

Chapter 6

Activity, Age and Color

The goals for this project as previously stated are to determine:

- How does the character of photospheric activity change with age?
- How does the character of photospheric activity depend on spectral type?
- How is the photospheric activity influenced by the binary nature of stars?
- Can we determine rotation periods for any stars, based on their activity?
- Can we see any long term trends in the data analogous to the solar cycle?

The activity of stars on the binary sequence was discussed in the previous chapter, so I will not address the subject here. In this section, I will be considering the Phase II data for the nightly timescales and the combined Phase I and Phase II data for the yearly timescales, unless stated otherwise.

6.1 Activity vs. Age

The clusters observed in this project range from 1.6 to 7 Gyr. As discussed in § 1.3.1, the activity of stars should decline with age as the stars spin down.

Cluster	Age (Gyr)	% Active, Nightly	# Active, Nightly (mmag)	Median A_v , Active (mmag)	Median A_v , Main Seq.
NGC 7789	1.6	12%	16 ± 4	19.5	6.3
NGC 6819	2.5	4%	9 ± 3	12.6	7.7
M67	4.0	28%	15 ± 4	18.3	10.8
NGC 188	7.0	0%	0	...	8.2

Table 6.1: Summary of the nightly activity of the cluster stars as a function of age. The uncertainties in the numbers of active stars is the square root of the number.

Cluster	Age (Gyr)	% Active, Yearly	# Active, Yearly (mmag)	Median A_v , Active (mmag)	Median A_v , Main Seq.
NGC 7789	1.6	12%	51 ± 7	7.9	5.4
NGC 6819	2.5	19%	99 ± 10	16.5	12.4
M67	4.0	3%	2 ± 1	4.1*	5.3
NGC 188	7.0	3%	5 ± 2	8.5	6.0

Table 6.2: Summary of the annual activity of the cluster stars as a function of age. The uncertainties in the numbers of active stars is the square root of the number. * : A mean was taken for the activity index of the annual data for M67 since only two stars were active.

The percentage of active stars and the median activity index for those stars are listed for each cluster in Tables 6.1 and 6.2. The nightly and yearly timescales are both included. On the nightly timescale NGC 7789 and M67 have a relatively large fraction of active stars, but NGC 6819 and NGC 188 have a much smaller fraction of active stars. On the yearly timescale, the two younger clusters have a larger fraction of active stars than the older clusters.

NGC 6819 had only sixteen nights of observations in Phase II, spread over three months, which is the fewest number of observations of any of the clusters in Phase II. The short timescale of the observations may be affecting the search for activity on the rotational timescale: over the course of a few months, the amount of activity on the stars may not have changed much.

To test whether the short time span of the NGC 6819 observations would affect the fraction of active stars found, I removed the first seven nights of observations for NGC 7789 so that the data for NGC 7789 now had the same number of nights of observations over approximately the same number of months. When I repeated the analysis for NGC 7789, I found that only seven of 132 (5%) main sequence stars were active. This percentage of active stars is much lower than was found for the full data set, and it is very similar to the percentage of active stars in NGC 6819.

If the time span of the observations affects the fraction of active stars found, does M67 have a high fraction of active stars only because it had the most nights of observations in Phase II? I re-analyzed the data for M67, using only sixteen nights of observations spanning approximately three months. In this case, I found 12% of the 26 main sequence stars to be active. This is a lower percentage than were found to be active using the full data set (28%), but still higher than in NGC 6819 or the reduced data set for NGC 7789. Thus, the timescale of the observations does not wholly determine the percentage of active stars found on the rotational timescale.

There is another possible explanation for the lower percentage of active stars in NGC 6819, although it is less likely considering the analysis of the timescale above: NGC 6819 may be in the Vaughan-Preston gap. As discussed in § 1.3.1, the Vaughan-Preston gap falls between branches of different types of chromospheric activity; various researchers (e.g., Soon, Baliunas & Zhang (1993), Brandenburg, Saar & Turpin (1998)) have speculated that stars evolve from the active branch through the gap to the inactive branch because of a change in the magnetic dynamo. The age at which stars transit the gap is 2 - 3 Gyr (Brandenburg, Saar & Turpin 1998). The main sequence stars in NGC 6819 may be undergoing a reorganization of the magnetic dynamo and currently have low levels of activity.

The data set for NGC 7789 reduced to the same number of nights as NGC 6819 results in NGC 7789 having nearly the same percentage of active stars as NGC 6819 (5% and

4%, respectively). The equivalent-length data set for M67 has 12% active main sequence stars. Since one would expect the younger stars to be more active than the older stars in M67, perhaps both NGC 7789 and NGC 6819 are currently in the Vaughan-Preston gap. M67 has reached the inactive branch on the older side of the gap and the stars have settled into their new dynamo states, although they are more active than has commonly been thought prior to observations by Stassun et al. (2002).

The activity indices for the active stars on the nightly timescale (Table 6.1) are similar in the three clusters with active stars. The Sun’s “activity index” would be approximately the amplitude of its brightness changes due to the passage of sunspots across its disk, which is approximately 2 mmag. The active stars analyzed here have activity indices six to ten times larger. The median activity indices for the main sequence stars in each cluster are three to five times larger than the Sun’s.

The activity indices for active stars on the yearly timescale (Table 6.2 for all the clusters except NGC 6819) are noticeably smaller than the activity indices on the nightly timescale. The Sun’s activity index on this timescale would be approximately 1 mmag; the activity indices of the active stars are four to sixteen times larger. The activity indices of the main sequence population are five to twelve times larger than the Sun’s. However, as the discussion in § 1.4 of models by Unruh et al. (2000) indicated, the inclinations of the individual stars will affect the amplitudes of the long-term cycles by a factor of three or more; if these stars were all observed with their poles perpendicular to the line of sight, the activity indices could be reduced to levels much closer to the amplitude of the Sun’s solar cycle variability.

6.1.1 General Activity Level

In § 4.2.1, Figure 4.9, I plotted V versus B nightly mean magnitudes and V versus R nightly mean magnitudes for main sequence and active stars in NGC 7789. Then I plotted histograms of those distributions along the direction of the best fit line and perpendicular

to the best fit line, which can be seen in Figure 4.12. The histograms perpendicular to the best fit line represent the noise in the nightly mean magnitude data, and the histograms along the best fit line are the convolution of the actual activity amplitudes and the noise; the results are in Table 4.4. I assumed that the distributions were Gaussian and deconvolved the noise from the combination of signal and noise. I repeated this procedure for the other clusters (see Figures 4.9, 4.10, 4.13, 4.14, 4.15, and Table 4.4).

Table 6.3 lists the FWHMs for the active and main sequence stars in each of the clusters, determined from the deconvolution of the Gaussian noise from the signal and noise distribution of the ΔV vs. ΔB and ΔV vs. ΔR plots. The relationship between the FWHM and the RMS dictates that the FWHMs be approximately $\sqrt{2}$ larger than the activity indices for the main sequence stars; the activity indices in Tables 6.1 and 6.2 confirm that this is roughly the case.

The FWHMs of the active stars are all much larger than those of the main sequence stars, as would be expected. The FWHMs of the active stars in NGC 6819 are smaller than those of NGC 7789 and M67. This is reflected also in the median activity indices on the nightly timescale in Table 6.1. The decreased activity index and FWHMs for NGC 6819 are why most of the cluster stars had significance indices less than three and therefore why the cluster has a much lower percentage of active stars than NGC 7789 and M67 on the nightly timescale.

The FWHMs for the main sequence stars in the three younger clusters are all quite similar for the ΔV vs. ΔB distributions, approximately 11 mmag. The FWHMs for the ΔV vs. ΔR increase slightly with age. The FWHMs for the main sequence stars in NGC 188 are considerably smaller, especially in the ΔV vs. ΔR population. The FWHMs for the main sequence stars in the three younger clusters are also considerably larger than the error FWHMs (see Table 4.4). This implies that many, if not most, of the main sequence stars in the young clusters are active on the rotational timescale – their amplitudes are simply too small to be detected individually here. As photometric

techniques improve, many of these stars will be found to be “active” in the sense I have defined here: brightness fluctuations significantly larger than the measurement errors and correlated between different wavelengths; however, the amplitudes may be very small, even smaller than the Sun’s variability.

At what point is the amplitude of variability too small to be considered to be caused by stellar activity? At the level of micromagnitudes, stars will vary in brightness due to acoustic oscillations, although these fluctuations are on the timescale of minutes and should average out over the course of a night. Even so, as photometric precisions improve to enable astronomers to uncover fluctuations at amplitudes of less than 0.1%, virtually all late-type stars will be found to be active. As more and more stars are classified as active, the stars will need to be categorized not by whether or not they are active, but by the amplitude of the variability.

Cluster	Age (Gyr)	FWHM	FWHM	FWHM	FWHM
		ΔV vs ΔB , Active (mmag)	ΔV vs ΔB , Main Seq. (mmag)	ΔV vs ΔR , Active (mmag)	ΔV vs ΔR , Main Seq. (mmag)
NGC 7789	1.6	64.79	14.54	49.54	11.15
NGC 6819	2.5	31.68	14.19	36.41	12.64
M67	4.0	57.33	17.05	64.30	16.78
NGC 188	7.0	...	11.38	...	6.60

Table 6.3: The Gaussian FWHMs for the nightly mean differential magnitudes for the active and main sequence stars in each cluster, calculated as described in § 4.2.1.

6.1.2 Ensemble Error

The ensemble error was determined by finding the offset between σ_{rms} and σ_{mean} , as first explained in § 3.3.1. I attributed this error to both intrinsic variability in the ensemble stars and possibly unknown calibration errors. The decrease in the ensemble errors from the Phase I to the Phase II analysis demonstrates the improvement in the photometry. The decrease is especially apparent in NGC 6819, which is crowded, and NGC 188, which

was underexposed in Phase I. The decrease in the ensemble error is purely due to the reduction of photometric noise by improved observing techniques and calibration; it is unlikely that all the stars in the clusters would have been observed in less-active states during Phase II.

Cluster	Age (Gyr)	σ_{ens}	
		Phase I (mmag)	Phase II (mmag)
NGC 7789	1.6	3.0	2.5
NGC 6819	2.5	6.0	1.5
M67	4.0	2.5	2.0
NGC 188	7.0	4.0	1.5

Table 6.4: The ensemble error compared to the age of the clusters.

Since the ensemble error is largely caused by the variance of the brightness of the ensemble stars, it should be related to the activity indices; specifically, the ensemble error should be roughly $\sqrt{11}$ smaller than the activity indices (Tables 6.1 and 6.2), since the minimum number of ensemble stars was eleven. The relative sizes of the ensemble error follow the proportion of active stars: the ensemble errors for NGC 7789 and M67 are somewhat larger and those for NGC 6819 and NGC 188 are smaller.

6.1.3 α_v , A_v , and σ_{A_v} Distributions

How do the distributions of the significance index, the activity index, and the error in the activity index vary with V magnitude? First I will present the distributions for the Phase II data on the nightly timescale. Figure 6.1 shows histograms of the significance as a function of magnitude for the main sequence stars, and then divides the stars into groups brighter and fainter than the Sun would be at the distance of each cluster. (One must keep in mind that the value of the significance index is not the only criterion for determining if a star is active; the correlation coefficient between colors must also be positive and significant at a 99% level.) The percentage of active stars (using the additional correlation coefficient test) in each panel is noted. All of the clusters show peaks in the significance

index at $\alpha_v \approx 1$, which is not unexpected, since one would hope that for most of the stars, the photometric fluctuations are evenly matched by the photometric errors. There is a significant tail on each peak leading to higher values of the significance index. This peak at unity is obvious again in the panels for the stars brighter than the Sun; the distribution for NGC 7789 also shows many stars falling just under $\alpha_v \approx 1$. For stars fainter (or as faint) as the Sun, the peak is present, except for in the M67, which show a very large spread in significance indices. NGC 7789, NGC 6819, and NGC 188 show similar distributions for each population of stars. The significance indices in M67 are more dispersed.

