THE ASTROPHYSICAL JOURNAL, 450:896–901, 1995 September 10

ARE VARIATIONS IN THE LENGTH OF THE ACTIVITY CYCLE RELATED TO CHANGES IN BRIGHTNESS IN SOLAR-TYPE STARS?

SALLIE BALIUNAS AND WILLIE SOON
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
Received 1995 February 2; accepted 1995 March 21

ABSTRACT

We compare the average level of chromospheric activity and cycle length for solar-type stars as determined from 25 yr records of Ca II fluxes and from the sunspot record from 1750 to 1990. Both sets of data show an inverse relation between the cycle length and average activity level, with only a minor difference in the slopes. In turn, the amplitude of Ca II variability is positively correlated with the photometric brightness change during an activity cycle. The relationship between those observables provides a physical basis for the close correlation between the length of the sunspot cycle and mean terrestrial temperature over the last few centuries as shown by Friis-Christensen & Lassen.

Solar brightness variations over the last several centuries can be estimated from this relationship by including stars with low Ca II fluxes which, we assume, are in states resembling the phase of solar activity known as the Maunder minimum (circa 1645–1715). Although the value of the slope connecting the mean level of Ca II activity and the cycle length is sensitive to the statistical treatment of the data, a lower limit to the slope can be determined reliably. This lower limit yields an increase of 0.4% of solar brightness from the solar Maunder minimum to the cyclic phase of sunspot activity which immediately followed the Maunder minimum.

Subject headings: stars: activity — stars: chromospheres — stars: late-type — stars: magnetic fields — Sun: activity — sunspots

1. INTRODUCTION

In a recent study, Friis-Christensen & Lassen (1991) illustrated a correlation between the sunspot cycle length and changes in both the mean northern hemisphere or global land air temperature over the last century. The close timing between changes in the two quantities adds to the long history of evidence for the effects of solar variability on terrestrial climate change over decades to centuries (e.g., Eddy 1977a; Mitchell, Stockton, & Meko 1979; Wigley & Kelly 1990; Parker 1994). Such short timescale variations are related to near-surface magnetic changes. Those short-term variations are distinct from the variations connected with the thermal relaxation of the entire solar convective zone, which occurs on a timescale $\sim 10^5$ yr (e.g., Gough 1990), or the variations associated with the hypothesized connection between the secular changes in Earth's orbit about the Sun and climate (97, 40, and 21 kyr; Milankovitch 1941).

One possible explanation of the correlation shown by Friis-Christensen & Lassen (1991) is a climatically significant change in solar total irradiance, for which the changes in the length of the sunspot cycle are a proxy (we will not consider other possible mechanisms of solar influence on climate change, e.g., a hypothetical effect of changes in solar ultraviolet flux which would alter the dynamics of the atmosphere). We examine the possibility of solar total irradiance change linked to changes in surface magnetic activity by comparing information derived from observational results of the Sun and solar-type stars which are close in mass and age (e.g., Lockwood et al. 1992; Zhang et al. 1994; Baliunas et al. 1995).

The underlying premise in comparative studies of the Sun and other solar-type stars is stellar equivalence, i.e., that statistically similar magnetic activity behavior is the result of similar physical properties. Stellar equivalence implies that the magnetic behavior (and the associated brightness changes) of the Sun is not unique compared to its cohort of solar-type stars, and differs from other solar-type stars mainly because each star is observed over relatively short intervals (e.g., decades) and thus in different phases of its long-term (e.g., centuries) activity. It follows that observations of a large sample of solar-type stars over a limited period may reveal, in ensemble, the possible behavior of any one star, e.g., the Sun, captured in random phases of its long-term variability (e.g., Baliunas & Jastrow 1990; Soon, Baliunas, & Zhang 1994).

The approach is necessarily indirect and empirical since the interval of accurate measurements of total solar irradiance variations is still relatively short (e.g., Chapman 1987; Hudson 1988; Livingston, Wallace, & White 1988; Nishikawa 1990; Fröhlich et al. 1991). In addition, the mechanisms that produce total irradiance changes (e.g., Foukal, Harvey, & Hill 1991; Kuhn & Libbrecht 1991; Willson & Hudson 1991), i.e., whether they are caused by a net change in total energy or a redistribution of it, are incompletely understood. Nevertheless, the net modulation of total solar irradiance over a cycle is closely tied to the variability of the surface magnetic field (e.g., Spruit 1994).

2. LENGTH OF THE ACTIVITY CYCLE OF THE SUN

Sunspot records going back several centuries show two distinct classes of activity behavior—cyclic or virtually steady. Variations of cosmogenic isotopes from geological records (^{10}Be and ^{14}C, e.g., Beer et al. 1990; Damon & Sonett 1991) indicate that alternating intervals of cyclic activity and much lower activity levels have occurred for the past several millennia.

