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THE CHROMOSPHERIC ACTIVITY AND VARIABILITY OF CYCLING AND FLAT ACTIVITY SOLAR-ANALOG STARS

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ABSTRACT

We present an analysis of more than 3700 observations of the Ca II H and K lines in 57 Sun-like stars and over 3000 analogous observations of the Sun. Ten of the 57 stars under consideration are observed in flat states, but these stars do not always exhibit overall Ca II H and K core brightness below that of solar minimum. Solar activity minimum lies near the lowest level observed for stars with cyclic or irregular variability, but many flat stars have HK activity levels comparable to or exceeding that of solar minimum. While flat activity stars may be in periods of extended activity minima analogous to the solar Maunder minimum, a significant reduction in magnetic activity during such periods is not implied (although it is also not rejected) by the data.

Subject headings: stars: activity — Sun: activity

1. INTRODUCTION

In the past quarter century, major efforts have been made to understand the Sun's role in climate change, spurred in large part by Eddy (1976), who coined the term "Maunder minimum" to describe the period between 1645 and 1715 during which solar activity was greatly reduced and which coincides neatly with one of the severe episodes of the so-called Little Ice Age. Space-based measurements of the total solar irradiance (TSI) began in 1978 with the Earth Radiation Budget Experiment aboard *Nimbus 7* (Hoyt et al. 1992), which allowed workers to attempt reconstructions of long-term solar irradiance by connecting the TSI data with proxies (such as the sunspot number) for which longer time series are available (Lean & Foukal 1988; Foukal & Lean 1990).

Foukal & Lean (1990), among others, have noted that the well-determined 0.1% TSI excursion from solar minimum to maximum (Willson & Hudson 1988; Fröhlich 2000) appears quite insufficient to account for the observed rise in global temperature over the past century. If the Sun is the dominant driver of recent global warming, either the effects of its 0.1% variation must be significantly underestimated by present models, or it must be capable of larger variations than have been directly observed since 1978.

A suggestion that the latter possibility may be the case appears in a widely cited paper by Baliunas & Jastrow (1990; hereafter BJ90). These authors used data series from the Mount Wilson Observatory (MWO) stellar cycles program to examine the Ca II H and K behavior in a set of Sun-like stars, measured using the familiar activity index *S*. Their paper has two essential results. First, approximately one-third (4 out of 13) of the stars with extended time series displayed flat or nearly flat activity records. This agreed well, in a statistical sense, with the inferred record of solar activity over the past 1000 yr, which suggests the Sun may have spent about one-third of that time in a noncycling state (Eddy 1977), although it was noted thereafter (Saar & Baliunas 1992; Baliunas et al. 1998) that in the full MWO records, only about 15% of stars had flat time series. Second, the stars with flat activity records also showed Ca II H and K activity levels below that of solar minimum. Since the TSI is positively correlated with magnetic activity level, BJ90's result suggests that Sun-like stars (and, by inference, the Sun) may become fainter in Maunder minimum states by considerably more than their cycle excursion variability.

These results were extended quantitatively to the solar context (White et al. 1992; Lean et al. 1992) with the result that if the reduction in overall magnetic activity found by BJ90 is used to reconstruct long-term solar irradiance variations, the TSI may have been as much as 0.24% lower during the Sun's Maunder minimum than at its present cycle mean—a much larger excursion than currently observed by TSI experiments, possibly accounting for half of the observed global warming since 1860 and one-third of the warming since 1970 (Lean et al. 1995).

We have revisited this issue using 10 yr of data collected with the Solar-Stellar Spectrograph (SSS) at Lowell Observatory in Flagstaff, Arizona. Using a larger sample of well-observed stars, we find that the essential feature of the BJ90 stellar activity ensemble, a distinct difference between the activity level of cycling stars versus that of flat stars that leads to a bimodal activity distribution, is not recovered. The distributions of Ca II H and K core brightness in cycling and flat stars are identical at a very high confidence level. In this paper we present these results and discuss their implications.