Figure 6.2 shows the activity index as a function of magnitude for each of the clusters, with the stars again split into groups brighter and fainter than the Sun. These distributions differ from the significance index. Each cluster has a peak between 2 and 4 mmag; recall that the ensemble error for each cluster is approximately 2 mmag, so these peaks are likely due to photometric noise. However, the distributions appear bimodal. Separating the stars brighter and fainter than the Sun shows a small peak at $A_v \approx 12$ mmag for NGC 7789 and NGC 6819 for the stars fainter than the Sun. For these clusters, the stars brighter than the Sun appear to have a single peak at approximately 3 mmag. The M67 stars have a second peak at approximately 18 to 20 mmag. The stars in this peak are split between those brighter and fainter than the Sun. The distribution of activity indices in NGC 188 also has two peaks, the second one at 8 - 10 mmag. This peak is evident in both the stars brighter and fainter than the Sun, although it has shifted slightly lower for the brighter stars and somewhat higher for the fainter stars. Is the high activity index peak a real consequence of the stars' fluctuations? If the peak is caused by noisy photometry, one would expect the error distribution to mirror the peak. The distribution of the error in the activity index is shown in Figure 6.3.

The distribution of the error in the activity index is similar to that of the activity index, except that it is not as strongly bi-modal. All of the distributions show large peaks at 2 - 4 mmag, especially in the distribution for brighter stars. This is where the

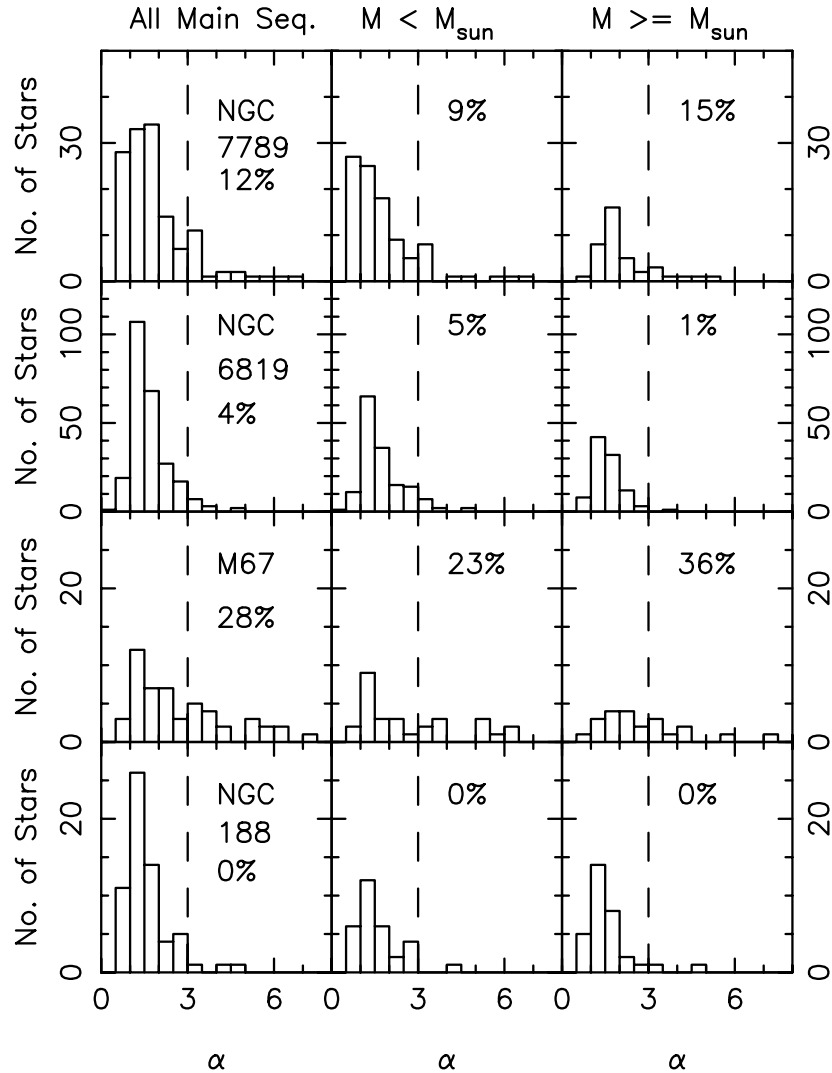


Figure 6.1: The significance indices for the main sequence stars in each cluster on the nightly timescale. The first column of panels shows all the main sequence stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun’s would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun. The percentage of active stars is noted, and the cut-off for a star to be a candidate variable at $\alpha_v = 3$ is marked. Recall that a candidate variable has $\alpha_v \geq 3$, but to be called an “active” star, it must also have a positive correlation between colors significant at the 99% level.

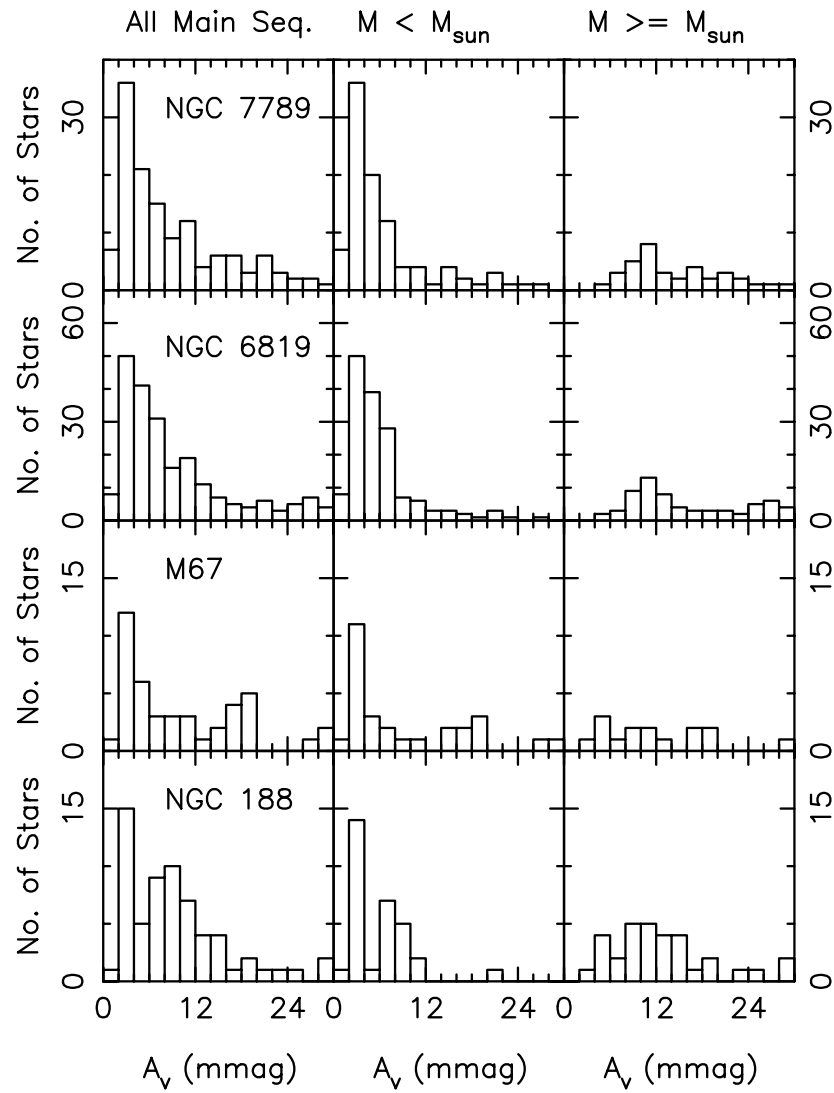


Figure 6.2: The activity indices for the main sequence stars in each cluster on the nightly timescale. The first column of panels shows all the main sequence stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

ensemble error dominates the distribution, preventing any stars from having lower errors. The distributions fall off rapidly after these peaks. Are there analogous high-error peaks for the high activity index peaks? The faint stars in NGC 7789 and NGC 6819 have a flat distribution of errors ranging from approximately 4 - 30 mmag. The faint stars in M67 have a distribution slightly higher on the low end, but tailing off to approximately 24 mmag. Only the faint stars in NGC 188 have a peak in the errors in about the same location as the peak in the activity index. It is not clear why the errors in NGC 188 are noticeably higher than those in the other clusters, since the field was sparse and the images were well-exposed.

Now I present similar plots for the active stars in the Phase II nightly data. NGC 188 had no active stars, so it is not included. Figure 6.4 shows the distributions of the significance index. In this plot, the stars obviously must have $\alpha_v \geq 3$, since that was one criterion for choosing them. However, in each of the clusters many of the stars have significance indices that fall just above this cut-off. After this bin, the distribution flattens out. The small number of stars makes it difficult to assess the behavior of the distributions. A more severe significance index criterion in the determination of active stars would have considerably decreased the number of active stars.

Figure 6.5 shows the distribution of the activity index for the active stars. This distribution appears flat for each of the clusters and each population. Figure 6.6 shows the distribution of the error in the activity index. These distributions peak at about 3 mmag for each cluster. The distribution in M67 has a tail to higher errors; it is difficult to tell if this tail exists for the younger clusters because there are so few active stars.

I present the distributions of the significance index, the activity index, and the error in the activity index for the data on the yearly timescale. Figure 6.7 shows the distribution of the significance index for main sequence stars. These stars are again split into populations brighter than and fainter than the Sun. These distributions are much flatter than those on the nightly timescale. There is no peak at $\alpha_v \approx 1$. NGC 7789 and NGC 6819 show

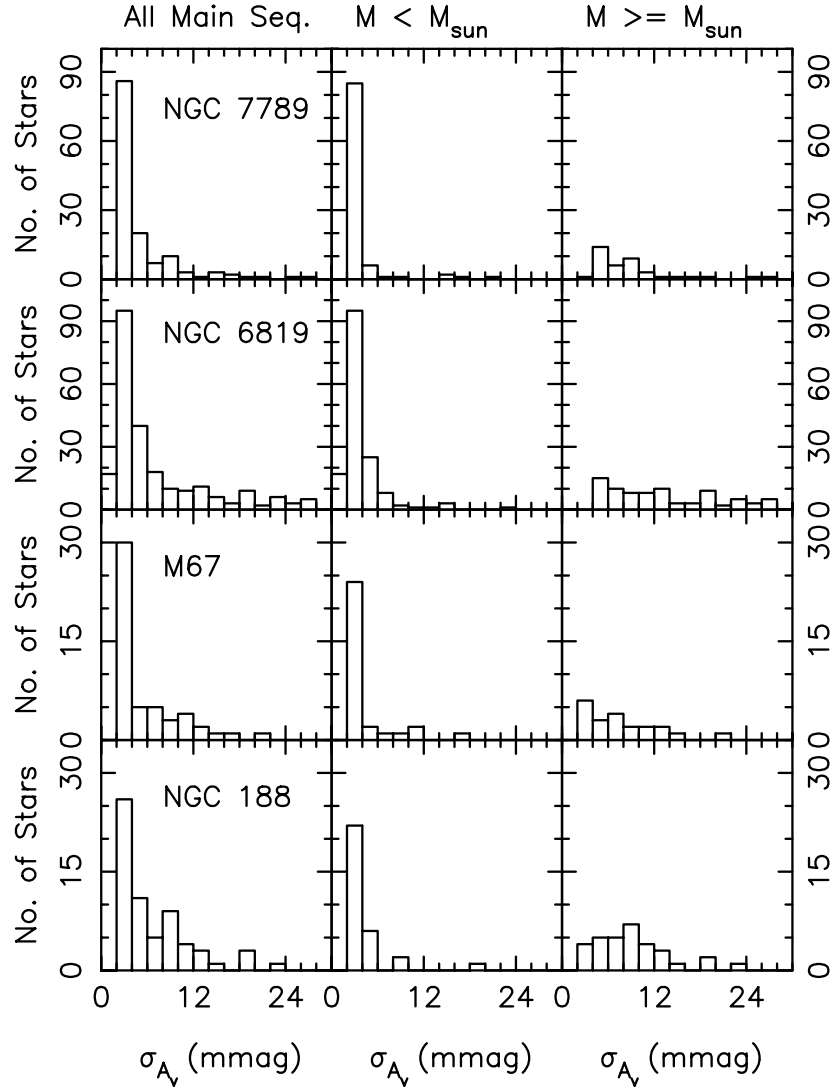


Figure 6.3: The errors in the activity index for the main sequence stars in each cluster on the nightly timescale. The first column of panels shows all the main sequence stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

nearly flat distributions that are similar for the stars brighter and fainter than the Sun; the distributions have a maximum around $\alpha_v \approx 4$. The distributions for the stars in M67 are flat; M67 has significantly fewer stars included than the other clusters. The distributions for the stars in NGC 188 show the most distinct peak. The peak in the distribution for all main sequence stars is at $\alpha_v \approx 2$; the distribution may be slightly bi-modal, since

