally been attributed to composition differences (Barry 1974; Strömgren, Olsen, and Gustafsson 1982; Alexander 1986)—the well-known metal enhancement of the Hyades or their assumed helium deficiency have both been invoked. Recently, several authors (Campbell 1984; LaBonte and Rose 1985) have suggested instead that the Hyades anomaly arises from a difference in stellar activity. This possibility is indirectly supported by the fact that the Strömgren m_1 metallicity index demonstrably responds to the difference in mean activity between solar plages and quiet regions (Giampapa, Worden, and Gilliam 1979). The behavior of the c_1 index itself, however, has not yet been tested by solar observations.

Activity-related explanations for the Hyades anomaly share a necessary condition: Hyades stars must be *more* active, on average, than their counterparts in the Coma cluster or the field. Indeed, Hyades stars *are* more active than typical field stars (e.g., Wilson 1963). The two clusters, however, show little difference. Measurements of Ca II H+K emission from Mount Wilson Observatory (Duncan *et al.* 1984; Baliunas 1988) reveal that Hyades stars, if anything, are slightly *less* active than their Coma counterparts, although the difference is comparable to

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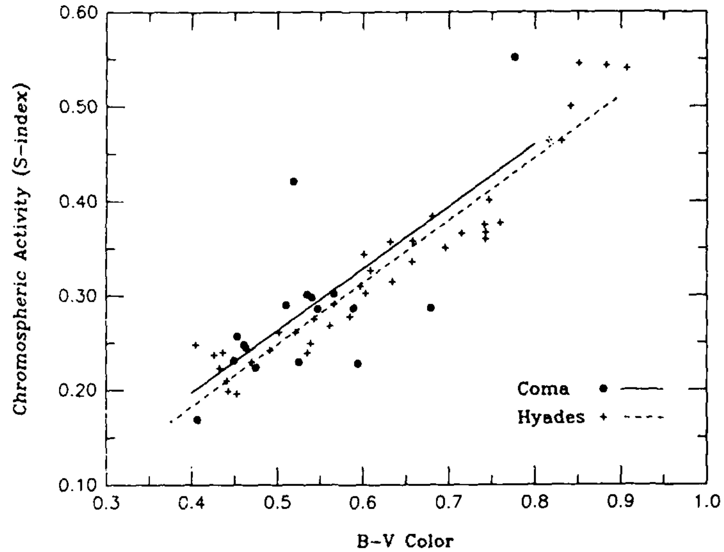

FIG. 1. The distribution of chromospheric Ca II H + K emission, measured in units of the Mount Wilson S-index, as a function of $B-V$ color for stars in the Coma and Hyades clusters. The Hyades data are means from one or more seasons, and represent observations from as many as 120 nights. The Coma data, on the other hand, are single measurements from one night. Hence, the sampling differs vastly. The difference between common-slope linear fits to the two distributions, however, is only marginally significant.

the standard error of a least-squares fit to the observations (Fig. 1). An independent comparison (Barry, Cromwell, and Hege 1987), however, supports the impression that Hyades stars are slightly less active than Coma stars. This evidence alone is probably insufficient to undermine the activity hypothesis, if only because the effects of metallicity differences on stellar Ca II H + K emission indices are not well understood. More importantly, some aspect of stellar activity other than chromospheric emission—starspots, perhaps—could be the causal agent for the Hyades anomaly. For example, Campbell (1984), who invoked starspots to account for certain photometric anomalies particularly noticeable among Hyades stars, suggested that the Hyades anomaly itself might also be a consequence of spottedness and predicted that "Coma stars are not as heavily spotted as the Hyades." Although Campbell's arguments have since been challenged (Soderblom 1989), his prediction was one of the original motivations for the present observational study.

Since stellar activity is tightly coupled to rotation (e.g., Noyes *et al.* 1984), a rotational comparison of the two clusters offers a second way to test the activity explanation for the Hyades anomaly. Published spectroscopic measurements of projected rotational velocities for Hyades and Coma stars suggest that the lower main-sequences of the two clusters are rotationally very similar. Kraft's (1965) conclusion that the rotational velocities of late F-type Coma stars do not differ significantly on average from similar stars in the Hyades is, however, qualified by the fact that the rotational velocities of such stars approach the resolution limit (~ 12 km s^{-1}) of his equipment. The considerably better precision (~ 1 km s^{-1}) of the CORAVEL spectrometer (Benz, Mayor, and Mermilliod 1984) clearly overcomes this particular handicap, but does nothing to alleviate the more fundamental problem posed by the intrinsic shortage of lower main-sequence stars in the Coma cluster. Certainly, projection effects could easily bias an analysis based on a sample totaling eight stars, which was further split into five bins (Benz, Mayor, and Mermilliod 1984). The possibility that nonrotational broadening mechanisms may become important among cooler stars (Benz and Mayor 1984) adds to the difficulties, especially when such effects are imputed to stellar magnetic activity. Once again, the available evidence, although unsupportive, does not decisively undermine the activity hypothesis.

