N89-13321

MONITORING SOLAR-TYPE STARS FOR LUMINOSITY VARIATIONS

G. W. Lockwood and B. A. Skiff
Lowell Observatory, Flagstaff, Arizona

Abstract

Since 1984, we have made more than 1500 differential photometric *b* (471 nm) and *y* (551 nm) measurements of three dozen solar-like lower main-sequence stars whose chromospheric activity was previously studied by O. C. Wilson. We describe our methodology and the statistical tests used to distinguish intrinsic stellar variability from observational and instrumental errors; we summarize the incidence of detected variability among the program and comparison stars. Many are variable on timescales of days to years. Among the 100+ pairs of stars measured differentially, we find only a dozen that are unusually constant, with peak-to-peak amplitudes of seasonal mean brightness smaller than 0.3% (0.003 mag) over a two-to-three-year interval.

Introduction

The recent detection of a slow downward drift in total solar output, S, (the "solar constant") recorded by the *ACRIM* experiment on board the *Solar Maximum Mission* (*SMM*) satellite, presents a formidable challenge to stellar observational photometry: can such small luminosity fluctuations be detected in solar-type stars generally? Since 1980, the decrease in S has amounted to about 0.1% [Willson *et al.*, 1986]. Dips as large as 0.25%, corresponding to the rotation of sunspot groups across the Sun's visible disk, were observed soon after the launch of *SMM* in 1980; and the power spectrum of *S* contains a persistent significant peak corresponding to solar rotation [Fröhlich, 1987]. The conventional wisdom of stellar photoelectric photometry, basically unchanged since the introduction of photon-counting electronics 20 years ago, asserts that precision better than about 1% is difficult to achieve, while solar variations are an order of magnitude smaller.

At the Lowell Observatory, strict adherence to a fairly elementary observational and instrumental protocol has yielded much higher precision in several programs; for example, measuring small luminosity variations of young, active, solar-type stars in the Hyades open cluster [Lockwood *et al.*, 1984; Radick *et al.*, 1987]. These stars exhibit exaggerated elements of solar-like activity: their light curves are rotationally modulated by a few percent by the disk passage of what seem to be spotted regions, and secular changes in mean brightness generally much less than 1% occur from year to year.

In 1984, we undertook to measure the long-term variation of a sample of solar-like stars and have found that changes in the seasonal mean brightness smaller

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than 0.1% can be reliably measured. This paper presents a statistically oriented discussion of the results, with special attention to the question of data validation, systematic and random error, and possible instrumental effects.

Observations

Since 1984, Skiff has made more than 1500 differential photoelectric observations of three dozen sun-like stars including some of solar age and activity levels, i.e., the most boring stars imaginable. Their chromospheric activity was previously monitored by O. C. Wilson [1978], whose decade-long series of measurements of the strengths of the H and K lines of ionized calcium provides the first evidence of sun-like activity cycles in stars. Subsequent observations have provided data at higher time resolution, leading to the discovery that the line strengths are rotationally modulated, as on the Sun [cf. Baliunas and Vaughan, 1985 and references therein].

Our observational sample comprises "Wilson stars" (their current familial nickname) with well-defined activity cycles, constant stars, and a few young, active stars showing strong rotational modulation of H+K line strengths. Historically, all have been photometrically uninteresting; some are, in fact, photometric standard stars. Several were observed for a decade by Jerzykiewicz and Serkowski [1966], who found no evidence for variability at levels below 1%. However, almost immediately we discovered two Wilson stars, each *UBV* and *uvby* standards, that showed rotationally modulated brightness variations with amplitudes of 1% and 3%, respectively, and 1% changes of mean brightness from one year to the next [Skiff and Lockwood, 1986].

The stars are organized into trios (or quartets), containing one (or two) Wilson stars and two presumed constant comparison stars of similar brightness and spectral type (F0 to mid-K) located nearby on the sky. Early detections of variability among the comparison stars, many of which were giants or stars of unknown luminosity class, forced us to promote many of the trios into quartets containing an additional comparison star.

An observation consists of four cycles of measurement, recording each star in turn along with a background measurement of sky brightness through either the b or the y filter (471 nm or 551 nm, respectively) of the Strömgren photometric system. The order of the cycles is fixed in the sequence y,b,b,y for convenience during observation, and later simplicity in data analysis; hence, for statistical purposes, we do not have the much-desired "randomized block design." Details of the observing scheme have been given elsewhere [Lockwood, 1984; Lockwood *et al.*, 1984; Radick *et al.*, 1987].

Spatially, the stars in a given trio or quartet are separated at most by a few degrees; temporally they are separated by a few minutes, since the observation of