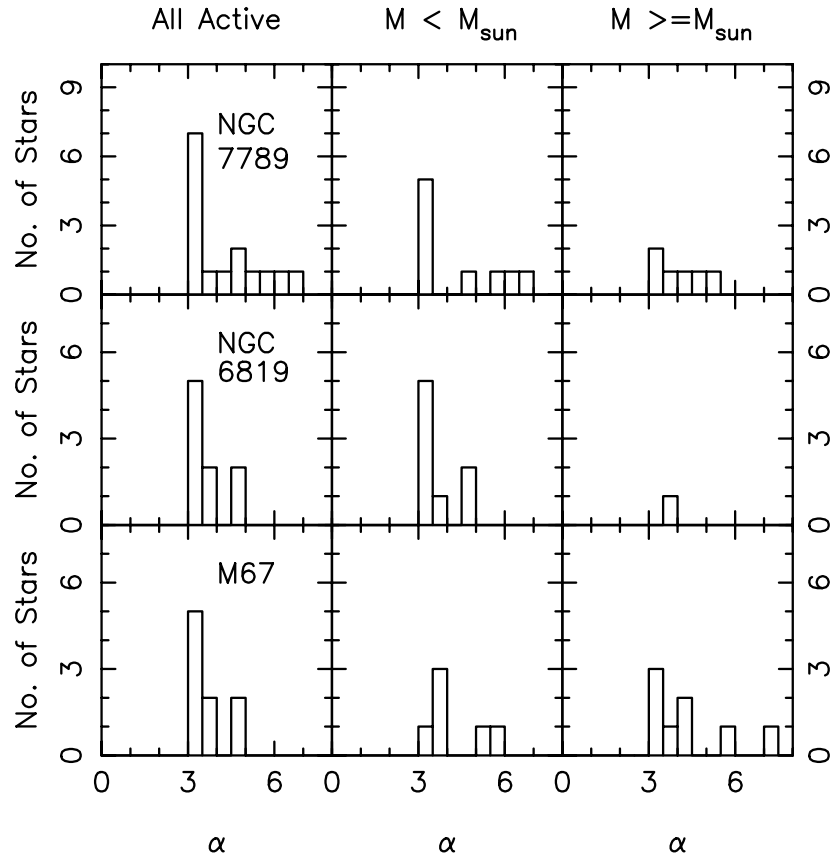


Figure 6.4: The significance indices for the active stars in each cluster on the nightly timescale. The first column of panels shows all the active stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

the distribution for the stars brighter than the Sun peaks about about three, but the distribution for the stars fainter than the Sun peaks lower, at 1.5 - 2.

The distributions of the activity index are shown in Figure 6.8. These distributions are markedly different from those of the significance index. Each of the clusters has a peak in the distribution for the plots of all main sequence stars. For NGC 7789 and M67, that peak is at approximately 2.5 mmag. For NGC 188 it is at nearly 5 mmag, and for NGC 6819, it is approximately 7 mmag. For the three younger clusters, the peaks are clearly attributable to the stars brighter than the Sun, whose distributions show the same

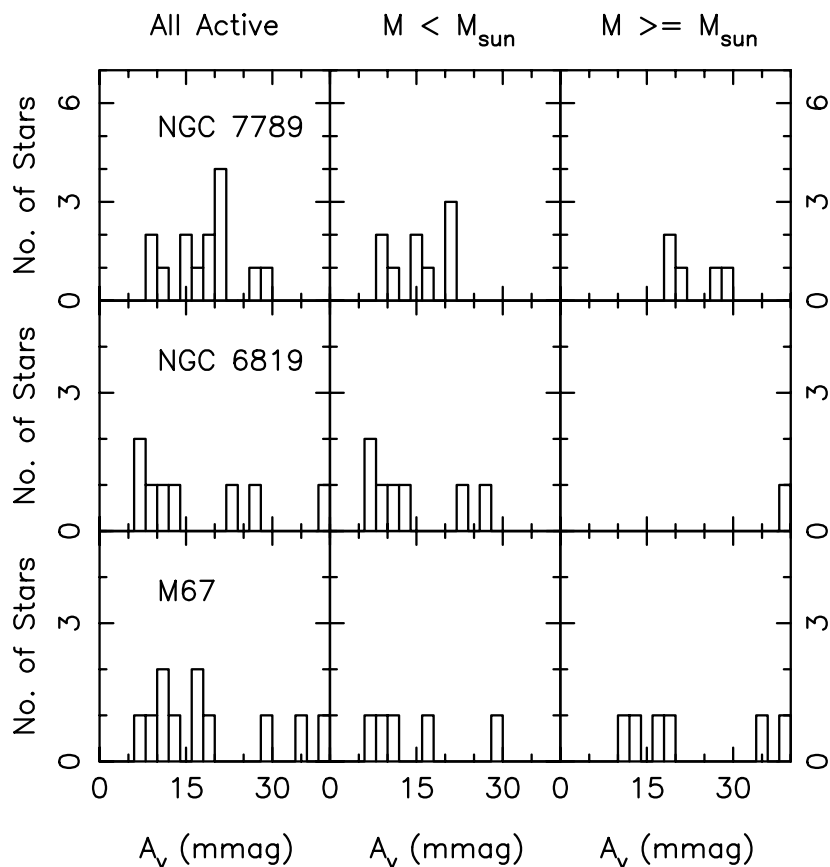


Figure 6.5: The activity indices for the active stars in each cluster on the nightly timescale. The first column of panels shows all the active stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

peaks. These clusters also have flat distributions of the activity index for the stars fainter than the Sun. However, both the bright stars and faint stars in NGC 188 show peaks in the activity index distribution; the peak is at a slightly higher value for the fainter stars than the brighter stars.

The stars fainter than the Sun in the three younger clusters (NGC 7789, NGC 6819, and M67) show very different ranges of activity indices than the stars brighter than the Sun in the same cluster. While this might be attributable to errors, this seems unlikely since the faint stars in NGC 188 do not show the same behavior. The stars brighter than the Sun in all four clusters, as well as the stars fainter than the Sun in NGC 188, exhibit

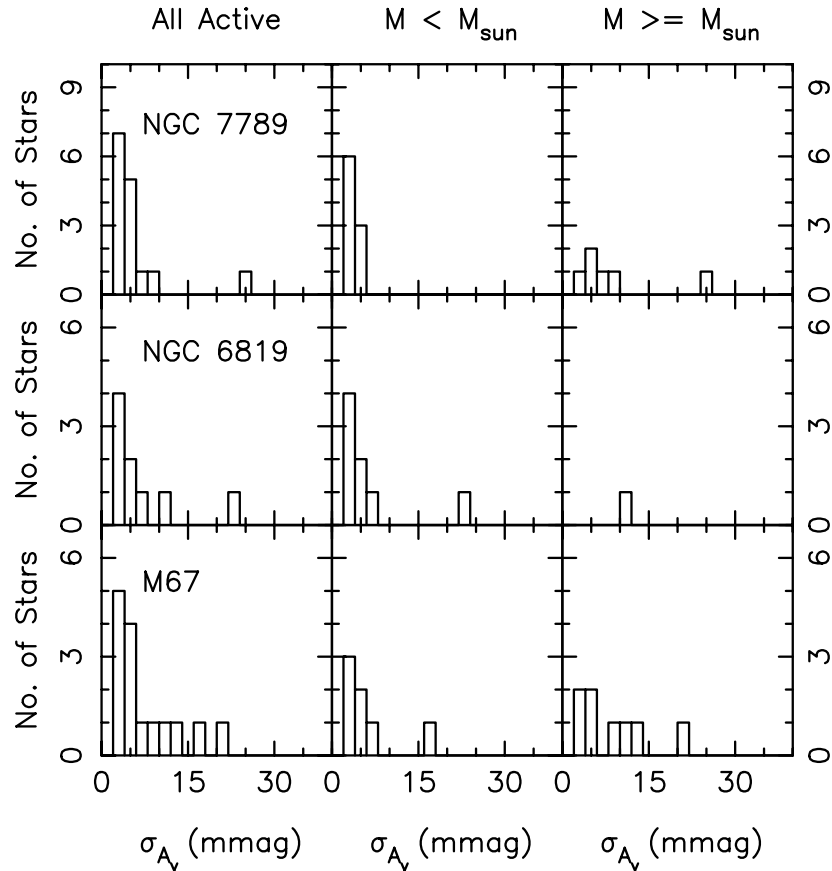


Figure 6.6: The errors in the activity index for the active stars in each cluster on the nightly timescale. The first column of panels shows all the active stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

primarily low-levels of activity on the yearly timescale. The fainter stars in the three young clusters show a much wider range of activity.

The distribution of the errors in the activity index on the yearly timescale are shown in Figure 6.9. The distributions are all quite similar. All clusters except NGC 6819 have peaks below 2.5 mmag for their entire main sequence populations as well as for the stars brighter than the Sun. The distributions of errors in NGC 6819 is similar, but is shifted to slightly higher values so that it peaks at about 4 mmag. The stars fainter than the Sun all show a broader distribution of errors, still strongly biased toward lower values.

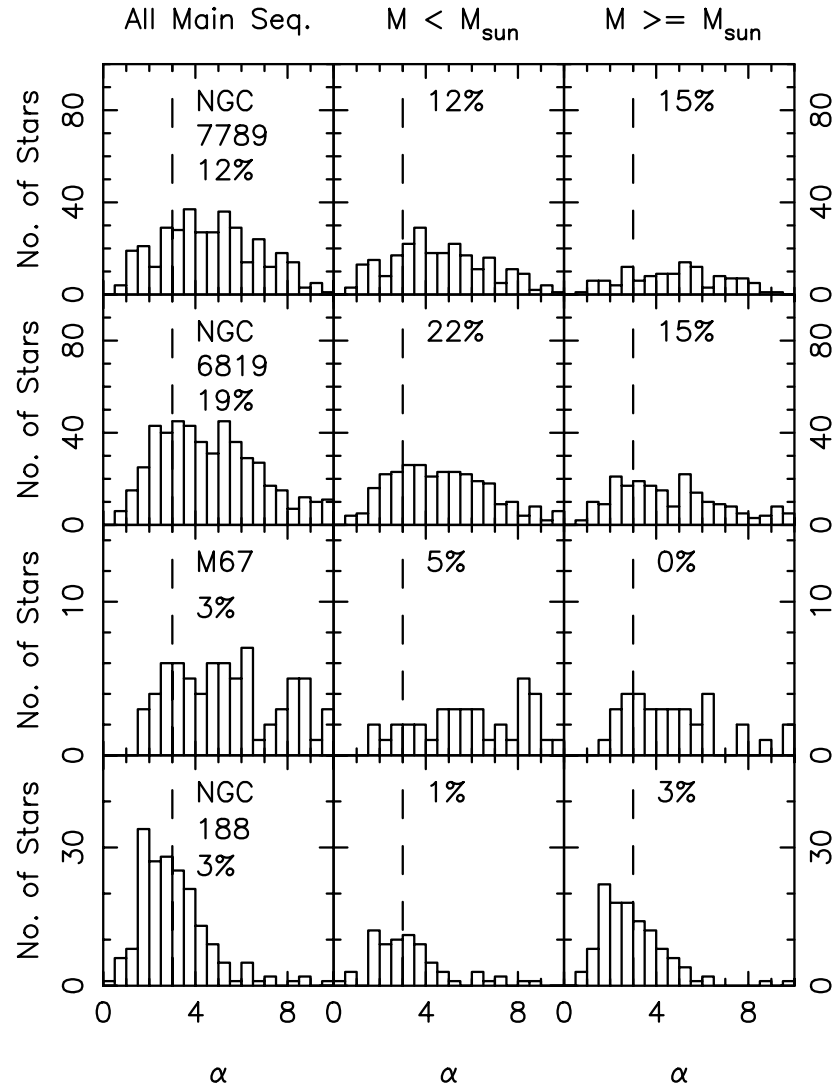


Figure 6.7: The significance indices for the main sequence stars in each cluster on the yearly timescale. The first column of panels shows all the main sequence stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun’s would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun. The percentage of active stars is noted, and the cut-off for a star to be a candidate variable at $\alpha_v = 3$ is marked. Recall that a candidate variable has $\alpha_v \geq 3$, but to be called an “active” star, it must also have a positive correlation between colors significant at the 99% level.

