New Quests in Stellar Astrophysics III: A Panchromatic View of Solar-like Stars, With and Without Planets
ASP Conference Series, Vol. 472
Miguel Chavez, Emanuele Bertone, Olga Vega, and Victor De la Luz

Decadal Variations of Sun-Like Stars

G. Wesley Lockwood,[1] Gregory W. Henry,[2] Jeffrey C. Hall,[1] and Richard R. Radick[3]

[1]*Lowell Observatory, 1400 W. Mars Hill Road, Flagstaff, AZ 86001*

[2]*Tennessee State University, 3500 John A. Merritt Blvd. , Nashville, TN 37209*

[3]*Air Force Research Laboratory, Sunspot, NM 88349*

Abstract. Observations of more than 300 Sun-like field stars carried out at Fairborn Observatory since 1993 now include 168 observed for 10 years or longer. This project, a successor to previous work at Lowell Observatory and Cloudcroft Observatory, beginning in 1955 and continuing for nearly half a century, demonstrates finally that variability at the Sun's low level of total irradiance variation can be detected in stars. By also including Ca II H&K observations from the Mount Wilson and Lowell observatories, we have discovered how the patterns of photometric variability are related to chromospheric activity. We discuss the limitations of detectability imposed by comparison star variability and as an example of a star close to the detection limit we show the evidence for cyclic variability in the solar twin 18 Sco.

1. Historical perspective

Total solar irradiance (TSI) variability, revealed finally in 1980 by the Solar Maximum Mission spacecraft after a nearly century-long quest, is now a well-established component of solar lore. From three full solar cycles of observation recorded by a series of spacecraft, we learned that the Sun's output rises and falls by about 0.07% in step with the sunspot number. Transient dips several times larger can occur as large sunspot groups cross the solar disk (Willson et al. 1981, 1984).

The search for solar variation spawned a half century of effort by Charles Abbott, whose famed Smithsonian Astrophysical Observatory solar constant program finally drew to an inconclusive close in 1955. As it was ending, Lowell Observatory, taking advantage of newly developed techniques of astronomical photoelectric photometry, began measurements to look for variability in the sunlight reflected from Uranus and Neptune. The results, documented in a series of papers optimistically titled *"The Sun as a Variable Star"* (Johnson & Iriarte 1959; Serkowski 1961; Jerzykiewicz & Serkowski 1966) were just as inconclusive as Abbot's had been due to intrinsic and seasonal planetary variability.

The Lowell project, however, produced an unexpected dividend related to the solar variability question. Parallel *B*, *V* observations of 16 F- and G-type main sequence "10-year standards" had been made from 1955 to 1966 along with the planets. M. Jerzykiewicz and K. Serkowski, authors of the final report, recognized the significance of the collateral observations of the 10 year standards:

> "In our opinion, this long sequence of photoelectric observations has taught us more about the variations of solar-type stars than about the sun itself. The observations of 15 stars of spectral types F and G in the years 1955-1966 indicate that for none of these stars does the standard deviation of the yearly mean magnitudes exceed 0.008, and for the stars 40 Leo, β CVn, and η Boo this deviation is less than 0.004 mag. No evidence of variability in the stars which are similar to the sun has been detected during this program. *If we assume the sun acts in similar fashion to each of these stars, its variability over a fifteen year period probably does not exceed one-half of one percent.*" (Emphasis added).

The solar variability prognosis went unchallenged by other stellar data for two decades but in the meantime retrospective analysis of direct and indirect solar data produced alternative constraints on the Sun's variation. Sterne & Dieter (1958) applied a digital computer to a 30-year stretch of Abbot's solar constant data and derived a 0.17% rms upper limit of possible variability. Labs & Neckel (1971) revisited the Lowell Uranus and Neptune data and found no correlation with the sunspot number. However, they were unable to rule out solar variation at the 1% level.