2. OBSERVATIONS AND DATA CALIBRATION

2.1. *Target List and Observing Protocol*

We have monitored the chromospheric emission level and variability of the Sun and 300 Sun-like stars with the SSS since 1994. Our instrument is a fiber-fed dual spectrograph. One spectrograph operates in Littrow mode, obtaining spectra of the Sun and stars from $\lambda\lambda 3860$ to 4010 Å, and the other is an echelle covering 19 spectral orders in the optical and near-IR region from $\lambda\lambda 5100$ to 9000 Å with 70% coverage and resolution $\Delta\lambda/\lambda \approx 12{,}000$. The 20 spectral orders imaged from the two cameras are combined by the control software into a single frame for reduction and analysis. We obtain observations of the Sun using an optical fiber mounted in an enclosure on the south side of the telescope dome, while starlight is directed during nighttime observations into an identical fiber at the 1.1 m telescope focus. The light paths are arranged so that sunlight and starlight are directed into the instrument through the same input, allowing direct comparison of the solar and stellar spectra.

We have presented a detailed description of the instrument and its characteristics (Hall & Lockwood 1995).

Our target list consists of approximately 300 stars with a limiting visual magnitude of 7.1. The list includes two sets of stars: Sun-like stars, e.g., dwarfs with near-solar temperature ($0.58 \leq B - V \leq 0.72$, bracketing the solar value of 0.65), and a set of dwarfs or marginally evolved stars covering a broader range of temperatures (the warmest star on our program is Procyon, F5 IV-V, $B - V = 0.42$, and the coolest is 61 Cygni B, K7 V, $B - V = 1.37$). We observe the first set of about 100 stars intensively, obtaining many observations each observing season to characterize their time variability, and we observe the second set up to three times per season to obtain a complementary snapshot of stellar chromospheric behavior from spectral types F through K. Typically, a 10 minute exposure is required to obtain an adequately exposed spectrum for a star of $V = 5.0$. The solar and stellar data are self-consistent, being reduced identically from fiber-fed observations using a mechanically and thermally isolated spectrograph.

Throughout our program, we have refined our observing priority list to emphasize the stars within our instrument's grasp that most closely resemble the Sun. Cayrel de Strobel (1996) has defined the terms "solarlike star," "solar analog," and "solar twin" as progressively restrictive descriptions of a truly Sun-like star, where "solar twin" means a star nearly indistinguishable from the Sun in all its pertinent gross characteristics. We concur, and we extend the requirement of "twin-ness" to include not only a snapshot of a star's behavior but also its time variability. The best (and, by the most restrictive definition, the only) known solar twin is 18 Sco (= HD 146233; Porto de Mello & da Silva 1997). Details regarding the data sets for the stars under consideration in this paper appear in the discussion in § 3.

2.2. *Calibration of SSS to MWO Data*

We have calibrated our data to the MWO S index, the measure of chromospheric activity employed by the largest and longest-running stellar cycles program (Baliunas et al. 1995, hereafter B95; Wilson 1978). The S index is a dimensionless quantity proportional to the total flux in the Ca II H and K line cores divided by the flux in two nearby reference continuum bandpasses. It therefore contains a color term arising from the temperature dependence of the stellar continua. We (Hall & Lockwood 1995) have discussed at length how we place our data on an absolute intensity scale for subsequent calibration to absolute flux units via empirical flux scales (Hall 1996). Conversion of S to flux has engendered a long discussion (Middelkoop 1982; Oranje 1983; Rutten 1984; Schrijver et al. 1989). Hall & Lockwood (1995) reviewed the issue and established a conversion that correctly places both the Sun and Sun-like stars on a mutually consistent scale. The raw solar Ca II K indices from our data set also agree well with the equivalent National Solar Observatory (NSO) K index (e.g., White & Livingston 1981).

Using the method described by Hall & Lockwood (1995), we have calculated S values from the SSS Ca II H and K core fluxes. This conversion depends on $B - V$, $T_{\rm eff}$, and the raw measured HK indices. We determine effective temperatures using a log-linear relation with $B - V$ analogous to that used by Noyes et al. (1984); our relation, $\log T_{\rm eff} = 3.923 - 0.247(B - V)$, yields values of $T_{\rm eff}$ that are uniformly about 1% warmer than those of the Noyes et al. (1984) relation but agree more closely with the solar $T_{\rm eff}$ of 5780 K for $(B - V)_{\odot} = 0.65$. For consistency with B95, we use the same $B - V$ values as in that paper for all our target stars that overlap the MWO target set; other values were taken from the catalog of Nicolet (1978).

