Composite Spectral Indices: A New Method for the Interpretation of Activity in the Sun and Solar Analogs

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1 Introduction

Discussions of the behavior of the H and K lines of singly ionized calcium in large samples of cool stars span the modern literature (e.g., Wilson & Bappu 1957, Baliunas et al. 1995). The long- and short-term behavior of these lines, which serve as proxies for chromospheric activity, has revealed direct observational evidence for stellar activity cycles, rotational modulation, and even differential rotation. As this workshop has demonstrated, however, it has been very difficult to properly evaluate the Sun as a star, and almost impossible to agree on what star is most nearly solar-like.

2 Origin of the problem

- [1] It is difficult to observe the Sun in exactly the same way that we observe the stars.
- [2] Detailed, high-resolution spectral studies (leading to precise determination of fundamental parameters, e.g., T_{eff}) preclude large, synoptic surveys (leading to a knowledge of the behavior of the general stellar ensemble), and vice versa.
- [3] The only very long-term, synoptic database of stellar activity (the 30-year time series from Mt. Wilson) is limited to one spectral feature, and while the contribution of these data to our understanding of stellar activity has been enormous, we know that a star that is a solar twin in terms of parameter X may look decidely un-solar in terms of parameter Y.
- [4] Identifying solar analogs in terms of *variability* is of critical importance, considering the present evidence that solar irradiance variations may profoundly affect terrestrial climate. But the link between chromospheric variability and total irradiance variability is tenuous, although Lockwood, Skiff, & Radick (1997) have presented a large observational database addressing this issue, and inferring irradiance variations from Ca II data is not possible at present.

3 Approaches to solving this problem

Our Solar-Stellar Spectrograph (S^3) program (see, e.g., Hall & Lockwood 1995) offers a method of addressing issues [1] through [3] above.

- Re [1]: We transmit starlight and unresolved solar light through optical fibers to the same spectrograph, obviating inter-instrument calibration difficulties and coming as close to true "Sun-as-a-star" observing as the diurnal atmospheric variability permits.
- Re [2]: The S^3 has an echelle spectrograph spanning $\lambda\lambda$ 5100-9000 with 70% coverage, and a Littrow spectrograph spanning $\lambda\lambda$ 3860-4010 (Ca H&K). We have $\Delta\lambda/\lambda = 12,000$ for the echelle, and slightly lower for the Littrow, which does not directly solve the central problem of issue [2] above. But, see next section.
- Re [3]: Instead of one spectral feature, we observe well over 200, including all the classic chromospheric diagnostics. These spectral features cover atomic species with a wide range of characteristics (e.g., equivalent width, excitation potential, depth of formation). With approximately 7800 data frames at our disposal, we have about 1.6 million measurements of spectral features in the Sun and hundreds of solar-like stars at our disposal.

- Re [4]: But, says the skeptic in us, we know the total solar irradiance (TSI) variability is under 1%; how can we hope to identify variability in inactive, solar-like stars, especially given our typical signal-to-noise of 50-100?

4 The Solar Rotation in SSS Data

4.1 Periodogram analysis of solar data

We calculated the Scargle periodogram (as presented by Horne & Baliunas 1986) of our solar Ca II K data set. This comprised observations on about 300 days between the beginning of 1994 and late 1997. Although we observed power in the periodogram at the 27-day rotation period of the Sun, it was not significantly above the multitude of noise spikes typically present in such analyses.

But, then we did the following:

- [1] We calculated periodograms for 120 lines in the solar spectrum.
- [2] We filtered out the strongest peak in each of these periodograms with $\omega > 0.01$ d^{-1}.
- [3] We recalculated the periodogram with this one dominant frequency now removed.
- [4] We averaged the resulting set of periodograms.

The results of this procedure are shown in the figures. In the following figures, we show the results obtained from this procedure. These figures are similar to the figure published by Hall & Lockwood (1998), but they incorporate additional solar data from the end of 1997. The greyscale image in the bottom part each figure shows the 120 periodograms stacked vertically. No attempt to identify specific spectral lines is made; they are simply numbers 1-120. The greyscale bar in the central part of each plot is the average of the 120 periodograms, and at the top of each is a graph of the average.

4.2 Raw periodogram analysis

We produced Figure 1 by using steps [1] and [4] of the above procedure only. That is, we calculated the periodograms and averaged them. There are prominent peaks in the power spectrum at 27.4, 13.7, and 9.13 days. These are the fundamental, 2:1, and 3:1 harmonics of the solar rotation period, and they are identified by the dashed vertical lines. The centroids of these peaks fall precisely at the harmonic frequencies (within 1%). At extreme left are three very large peaks, identified by the solid line. The lowest-frequency peak goes well off the vertical scale plot. These peaks lie at 355, 180, and 120 days, and are the fundamental, 2:1 and 3:1 harmonics of the annual variation in the telluric water vapor lines. (In Arizona, this is a pronounced yearly variation, with the July-September monsoon producing a noticeable increase in water vapor absorption across the entire SSS echelle spectrum.)

