LONG-TERM STELLAR ACTIVITY: THREE DECADES OF OBSERVATIONS

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1. Introduction

Knowledge of the solar sunspot cycle extends back to the mid-19th century with the work of Schwabe (1843) and Wolf (1856). The mean cycle period of the Sun is 11 years, however, individual cycle lengths range from 7 to 13 years (Eddy 1977). In this century, however, the length of the solar cycle has been closer to 10 years (Donahue and Baliunas 1992a). A complete explanation of the solar magnetic activity and its variations has not yet been produced, although a hydromagnetic dynamo is frequently posited as the source of solar (and therefore stellar) magnetic activity. Empirical measurements of those stars in the H-R Diagram which have convective zones and surface magnetic activity provide the boundary conditions and the range of behavior which must be explained by any all-encompassing theory explaining stellar magnetic activity, and activity cycles.

2. The Detection and Measurement of Activity Cycles

2.1. CHROMOSPHERIC ACTIVITY CYCLES

The longest running program to monitor activity cycles of main sequence stars is the "HK Project" at Mount Wilson Observatory (MWO), started in 1966 by Olin Wilson (Wilson 1968, 1978). Chromospheric activity cycle periods have been measured for just over 50 stars (Baliunas et al. 1995a), the remainder of the 111 star sample having long-term trends, variable activity without a clear period, or are inactive. Time series measurements (monthly means) for six stars are shown in Figure 1. The observed quantity, S, is the ratio of the fluxes measured in 0.1 nm passbands centered on the H and K lines of Ca II normalized, by the fluxes in two 2.0-nm continuum passbands at 390 and 400 nm, respectively.