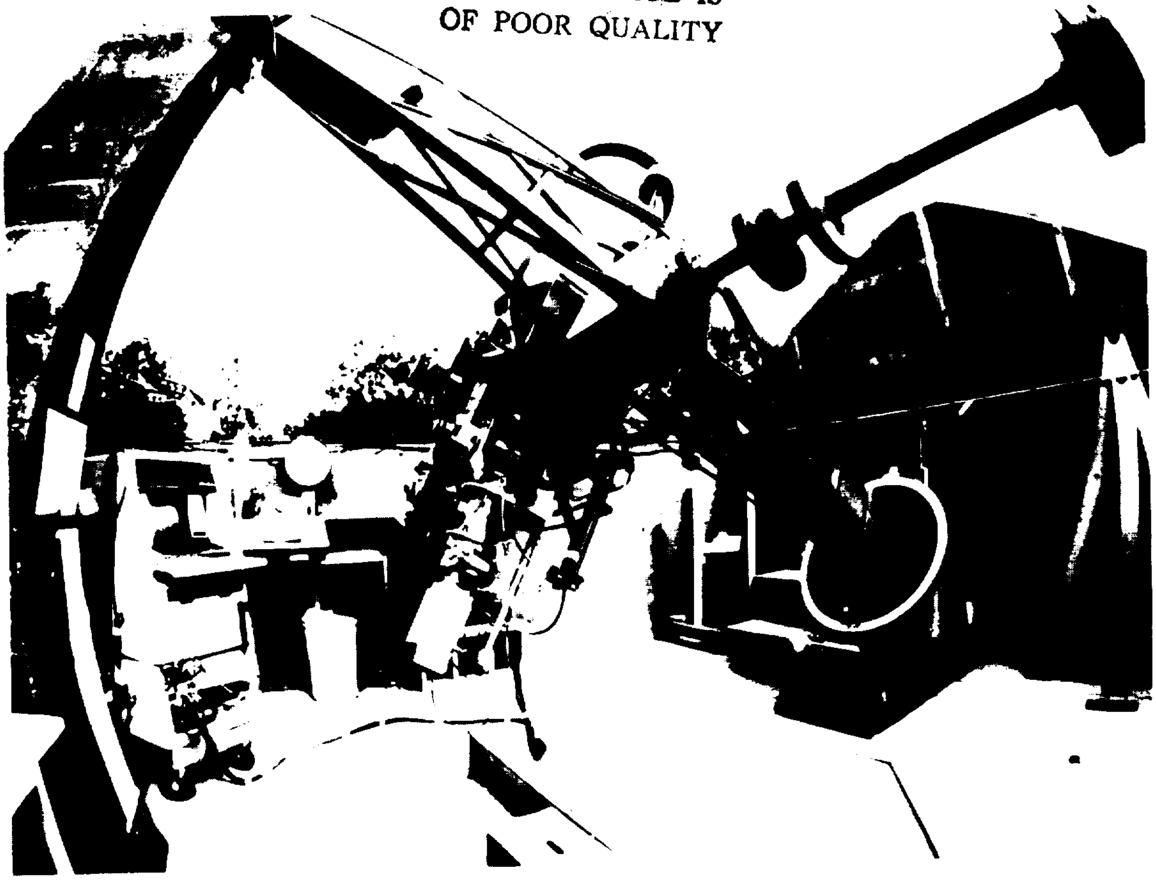

Figure 1. The venerable 0.5-m telescope with photometer attached, and LSI-11 data system. The telescope itself is essentially unimproved since the 1950s, when it was used by Harold Johnson for early *UBV* work; but the position encoding system, photometer, and data-recording system have been periodically upgraded, most recently in 1984. Photograph by B. A. Skiff.

a full cycle requires only 7 minutes for a trio and 10 minutes for a quartet. Four cycles require, therefore, half to three quarters of an hour, and a dozen or so groups can be measured in a single night. Observations on roughly 100 nights per year yield 15–30 nightly data points for each group every season.

The 0.5-m, manually slewed telescope, photometer, and photon-counting data system are of the most commonplace variety (Figure 1). Data collection is controlled by a DEC LSI-11/03 microcomputer equipped with commercial interface cards that perform pulse counting, timing, switch sensing, etc. Utilization of the telescope is unusual, however, being dedicated (and restricted) to two long-term programs of precision photometry which are scheduled for practically every clear night. The photometer is removed from the telescope only for maintenance, and the electronics are always energized.

An Sr^{90} Cerenkov source inside the photometer provides a highly reassuring standard light source whose frequent measurement tells us that the photometer and its electronics are operating satisfactorily. We know from measurements of this source that the overall gain of the photomultiplier+amplifier combination changes seasonally, as well as slowly through the night, presumable due to changing temperature. This effect appears to have no consequences as far as data quality is concerned.

Results

The nightly reduced data output of the program at its most elemental level consists of sets of 3 differential magnitudes (per cycle) for trios and 6 for quartets: viz star 1−star 2, star 1−star 3, star 2−star 3, ... (Nonastronomers please note: a magnitude difference of 0.01 mag corresponds very nearly to 1.0%, 0.001 mag = 0.1%, etc.) Normally, there are four cycles per night, two in b and two in y, in the order y,b,b,y. For much of the analysis, the independent but highly correlated individual b and y differential magnitudes are simply averaged. In each season, there are as many as 30 nights of data for certain intensely observed groups. Some groups have now been observed through three full seasons, others through four; thus, the total number of data points per group typically is in the range of 50 to 150.

In our analysis, we consider variations on various time scales: interannual variations are germane to the question of possible cyclical luminosity variation like that suspected of the Sun; intraseason variations may foretell rotational modulation of brightness; intranight cycle-to-cycle variations are an indication of the quality of the night. Systematic or random errors of observation can enter at any stage and can affect the results on any timescale. In the discussion that follows, we shall describe the procedures and tests we use to differentiate stellar variations from observational errors, and to set upper limits upon the variability of seemingly constant stars.

Interseason Variations: 12 Constant Pairs of Stars

In Table 1 we present the vital statistics of 12 pairs of stars (out of the total set of more than 100 such pairs in 30 groups) whose seasonal mean differential magnitudes are unusually constant by ordinary standards (i.e., to much better than 0.5%). Seven of the pairs contain a Wilson star as one of the members; the other five are comprised of two comparison stars. Their averaged b and y interseason light curves are displayed on Figure 2 where the solid line indicates the seasonal means and 95% confidence intervals of the differential magnitudes for the pairs. Solid dots show the seasonal medians, which we have found useful as a confirming second opinion on the true location of the center of the data distributions, which, for the more variable stars, often are skewed and deviate significantly from normality.