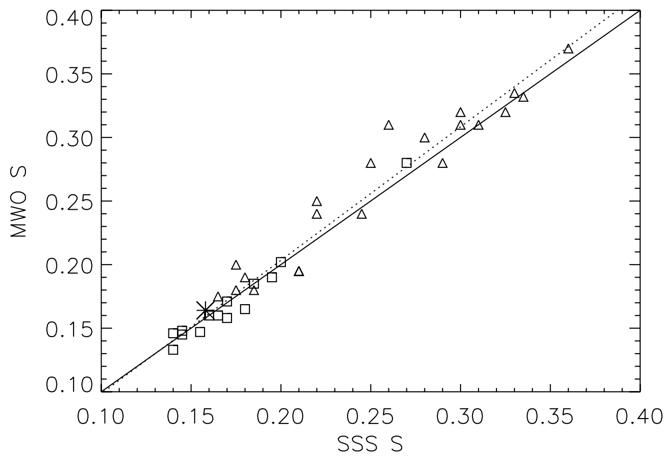

FIG. 1.—Derived SSS S values versus measured MWO S values. Solar minimum is shown with an asterisk, and we have qualitatively divided the 34 overlapping SSS/MWO stars into low-variability (*squares*) and high-variability (*triangles*) subsets. The solid line shows a perfect correlation; the dashed line is the linear regression of the SSS and MWO S values. Our derived S values agree well with the MWO data for the Sun and stars.

In Figure 1, we display our derived mean values of S compared with directly measured mean S for 34 stars on the MWO program for which the MWO and SSS data sets overlap with a significant number of observations. The Sun is marked with an asterisk, and for this figure we have qualitatively divided the stars into low-variability (total amplitude of variations in seasonal mean S less than or equal to that of the Sun, shown by squares) and high-variability (*triangles*) subsets. The solid line shows a perfect correspondence, while the dashed line is the linear regression of our S values to the MWO values; we find $S_{\rm SSS} = -0.006 + 1.048 S_{\rm MWO}$. The standard deviation on the overall fit is 0.015 in S, while that for the low-variability stars is only 0.006 in S. The variance in the fit to the low variability should arise from random errors, stellar variability, and uncertainty in the flux-S conversion. The use of the mean $\langle S \rangle$ for each star reduces the first source by $\sqrt{N}$, where N ranges from 60 to 250 for the stars used in Figure 1, and the second source is small (<3%) for low-variability stars. The variance of 0.006 is, therefore, a good estimate of any "smearing" of the activity distribution introduced by the flux-S conversion. The uncertainty in our individual measurements is about 3%, so for $S = 0.160$ we estimate the total uncertainty of our derived S values for individual measurements to be ± 0.0075.

3. DISCUSSION

3.1. *Maunder Minimum Stars*

It is well established that relative to stars of its activity level, the Sun has a vigorous chromospheric activity cycle but is photometrically sedate—more so than almost any other star of its effective temperature and activity level (Radick et al. 1998). (The solar twin 18 Sco recently had its twin status reinforced with the discovery that its photometric variations may be as small as the Sun's [Lockwood et al. 2003]. However, despite this pronounced broadband inactivity, 18 Sco has a noticeable activity cycle [Hall & Lockwood 2000].)

BJ90 suggested that roughly one-third of Sun-like stars have been sampled in Maunder minimum-like phases in which the Maunder minimum candidates exhibited (1) S values consistently below solar minimum and (2) a flat time series. These authors used data from extended time series of nine cycling stars and four magnetically flat stars and found that cycling stars, like the Sun, exhibit magnetic minima comparable to the value of S at solar minimum (0.164), while magnetically flat stars lie in a somewhat lower state, around $\langle S \rangle = 0.145-0.158$, with few stars exhibiting intermediate levels of chromospheric activity. The distribution of activity obtained was bimodal, with a roughly Gaussian envelope of cycling stars centered near $S = 0.170$ and a separate, narrow distribution centered near $S = 0.145$.