K. G. Strassmeier and J. L. Linsky (eds.), Stellar Surface Structure, 261–268.

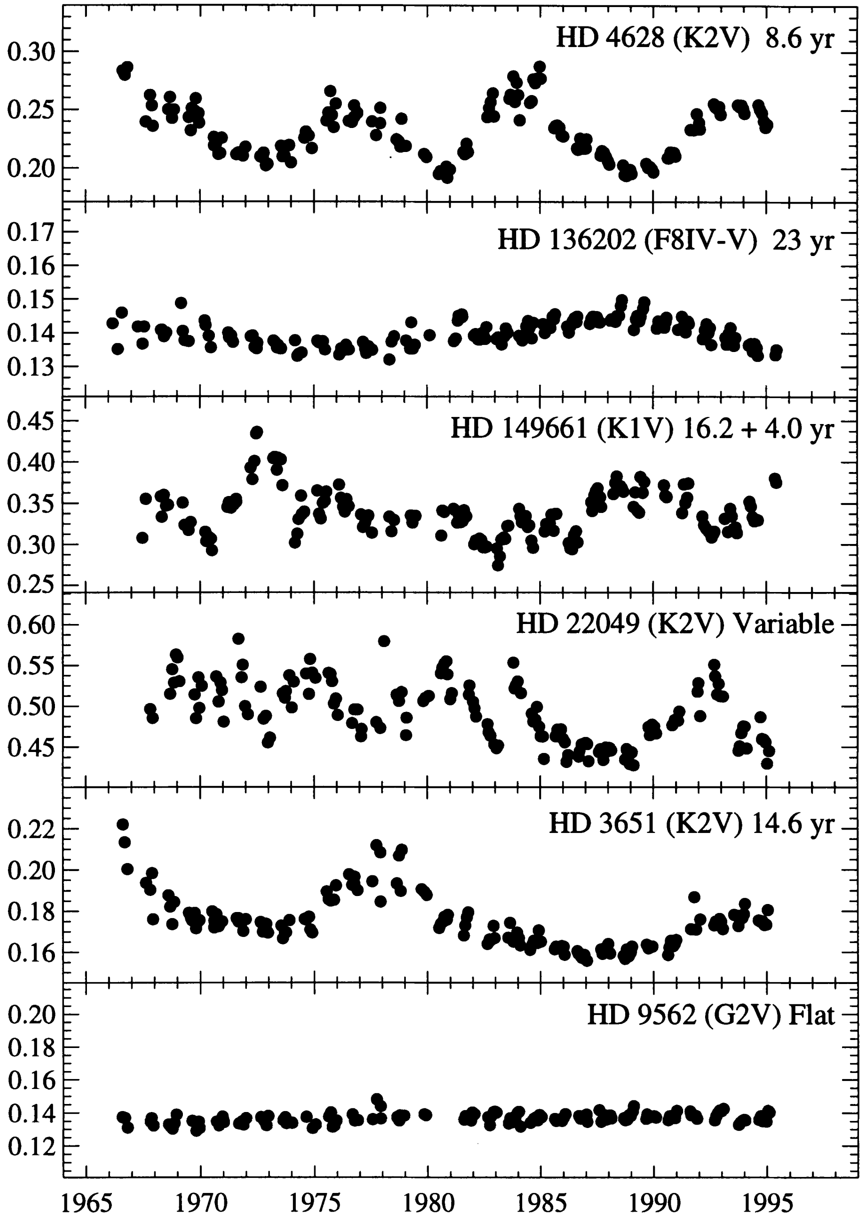

Figure 1. The long-term chromospheric activity (monthly means) for six stars highlight the differences in their behavior. *From top to bottom:* HD 4628 (K2V) has an 8.6-yr activity cycle with varying shapes of activity maxima and minima; HD 136202 (F8IV-V) has just completed a single 23-yr activity cycle; HD 149661 (K0V) has two activity cycle periods at 16-yr and 4-yr; HD 22049 (K2V) has only a variable activity record; HD 3651 (K0V) has a 15-yr cycle – however, there is a long term trend which might indicate a progression into a Maunder Minimum state; and HD 9562 (G2V) has been at nearly constant activity for the last 30 years.

https://doi.org/10.1017/S0074180900083285 Published online by Cambridge University Press

The original observations by Olin Wilson (1966–1979) were taken on 3–5 consecutive nights each month on the 100-inch telescope at MWO. Beginning in 1980, observations were scheduled nightly at the 60-inch telescope (Vaughan, Preston, and Wilson 1978). The increased observing frequency permitted the detection and measurement of stellar rotation (Vaughan et al. 1981; Baliunas et al. 1983; Noyes et al. 1984). Analysis of cycle periods, amplitudes, and possible correlations with other quantities have been recently been reviewed by Baliunas et al. (1995a) and by Saar and Baliunas (1992).

2.2. PHOTOSPHERIC ACTIVITY CYCLES

Observations made from space-borne instruments such as those aboard the Nimbus 7 and Solar Maximum Mission spacecraft show that the variation of the Sun's irradiance changes by $\sim$ 0.1% over the course of the 11-year activity cycle (e.g., Hudson 1988; Foukal 1992), corresponding to a change of approximately 1 mmag. Until recently, such long-term precision in ground-based photometry was difficult to obtain; however, two projects have achieved such precision for a sample of solar-like stars. The first program at Lowell Observatory (Lockwood and Skiff 1987; Lockwood et al. 1992), has observed approximately three dozen program stars in differential groups with Strömgren b and y since the mid-1980's. Yearly means for two stars are shown in Figure 2 along with their corresponding MWO Ca II fluxes.

The second project, a joint effort between Tennessee State University and the Harvard-Smithsonian Center for Astrophysics, intends to monitor approximately 150 stars using two fully-automated telescopes (with apertures of 30 and 32 inches, respectively) at Mt. Hopkins. Results from the initial two years of data from the 30-inch telescope have been encouraging: yearly means of differential pairs including the G1V star HD 126053 show a change in luminosity of $\sim$ 200 μmag from the 1993 to 1994 observing seasons – approximately the expected change in the Sun's brightness in one year due to the 11-yr activity cycle – whereas the seasonal change in the comparison stars observed along with HD 126053 ranges from $\leq$ 50 μmag to $\sim$ 100 μmag (Henry 1995)! Thus, it appears that it is now possible to accurately monitor the minute changes in luminosity related to the activity cycles even in inactive solar-like stars.

