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Stellar Irradiance Variations

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Abstract. The variability of several dozen stars similar to the Sun in mass, age, and average activity has been monitored regularly in chromospheric Ca II HK emission for over three decades, and photometrically for over fifteen years. Larger samples have been observed less comprehensively. Analogous solar time series exist. A comparison of solar variability with its stellar analogs indicates that the Sun's current behavior is not unusual among sunlike stars. Both solar models and stellar measurements suggest that a true luminosity variation underlies the cyclic total irradiance changes observed on the Sun.

1. Introduction: The Sun as a Star

The increase and decrease in sunspot number that accompanies the solar cycle undoubtedly remains the most familiar manifestation of solar variability. Comparison of solar variability with its stellar analogs, however, must make use of diagnostics that, unlike sunspot number, treat the Sun as an unresolved star. Among these, the most useful are measurements of chromospheric Ca II K-line emission since 1974 from the National Solar Observatory (White et al. 1998), and total irradiance measurements since 1978 from a series of spaceborne radiometers such as the ACRIM experiment aboard the Solar Maximum Mission (SMM) satellite (Willson 1997).

From such observations, we know that the amplitude of the solar cycle exceeds 20% in Ca K-line emission. The amplitude of the total irradiance variation is much smaller, but the ACRIM radiometry clearly showed that the Sun dimmed by about 0.1% between 1980 and 1989, in phase with decreasing solar activity during the declining half of cycle 21, and then brightened again with the onset of cycle 22. Radiometric measurements from subsequent space experiments indicate comparable total irradiance variability for cycles 22 and 23 (e.g., Lean 2001). This variation is generally interpreted as a slight imbalance between the flux deficit produced by dark sunspots and the excess flux produced by bright faculae, with the facular effects dominating the competition (e.g., Foukal & Lean 1988; Lean et al. 1994).

For 20 years, authors have felt obliged to remind their readers of the distinction between total irradiance and luminosity variability. We are repeatedly cautioned that variations in solar irradiance, observed from our location in the ecliptic inclined by only some 7°with respect to the solar equator, do not warrant the conclusion that the solar luminosity itself is changing (e.g., Sofia &

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Li 2000). Clearly, measurements of solar irradiance variations from outside the Sun's equatorial plane - from mid-latitudes and the poles - would settle the question. Absent these, however, evidence from solar models as well as stellar observations can be adduced pointing toward the conclusion that true luminosity variability does underlie the observed changes in solar total irradiance. Rather than confining this paper simply to another review of stellar variability observations (for which, see Radick (2000)), I will devote some space to presenting this evidence.

2. Stellar Variability

It is well established that cool main-sequence stars ranging from a few tenths up to about 1.5 times the Sun's mass generally show evidence of magnetic activity in the form of chromospheric calcium emission. In 1966, Olin Wilson began to monitor the Ca II H+K emission for about 100 stars from the Mount Wilson Observatory (Wilson 1978). Since 1977, Wilson's observations have been continued as part of the Mount Wilson HK program (Baliunas et al. 1995). In considerable measure because of these efforts, it is now recognized that the activity of a cool dwarf star is governed by its mass and rotation rate. It is also known that a star's rotation slows and its average activity level declines as it ages.

The temporal variation of stellar activity may be classified into three categories (Baliunas et al. 1997). Young, rapidly rotating stars tend to vary erratically, rather than in a smooth cycle like the Sun. Older, more slowly rotating stars, including the Sun, tend to show either regular activity cycles (about 80%), or little or no variation at all (about 20%). It is not unusual to find stars with activity cycles about a decade in length. Among the older stars, those more massive than the Sun tend to show low amplitude cycles, whereas those less massive than the Sun often have strong cycles. The Sun currently has a fairly prominent activity cycle, as traced by its HK emission, for a star of its mass.

In 1984, a program was begun at Lowell Observatory to study the long term photometric variability of lower main-sequence stars (Lockwood et al. 1997; Radick et al. 1998). The program sampled stars bracketing the Sun in temperature and average activity level. It included 41 program stars, 34 of which were selected from the stars of the Mount Wilson HK program. From these measurements, we now know that the amplitude of the year-to-year photometric variation for young, active stars is typically several percent. It decreases dramatically among stars more closely resembling the Sun in age and average activity, by a factor of ten, twenty, or even thirty, to a level approaching the detection limit (0.1% or better) of the measurements. In contrast, the corresponding decrease in chromospheric Ca HK variation is only about a factor of three.