A renaissance of photometric studies of Sun-like stars using Strömgren *b* and *y* filters began in 1980 at the automated 1.2-m Air Force telescope at Cloudcroft Observatory in New Mexico. Young main-sequence stars in the Pleiades and Hyades clusters and older stars in the Malmquist field near the North Galactic Pole were the first targets, and after the Cloudcroft survey detected probable variability at the 1% level in the Pleiades and Hyades stars, Cloudcroft and Lowell Observatory teamed up on a campaign to observe 36 F, G, and K Hyades stars in 1981/1982. They found 15 variable stars (Radick et al. 1983) and went on to derive photometric rotation periods (Lockwood et al. 1984), conclusively tying the variability to starspots by comparing the photometry with Ca II H&K variations measured at Mount Wilson.

2. Lowell and Fairborn observations of main-sequence solar type field stars

These preliminaries set the stage for a full scale multi-year assault, beginning in 1984, to study the variability of 41 F, G, and K stars selected mainly from Olin Wilson's (1978) Ca II H&K survey sample. We used the Lowell 0.5-m photometric telescope to make *b*, *y* differential measurements in trio and quartet groups that included at least two comparison stars of similar brightness and spectral type. The mean chromospheric activity level of these stars estimated from their "chromospheric emission ratio" values, log R'_{HK}, came from work by Noyes et al. (1984) and covered the range -4.2 to -5.2, bracketing the Sun's mean activity level.

Over 15 years, observer Brian A. Skiff accumulated thousands of differential observations that led to a series of papers characterizing the patterns of photometric variability (Radick et al. 1990; Lockwood et al. 1992, 1997; Radick et al. 1998) and their relationship to parallel H&K observations obtained at Mount Wilson (Baliunas et al. 1995). By 1993, automated photometric telescopes (APTs) were coming into service at Fairborn Observatory and in our final survey paper (Lockwood et al. 2007) we merged Lowell and Fairborn data to attain a span of 20 years. Combining the photometric and H&K data, we derived power law relationships for both the photometric and the H&K variations as a function of the stellar activity/age metric, log R'_{HK}. We located the crossover point between spot-dominated and faculae-dominated b, y variation, finding it close to the Sun's average log R'_{HK} value, -4.94. Later, combining new APT photometric data and H&K data from Lowell's Solar Stellar Spectrograph (SSS) project, Hall et al. (2009) improved the power law relationships and added the first well-observed solar twin, 18 Sco.

3. The Fairborn APT program

Variability at the low end of the log R'_{HK} scale, below -4.8, poorly defined in the small Lowell sample, is now more clearly delineated in data from more than 300 stars observed by four APT telescopes (Henry 1999). Although the night-to-night APT precision is only slightly better than Lowell's, the vastly denser temporal coverage (50-100 observations per season) plus rigorous long-term calibration of the photometric system produces more precise annual mean magnitudes than Lowell's typical 6-10 observations per season achieved. The vagaries of comparison star variability have plagued both programs but the larger sample gives a better statistical picture of how badly this impacts the goal of detecting solar-level variation.

Here we describe results for 168 stars observed for 10 years or longer (average duration 15 years). Our analysis is far from complete, and in particular, still awaits the inspection of individual lightcurves one by one, a time-consuming task. But we have completed the ensemble statistical profile and will show, as one example, detailed results for a high-priority target, the solar twin 18 Sco.

To cope with tens of thousands of individual measurements we automated the initial screening process of the twelve pairwise b, y differential magnitude seasonal time series for each star, first using an intra-night "cloud filter" and then adopting median-based statistics to minimize the effect of outliers. Guidance came from a paper by Rosenberger & Gasko (1982), who described the relative efficiency of common estimators of location. We selected the tri-mean as most appropriate for our task after first comparing a few light curves based on the median, the 95% trimmed mean, and the tri-mean. For computational simplicity the tri-mean is adequately approximated by $^1/_4\times$first quartile+ $^1/_2\times$median+ $^1/_4\times$third quartile in an ordered set of values. We then chose the best two of the three comparison stars, and using variance arithmetic, compensate for comparison variability and a small instrumental term to produce an estimate of net program star rms variability (see Lockwood et al. 2007, equation on p. 239).

4. Power law relationship for 168 stars

Figure 1 shows b and y power law relationships for annual tri-mean net rms program star variations as a function of log R'_{HK}. Stars with negative net variance must be excluded, so the number of stars on the two panels is less than 168. The position of the solar twin 18 Sco (see section 6) is indicated by arrows. The regressions for the two filters are almost identical, a fact that led us in previous papers to average the differential magnitudes, i. e. , $^1/_2(\,b + y)$. On Figure 1 there is a sharp cutoff of points near 0.0001 mag that seems noteworthy. However, this is an artifact of the noise-imposed detection limit and the expanding logarithmic scale. It is not astrophysically significant.