Beginning in 1984 and extending through 1987, intensive, high-precision, differential, Strömgren b, y photometric observations of nine stars in the Coma cluster, ranging in spectral type from F3 V to K0 V, were obtained at Lowell Observatory. The specific objectives of this project were (1) to measure the photometric variability of lower main-sequence stars in the Coma cluster on time scales ranging from days to months (characteristic of stellar rotation and active-region evolution) to years (characteristic of stellar activity cycles); (2) to measure rotation periods for these stars; and (3) to compare the variability and rotation of stars in the Coma cluster with the behavior of similar stars in the Hyades, in order to strengthen the evidence bearing on activity explanations for the Hyades anomaly. Since the two clusters are about the same age, such comparisons also test the generality of stellar activity-age and rotation-age relations.

II. OBSERVATIONS AND ANALYSIS

Our photometric observations and their subsequent analysis both followed established procedures. Since full discussions of these have already been published (Lockwood *et al.* 1984; Radick *et al.* 1987; Lockwood and Skiff 1988), we will confine our present description to a brief summary.

a) Photometry

The program stars were observed as quartets, with one (presumably) nonvariable mid F-type star included in each quartet as the photometric reference. One of the two quartets remained unchanged during the entire 4 years; a single substitution was made midway through the program in the other. Hence, seven of the nine stars were observed during four seasons and the other two were observed for two seasons only. Our expectation that mid F-type dwarfs make stable photo-

TABLE 1

SUMMARY OF PHOTOMETRIC OBSERVATIONS

Quartet No. 1, N=16, 1984 Mar 03 - Jun 15

Pair	Δy	s.d	Δb	s.d.
T36-T114	-0.484	±0.003	-0.516	±0.004
T36-T65	-0.922	±0.007	-1.011	±0.008
T36-T76	-0.959	±0.007	-1.039	±0.008
T114-T65	-0.438	±0.008	-0.495	±0.010
T114-T76	-0.475	±0.008	-0.524	±0.008
T65-T76	-0.037	±0.011	-0.029	±0.014

Correlations

Star	95.0%-99.5%	≥99.5%	Decision
T36 (F3V)	0	0	Nonvariable
T114 (F8V	0	0	Nonvariable
T65 (G0V)	0	6	Variable
T76 (G0V)	0	6	Variable

Quartet No. 1, N=17, 1985 Dec 21 - 1986 May 20

Pair	Δy	s.d	Δb	s.d.
T36-T114	-0.482	±0.006	-0.514	±0.004
T36-T65	-0.906	±0.006	-0.993	±0.006
T36-T76	-0.958	±0.008	-1.038	±0.009
T114-T65	-0.424	±0.006	-0.480	±0.005
T14-T76	-0.476	±0.008	-0.524	±0.009
T65-T76	-0.052	±0.009	-0.045	±0.009

Correlations

Star	95.0%-99.5%	≥99.5%	Decision
T36 (F3V)	0	0	Nonvariable
T114 (F8V)	0	0	Nonvariable
T65 (G0V)	2	1	Nonvariable
T76 (G0V)	0	6	Variable

Quartet No. 1, N=20, 1985 Jan 01 - May 21

Pair	Δy	s.d	Δb	s.d.
T36-T114	-0.482	±0.004	-0.514	±0.003
T36-T65	-0.923	±0.008	-1.014	±0.010
T35-T76	-0.972	±0.011	-1.056	±0.012
T114-T65	-0.441	±0.008	-0.500	±0.010
T114-T76	-0.489	±0.011	-0.541	±0.013
T65-T76	-0.048	±0.012	-0.041	±0.016

Correlations

Star	95.0%-99.5%	≥ 99.5%	Decision
T36 (F3V)	0	0	Nonvariable
T114 (F8V)	0	0	Nonvariable
T65 (G0V)	2	4	Variable
T76 (G0V)	0	6	Variable

Quartet No. 1, N=13, 1987 Feb 02 - Jun 02

Pair	Δy	s.d	Δb	s.d.
T36-T114	-0.481	±0.004	-0.514	±0.006
T36-T65	-0.920	±0.007	-1.009	±0.011
T36-T76	-0.955	±0.005	-1.034	±0.006
T114-T65	-0.438	±0.008	-0.496	±0.009
T114-T76	-0.473	±0.005	-0.520	±0.008
T65-T76	-0.035	±0.007	-0.024	±0.010