In 1993, measurements similar to the Lowell program were begun at the Fairborn Observatory (Henry 1999). Although detailed comparison of the observations has only begun, it is already clear that these newer observations validate the broad outline of variability among sunlike stars sketched in the preceding paragraph. In general, photometric variation is fairly common across the entire lower main sequence, with about half of the combined sample of several hundred

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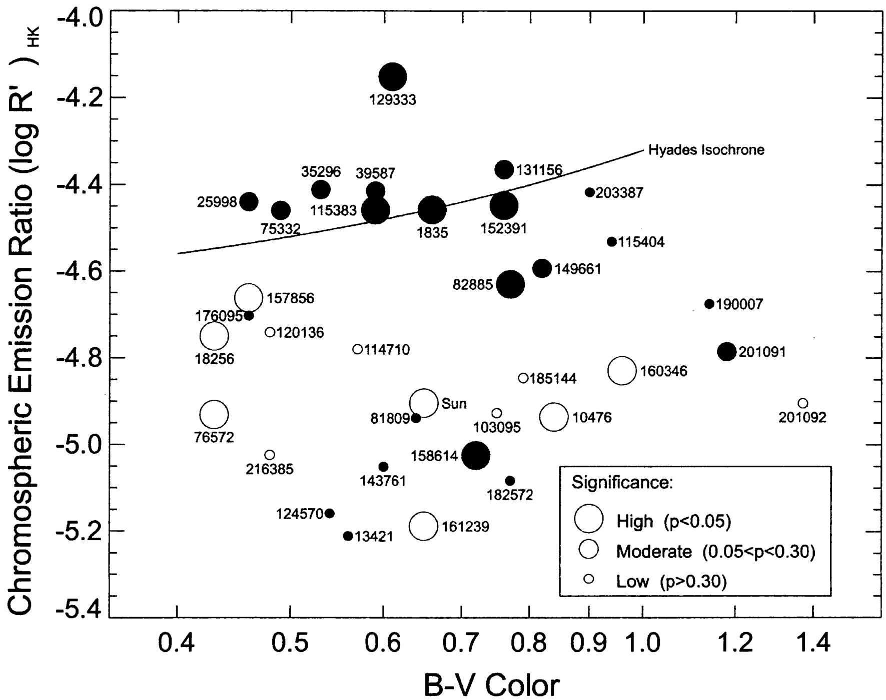

Figure 1. The stars of the Lowell Observatory photometric study, distributed in $B-V$ color (or temperature) and average activity as measured by chromospheric Ca HK emission. The stars are identified by their HD numbers. The position of the Sun is also indicated. The symbols represent the correlation pattern between variations in photometric brightness and Ca HK emission on the year-to-year time scale. The size of each symbol indicates the significance of the correlation. Open symbols are used to represent stars, like the Sun, that become brighter as their HK emission increases. Filled symbols represent stars that become fainter as their HK emission increases.

stars showing detectable variability on the year-to-year time scale (Lockwood et al. 1997; Henry 1999).

When the temporal behavior of chromospheric HK emission and photometric variations is examined in detail, an interesting distinction between young, active stars and older, more sunlike stars emerges (Figure 1). Unlike the Sun, young stars with normalized HK activity greater than about log $R'_{HK} = -4.6$ become fainter photometrically as their chromospheric emission increases, without exception. In contrast, older, more Sun-age stars tend to show the same pattern of direct correlation that the Sun has. The most prominent violation of this rule, the star HD 158614, may not not a valid exception, if only because it is a binary with two comparably bright components. If we assume that the same mechanism, namely, the imbalance between the flux deficit produced by dark spots and the excess flux produced by bright faculae, is responsible for the

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variability in both stellar age groups, then we are forced to conclude that the dark spot component dominates the competition for young stars, whereas the bright facular component dominates for older stars like the Sun.

3. From Irradiance to Luminosity

Suppose we had measurements of solar total irradiance spanning the Sun's activity cycle from observers situated at all heliographic latitudes. We would then be able to deduce the Sun's cyclic luminosity variation (or lack thereof) by simply weighting and summing those irradiance time series. In fact, all we have is the irradiance time series for the Sun's equatorial latitudes, a model for that variation in terms of sunspots and faculae, and rather heterogeneous measurements of areas and contrasts (including center-to-limb contrasts) for those features. Nevertheless, this information is sufficient to constrain the problem, especially if we are interested only in testing the hypothesis that no luminosity variation accompanies the solar activity cycle. Supposing the hypothesis to be true, the Sun would somehow have to cancel the effect of its well-established equatorial irradiance variation - in other words, there would have to be a comparable, but opposite, irradiance variation visible to an observer situated at some other latitude. If this cannot be found, then the hypothesis must be false.

