THE GROWTH AND DECAY OF MAGNETIC ACTIVITY
IN LOWER MAIN SEQUENCE STARS

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I. Introduction

The intensive set of observations of Ca II variations reported by Vaughan et al. (1981) and Baliunas et al. (1982, see also Baliunas 1982, these proceedings) contains useful information about the behavior of surface activity on lower main sequence stars over timescales of days to months. In some cases, rotational modulation seems to be persistent in phase and amplitude over two successive observing seasons separated by nearly a year. In turn, this persistence suggests that the now 15-year-long program of activity monitoring begun by Wilson (see Wilson 1978) can be used to study amplitude and phase coherence of lower main sequence stars over ever longer timescales.

In this paper we discuss characteristics of growth and decay of stellar active areas, and overall lifetimes of active region complexes, as determined from the two data sets mentioned above. We tacitly assume that the Ca II modulation in lower main sequence stars is due to the rotation of chromospheric plages overlying photospheric magnetic flux concentrations, as for the Sun.

II. The Growth and Decay of Rotational Modulation and Its Implications

The rotational modulation curves discussed by Vaughan et al. (1981) and by Baliunas et al. (1982) often show behavior similar to that expected for solar chromospheric active regions. The Ca II light curves often show abrupt increases or decreases in amplitude, or changes in phase, as expected if active regions grow and decay at different stellar longitudes. For example, Figure 1a (Baliunas et al. 1982) shows the onset of marked rotational modulation in the star HD 20630 (G5V, rotation period 8.5 days).

Frequently, however, rotational modulation is seen to develop more gradually, and as a growing oscillation both above and below a previously existing unmodulated level of emission. Figure 1b (Baliunas et al. 1982) is perhaps the clearest example in the present data. Such behavior requires a more complex description than simply superposition of new activity on a previously existing unmodulated (i.e., rotationally symmetric) "quiet" chromospheric emission; rather increased emission at one stellar longitude is somehow associated with decreased emission at other longitudes. One mechanism which might possibly give rise to such an effect, as noted by Vaiana (1981), is suggested by the global decrease in the rate of emergence of solar X-ray bright points (i.e., ephemeral active regions) that was observed to occur at and
Figure 1. (a) The Ca II H-K flux index S plotted versus time for HD 20630, a G5V star with rotation period 8.5 days. A pronounced onset of larger-amplitude rotational modulation occurs at day 493. (b) The H-K flux index versus time for the KOV star HD 149661. The rotational modulation decreases gradually starting about day 680, peaks about day 750, then decreases at a similar rate; the modulation swings both above and below the non-modulated level (from Baliunas et al. 1982).
following the development of a major new center of activity during the Skylab mission (Golub and Vaiana 1980). If a similar global decrease of magnetic flux emergence occurs uniformly over stellar surfaces in synchronism with development of active region complexes, the unmodulated lower envelope of curves such as that in Figure 1b could decrease, as observed.

Another possible mechanism for behavior like that shown in Figure 1b would be provided by the existence of two or more active regions on the surface of a star, rotating at substantially different angular velocities; this might occur in a star with a large latitudinal rotation gradient, containing two or more active regions at different latitudes. It is apparent in Figure 1b that for HD 149661 (rotation period 21 days), the oscillation grows and decays with a characteristic time of about three to four rotation periods. This means that the differential rotation must be such that one active region completes one rotation more than the other in six to eight rotations, or that the periods differ by about 15%. Dorren and Guinan (1982a) draw similar conclusions about this star from independent broadband photometric light curves. On the Sun, a rotational shear as large as 15% occurs only over a large latitude range (e.g. 20° to 50°), very much larger than the width of solar activity zones. Thus, if this explanation is correct the star HD 149661 experiences either much larger differential rotation than the Sun, a wider latitudinal spread of active region emergence than the Sun, or both. Dorren and Guinan (1982b) analyze photometric data for the G8 III-IV star and using a model of differentially rotating starspots. They find a differential rotation shear of 4%, between the latitudes of 25° and 30°; the direction of the shear is the same as for the Sun (i.e. lower latitudes rotate faster) but the amount is about twice that for the Sun.

Present data do not yet allow an unambiguous physical interpretation of the rotational modulation of HD 149661 or similar stars, but continued observation of the sort discussed here should provide such a description in the future.

