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The Photometric Variability of Solar-Type Stars

Mark S. Giampapa

National Solar Observatory,
950 N. Cherry Ave., POB 26732, Tucson, Arizona USA
email: giampapa@nso.edu

Abstract. The joint variability of chromospheric emission with the integrated flux in the *Kepler* visible band for the Sun as a star is examined. No correlation between our Ca II K line parameter and the *Kepler* passband is seen, suggesting that visible-band variability in solar-like stars is mostly independent of solar-like chromospheric activity. However, the K-line parameter time series and the total solar flux in the infrared *K* band appear weakly correlated, reflecting the wavelength dependence of the relationship between magnetic activity and broadband variability. We then apply a schematic, three-component model as a framework for the discussion of stellar photometric variability as observed by *Kepler*. The model confirms that spots tend to dominate stellar photometric variability in the visible though interesting cases do emerge where the facular disk coverage may become important in determining the amplitude of broadband variability.

Keywords. Variability, spots, faculae, plage, *Kepler*

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1. Introduction

The Sun and solar-type stars exhibit photometric variability on short and long time scales that is associated with magnetic structures. The amplitude of the brightness changes is wavelength-dependent according to the nature of the magnetic field-related component that is the dominant contributor to the variability. Prior to the *Kepler* mission, the most extensive, long-term study of brightness changes in solar-type stars utilizing high-precision, ground-based differential photometry is summarized by Lockwood *et al.* (2007). Hall *et al.* (2009) discuss an extension of this effort to a larger sample of more nearly sun-like stars.

In this invited paper, we carry out an initial exploration of the applicability of the solar paradigm to the interpretation of stellar photometric variability. We conclude with suggestions for achieving a more comprehensive picture of the origins of magnetic field-related variability, which is a topic of renewed importance given that magnetic fields in solar-type stars modulate the radiative and energetic particle environments in which exoplanetary systems form and evolve.

2. The Sun as a Star

A comparison of stellar variability with that of the Sun-as-a-star becomes appropriate given that (1) solar variability can inform our interpretation of stellar variability, (2) the amplitude of solar irradiance variability in the visible at the 1 – 3 mmag level overlaps with that seen in solar-type stars in the *Kepler* field sample, and (3) near-simultaneous, space - and ground-based data of superb quality are available for the Sun as a star.

We utilize the parameter time series for the 1 Å bandpass centered at the Ca II K line (hereafter referred to as K-line) at 3933.68 Å as derived from high resolution spectra (R $\simeq$ 300 000) obtained daily since 2006 by the Integrated Sunlight Spectrometer (ISS),

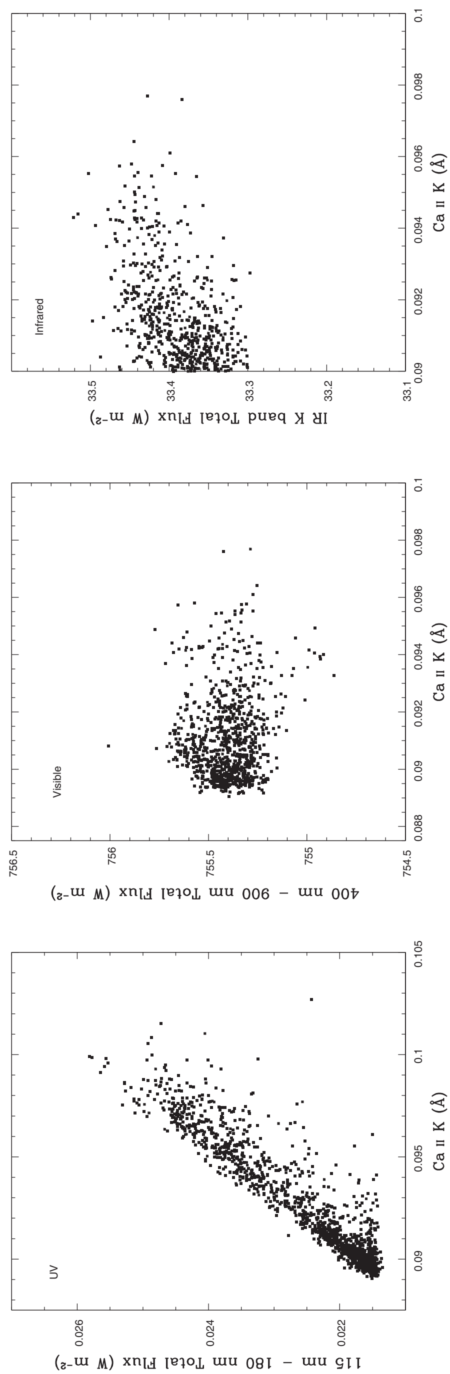

Figure 1. The daily variation of total flux with the Ca II K 1 Å parameter in the Sun as a star. The selected bandpasses include the far UV (*bottom*), the visible *Kepler* bandpass (*middle*) and the infrared *K* band (*top*). The accuracy of the daily monochromatic flux measurements is 2% while a typical measurement error in the K-line parameter is $\sim 0.001\%$. The correlation between the K-line and the far UV bandpass confirms that each has qualitatively similar origins in magnetic active regions. Variability in the visible tends to be spot dominated with little or no correlation with K-line emission. In the infrared the spot contrast has declined significantly accompanied by an emerging weak correlation with the K-line.