Much of the flux contribution to S in low-activity stars is not related to the dynamo-induced activity cycle but is the result of photospheric, mechanical, or quiet network emission. Since the lowest observed value of S for stars with $T_{\rm eff}$ comparable to the Sun is roughly 0.140, this value has been adopted as an estimate of the contribution to S by these noncyclic sources (Schrijver et al. 1989; Schrijver 1995). If the flux in S above this baseline value is a good measure of the star's overall magnetic activity, then the implied difference in magnetic activity for a star with $S = 0.160$ and a star with $S = 0.145$ may be significant. In this case, BJ90's data suggest that cycling Sun-like stars may undergo a transition to a physically different Maunder minimum level of magnetic activity of as little as 25% of that of solar minimum, with a frequency approximately similar to that exhibited by the Sun over the past 1000 yr. Accompanying this transition might be a change in the star's brightness in excess of the currently observed 0.1%, since the total irradiance is directly correlated to the magnetic activity level for both the Sun (e.g., Fröhlich 2000) and solar-age stars (Radick et al. 1998).

Complicating this issue is the open question of just how inactive the Sun was during the Maunder minimum. There is evidence that flat-activity MWO stars may be in "grand" magnetic minima analogous to the solar Maunder minimum, i.e., that they are cycling stars undergoing a temporary near-cessation of cyclic activity (Saar 1998). However, it seems likely that the solar activity cycle continued to operate throughout the period (although at a much reduced level; Beer et al. 1998). We must therefore carefully consider what constitutes a Maunder minimum star in the sense exhibited by the Sun during its Maunder minimum phase (and, by proxy inference, at other times in the past millennium).

3.2. *Flat Activity Stars in the Original Sample*

The data set presented by BJ90 includes extended (23 yr) samples of four stars they term "flat": HD 3795, HD 9562, HD 43587, and HD 143761. We have observed all of these, and three of them (all except HD 3795) are part of our regular observing program. Since these stars constitute the basis for comparison of our data with flat MWO stars, we discuss them briefly.

HD 3795.—BJ90 give this star $\langle S \rangle = 0.158$, and B95 classify it as "Var." The record for this star shows varying seasonal mean S values between about 0.152 and 0.160, or a variability amplitude of roughly 5%. The "Var" classification is well justified in light of the more rigorous classification of "flat activity" of $\sigma(\langle S \rangle)/\langle S \rangle \leq 1.5\%$ adopted by B95 and used in our discussion below). Our observations of this star agree almost perfectly with the MWO data, with a derived S of 0.160.

HD 9562.—This star is classified as "Long" by B95. It is quoted in BJ90 as having $\langle S \rangle = 0.146$ but shows a possible very slow rise in S from 0.135 to about 0.140 between 1966 and 1991 in the B95 time series. Our time series is essentially flat at a derived S of 0.145 between 1997 and 2003, in close agreement with the MWO data. However, this star is probably marginally evolved (Hoffleit & Warren 1991), so it is likely not a solar analog candidate by the definition of Cayrel de Strobel (1996).

HD 43587.—Classified as "Flat?" by B95, this star has $\langle S \rangle = 0.158$ (BJ90). Our derived S is somewhat higher, about 0.167, and exhibits a very slow secular rise over eight observing seasons.

HD 143761.—Also classified as "Long" by B95, this star drifts slowly from $S \approx 0.155$ in 1966 to $S \approx 0.150$ in the time series in B95; BJ90 give $\langle S \rangle = 0.147$. Our data series shows a slow rise at a derived $\langle S \rangle$ of 0.155.

The Sun.—For comparison, we briefly discuss the Sun. The MWO data yield $S = 0.164$ at solar minimum, with $\langle S \rangle = 0.179$ for data from solar cycles 21 and 22 (B95). The SSS data, which begin near the end of cycle 22, yield a derived mean seasonal S at solar minimum of about 0.162, rising to $S \approx 0.175$ at the solar maximum of 2000–2001. This amplitude of 0.13 in S is noticeably less than that reported by B95 for the stronger cycle 22.

There are some important points in the summaries above. First, the difference in the SSS and MWO S for HD 43587 is significant; where the MWO data suggest that HD 43587's activity lies close to solar minimum, our data place it higher, well within the excursion of the solar cycle yet still only marginally variable. Taken by itself, this might be passed over as an example of the inevitable scatter between ensemble members of a directly measured quantity versus a derived value of that quantity. As we will discuss below, however, we find many stars in our present sample that meet the adopted criterion of being "flat" (i.e., variability amplitude of 1.5% or less, similar to the B95 definition of a flat star noted in their Table 2) that have mean derived S of 0.180 or even 0.185.

