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EVIDENCE OF DIFFERENTIAL SURFACE ROTATION IN THE SOLAR-TYPE STAR HD 114710

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ABSTRACT

Observations of the chromospheric Ca II H and K emission variability of the intermediate-age solar-type star HD 114710 (β Comae Berenices, G0 V) obtained at Mount Wilson Observatory over the past 10 years reveal a secular change in the seasonal rotation period that can be interpreted as surface differential rotation. The dependence of rotation period on chromospheric flux (i.e., activity-cycle phase) suggests that the star may have two latitudinal *zones* of activity: one in which changes in rotation period appear to follow the starspot activity cycle, and another confined to a narrow range of periods that does not. The pattern of rotation that depends on stellar cycle phase is opposite that of the Sun: the rotation period *increased* as activity declined during the last activity cycle. Active region growth and decay is ruled out as the explanation for the systematic change of the seasonal rotation periods.

Subject headings: stars: rotation — stars: activity — stars: chromospheres — stars: individual (HD 114710)

1. INTRODUCTION

Wilson's (1978) landmark observations of stellar magnetic activity cycles made with the 100 inch telescope at Mount Wilson Observatory generated an expanded program of measurements which began in 1978 with the Mount Wilson 60 inch telescope. Observations have continued on a near-nightly basis in order to intensify the sampling of Wilson's stars and thereby detect and monitor stellar rotation (Vaughan et al. 1981; Baliunas et al. 1983; Noyes et al. 1984). With over a decade of observations, it is now possible to concentrate on the seasonal change of observed rotation period with time (i.e., phase of the activity cycle) in the search for stellar surface differential rotation (DR).

A preliminary investigation of stellar DR (Baliunas et al. 1985) was based upon three seasons of observations. That survey produced a list of approximately one dozen stars whose season-to-season behavior strongly suggested the presence of DR. The limited length of those observations prevented a firm confirmation of DR.

However, nightly monitoring over the course of most (or all) of an activity cycle yields systematic changes of rotation period with cycle phase for several stars. The 10 yr baseline supports the Baliunas et al. (1985) interpretation based on a shorter segment of data of secular changes in the mean latitude of chromospheric activity as the cause of season-to-season differences of the observed rotation periods.

We present results for one star, HD 114710 (β Com, G0V), in which the rotation period depends upon the phase of the activity cycle. We also find that the contribution of active region (AR) growth and decay or uncertainty in the period determination is *not* the leading source of variance on a rotational to seasonal time scale (i.e., weeks to months) for this star.

2. OBSERVATIONS

Observations were made with the Mount Wilson Observatory 60 inch telescope and the Ca II H and K spectrophotometer (Vaughan, Preston, & Wilson 1978) which measures the emission flux centered on the Ca II H and K (396.8 nm, 393.3 nm) line cores in 0.1 nm passbands relative to two nearby 2 nm wide windows of the photospheric flux centered at 380 and 400 nm. The relative chromospheric H and K flux is defined by the activity index, S:

$$S = \alpha \frac{H + K}{V + R}, \tag{1}$$

where α is a constant that removes instrumental fluctuations (through nightly measurements of a standard lamp and standard stars) and $V + R$ is the combined flux from the two photospheric passbands. The chromospheric H and K flux variations mark the change in coverage by and field strength of magnetic surface structures (Skumanich, Smythe, & Frazer 1975; Schrijver et al. 1989; Saar & Baliunas 1992).

Observations of HD 114710 were scheduled on a near-nightly basis beginning in early 1981 and have continued to the present. The long-term activity record (including Wilson's earlier observations which have been transformed to the scale of the 60 inch data) is shown in Figure 1. HD 114710 appears to have an activity cycle period of roughly 17 yr—longer than the Sun's mean period of 11 yr. The data enclosed by the box in Figure 1 are monthly averages of the observations which were frequent enough to establish a rotation period for nearly every season (see Table 1). We have sampled rotation over roughly half of an activity cycle: from cycle maximum in 1981–1984 and down to cycle minimum, roughly in 1989. The mean level of activity, $\langle S \rangle = 0.200$, suggests that HD 114710 is younger than the Sun; Duncan (1981) infers an age of 2.1 Gyr based upon its lithium abundance and mean chromospheric emission. From the chromospheric flux-Rossby number relationship (Noyes et al. 1984) we predict a rotation period of 11.4 days.

