Cool Stars, Stellar Systems and the Sun
ASP Conference Series, Vol. 154, 1998
eds. R. A. Donahue and J. A. Bookbinder

Activity Cycles in Lower Main Sequence and Post Main Sequence Stars: The HK Project[1]

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1. Introduction

Olin Wilson became interested in stellar activity cycles in the 1930s, after having been shown by Seth Nicholson a chart of the solar cycle neatly traced by disk-integrated emission of the Ca II K (393.4 nm) emission core. That eventually led to Wilson's masterwork — the 12-year records of Ca II H (396.8 nm) and K variability, beginning in 1966, of 91 stars "on or near the lower main sequence" (Wilson 1978). Every month for 12 years Wilson climbed the stairs to the Coudé focus at the 100-inch Hooker telescope with hopes of providing theorists some "ground truth" concerning magnetic cycles in other stars.

In parallel, Eugene Parker began in the 1950s his fundamental work on kinematic solutions of the astrophysical magnetic dynamo.

The legacy of those early works has been the development of both the observations and the theory that seeks to explain them.

There are observational advances in four areas from Wilson's work that will be discussed:

1. The utility of Ca II H and K fluxes in estimating age and long-term variations in lower main sequence stars;
2. The continuation of Wilson's records in lower main sequence stars and the extension of such records to post-main sequence stars;
3. The coinciding efforts to obtain records of photometric variability associated with long-term magnetic variability;
4. The service of Ca II H and K fluxes and precise photometry in the study of lower main sequence stars around which exoplanets have been reported.

2. Magnetism by Proxy

A proxy of surface magnetism accessible to ground-based telescopes is the singly-ionized spectrum of calcium, and especially, the H and K doublet in the visible violet. On the Sun, the emission cores of the H and K lines brighten in areas with increased magnetism. Changes in magnetic activity, for example, through the

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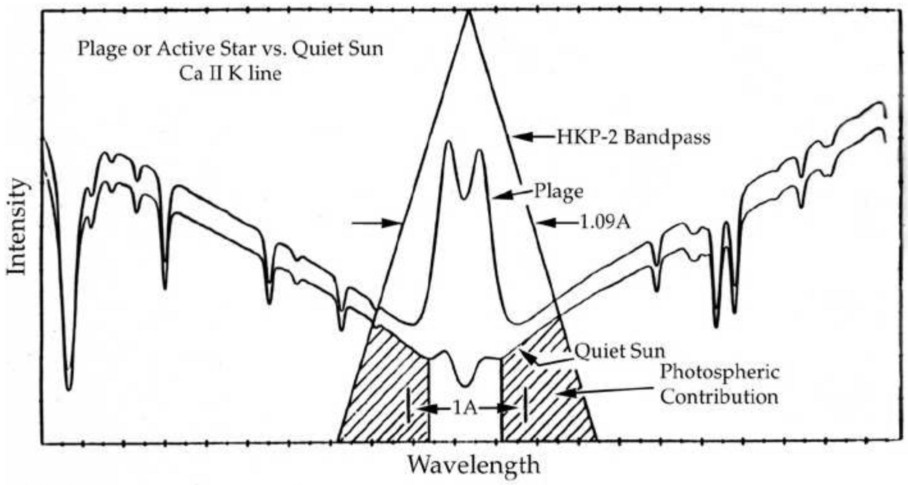


Figure 1. Schematic spectrum near the Ca II K emission core in the magnetically quiet and active Sun. The 0.1 nm HK passband is also shown (Duncan et al. 1991).

eleven-year sunspot cycle, produce relative changes in the disk-integrated fluxes of the H and K emission cores with amplitudes on the order of 20% (White and Livingston 1981).

The HK instrument is a spectrophotometer with good long-term stability; the long-term precision of its records is $\sim 1-2\%$ as judged by the least variable stars. For each measurement of the relative surface Ca II flux of a star, the fluxes in the H and K passbands (see Figure 1) and two nearby reference passbands (2 nm wide and centered at 390.1 and 400.1 nm) from the stellar phototosphere are recorded. The quantity S, is proportional to the ratio of the fluxes in the H and K emission cores to that of the nearby continuum fluxes, and is assumed to be a measure of surface magnetism, i.e., coverage and strength of surface magnetic fields. The quantity S_{II} is obtained from a wider (0.2 nm) passband in the H and K emission cores (using the same reference passbands in the continuum as in the case of S) and is used for giants, whose emission cores are wider than those of lower main-sequence stars.

The HK Project began in 1966 with Wilson's monthly measurements of lower main sequence stars at the 100-inch Hooker Telescope. In 1978, Arthur Vaughan and George Preston moved the program to the 60-inch telescope. In 1980, the HK Project expanded to nightly observations. Douglas Duncan expanded the program to include evolved stars in 1983. In 1995, the program moved back to the newly-refurbished 100-inch telescope, which now has computer-controlled pointing.

The project has measured the fluxes of over 2,200 stars and has gathered over 400,000 measurements. From 1983 to 1993, the program included 300 post-main-sequence stars. In 1991 monitoring began of over 120 "The Next Generation" (TNG) stars — sun-like stars close in mass and overall surface activity level (i.e., age) to the Sun.

A parallel effort of observations of the photometric variations of stars in the Wilson sample began in 1984 by Wes Lockwood, Richard Radick and Brian Skiff at Lowell Observatory. They obtained high-precision photometric Strömgren b and y fluxes in roughly three dozen of the Wilson stars The purpose of photometric monitoring is to understand the analog of the total solar irradiance variations that accompany the activity cycle. One by-product of such efforts is the study of the influence of solar irradiance variations on terrestrial climate change, led by Willie Soon (Soon, Posmentier, & Baliunas 1996).

In order to expand the photometric program to a much larger sample of stars, we developed the capability to do precision photometry with automatic telescopes (Henry 1995a,b). By April, 1993, we were making routine, nightly measurements of 75 solar-type stars with a 0.75m automatic photoelectric telescope (APT) at the Fairborn Observatory site on Mount Hopkins. Roughly two thirds of the 75 target stars are from Wilson's (1978) survey; the rest are TNG stars. Following many of the precepts of the Lowell program (Lockwood, Skiff, and Radick 1997), the APT makes differential observations of each program star in Strömgren b and y passbands with respect to three comparison stars carefully chosen for high photometric stability. Extensive quality control and calibration measurements with the APT result in a precision of 0.0010 mag for a single nightly observation and 0.0001 to 0.0002 mag for seasonal means. In April, 1996, we began observing an additional 75 sun-like stars with a new 0.8 m APT,

Figure 2. Fairborn Observatory's new APT site in the Patagonia Mountains of southern Arizona. Currently, eight operating telescopes are housed in two roll-off-roof enclosures (shown in their open position). Four additional automatic telescopes to be housed in the third (closed) enclosure in the background are under construction. The 30-inch and 32-inch APTs used in this study are the rightmost telescopes in the picture. (Photo by Frank Fekel)

also located at Fairborn Observatory. These stars were chosen to be as close to the Sun in mass and age as practical; the majority are TNG stars while the rest were chosen from old moving groups. The precision we obtain with these APTs allows us to trace long-term brightness changes that are similar to brightness changes in the Sun observable only with space-based radiometers. During the summer of 1996, Fairborn Observatory and the APTs were relocated to a new privately-owned site in the Patagonia mountains of southern Arizona (Figure 2).