3.1. A Question of Inclination

Attempts to model the Sun's irradiance variation outside its equatorial plane began several years ago (Schatten 1993). Subsequent models have had curiously diverse heritages, ranging from an adaptation of a planetary light curve simulator (Radick et al. 1998) to a modified stellar Doppler imaging code (Unruh et al. 2000; Knaack et al. 2001). The fact that they all deliver qualitatively similar results is certainly reassuring. The primary purpose for developing these models was originally to investigate whether or not variations in viewing angle, or inclination, could resolve a putative discrepancy between the amplitude of the cyclic solar variation and its stellar analogs. Here we will use the models for a somewhat different purpose.

Qualitatively, the argument runs as follows: We know that (1) the sunspots and faculae thought to be responsible for the Sun's total irradiance variation are confined to low and intermediate heliographic latitudes, and (2) the unusual angular radiance pattern of the faculae renders them essentially invisible at disk center but easily visible near the limb, whereas foreshortening, accentuated by the Wilson depression, reduces the visibility of sunspots as they approach the limb. Accordingly, we might expect that, viewed from increasing heliographic latitudes, an ever increasing fraction of the faculae would be seen close to the limb and therefore appear bright, and the dark sunspots would tend to disappear. In other words, the balance between the spots and faculae would tilt more and more in favor of the faculae, and the amplitude of the cyclic variation in total irradiance would therefore increase as we moved from the solar equator toward the poles.

In fact, all three models confirm this qualitative expectation (Figure 2), even though they differ over the quantitative magnitude of the effect. Much of the disagreement between Schatten's (1993) model and the other two seems

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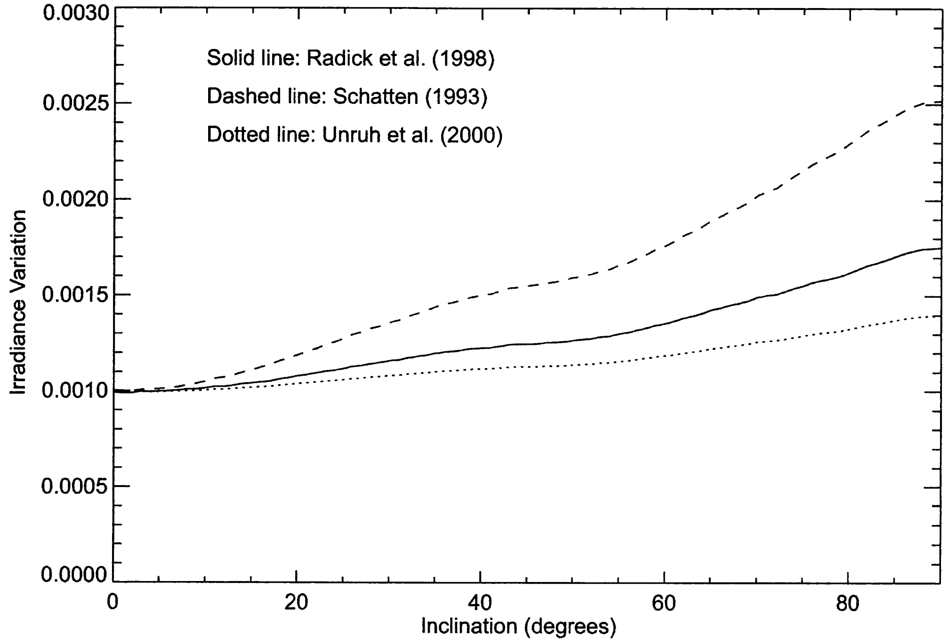

Figure 2. The cyclic variation of solar total irradiance as a function of inclination angle, or heliographic latitude.

traceable to differences in assumptions concerning the amplitude of the Sun's cyclic variation, the relative strength of the facular and spot components, and the center-to-limb facular contrast. (Note: for comparison with the other models, the curve for Schatten's model has been offset by -0.0008 units in Fig 2, to a common irradiance variation of 0.0010 at the solar equator.) It has been suggested that the discrepancy between the two more recent models may be due to implicit differences in values adopted for spot and facular areas (Unruh et al. 2000; Knaack et al. 2001). These areas are not explicit inputs into the model used by Radick et al. (1998), but may be implied to some measure by the heliographic latitude bounds specified for the sunspot and facular belts.