Correlations

Star	95.0%-99.5%	≥99.5%	Decision
T36 (F3V)	1	0	Nonvariable
T114 (F8V)	2	0	Nonvariable
T65 (G0V)	1	5	Variable
T76 (G0V)	1	1	Nonvariable

metric standards was based on our experience observing such stars in the Hyades cluster (Radick *et al.* 1987). The recent discovery of low-level photometric variability among such stars in the field (Lockwood and Skiff 1988) suggests that we were a bit overconfident, but the mid F-type Coma stars at least, did behave according to script. The quartets were observed differentially in the *b* and *y* passbands of the Strömgren photometric system using the Lowell Observatory [illegible] telescope. A total of at least 90,000 counts, compensated for sky, was demanded for all stars by increasing as necessary the integration times for the fainter stars of the program. Thus, the maximum contribution to the night-to-night rms measurement precision from photon statistics was ~0.003 mag. Empirically, the night-to-night rms precision of the observations was found to be ~0.004 mag. The excess reflects the fact that the total error budget includes contributions from effects such as residual extinction, atmospheric transparency fluctuations, scintillation, and variable light loss caused by centering errors, as well as photon statistics (Lockwood and Skiff 1988).

b) Seasonal Variability

Differential light curves in *b* and *y* were produced for the six possible different pairs of stars from each quartet (i.e., [star 1-star 2], [1-3], [1-4], [2-3], [2-4], and [3-4]) and were examined for evidence of short-term, seasonal variability. For each star, correlation coefficients were computed for all pairs of light curves involving that star (e.g., for star 3, [1-3] vs. [2-3], [1-3] vs. [3-4], and [2-3] vs. [3-4], for both colors), yielding six coefficients per star. In order to maintain consistency between the present analysis and our previous variability studies of Hyades stars (Lockwood *et al.* 1984; Radick *et al.* 1987), we continued to discriminate as definitely variable (within a given season) any star that produced four or more correlation coefficients having at least 95% significance. Using this criterion, we found that five of the nine Coma stars were never variable. Four of these were F-type dwarfs, two being the reference stars. The fifth, spectral type K0 V, was observed for only two seasons, and it exhibited a suspicion of variability during one of those two years, even though it failed to satisfy our formal criterion. The remaining four stars, all G-type dwarfs, were observed for the full four seasons, and all clearly varied. Two of these were judged to be variable during every season. The other two each missed one season, at least formally, but both retained a hint of variability during those lulls. The rms amplitude of the observed variability never exceeded 2%. Table 1 summarizes our photometric observations. For each quartet, we list by season the mean differential *y* and *b* magnitudes (Δ*y* and Δ*b*) and dispersions (standard deviation = s.d.) for each pair of stars, identified by their widely used Trumpler (T) or Trumpler Appendix A (TA) numbers (Trumpler 1938). We also summarize the correlation analyses, listing for each star the number of coefficients falling

TABLE 1 *Continued*

Quartet No. 2, N=16, 1984 Mar 03 - Jun 22

Pair	Δy	s.d	Δb	s.d.
T101-T162	-0.186	±0.004	-0.201	±0.003
T101-T85	-0.924	±0.006	-0.993	±0.007
T101-T132	-1.482	±0.010	-1.595	±0.012
T101-TA13		Not Observed		
T162-T85	-0.738	±0.006	-0.792	±0.008
T162-T132	-1.296	±0.010	-1.394	±0.013
T85-T132	-0.559	±0.012	-0.602	±0.015
T85-TA13		Not Observed		
T132-TA13		Not Observed		

Correlations

Star	95.0%-99.5%	≥99.5%	Decision
T101 (F5V)	0	0	Nonvariable
T162 (F7V)	0	0	Nonvariable
T85 (G1V)	3	2	Variable
T132 (G5V)	0	6	Variable
TA13 (K0V)		Not Observed	

Quartet No. 2, N=21, 1985 Jan 01 - Jun 07

Pair	Δy	s.d	Δb	s.d.
T101-162	-0.186	±0.005	-0.202	±0.004
T101-T85	-0.914	±0.009	-0.985	±0.008
T101-T132	-1.473	±0.008	-1.582	±0.007
T101-TA13		Not Observed		
T162-T85	-0.728	±0.007	-0.783	±0.008
T162-T132	-1.287	±0.007	-1.380	±0.008
T85-T132	-0.558	±0.010	-0.598	±0.010
T85-TA13		Not Observed		
T132-TA13		Not Observed		

Correlations

Star	95.0%-99.5%	≥99.5%	Decision
T101 (F5V)	2	0	Nonvariable
T162 (F7V)	1	0	Nonvariable
T85 (G1V)	0	6	Variable
T132 (G5V)	1	5	Variable
TA13 (K0V)		Not Observed	