3. Magnetic Activity of Stars in the Solar Neighborhood

For three decades it has been known that the mean level of stellar surface magnetism decreases gradually with age and rotation during the lengthy main-sequence phase of a star.

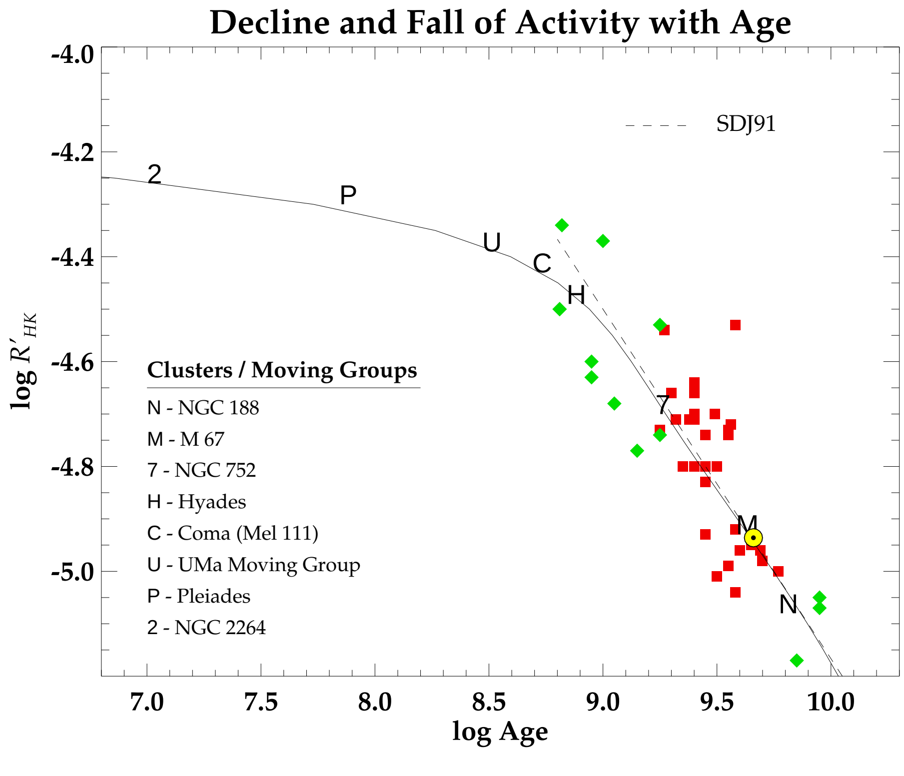


Figure 3. An estimate of the functional dependence of activity on age from Soderblom et al. (1991). The dashed line is their fit. $R'_{\rm HK}$ is the radiative loss due to surface magnetic activity, normalized by bolometric luminosity as a function of age, computed according to Noyes et al. (1984).

An empirically-derived function can represent the decrease in magnetic activity with increasing main-sequence age (Figure 3, Donahue 1993; Baliunas et al. 1995a). The youngest stars, such as those of the Pleiades, with ages about one-hundredth the Sun's age show the strongest magnetic activity levels and the greatest rotational velocities. Stars of the Hyades cluster, with ages about one-tenth the Sun's, have intermediate levels of magnetic activity and rotation. The old stars, such as the Sun, and those in the old, open cluster M 67, display the weakest magnetic activity levels and slowest rotation.

To place the Sun in the context of stellar surface magnetism we turn to a cross-sectional survey of the globally-averaged strength of magnetic activity of dwarf stars in the solar neighborhood, mostly drawn from the Woolley et al. (1970) catalogue (see earlier results by Vaughan & Preston 1980). Among those stars the Sun is relatively weak in chromospheric emission in the stellar distribution because of its age. The run of magnetic activity in the sample is transformed to age by way of the function in Figure 3, and is plotted (Figure 4) as a function of the $(B-V)$ color index, i.e., a parameterization of lower main sequence mass.

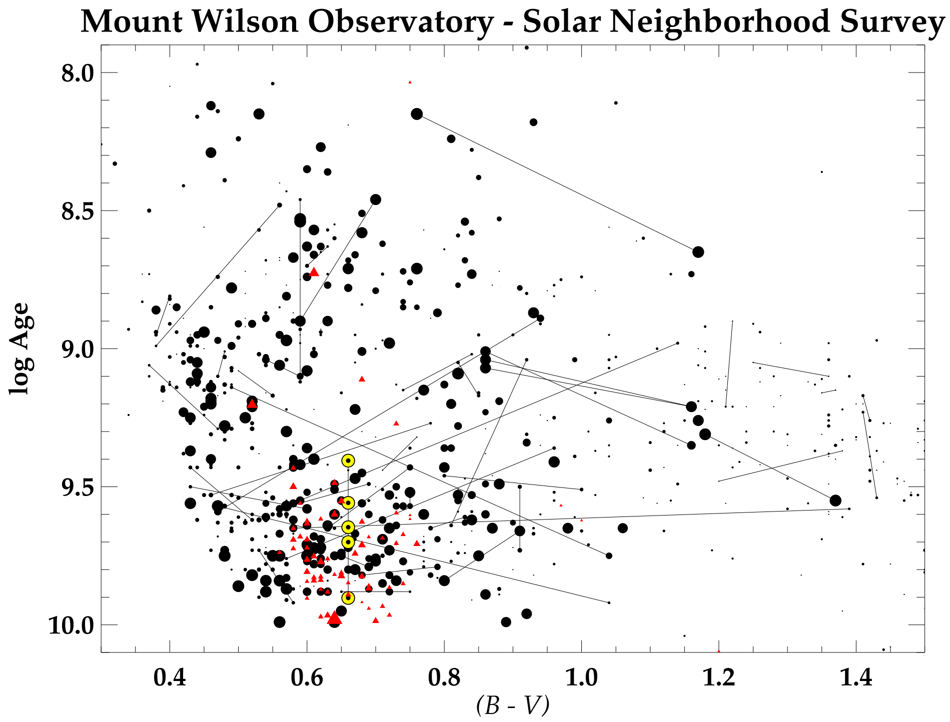


Figure 4. Age, in years, calculated from observed S and the function in Figure 3, as a function of $(B-V)$ color.

This type of study can say something about the variability of the Sun and other stars over decades or longer time scales, despite the fact that the individual stars are neither densely sampled nor monitored continuously over such long time scales. Consider the five multiple points given for the Sun (connected with a vertical line). Along the bar, the last 400 years of solar activity variations, including the Maunder Minimum, are mistaken for an apparent uncertainty in age of 3 to 8 billion years. The underlying reason for the mis-perception of the Sun's age is of interest: the imprecision in age arises from long-term surface-average magnetic variability.

To study the amount of variability, visual binaries have been measured (Donahue, these proceedings). The component stars within a binary should have the same age. Binary component stars are shown on the plot as pairs of points connected with a line, which would have zero slope if both components were the same age. Nonzero slopes presumably mean long-term variability. The slopes can help to develop statistics on the distribution of activity over long time scales.