Following the analysis of Friis-Christensen & Lassen (1991), Hameed & Gong (1994) found a similar correlation back to 1750 between the length of the sunspot cycle and proxy temperatures in the lower-middle Yangtse River Valley. Hameed

& Gong (1994) found that changes in their regional temperature proxies represented mean global temperature changes quite well where the overlapping records exist.

The solar magnetic cycle is actually ~22 yr when the polarity reversal of bipolar magnetic regions between the northern and southern hemispheres is considered (Hale & Nicholson 1925). Figure 1 shows that the length of the 22 yr polarity cycle is also well correlated with terrestrial temperature, suggesting that either the 11 yr sunspot cycle or 22 yr polarity cycle may be relevant to terrestrial climate change. However, we ignore the polarity of solar magnetic activity for several reasons. First, it is not obvious what the reversal in polarity would mean energetically as a forcing to the terrestrial climate. We so far know only that solar total irradiance shows an 11 yr cycle; we do not know about a possible 22 yr cycle of irradiance change. Second, the stellar Ca II and the solar irradiance records are insensitive to polarity reversal. Third, the correlations between the length of the polarity cycle (Fig. 1) or the length of the sunspot cycle and terrestrial temperature are similar.

We use the sunspot cycle length of Waldmeier (1961), who measured the cycle length from one sunspot minimum to another. The length of the sunspot cycle, P_{cyc}, varied irregularly from 9 to 14 yr over the past 250 yr (cycles 1–21). The small dynamical difference in the sunspot cycle length measured between minima (m–m) and maxima (M–M) (e.g., see Gleissberg 1944) does not significantly alter our results.

We obtained similar results for the sunspot cycle length from a periodogram analysis using 20 yr segments of the sunspot record. The 20 yr segments resolve changes in the cycle length that are blurred over longer intervals and are also comparable in length to the records of the solar-type stars. (For a more elaborate confirmation of the detection of periods in the sunspot record, see the application of wavelet analysis by Ochadlick, Kritikos, & Giegengack 1993). The periodogram technique is also used to determine the Ca II activity cycle length for solar-type stars.

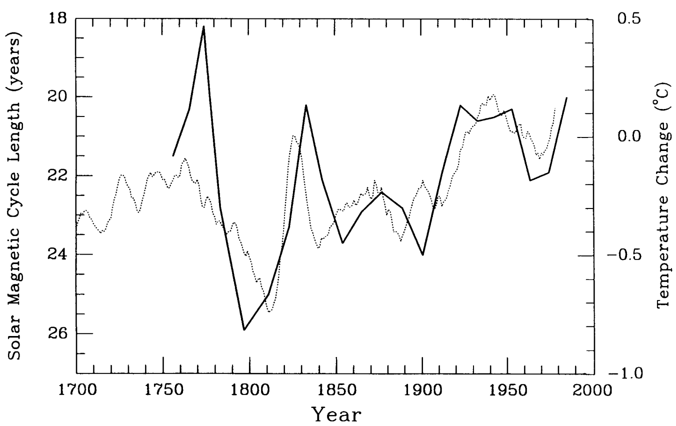

FIG. 1.—An example of the coincidence in timing and amplitude of the solar 22 yr magnetic polarity cycle and records or reconstructions of terrestrial temperature. Several other reconstructed temperatures show a similar correlation with either the length of the 11 yr or 22 yr cycle; see text. Yearly mean terrestrial northern hemisphere temperature (*dotted line*) combined from the records of Groveman & Landsberg (1979) and Jones et al. (1986). The temperature record was smoothed with an 11 yr moving average filter to emphasize long-term variations. The solid line is the length of the solar magnetic polarity cycle obtained by inverting the odd-numbered sunspot cycles (Bracewell 1953). The curve of the solar polarity cycle lengths is unsmoothed, and begins with cycle 1 in 1750. Determination of the length of the polarity cycle prior to 1750 is difficult due to the lower quality of the record (Hoyt, Schatten, & Nesme-Ribes 1994) and the indeterminancy of the cycle length in that interval.

3. ACTIVITY CYCLE LENGTHS OF SOLAR-TYPE STARS

The results on solar-type stars are based on measurements of the Ca II H (396.8 nm) and K (393.4 nm) chromospheric emission fluxes which serve as a proxy of the surface magnetic fields (Leighton 1959; Skumanich, Smythe, & Frazier 1975; Schrijver et al. 1989; Baliunas et al. 1995) and measurements of the combined photometric variability in the Strömgren *b* (centered at 471 nm) and *y* (centered at 551 nm) passbands which is a proxy of the total stellar irradiance (e.g., Lockwood et al. 1992; Zhang et al. 1994; Livingston et al. 1991 discuss other available surrogates for the total irradiance).