Quartet No. 2, N = 16, 1986 Feb 27 - May 20

Pair	Δy	s.d.	Δb	s.d.
T101-T162		Not Observed		
T101-T85	-0.914	±0.008	-0.986	±0.008
T101-T132	-1.479	±0.008	-1.592	±0.011
T101-TA13	-2.066	0.006	-2.228	±0.006
T162-T85		Not Observed		
T162-T132		Not Observed		
T85-T132	-0.565	±0.010	-0.606	±0.013
T85-TA13	-1.152	±0.009	-1.241	±0.009
T132-TA13	-0.587	±0.008	-0.636	±0.011

Correlations

Star	95.0%-99.5%	≥99.5%	Decision
T101 (F5V)	0	0	Nonvariable
T162 (F7V)		Not Observed	
T85 (G1V)	4	2	Variable
T132 (G5V)	1	4	Variable
TA13 (K0V)	1	0	Nonvariable

Quartet No. 2, N = 13, 1987 Feb 02 - Jun 03

Pair	Δy	s.d.	Δb	s.d.
T101-T162		Not Observed		
T101-T85	-0.912	±0.009	-0.983	±0.009
T101-T132	-1.470	±0.007	-1.578	±0.012
T101-TA13	-2.070	±0.007	-2.230	±0.007
T162-T85		Not Observed		
T162-T132		Not Observed		
T85-T132	-0.558	±0.011	-0.595	±0.016
T85-TA13	-1.158	±0.012	-1.247	±0.012
T132-TA13	-0.599	±0.008	-0.652	±0.010

Correlations

Star	95.0%-99.5%	≥ 99.5%	Decision
T101 (F5V)	0	0	Nonvariable
T162 (F7V)		Not Observed	
T85 (G1V)	1	5	Variable
T132 (G5V)	3	2	Variable
TA13 (K0V)	3	0	Nonvariable

TABLE 2

CUMULATIVE SUMMARY OF PERIOD ANALYSES

				Period				
Star	$B-V$	Spectral Type	Season	Predicted	Observed	S/N	P_0	Quality
T65	0.566	G0 V	1984	5.33	4.98 ± 0.03	1.57	0.096	B
			1985	...	5.14 ± 0.03	1.16	0.212	C
			1986	...	5.13 ± 0.02	1.76	0.067	B
			1987	...	5.59 ± 0.02	2.28	0.073	C
			all	...	5.11 ± 0.01	0.90	0.004	B
T76	0.547	G0 V	1984	4.97	5.91 ± 0.04	1.73	0.130	C
			1985	...	5.96 ± 0.03	1.47	0.212	C
			1986	...	5.88 ± 0.03	1.25	0.236	C
			all	...	5.99 ± 0.01	0.68	0.085	C
T85	0.589	G1 V	1984	7.34	7.09 ± 0.06	1.42	0.204	C
			1985	...	7.52 ± 0.04	1.45	0.052	C
			1987	...	7.37 ± 0.04	2.08	0.122	B
			all	...	7.5[illegible] ± 0.01	[illegible]	0.00[illegible]	B
T132	0.679	G5 V	1984	13.53	8.57 ± 0.08	1.66	0.091	C
			1986	...	8.14 ± 0.09	1.69	0.069	B
			all	...	8.41 ± 0.01	0.87	0.009	B