Fully unraveling these discrepancies may safely be deferred to another time and place - what matters here is that all the models agree that the cyclic irradiance variation does not reverse sign for any heliographic latitude. This, in turn, requires us to reject the hypothesis that the solar luminosity remains unchanged through the activity cycle. Of course, the models all share the assumption that solar irradiance variability arises from the effects of sunspots plus faculae, alone. If this assumption is not correct, then conclusions based on the models are empty. That caveat noted, let us proceed to a consideration of empirical evidence from the observations of sunlike stars that points toward the same conclusion concerning solar luminosity variability.

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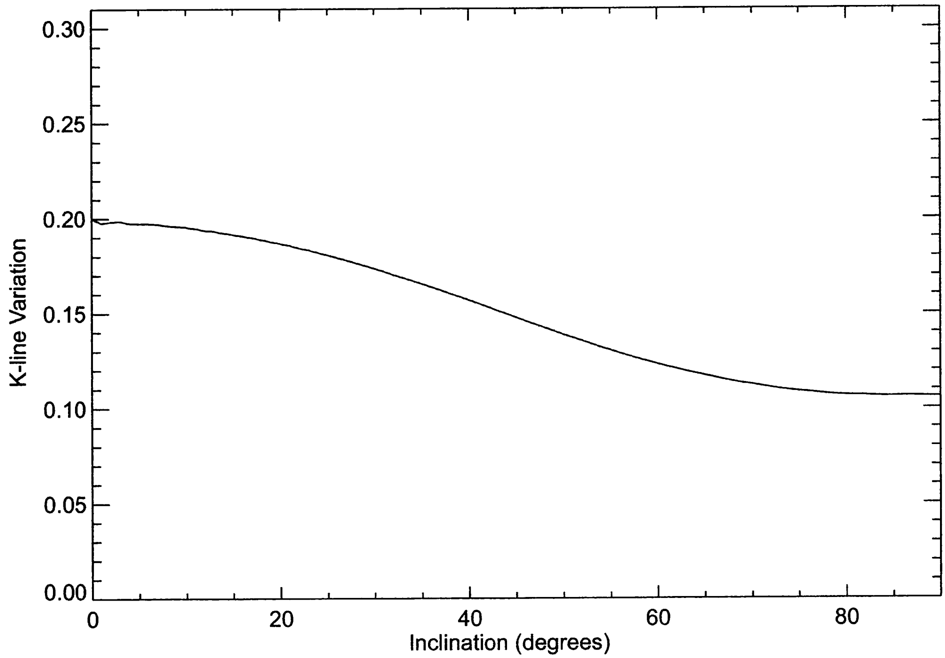

Figure 3. The cyclic variation of solar chromospheric Ca II K-line emission as a function of inclination angle.

3.2. No Place to Hide

Recall that, for stars similar to the Sun in age and mean activity, there seems to be a direct correlation between photometric brightness and chromospheric calcium HK variation (Fig 1). The evidence is even stronger that stars substantially younger than the Sun show the opposite pattern.

This is remarkable. Consider that (1) a sufficiently large assemblage of field stars presumably presents the entire distribution of possible inclinations, and (2) a sample of 30+ stars, such as that shown in Fig 1, probably samples that distribution reasonably well. Nevertheless, the stars of Fig 1 manage to sort themselves into two clearly distinguishable groups - young stars and older stars - based on their observed patterns of year-to-year variability. In other words, regardless of inclination, young stars show one pattern of variation, and Sun-age stars show another, shared by the Sun itself. Inclination doesn't matter!

There remains a bit of wriggle room. If, viewed at some particular inclination, a Sun-age star were to reverse the sense of both its photometric and Ca HK variation, the direct correlation would be preserved. Additional modeling efforts, however, argue that this does not happen. During the past summer, the solar inclination model was modified once again to explore Ca K-line variability (Carlson & Radick 2000). Somewhat surprisingly, it was found that the amplitude of the solar cycle, observed in the K-line, should decrease significantly as one moves away from the equator (Figure 3). Nevertheless, it never reverses its sense. While it would probably be worthwhile to verify this result using,

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for example, data from the Precision Solar Photometric Telescopes (PSPTs), it certainly does suggest that Ca K-line emission is a reliable indicator for stellar magnetic activity, in the sense that high emission corresponds to high magnetic activity, regardless of inclination. The stars are not deceiving us, at least in this manner.