The Ca II fluxes in about 100 dwarf stars have been observed since 1966 at the Mount Wilson Observatory. The activity records are measurements of the fluxes in the chromospheric emission cores relative to the nearby photospheric continuum, the *S* index (Wilson 1978; Vaughan, Preston, & Wilson 1978). Twenty-five yr records (Baliunas et al. 1995) show two classes of long-term activity records in solar-type stars: cyclic (analogous to the 11 yr cycle of solar activity) or low and nonvariable (possibly similar to the Maunder minimum state). Records of the Ca II emission fluxes for all the 19 solar-type stars (including the Sun) from the survey and included in this analysis are shown in Figure 2. Those stars[1] range in mass from 1.0 to 0.5 $M_\odot$ [$0.6 \lesssim (B-V) \lesssim 1.4$, or spectral type G0V to K7V] and are older than 1–2 billion yr (see Soderblom, Duncan, & Johnson 1991) or have a rotation period, $P_{rot} \gtrsim 20$ days.

We have omitted stars with high average activity levels in order to isolate magnetic behavior that is relevant to the current Sun. The stars with high average activity levels rotate more rapidly and are much younger than the solar-type stars. In addition, the young stars show variations of activity on timescales of a decade that are materially different from those of solar-type stars (Baliunas et al. 1995). One important distinction between the young and old stars is the observed reversal of the sense of the time-serial correlation between chromospheric activity and photometric variability (Radick, Lockwood, & Baliunas 1990). All the solar-type stars for which photometric data are available show the positive correlation between changing activity and brightness (e.g., Zhang et al. 1994). That distinction is underscored by differences in the observed relations among the level of activity (averaged over 25 yr), rotation and activity cycle periods (Soon, Baliunas, & Zhang 1993a).

The existence of a periodicity, P_{cyc}, is determined from a periodogram (Scargle 1982; Horne & Baliunas 1986) computed over the 25 yr interval of observation of the solar-type stars. The estimate of the reality of a suspected frequency is based on the false alarm probability (FAP), i.e., the likelihood that the height of a specific peak in the periodogram would be as high as a peak in a periodogram computed from data whose

[1] A lower main-sequence star shows an average level of surface magnetic activity (indicated by the Ca II proxy) determined primarily by its age (through rotation and angular momentum loss) and mass (through the depth of the subsurface convective zone) and is more or less independent of initial stellar conditions (Wilson 1963; Skumanich 1972; Soderblom 1982). The narrow confines of the subsample attempt to minimize the possible influence of mass and age on the interpretation of cycle period in solar-type stars (see below).