Also visible are several other prominent peaks, the most significant of which lies at $\omega \approx 0.024$ (41.6 d). The two other dotted lines in this figure lie at 2:1 and 3:1 harmonics of this 41.6-day period. Although other peaks exist in Figure 1, they do not coincide with these harmonics.

4.3 Filtered periodogram analysis

In Figure 2, we have added steps [2] and [3] above. For each of the 120 spectral lines, we calculated the periodogram, filtered out the strongest period in the data less than 100 days, and recalculated the periodogram. We then averaged them as before. The rationale here is that if the solar rotational signal is comparable to or less than the noise, it will usually not be the strongest peak in the spectrum. Thus the filter should preferentially remove noise, and any surviving peaks arising from a real signal are likely to be enhanced. We limited this filter to $P < 100$ d because (1) this is the regime of physical interest and (2) the telluric signals dominate the $P > 100$ d area.

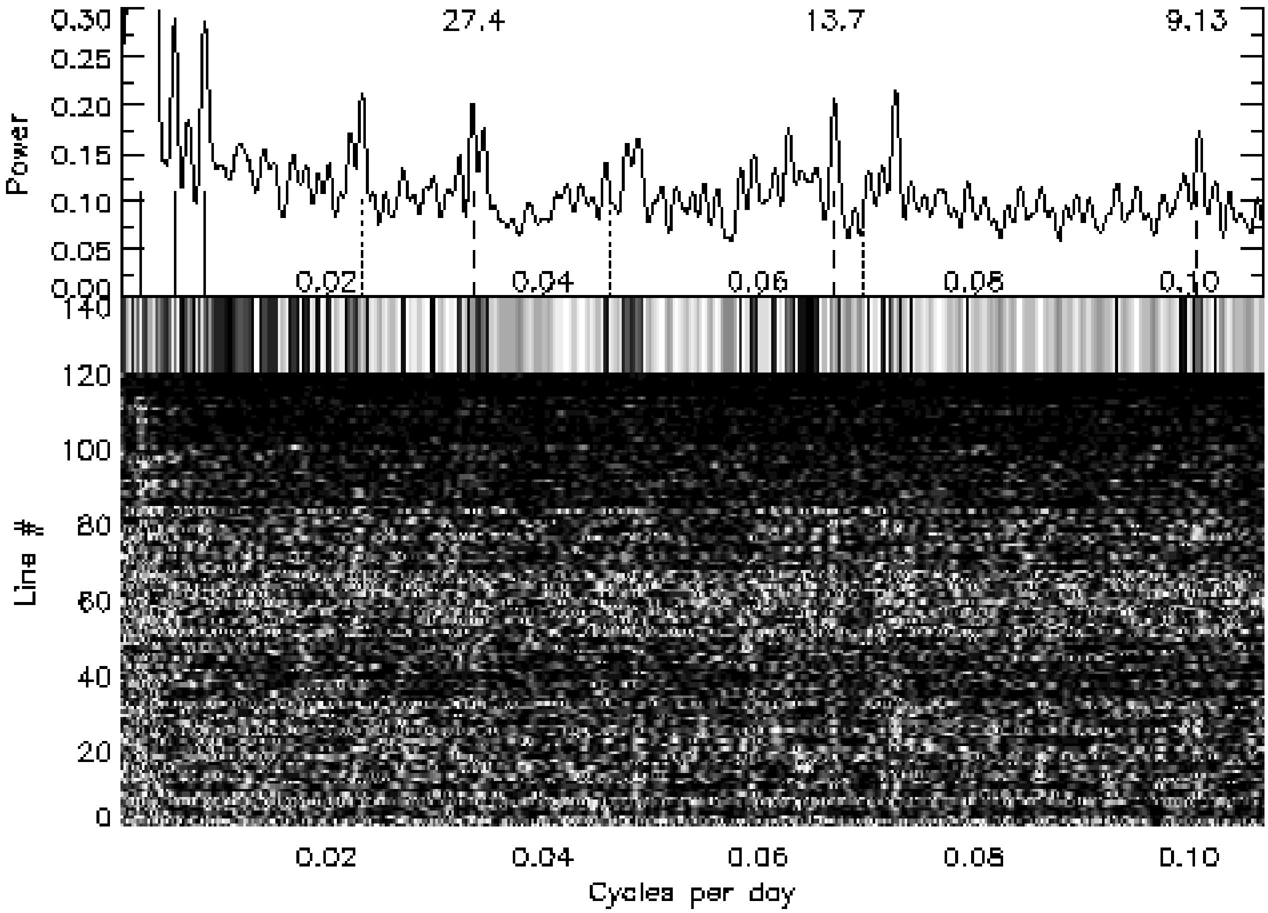

Figure 1: The averaged periodogram of 120 spot-sensitive lines in the solar spectrum. The greyscale image at bottom shows the stacked individual periodograms, while the greyscale bar and the graph above it are the average of these 120 periodograms. A series of peaks, at 27.4 days and at 2X and 3X harmonics of this period, is apparent. These correspond to the solar rotation period. A 355-day telluric peak and its 2X and 3X harmonics are also apparent (solid lines at left). None of the other peaks in the spectrum are harmonically related. Note that the x-axis of this scale is a synodic frequency scale, while the labeled peaks have been corrected to the sidereal period corresponding to the solar rotation.

We have left all the solid, dashed, and dotted lines from Figure 1 unchanged in Figure 2, to allow easy comparison of the location of the peaks from figure to figure. The essential result in Figure 2 is that *the only peak that survives the filtering procedure discussed above is the 27.4-day peak.* The other pronounced peaks apparent in Figure 1 are gone, as are the harmonics of the posited solar signal. We believe the 27.4-day peak arises from a real signal in the data, therefore, for two reasons:

- In Figure 1, we know the telluric peaks are real, and they show perfectly-spaced 2:1 and 3:1 harmonics. The 27.4-day peak shows identical harmonics, while none of the other significant peaks in Figure 1 show any harmonic relationships.

- In Figure 2, application of a procedure that preferentially removes noise gets rid of all the peaks *except* one, at 27.4 days.

It seems quite likely that we have detected the solar rotation at solar minimum, with resolution 12,000 data of S/N ranging from 50 to 150.