3. ANALYSIS

Periodograms were computed based opon the method given by Scargle (1982) and Horne & Baliunas (1986). Table 1 lists each seasonal interval (col. [1]), the number of nights the star was observed within the season (col. [2]), the mean activity level, S (col. [3]), the rotation period and its uncertainty as

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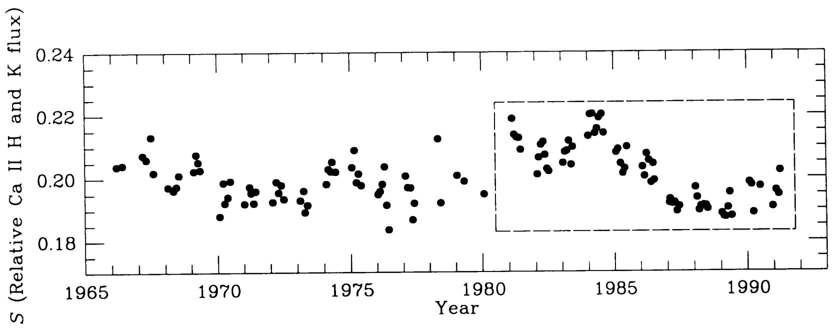

FIG. 1.—Monthly means of chromospheric activity of HD 114710 from 1966 to the present. The boxed area highlights the period of time over which sufficient sampling exists to observe rotational modulation. An activity cycle of ~17 yr is apparent. Wilson's (1978) observations have been transformed to the scale of the newer (after 1978) observations.

determined from the periodogram peak (col. [4]), the semi-amplitude of the sinusoid resulting from the periodogram analysis (col. [5], in units of S), and the "false-alarm probability" of the peak frequency (col. [6]). This last quantity estimates the likelihood a peak of that height could result from a similar sample of Gaussian noise with equal variance (see Horne & Baliunas 1986). In 1984, 1985, and 1989, no clear period was detected. Although there was substantial variability during those seasons, no significant frequency was evident in the periodogram. In such cases the variability might result from ARs at different longitudes or with short lifetimes, which would not produce coherent rotational modulation.

In several seasons (1982, 1983, and 1986) *two* rotation periods are present. The existence of the second period is established by comparing a residual periodogram with the original after filtering the signal introduced by the primary frequency (Baliunas et al. 1985).

The mean observed rotation period is roughly 12 days and in good agreement with the predicted value of 11.4 days. However, the 2.1 day range in rotation period is significantly higher ($\pm 10\ \sigma$) than the computed precision of ≤ 0.1 days. One explanation for the wide deviation of observed rotation is that surface DR occurs as a function of cycle phase over the 10 yr interval, modifying the observed period, as suggested by the initial results of Baliunas et al. (1985).

Figure 2 shows the seasonal rotation periods plus uncertainties (Table 1, col. [4]) plotted against the mean seasonal activity level (Table 1, col. [3]). The rotation periods describe two loci, both well separated from each other. The upper locus follows a linear trend of increasing rotation period during the declining phase of the activity cycle, with a highly significant linear correlation coefficient of $r = -0.96$. The probability of a random distribution (i.e., zero slope), $P(r, N)$, is only 1%. The lower locus of points is randomly distributed.

4. DISCUSSION

The direct confirmation of surface DR is not possible since the stellar disk is not spatially resolved. However, our results can be compared with the known solar DR, under the assumption that the Sun is representative of other solar-like stars and that DR would be present.