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an instrument of the NSO SOLIS facility (see Keller *et al.* 2003). We compare the relative strength of the K-line core with solar monochromatic absolute flux measurements recorded by the Spectral Irradiance Monitor (SIM) on board the SORCE satellite (McClintock *et al.* 2000; Rottman *et al.* 2006). We utilized those SIM data that overlapped with the *Kepler* visible bandpass of approximately 400 nm – 900 nm.

SIM flux measurements and SOLIS/ISS K-line spectra obtained for the same Julian Day number, respectively, yield the plots displayed in Fig. 1. There is no, or very little correlation, of the relative flux in the core of the K-line with the solar flux measured by the SIM instrument in the *Kepler* visible bandpass. Hence, the solar flux in the *Kepler* bandpass is effectively independent of chromospheric activity in the Sun at primarily quiescent solar levels. We then extended this comparison to the Johnson K band in the infrared, which is centered at approximately 2.2μm. Interestingly, some correlation appears to be present, especially in contrast to what we see in the visible band. The result for the infrared K band is reminiscent of some early work in the solar infrared that revealed substantial intensity structure in a deep photospheric band at 1.64 μm correlated with the chromospheric emission network as seen in the Mg I feature at 1.72 μm (Worden 1975). We also show in Fig. 1 the expected correlation between the K-line parameter and far UV emission, thereby completing the sequence illustrating the wavelength dependence of the behavior of broadband flux with narrow band chromospheric emission.

In brief summary of the variability of the Sun-as-a-star, we find that (a) chromospheric activity and photometric variability are uncorrelated in the *Kepler* visible (400 nm – 900 nm) band *at solar-like levels of activity*; (b) there may be an emerging correlation of the K-line with IR photometric bands in the Sun-as-a-star; (c) chromospheric emission levels can be a somewhat ambiguous guide to the predicted amplitude of photometric light-curve variations in the visible; and, (d) low-amplitude photometric variability is not necessarily an indication of only quiet chromospheric activity. Though over the ∼ 11-year solar cycle time scale the spot and facular disk coverage are directly correlated, the daily spot and facular disk coverage do not appear to be correlated. The variability in the visible passband is dominated by sunspots on rotational time scales. The Ca II K line does not provide much information about the filling factor of spots on the solar disk and, therefore, it is not really informative about variability in the visible band on daily time scales.

3. The Applicability of the Solar Paradigm

In Fig. 2 we display the normalized photometric variability of a solar-type star in the open cluster M35 (age ∼ 150 Myr; Meibom *et al.* 2010) as observed with the repurposed *Kepler* mission, $K2$, along with that of the Sun-as-a-star as seen in the same *Kepler*/$K2$ visible band. The relatively high-amplitude, sinusoidal variations in the active M35 star are in vivid contrast to the comparatively flat "continuum" of solar variability, punctuated by the disk passage of sunspots. It was a similar comparison that prompted H. Hudson (Hudson 2015) to observe, "*The photometric behavior of these two stars could hardly be more different.*"

To begin to gain some quantitative insight on the stellar photometric variability illustrated in Fig. 2, we adopt a simple three-component model—or, really, a schematic representation—of the normalized broad band flux. The three components are assumed to consist of the "immaculate" stellar photosphere (i.e., pure photosphere without any magnetic structures), cool spots analogous to sunspots, and faculae. Recall that faculae are bright spots in the solar photosphere that are often associated with concentrations of magnetic field lines and a higher ionization fraction of neutrals. Plage is the