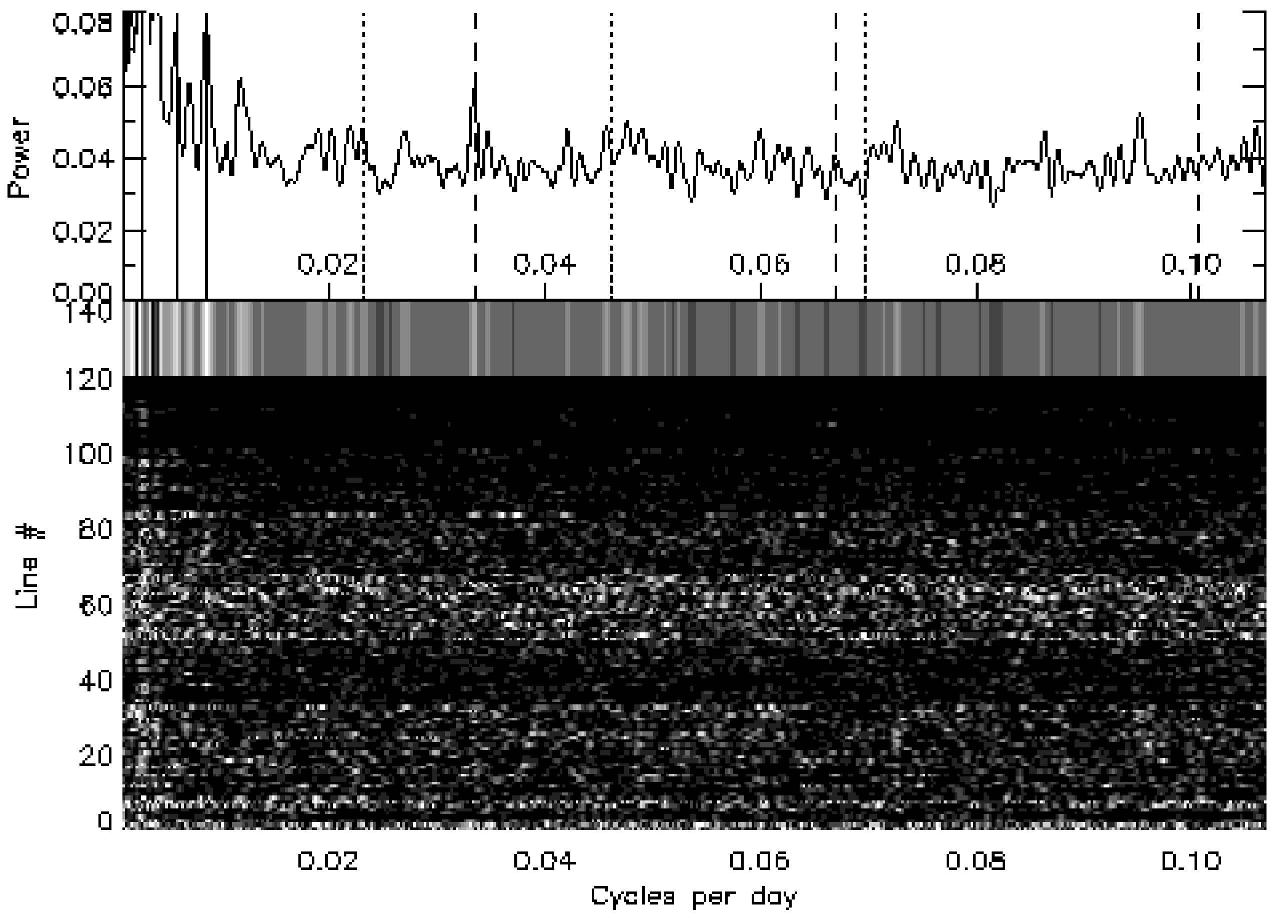

Figure 2: This is the same plot as Figure 1, except that in each individual periodogram, we have filtered the strongest peak with frequency $\omega > 0.01$ cyc d^{-1}. The solid, dashed, and dotted lines are in the same locations as in Figure 1. The harmonics of the solar signal are gone, as is the strong peak around 0.024 cyc d^{-1}. A weak, high-frequency signal has appeared around 0.095 cyc d^{-1}, but it is insignificantly above the other weak peaks scattered through the spectrum. The telluric peaks are unaffected by the filtering, as they lie outside the frequency region subjected to it. The only significant feature lying in the physically significant frequency region (as far as stellar rotation is concerned) is at 27.4 days.

5 Composite Spectral Indices

Athay & White (1992) found, in an examination of early SSS data, "no rotational modulation of the solar irradiance spectrum at either Hα or Ca II." We did not, either, using the individual spectral indices examined by Athay & White. But in the previous section, we have created what we term a *Composite Spectral Index* (CSI) of solar irradiance data. We can measure over 200 lines in our SSS solar data; for Figures 1 and 2 we have used only the 120 that Moore et al. (1966) classifies as either strongly or weakly affected by the presence of sunspots. Figure 1 and Figure 2 therefore result from a subset of our data that we expect to be (a) related and (b) indicative of solar activity. This leads us to the basic definition of this paper:

A **composite spectral index** is *an indicator of solar and stellar activity produced by combining time-series data for some number N of spectral lines that are related in terms of properties $(p_{1,\ldots,n})$.* Although the idea of the CSIs came to us as a result of the periodogram analysis, we will not, in general, define our CSIs in this way. Periodogram analysis of our stellar targets, as we have done for the Sun, will be difficult for some targets and impossible for most, because the data sets are much smaller.

However, examination of the flux variability in sets of lines with different characteristics is more encouraging. The variability in spot-sensitive sets of lines in our solar data, both on yearly and monthly timescales, is *significantly greater* than that in spot-insensitive lines. The same holds for our 18 Sco data set. It therefore seems that CSIs, particularly those based on physical properties of the lines in question (e.g., excitation potential), can serve as new indicators of solar and stellar activity that are closely tied to the physical processes at work in the atmospheres. We are still in the stage of developing different CSIs and testing them on our data as of this writing, so no results in this direction are presented here.