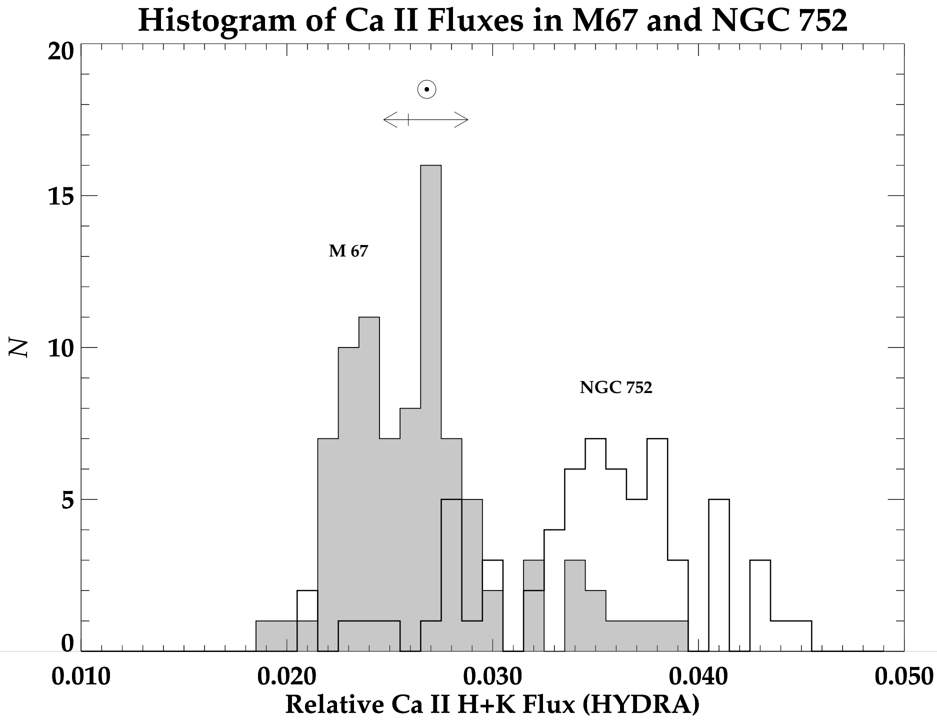


Figure 5. Distribution of Ca II H and K fluxes on an arbitrary scale for dwarf stars in the clusters M 67 (age 4 Gyr) and NGC 752 (age 2 Gyr).

A specific application of this technique is the example of M 67, a cluster of roughly solar age with several hundred sun-like stars. The distribution of Ca II H and K fluxes (Figure 5) for stars close in mass and age to the Sun has a significant width. This distribution can be interpreted as a measurement of one star at random phases of its long-term activity. The range of Ca II activity for the Sun is marked at the top of the chart. The boundaries of the bar are the lowest and highest values transformed from the sunspot record over the last 400 years, and includes the Maunder Minimum.

An advantage to the cross-sectional method is that it gives information on long time scales in a relatively short amount of time. But a defect is that there is no easy way to determine the upper limit of the time scale of the distribution. That is, is this the range of variability relevant to a millennium or 100 million years? Theoretical investigations should be useful in estimating the time scale of variability caused by different physical processes.

The time scale is more straightforwardly derived from time serial records.

4. Magnetic Variability Records

The longest records of stellar magnetic variability are for the Sun: direct records of sunspots go back nearly 4 centuries; cosmogenic isotope records of radiocarbon and ^{10}Be go back several millennia.

In contrast, the records for Wilson's stars go back only 30 years; however, they comprise nearly 100 independent examples over a range of stellar properties. Wilson's sample of stars ranged in activity level and spectral type from early F- to one early M-dwarf. Close binaries were shorn from the initial list in 1966. Modern technology has yielded a few surprises, e.g., HD 81809 is a visual binary with a $0\farcs3$ separation (Figure 6) when imaged with the 100-inch telescope's new adaptive optics system (Shelton et al. 1995).

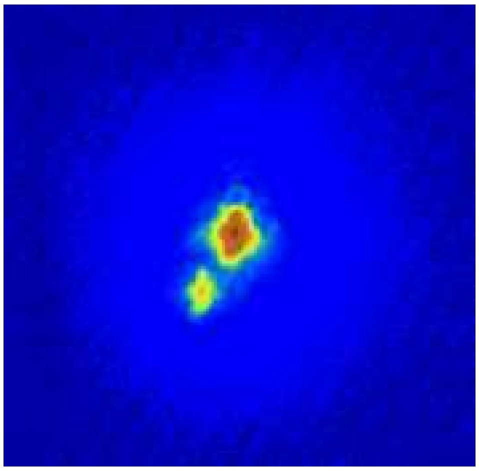


Figure 6. ADOPT image of the binary HD 81809 in I-band obtained with the adaptive optics system of the 100-inch telescope. The separation of the components is $0\farcs3$. No post-processing has been done to the image.

Wilson found that the records of Ca II variability in his sample could be broadly classified into three categories:

First, smooth cycles on the order of a decade — reminiscent of the 11-year sunspot cycle.

Second, variable — that is, significant, long-term fluctuations occur but not with a clear periodicity.

Third, no significant variations.

Each of these three types of magnetic activity exist in records extending over 30 years. Examples can be seen in Figure 7.

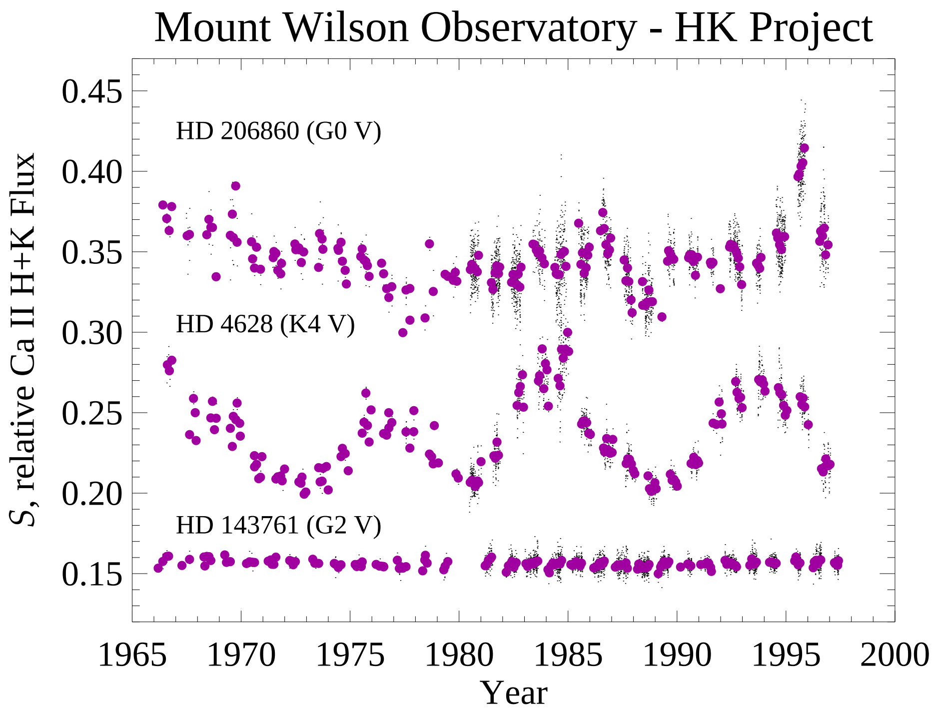


Figure 7. Three classes of Ca II flux variability: variable (top, HD 206860), cyclic (middle, HD 4628), and non-variable (bottom, HD 143761 = ρ CrB). The small points are nightly measurements; larger points are averaged every 30 days.