III. **Long-Term Behavior of Rotational Modulation**

The coherence time in amplitude and phase of stellar rotational signals may vary from a few rotations (i.e. several weeks) to many months. For example, the F8 star HD 154417 is reported by Baliunas et al. (1982) to show steady rotational modulation, with constant phase to within the errors of its period determination, for at least 280 days, or 37 rotations. This suggests that Wilson's (1978) survey may indicate whether rotational modulation remains coherent over even larger intervals. The survey data were obtained at intervals typically of the order 30 days throughout each annual observing season starting with 1966. In spite of the large sampling interval, Stinemets and Giles (1980) measured rotational modulation periods for several stars; their success also shows that there must be significant coherence times for these stars. We have therefore begun a study of Wilson's data and its extension to the present (data kindly supplied by A.H. Vaughan) for evidence of long-term coherence. The study is not yet complete, and only two stars will be discussed in this preliminary report.
HD 82885, a G8IV star, was recently found by Frazier, Lanning, and Vaughan (1981) to show rotational modulation with remarkable stability in phase and amplitude over the interval November 1980 to June 1981. The period measured for the rotation is $18.3 \pm 0.3$ days, with the precision limited mainly by the 8-month observing window (Figure 2a). Using this period and examining Wilson's survey data, we find that the entire set of observations from mid-1971 to mid-1975 was consistent with modulation with constant phase over the interval. A refined period as determined for this data set as a whole, using the period search algorithm of Lafler and Kinman (1965) is $18.49 \pm 0.05$ days. Folding the four years of data at that period yields a clearly significant periodogram (Figure 2b). Furthermore, assuming a rotation period of $18.49 \pm 0.05$ days, we find the phase shift of Frazier, Lanning, and Vaughan's 1981 periodic modulation data to be $\Delta \phi/2\pi = -0.04 \pm 0.2$. In other words, the data are consistent with phase constancy at period 18.48 days from 1971 to 1981. We note in passing that the independently determined periods of $18.49 \pm 0.05$ days for 1971-75 and $18.3 \pm 0.3$ days for 1980-81 rule out a period change during the interval (as might be produced by latitudinal migration of activity on a differentially-rotating star) greater than 2%.

Wilson's data for HD 82885 during other years are consistent with rotational modulation near 18 days, but with considerable scatter in phase from year to year. This would be understandable if the star exhibited both short-lived activity at random longitudes and long-lived or recurrent activity at a single longitude, over at least a ten-year time span.

The K5V star HD 165341 also shows evidence in Wilson's data for phase coherence over several years. The period of the star was in fact first determined from Wilson's data by Stimets and Giles (1980) to be 20.1 days. Recent data obtained by Vaughan and his colleagues (Vaughan 1982) give a more accurate period of 19.6 $\pm$ 0.3 days. We have determined the phase of Wilson's data for each observing season which best matches a continuous sinusoidal oscillation of period 19.60 days; the results are shown in Figure 3a. It is clear that the phases are not strictly constant over the fifteen-year interval 1966 to 1981, but neither are they random. There is a trend toward an increase of phase with time during the first part of the interval, and a decrease of phase during the last part. This is equivalent to a mean rotation period of about 19.68 days during the first half of the interval and 19.52 days during the second half of the interval. During this time the star exhibited a sharp rise and gradual fall of chromospheric activity, somewhat reminiscent of the solar activity cycle (Figure 3b). The sense of variation of rotational period as inferred from the phase migration during the interval is consonant with expectations if the star experiences differential rotation and latitude migration of activity similar to the Sun.

This interpretation of the data in Figure 3a is not unique. For example active areas could be rotating at the constant period of 19.68 days (dashed line in Figure 3a). In this case there would have been anomalous activity in the opposite hemisphere of the star during the years 1975 to 1978, which would have dominated the rotational modulation signal for those years. Unfortunately the existing data are too sparse to permit an unambiguous choice.
Figure 2. (a) The folded light curve, or periodogram, of H-K flux data for the interval November 1980 through June 1981, folded at a period of 18.48 days. (b) The H-K flux periodogram for November 1971 through March 1975 folded at a period of 18.48 days.

In each case the period of 18.48 days falls within the range of uncertainty of independent period determinations for the respective data sets; it also yields phase coherence over the entire data set, as shown.
Figure 3. (a) Phase shifts of Wilson's (1978) seasonal data for the star HD 165341, compared to a continuous cosine wave of period 19.60 days and zero phase at JD 2444000.0. Error bars are the phase uncertainty in a least squares fit to the seasonal data; variations in stellar surface activity also introduce phase fluctuations. The dashed line shows phase shifts expected if the plage rotation period is a constant 19.68 days. (b) Wilson's (1978) data, as updated by Vaughan (1982), showing the long-term variation of H-K emission from HD 165341. The vertical line for 1981 gives the range of H-K
between these two possibilities. All that can be definitively said at present is that in HD 165341, active longitudes preserve their identity over time-scales approaching or possibly exceeding a decade.

IV. Conclusion

The results described above are tantalizing in that, if confirmed and extended by further rotational modulation observations, they will be of obvious importance to dynamo theories of the generation of solar and stellar magnetic fields. Active longitudes have been reported for the Sun's large-scale surface magnetic field and its extension into interplanetary space, persisting for as long as five sunspot cycles, or 47 years (Svalgaard and Wilcox 1975). However, evidence for long-term phase persistence of the Sun's Ca II modulation, which is primarily associated with individual centers of activity rather than large-scale magnetic regions, is much weaker (although not absent; see for example, Dodson and Hedeman 1975, Prata 1971). Both the visibility and phase persistence of rotational modulation on several young active chromosphere stars seem considerably greater than on the Sun. Whether this difference is a fundamental one or simply a result of the enhanced visibility of chromospheric activity in younger stars is not yet clear. In any case, the persistence of active longitudes is in itself useful input to dynamo theory, and will become particularly useful when such studies are extended to many stars of different age, spectral type, and rotation rate. It is also possible that the data are already beginning to show differential rotation, either instantaneously through the presence of differentially rotating active areas (Figure 1b) or over times comparable to a stellar cycle, due to latitude migration of activity (Figure 3a). It is clear that if further rotational modulation data can be gathered for a variety of lower main sequence stars, over a large fraction of their cycles, then very significant progress can be expected in our understanding of the nature of solar and stellar magnetic activity.

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