The essential difference between this approach and that of extant long-term studies is the use of *many* related spectral features to uncover signals in the data that are hidden in *individual* features by noise. The broad-based nature of a well-chosen CSI may make it a more physically significant indicator of the mechanisms producing solar and stellar variability than an indicator based on a single line. Additionally, we can compare the Sun with *individual* stars in this way, rather than with snapshots of the stellar ensemble. This is a basic shift in our analysis paradigm for our SSS data. Instead of studying "the Sun as a star," we will now be examining in detail the myriad features in our spectra of solar analogs, to study "the stars as a Sun."

6 Conclusion

More or less by accident, we discovered that we can detect the solar rotation in moderate-resolution, moderate- to good-quality solar spectra with approximately 4-day time resolution, at solar minimum. The decision to run 200 periodograms on supposedly "boring" spectral lines was more of a "let the workstation run all night and see what it coughs up" decision than a burst of physical insight. Yet we now have a potential avenue for an exhaustive investigation of our 10,000 solar and stellar data frames. The 20 spectral order in an SSS data frame span 5,120 CCD pixels. By studying just the traditional Ca II H & K, Hα, and the Ca II IRT lines, we were *using* about 10 of those pixels. We are now examining the content of our data in detail, to sort the spectral features we observe into meaningful classes, and to derive information about solar and stellar variability from them. Our hope is that examination of variability in a large number of lines formed throughout the photosphere, rather than just the chromosphere, will allow us to tie our spectroscopic data to broadband irradiance variations from other programs (e.g., Lockwood, Skiff, & Radick 1997). Results of these investigations will be forthcoming in the literature over the next few years.

References

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