One explanation for fluctuations or large uncertainties in the observed rotation periods is that of AR evolution. The growth and decay of ARs interferes with the measurement of rotational modulation by producing *shifts* in phase and amplitude which cause frequency shifts of the peaks in the computed periodogram. Over time, a mean period of rotation is still detected, but with an uncertainty high enough that systematic departures from the mean caused by components of DR and

TABLE 1

SEASONAL INFORMATION FOR HD 114710

Julian Date Range (−2,440,000) (1)	Number of Nights Observed (2)	⟨S⟩ (3)	$P \pm \Delta P$ (days) (4)	Semi-Amplitude (S) (5)	False Alarm Probability (%) (6)
4641–4779.........	51	0.212	12.77 ± 0.06	0.006	6×10^{-9}
4992–5151.........	75	0.207	13.12 ± 0.06	0.004	8×10^{-10}
[a]			11.85 ± 0.07	0.003	4×10^{-5}
5345–5485.........	56	0.208	11.63 ± 0.05	0.005	1×10^{-11}
			12.83 ± 0.07	0.003	2×10^{-9}
5697–5922.........	39	0.217	...[b]	...	...
6086–6250.........	80	0.205	...[b]	...	...
6457–6624.........	78	0.203	11.70 ± 0.04	0.005	8×10^{-13}
[a]			13.16 ± 0.07	0.003	1×10^{-6}
6827–6970.........	40	0.192	11.77 ± 0.06	0.006	2×10^{-7}
7181–7351.........	65	0.192	11.43 ± 0.04	0.004	6×10^{-9}
7543–7687.........	40	0.190	...[b]	...	...
7917–7977.........	11	0.196	13.54 ± 0.13	0.008	1×10^{-2}

[a] Period determined from a significant second peak in the periodogram.
[b] No significant period detected.

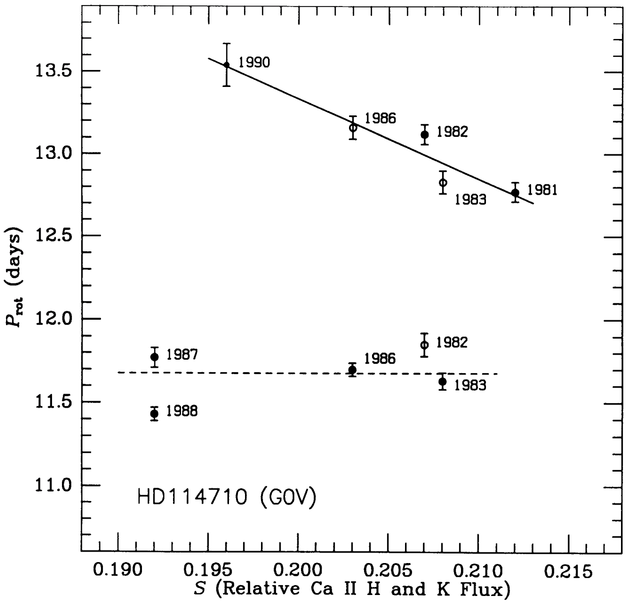

FIG. 2.—Observed periods vs. mean activity level are plotted. Two distributions are present, one nearly constant at 11.6 days, and the other near 13 days anticorrelated with stellar activity. The upper trend is interpreted as differential surface rotation with latitude. However, unlike the Sun, the rotation periods lengthen through the descending branch of the activity cycle (1981–1990).

fluctuations introduced by a signal heavily corrupted by AR evolution cannot be credibly distinguished.

Previous studies of disk-averaged measurements of solar activity were unable to reveal the solar DR (LaBonte 1982, 1984; Harvey 1984; Gilliland & Fisher 1985). All concluded that AR evolution overwhelmed the rotation signal, thereby casting doubt on the ability to infer DR from a stellar time series.

However, Dobson et al. (1990) and Donahue et al. (1992) suggested an alternate approach to this problem. They analyzed the components of variance present in the Mount Wilson chromospheric time series of lower main-sequence stars over different time scales (ranging from hr to yr) and found that it is possible in some cases to assess the relative contribution of components of variability at different time scales. Specifically, we can compare the contribution of AR evolution to that of rotational modulation.