TABLE 1. Variability Characteristics of Some Extremely Constant Pairs of Stars

HD	Spectral Type	V mag	Range (%)	Analysis of Variance	Slope (% yr^{-1})	Attained Significance	No. of Yrs.	Note
2488	F5	6.9	0.06	Constant	0.03	Constant	3	
1388	G0V	6.5						
10697	G5IV	6.3	0.09	Constant	0.04	Constant	3	
11326	G5	6.7						
13421*	G0V	5.6	0.10	Constant	0.04	Constant	3	Mt. Wilson std. star
13683	F0	6.6						
18256*	F6V	5.6	0.11	Constant	0.04	Constant	3	H+K similar to Sun
18404	F5IV	5.8						
61295	F6II	6.2	0.04	Constant	0.02	Constant	4	
78234	F2V	6.3						
83951	F3V	6.1	0.19	Var(>99%)	0.09	Var(>99%)	4	
83525	F5	7.0						
103095*	G8V	6.4	0.14	Var(>99%)	0.05	Var(>95%)	4	*uvby* std. star
103520	K0III	7.0						
124570*	F6IV	5.5	0.25	Var(>99%)	0.09	Var(>99%)	4	Mt. Wilson std. star
125451	F5IV	5.4						
156635	F8	6.7	0.10	Constant	0.04	Constant	4	
157347	G5IV	6.3						
176095*	F5IV	6.2	0.24	Var(>99%)	0.08	Var(>99%)	4	
175515	K0III	5.6						
182572*	G8IV	5.2	0.14	Var(>95%)	0.05	Var(>95%)	4	H+K lower than Sun
180868	F0IV	5.3						
215704*	K0	7.9	0.26	Var(>99%)	0.11	Var(>99%)	4	
216175	G5	8.0						

*Wilson star [Wilson, 1978].

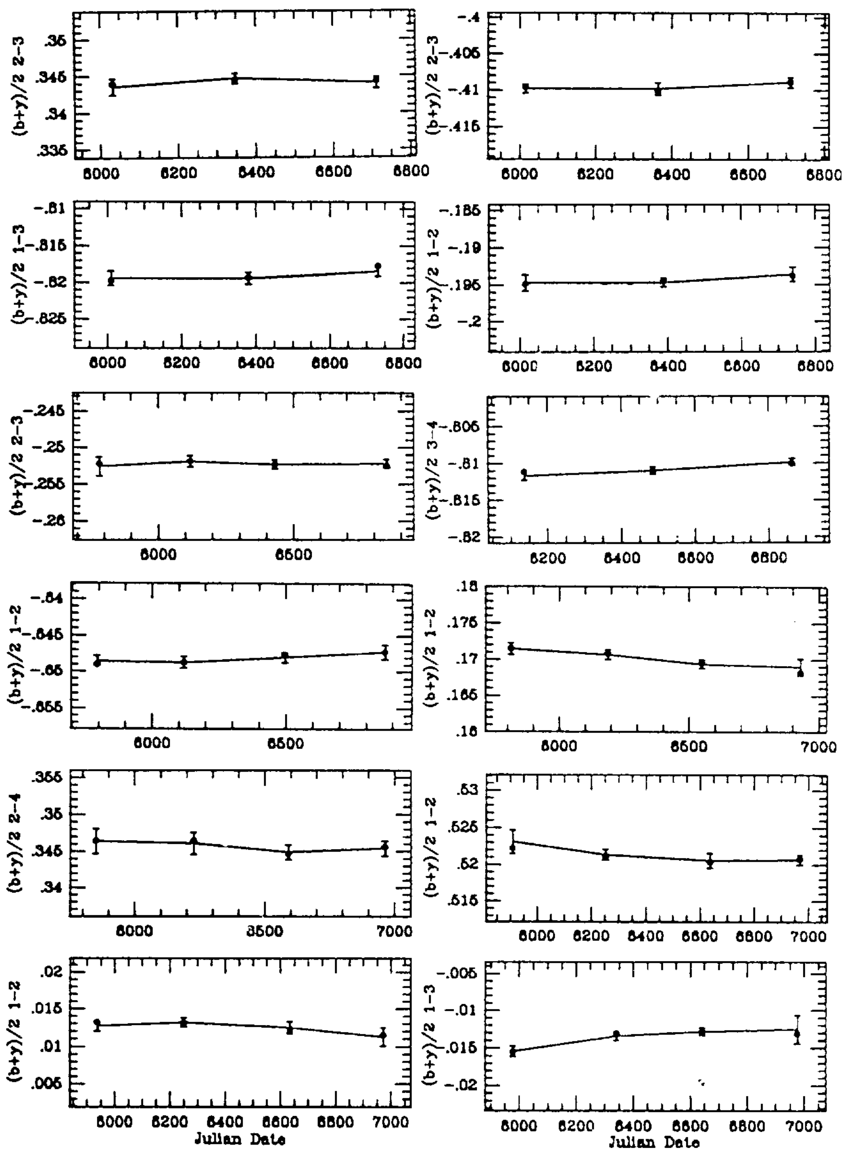

Figure 2. Differential light curves of twelve constant or nearly constant pairs, *b* and *y* averaged. The solid lines, with 95% confidence interval error bars, indicate seasonal means over three (or four) years. Dots denote the seasonal medians. The order of the light curves, left to right from upper left, is the same as the data in Table 1.

While the median is more robust in the presence of outliers (such as observational errors), its variance is over 50% larger than that of the mean for a given sample size [Hoaglin *et al.*, 1983].

The pairs of stars in Table 1 share the following properties: (1) their intraseason rms variation was less than about 0.3% mag (0.003 mag) and (2) their interseason peak-to-peak amplitudes were less than 0.3%; i.e., by conventional standard, these are very constant stars. Even so, in formal tests of variability, six of the twelve pairs show significant, albeit very low amplitude, variations.

Two indicators of variability are separately listed in Table 1. The first is derived from an analysis of variance in which the overall pooled standard deviation of the total set of observations is tested against the intraseason standard deviations, via the F-test. If the pair shows variability, the attained significance level is listed. The second indication of variability is more restrictive: it tests for a nonzero slope of the light curve, expressed in the table in units of percent yr^{-1}. The first test thus merely indicates that the seasonal mean magnitudes are not all alike, while the second reflects the presence of a significant linear trend.