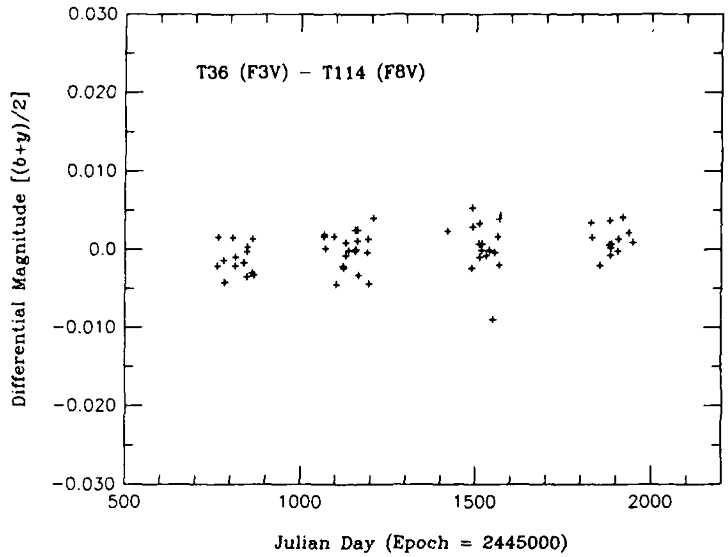

FIG. 2a

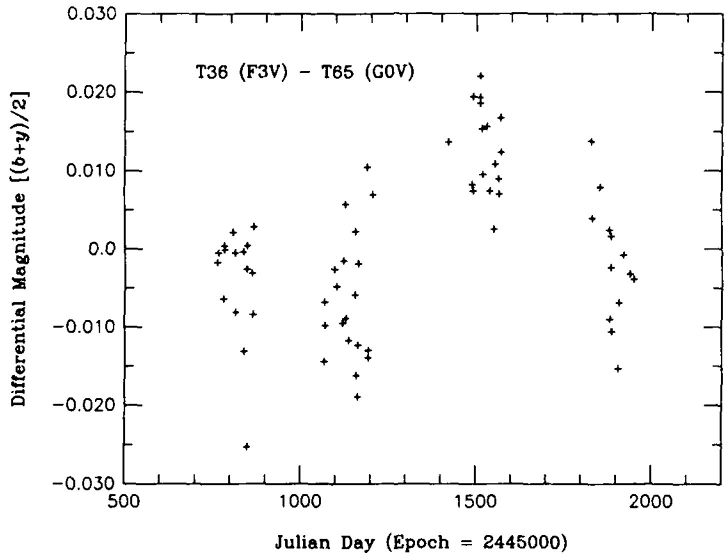

FIG. 2b

FIG. 2. Photometric observations spanning four seasons for two pairs of stars in the Coma cluster. The dispersion shown in (*a*) illustrates the instrumental precision and long-term stability of the measurements. Neither star of this pair is detectably variable. The pair shown in (*b*), plotted on the same scale, illustrates intrinsic stellar variability on both the seasonal and the year-to-year time scales. Since one of the two stars (T36) of the pair shown in (*b*) is nonvarying (see [*a*]), the variability can be unambiguously attributed to the other, T65.

in two significance ranges, 95.0%–99.5% and greater than 99.5%. The number falling below 95.0% significance can be inferred, since there is always a total of six coefficients per star. The formal decision concerning variability is indicated for each star.

c) *Year-to-Year Variability*

We also examined the observations for evidence of variability on longer term (year-to-year) time scales. The four G-type stars were all found to vary on this time scale, with amplitudes of 1% or so, whereas none of the remaining five were convincingly variable. Once again, however, the single K-type star in the sample (observed during only two seasons) showed a hint of variability on the year-to-year time scale. Examples of light curves are shown as Figure 2.

d) *Color Variability*

Three of the four variable G-type stars also showed small variations in $b-y$ color. This was especially evident on the year-to-year time scale. The correlation between color and brightness variations was significant at considerably greater than 99% confidence for T65 and T76, and at $\sim 90\%$ for T132. In all three cases, the sense of the correlation implied that the star became bluer as it brightened. The slope of the linear regression between color and brightness averaged 0.18 ± 0.05 for the three stars; accordingly, the amplitude of the year-to-

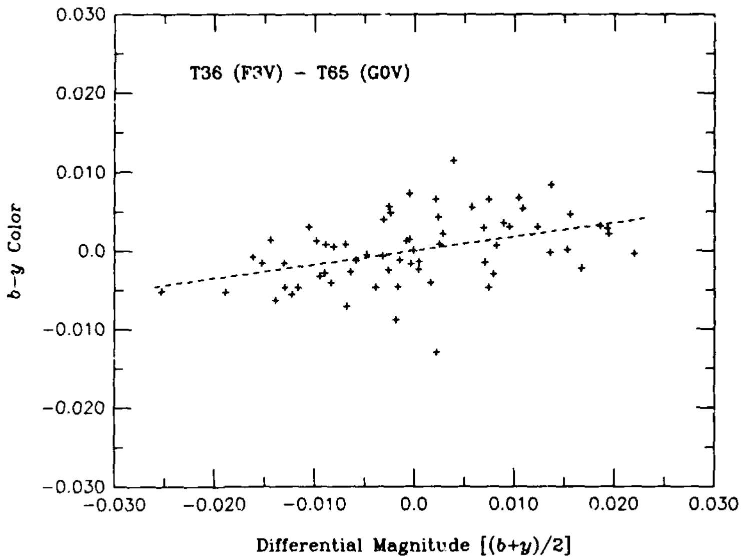

FIG. 3.—The relationship between $b-y$ color and brightness variations for a pair of stars in the Coma cluster. Assuming that T36 is nonvarying in both color and brightness, the axes are scaled such that the other star, T65, is brighter toward the right and bluer toward the top. The dashed line is the least-squares best-fit to the observations, and has a slope of 0.18.

year color changes was at most a few thousandths of a magnitude. The relationship between color and brightness variations for T65 is shown in Figure 3.