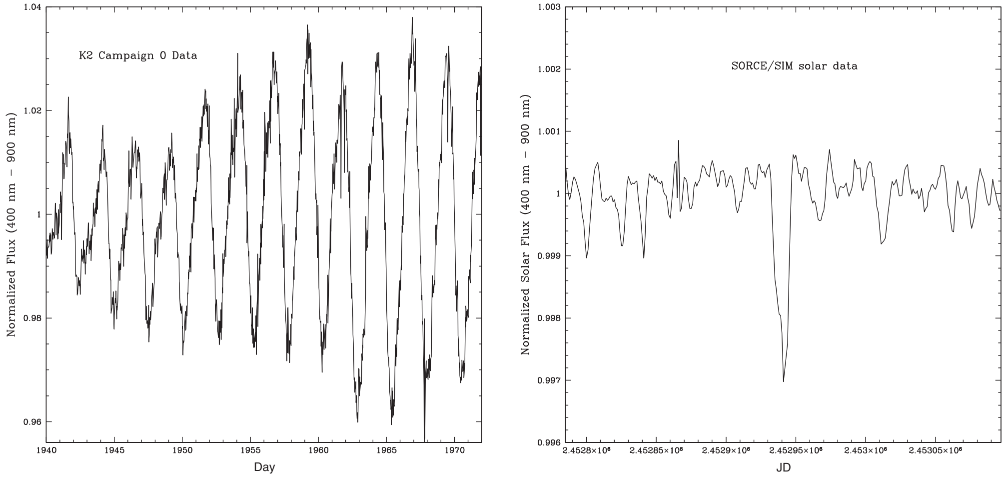

Figure 2. Rotational modulation of the light curves in (*left*) an active solar-type star in M35 and (*right*) the Sun, each over ten respective rotations as seen in the visible bandpass.

chromospheric counterpart of a facular region. The ratio of the observed flux to the undisturbed or normal stellar photosphere is given by

$$F/F_{star} = 1 - f_{spot}(1 - F_{spot}/F_{star}) + f_{fac}(F_{fac}/F_{star} - 1). \quad (1)$$

Since (1) involves the products of spot and facular filling factors (i.e., fractional area coverages) and a function of their respective contrasts, it is difficult to obtain unique solutions with single band photometry alone: a large, warm spot is equivalent to a cooler, small spot. We know from models that $F_{spot}/F_{star} \sim 10^{-3} - 10^{-1}$ and from solar observations that $F_{fac}/F_{star} \approx 1$. In these approximations, (1) simplifies to $F/F_{star} = 1 - f_{spot}$, meaning that the photometric modulation could be entirely attributed to cool spots. But since we typically see enhanced K-line emission in active stars with strong spot modulation as well as rotational modulation of photospheric lines in the Sun-as-a-star (Hall & Lockwood 2000), we retain a potential contribution due to faculae and plages so that (1) can be approximately expressed as

$$F/F_{star} \simeq 1 - f_{spot} + \epsilon f_{fac},$$

where ϵ is the facular contrast. The average contrast of solar magnetic elements is 3.7% in the quiet Sun (Kobel *et al.* 2011). Therefore, the above approximation suggests that the modulation of the photometric light curve is controlled primarily by spots *unless* the spot filling factor is only $\sim$ a few percent (which is still an order of magnitude higher than in the Sun) *and* the fractional area coverage of faculae/plage-like regions is near unity. In such a case the facular contrast competes with spots in the modulation of the light curve. We explore the implications of this perspective in the following where we assume that the values at the maximum and minimum phases in the photometric light curve are excursions from a mean value representing pure stellar photosphere.

We utilize equation (1) to find the range of facular and spot filling factors at maximum and minimum light in a light curve such as that for the M35 star (Fig. 2), which exhibits excursions of roughly ±2.5%. We adopt $T_{eff} = 5600$ K ($\sim$ G5–6 V) and a solar-like $T_{spot}/T_{eff} = 0.70$. We estimate spot-to-star flux ratios from PHOENIX model atmospheres (Husser *et al.* 2013) yielding $F_{spot}/F_{star} = 0.074$ in the 400 nm – 900 nm *Kepler* visible bandpass. The results are graphically displayed in Fig. 3.

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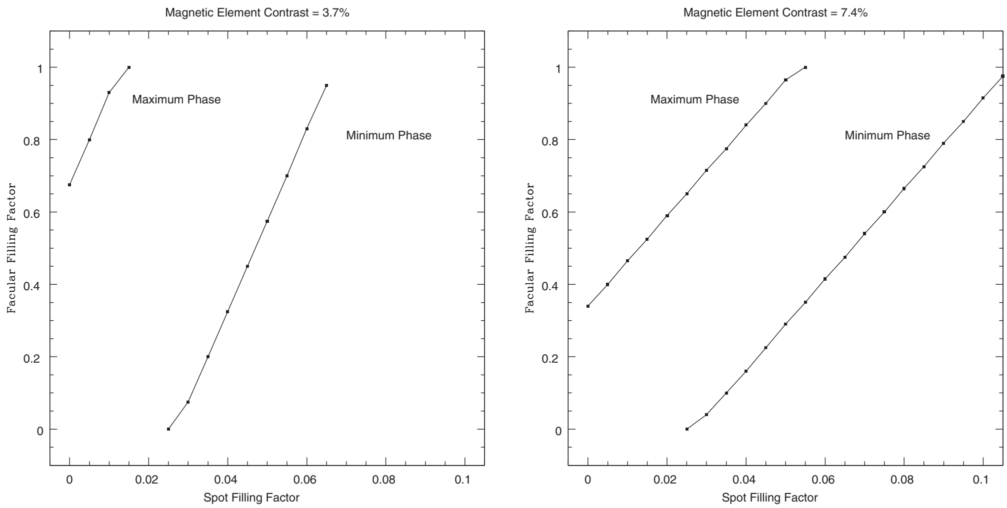

Figure 3. Relative photometric maximum and minimum for solar (*left*) and non-solar (*right)* values of facular contrast value in the spot—facular filling factor plane.