The lengthened records have yielded refinements on the statistics concerning surface magnetic variations of stars in the total sample:

About 60% of the total sample of lower main sequence stars has periodic, or apparently periodic, records of Ca II H and K fluxes. Cycles occur in stars of all spectral types and all ages. This is an empirical fact that seems important for the development of theory on stellar surface magnetic activity. The upper limit of periods is longer than thirty years, the current limit of the records, under the assumption that records with systematic trends eventually reverse. But in the older stars there is a cutoff for short periods: older stars never show cycles shorter than 7 years. Another subtlety is that there are records with two independent periodicities.

About 25% of the records are variable, but with no obvious periodicity. The stars that vary erratically with time are generally young, rapidly rotating and magnetically active.

About 15% of all records are constant with time. Stars with flat magnetic activity records may be in a Maunder Minimum-like state, similar to the Sun in the 17th century, or the stars may be in a sustained state of insignificant variability.

5. Dynamo Implications

The classes of observed records can be compared to results from studies of dynamo models. Only two general comments will be made.

First, it is difficult to know what the important parameters of comparison are between the records and the model results. For example, one difficulty arises from the assumption that $P_{\rm cyc} \propto D^i$, where $P_{\rm cyc}$ is the cycle period, D is the dynamo number, and i has a predicted range of $-1.0 < i < +0.5$, i.e., not even the sign of the dependence is certain. So what are the important comparisons in the linkage to models? The average surface flux and rotation? Cycle period and flux? Figure 8 is an example of a significant correlation (Baliunas et al. 1996) among 111 stars in the sample: the magnetic moment (proportional to $R'_{\rm HK}$) versus the rotational moment (proportional to the angular velocity). Such a relation emphasizes the importance of rotation in the generation of magnetic activity, certainly in accord with the concept of the large-scale magnetic dynamo. That approach can be compared to the alternative parameterization (Noyes et al. 1984) of $\langle R'_{\rm HK} \rangle$ versus Rossby number, where the rotation period is normalized by the model-derived parameter, the convective turnover time. But without much closer linkage to theory, it is difficult to establish the empirical "ground truths."

The second comment is that despite the lack of closure between the records and model results, there are expectations from the theory that seem to map the observed classes of activity records. For example, the totality of behavior in the records may be cast in terms of the dynamo number, D, which depends on the product of the mean helicity and differential rotation shear. Below a threshold value of D, the dynamo cannot be sustained. At this threshold, the dynamo may start locally but cannot hold globally. Above that threshold, the dynamo may barely operate, producing the scant surface magnetism and "flat" activity records. At higher values of D, the dynamo is maintained with a cyclic periodicity. At even higher dynamo numbers, the behavior becomes more and more complex, showing perhaps first several dynamo wave modes excited (as in the double-period cycles) and finally many modes (as in the "variable" records).

6. Magnetic and Brightness Variations

Experiments on the *Solar Maximum Mission*, *Nimbus-7*, and *Earth Radiation Budget* satellites showed that over the course of the 11-year sunspot cycle the Sun's increased coverage by sunspots is accompanied by a brightening in its total irradiance. Models (Foukal & Lean 1988) suggest that the irradiance variations are governed by bright, magnetic regions such as faculae, which thereby produce a positive correlation between sunspots and irradiance changes.

That aspect of solar magnetic behavior has also been confirmed, as mentioned earlier, for solar-type stars (Radick et al. 1990). Cross-analysis of the H and K observations from Mount Wilson and the photometric measurements from Lowell revealed behavior that is similar to the Sun's for the sun-like stars that

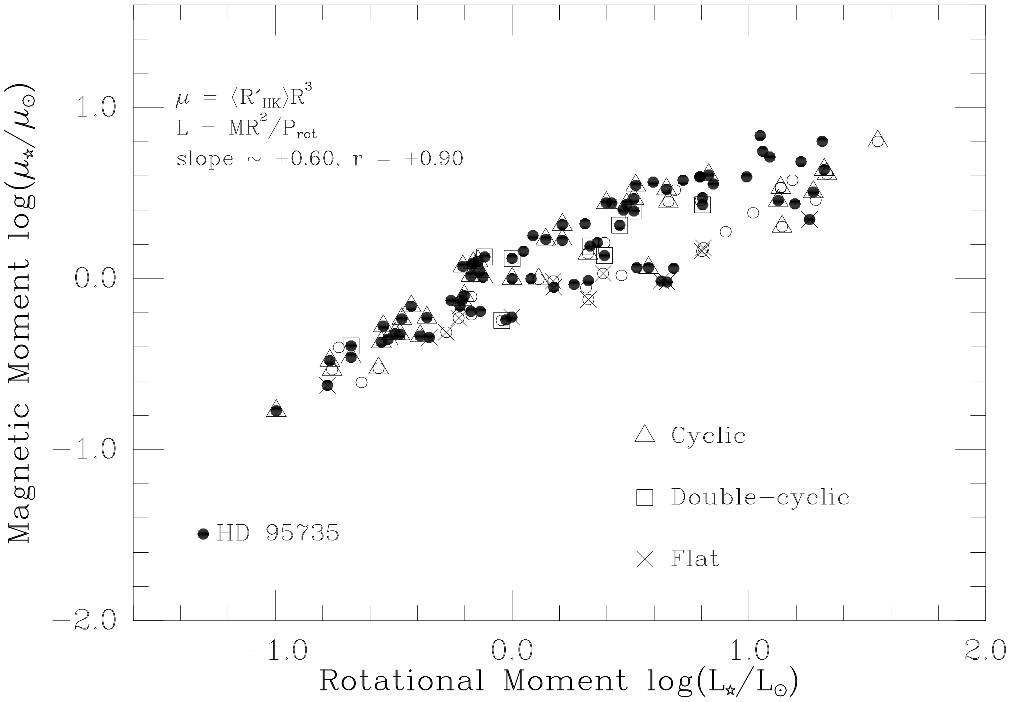


Figure 8. Magnetic moment vs. rotational moment normalized to the Sun's values for the Wilson sample of 112 lower main-sequence stars, including the Sun. Filled circles denote stars with measured rotational moments; open circles denote stars with rotational moments calculated using the rotation period estimated from the Ca II activity-Rossby number relation (Noyes et al. 1984). The slope for the log (μ)-log (L) relation is $d \sim +0.60$, and the Pearson correlation coefficient is about +0.90. The three classes of variability in Ca II based on 25 yr records discussed in Baliunas et al. (1995b) are also indicated. Circles within triangles denote stars with a periodic cycle; circles within squares denote stars with two distinct periods ("double cyclic"); circles with superimposed crosses denote stars with inactive (i.e., rms variability less than $\sim 2\%$ over 25 yr) long-term Ca II variability (from Baliunas et al. 1996).

occur in both samples, namely, that *brightness and magnetic activity increase (or decrease) together* on time scales of activity cycles.