In previous papers we noted that the rms variation of annual means, σ_b, was only slightly greater than σ_y. We can now examine that difference in more detail. Figure

2 shows the ratio of net b variance to net y variance, σ_b^2 / σ_y^2. The median, 1.22, is statistically significant (95% confidence interval 1.07 - 1.31) and the lowess (locally weighted scatterplot smoothing) fit shown by the dashed line never falls much below the 1.0 level even in the noisy low-level variability regime < 0.001 mag rms.

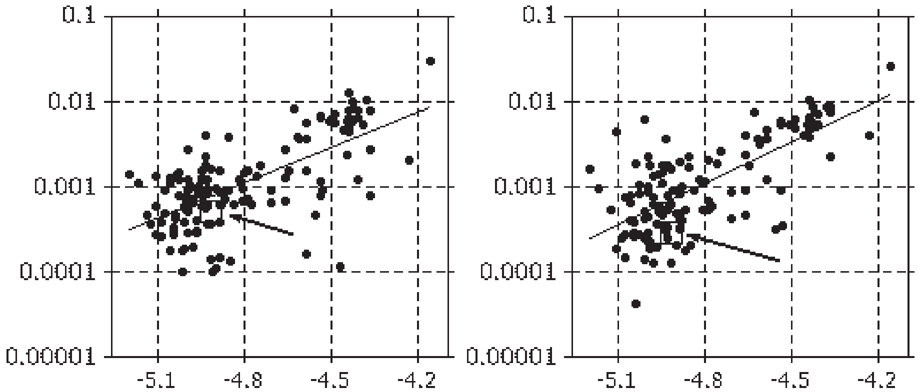

Figure 1. Left. Power law relation for year-to-year net rms variation σ_b (left, 141 stars), and σ_y (right, 132 stars) as a function of log R'_{HK}. The arrow locates the solar twin 18 Sco (open square).

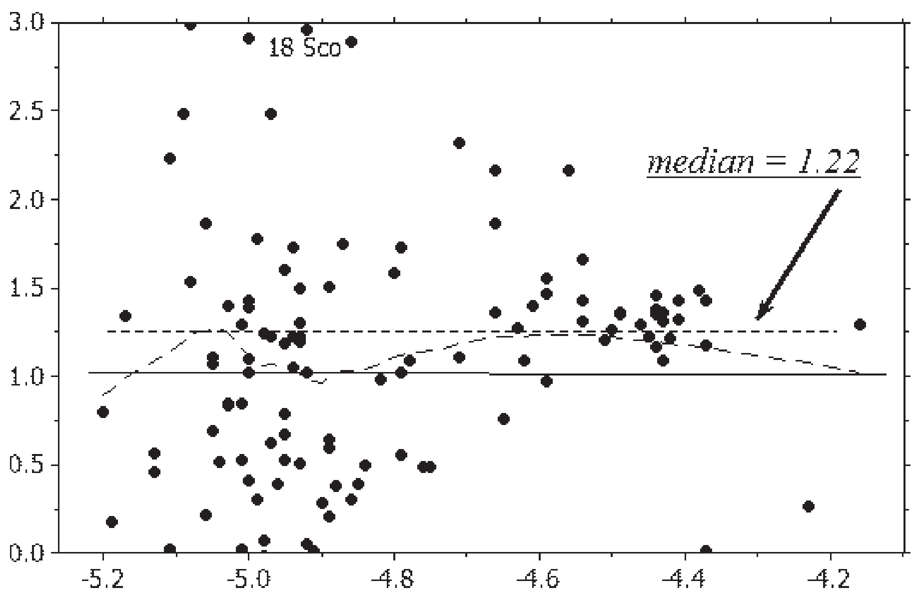

Figure 2. Net variance ratio σ_b^2 / σ_y^2 as a function of log R'_{HK}

5. 18 Sco, the solar twin

The G2Va star 18 Sco (HR6060, HD146233) has been a high priority target for APT photometry and Lowell SSS observation since being identified as a solar twin by Porto de Mello & da Silva (1997). Although additional twin candidates adhering to the specification proposed by Cayrel de Strobel (1996) have been added to the list — e. g. , Meléndez et al. (2012); Soubiran & Triaud (2004); Datson (this conference, 2012) — 18 Sco remains the only one having a decade-long photometric and Ca II record.