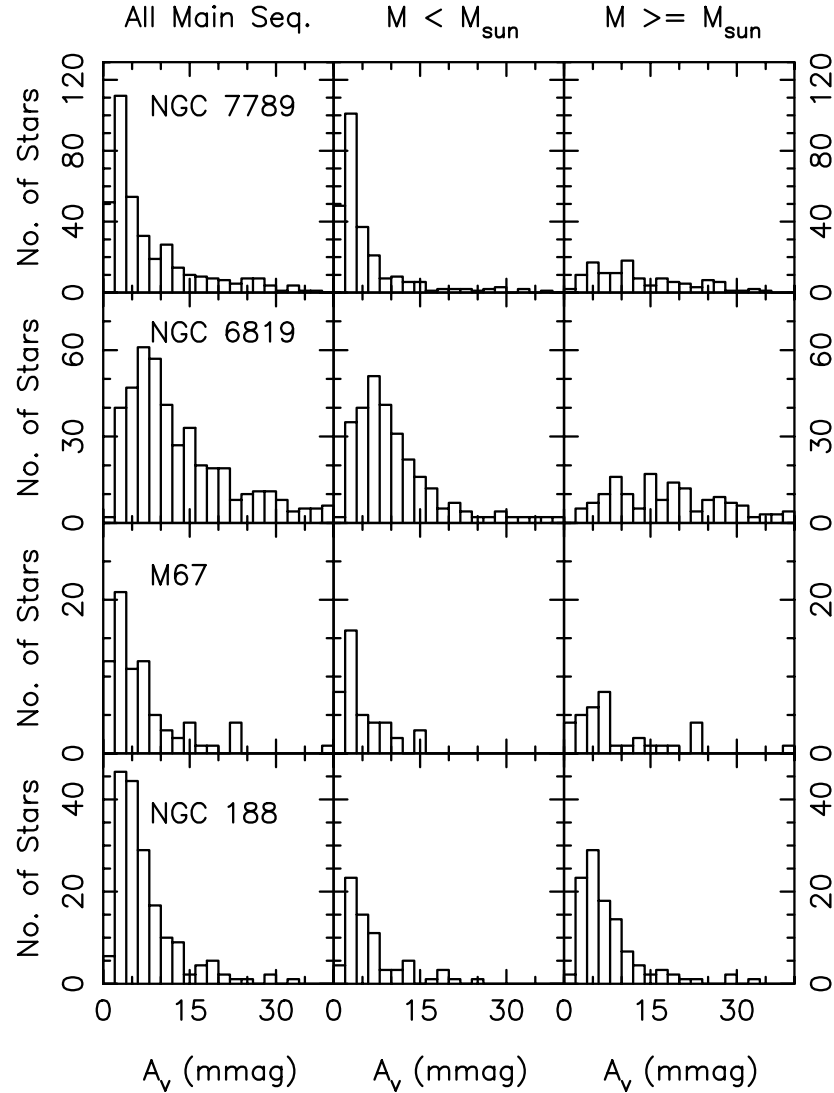


Figure 6.8: The activity indices for the main sequence stars in each cluster on the yearly timescale. The first column of panels shows all the main sequence stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

NGC 6819 has higher errors due to its crowded field.

I next present similar plots for the stars that are active on the yearly timescale. M67 only has two active stars on this timescale, so it is not included. NGC 188 has five active stars and is included in the plots. The distribution of significance indices for NGC 7789 is flat for all populations. The distribution for the main sequence stars in NGC 6819 peaks at

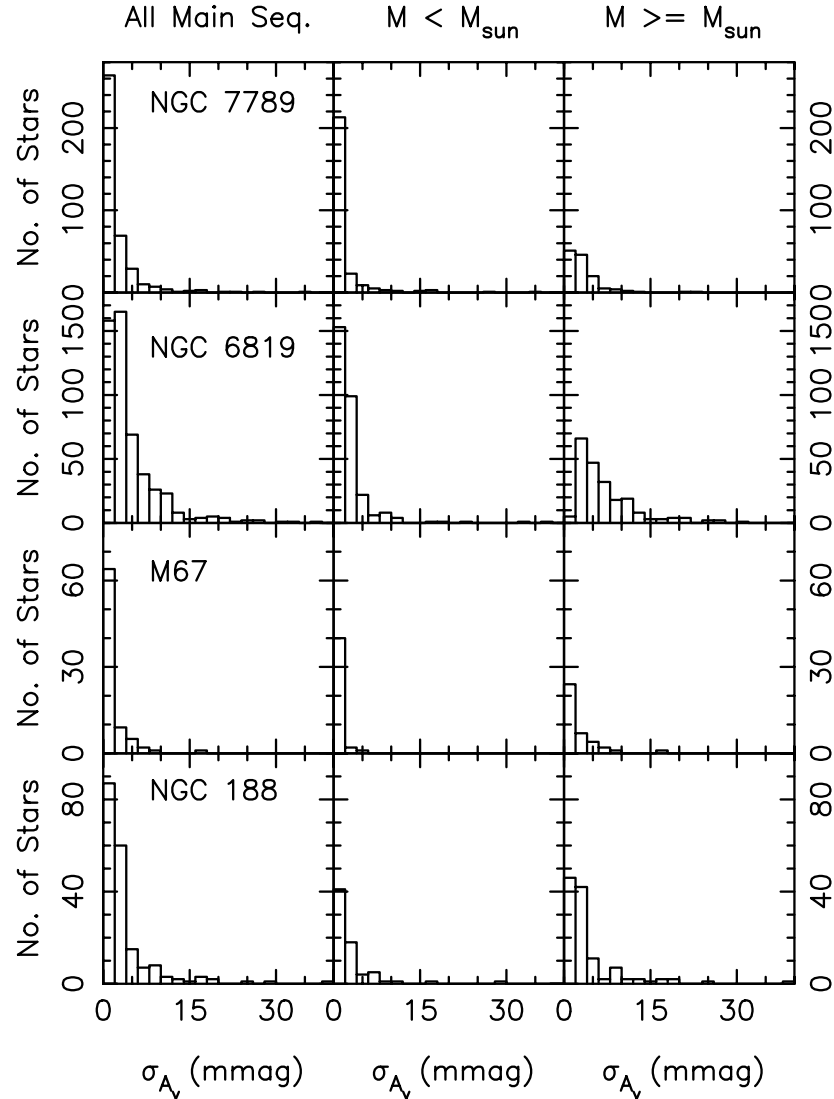


Figure 6.9: The errors in the activity index for the main sequence stars in each cluster on the yearly timescale. The first column of panels shows all the main sequence stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

approximately seven; this peak is seen again in the distribution for stars brighter than the Sun. The distribution for stars fainter than the Sun is flat. The distribution for NGC 188 is too sparse to comment upon, except to note that one star with a high significance index falls off the plot.

Figure 6.11 shows the distribution of activity indices for the active stars in these three

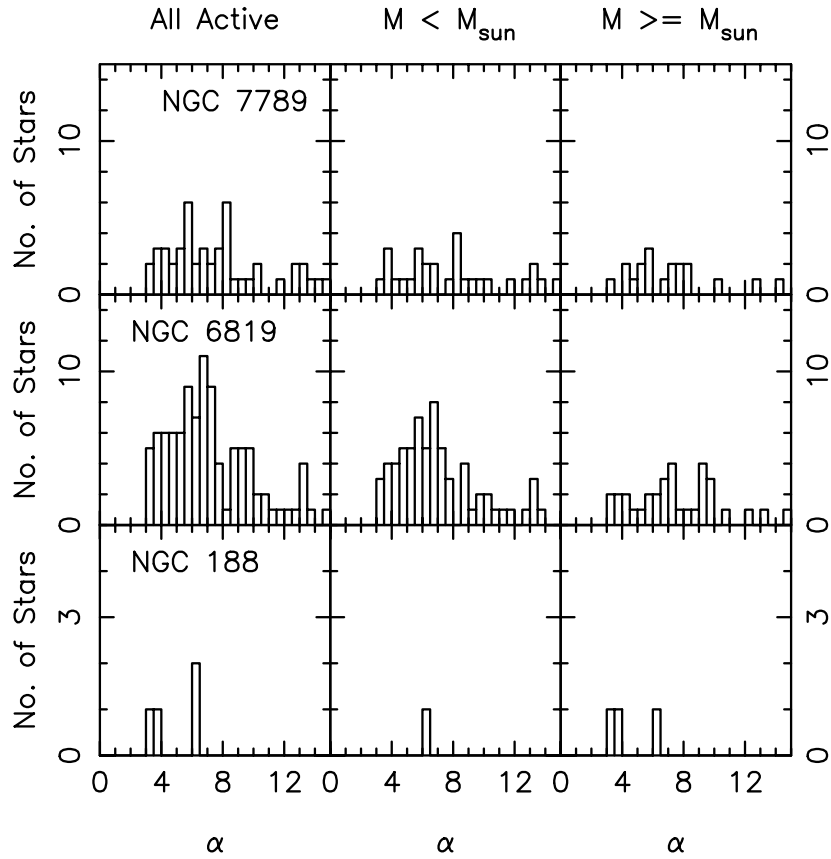


Figure 6.10: The significance indices for the active stars in each cluster on the yearly timescale. The first column of panels shows all the main sequence stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

clusters. The bright stars in NGC 7789 and NGC 6819 have a distinct peak, at about 3 mmag for NGC 7789 and nearly 10 mmag for NGC 6819. The bright stars, then, create the peak in the distribution for all main sequence stars. The faint stars in NGC 7789 and NGC 6819 have flat distributions. These stars are the stars with large activity indices in Figure 6.8 that passed our second criterion of having well-correlated brightness changes in other colors.

Finally, Figure 6.12 shows the distribution of the errors of the activity index. The distributions for the bright stars in NGC 7789 and NGC 6819 peak at 2.5 mmag and

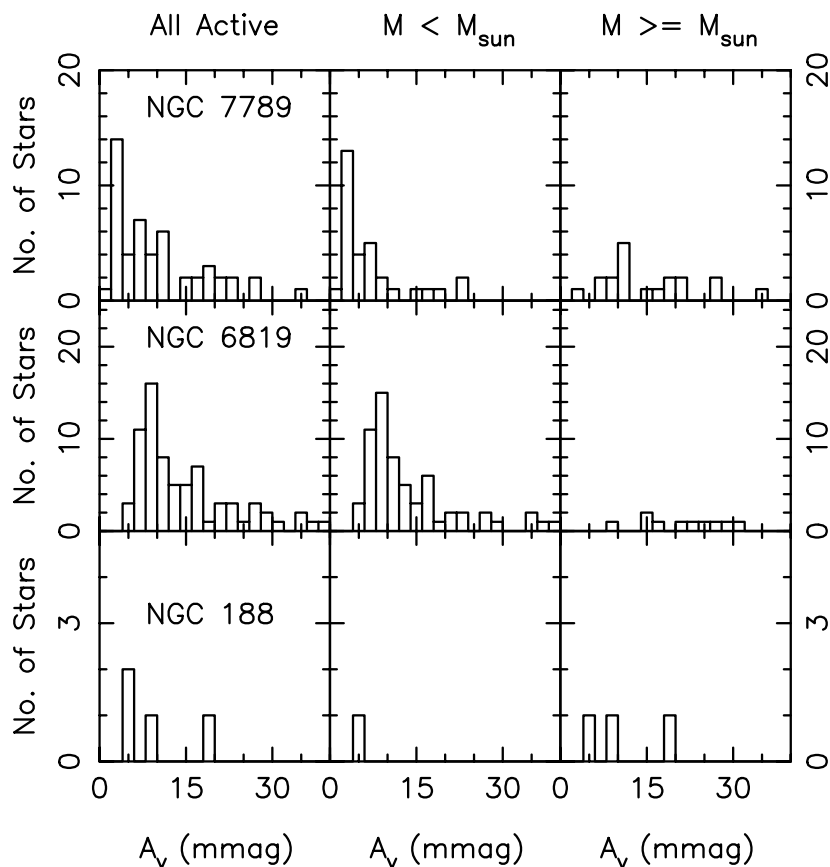


Figure 6.11: The activity indices for the active stars in each cluster on the yearly timescale. The first column of panels shows all the main sequence stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

below. The faint stars have a flatter distribution, which tails off toward higher values for NGC 6819. All of the active stars in NGC 188 have errors below 5 mmag.