Both tests happen to give the same result, perhaps fortuitously, or perhaps because of some degeneracy in the derived statistics (owing to the common use of various sums of squared errors). Six of the pairs show significant variation averaging 0.08% yr^{-1} at a significance level of 95% or greater, while the other six are "constant," changing by an average of 0.03% yr^{-1}.

As an example of the data from which the star pairs in Table 1 were taken, individual b and y light curves for the entire trio containing the Wilson star HD10476 are shown in Figure 3. Each cycle of measurement is denoted by a single plotted point on the figure. Star 1 (the program star, a K1V star and, incidently, a *uvby* photometric standard) is clearly variable since the two b and two y light curves containing star 1 have the same shape. The differential light curve for (star 2−star 3) is the source for the constant pair listed in Table 1. The right-hand panels of the figure illustrate interseason light curves in b and y for each of the combinations in the trio.

No adjustments have been made thus far in any of our data to take into account the very slow drift in the spectral response of our filter+photomultiplier combination, which in the course of ordinary photometric reductions is compensated by a "color term" that has changed by a few percent over the 15 years that this particular EMI 6256S photomultiplier has been in service. An expected artifact of an uncompensated color term would be a systematic secular drift in the differential magnitudes of two stars having different $(b - y)$ colors. No such effect is evident among the pairs in Table 1. We conclude for the time being that instrumental color effects are undetectable.

Interseason Variations

Among the 100+ pairs of differential magnitude data sets contained in the groups of stars observed, the incidence of apparent interseasonal variability is quite high. The histograms, Figure 4, give the distribution of peak-to-peak three (or four) season amplitudes (in magnitudes) for stars classified as "constant" (18 cases),

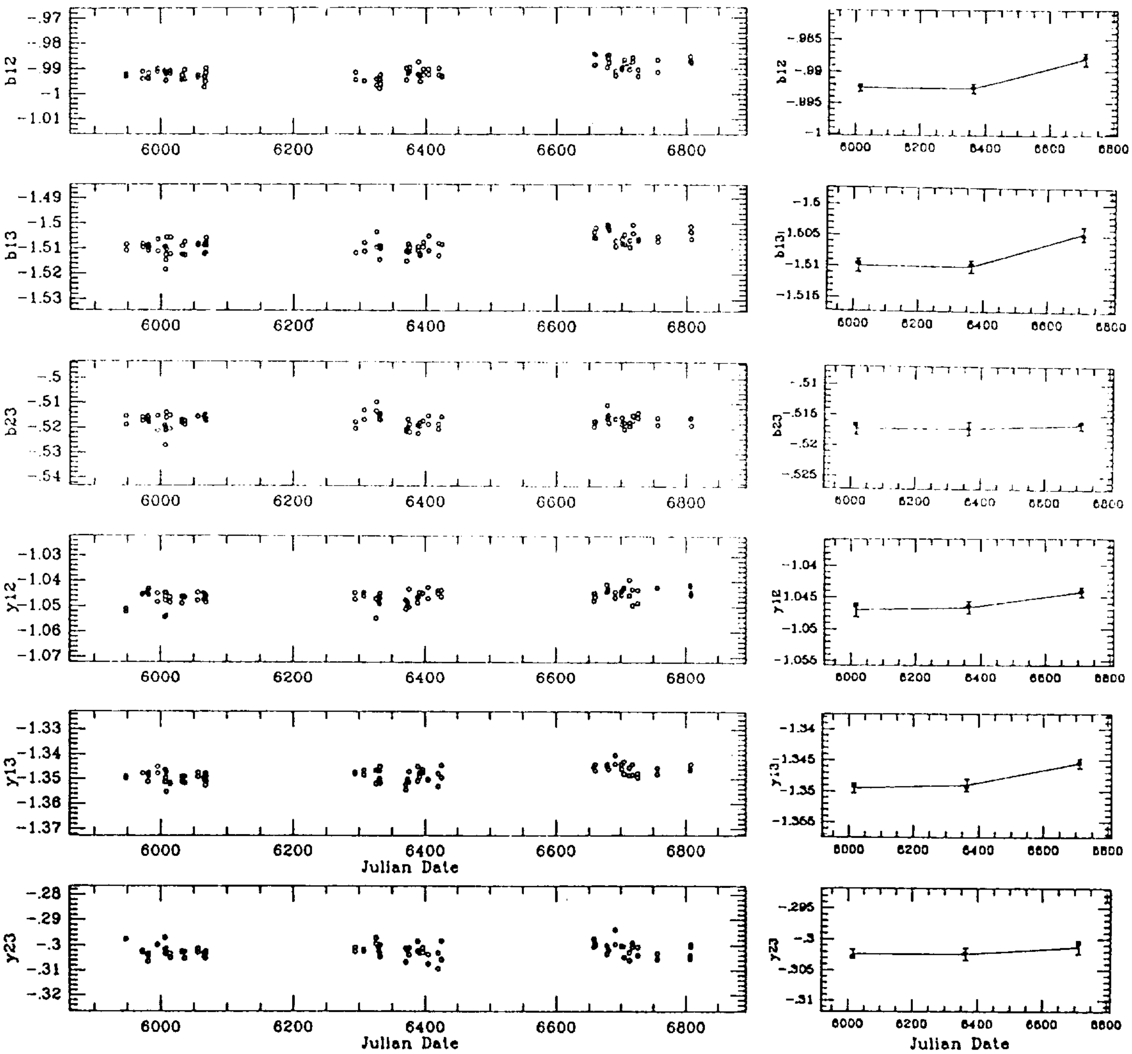

Figure 3. The left-hand panels show the individual differential b and y light curves for the stars in the trio containing the Wilson star HD10476 (star 1), a K1V star whose H+K index is similar to that of the Sun. There are usually two data points (cycles) acquired each night in each filter. The right-hand panels show the corresponding seasonal mean light curves. The obvious correlation between the mean light curves for (star 1−star 2) and (star 1−star 3) (panels 1 and 2, 4 and 5 from the top) indicates that star 1 is rather grossly variable relative to the size of the changes seen in the stars shown in Figure 2.