Rising Ca II emission from 1995 to 2000 (Hall & Lockwood 2000) hinted at cyclic activity and subsequent APT photometry and Lowell spectroscopy from 1998 to 2006 showed a 2005 activity minimum (Hall et al. 2007). Replacement of a comparison star in 2000 improved the photometry and Figure 3 shows the subsequent 11-year APT time series. The upper panels illustrate the individual *b* and *y* observations and the lower panels show the seasonal median values. (For plotting purposes we show the median and its uncertainty, but our final statistics will use the nearly identical tri-mean).

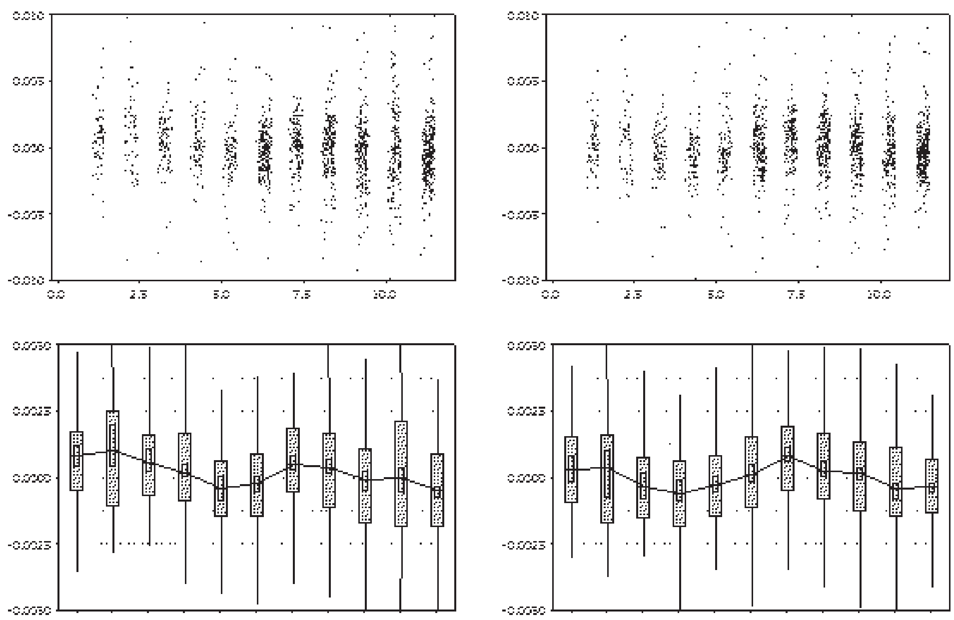

Figure 3. The top two panels show 1749 individual *b* (left) and *y* (right) differential magnitudes of 18 Sco from 2000 (season 1 on the x-axis) through 2010 (season 11). Brightness increases upward. The bottom panels show the medians with a connect line, the 95% confidence interval of the median (inner box), and the interquartile range (outer box). Whiskers mark 1.5x the interquartile range.

When we combine *b*, *y* observations from Fairborn with H&K observations from the Lowell SSS, the correlated variation patterns shown on Figure 4 reveal cyclic variability like that of the Sun in which Ca II activity rises and falls in step with irradiance. The *b*, *y* amplitudes are about 0.0011 mag. Adjusting the Sun's 0.07% TSI variation by the factor 1.39 adopted by Lockwood et al. (2007) to account for the difference between *b*, *y* and TSI variation (based on blackbody considerations) we get an estimated solar *b*, *y* variation of 0.0010 mag, making 18 Sco a candidate for the first photometric solar twin.

Considering the earlier Ca II observations (Hall et al. 2007) we have recorded three minima (approx. 1996, 2004, 2010 or possibly later) and two maxima (2001, 2006). This gives a cycle length on the order of 6-7 years, somewhat shorter than the Sun's typical 11-year period.