I have presented the distributions of the significance index, the activity index, and the error in the activity index for the main sequence and active stars on both the nightly and yearly timescales. On both timescales, the stars fainter than the Sun in NGC 7789, NGC 6819, and possibly M67, show a much larger range of activity index with a much higher average value. The faint stars in NGC 188 on the nightly timescale show similar behavior; however, their errors are also much higher than those in the younger clusters, which seems to cancel the effect. The faint stars in NGC 188 on the yearly timescale do

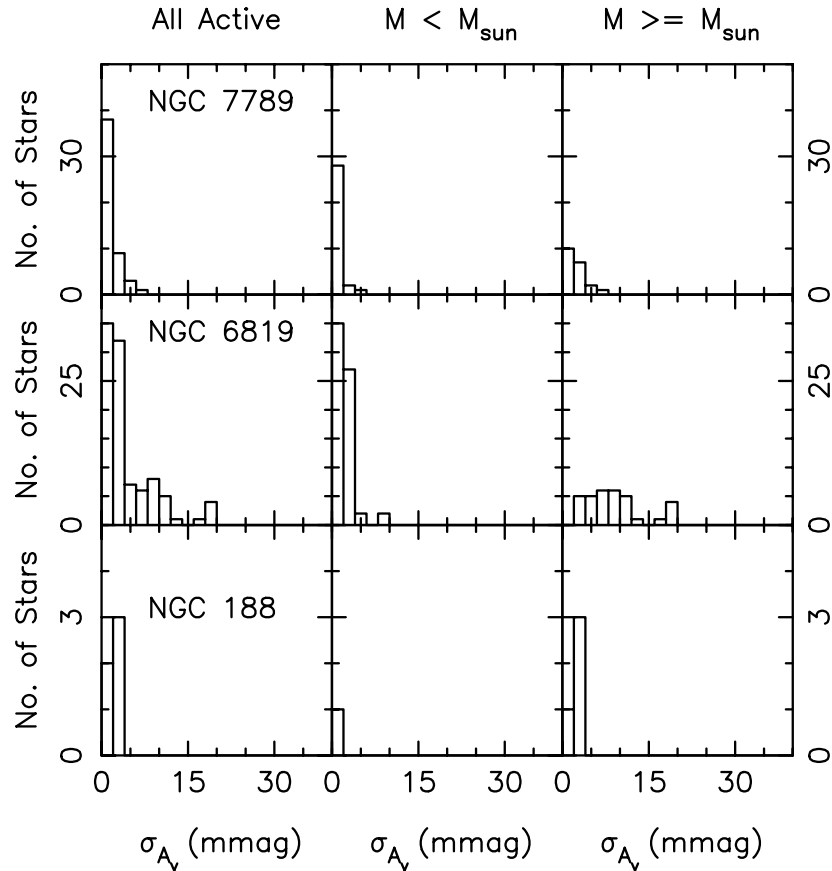


Figure 6.12: The error in the activity indices for the active stars in each cluster on the yearly timescale. The first column of panels shows all the main sequence stars in each cluster. The second column shows the stars with magnitudes brighter than the Sun's would be at that distance. The last column of panels shows the stars that would be as bright or fainter than the Sun.

not show the wider range of behavior.

In each of the analyses presented thus far, the most distinctive result is that NGC 188 is much less active than the other clusters. It lacks active stars on the nightly timescale. The FWHMs of the distributions of the nightly mean differential magnitudes in each color are much smaller for NGC 188. The histograms of the distributions of the significance indices, activity indices, and the errors all indicate that NGC 188 is much less active. The three younger clusters have comparable levels of activity, given the differences in the time span of the Phase II observations; the level of activity does not appear to decline with

age in these clusters. In particular, the stars in M67 seem more active than those in the younger clusters on the nightly timescale, but less active on the yearly timescale.

6.2 Activity vs. Color

6.2.1 Correlation Between Activity Indices in Different Colors

One of my criteria for selecting active stars was that the variability in different colors should be correlated. However, I did not require that the fluctuations have the same relative amplitude, only that the star increased or decreased in brightness through each filter simultaneously. Now I look at the activity indices calculated for the data through each filter to see if there are any correlations. The activity index was only calculated for a star for a specific color if the star had at least five nights of observations through that filter. Figures 6.13 and 6.14 show the A_v plotted versus A_b and A_r for the main sequence stars and for the active stars, respectively.

The figures show that the activity indices are indeed correlated between the colors, for both the main sequence stars and the active stars. The correlation is obvious even at very low values of the activity index, especially for the active stars. Lines were fit to the data using least-squares fitting, and the slopes and χ^2_ν for each fit are listed in Table 6.5. The high χ^2_ν indicates that the fits are not highly significant. For NGC 7789 and M67, the V-B slopes are much larger than the V-R slopes, for both the active and main sequence stars. For NGC 6819 and NGC 188, the slopes are less disparate between the colors. It should be noted, however, that the activity indices for each color could be correlated if random, unrelated fluctuations occurred in each color on any of the nights used in the analysis. These figures therefore only serve as confirmation of the expected correlation.

For the active stars, the V-B slopes are greater than unity, as I showed would be expected due to stellar activity consisting of starspots or faculae in § 1.4. Similar behavior was noted in Strömgren photometry of Mt. Wilson HK Project field stars (Lockwood, Skiff & Radick 1997). Also, the slopes for V-B are much larger than the V-R slopes for the three

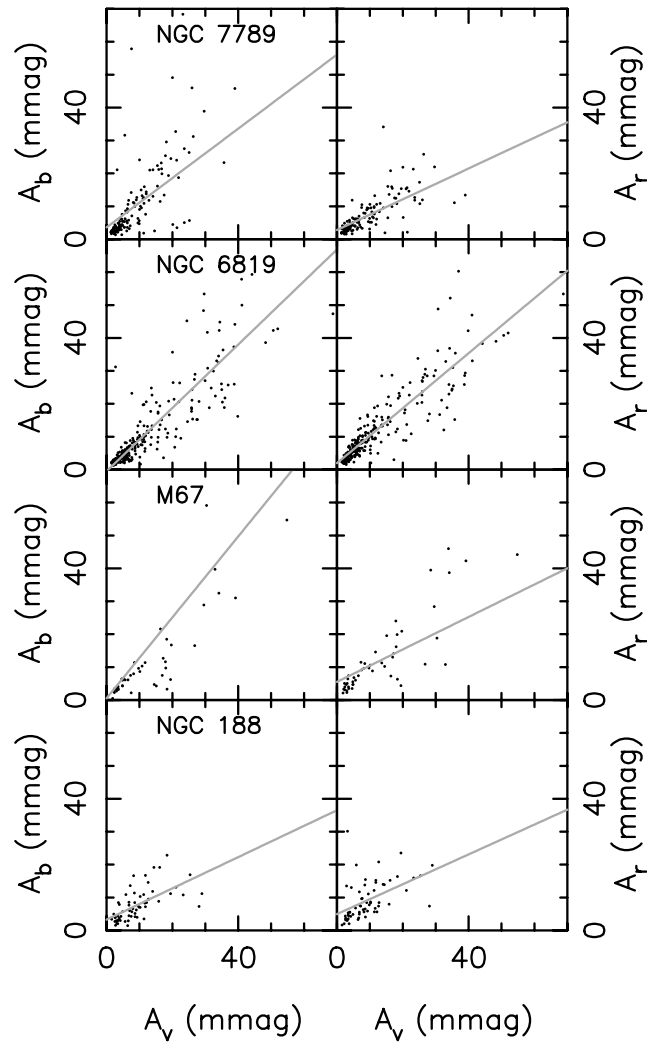


Figure 6.13: A_v vs A_b and A_v vs A_r for the main sequence stars in each cluster on the nightly timescale. The slopes for the fitted lines can be found in Table 6.5.

younger clusters. The V-R slopes are less than unity for the active stars in NGC 7789 and M67, but greater than one for NGC 6819, although this is likely due to one star with large activity indices.

I have examined the correlation between the activity indices of different colors for the annual data as well. The activity index was only calculated for the data through a specific filter if there were at least five seasons of observations through the filter. This severely limited the data. NGC 7789 and NGC 6819 had only sufficient B and V data for the

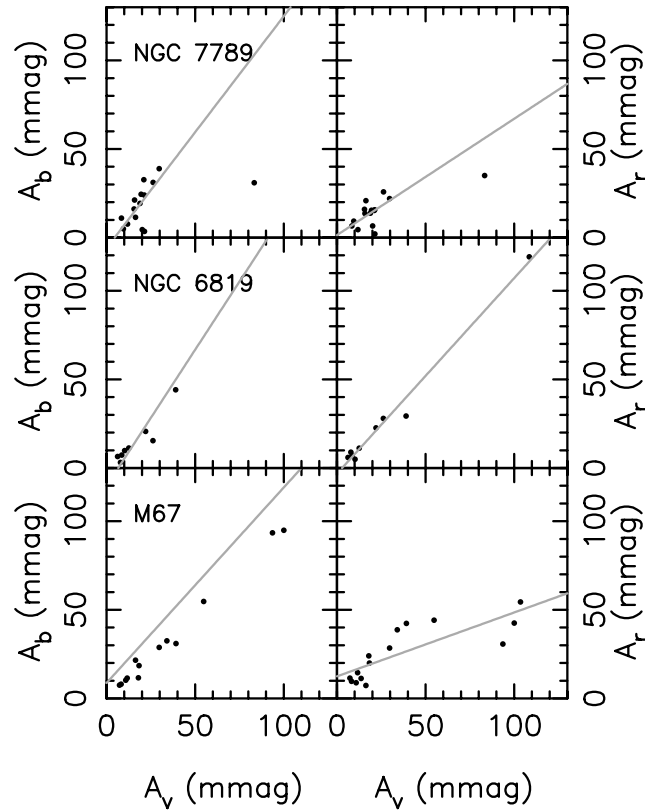


Figure 6.14: A_v vs A_b and A_v vs A_r for the active stars in each cluster on the nightly timescale. The slopes for the fitted lines can be found in Table 6.5.

analysis. M67 had only sufficient V and R data. NGC 188 had sufficient B, V, and R data. The activity indices are plotted in Figures 6.15 and 6.16 for the main sequence stars and the active stars, respectively. The lines were fit by the least squares method and the slopes and other fit results can be found in Table 6.6. As with the nightly data, the fits are not very significant. The slope for NGC 7789 is obviously lowered by the inclusion of a few outlying points.

The correlation between activity indices of different colors is again obvious in the main sequence data, but there is more scatter than in the nightly data, especially among the NGC 188 stars. It is not clear whether the larger scatter is because of the real consequences of the long-term variability in the stars or from the inclusion of the noisier Phase I data.