"possibly variable" (95% attained significance level, 10 cases), or "variable" (99% significance, 85 cases) according to the outcome of the analysis of variance of the seasonal mean.

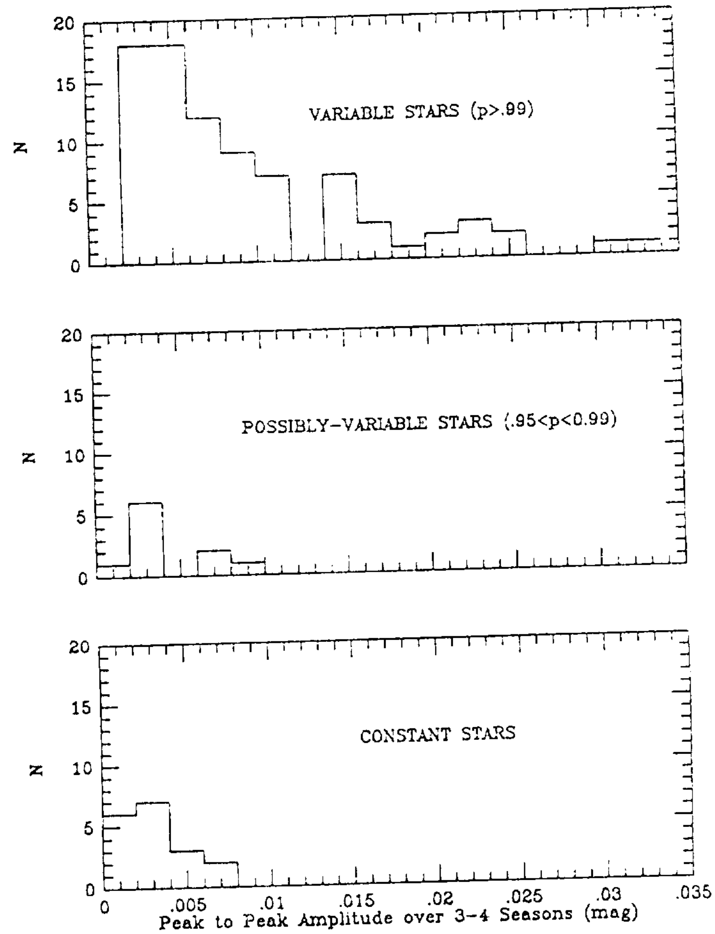

Figure 4. Distributions of the year peak-to-peak amplitudes of the complete sample over three (or four) observing seasons, classified by the outcome of the analysis of variance of the seasonal mean magnitudes (b and y averaged).

Can it be true that nearly every pair of stars we have looked at is intrinsically variable? This result certainly contradicts our expectation; yet, we have been unable to discover a plausible source of systematic error that would permit a small, evidently random, subset of the light curves to remain flat to better than 0.3% over three or four years. The pairs of stars in Table 1 cover the full spectral range of our survey, early-F to mid-K, and apart from the two stars that are Mount Wilson H+K standards, none has a prior record of study or other unique distinguishing characteristics.

Taking a somewhat conservative stance, we leave the question of the true frequency of intrinsic variability among solar-like stars open for the time being. Our experience shows that as the threshold of detection of variability has moved downward toward the 0.1% level, the proportion of variable stars has increased dramatically. If the Sun is, indeed, a typical G star that may vary by 0.1% over its 22-year magnetic cycle, then there may be no truly constant solar-like stars, whatsoever.

Intraseason Variations

Intraseason (i.e., night-to-night) variations provide information about the intrinsic variability of the stars on timescales of days to weeks, and, perhaps more importantly, define the baseline noise level needed to assess the reality of interseason variations. A variability diagnostic that we have used extensively is the correlation (or, more precisely, the cross correlation of the two time series with zero lag) between pairs of light curves. For example, if the light curve for (star 1−star 2) is inversely correlated with the light curve for (star 2−star 3) we surmise that star 2 is variable, provided that the light curve for (star 1−star 3) is suitably flat. We have used this test regularly in analyzing the intraseason, particularly rotationally modulated, variation of stars [Lockwood *et al.*, 1984, for example]. For the interseason light curves having only three or four annual points described above, this test is premature; but, after a few more seasons, it will become more persuasive.

Usually the correlations between the various pairs of light curves leads to an unambiguous identification of the variable star in a trio or quartet. Sometimes, however, more than one star is variable, and these cases must be examined with more care. To resolve ambiguities, several trios have been promoted into quartets by adding another comparison star, with the expectation that the variability within the group can ultimately be untangled.

Applied to the ensemble of sets of differential measurements obtained since 1984, the correlation technique yields the results in Figure 5, where the distinction between constant and variable stars is based on the standard test of the attained significance level of the correlation coefficient [e.g., table c-3, Bevington, 1969]. As in the interseason case, a majority of the stars are variable at low levels. Happily, the boundary between variable and constant stars is fairly clear. The first quartile among the variable stars (significance level greater than 99%) occurs at 0.0045 mag (0.41%) while the third quartile among the constant stars lies at 0.0026 mag (0.24%). Roughly a tenth of the cases lie in the intermediate ($95\% < p < 99\%$) range of attained significance; we designate these as "possibly variable."

Two elements of the analysis not shown here give us confidence that the detections of intraseason variability are meaningful: first, among the Wilson stars, the young, active stars (as determined by their chromospheric activity indices) are consistently variable photometrically at about the same level every year. Second, the night-to-night rms variations in b and y are always highly correlated.

