VARIATIONS IN SURFACE ACTIVITY OF THE SUN AND SOLAR-TYPE STARS

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Abstract. Twenty-five-year records of relative Ca II H and K emission fluxes of lower Main-Sequence stars have been measured at Mount Wilson Observatory and reveal surface activity in most of the older G- and K-type dwarf stars that is similar to the aperiodical activity cycle of the contemporary Sun (i.e., the cyclic and the occasional episode of reduced activity in the past few centuries). We find an inverse relationship between the amplitude of the activity cycle and the length of the cycle for the ensemble of those solar-type stars. We also find a similar relationship using the 250-year sunspot record (Cycles 1 to 21). The similarity between the two inverse relationships for the solar-type stars observed for 25 years and the Sun for a longer interval of time may suggest one common underlying physical mechanism that is responsible for the variations in surface activity ranging from decades to centuries.

1. Introduction

Magnetically active regions on the Sun can be identified by an enhancement in the intensity of the Ca II H (396.8 nm) and K (393.3 nm) chromospheric emission cores that results from non-thermal (e.g., magnetic) heating (Leighton, 1959; Skumanich, Smythe, and Frazier, 1975). Records of variations in the disk-averaged fluxes of the solar Ca II emission, produced by surface magnetic inhomogeneities, can provide information on solar rotation, the growth and decay of magnetically active areas, and the 11-year solar cycle (related to the 22-year cycle of magnetic activity; Hale, 1908; Babcock, 1961; Sheeley, 1967). Solar and geological (terrestrial 14C and 10Be isotope abundances; e.g., Damon and Sonett, 1991; Beer et al., 1990) records over several centuries show behavior ranging from cyclic with a period ≈ 11 years to virtually steady activity (such as the Maunder Minimum interval, A.D. 1645–1715; Eddy, 1976).

We wish to study whether the observed solar magnetic activity is unique or, if not, how it compares to activity in other stars. In 1966, Olin Wilson (1978) began research on those questions by monitoring the relative Ca II H and K emission fluxes (F-index) in 91 lower Main-Sequence stars at the 100-inch Hooker telescope of the Mount Wilson Observatory. In 1977, the project was transferred to the 60-inch telescope (Vaughan, Preston, and Wilson, 1978). Since 1980, observations have been scheduled on a nightly basis for the purposes of monitoring stellar chromospheric variations (S-index) that might reveal rotation periods and expanding the sample of stars observed (Vaughan et al., 1981; Baliunas, 1991). We report on recent results of the comparison between the surface activity in the Sun and

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the chromospheric activity of a subset of the Wilson sample – those stars with activity similar to that observed on the Sun. The analysis leads to a discussion of the definition of solar-type stars and what may be learned from this ensemble of results.

2. Working Definition of Solar-Type Stars

The term ‘solar-type stars’ is not a precise concept. Its imprecision arises in part because estimates of stellar age are uncertain. For example, one method of estimating age is based on the decline of the observed level of chromospheric activity with age (e.g., Soderblom, Duncan, and Johnson, 1991). However, the existence of variability of chromospheric emission, including episodes of greatly reduced activity level such as the solar Maunder Minimum interval, introduces ambiguity into the chromospheric emission-age relation, particularly for stars with activity variations similar to the Sun.

We divide the stars in the Wilson sample into two groups according to their mean level of activity and rotation: one group has high levels of average activity and fast rotation, while the other group has lower levels of activity and slower rotation (the criteria adopted produce nearly the same results as Vaughan, 1980, and Noyes et al., 1984). Such a distinction between the two stellar groups is supported by the observed relations among time-averaged level of activity, rotation and activity cycle period (Soon, Baliunas, and Zhang, 1993). The present Sun appears to fit into the second group of stars, with lower activity levels. An additional factor distinguishing the two groups is the observed reversal of the sense of the correlation between chromospheric activity and photometric variability (in the Strömgren photometric \( b \) and \( y \) passbands, centered at 472 and 551 nm, respectively; Radick, Lockwood, and Baliunas, 1990). In this respect also, the present Sun has the same characteristics as the stars in the older and less active group. We will adopt those characteristics as the working definition of a solar-type star.