Second, since HD 3795 and HD 43587 are found in both the MWO and SSS data to lie in the lowest bins of the solar distribution, they do not contribute significantly to the low-activity spike in the BJ90 bimodal distribution. This low-activity spike therefore incorporates the extended samples of only two stars (HD 9562 and HD 143761), one of which (HD 9562) is likely evolved.

Third, there are small differences in the quoted $\langle S \rangle$ in BJ90 and B95 for HD 9562 (0.146 versus 0.136) and HD 143761 (0.147 versus 0.150) that would smear the original BJ90 low-activity distribution. Revised reductions of the difficult Ca II H and K data are entirely reasonable; we have had to do the same with the SSS data as very low level, long-term instrumental effects became apparent after several observing seasons. As is obvious from the numbers quoted above, as well as in our own experience with the SSS data, such recalibrations do not produce radical changes in S or in the internal self-consistency of the time series for a given star, but they may result in small changes that compromise results based on a very limited number of stars.

The small number of stars involved in constructing the original distribution, as well the presence of flat or nearly flat stars in the SSS data set distributed throughout the solar activity excursion, prompted us to revisit the overall distribution of activity in Sun-like stars.

3.3. *Reexamining the Distribution*

Our HK data, converted to the MWO S index, do not recover the BJ90 bimodal distribution. In Figure 2, we show the histogram of derived S indices of 3709 observations of 57 of the most nearly Sun-like stars in our target list. For this analysis, we used those stars in our sample that fall within the same color range used by BJ90 ($0.60 \leq B - V \leq 0.76$) and within the

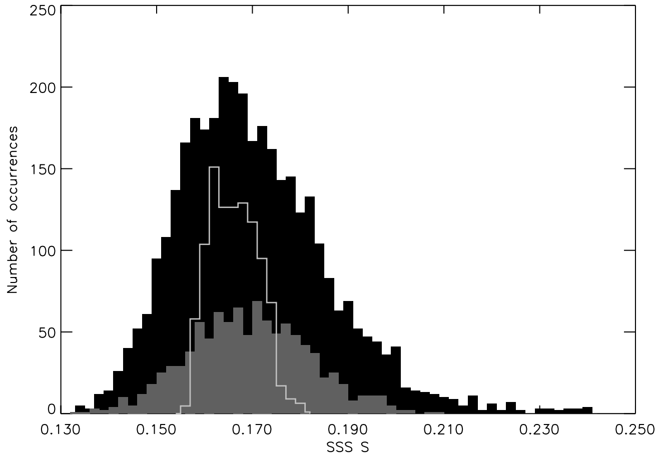

FIG. 2.—Distribution of chromospheric activity in 57 Sun-like stars. The black histogram shows 3709 individual observations for all the stars in the sample. The superimposed gray histogram shows only those observations for the 10 stars classified as "flat." The white-outline histogram shows our 3038 direct measurements of the solar HK emission converted to S and scaled down by a factor of 3 to fit on the plot.

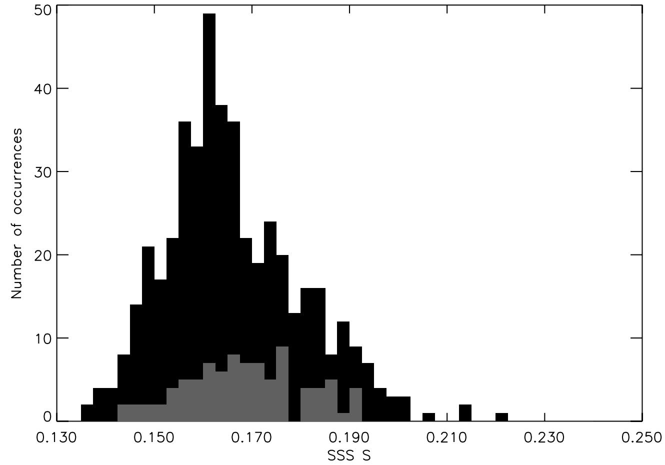

FIG. 3.—Distribution of chromospheric activity in 57 Sun-like stars. The black and gray histograms show the seasonal means of observations of stars in the target sample, rather than individual observations. This weights all stars equally, and the deviation of these means is small (less than 0.002 in S). As in Fig. 2, the distributions of cycling and noncycling stars are the same.