In addition, the stars judged variable according to the above criteria share yet another common property: the ratio of the rms dispersion in b to that in y is about 1.1, while the same ratio is close to 1.0 for the constant stars (shown as a function

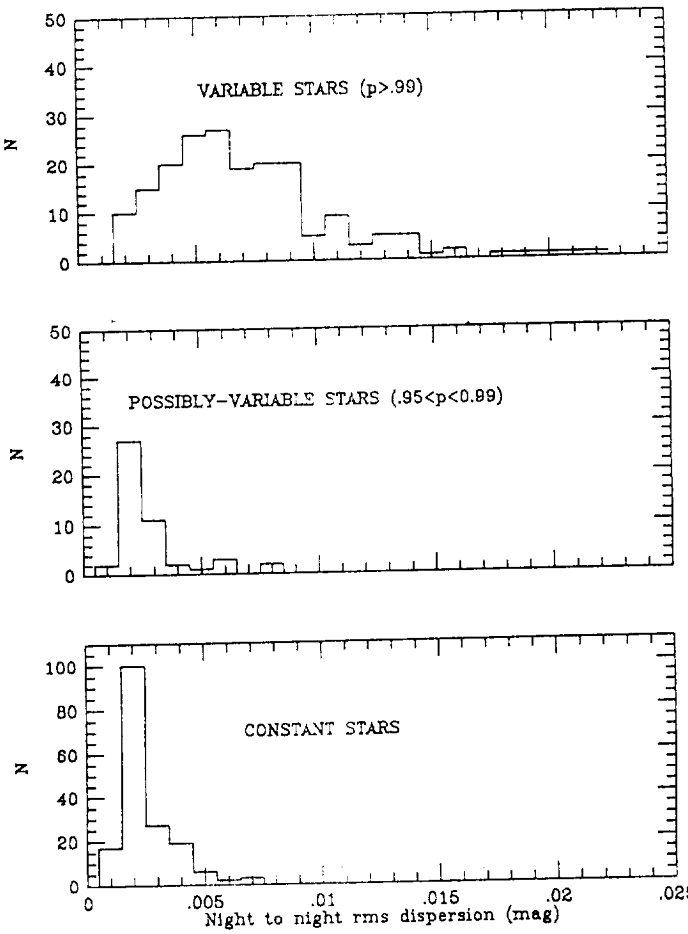

Figure 5. Distribution of intraseason rms dispersions (*b* and *y* averaged) for stars classified as variable, possibly variable, or constant, according to the significance of the correlation between pairs of light curves. Each star is included three (or four) times, i.e., once per season; however, its status is usually the same each season.

of the rms dispersion in *b* on Figure 6). The ratio becomes very noisy close to the night-to-night instrumental noise limit of about 0.0015 mag rms; hence, it alone is not a particularly good diagnostic of variability.

Astrophysically, the observed ratio of dispersion in *b* to the dispersion in *y* is plausible, since the *b* filter lies shortward of the blackbody maximum in cool stars, while *y* is near the peak. Luminosity variations imply a temperature change (i.e., a corresponding change in the Planck function), so the stars must become bluer (hotter) or redder (cooler). However, we cannot explain why the ratio approaches the value 1.04, not 1.00, for constant stars, unless there is a small residual instrumental or atmospheric effect.

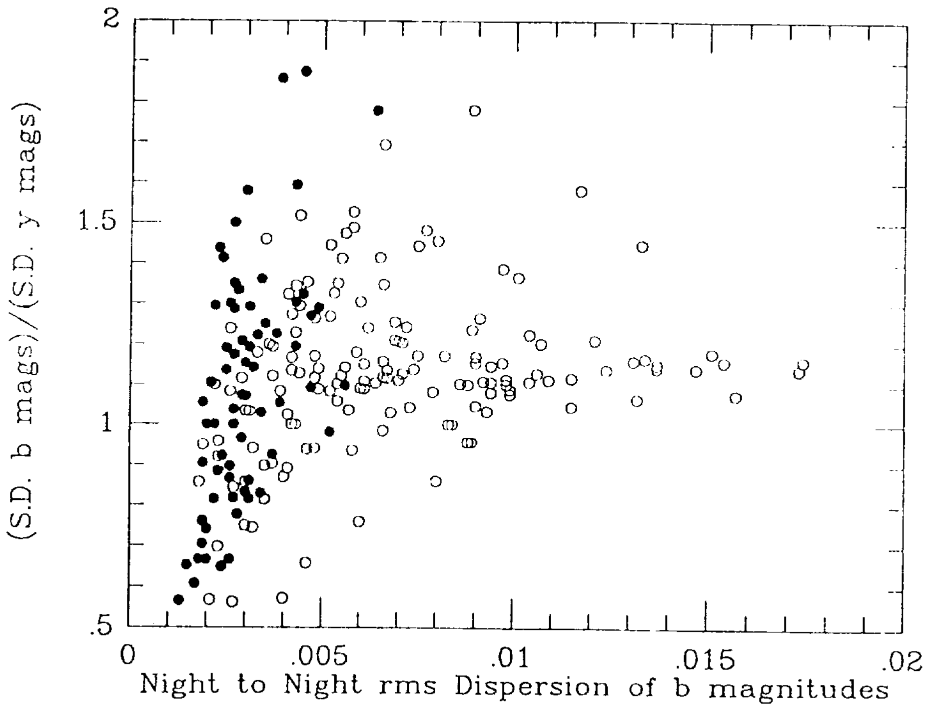

Figure 6. The ratio of the intraseason standard deviation of the b magnitudes to the standard deviation of the y magnitudes, as a function of the former. Filled circles are constant stars and open circles are variable stars (cf. Figure 5).