Cluster	Age (Gyr)	Plot	Slope	χ^2_ν	# Points
NGC 7789	1.6	A_v vs A_b , Main Seq.	0.75 ± 0.08	87	136
		A_v vs A_r , Main Seq.	0.47 ± 0.03	14	136
		A_v vs A_b , Active	1.31 ± 0.40	75	14 (15)
		A_v vs A_r , Active	0.66 ± 0.28	35	14 (15)
NGC 6819	2.5	A_v vs A_b , Main Seq.	0.96 ± 0.03	58	249
		A_v vs A_r , Main Seq.	0.84 ± 0.03	49	249
		A_v vs A_b , Active	1.54 ± 0.08	54	9
		A_v vs A_r , Active	1.10 ± 0.05	22	9
M67	4.0	A_v vs A_b , Main Seq.	1.23 ± 0.13	560	53
		A_v vs A_r , Main Seq.	0.49 ± 0.04	63	53
		A_v vs A_b , Active	1.10 ± 0.31	1600	15
		A_v vs A_r , Active	0.36 ± 0.07	92	15
NGC 188	7.0	A_v vs A_b , Main Seq.	0.47 ± 0.08	15	62
		A_v vs A_r , Main Seq.	0.45 ± 0.10	27	62

Table 6.5: Results of the line fits to the data in Figures 6.13 and 6.14 for all clusters on the nightly timescale. The lines were fit using the least squares method. The last column is the number of data points plotted in each panel of the figure. The outlying point at $A_v \approx 80$ mmag for the NGC 7789 active stars was not included in the fit for the active stars.

The active stars in NGC 7789 and NGC 6819 show a very strong correlation. Since only five stars are active in NGC 188 it is not clear if the correlation is significant; this is confirmation of the lack of activity in this cluster.

The B-V slopes for stars in NGC 7789 and NGC 6819 are again equal to or greater than unity for both the main sequence and active stars. However, the B-V slopes for stars in NGC 188 are less than one. The V-R slope for stars in M67 is much less than unity for both the main sequence and active stars. A line was not fit to the active stars in NGC 188 since only five stars were active.

6.2.2 Distribution of α_v , A_v , and σ_{A_v} by Spectral Type

As discussed in the Introduction, the amplitude of stellar activity should increase with later spectral types and decrease with age. The thicker convection zones of later type stars provide a stronger magnetic field, which in turn amplifies the production of active

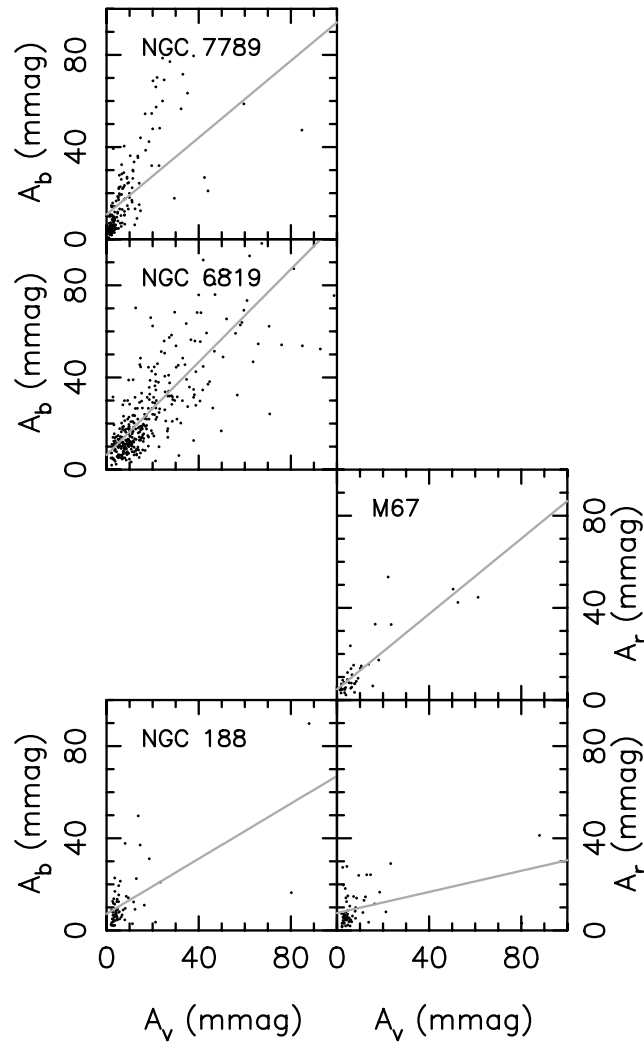


Figure 6.15: A_v vs A_b and A_v vs A_r for the main sequence stars in each cluster on the yearly timescale. The slopes for the fitted lines can be found in Table 6.6. The activity index was only calculated for a color if the star has at least three seasons of observations through that filter. NGC 7789 and NGC 6819 only have sufficient B and V data. M67 only has sufficient V and R data.

regions. However, as stars age, they spin down gradually, which decreases the vigor of the magnetic dynamo. Can these effects be seen in the clusters studied here? Using the reddening for each cluster (Table 2.1), I have split the active stars in each cluster into spectral types.

The distribution of active stars on the rotational (nightly) timescale can be seen in

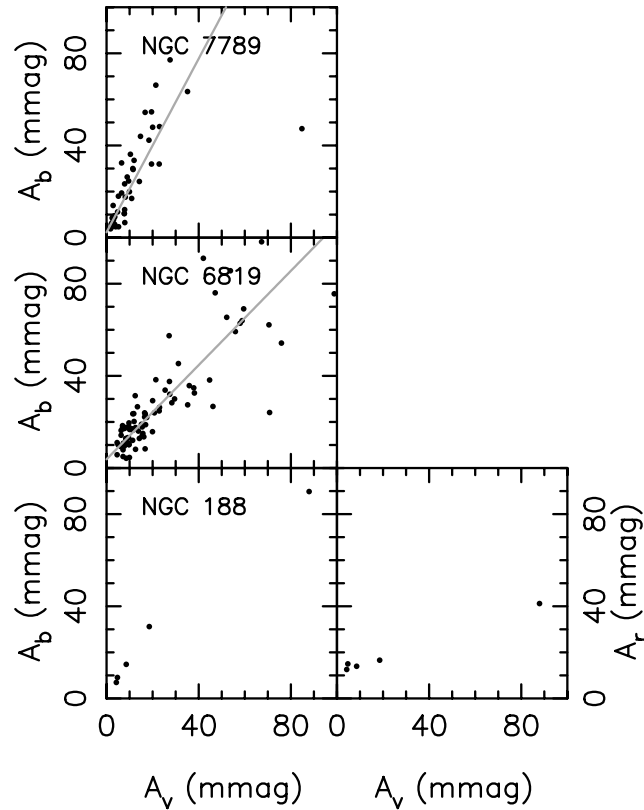


Figure 6.16: A_v vs A_b and A_v vs A_r for the active stars in each cluster on the yearly timescale. The slopes for the fitted lines can be found in Table 6.6. The activity index was only calculated for a color if the star has at least three seasons of observations through that filter. NGC 7789 and NGC 6819 only have sufficient B and V data. M67 only had one active star with sufficient V and R data, so it was not plotted.

Figure 6.17. NGC 188 has no active stars at this timescale, so it is not included. Activity due to rotation is found over a wide range of spectral types for each cluster. Late-G and K stars in NGC 7789 do not show rotational activity, even though they were observed. Few stars in NGC 6819 are rotationally active, and those few are primarily late-F. As mentioned previously, the observations of NGC 6819 were spread over only three months, which could have artificially altered the level of activity seen; the stars may not have had enough time to change their activity states significantly. M67 has a high fraction of active stars, but far fewer stars were observed in the cluster, so this may be an effect of small

Cluster	Age (Gyr)	Plot	Slope	χ^2_ν	# Points
NGC 7789	1.6	A_v vs A_b , Main Seq.	1.01 ± 0.03	590	170
		A_v vs A_b , Active	0.95 ± 0.16	210	48
NGC 6819	2.5	A_v vs A_b , Main Seq.	0.83 ± 0.08	100	361
		A_v vs A_b , Active	0.98 ± 0.04	250	97
M67	4.0	A_v vs A_r , Main Seq.	0.82 ± 0.08	52	40
NGC 188	7.0	A_v vs A_b , Main Seq.	0.23 ± 0.07	57	61
		A_v vs A_r , Main Seq.	0.60 ± 0.09	110	61

Table 6.6: Results of the line fits to the data in Figure 6.15 for all clusters on the yearly timescale. The lines were fit using the least squares method, which yields the slope and the χ^2_ν of the fit. The last column is the number of data points plotted in each panel of the figure. The activity index was only calculated for the filters through which a star had at least five seasons of observations.

number statistics.

The late-F bin has relatively high fractions of active stars for each of the clusters; observations of other star populations have noted the on-set of variability at this spectral type (e.g., Lockwood, Skiff & Radick (1997), Radick, Skiff & Lockwood (1990), Radick et al. (1987)). More interestingly, a relatively large fraction of active A and early-F type stars were seen in NGC 7789 and a small number of active early-F type stars in NGC 6819. Since stars of these types have little to no convective layer, they are not expected to show variability due to stellar activity phenomenon. However, Stassun et al. (2002) observed variability in stars of these spectral types in M67, at a level of 16 mmag. The A and early-F stars observed in the clusters are at the main sequence turn-off. Stars at the turn-off are undergoing structural changes that could have some photometric consequences.

Figure 6.18 shows the distributions of activity indices and errors in the activity index by spectral type. The unfilled bars are the mean activity indices in each spectral type bin, and the cross-hatched bars are the mean errors in the activity index. The left panels show all of the main sequence stars. The right panels show all the active stars. For the main sequence stars the activity index generally increases with spectral type as would be expected. The errors in the activity index also increase with spectral type. For the

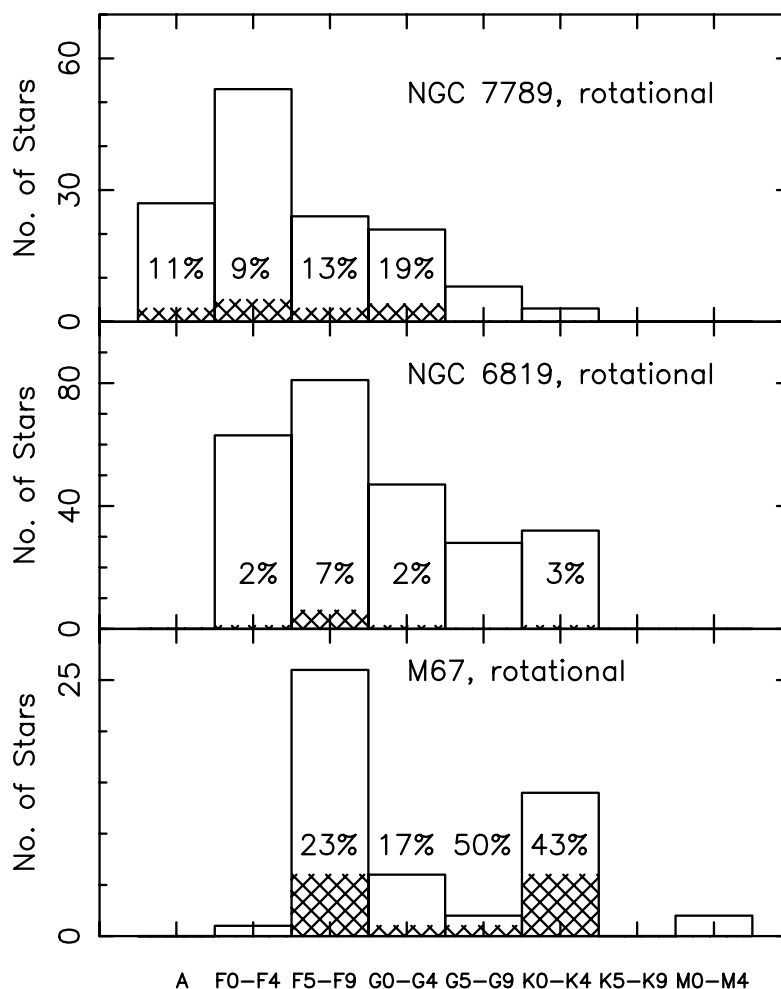


Figure 6.17: Distribution of active stars by spectral type in all clusters on the nightly timescale. The unfilled bars are the number of stars observed falling in the indicated spectral type; the cross-hatched bars are the number of active stars of that type. The percentage of active stars is noted above each bin.

active stars, the activity index is roughly flat across the spectral types. The errors are significantly larger for the main sequence stars than the active stars.