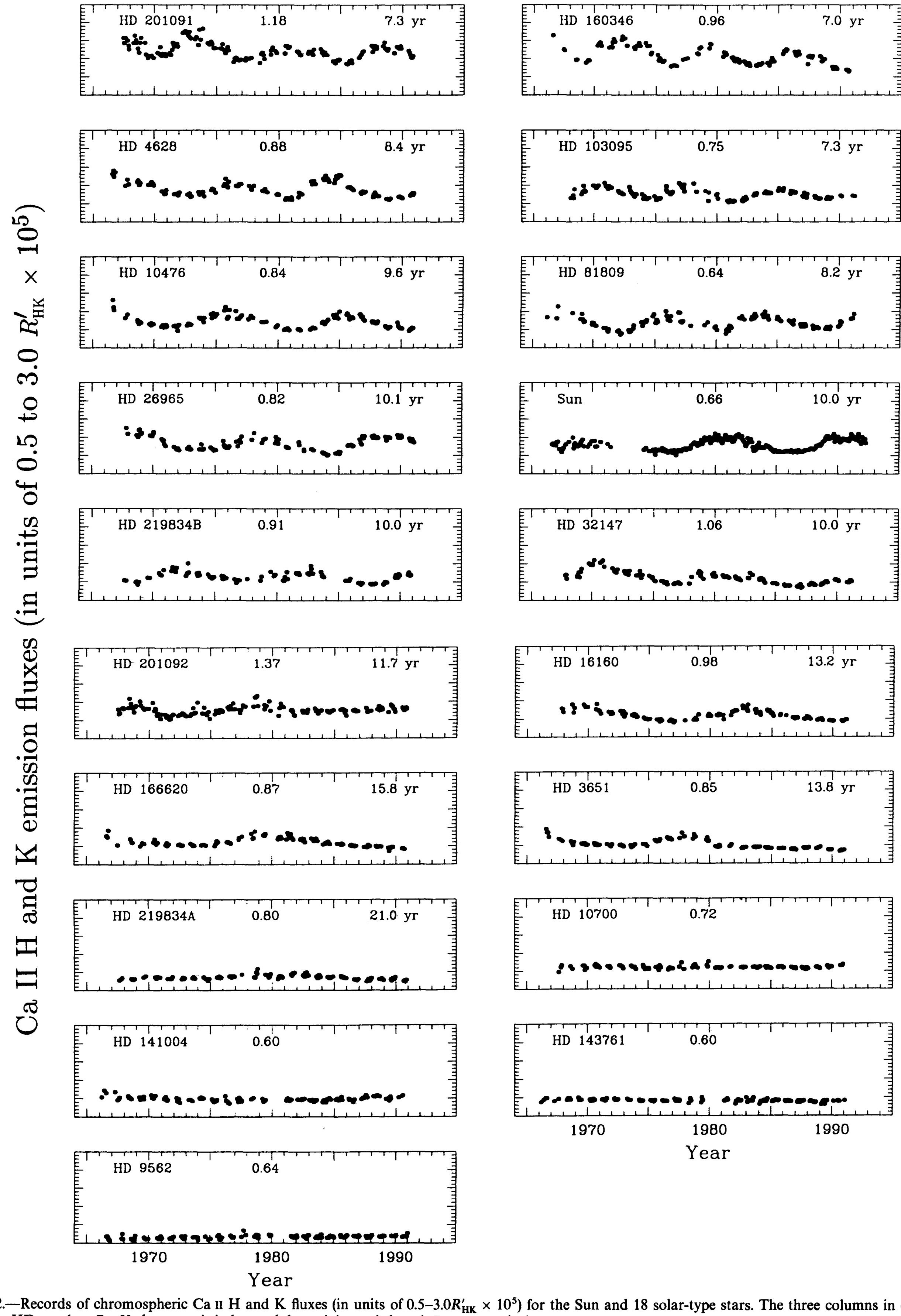

FIG. 2.—Records of chromospheric Ca II H and K fluxes (in units of 0.5–3.0R'_{HK} × 10^5) for the Sun and 18 solar-type stars. The three columns in each panel denote the HD number, $B-V$ photometric index, and the activity cycle length P_{cyc}, respectively.

variance is caused by Gaussian noise. The FAPs computed for solar-type stars in the cyclic phase are very small (FAP $\leq 10^{-7}$), indicating relatively small dispersion in amplitude and length of individual cycles over the intervals of the periodogram computation (see Baliunas et al. 1995 for additional comments).

4. MEAN LEVEL OF ACTIVITY AND ACTIVITY CYCLE LENGTH OF THE SUN AND SOLAR-TYPE STARS

The time-averaged activity level in units of R'_{HK} is inversely related to the activity cycle length, P_{cyc}, for both the sunspot record (cycles 1–21) and the Ca II records (Fig. 3). The quantity, R'_{HK}, is an estimate of the net chromospheric magnetic heating caused by the magnetic fields relative to stellar bolometric luminosity (Middlekoop 1982; Noyes et al. 1984); its use allows comparison of the activity in stars of differing masses.

The value of the time-averaged solar Ca II flux is computed from the relative Ca II K fluxes, K index, measured at the National Solar Observatory 1976–1991 (White & Livingston 1981; White et al. 1992), and converted to the S index by using $S = 0.04 + 1.53 \times K$ (White et al. 1992).

We transformed the sunspot record into the equivalent series in S by using the relation between the annual mean sunspot number, SN, and the coincident Ca II solar S for 1976–1991 (Fig. 4, $S = 0.171 + 1.2 \times 10^{-4}$ SN). Then the average value of S is calculated for each cycle 1 to 21 and converted to R'_{HK} values.

Superposed on the Ca II points in Figure 3 are bars whose lengths equal the peak-to-peak amplitudes of the variability of stellar Ca II fluxes over the past 25 yr. The *amplitude* of Ca II variability also decreases as the activity cycle length increases. An interesting result from Figure 3 is the lack of stars of cycle periods shorter than 6–7 yr, which would be revealed by the Ca II records if such short period existed. We have also indicated in Figure 3 the assumed lower bound of the activity period in the stars with very low Ca II variability. The precise location of these low-variability stars is important for lengthening the domain of the calibration of brightness