Figure 9 shows samples of APT photometry and Ca II measurements of the star HD 103095. This star shows Ca II variations similar to the Sun's and a positive correlation of activity and brightness in the five-year record. HD 103095's amplitude of brightness variation during its magnetic cycle should be, when fully observed over a cycle, solar-like — roughly 0.1%. One interesting point about this star: it is Groombridge 1830, a ∼10 Gyr-old metal-deficient subdwarf. Age has not extinguished its periodic activity.

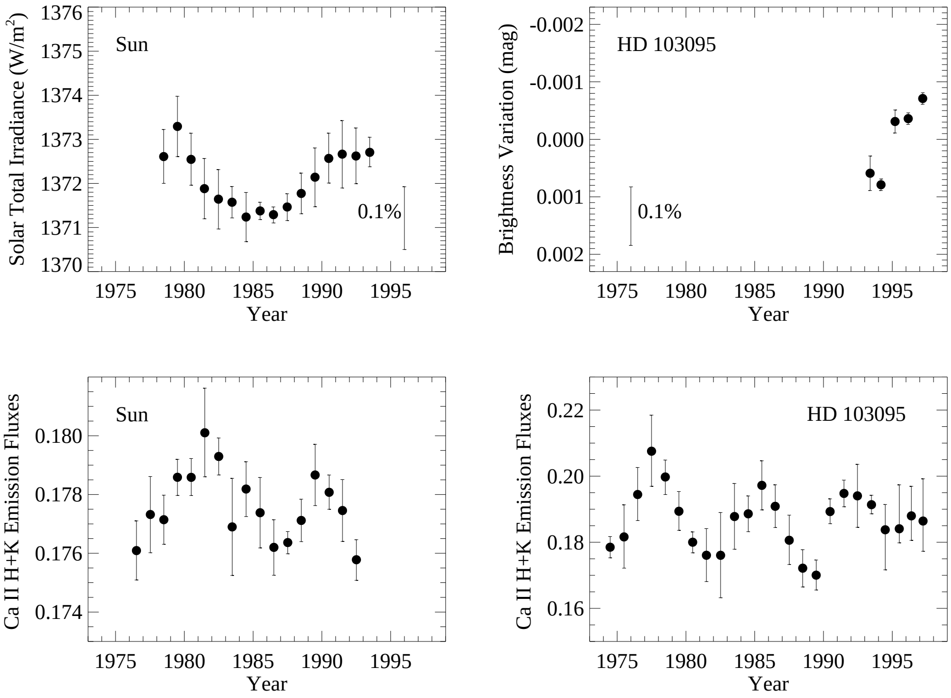


Figure 9. Left panels: records of (top panel) solar irradiance variations and Ca II H and K variations. Right panels: photometric variations (top panel) and Ca II H and K variations of HD 103095.

On the other hand, young stars similar to the young Sun, show brightness and magnetic changes that are *anti-correlated* over the course of years-long variability. In the young Sun, the presence of large, dark sunspots (which must have covered several percent of the area of the disk) would have dominated the bright emission from magnetic areas. Thus, in contrast to the current Sun, the irradiance variations of the young Sun would have been controlled by the dark sunspots and would have varied about several percent over a decade or so.

Figure 10 shows the relationship between the day-to-day photometric variability of our sample of 145 APT program stars (as measured by the standard deviation of a single nightly observation from the seasonal mean) and the chromospheric emission ratio, R'_{HK}. Age increases from $\lesssim$ 0.1 Gyr to $\gtrsim$ 10 Gyr from left to right. As a lower main-sequence star ages, its rotation slows, its dynamo weakens, and its chromospheric emission ratio decreases. As seen in Figure 10, this is accompanied by a decrease in the amplitude of its short-term variability. Corresponding standard deviations of the nightly brightness measurements decrease from nearly 0.030 mag to only 0.001 mag. The inset to Figure 10 shows the relationship for stars near solar age. Few standard deviations lie below $\sim$ 0.0010 mag because this represents the limit of our precision for a single observation. The standard deviations for the 0.80 m APT (filled circles) lie systematically below the those from the 0.75 m APT (open circles) in spite of the fact that the 0.80 m stars are systematically fainter. This is due to the use of a dual-channel photometer on the 0.80 m APT, which allows the integration times to be doubled without reducing the number of stars that can be measured. The Sun's day-to-day photometric variability is represented by the connected "Sun" symbols based on satellite radiometer measurements, corrected for the difference between the total solar irradiance and the Strömgren b and y bandpasses. The lower symbol represents the photometric variability of the quiet Sun, during sunspot minimum, while the upper symbol represents the observed photometric variability during sunspot maximum.

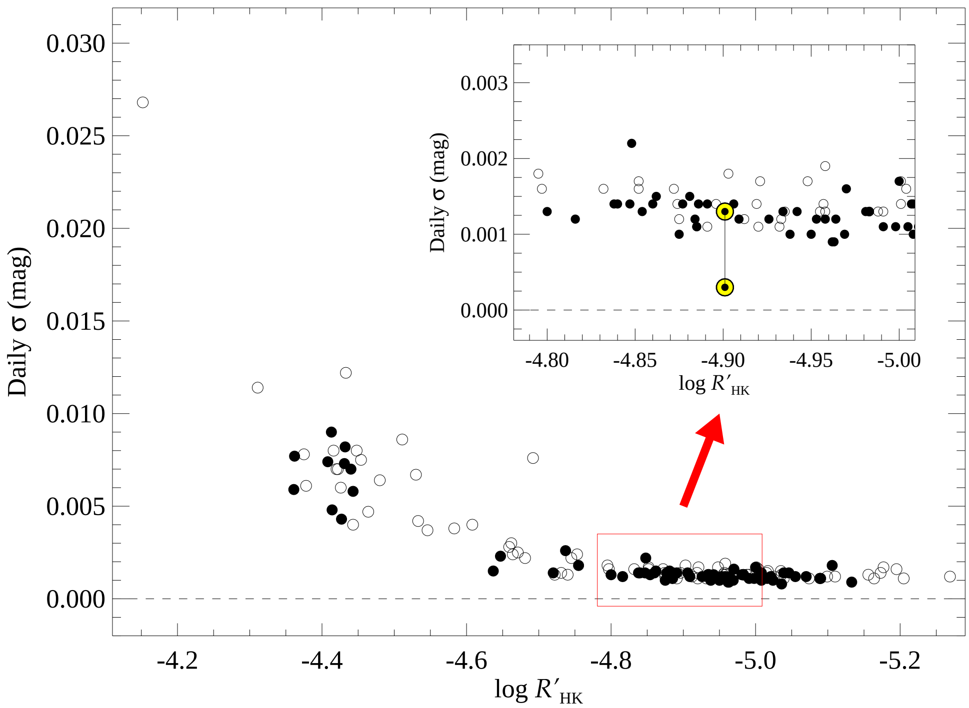


Figure 10. Standard deviation of day-to-day photometric variability, versus chromospheric activity for our sample of 145 APT program stars. The inset panel expands the plot in the region of the Sun. The range of solar day-to-day variations are shown by the connected "Sun" symbols in the inset panel. The lower symbol corresponds to the quiet Sun at activity minimum, the upper symbol is for the variations during sunspot maximum.

7. Evolved Stars

In post-main sequence giants, there is long-term variability of surface activity. Giants exhibit records morphologically similar to the dwarfs: variable, cyclic and flat (Figure 11).