On the intraseasonal time scale, the correlation between color and brightness variations was significant at greater than 95% confidence in only one instance (T65, in 1984). The star became bluer as it became brighter, and the slope of the fitted regression was 0.27. Thus, the sense of the relationship between color and brightness variability appears to be the same on both seasonal and year-to-year time sales, and the relative amplitudes may also be similar.

e) *Period Analysis*

We used Scargle's (1982) modified periodogram algorithm, which is specifically tailored to handle unevenly spaced data, to analyze our observations for rotational signal. This technique provides a quantitative estimate of the statistical significance of a suspected signal, namely, the "false alarm probability," which is the probability that pure noise, alone, could give rise to a periodogram peak at least as large as that produced by the suspected signal. Table 2 summarizes the results of this analysis; Figure 4 shows an example of a phased light curve.

The periodograms were calculated using color-averaged differential magnitudes (Δm_{ij}) of the form

$$\Delta m_{ij} = \frac{\Delta b_{ij} + \Delta y_{ij}}{2}, \tag{1}$$

where Δb_{ij} and Δy_{ij} are the b and y differential magnitudes for

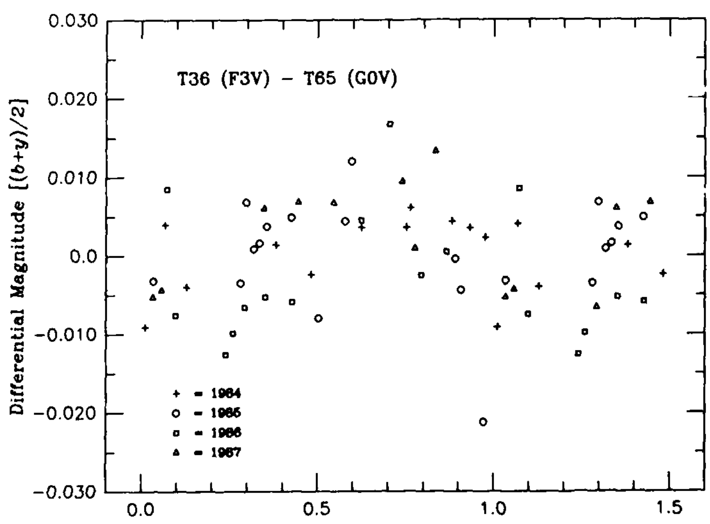

FIG. 4.—The light curve for the pair T36–T65, folded by the best-fit period of 5.11 days. The mean differential magnitude for each of the four seasons has been adjusted to zero. The persistence of the modulation in both amplitude and phase suggests that the distribution of surface markings on T65 remains relatively stable from year to year.

the $i-j$th pair of stars. Although there are three such periodograms for any particular star within a quartet, we gave strong preference to those involving one of the two nonvariable mid F-type reference stars (T36 or T101) as the second star, and used the others primarily to check consistency. The rotational signals were generally weaker than those we encountered in our analysis of Hyades star observations (Radick *et al.* 1987), undoubtedly because the Coma observations were both sparser and noisier, the latter simply because the Coma stars are fainter. We analyzed the observations from each individual season, as well as from all seasons combined. The measured rotation periods listed in Table 2 are not strictly independent, because our final decision to accept as real any candidate signal was based partly on whether or not it appeared with some persistence throughout the data base. Another consistency check was performed by comparing our measured rotation periods with those predicted using the "Rossby relation" (Noyes *et al.* 1984). Such predictions exploit the empirical fact that mean chromospheric Ca II H+K emission level and rotation are tightly linked among lower main-sequence stars.

Formal uncertainties for the measured periods were calculated using Kovacs's formula

$$\Delta P = \frac{3\sigma_N P^2}{4ATN_0^{1/2}} \qquad (2)$$

(Kovacs 1981; Horne and Baliunas 1986), where P is the measured period, A is the amplitude of the signal, σ_N is the rms noise remaining after the signal has been removed, and N_0 is the number of observations in a data set of total length T. This formula gives an optimistic estimate for the accuracy of a period measurement, since it is strictly valid only for evenly spaced data containing a single sinusoidal signal (Radick *et al.* 1987). Signal amplitudes (A) were determined by least-squares fits of sinusoids to the observations, and the rms noise values (σ_N) were calculated from the residuals.

As a measure of signal strength, we calculated values for the signal-to-noise ratio

$$S/N = A/\sigma_N , \qquad (3)$$

for all the measurements (Table 2). False alarm probabilities

$$P_0 = 1 - (1 - e^{-Z})^N , \qquad (4)$$

were also calculated, where Z is the height of the suspected signal peak and $N \approx N_0/2$ is the number of independent frequencies searched. Inspection of Table 2 shows that false alarm probabilities in excess of 10% were not uncommon for the individual seasons, another reminder that we were pushing the analysis a bit. We also assigned a subjective quality rating to each period measurement, adopting the same three-valued scheme (A = excellent, B = acceptable, C = marginal) devised previously for our Hyades measurements (Radick *et al.* 1987). We were unable to asign an "A" rating to any rotation period measurements for the Coma stars.