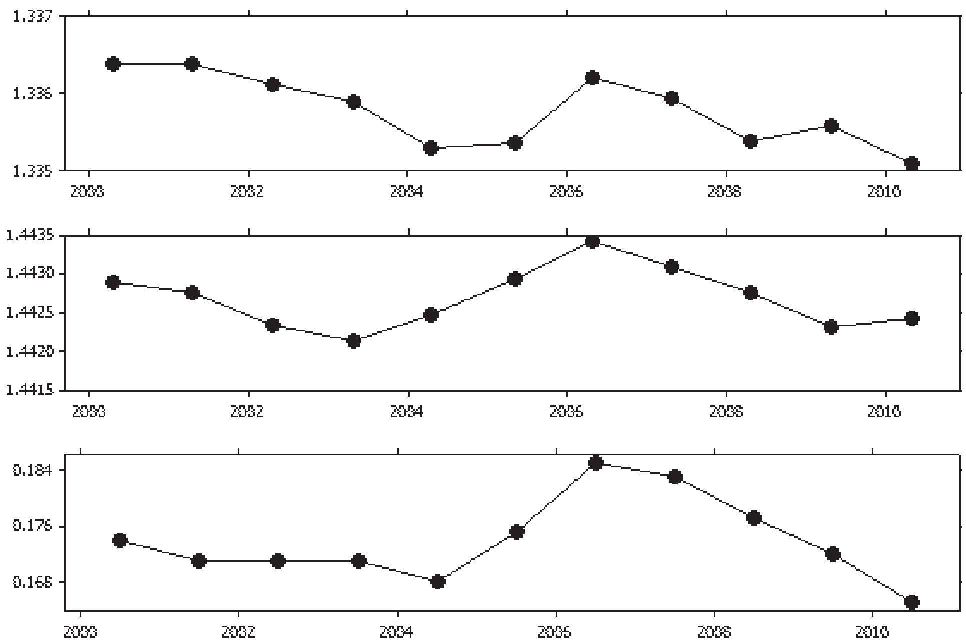

Figure 4. Annual differential magnitudes of 18 Sco in *b* (top) and *y* (middle) relative to three comparison stars, and the Ca II H&K instrumental S index (bottom).

6. Could we detect the Suns variation?

Successful detection of a 0.1% cycle in 18 Sco suggests that other photometric twins may be found in our large sample. An alternate reality check comes from a simulation where we degraded the ACRIM (Active Cavity Radiometer Irradiance Monitor) composite TSI record by adding noise to match the stellar photometric precision and windowing the results by the 18 Sco observation dates. The illustration, Figure 5, shows that if we were to observe the Sun from afar we would see its cyclic photometric variation.

Unstable comparison stars remain the principal hazard to measuring low level photometric variation and Figure 6 shows a cumulative histogram of comparison star variability for our sample of 168 comparison star pairs. The somewhat discouraging news here is that a mere 30% of the comparison star pairs are stable enough to detect variability at the solar or 18 Sco level. This means that many solar twin candidates ultimately may have to be excluded from the survey results because of contamination by comparison star variability.

Another way of looking at this question is to consider how many stars have been excluded from consideration because they failed to show a positive net variance after accounting for the comparison star variance. This is not so much a problem for the most active stars which typically vary by more than 0.001 mag rms. We show on Figure 7 a linear regression for the 110 most Sun-like stars in our sample, those with log R'_{HK} <-4.8, retaining the stars with negative net variance. We did this by changing the net variance sign, thereby permitting an ersatz "negative" rms variation to be included in the regression. The result, a fitted line plot with its 95% confidence band, shows that only a small fraction of stars are lost entirely in the net variation calculation. We can detect variation in stars as much as 0.15 dex below the Sun's mean chromospheric activity level. The filled square shows the location of 18 Sco on this diagram. The Sun, if included, would be nearby on the plot.