Is the origin and nature of the activity in giant stars the same as in dwarfs? This question is open. Raschke et al. (in prep) are studying giants near the

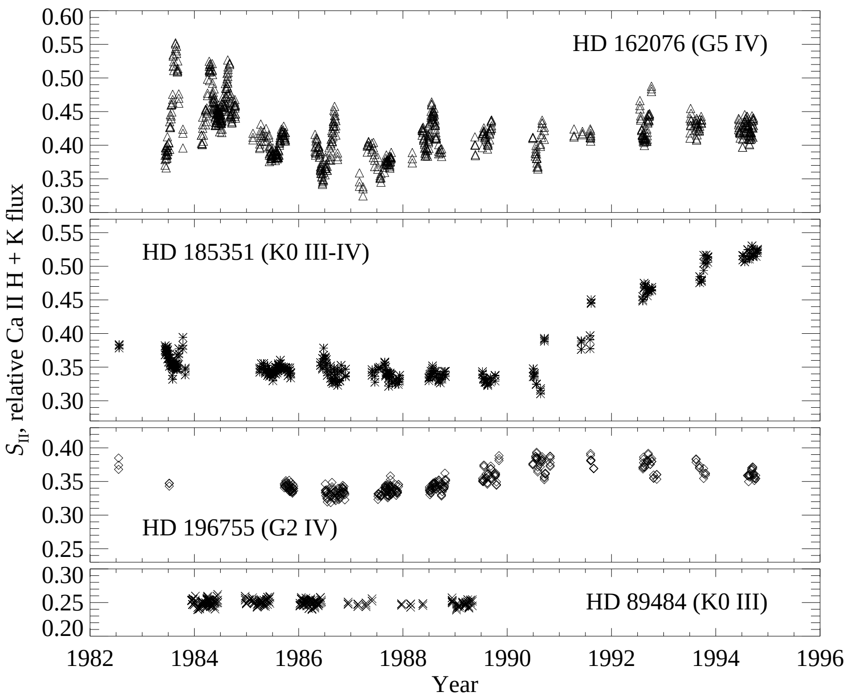


Figure 11. Records of Ca II H and K fluxes in giants showing different classes of activity variability (*from top to bottom*): variable, long-term trend, cyclic, and flat.

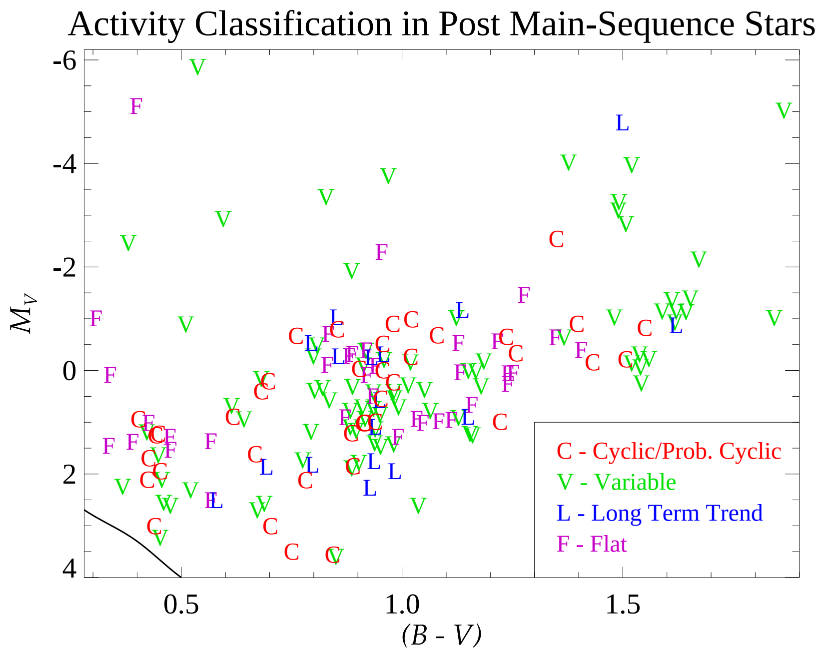
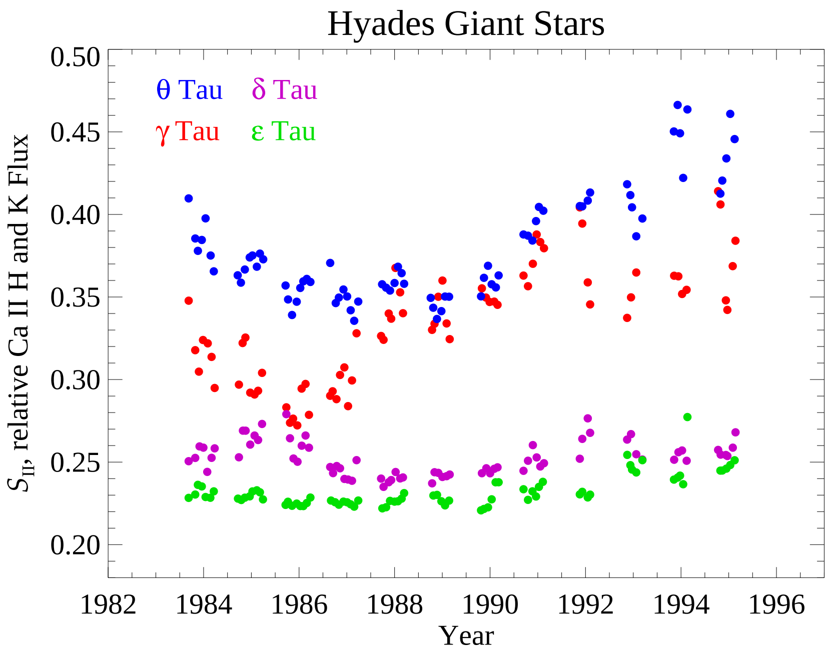


Figure 12. The distribution of classes of records of variability in evolved stars. The line in the lower-left corner is the main sequence (Raschke et al. in prep).



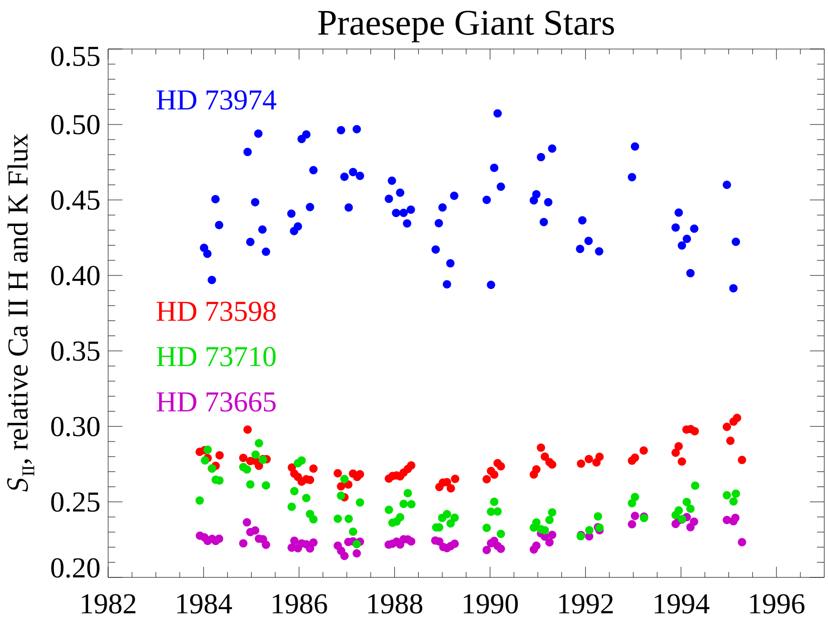


Figure 13. Records of Ca II H and K fluxes in the four Hyades K0 III stars (upper plot) and four Praesepe K0 III stars (lower plot).