Possible Instrumental Errors

Among those relatively few stars that have not shown any sign of variability in any season, we have sought to identify systematic, perhaps instrumental, effects relating to the size of the night-to-night rms dispersion of the differential magnitudes. What is the source of the breadth of the histogram for constant stars shown in the bottom panel of Figure 5? Some pairs of stars are consistently quiet at the level of 0.15% night-to-night, while others, not evidently variable by our formal tests, fluctuate each season by two or three times as much.

In Figure 7, we have plotted the standard deviations of the intraseason differential magnitudes (b and y averaged) as a function of four likely candidates for the source of noise: (1) The mean airmass of the group. Groups at high airmass should be noisier than groups at low airmass. No significant effect is seen in this sample; however, we have sparse data at high airmasses. (2) The difference in $(b-y)$ color between the stars in a pair. An instrumental effect, possibly temperature-related, should show up here. No effect is seen. (3) The difference in V magnitude. Time dependent nonlinearities in the photometer electronics (e.g., deadtime errors) could cause trouble. No effect is seen. (4) The V magnitude of the fainter star of the pair. Photon noise becomes significant only at the lower right corner of the figure.

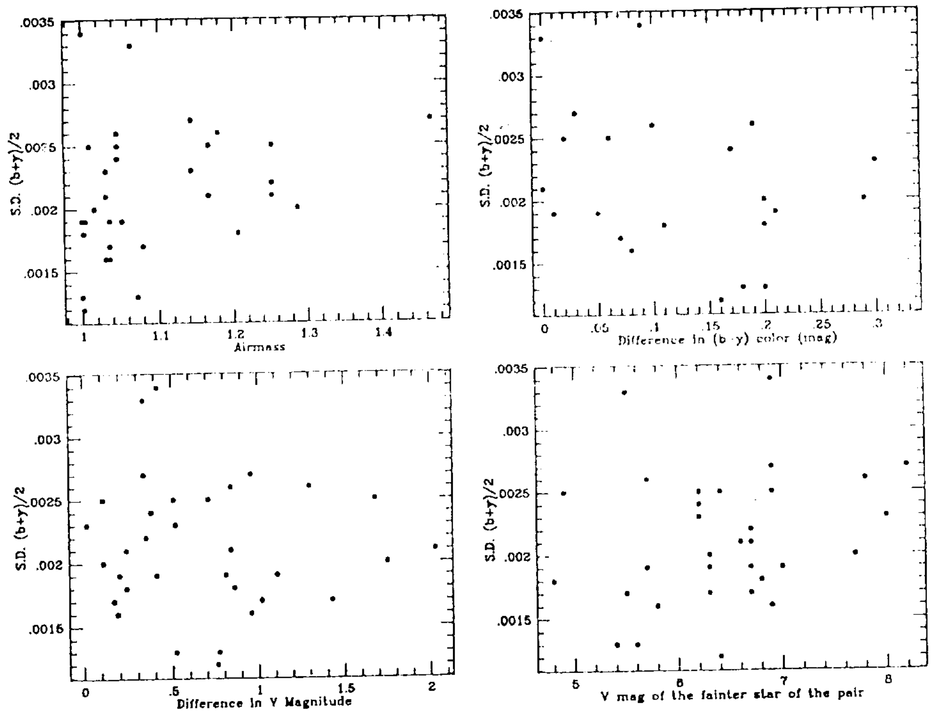

Figure 7. Averaged b,y intraseason standard deviations (for star pairs showing no sign of intrinsic stellar variability) plotted against four parameters that are conceivable sources of observational error.

(A noise level of 0.0015 mag occurs at $V=8$ mag, approximately.)

Having failed to identify a source of the range of variances occurring among supposedly constant stars, we are, as in the case of the interseason variations discussed above, forced to conclude, hesitantly, that (1) there may be an as-yet unrecognized instrumental or observational effect or (2) intrinsic variability may be common among those stars.

Intranight Considerations

We have noted above that often the night-to-night repetition of a series of measurements is noisier than expected from the internal cycle-to-cycle errors during the night. One possible source of noise worth considering is differential atmospheric extinction, since we reduce our data using seasonally adjusted mean values of the extinction coefficients [Lockwood and Thompson, 1986]. Figure 8 (lower panel) shows the distribution of differential airmass for all of our data. The median is less than 0.01, and the upper quartile is less than 0.02 airmass. Assuming a rather generously large random error in the extinction coefficient, say 0.05 mag airmass^{-1}, the resulting error is on the order of 0.001 mag (0.1%). Clearly, this effect should be imperceptible among even our most constant stars.

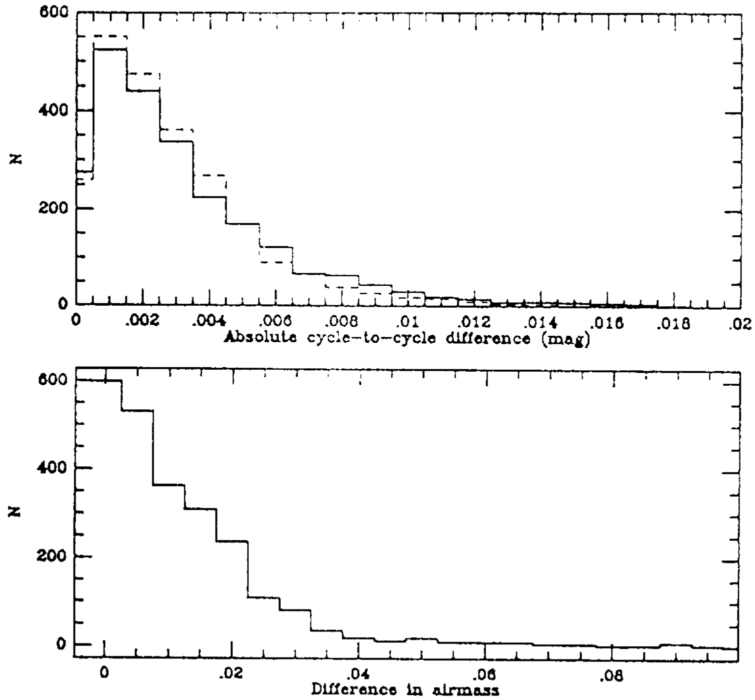

Figure 8. (Upper panel) Distributions of the absolute intranight, cycle-to-cycle differences in the differential magnitudes. (Solid line) cycle 1−cycle 4 [y filter]; (dashed line) cycle 2−cycle 3 [b filter]. The median for y (0.0024 mag) is always greater than the median for b (0.0022 mag). (Lower panel) Distribution of the absolute values of the difference in airmass between the various pairs of stars, summed over all groups and all nights. The median lies at 0.008 airmass.