3. Results

Fourteen of the less active solar-type stars in the Wilson sample have highly significant cycle periods in their surface activity. The properties for the solar-type stars used in this analysis are summarized in Table I. In Figure 1 we show the relationship between the amplitude of an activity cycle and the length of the cycle for this group of stars, in terms of the parameterized ratios \( \Delta P_{\text{HK}}/\langle P_{\text{HK}} \rangle \) (ratio of the peak-to-peak activity cycle amplitude to the 25-year averaged level of activity) and \( (P_{\text{cyc}}/P_{\text{rot}})^2 \) (square of the ratio of the activity cycle period to the rotation period). The inverse correlation between \( \Delta P_{\text{HK}}/\langle P_{\text{HK}} \rangle \) and \( \log(P_{\text{cyc}}/P_{\text{rot}})^2 \) is highly significant (with a probability of <0.001 that the null hypothesis of zero correlation is disproved).
TABLE I
Stellar quantities

<table>
<thead>
<tr>
<th>HD No.</th>
<th>B - V</th>
<th>( \log(P_{\text{cyc}} / P_{\text{rot}}) )</th>
<th>( \Delta R'<em>{\text{HK}} / \langle R'</em>{\text{HK}} \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>0.66</td>
<td>4.32</td>
<td>0.22</td>
</tr>
<tr>
<td>3651</td>
<td>0.85</td>
<td>4.12</td>
<td>0.36</td>
</tr>
<tr>
<td>4628</td>
<td>0.88</td>
<td>3.79</td>
<td>0.38</td>
</tr>
<tr>
<td>9562</td>
<td>0.64</td>
<td>&gt;4.80^a</td>
<td>0.12</td>
</tr>
<tr>
<td>10476</td>
<td>0.84</td>
<td>4.00</td>
<td>0.38</td>
</tr>
<tr>
<td>10700</td>
<td>0.72</td>
<td>&gt;4.71^a</td>
<td>0.07</td>
</tr>
<tr>
<td>16160</td>
<td>0.98</td>
<td>4.00</td>
<td>0.32</td>
</tr>
<tr>
<td>26965</td>
<td>0.82</td>
<td>3.86</td>
<td>0.38</td>
</tr>
<tr>
<td>32147</td>
<td>1.06</td>
<td>3.78</td>
<td>0.42</td>
</tr>
<tr>
<td>81809</td>
<td>0.64</td>
<td>3.72</td>
<td>0.36</td>
</tr>
<tr>
<td>103095</td>
<td>0.75</td>
<td>3.87</td>
<td>0.27</td>
</tr>
<tr>
<td>141004</td>
<td>0.60</td>
<td>&gt;4.90^a</td>
<td>0.14</td>
</tr>
<tr>
<td>143761</td>
<td>0.60</td>
<td>&gt;5.25^a</td>
<td>0.08</td>
</tr>
<tr>
<td>160346</td>
<td>0.96</td>
<td>3.68</td>
<td>0.44</td>
</tr>
<tr>
<td>166620</td>
<td>0.87</td>
<td>4.26</td>
<td>0.30</td>
</tr>
<tr>
<td>201091</td>
<td>1.18</td>
<td>3.76</td>
<td>0.32</td>
</tr>
<tr>
<td>201092</td>
<td>1.37</td>
<td>4.10</td>
<td>0.21</td>
</tr>
<tr>
<td>219834A</td>
<td>0.80</td>
<td>4.53</td>
<td>0.18</td>
</tr>
<tr>
<td>219834B</td>
<td>0.91</td>
<td>3.86</td>
<td>0.29</td>
</tr>
</tbody>
</table>

^a \( P_{\text{cyc}} \) was assumed to be at least 20 years in the low-variability stars.