7. Discussion

Ever since Eddy's (1976) discovery of the connection between missing sunspot activity during the 1645-1715 Maunder Minimum and the Little Ice Age climate anomaly, astronomers have sought ways to estimate historic TSI variations. Our present un-

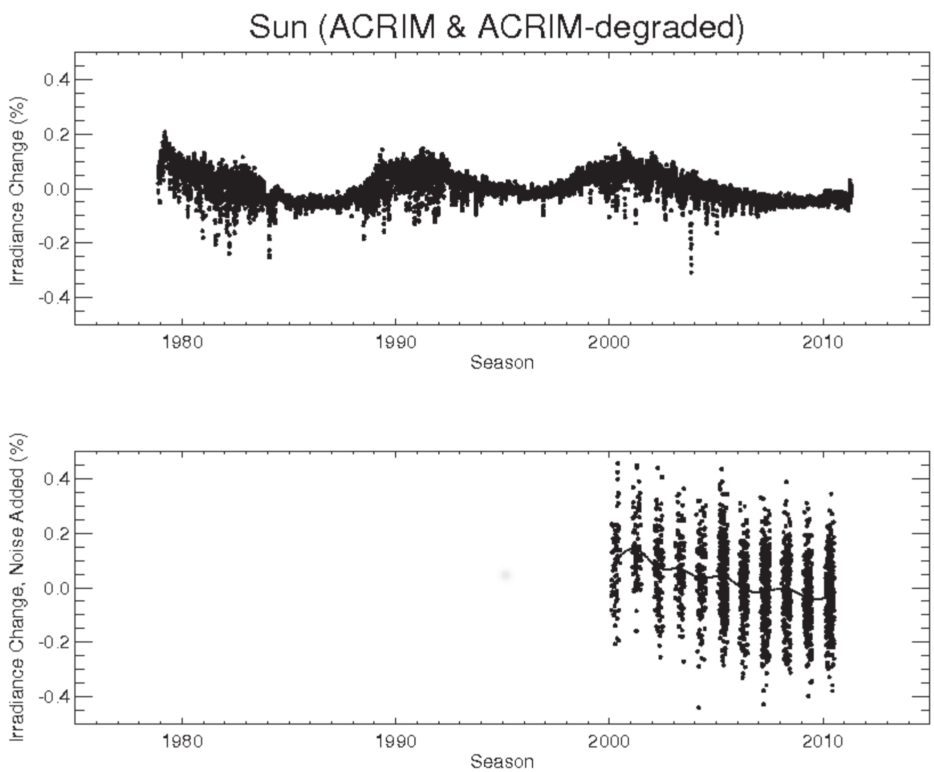

Figure 5. Top.ACRIM composite TSI time series. Bottom. ACRIM data with photometric noise added, windowed by the 18 Sco observation dates.

derstanding of global change gives the Sun only a small role to play in recent global warming, but this may not have always been the case.

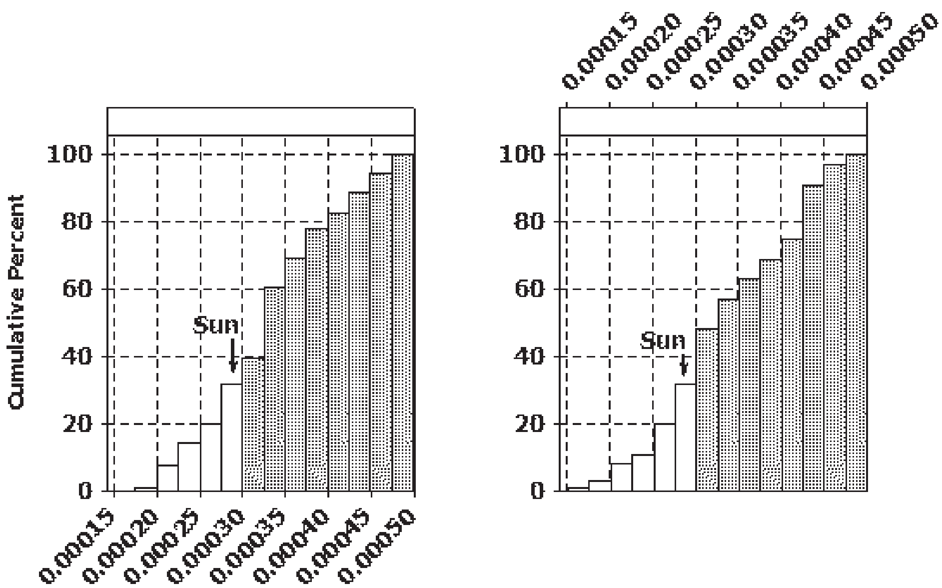

Figure 6. Cumulative histogram of comparison star year-to-year rms variability for *b* (left) and *y* (right). Two thirds of the comparison star pairs are too noisy to allow detection of variations as small as the Sun's.