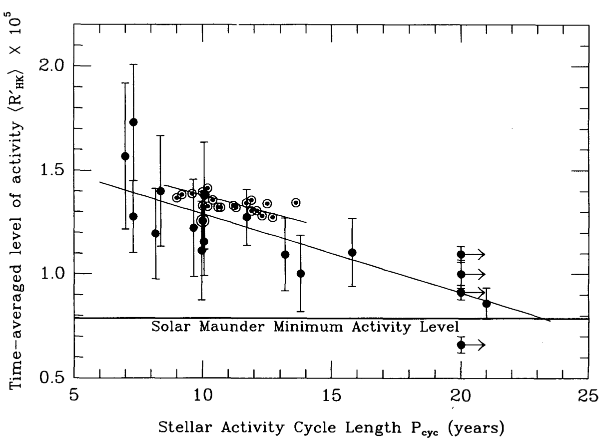

FIG. 3.—The comparison of mean level of activity, $\langle R'_{HK} \rangle$, vs. cycle length, P_{cyc}, from (*a*) records of Ca II emission in the Sun (larger dotted circle point) and solar-type stars (*filled dots*) and (*b*) sunspot cycle 1 to 21 (*dotted circle*). The observed range (peak-to-peak) of Ca II variability over 25 yr is indicated by the vertical bars which are *not* error bars. The horizontal arrows mark the lower bounds of the four low Ca II stars assuming a characteristic length of at least 20 yr. The two solid lines represent the OLS bisector linear regression through the sunspot and Ca II data (corresponding to data sets [2] and [3] in Table 1). The estimate of the solar Maunder minimum Ca II activity level is indicated by the horizontal solid line.

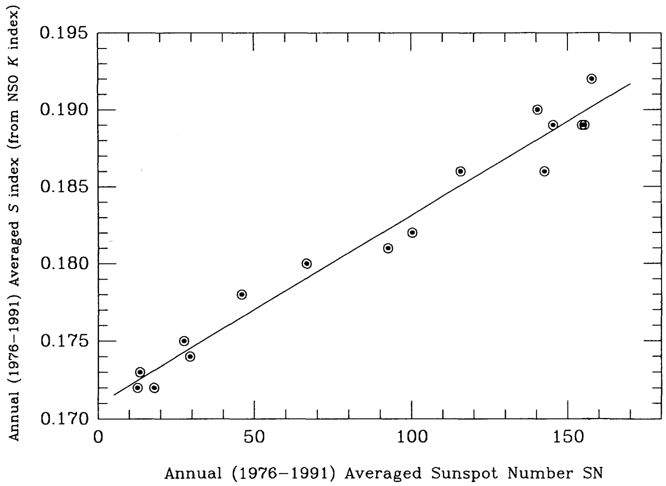

FIG. 4.—The correlation between annual mean Ca II S-index and sunspot number, SN, for the Sun (1976–1991). The solid line is the linear regression of the data ($S = 0.171 + 1.2 \times 10^{-4}$ SN).

changes and activity changes, and their quantitative influence on the correlation is discussed below.

To obtain a result from the solar-type stars relevant to the Sun, we examine the possible influence of mass and age in the correlation. Comparing stars of different $B-V$ color indices (i.e., mass for lower main-sequence stars), we find no systematic trend and conclude that the relation is essentially independent of mass. The more difficult consideration is the possible effect of age in the relation. Difficulty arises primarily because of the uncertainty in determining an accurate stellar age. One widely used empirical relation is the function fitted to time-averaged values of Ca II emission versus age (e.g., Soderblom et al. 1991). However, Figure 3 indicates that the interpretation of that relation between mean level of Ca II emission and age must have substantial uncertainty due to significant long-term Ca II variability—not only during the activity cycle, but also between Maunder minimum and cyclic phases. For example, observations of the Sun in the Maunder minimum would yield an age estimate of 8 billion yr based on its temporary state of low activity. Nonetheless, in a previous study for nearly the same group of stars, Soon et al. (1994) showed that the influence of age on the correlation presented in Figure 3 is small, implying that the relation may be best understood as random observations of different phases of Ca II activity variations occurring on timescales of centuries.

The results presented in Figure 3 indicate that for both the Sun and solar-type stars, the cycle amplitude and average level of activity increase as the cycle period shortens. Since activity variations are positively correlated with brightness changes in solar-type stars (Radick et al. 1990), the relation in Figure 3 suggests *a decrease in amplitude of solar brightness variability as the sunspot cycle length increases.* These empirical results support a causal connection between the terrestrial land air temperature change with the variations in sunspot cycle length discussed by Friis-Christensen & Lassen (1991).

5. VARIATIONS OF ACTIVITY CYCLE LENGTH AND PHOTOMETRIC BRIGHTNESS OF THE SUN AND SOLAR-TYPE STARS

In order to attempt a quantitative estimate of solar change over the past several centuries, we applied the linear regression analysis to the data sets in Figure 3 (Isobe et al. 1990). The results of both the ordinary least-squares (OLS) regression of $\langle R'_{HK} \rangle$ on P_{cyc} and the bisector OLS, which treats the two observed quantities symmetrically, are given in Table 1. The statistical significance for each fit is high, with correlations that are at least 95% confident. We prefer the results based on bisector linear regression because of its symmetric treatment of data.