2 $M_\odot$ evolutionary track, and they find different statistics for the classes of variability records between giant and dwarf stars. Recall that in lower main sequence stars, 60% of the 111 stars showed cyclic or apparently cyclic records. In the giant stars, cyclic activity is possibly seen in only about 40% of 175 stars and nearly the same fraction of variable records (Figure 12). The sample of giant stars has a larger fraction of variable activity records compared to the dwarf stars.

Giants in clusters are particularly interesting. In the Hyades cluster are four K0 III stars, whose progenitors were early A-type main sequence stars (Figure 13, top panel). As such, they had no dynamo activity during their main sequence lifetime. During post-main sequence evolution, a subsurface convective zone developed and dynamo activity began. Since the Hyades giants are so similar in, e.g., angular velocity, age, mass, and composition, the explanation for their disparate Ca II variations may lie with having our observed them at random phases of longer-term variations. A similar situation exists for the Praesepe cluster — four K0 III stars[5] with different Ca II records (Figure 13, bottom panel).

8. Exoplanet Studies

Roughly Jupiter-sized planets have been inferred from radial velocity measurements of sun-like stars (Table 1). Studies of stellar surface magnetism, from both brightness and Ca II flux records, can provide four pieces of corollary information on these stars (Henry et al. 1997; Baliunas et al. 1997).

First, the age of a star can be estimated from the average level of Ca II flux and the function describing the dependence of Ca II flux on age (see Figure 3). Most of the stars with reported planets are at least several billion years old.

Second, axial rotation might be detectable. Periodicities in the H and K records on time scales of days to months are almost certainly caused by rotation, and the measured rotation periods can be confirmed by recurring periodicities and by comparison with Doppler-broadening measurements of projected rotational velocities. Thus, *rotation periods* can be measured directly (and the angle of inclination of the rotation axis to our line of sight can be inferred) from the H and K records (Figure 14). Most of the stars in the exoplanet survey have little surface magnetic variability, a point to be discussed in a moment. Because of the inactivity of most of these stars, surface features must be generally absent, so rotational modulation is absent. In the case of 51 Peg, only two seasons showed any significant modulation, with an average period of 37 d, which is the expected period of a star of its age, spectral type and average level of surface activity. It is an old, single star.

The third aspect of surface magnetism in these stars is their relative inactivity — due in part to their great age. The class of Ca II record of 51 Peg is typical of these stars: "flat." The lack of variability in surface magnetism is an observational bias in favor of detecting low-amplitude reflex velocities. Time-varying surface features create radial velocity signatures that may compete with or mask low-amplitude reflex velocities. For example, time-varying surface fea-

[5]There is also a G0 III star in this cluster, HD 72779, which is not discussed here.

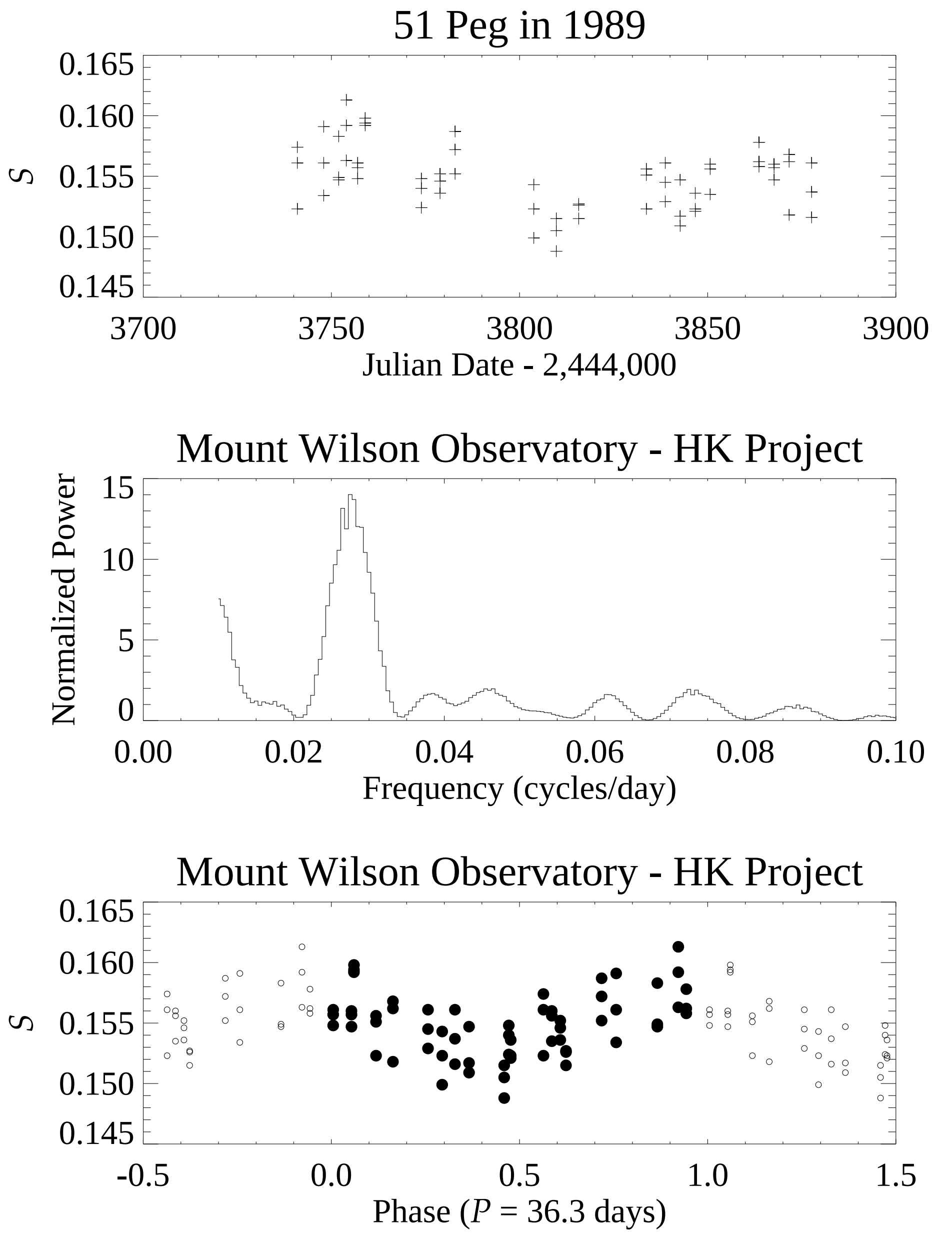


Figure 14. Seasonal record of Ca II H and K fluxes in 51 Peg (top plot), the periodogram of that record showing a significant peak at 36.3 days (middle plot) and the record folded around the period of the significant peak (bottom plot). The phase-folded points are repeated and plotted as open circles.