III. DISCUSSION AND CONCLUSIONS

The photometric variability observed among lower main-sequence stars in the Coma cluster is very similar to that observed among their counterparts in the Hyades on both seasonal and year-to-year time scales (Radick, Lockwood, and Thompson 1986; Radick *et al.* 1986; Radick *et al.* 1987). Variability on both time scales with an amplitude of 1% or so is commonly encountered among the G-type stars of the two clusters. Early to mid F-type stars, on the other hand, are not detectably variable on either time scale. The tendency for seasonal variability (or its absence) to persist from year to year is also a shared characteristic of Coma and Hyades stars.

The distribution of seasonal variability amplitude with spectral type is virtually identical for the Coma and Hyades clusters. Using the bluest (earliest) star in each quartet as the photometric reference, we compiled seasonal rms dispersions of the color-averaged differential magnitudes Δm_{ij} (eq. [1]) for the remaining program stars in both clusters over 4 year intervals. Hence, a given pair could appear as many as 4 times in our enumeration, once for every season it was observed. In total, 64 Hyades pairs and 24 Coma pairs were accumulated. The two variability distributions are plotted on common axes in Figure 5. In this figure, the abscissa values ($B-V$ colors) refer to the redder star of each pair, and not to the reference

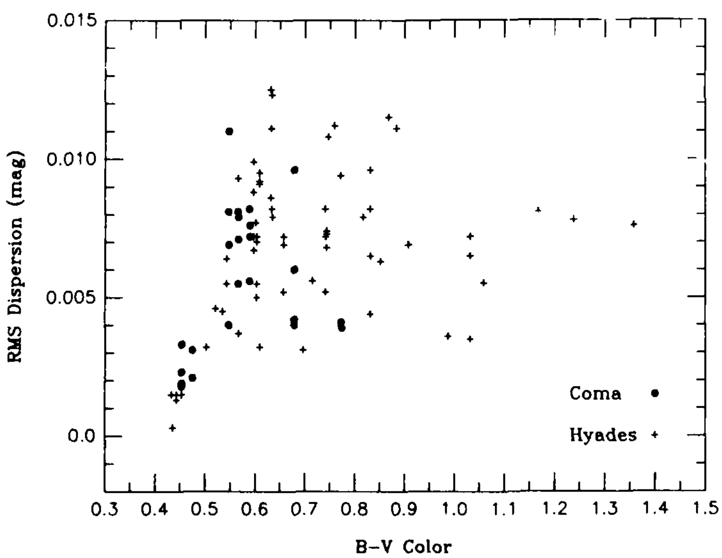

FIG. 5. The distribution of photometric variability, represented by seasonal rms dispersions, as a function of $B-V$ color for pairs of stars in the Coma and Hyades clusters. A given pair is represented once for each season it was observed, up to four times. The envelopes of the two distributions are very similar.

star, which was never later than spectral type F7 V ($B-V \sim 0.5$). As the figure indicates, the mid F-type stars ($B-V \sim 0.5$) in both clusters all show very small seasonal dispersions which may be mainly instrumental; the slightly larger values for the Coma stars can easily be accounted for in terms of the somewhat higher level of photon noise that characterized their observations. The variability increases dramatically among the G-type stars in both clusters, ranging between limits of ~ 0.003–0.013 mag in both cases. The mean variability amplitude may then decline somewhat among the K-type stars, although this particular point remains speculative, certainly on the basis of Figure 5 alone.

Nonuniformities in the spatial distribution of stellar surface markings, as well as real temporal changes in overall coverage or contrast arising from the evolution of these features, contribute to photometric variability on the seasonal time scale as periodic rotational modulation and as secular level changes, respectively (Radick *et al.* 1987). In contrast, year-to-year variations in mean brightness, which contain little residual rotational signal, reflect mainly temporal changes in stellar activity on time scales characteristic of both active region evolution and stellar activity cycles. Neither measure is sensitive to the absolute level of stellar activity, however, an unfortunate fact that limits us to inferences of lower bounds, only, for the fractional surface coverage by the starspots that are presumably responsible for the photometric variations. All evidence indicates that these lower bounds are comparable for stars of the Coma and Hyades clusters. Since measurements of chromospheric Ca II H+K emission *are* sensitive to the absolute level of stellar activity, a stronger conclusion may be drawn concerning bright emission regions: the surface coverage by bright features is comparable for stars in the two clusters, provided the contrast of those features is similar.

The rotation periods of G-type stars in the Hyades (Radick *et al.* 1987; Radick and Baliunas 1987) and Coma clusters are virtually identical, as Figure 6 illustrates. This conclusion is now grounded on direct measurements of rotation periods rather than spectroscopic observations $V \sin i$: the objections that can be raised against inferences drawn from $V \sin i$ measurements do not apply to modulation determinations.