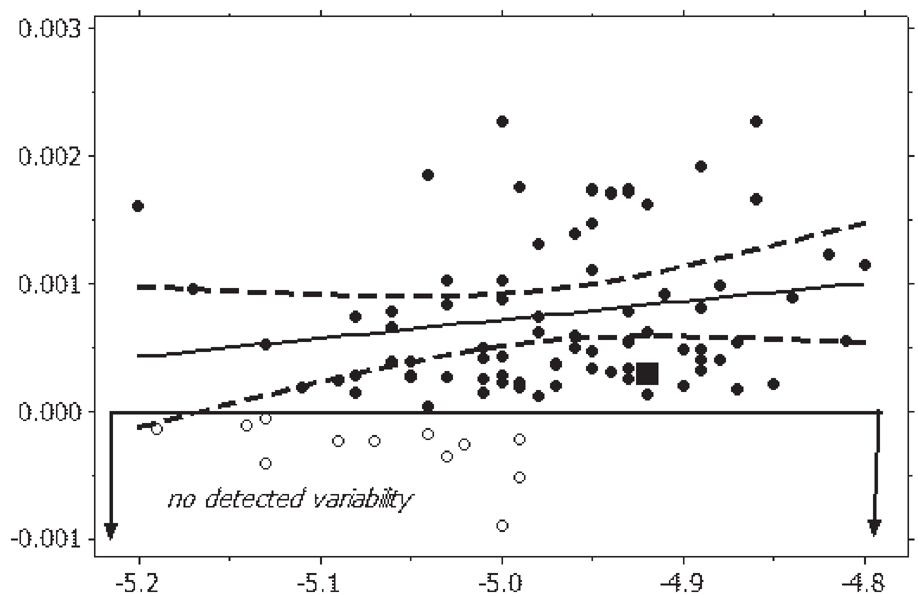

Figure 7. Filled circles. Linear regression and 95% confidence band of net rms y variation for 110 stars with log R'_{HK} <4. 8. Open circles below the zero line indicate stars with a negative net variance. The filled box marks the solar twin 18 Sco.

Two recent controversies have emerged that highlight residual questions about solar behavior where stellar observations may provide useful input. A recent calculation by Shapiro et al. (2011) indicated a much larger TSI deficit, about 0.5%, during the Maunder Minimum than had been generally adopted, bringing this question back into sharp focus. Judge et al. (2012) presented a revised smaller estimate, incorporating our stellar photometric data to set an upper bound to how much the Sun might vary on a 15-year timescale. The matter remains unsettled.

A second controversy concerns the cyclic spectral variation of solar irradiance. It erupted when the SIM (Spectral Irradiance Monitor) experiment on the SORCE (Solar Radiation and Climate Experiment) satellite showed an apparent increase rather than a decrease in visible light output during the declining phase of solar cycle 23, opposite the declining trend in TSI variation (Harder et al. 2009). Although Lean & DeLand (2012) have now put forth an instrumental explanation, we can still look for stellar confirmation. An illustration by Haigh et al. (2010) suggests that Strömgren *b* filter (472 nm) magnitudes should vary differently from *y* (551 nm) magnitudes. Our results, shown on Figures 1 and 2, are inconsistent with the SIM result: stellar *b* and *y* variations are nearly identical.

We conclude with these final remarks. First, we have demonstrated that we can detect cyclic stellar variability at the Sun's low level of about 0.1%, minimum to maximum. Second, the Fairborn observations, together with early work at Cloudcroft and Lowell, show that long-term variability among Sun-like main sequence stars is fairly ubiquitous at levels below 1% rms. As work continues at Fairborn, we shall soon have a 10-year or longer record for all 300 stars on the current program, thus doubling the sample we have described here. Ongoing work by the SSS project at Lowell will increase the number of stars with both Ca II and photometric measurement, and will allow a more definitive test of the puzzling irradiance variability measured by the SORCE SIM instrument.