2.3. EVOLVED STARS

Observations of several dozen giant stars have also been obtained at MWO since 1983. While the available records for these stars is slightly less than half the length of the corresponding records for lower main-sequence stars,

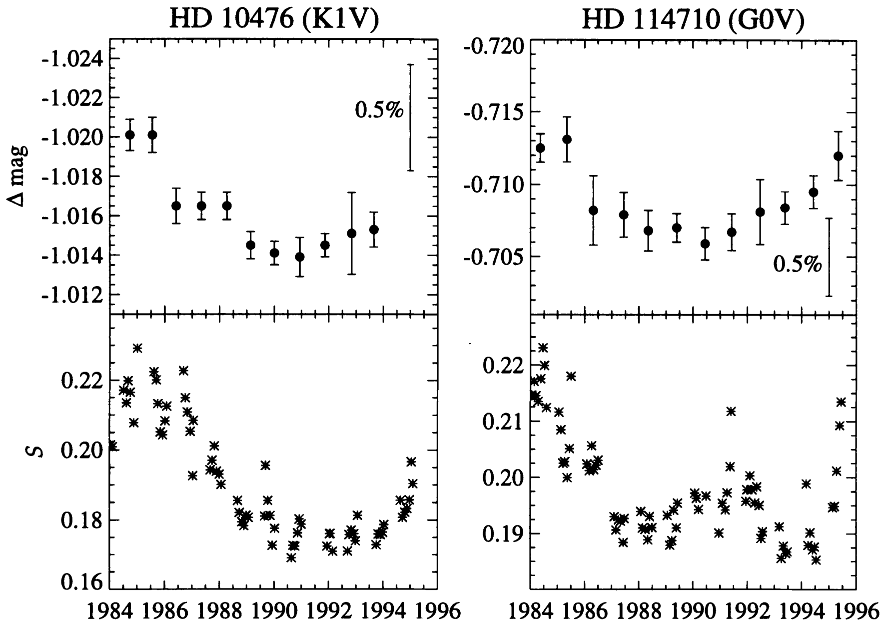

Figure 2. A comparison of the photospheric and chromospheric variability of the activity cycle for two stars: HD 10476 (*left panels*) and HD 114710 (*right panels*). The top two panels show yearly irradiance change from long-term high-precision Stromgren photometry taken at Lowell Observatory (Lockwood 1995, private communication). The bottom panels are nearly-contemporaneous chromospheric activity measurements from MWO. The amplitude in luminosity due to the activity cycle for both stars is approximately 0.6 percent.

long-term trends are evident, suggesting the presence of activity cycles. In Figure 3, the yearly means in chromospheric activity for the four Hyades K0 III stars are plotted, along with Lowell photometry of the G9 III star HD 112989.

3. Discussion

3.1. EXTRA-CYCLIC ACTIVITY

Of recent interest is the variation of activity on time scales longer than the sunspot cycle. In particular, departures from the normal sunspot cycle occur every few centuries; the most recent episode occurring in the mid-17th century, the "Maunder Minimum" (Maunder 1890; Eddy 1976). During such an episode, activity is diminished in both the chromospheric (Baliunas and Jastrow 1990), and the photosphere (Zhang et al. 1994), resulting in change of 0.2 – 0.6% in the Sun's luminosity. These extra-cyclic variations also appear to be correlated with land temperature changes on Earth (Friis-