For the solar-type stars, the quantities \( \langle R'_{\text{HK}} \rangle \) and \( \Delta R'_{\text{HK}} \) are directly computed from the observed Ca II H and K emission \( S \)-index time series over the past 25 years. We have converted the relative Ca II H and K emission fluxes in instrumental units of \( S \) to \( R'_{\text{HK}} \) to allow for a direct comparison of the activity levels in stars of differing masses (Middlekoop, 1982; Noyes et al., 1984). \( P_{\text{cyc}} \) and \( P_{\text{rot}} \) are the activity cycle periods and rotation periods detected from a periodogram analysis suited for an unevenly-spaced time series (Horne and Baliunas, 1986). The current (1976–1991) value of \( \Delta R'_{\text{HK}} \) for the Sun is based on the Ca II K emission (\( K \)-index) measurements from the National Solar Observatory (White and Livingston, 1981; White et al., 1992). We converted the solar \( K \) index to the \( S \) index of Mount Wilson Observatory by using \( S = 0.04 + 1.53 \times K \) (White et al., 1992). The sunspot record yields the historical series of transformed solar ratios of \( \Delta R'_{\text{HK}} / \langle R'_{\text{HK}} \rangle \) (ratios of peak-to-peak amplitude of the activity cycle to average level of activity for Cycles 1 to 21; we connected these solar points in Figure 1 to study the phase memory of the 250-year sunspot cycle). We first transformed the sunspot record into the equivalent series in \( S \), using the relation between the annual mean sunspot number, SN, and
Fig. 1. Ratio $\Delta R_{\text{HK}}'/(R_{\text{HK}}')$ versus $\log(P_{\text{cyc}}/P_{\text{rot}})^2$ for the solar-type stars with cyclic activity (derived from the 25-year records of S-index of the Mount Wilson Observatory) and the Sun (transformed from the sunspot record; the solid line connects the progression from Cycles 1 to 5 which highlights the period of high phase coherency (i.e., the ‘great solar anomaly’ discussed by Dicke, 1988) and the dotted line connects Cycles 5 to 21, which seem to be randomly distributed). The value for the current Sun (1976–1991, marked by arrow) was derived from its Ca II K record which is comparable to the stellar Ca II H and K records. Also included are four solar-type stars which exhibit low and quiescent Ca II H and K emission that resembles the solar activity during the late 17th and early 18th centuries (i.e., A.D. 1645–1715, the Maunder Minimum interval). For the four low-activity stars, we have indicated the observed $\Delta R_{\text{HK}}'/(R_{\text{HK}}')$ and lower bounds of $\log(P_{\text{cyc}}/P_{\text{rot}})^2$ (labeled with horizontal arrows, where the lower limit of $P_{\text{cyc}}$ is taken to be 20 years).

the available Ca II solar S for 1976–1991 ($S = 0.171 + 1.24 \times 10^{-4}$ SN). (See, however, Schrijver and Harvey, 1989, for a possible nonlinear relation between the solar photospheric magnetic flux and chromospheric flux within an activity cycle, which may stretch the transformed sunspot data in Figure 1 along the vertical axis). Then the record in instrumental $S$ units was converted into units of $R_{\text{HK}}'$ using the formula of Noyes et al. (1984) and the solar values of $\Delta R_{\text{HK}}'$ and $\langle R_{\text{HK}}' \rangle$ for each cycle were calculated.

The average surface rotation periods, $P_{\text{rot}}$, for Cycles 12 to 20 are from Balthasar, Vázquez, and Wöhl (1986), who derived them from the historical record of the positions of sunspot groups measured at the Royal Greenwich Observatory. The value of $P_{\text{rot}}$ for other solar cycles is taken to be 25 days.

The sunspot cycle lengths, $P_{\text{cyc}}$, are from Waldmeier (1961). We caution that some differences may exist between the cycle lengths obtained from the sunspot record and those obtained from the stellar Ca II chromospheric records. Even within the sunspot record, the cycle length measured between sunspot minima (m–m)
differs slightly from that measured between sunspot maxima (M–M) (e.g., see Gleisberg, 1944).