The distribution of the absolute values of the intranight cycle-to-cycle differences in the differential magnitudes has some interesting properties that we do not understand. First, the absolute dispersion in y (median value 0.0024 mag, cycle 1−cycle 4) is consistently greater than that in b (0.0022 mag, cycle 2−cycle 3) by about 4%, a small but statistically very significant amount (Figure 8, upper panel). This difference persists among all the star pairs in trios and quartets alike; it is a fixed constituent of the measurements as presently recorded. Moreover, it is independent of the temporal order of the observations within a cycle: stars observed consecutively in time behave the same as pairs separated by an intervening star. Since our data are always taken in the cycle order y,b,b,y, we might suspect a mysterious temporal effect in our equipment, possibly just the result of moving the filter wheel from y to b (for 2 consecutive cycles), then back to y again.

An extinction effect is clearly ruled out here, because the extinction in y is 30% lower than in b and because the differential airmasses are so small. A purely temporal effect of unknown origin seems excluded by our previous finding [Lockwood, 1984] that the precision of differential magnitudes is unchanged when the time between the measurements of the two stars is extended from 2 minutes to 5 minutes to 7 minutes. The two y cycles are separated by 20 minutes (for quartets), while the two b cycles are separated by 10 minutes.

A hypothesis previously put forth [Lockwood, 1984] has to do with possible inhomogeneities in the sky background brightness around the stars. Our practice is to measure the sky in the first two cycles (y,b) in one direction away from the stars (say, North) and in the second two cycles (b,y) in the opposite direction. These values are then subtracted from the corresponding measurements of star+sky. Since the sky background is littered with unseen generic, probably red, field stars, a possible source of error is introduced. Typically, the stars on the program are 6th magnitude; hence a single, undetected background star 7.5 magnitudes fainter would introduce an effect at the level of 0.001 mag (0.1%). However, a single star this bright would easily be seen and avoided by the observer except, perhaps, on moonlit nights. Further, star count data summarized by Roach and Gordon [1973] suggests that this particular explanation is implausible owing to the rather low density of stars in the appropriate magnitude range.

We have the data to test this admittedly implausible scenario, but have not yet done so. For example, the problem should be worse for fainter stars than brighter stars; it should be worse on moonlit nights when stray background stars might not be noticed; and it should be worse near the galactic plane. Also, we should make a series of measurements in the cycle order b,y,y,b to see if the temporal order of observation is important.

Conclusions

Low-level variability is a widespread observable characteristic of early F to mid-K stars of all luminosity classes, including lower main-sequence stars quite similar to the Sun. This finding is completely consistent with the observed variation of the Sun itself, which has evidently decreased in total output by about 0.1% since 1980. In both the stellar and the solar case, the existence of luminosity cycles corresponding to the magnetic cycles has yet to be demonstrated, but further observations seem certain to be capable of providing this badly needed information.

Of the three dozen program stars observed differentially for brightness variations since 1984, a majority have proven to be variable at levels typically below 1%, as have many of their comparison stars. None of the program stars that were variable on intraseason timescales were constant from one season to the next, but a few that were completely quiescent within each season seem to vary from one year to the next. More often the variation detected within each season produced an interseasonal change.

We have satisfied ourselves that instrumental or other systematic effects, if present, are quite small indeed, but we have not clearly identified a lower level of instrumental precision as a fixed element of the observational record for all pairs of stars. While some pairs are observable every year with a night-to-night dispersion as small as 0.15% and possibly even approaching 0.10% (averaging *b* and *y* together), others are much noisier without showing clear evidence of an identifiable stellar signal from the statistical tests that we have utilized so far. One reason for this limitation is quite simply that within each group, the quietest pair of stars is taken to be the "constant" by which the variability of the others is judged; i.e., we do not assume an a priori level of instrumental performance, based, for example, on simple photon statistics.

Over the three-year span of the observations, a dozen pairs of stars have shown remarkable constancy, although six of these are evidently variable according to the formal analysis, with an average linear slope of 0.08% yr^{-1}. The six pairs that are constant according to the same criteria show an average interseason slope of 0.03% yr^{-1}, comparable to that observed for the Sun. Thus, if stars like the Sun vary over the course of their solar-like magnetic activity cycles with amplitudes of, say, 0.1 to 0.5%, it should be possible to measure and characterize these variations through continued application of the techniques we have described.

Acknowledgments

This work has been supported since 1984 by the Air Force Geophysics Laboratory under contract F-19628-84-K-0013. We thank L. H. Wasserman for programming the DEC LSI-11/03 data acquisition computer, and C. Gullixson for assistance with the telescope encoding system and its computer. Many of the observational protocols we follow were first demonstrated to us by M. Jerzykiewicz, whose exemplary technique has served us well.

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AUTHOR ADDRESS LIST

G. W. Lockwood
Lowell Observatory
1400 West Mars Hill Road
Flagstaff, Arizona 86001

Brian A. Skiff
Lowell Observatory
1400 West Mars Hill Road
Flagstaff, Arizona 86001