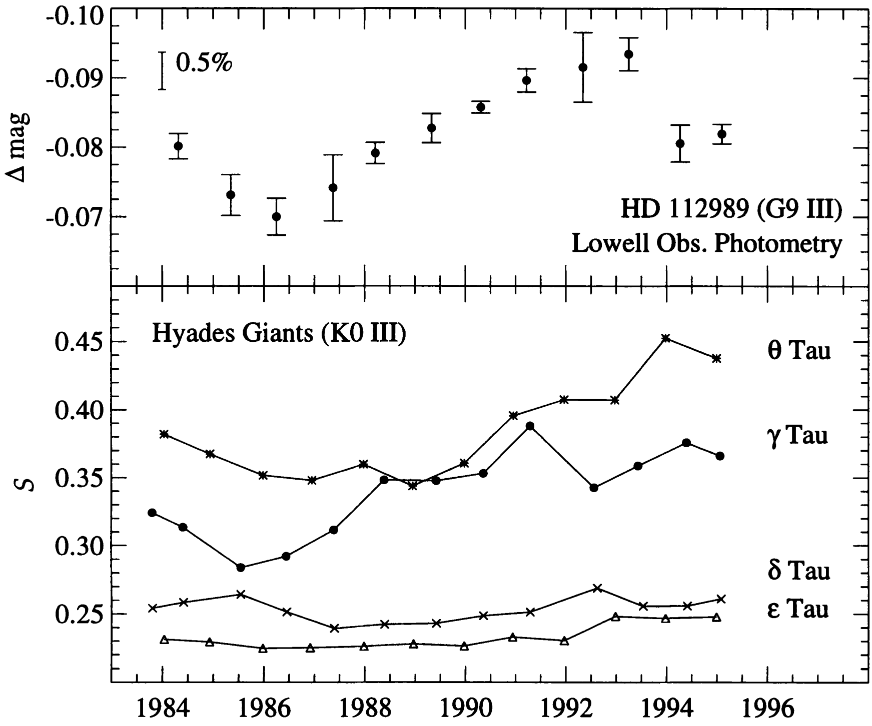

Figure 3. *Top Panel:* Seasonal means of irradiance for the G9 III star HD 112989, from high-precision photometry taken at Lowell Observatory. A cycle of length ~ 13yr is apparent, with a ~ 2% change in brightness. *Lower panel:* Yearly means of the chromospheric activity for the four giant stars in the Hyades shows the range of behaviors possible for stars off of the main sequence.

Christensen and Lassen 1991; Baliunas and Jastrow 1993) with deviations up to 0.4 – 0.6 C below average (Stuvier and Braziunas 1988). Thus, further investigation of this phenomenon is of great importance.

Snapshot measurements of large sample of solar-like stars can be used to obtain the approximate distribution of solar activity over long time scales. Ideally, the sample of stars should have the same age, making observations of open clusters near the age of the Sun ideal. In Figure 4, histograms of the distribution of activity in M67 (Baliunas et al. 1995b) obtained from high-resolution spectra taken with the HYDRA instrument at Kitt Peak are shown along with a field-star sample of 74 solar-like stars (Baliunas and Jastrow 1990). The M67 sample is broader, probably because of the comparatively low signal-to-noise and the possible existence of active binaries. Still, the distribution of activity is similar for both samples. The total range of solar activity (from Maunder Minimum to cycle maximum) is plotted above the distributions; the vertical line indicates the position of

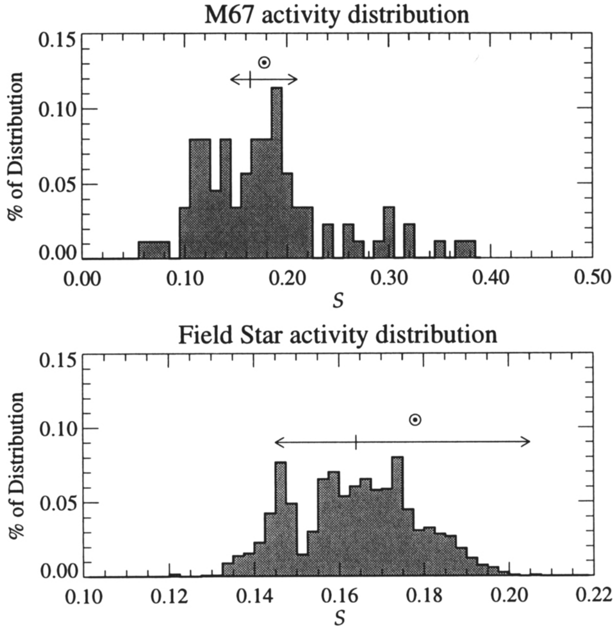

Figure 4. Distribution of activity for lower main-sequence stars (Baliunas and Jastrow 1990), and for the open cluster M67 (Baliunas et al. 1995b).

activity cycle minimum. Therefore, stars with nearly the same mass and age as the Sun appear to spend approximately one-quarter to one-third of their time in inactive states. The "gap" in both distributions between the presumed Maunder Minimum stars and those with "normal" activity suggests that the transition between the active and inactive states is short compared to the time spent in them.