Finally, we end with a cautionary note. The results we show are somewhat provisional pending a star by star examination of the twelve individual differential lightcurves for each star (six for *b* and six for *y*); and we must stress that except for 18 Sco, which we have studied carefully, what we offer is a broad statistical picture. That picture will become richer as we study how variability changes with spectral type and luminosity (our sample includes several subgiants), and how often we encounter actual cycles as opposed to random year-to-year variation.

Acknowledgments. GWL and JCH acknowledge support from the NSF under grant ATM-0742144. GWH acknowledges long-term support from NASA, NSF, Tennessee State University, and the State of Tennessee through its Centers of Excellence program.

References

Baliunas, S. L., Donahue, R. A., Soon, W. H., et al. 1995, ApJ, 438, 269
Cayrel de Strobel, G. 1996, A&A Rev., 7, 243
Eddy, J. A. 1976, Science, 192, 1189
Haigh, J. D., Winning, A. R., Toumi, R., & Harder, J. W. 2010, Nat, 467, 696
Hall, J. C., Henry, G. W., & Lockwood, G. W. 2007, AJ, 133, 2206
Hall, J. C., Henry, G. W., Lockwood, G. W., Skiff, B. A., & Saar, S. H. 2009, AJ, 138, 312
Hall, J. C., & Lockwood, G. W. 2000, ApJ, 545, L43
Harder, J. W., Fontenla, J. M., Pilewskie, P., Richard, E. C., & Woods, T. N. 2009, GRL, 36, L07801

Henry, G. W. 1999, PASP, 111, 845
Jerzykiewicz, M., & Serkowski, K. 1966, Lowell Observatory Bulletin, 6, 295
Johnson, H. L., & Iriarte, B. 1959, Lowell Observatory Bulletin, 4, 99
Judge, P. G., Lockwood, G. W., Radick, R. R., et al. 2012, A&A, in press
Labs, D., & Neckel, H. 1971, Solar Phys., 19, 3
Lean, J. L., & DeLand, M. T. 2012, Journal of Climate, 25, 2555
Lockwood, G. W., Skiff, B. A., Baliunas, S. L., & Radick, R. R. 1992, Nat, 360, 653
Lockwood, G. W., Skiff, B. A., Henry, G. W., et al. 2007, ApJS, 171, 260
Lockwood, G. W., Skiff, B. A., & Radick, R. R. 1997, ApJ, 485, 789
Lockwood, G. W., Thompson, D. T., Radick, R. R., et al. 1984, PASP, 96, 714
Meléndez, J., Bergemann, M., Cohen, J. G., et al. 2012, A&A, 543, A29
Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Porto de Mello, G. F., & da Silva, L. 1997, ApJ, 482, L89
Radick, R. R., Lockwood, G. W., & Baliunas, S. L. 1990, Science, 247, 39
Radick, R. R., Lockwood, G. W., Skiff, B. A., & Baliunas, S. L. 1998, ApJS, 118, 239
Radick, R. R., Mihalas, D., Lockwood, G. W., et al. 1983, PASP, 95, 621
Rosenberger, J. L., & Gasko, M. 1982, in Understanding Robust and Exploratory Data Analysis, edited by D. C. Hoaglin, F. Mosteller, & J. W. Tukey (New York: John Wiley and Sons), 195
Serkowski, K. 1961, Lowell Observatory Bulletin, 5, 157
Shapiro, A. I., Schmutz, W., Rozanov, E., et al. 2011, A&A, 529, A67
Soubiran, C., & Triaud, A. 2004, A&A, 418, 1089
Sterne, T. E., & Dieter, N. 1958, Smithsonian Contributions to Astrophysics, 3, 9
Willson, R. C., Gulkis, S., Janssen, M., Hudson, H. S., & Chapman, G. A. 1981, Science, 211, 700
Willson, R. C., Hudson, H., & Woodard, M. 1984, S&T, 67, 501
Wilson, O. C. 1978, ApJ, 226, 379

From left: Wes Lockwood, Eric Mamajek, and Dave Latham