Table 1. Sun-Like Stars with Planets

Star	$P^{\mathrm{a}}_{\mathrm{orbital}}$ (days)	Rotation (days) Observed	Estimated	Age (Gyr)
47 UMa	1092.	···	21	7
70 Vir	116.	···	36	9
16 Cyg B	802.	···	28	7
51 Peg	4.2	37	30	10
τ Boo	3.3	3.3:	5	2
ρ^1 Cnc	14.6	42	42	5
υ And	4.6	···	12	5
ρ CrB	39.6	17	20	6

[a]Spectroscopic periods, presumed to be orbital periods are taken from the summary of Marcy & Butler, these proceedings.

tures would produce velocity components on time scales of their growth and decay, as well as over the period of axial rotation. The observational bias of stars with low surface magnetism presents an opportunity to improve chances of detecting exoplanets among stars with such planets. Conversely, active (i.e., young) stars may show too much surface variability to permit detection of reflex velocities $\lesssim 100\ \mathrm{m\,s^{-1}}$ (Baliunas et al. 1997; Saar & Donahue 1997). The magnetically quiet stars would be candidates with the least potential interference for radial velocity studies, although note that ρ^1 Cnc is at least as active as the Sun.

Finally, photometric studies provide limits on surface pulsations, an alternative explanation to planets sometimes used to interpret the radial velocity variations, as discussed by Marcy & Butler (these proceedings).

One note: the reasons for consideration of magnetically quiet stars for planetary searches by radial velocity measurements also apply to the technique of planet searches by photometric searches for possible transit events. If the orbit of the planet is aligned to within a few degrees of our line of sight, it might be possible to observe a transit as a repeated, geometric dimming of starlight. Because surface features create photometric variability, magnetically quiet stars would present a less-variable background against which to see a planet. In this regard, it is interesting to note that under some circumstances, our automated telescopes have the photometric precision required to see the transit of a planet as small as the size of earth around nearby sun-like stars (Henry et al. 1997; Baliunas et al. 1997). No transits have been seen in the extant records of the stars listed.

9. Summary

Since the time of Olin Wilson and Gene Parker's ideas, observations of Ca II fluxes and photometric brightness in cool stars have begun to illuminate the physical properties that govern stellar surface magnetism, both in terms of its time-averaged level and variability. For example, angular velocity is a key property in the case of surface magnetism in lower main sequence stars. Similar studies of giants offer hope for similar progress in the future.

Photometric measurements have improved in precision to the point where the level of subtle photometric variations present on the Sun as a result of surface activity is visible on other stars. Sun-like stars have sun-like behavior; especially noteworthy is the positive correlation seen between surface magnetism and brightness over the activity cycle.

In the case of programs searching for planets orbiting sun-like stars, studies of surface magnetism suggest observational biases favoring or inhibiting detection strategies. Our photometric measurements are useful for confirming new planetary discoveries by eliminating alternative explanations for the radial-velocity variations. The long-term measurements of brightness changes in these stars with planets will reveal which have the stable energy output necessary to sustain life on any planets within their habitable zones. Finally, the successful photometric detection of planetary transits would lead directly to absolute masses, radii, and densities of these new planets and, therefore, provide crucial insight into their composition and origin.

Acknowledgments. The HK Project was more recently supported by the Richard Lounsbery Foundation, the Electric Power Research Institute, the Mobil Foundation Inc., MIT Space Grant GC–R–277767, Paul Gerstley, Hugh Downs, Scott Carpenter, and other individuals. We are grateful to our colleagues, past and present, in obtaining the observations discussed here. Among them are Lou Boyd, Michael Bradford, Laura Eklund, James Frazer, Howard Lanning, Tony Misch, Jean Mueller, and Kirk Palmer. We thank V. Cristina Cristian and Lynne Raschke for assisting in calibration of the data. We are especially thankful for advice from Robert Jastrow, Eugene Parker, Allan Sandage, Arthur Vaughan, and Olin Wilson, whose great vision for the future of Mount Wilson Observatory never faltered.

Astronomy with the SAO–TSU APTs at Tennessee State University has been supported for several years by the National Aeronautics and Space Administration, most recently through NASA grants NAG8–1014, NCC2–883, and NCC5–228 (which funds TSU's Center for Automated Space Science), and the National Science Foundation, most recently through NSF grant HRD–9550561 and HRD–9706268 (which funds TSU's Center for Systems Science Research).

Discussion

R. Kraft: Have you checked the Ca II H & K ages against the c_1 ages based on Strömgren photometry (for stars near G0)?

S. Baliunas: Yes, Eric Ford and Willie Soon (in prep.) have.

L. Pasquini: Does the large spread in Ca II observed in M 67 imply that we cannot determine the ages of old stars?

S. Baliunas: No. Figure 5 shows a clear separation between the stars in NGC 752 (age 2 Gyr) and M 67 (age 4 Gyr), and suggests that the ages of old stars can be determined within 1 Gyr, assuming the stars in the cluster are essentially coeval.

K. Strassmeier: How do you know what the underlying mechanism is in the observations of giants as early as G0? Could $\langle S_{\mathrm{II}} \rangle$ be made up by two mechanisms, e.g., activity and pulsation/winds?

S. Baliunas: Yes. The instrument cannot discriminate among mechanisms that produce or mimic flux changes in the passbands, including significant radial velocity changes. However, in the case of variability seen on time scales of years, pulsation seems unlikely.

G. Basri: Do you have information on the individual rotation periods of the stars in M 67 which show high or low activity levels? Could they be rotating at different rates?

S. Baliunas: No information on rotation rates is available. It would be critical in understanding the distribution of activity in M 67.

D. Mozurkewich: You have only seen one star that may be switching between a cyclic state and a steady state. Isn't this a bit worrisome for claiming the Sun is like other stars? The Sun switches state about every 150 years (200 years active and 100 years inactive). If other stars switch at the same rate, you should have seen

$$\frac{(\text{number of stars}) \times (\text{time per observation})}{\text{time per switch on the Sun}} = \frac{120 \text{ stars } \times \text{ } 10 \text{ years}}{150 \text{ years}} = 8 \text{ stars.}$$

S. Baliunas: It is not clear which stars in our sample (and therefore how many) should have "switching states." If there are only 20 appropriate stars in the sample then we should have seen only one, which we may have. The other factors are not well known either.

H. Gursky: You showed three classes of stellar variability; one was irregular variability, the second was cyclic variability, and the third was flat, with no evidence of variability. Is there anything else which distinguishes these three classes of variations? Also is there a continuous range of variability leading to the "flat" category, or do they really appear as distinct classes?

S. Baliunas: Primarily rotation (i.e., age) distinguishes variable from the other two classes.

A. Dupree: In your giant star program, spectroscopic observations of the Ca II line profiles would be useful to distinguish wind variations from changes in magnetic activity.

S. Baliunas: Indeed. Spectroscopic observations would be illuminating.

B.H. Foing: With what accuracy can you predict from HK time series and visible photometry the range of solar variations relevant to global change, in particular the solar constant and the ultraviolet spectral irradiance? How would these parameters change in the last 100 years, and at Maunder Minimum?

S. Baliunas: See Zhang et al. (1994), Baliunas & Soon (1995), and Soon et al. (1996).

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