4.1. *Pooled Variance Profile of HD 114710*

Following such an approach, we plot the variance profile of HD 114710 at several time intervals chosen arbitrarily (Fig. 3*a*). We then compare the pooled variance (Dobson et al. 1990) at 12 days (the rotational time scale) to the total variance at the seasonal observing window length (approximately 160 days). The relative contribution of the rotational amplitude to the total variance is twice as large compared to the *additional* variance on longer time scales (up to $\sim$160 days). The latter variance is presumably caused by AR evolution. Since our observing seasons are only $\sim$160 days long, the additional contributions to the variance profile from processes occurring at longer time scales (i.e., the complete AR evolution component and activity cycles) do not significantly degrade the accuracy of seasonal period determinations.

From the pooled variance profiles, we estimate the relative contributions and time scales of rotation compared to AR evolution. The mean semi-amplitude of sinusoidal fits to the data (Table 1, col. [5]) is approximately 0.0045 S units. The difference between the pooled variance computed on the time scale of rotation, $\sigma^2_{\rm rot}$, and the pooled variance at the shortest measurable time scale, $\sigma^2_{\rm base}$ (presumably instrumental, however, see Dobson (1992) for an interesting interpretation), gives a mean semi-amplitude, A, of 0.0046 S units, where

$$A = \sqrt{\sigma^2_{\rm rot} - \sigma^2_{\rm base}}\,. \qquad (2)$$

The insignificant difference between the projected and observed variance amplitudes suggests that at the rotational time scale of $\sim$12 days, the variance of the signal arises almost completely from rotation; variance attributable to AR evolution is virtually nonexistent at that time scale. Further, the increase in variance caused by AR evolution does not become noticeable until about 35 days or after $\sim$3 full rotations.

We also created simulative data with the same sampling times as the HD 114710 time series to test the variance profile of an object with rotation, activity cycle and instrumental error

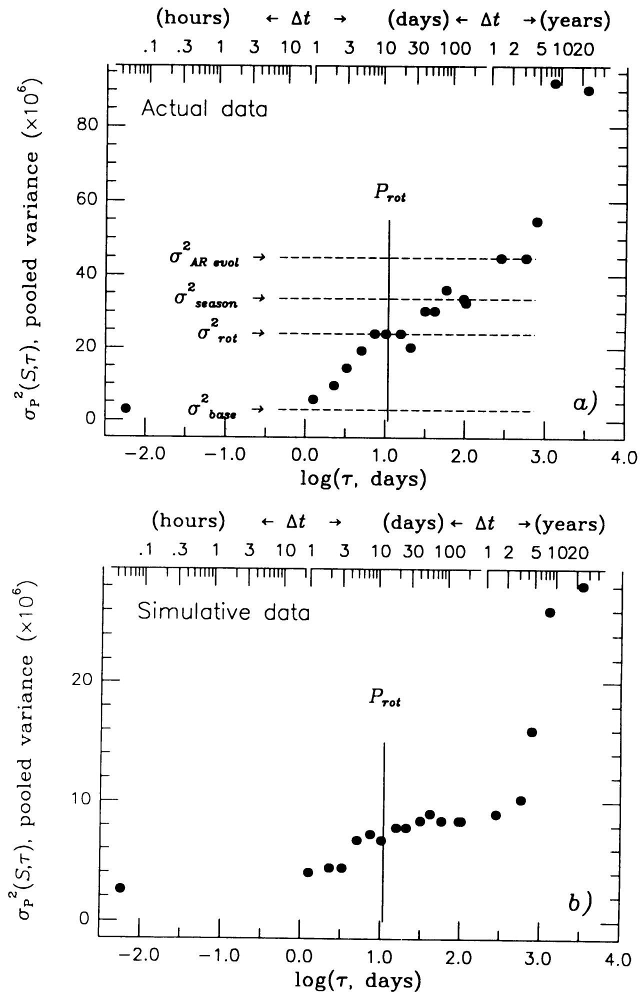

FIG. 3.—(*a*) The variance profile of HD 114710 is plotted against time scale, τ. Each datum is the mean variance within a series of bins of length τ evaluated along the entire time series. The contribution of rotation to the total variance ($\sigma^2_{\rm rot} - \sigma^2_{\rm base}$ at $\tau \sim 12$ days) is about twice as large as the variance presumably by AR evolution $\sigma^2_{\rm AR\ evol} - \sigma^2_{\rm rot}$ computed over an observing season ($\tau \sim 150$ days). (*b*) Simulative data with all the properties of the observed data except AR evolution. Comparison of this profile with the one in Fig. 3*a* shows the time scales over which AR evolution is most important.