The primary difficulty in estimating the total solar irradiance variation from available proxies is the determination of a suitable calibration of their *change*. One useful choice of a reference level is the Maunder minimum interval where the magnetic activity level is significantly weak. We would like to extend the concept of P_{cyc} to accommodate such a phase of solar activity. A synoptic reconstruction of the sunspot distribution (see the butterfly diagram in Fig. 6 of Ribes & Nesme-Ribes 1993) suggests that sunspots seemed to disappear completely in the northern hemisphere, and the appearance of spots in the southern hemisphere is narrowly confined between the equator and 20°S latitude. No means of measuring the "cycle" during this phase can be offered. In spite of the difficulties in defining the Maunder minimum phase in the sunspot record, we propose that a general Maunder minimum episode is a long interval (several decades) with very low average level and amplitude, similar to intervals in the Ca II records of solar-type stars. The Maunder minimum stars are the four lower bounds in Figure 3, with $P_{cyc} \gtrsim 20$ yr. Note that advanced stellar age is not necessarily the explanation of the low Ca II variability occasionally observed in solar-type stars because one very old star in our sample, HD 103095 (as indicated by its kinematics, e.g., Eggen & Sandage 1959, and metal deficiency, e.g., Soon et al. 1993b), displays cyclic variations (see Fig. 2).

The dynamic range of the sunspot number is limited and as a result, the sunspot number yields too high an estimate of the average activity level during the Maunder minimum (Eddy 1977b). Thus the low-variability stars can provide a better reference for the solar Maunder minimum phase. In order to incorporate them into the analysis, we computed the linear regression using the method for censored data (Isobe, Feigelson, & Nelson 1986). We used the nonparametric method of Buckley-James (see Isobe et al. 1986) and the EM (expectation-maximization) algorithm, which assumes normally distributed errors. Both methods yield similar results. The bisector slope of −0.038, computed using all stellar data, including the Ca II solar point, does not differ significantly from the bisector OLS slope of −0.033 for the transformed sunspot cycles.

We assumed a lower limit of characteristic length scale of 20 yr for the four stars with the low values of Ca II. If we had assumed a longer length, 25 yr, the bisector slope would have dropped to −0.028. The different slopes derived from the entire set of Ca II data are all steeper than that from the group of 14 cyclic solar type stars and the Sun of 1976–1991 (data set [1] in Table 1). We infer that the slope of −0.038 is a lower bound for the $\langle R'_{HK} \rangle$-P_{cyc} relation.

In Figure 3 we have indicated the activity level ($\langle R'_{HK} \rangle \approx 0.79 \times 10^{-5}$) of the Sun during the Maunder minimum level (Baliunas & Jastrow 1990; White et al. 1992). If we assume the results for the bisector censored linear regression (set [3] of Table 1) are representative of the Ca II emission and the activity cycle length relation, then a characteristic timescale of about 23 yr for the low Ca II phase is inferred from

$$\langle R'_{HK} \rangle = 1.670 - 0.038 P_{cyc} , \quad (1)$$

where R'_{HK} is in units of 10^{-5} and P_{cyc} is measured in years.

Increases in solar activity are associated with increases in solar total irradiance (e.g., Hickey et al. 1988; Willson & Hudson 1991). A similar positive correlation exists between the photometric brightness change and Ca II activity change for solar-type stars. One empirical relation between brightness change and activity change is

$$\Delta \text{ brightness } (\%) \approx 8.0 \times 10^4 \Delta R'_{HK} , \quad (2)$$

where $\Delta R'_{HK}$ is the amplitude of the variability in Ca II H and K emission (Zhang et al. 1994). If a typical value of $P_{cyc} = 11$ yr is adopted for the cyclic phase, then a change in brightness (or total irradiance) of ≈0.4% is estimated between the Maunder minimum and cyclic phases of solar activity, e.g., the present day.

6. DISCUSSION

Establishing the timescale of the variations in magnetic activity that occurred during the solar Maunder minimum is the key to the quantitative estimate of solar brightness changes since then. The Ca II mean flux and its amplitude of variation are robust measures of magnetic activity during the Maunder minimum–like phase, but reveal no periodicity. Physical theory or additional measurements may provide information on magnetic variations during Maunder minimum. For example, a Fourier analysis of the central England temperature record from 1659 to 1973 by Hameed & Wyant (1982) does suggest a prominent ∼21–23 yr period *during* the Maunder minimum. We independently confirmed that result using the same periodogram analysis applied to the stellar records as well as a Bayesian spectral estimation technique developed by

TABLE 1

SUMMARY OF LINEAR REGRESSION ANALYSIS OF DATA IN FIGURE 3

Group	r	OLS (Y/X) A ± SD(A)	OLS (Y/X) B ± SD(B)	OLS Bisector A ± SD(A)	OLS Bisector B ± SD(B)
(1) $n = 15$; Ca II records[a]	−0.770	1.725 (±0.118)	−0.044 (±0.009)	1.890 (±0.158)	−0.060 (±0.014)
(2) $n = 21$; sunspot record[a]	−0.616	1.544 (±0.064)	−0.018 (±0.006)	1.710 (±0.050)	−0.033 (±0.004)
(3) $n = 19$; records[b]	...	1.550	−0.026 (±0.011)	1.670	−0.038[c]

NOTE.—r: Pearson correlation coefficient; OLS: ordinary least squares; A: intercept; B; slope; SD; standard deviation.