Barring fundamentally unanswerable objections such as "Why should we assume that the behavior of any sample of supposedly sunlike stars tells us anything about the Sun itself?", there seems to be no place to hide. The stellar observations suggest, by analogy, that solar total irradiance varies directly with magnetic activity for all heliographic latitudes. This, in turn, requires us once again to reject the hypothesis that the solar luminosity remains unchanged through the activity cycle.

It may be added, incidentally, that the solar inclination model results imply that the correlation coefficient between variations in chromospheric Ca emission and total irradiance does depend on inclination - a calibration based on the Sun is probably not valid for other stars. This promises to complicate even further the already difficult task of comparing solar variability to its stellar analogs, and once again drives home the lesson that reliance on proxies can lead to confusion and error.

4. Summary

Stellar observations provide a context which we can use to interpret the Sun's behavior. A comparison of solar variability with its stellar analogs indicates that the Sun's current behavior is not unusual among sunlike stars. Both solar models and the stellar measurements imply that a true luminosity variation underlies the cyclic total irradiance changes observed on the Sun.

References

Baliunas, S. L., Donahue, R. A., Soon, W. H., & Henry, G. W. 1997, in ASP Conf. Ser. Vol. 154, Cool Stars, Stellar Systems, and the Sun, 10th Cambridge Workshop, ed. R. Donahue & J. Bookbinder (San Francisco: ASP), 153

Baliunas, S. L., Donahue, R. A., Soon, W. H., Horne, J. H., Frazer, J., Woodard-Eklund, L., Bradford, M., Rao, L. M., Wilson, O. C., Zhang, Q., Bennett, W., Briggs, J., Carroll, S. M., Duncan, D. K., Figueroa, D., Lanning, H. H., Misch, A., Mueller, J., Noyes, R. W., Poppe, D., Porter, A. C., Robinson, C. R., Russell, J., Shelton, J. C., Soyumer, T., Vaughan, A. H., & Whitney, J. H. 1995, ApJ, 438, 269

Carlson, L. R., & Radick, R. R. 2000, NSO Internal Tech. Rpt.

Foukal, P., & Lean, J. 1988, ApJ, 328, 347

Henry, G. W. 1999, PASP, 111, 845

Knaack, R., Fligge, M., Solanki, S. K., and Unruh, Y. C. 2001, A&A, in press

Lean, J. 2001, this volume

https://doi.org/10.1017/S0074180900218810 Published online by Cambridge University Press

Lean, J., Skumanich, A., White, O. R., & Rind, D. 1994, in IAU Colloq. 143, The Sun as a Variable Star, ed. J. Pap, C. Froehlich, H. Hudson, & S. Solanki (Cambridge: Univ. Press), 236

Lockwood, G. W., Skiff, B. A., & Radick, R. R. 1997, ApJ, 485, 789

Radick, R. R. 2000, J. Atmos. &Solar-Terrest. Phys., in press

Radick, R. R., Lockwood, G. W., Skiff, B. A., & Baliunas, S. L. 1998, ApJS, 118, 239

Schatten, K. H. 1993, J. Geophys. Res., 98, 18907

Sofia, S., & Li, L. H. 2000, in The Solar Cycle and Terrestrial Climate, ESA Publ. SP-463, in press

Unruh, Y. C., Knaack, R., Fligge, M., & Solanki, S. K. 2000, in ASP Conf. Ser. Cool Stars, Stellar Systems, and the Sun, 11th Cambridge Workshop, ed. R. Lopez, R. Rebolo, & M. Osorio (San Francisco: ASP), in press

White, O. R., Livingston, W. C., Keil, S. L., & Henry, T. W. 1998, in ASP Conf. Ser. Vol. 140, Synoptic Solar Physics, ed. K. Balasubramaniam, J. Harvey, & D. Rabin (San Francisco: ASP), 293

Willson, R. C. 1997, Science, 226, 1963

Wilson, O. C. 1978, ApJ, 226, 379

https://doi.org/10.1017/S0074180900218810 Published online by Cambridge University Press