(with the same periods and amplitudes observed for HD 114710) but *without an AR evolution component* (Fig. 3*b*). A comparison of Figures 3*a* and 3*b* shows that AR evolution *does* play a role in the real time series of HD 114710 within an observing season, but enters only at around 35 days (well beyond the rotation time scale of ~12 days) and levels off at ~400 days.

4.2. *Pooled Variance Profile of the Sun*

On the other hand, the variance profile (Dobson et al. 1990) computed from 0.1 nm passband flux measurements of the full disk of the Sun observed at Sacramento Peak Observatory (Keil & Worden 1984) is quite different from that of HD 114710. The Sun shows a much lower amplitude of rotational modulation, plus a larger *relative* contribution from AR growth and decay over time scales of 30–150 days. In fact, solar AR evolution contributes more to the total signal than rotation. At time scales of ~200 days and longer the variance reaches a plateau. Thus, the results of Dobson et al. (1990) suggest that a window size of 1 yr may be too long to be useful in the detection of the solar DR. On time scales of 1 yr, variance caused by AR growth and decay dominates the variance profile and often prevents the detection of annual rotation. A seasonal window of 160 days might be optimal because it should be short enough to limit the effects of AR evolution but long enough to cover several rotations. A reanalysis with the shorter window of the Keil & Worden (1984) solar data *does* show a change in the solar rotation period over time consistent with the corresponding change of mean latitude of ARs as a function of sunspot cycle phase (Keil, Fleck, & Donahue 1992).

4.3. *Differential Rotation in HD 114710*

A comparison of the variance profiles of the Sun and HD 114710 indicates that the ARs on HD 114710 are longer lived than their solar counterparts. Both the shorter rotation period and relatively longer lived ARs of HD 114710 allow the clearer detection of DR compared to the Sun. Figure 2 suggests a pattern of rotation in HD 114710 consistent with *two* zones of latitude, one that is constant in time, and one that follows the phase of the stellar activity cycle.

The pattern of rotation in HD 114710 in Figure 2 can be compared with known solar behavior. At the beginning of the solar cycle, activity is low and ARs appear first at high latitudes, where they mark long rotation periods. As the activity cycle waxes and then wanes, the mean latitude of ARs moves toward the equator with the fastest (shortest) rotation period occurring at the next minimum of the activity cycle. However, for HD 114710 the rotation period *increases* from cycle maximum (1981) through cycle minimum (around 1990)—that is, behavior *opposite* the Sun's. This could mean that DR has poleward acceleration, or that DR has equatorward, solar-like, acceleration but the ARs marking rotation move away from the equator over the course of an activity cycle. In either case, HD 114710 apparently shows nonsolar-like behavior either in the surface acceleration pattern or the progression of mean latitude of ARs during the cycle.

Gilman's (1980) qualitative models include a pattern that is consistent with the nonsolar behavior we have inferred for HD 114710. The bifurcation of the observed period distribution may arise when the rotational period is close to the convective turnover time and causes surface angular momentum to be transported predominantly in a radial rather than an equatorward direction.

Continued observations of HD 114710 through another activity cycle will be required to determine whether the rotation periods accurately describe a pattern which is opposite that of the Sun. In 1990, the star was near activity minimum in its cycle. Based on our analysis, we predict that the rotation period should soon show shorter periods than those seen in the upper trend in Figure 2 (but longer than the periods along the lower locus), and then should *lengthen* with increasing activity during the coming cycle, again reaching the 1981 values of rotation near the next activity maximum, circa 1998.

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