Although we have focused on stars with cyclic activity, the relation in Figure 1 between $\Delta R'_{\text{HK}} / \langle R'_{\text{HK}} \rangle$ and $\log(P_{\text{cyc}} / P_{\text{rot}})^2$ may extend to solar-type stars showing the other type of chromospheric activity, i.e., the low and quiescent state of variability. We have added to Figure 1 the values of $\Delta R'_{\text{HK}} / \langle R'_{\text{HK}} \rangle$ versus $\log(P_{\text{cyc}} / P_{\text{rot}})^2$ for four stars having activity that resembles the low and apparently non-variable state of solar activity during the Maunder Minimum interval. We use a lower limit of 20 years for the value of $P_{\text{cyc}}$ (approximately the length of the observing window) for these stars while their mean levels of activity, activity amplitudes and rotation periods are derived from the 25-year $S$-index time series.

4. Discussion

A previous analysis showed that the quantity $(P_{\text{cyc}} / P_{\text{rot}})^2$ is a useful parameterization of stellar chromospheric activity (Soon, Baliunas, and Zhang, 1993). If we interpret $\Delta R'_{\text{HK}} / \langle R'_{\text{HK}} \rangle$ as the fractional change in the surface magnetic flux over the activity cycle (e.g., Schrijver et al., 1989), then the relationship in Figure 1 suggests that for the Sun and solar-type stars, the fractional change in the surface magnetic flux decreases as $(P_{\text{cyc}} / P_{\text{rot}})^2$ increases.

The empirical relation in Figure 1 includes stars with cyclic variations in chromospheric activity, as well as Maunder-minimum-type activity. The relation also includes variations in individual stars observed over approximately two decades ($\sim$ 1 to 2 $P_{\text{cyc}}$) as well as variations of one star, the Sun, over centuries. The fact that the Sun and solar-type stars lie along a line in Figure 1 suggests that a single physical process produces the two types of variations in chromospheric activity over the range of time scales from decades to centuries.

Comparison of $B - V$ values in Table 1 with the points in Figure 1 reveals no systematic dependence on mass in the $\Delta R'_{\text{HK}} / \langle R'_{\text{HK}} \rangle - \log(P_{\text{cyc}} / P_{\text{rot}})^2$ relation. Age differences (in the group of older solar-type stars) on an evolutionary time scale also do not seem to have a significant effect on the relationship, as can be seen by noting in Figure 1 the close proximity of the two stars, HD 3651 and 10476, which have similar masses (i.e., $B - V$) but substantially different mean surface rotation periods $P_{\text{rot}}$ (hence different ages; the observed mean rotation periods are 44 and 35 days, respectively). However, caution is necessary because the relation between $P_{\text{rot}}$ and age may be ambiguous due to surface differential rotation. It would be useful to undertake continued observations and an extension to a larger stellar sample in order to gain a better understanding of a possible age dependence in the relationship between cycle amplitude and cycle length.
5. Additional Comments

Long-term (century scale or longer) variations in solar and stellar magnetic activity, including the Maunder-minimum-like inactivity, may be describable within the framework of nonlinear dynamics (e.g., Weiss, Cattaneo, and Jones, 1984; Belvedere, Pidatella, and Proctor, 1990; Schmalz and Stix, 1991). However, the precise physical mechanism driving the change in the behavior of the underlying magnetic field generator has not been identified.

Two complementary observational approaches are available for the further study of the behavior of solar magnetic activity over long time scales. In the first approach, observations on one star — the Sun — would be continued in the hope that the richness of the Sun’s temporal behavior would be fully sampled over a sufficiently long period. If, on the other hand, a single physical mechanism is responsible for variations on time scales of decades to centuries, as suggested above, then the full ensemble of possible variations of surface magnetic activity might be sampled in a relatively short interval of time by observing a sufficiently large number of solar-type stars.

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References