The A and early F-type active stars have activity indices of 10 - 15 mmag, which is surprisingly high considering the fact that these stars are usually considered non-variable. The main sequence A and early F stars have activity indices of about 8 mmag. Nearby field stars of these types have been found to be constant at the level of a few millimagnitudes (Lockwood, Skiff & Radick 1997), well below the level of the activity indices here.

Although Stassun et al. (2002) found variability in stars of these spectral types in M67, those observations only had a time base sufficient to analyze the rotational timescale.

The mean activity index for the early G active stars decreases from approximately 25 mmag in NGC 7789 and NGC 6819 to about 12 mmag in M67. In the main sequence stars, the activity index is about 18 mmag in NGC 7789 and falls to about 9 mmag in NGC 188. The Sun's rotational variability is about six times smaller than the active stars in NGC 188, and about four times smaller than the main sequence stars in NGC 188.

Now I consider the distribution of activity by spectral type on the annual timescale. The distribution of the percentage of active stars on the annual timescale can be seen in Figure 6.19. NGC 7789 and NGC 6819 have active stars over the entire range of spectral types observed in the clusters. As on the rotational timescale, a relatively large fraction of A and early F stars are active in these two clusters. M67 only has two active stars, and both fall in the late F spectral type. The five active stars in NGC 188 fall in the G and K types.

Figure 6.20 shows the distributions of activity indices and errors in the activity index by spectral type for the yearly data. The unfilled bars are the mean activity indices in each spectral type bin, and the cross-hatched bars are the mean errors in the activity index. The left panels show all of the main sequence stars. The right panels show all the active stars. As in the rotational data, the activity index generally increases with spectral type. The errors also increase with spectral type, although the errors are not as large relative to the activity index as they were in the rotational data. This is partly because I did not include an ensemble error in the calculation of the error in the activity index.

The increase in the activity index is much more gradual for the main sequence stars in NGC 7789 and NGC 188 than it is for NGC 6819 and M67. The activity indices increase more rapidly with spectral type for the active stars in NGC 6819 than in NGC 7789 as well. M67 only has two active stars, which are both late F. The five active stars in NGC 188 show increasing activity indices with spectral type.

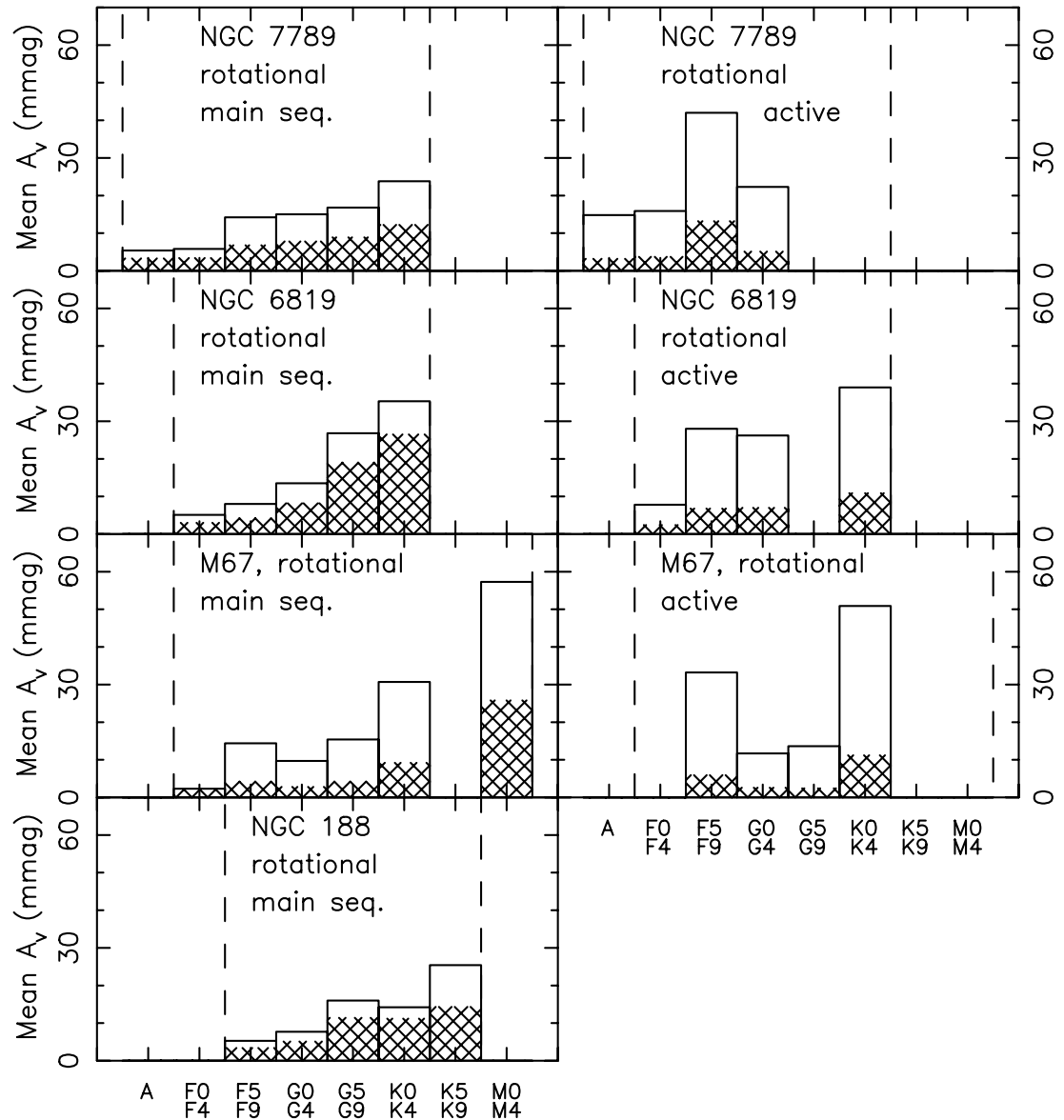


Figure 6.18: Distribution of activity indices for main sequence and active stars by spectral type in all clusters on the nightly timescale. The dashed lines indicate the range of spectral types that were observed in the program; if a bin is empty in this range, then the cluster had no active stars of that spectral type. The unfilled bars are the mean activity indices for stars of that spectral type; the filled bars are mean errors of the activity index for stars of that type.

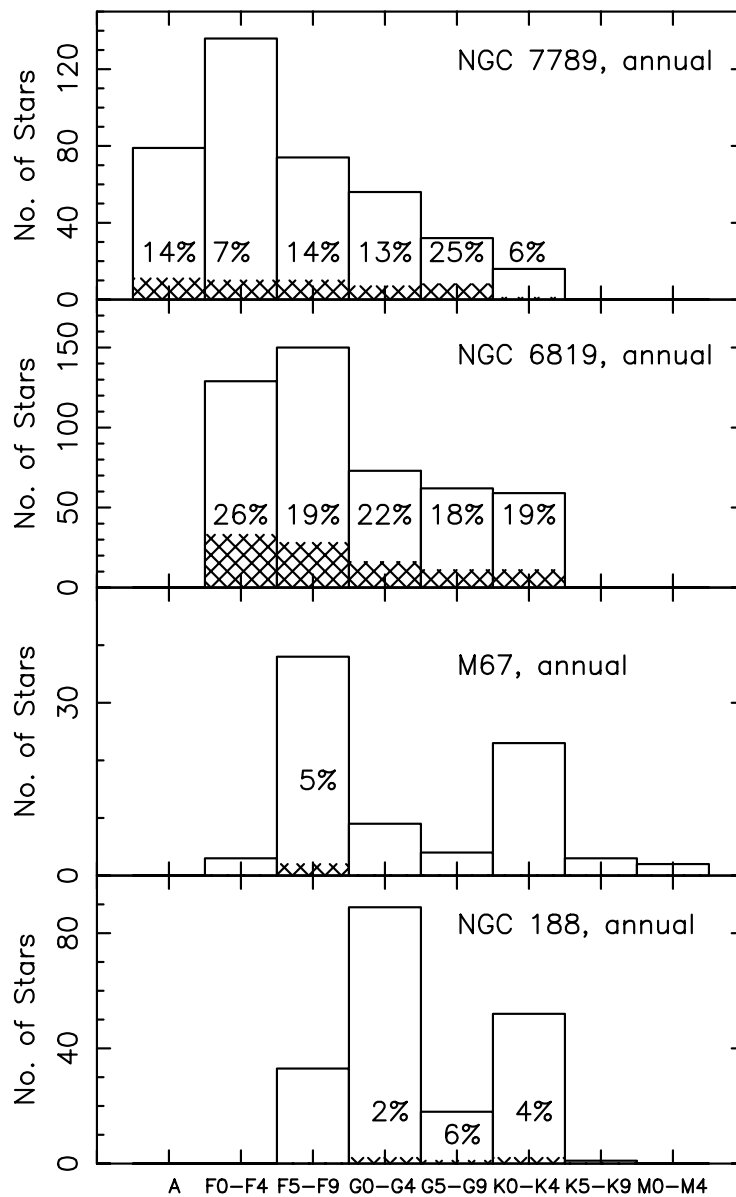


Figure 6.19: Distribution of active stars by spectral type in all clusters on the annual timescale. The unfilled bars are the number of stars observed falling in the indicated spectral type; the cross-hatched bars are the number of active stars of that type. The percentage of active stars is noted above each bin.

The A and early F-type active stars have activity indices of 4 - 8 mmag in NGC 7789 and nearly 20 mmag in NGC 6819. The activity indices of these stars on the main sequence are similar. These values of the activity index are comparable to those of the activity index for the same spectral type on the rotational timescale.

6.3 Comparison to Other Solar-Type Stars

In Chapter 1, I reviewed the amplitudes of activity measured through the V filter for other solar-type stars (Figure 1.1). Now I can add the mean activity indices for the G stars in clusters studied here. The activity indices are an RMS value of the variability; if we have sampled the full range of variability in a star, then the RMS of the fluctuations will be an underestimate of the amplitude. The sparseness of the data leave me with little choice, however, so I have added the activity indices as amplitudes in the plot. The non-detection of rotational activity for NGC 188 was plotted using the ensemble error (1.5 mmag) as an upper limit. The non-detection of annual activity for G stars in M67 was plotted using the average error of the activity index for G stars as an upper limit. Figure 6.21 shows the resulting distribution of activity with age. The averages for the clusters studied here are marked with triangles; the error bars are the mean errors in the activity indices. The references for the other data points are listed in Tables 1.1 and 1.2. On the rotational timescale, the average activity indices for NGC 7789, NGC 6819, and M67 fit in well with the activity levels of the other stars. An upper envelope of activity that decreases with age is evident. A similar envelope is seen in the yearly data.

The addition of the mean activity indices for the clusters studied here to the annual activity plot doubles the number of measurements of long-term activity for solar-type stars older than 1 Gyr. The mean activity index for NGC 6819 is much higher than any of the others, even considering the error bars. The cause of the very high activity index is unknown.