Activity-related explanations for the Hyades anomaly require that the activity of Hyades stars be enhanced in some way, relative to Coma stars. The identity of this enhancement remains a mystery. The fact that Hyades stars appear to obey the "Rossby relation" linking mean activity and rotation (Radick and Baliunas 1987) suggests that there is nothing unusual about their overall activity; the further fact that there is no perceptible difference in measured rotation between Coma and Hyades stars drives us to conclude that the overall activity levels of the two groups of stars are probably very similar. This conclusion is further supported by the available measurements of chromospheric emission, and the comparable photometric behavior of stars in the two clusters is also consistent with it. Thus, the difference in activity, if it exists at all, is subtle. For example, we cannot rule out the possibility that Hyades stars, perhaps for some reason connected with their higher metallicity, create active regions with relatively more spots, although it does seem somewhat contrived to suggest that two groups of stars that closely resemble one another in every measured aspect of stellar activity nevertheless systematically maintain a major difference in the configuration of their active regions. A comparison of the relative amplitude of temporal variations in photometric brightness and chromospheric emission (e.g., related changes traceable to active region evolution) for stars in the two clusters would test this possibility. Hyades stars should show relatively less change in chromospheric activity for a given amount of photometric variation, provided their Ca II H+K emission (or whatever chromospheric activity diagnostic is used in the comparison) is sufficiently unaffected by their higher metallicity. We should point out that the observations shown in Figure 1 do *not* offer useful evidence about this, since the dispersion effects present there are accounted for by sampling differences alone. A simpler alternative remains, of course: perhaps Hyades stars are not significantly more spotted than their Coma counterparts. This still leaves us with the Hyades anomaly. It would be

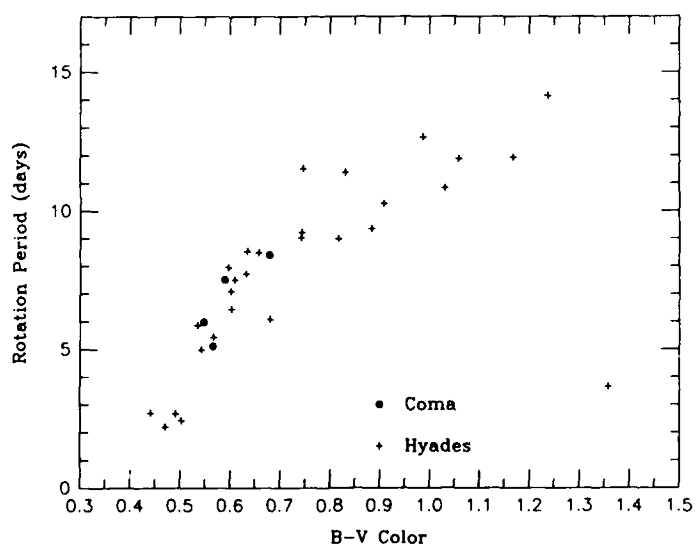

FIG. 6. The distribution of rotation period as a function of $B-V$ color for stars in the Coma and Hyades clusters. The G-type stars in the two clusters appear to have very similar rotation periods.

interesting to know how strongly (if at all) the Strömgren c_1 index responds to stellar activity; solar observations presently underway at the National Solar Observatory should answer this question. In the meantime, however, we remain inclined to believe that stellar activity does not account for the Hyades anomaly, because the activity hypothesis appears to fail the test provided by the stars of the Coma cluster.

In this discussion, we have implicitly assumed that "similar" stars show comparable activity, without specifying exactly what constitute "similar" stars. In light of present understanding of stellar activity, similar stars have the same rotational and convective zone properties. Although convective zone structure is sensitive to both stellar mass and composition, models suggest that the properties likely to influence activity, such as zone thickness and turnover time, change substantially only when $B-V$ color also changes (Rucinski and Vandenberg 1986). Accordingly, we consider two stars to be similar in the context of stellar activity if they have the same rotation and $B-V$ color, which is certainly very convenient from the empirical perspective, since these two quantities are observable. Given this assurance that we can, indeed, properly select stars for comparison, we conclude that our present results support the hypothesis that stellar age, rotation, activity, and variability are all tightly coupled among lower main-sequence stars, and demonstrate that these relationships are not greatly upset by modest differences in stellar chemical composition.

The observations reported in this paper were obtained as part of a broader study of the photometric variability of Sun-like stars which was undertaken in 1984 by Lowell Observatory, with support from the Air Force Systems Command's Geophysics Laboratory under contract F19628-84-K-0013 and the Lowell Observatory. We thank S. L. Baliunas for sharing with us unpublished data from the HK Project at Mount Wilson Observatory. The HK Project is supported by the National Science Foundation under grant AST-8616545, the Smithsonian Scholarly Studies Program, and funds from the Smithsonian Institution.

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