same activity limits ($0.130 \leq \langle S \rangle \leq 0.200$). The black histogram in Figure 2 shows the distribution of the individual observations for all 57 stars. The superimposed gray histogram shows the distribution of observations for the 10 stars that fit the adopted flat activity criterion of $\sigma(\langle S \rangle)/\langle S \rangle < 1.5\%$, where $\langle S \rangle$ is the seasonal mean of individual observations. We have also plotted the distribution of 3038 solar observations with a white outline. We typically obtain solar observations three times per week with three observations per day, and the data are plotted as the running daily mean of the individual observations.

To assess the implications of these results, we examine the ensemble characteristics of our data set. Of the 57 stars under consideration, 10, or 17.5%, exhibit flat time series over 6–10 observing seasons. The other 47 are variable in some way, exhibiting (1) cyclic behavior, (2) a long-term secular trend, or (3) noncyclic variability in excess of 1.5%. This agrees well with the figure of 15% quoted by Baliunas et al. (1998).

The critical difference lies in the distribution of the flat star activity levels. We concur with the MWO data on HD 9562; our mean S is 0.145, compared with 0.146 reported by BJ90 and 0.140 for the latter part of the B95 time series, and there is no secular trend in the data. However, the derived S values for the other nine flat stars occupy a broad and continuous range from $S = 0.145$ to $S = 0.180$, spanning the entire range of mean S values under consideration in this study. Therefore, where BJ90 report that "the magnetic activity of the four 'flat' stars is almost always lower than the activity of the 'cyclic' stars," we find, using a larger sample, that this is not necessarily the case.

Our sample has some sources of error and bias that must be addressed. First, the data in Figure 2 are not equally weighted. We can only maintain 18 stars on our "priority 1" list (nightly observations); the rest are observed once or twice per month. Thus, about one-third of the stars in Figure 2 contribute two-thirds of the observations. Additionally, our uncertainty of 0.0075 in S is a significant fraction of the width of the roughly five S bins (0.0125) occupied by the flat stars in BJ90, so the flux-S conversion and random errors in our data might be introducing some smearing that would obscure a sharp, well-defined feature in the distribution (although, as noted above, the original distribution itself is suspect following the revisions in the HD 9562 and HD 143761 calibrations). For these reasons, we redid the distribution using seasonal means, which has the dual benefit of unweighting the sample (by using a roughly equal number of data points per star, typically 7–9) and creating a low-variance picture of a star over a given time interval (this method was also employed by BJ90, who averaged their densely sampled data over 0.1 yr intervals). The result is shown in Figure 3. Each target in this plot has only 7–9 data points, and $\sigma(\langle S \rangle)$ ranges from 0.002 to less than 0.001 in S. Again, there is no tendency for flat activity stars to cluster at low values of S.

Second, our time series (7–9 yr) are considerably shorter than the MWO series, and there are numerous examples in the figures published by B95 in which a window of only 9 yr would lead to incorrect assessment of the star's variability. These are primarily examples in which a star displayed subdued activity for several years but is actually variable when observed for 20 yr (e.g., HD 6920 or HD 126053). The worst effect of this bias would be to give us an erroneous estimate of the frequency of flat stars. It is possible that some of our flat stars are variables in a quiescent state or have long cycles (as seen in a number