[a] Computed with the linear regression analysis package of Isobe et al. 1990.

[b] The data set consists of the 15 cyclic stars in group (1) plus the four low Ca II variability stars for which we assumed a lower limit of $P_{cyc} \gtrsim 20$ yr. The nonparametric linear regression method of Buckley-James for censored data was used (Isobe et al. 1986).

[c] The slope for the censored, bisector-OLS method was calculated using the formula given by Isobe et al. 1990; the OLS(X/Y) slope was calculated from the same Buckley-James censored data linear regression analysis as for OLS(Y/X).

Macaulay (1992), although a terrestrial origin of the timescale of the temperature record cannot be discounted (see e.g., Allen & Smith 1994).

Since surface activity similar to that on the Sun also occurs on other solar-type stars, solar surface activity is *nonunique* and quantitative estimates of changes in solar magnetic activity and related surface phenomena may be provided by observations of solar-type stars. The two distinct phases of activity—cyclic and Maunder minimum—in solar-type stars can be unified by considering the record of solar activity over centuries. We estimate the total solar irradiance change over the past 350 yr to be 0.4% based on the changes in the length of the activity cycle in solar-type stars, although the result depends on the uncertain timescale of variability during the Maunder minimum phase. This estimate is consistent with estimates of the range of solar irradiance change of 0.2%–0.6% over the same time interval based on the variation in the average Ca II flux (Zhang et al. 1994). These quantitative links between average activity level, length of cycle period, and brightness change in solar-type stars suggest that the Friis-Christensen & Lassen relation between sunspot cycle length and terrestrial mean temperature change is not a coincidence and has physical significance.

We thank Eric Feigelson who kindly provided the computer programs for the linear regression analysis used in this work. We thank Vincent Macaulay for sending us the central England temperature record and for performing the Bayesian spectral analysis. We also thank our collaborators Wes Lockwood, Richard Radick, and Qizhou Zhang for sharing their knowledge on the subject of solar and stellar variability. The dedicated efforts of our colleagues at Mount Wilson Observatory are the primary strength of this work.

This work was supported by the Electric Power Research Institute, the Mobil Foundation Inc., the Richard C. Lounsbery Foundation, the Scholarly Studies Program, Langley-Abbot, and James Author funds of the Smithsonian Institution, American Petroleum Institute, and the Center for Excellence in Information Systems at Tennessee State University. This research was based on observations made possible by a collaborative agreement between the Carnegie Institution of Washington and Mount Wilson Institute.