How do these activity levels on the rotational and yearly timescales fit in with the

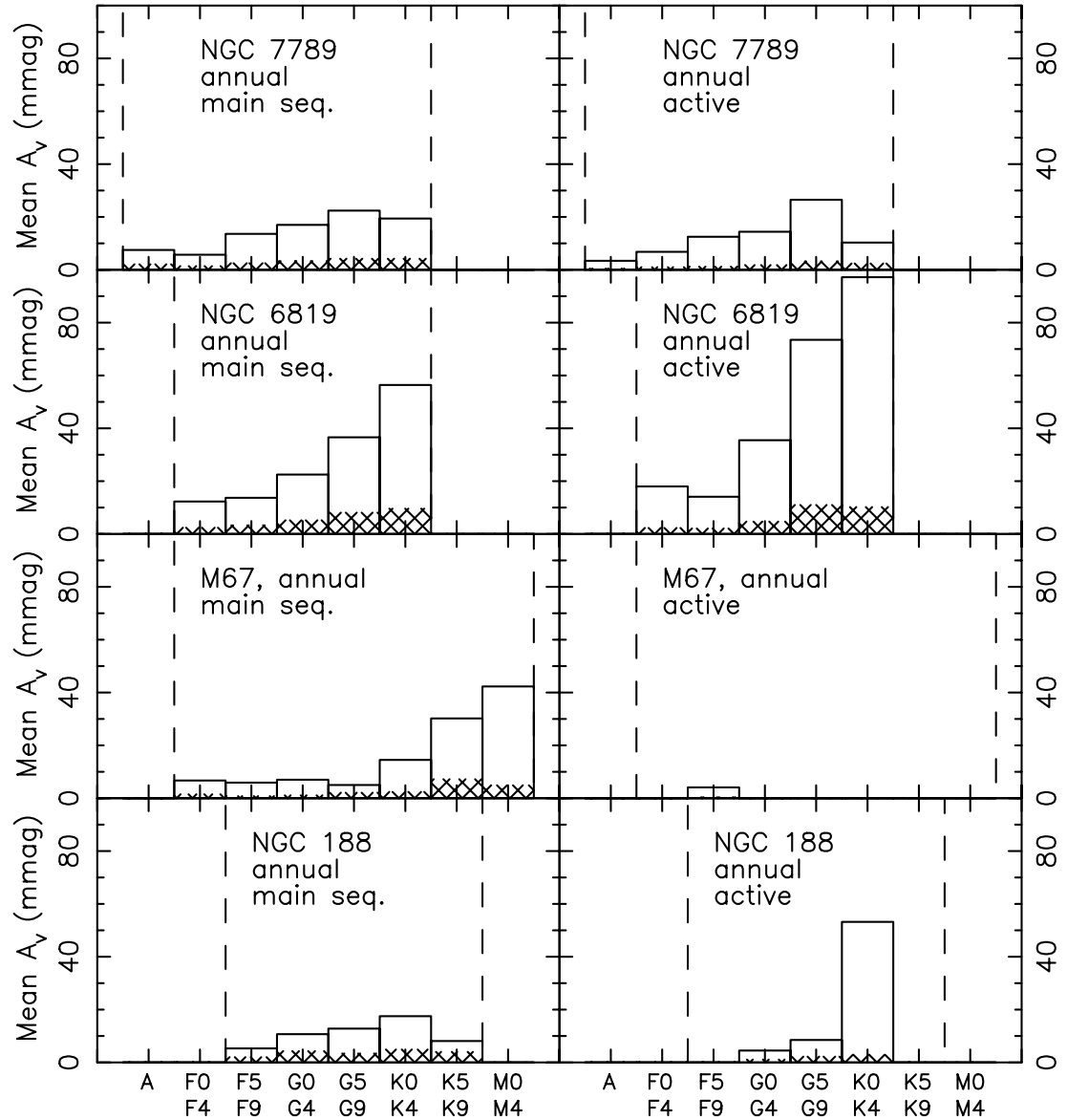


Figure 6.20: Distribution of activity indices for main sequence and active stars by spectral type in all clusters on the yearly timescale. The dashed lines indicate the range of spectral types that were observed in the program; if a bin is empty in this range, then the cluster had no active stars of that spectral type. The unfilled bars are the mean activity indices for stars of that spectral type; the filled bars are mean errors of the activity index for stars of that type.

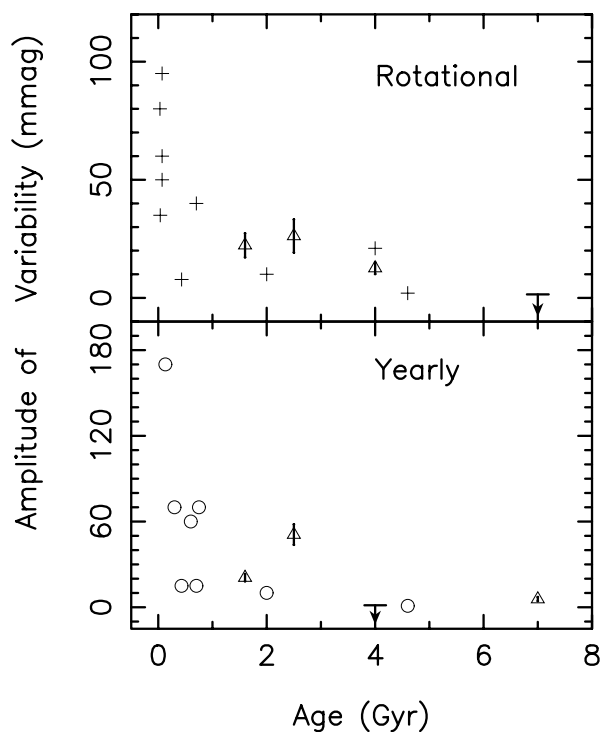


Figure 6.21: Age versus activity amplitudes on the rotational and yearly timescales for clusters studied here and other solar type stars. The clusters studied here are marked with triangles. The errorbars are the mean errors in the activity indices for the G stars. On the rotational timescale, NGC 188 is given as an upper limit of 1.5 mmag; on the yearly timescale, M67 is given as an upper limit of 1.1 mmag. The references for the other observations are listed in Tables 1.1 and 1.2.

expected relation that the activity is proportional to $t^{-1/2}$, where t is the age of the stars, as first proposed by Skumanich (1972)? This relation was determined by the rotational activity of stars; it is not clear whether it is or should be applicable to the yearly variability caused by stellar activity. I have fit a power law of the form:

$$\Delta V = bt^p, \quad (6.1)$$

where ΔV is the amplitude of the activity in millimagnitudes, t is the age of the star in years, and b and p are the quantities to be fit. In the usual procedure the logarithm is taken of the data so that a line may be fit. The results of the least square fits can be seen in the log-log plots in Figure 6.22, and the fit results are listed in Table 6.7.

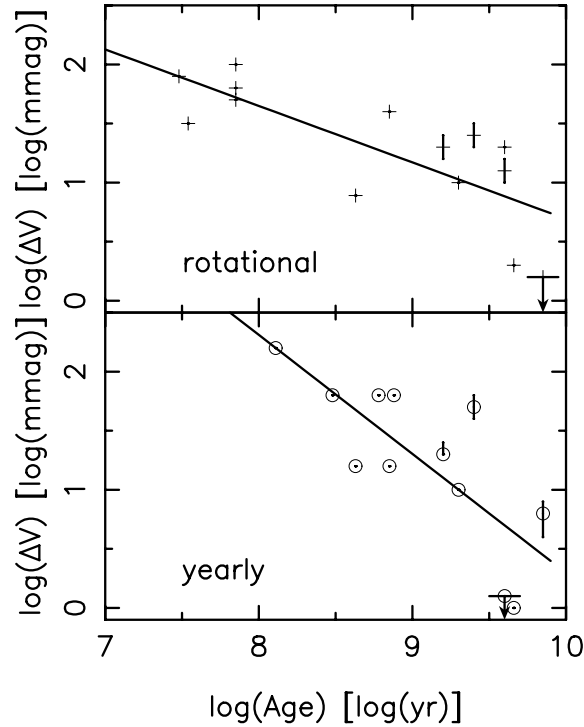


Figure 6.22: The lines are least square fits to the log of the ages of the stars versus the log of the amplitude of activity in mmags. Error bars are shown on the activity indices determined for the program clusters. NGC 188 is shown as an upper limit on the rotational timescale, and M67 is shown as an upper limit on the yearly timescale.

The fit to the rotational data has a slope of -0.40 ± 0.11 , close to the canonical value of -0.50 . The fit has a correlation coefficient of 0.73, which has greater than 99% significance. If I include the non-detection of rotational variability in NGC 188 as an amplitude of 1.5 mmag (equal to the ensemble error for NGC 188) at that age, then the slope becomes -0.48 ± 0.12 ; this fit also has greater than 99% significance. Thirty-four G stars were observed at least five nights in NGC 188 during Phase II, but none were active; the mean activity index of stars of this type was over 10 mmag, indicating that I should have been able to detect the variability if it was present. Therefore, including the non-detection is justified.

The fit to the annual data has a slope of -0.88 ± 0.26 , somewhat similar to the Skumanich relation. The correlation coefficient for the fit is 0.75, which is 99% significant.

Data Set	p	b	r	χ^2_ν	# Points	Significance
rotational	-0.40 ± 0.11	$10^{4.85 \pm 0.99}$	0.73	0.11	13	99% significant
rotational, nondetection	-0.48 ± 0.12	$10^{5.47 \pm 1.03}$	0.76	0.14	14	99% significant
annual	-0.88 ± 0.26	$10^{9.26 \pm 2.33}$	0.75	0.18	11	99% significant
annual, nondetection	-1.01 ± 0.26	$10^{10.37 \pm 2.37}$	0.77	0.21	12	99% significant

Table 6.7: Results of the least square fits to the activity amplitude versus age. The fits listed first for the rotational and annual data are shown in Figure 6.22. The second fits listed include the non-detection of rotational variability for G stars in NGC 188 and the non-detection of annual variability for G stars in M67.

Including the non-detection of variability on this timescale for M67, using the error in the activity index for the G stars (1.4 mmag), alters the slope to -1.01 ± 0.26 and the correlation coefficient to 0.77, which is significant at the 99% level. Thirteen G stars were observed in M67 and were not found to be variable on the long term timescale. Also, almost no stars of any type were found to be active, which indicates that the non-detection for the G stars is not a fluke. This power law is not as similar to the Skumanich relation, although since Skumanich’s original relation was based on measurements of chromospheric activity on the rotational timescale, it may not be applicable on the long-term timescale.

Some comments must be made about these fits. I have included data from the literature which were originally obtained using different observing techniques, equipment, and data analysis. The data points on the rotational plot and a few points on the yearly plot are averages of amplitudes of the active stars found in each population. However, the detection thresholds for each analysis are not the same, so some points may be higher because of a relatively high detection threshold so that only the most active stars were discovered. Many of the data points on the yearly plot represent observations of single stars; it is possible that these stars are not typical of other stars of the same age. Finally, I have included the Sun’s observed amplitudes in the fits, despite the fact that I would not be able to detect activity at the level of the Sun’s activity in this project.

The activity indices for the G stars on the rotational timescale mesh well with the

amplitudes for other solar-type stars in the literature. A fit to the amplitudes as a function of age including the data for the three young clusters yields a slope of -0.4 ± 0.11 , similar to the Skumanich relation. Including the non-detection of activity in NGC 188 alters the fit to match the Skumanich relation even more closely, with a slope of -0.48 ± 0.12 . The activity indices for G stars on the annual timescale doubles the number of known measurements for stars older than 1 Gyr. With the inclusion of the non-detection of activity in M67, a power law of -1.01 ± 0.26 is found to a fit of the amplitudes as a function of age, which is much steeper than the Skumanich relation.

6.4 Rotation Periods

The Phase II data were too sparse to be able to detect any rotation periods for the stars in any of the clusters. I analyzed the power spectra of the nightly mean magnitude data for the main sequence stars in the same manner as for the Phase I data (see § 3.3.3), but found no sensible periods for any of the stars. This result is not unexpected, because of the combination of the stars' expected rotation periods and the evolution of the active regions on the stars. As discussed in § 1.4, the rotation periods should range from about 12 days in NGC 7789 to over 30 days in NGC 188. Our Phase II data would generally have few data points during one rotation period, when the active regions are not likely to change significantly. However, during the time between the observing runs, perhaps four to six weeks, the active regions will probably have evolved enough to have significantly altered the lightcurves for the stars so that the phase or amplitude has changed. More closely-spaced observations are needed to determine rotation periods for these stars.

6.5 Long Term Trends

The final goal of the project was to determine if any long term trends reminiscent of the solar cycle could be seen in the data. As was seen in many of the individual lightcurves

plotted in previous chapters, a substantial minority of stars display long term trends that are well-correlated among different colors. The amplitude of the Sun's long term variability is very small, but that is apparently not true for all solar-type stars.