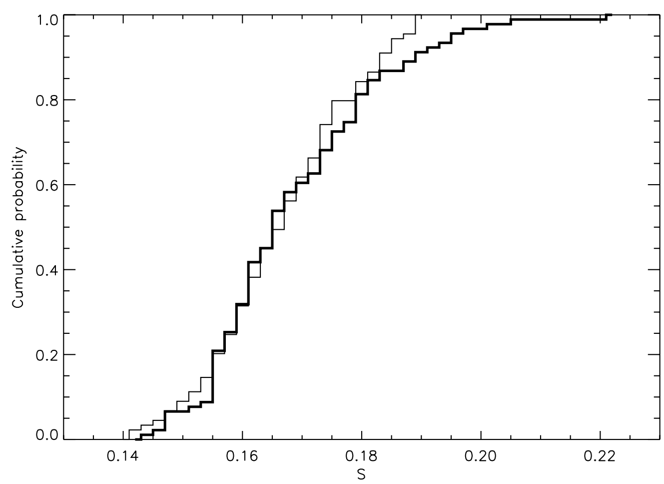

FIG. 4.—Cumulative probability distribution of seasonal mean activity in 47 cycling stars (*thick line*) and 10 flat activity stars (*thin line*). The Spearman rank coefficient ρ for these distributions is 0.969.

of cases in the series of B95); the reverse scenario is also possible. However, the two distributions in Figure 2 (observations of all 57 stars and of just the flat stars) are statistically the same. A Spearman rank correlation test applied to the two distributions of seasonal means (the 47 cycling stars and the 10 flat stars) yields an extremely high correlation ($\rho = 0.969$) that rejects the hypothesis that the distributions are independent at better than 99.99% confidence. The cumulative probability distributions of the 47 cycling and 10 flat activity stars upon which this result is based are shown in Figure 4.

4. CONCLUSIONS

During the Maunder minimum, the sunspot number, and thus presumably the Ca II H and K line core brightness, was greatly reduced (although the solar cycle continued to operate at some level; e.g., Ribes & Nesme-Ribes 1993), and by inference from the direct correlation between the sunspot number and the Ca II H and K emission flux (or S), the Sun was in a state of low magnetic activity. The stellar data presented by BJ90 suggest that a Maunder minimum state may entail a further reduction in magnetic activity to a state well below that exhibited at the present-day solar activity minimum. However, our stellar data lead us to differing conclusions.

1. Flat activity stars span a range of $\langle S \rangle$ from below solar minimum to near the higher levels of the present solar cycle. To the extent that the Ca II H and K core brightness is indicative of a star's overall magnetic activity level, a flat activity state does not necessarily imply weak (i.e., subsolar) magnetic activity. A transition to a noncycling state may entail a reduction in overall magnetic activity, but we do not yet know the magnitude of that reduction, that it is necessarily the same for different Maunder minimum-like events in the same star, or that the HK emission of the Maunder minimum Sun itself was substantially lower than its present minimum cycle value. The nonmagnetic contribution to S has been quoted as approximately 0.140 for stars near solar effective temperature (Schrijver et al. 1989), and we do find that $S \approx 0.140$ is a lower limit for our derived values, with HD 9562 the canonical near-zero-activity star (although even the so-called "basal" flux may well include a magnetic component [Schrijver 1995]). However, since we also find that flat activity stars may exhibit HK emission significantly above this level, the suggestion that Maunder minimum states imply a near-disappearance of magnetic activity, or even a level greatly reduced relative to a star's cycle minimum, is not supported by our data. In the latter case, however, our data also do not reject the idea of a Maunder minimum level below a given star's cycle minimum level, and we will not be able to draw firm conclusions about this issue until one or more definitive transitions between cycling and flat states have been observed.

2. As noted in the section above, a rank correlation test applied to the Ca II H and K brightness distributions of cycling and flat stars rejects the hypothesis that flat stars exhibit systematically lower HK core flux than cycling stars, at a very high level of confidence. If the flat stars are actually in grand minima akin to the Maunder minimum, then either (1) very weak magnetic activity is not a necessary condition for a Maunder minimum state, or (2) the Ca II H and K proxy is sufficiently contaminated with flux from magnetic but noncyclic sources that it is not a good discriminant of a true Maunder minimum state.

In conclusion, we note that although the MWO and SSS data sets contain numerous examples of flat stars, conclusive evidence for transitions to or from a Maunder minimum state remains sketchy. Detection of a transition to or from a Maunder minimum state may statistically require a very long time series and is dependent on fine points in instrumental performance and data calibration. Also, as this study demonstrates, flat activity is not necessarily indicative of a Maunder minimum state, and complementary observations of additional targets or other activity proxies are needed. In addition to our present high-priority targets, we have raised a number of flat and low-variability stars to the highest priority level on our observing program, to ensure that we obtain the best possible coverage for the most likely transition candidates.

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