Long-term measurements of inactive stars are necessary to fully model the likely behavior of the Sun on the time scale of centuries. A few of the stars in the Wilson survey, e.g., HD 9562 (Fig. 1) is possibly in a Maunder Minimum-like state (Baliunas et al. 1995a), and HD 3651 (Fig. 1) appears to be in transition to a similar state (Donahue et al., these proceedings). In 1993, approximately fifty additional mostly-inactive solar-type stars were added to the HK Project's observing list in the hopes of monitoring extra-cyclic variability.

3.2. SURFACE DIFFERENTIAL ROTATION

Another study which has benefited from activity cycle measurements involves the detection of surface differential rotation (SDR, Baliunas et al. 1985; Donahue 1993). Rotation periods measured from a 150–200 day ob-

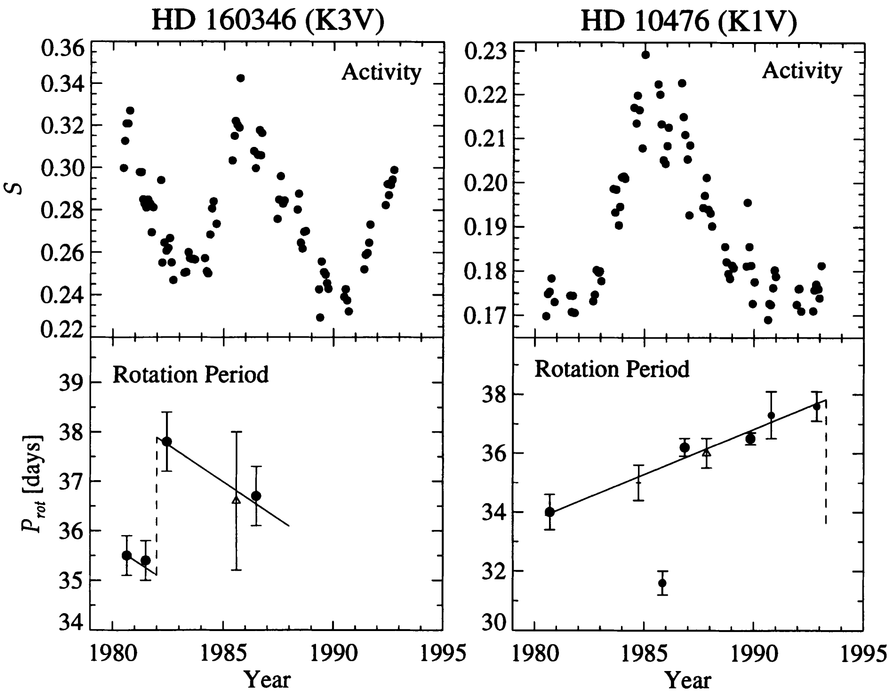

Figure 5. The time variability of rotation for two stars close in mass and age. In both cases, the rotation period modulates with the activity cycle, but with opposite behavior. *left:* HD 160346 (K3V) has a pattern similar to the Sun's, while HD 10476 (K1V) behaves in a manner opposite to the Sun.

serving "season" change with time, often in step with the phase of the activity cycle. In Figure 5, the variation of rotation and activity is compared for two stars. HD 160346 behaves in the same manner as the Sun: P_{rot} is at a maximum near the beginning of the cycle, and slowly decreases over the course of the cycle, with an abrupt change at the transition to the next cycle. On the other hand, HD 10476 shows the opposite behavior: P_{rot} *increases* during the activity cycle – similar to the behavior reported for the G0V star HD 114710 (Donahue and Baliunas 1992b). That the two stars in Figure 5 have similar rotation periods, and similar mass (and therefore presumably similar age), the difference in SDR pattern is interesting. Continued observations for rotation are necessary to create a larger sample of stars with detected SDR. This will prove invaluable to attempts to model the solar/stellar interior and assist in a deeper understanding of the processes involved with the generation and manifestation of photospheric and chromospheric activity.

I would like to thank Sallie Baliunas, Greg Henry, and Willie Soon and especially Wes Lockwood for access to material in advance of publication and for assistance with the preparation of this manuscript. I would also like to thank the observers and staff for Mount Wilson Observatory for their continued tireless efforts!

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