REFERENCES

Allen, M. R., & Smith, L. A. 1994, Geophys. Res. Lett., 21, 883
Baliunas, S. L., et al. 1995, ApJ, 438, 269
Baliunas, S. L., & Jastrow, R. 1990, Nature, 348, 520
Beer, J., et al. 1990, Nature, 347, 164
Bracewell, R. N. 1953, Nature, 171, 649
Chapman, G. A. 1987, ARA&A, 25, 633
Damon, P. E., & Sonett, C. P. 1991, in The Sun in Time, ed. C. P. Sonett, M. S. Giampapa, & M. S. Matthews (Tucson: Univ. Arizona Press), 360
Eddy, J. A. 1977a, Clim. Change, 1, 173
———. 1977b, in The Solar Output and Its Variation, ed. O. R. White (Boulder: Colorado Associated Univ. Press), 51
Eggen, O. J., & Sandage, A. R. 1959, MNRAS, 119, 255
Foukal, P., Harvey, K., & Hill, F. 1991, ApJ, 383, L89
Friis-Christensen, E., & Lassen, K. 1991, Science, 254, 698
Fröhlich, C., Foukal, P. V., Hickey, J. R., Hudson, H. S., & Willson, R. C. 1991, in The Sun in Time, ed. C. P. Sonett, M. S. Giampapa, & M. S. Matthews (Tucson: Univ. Arizona Press), 11
Gleissberg, W. 1944, Terr. Magn. Atmos. Electr., 49, 243
Gough, D. O. 1990, Phil. Trans. Roy. Soc. Lond. A, 330, 627
Groveman, B. S., & Landsberg, H. E. 1979, Geophys. Res. Lett., 6, 767
Hale, G. E., & Nicholson, S. B. 1925, ApJ, 62, 270
Hameed, S., & Gong, G. 1994, Geophys. Res. Lett., 21, 2693
Hameed, S., & Wyant, P. 1982, Geophys. Res. Lett., 9, 83
Hickey, J. R., Alton, B. M., Kyle, H. L., & Major, E. R. 1988, Adv. Space Res., 8, 5
Horne, J. H., & Baliunas, S. L. 1986, ApJ, 302, 757
Hoyt, D. V., Schatten, K. H., & Nesme-Ribes, E. 1994, Geophys. Res. Lett., 21, 2067
Hudson, H. S. 1988, ARA&A, 26, 473
Isobe, T., Feigelson, E. D., Akritas, M. G., & Babu, G. J. 1990, ApJ, 364, 104
Isobe, T., Feigelson, E. D., & Nelson, P. I. 1986, ApJ, 306, 490
Jones, P. D., Raper, S. C. B., Bradley, R. S., Diaz, H. F., Kelly, P. M., & Wigley, T. M. L. 1986, J. Clim. Appl. Meteorol., 25, 161
Kuhn, J. R., & Libbrecht, K. G. 1991, ApJ, 381, L35
Leighton, R. B. 1959, ApJ, 130, 366
Livingston, W. C., Donnelly, R. F., Grigoryev, V., Demidov, M. L., Lean, J., Steffen, M., White, O. R., & Willson, R. L. 1991, in Solar Interior and Atmosphere, ed. A. N. Cox, W. C. Livingston, & M. S. Matthews (Tucson: Univ. Arizona Press), 1109
Livingston, W. C., Wallace, L., & White, O. R. 1988, Science, 240, 1765
Lockwood, G. W., Skiff, B. A., Baliunas, S. L., & Radick, R. R. 1992, Nature, 360, 653
Macaulay, V. A. 1992, Ph.D. thesis, Univ. Oxford
Middlekoop, F. 1982, A&A, 107, 31
Milankovitch, M. M. 1941, Canon of Insolation and the Ice-Age Problem (in German) (Beograd: Royal Serbian Acad. Publ. 132 [English transl. by the Israel Program for Scientific Translations, Jerusalem, 1969])
Mitchell, J. M., Jr., Stockton, C. W., & Meko, D. M. 1979, in Solar-Terrestrial Influences on Weather and Climate, ed. B. M. McCormac & T. A. Seliga (Dordrecht: Reidel), 125
Nishikawa, J. 1990, ApJ, 359, 235
Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Ochadlick, A. R., Kritikos, H. N., & Giegengack, R. 1993, Geophys. Res. Lett., 20, 1471
Parker, E. N. 1994, J. Geophys. Res., 99, 19155
Radick, R. R., Lockwood, G. W., & Baliunas, S. L. 1990, Science, 247, 39
Ribes, J. C., & Nesme-Ribes, E. 1993, A&A, 276, 549
Scargle, J. D. 1982, ApJ, 263, 835
Schrijver, C. J., Cote, J., Zwaan, C., & Saar, S. H. 1989, ApJ, 337, 964
Skumanich, A. 1972, 171, 565
Skumanich, A., Smythe, C., & Frazier, E. N. 1975, ApJ, 200, 747
Soderblom, D. R. 1982, ApJ, 263, 239
Soderblom, D. R., Duncan, D. K., & Johnson, D. R. 1991, ApJ, 375, 722
Soon, W. H., Baliunas, S. L., & Zhang, Q. 1993a, ApJ, 414, L33
———. 1994, Sol. Phys., 154, 385
Soon, W. H., Zhang, Q., Baliunas, S. L., & Kurucz, R. L. 1993b, ApJ, 416, 787
Spruit, H. C. 1994, in The Solar Engine and Its Influence on Terrestrial Atmosphere and Climate, ed. E. Nesme-Ribes (Berlin: Springer), 102
Vaughan, A. H., Preston, G. W., & Wilson, O. C. 1978, PASP, 90, 267
Waldmeier, M. 1961, The Sunspot Activity in the Years 1610–1960 (Zurich: Schulthess)
White, O. R., & Livingston, W. C. 1981, ApJ, 249, 798
White, O. R., Skumanich, A., Lean, J., Livingston, W. C., & Keil, S. L. 1992, PASP, 104, 1139
Wigley, T. M. L., & Kelly, P. M. 1990, Phil. Trans. R. Soc. Lond. A, 330, 547
Willson, R. C., & Hudson, H. S. 1991, Nature, 351, 42
Wilson, O. C. 1963, ApJ, 138, 832
———. 1978, ApJ, 226, 379
Zhang, Q., Soon, W. H., Baliunas, S. L., Lockwood, G. W., Skiff, B. A., & Radick, R. R. 1994, ApJ, 427, L111