For a solar-like, 3.7% facular contrast we find that the possible range of facular filling factors is highly restrictive. At a 1% spot filling factor, the facular filling factor must be about 100% at maximum light (Fig. 3). In order to avoid unobserved, high-amplitudes in the rotational modulation of the K-line emission, facular filling factors of about 68% with spot filling factors of about $\sim 6\%$ account for maximum and minimum light, respectively. But this is for 0% spots on the bright side. In other words, this would imply a strong longitudinal asymmetry in at least the spot filling factor. As seen in Fig. 3 for a non-solar, 7.4% facular contrast, there is a broad range of possible facular filling factors though with a minimum facular coverage of 35%. At these levels, spot filling factors are at 6% (for the same facular coverage). Again, there is a strong asymmetry in the spot coverage. But with this high facular contrast, we avoid the possibility of modulation of the K-line emission at amplitudes that are not usually seen in active stars.

In brief summary, this interpretation of non-solar light curves in solar-type stars seems to drive us in the direction of high facular contrasts that may be non-solar combined with strong longitudinal asymmetry in the spot surface distribution. Could these non-solar facular/plage contrasts arise from high magnetic energy densities that, in turn, are the ultimate origin of "superflares"? Whether this is the case cannot be confirmed without flux-calibrated light curves. As pointed out in the discussion at this FM, the facular contrast may simply elevate the "DC signal" in the light curve with spots as the primary source of modulation. We explore this further in the next section where we focus on the range of photometric variability.

3.1. *The Range of Photometric Variability*

In the context of our schematic model, the range of the observed photometric variability from equation (1) is

$$\Delta F/F_{star} = (f_{smin} - f_{smax})(1 - F_{spot}/F_{star}) + \epsilon\,(f_{fmax} - f_{fmin}), \quad (2)$$

where ΔF is the range from maximum to minimum in the light curve, ϵ is the facular contrast, f_{smin} is the filling factor of cool spots at light-curve minimum, f_{smax} is the corresponding value at maximum, f_{fmax} is the filling factor of faculae at light-curve maximum and f_{fmin} is the fractional area coverage of faculae at minimum. The values

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of the facular filling factors range from zero to maximum values of $1-f_{smin}$ for f_{fmin} and $1-f_{smax}$ for f_{fmax}, respectively.

For the special case where the facular filling factors attain their maximum values in the hemispheres visible to us at light-curve maximum and minimum, respectively, we have that

$$\Delta F/F_{star} = (f_{smin} - f_{smax})\,(1 + \Delta),$$

where $\Delta = \epsilon - F_{spot}/F_{star}$, that is, the difference between the facular and spot contrasts. We see that the value of Δ ranges from a minimum of $-F_{spot}/F_{star}$ to a maximum of ϵ, i.e., the facular contrast. Normally, we would expect that $\Delta \ll 1$ in the visible band so that the range in the photometric light curve remains dominated by the difference in spot filling factors between maximum and minimum, *unless* stellar faculae have an unusually strong, non-solar contrast.

The final case we consider is where the filling factor of faculae at maximum (minimum) in the light curve dominates over the filling factor at minimum (maximum), suggesting a strongly asymmetric surface distribution of faculae and spots on the stellar surface. In this case we have

$$\Delta F/F_{star} = (f_{smin} - f_{smax})(1 - F_{spot}/F_{star}) + \begin{bmatrix} f_{fmax} \\ -f_{fmin} \end{bmatrix} \epsilon, \quad (3)$$

where the term in brackets takes on the value of either f_{fmax} or $-f_{fmin}$, whichever most appropriately represents the dominant facular surface distribution. In contrast to the previous cases where the photometric variability is governed primarily by spots, the contribution by faculae now plays a critical role in determining the range of photometric variability in equation (3). The photometric range is amplified if $f_{fmax} \gg f_{fmin}$. However, if faculae are concentrated mainly on the side of the star with the greatest fractional coverage of spots, that is, when $f_{fmin} \gg f_{fmax}$, and f_{fmin} is near its maximum value of $1 - f_{smin}$, then the amplitude of photometric variability is actually reduced. In this case, the second term is approximately $-\epsilon$. Given that the magnitude of the facular contrast can be similar to the difference in spot filling factors, i.e., $\epsilon \sim (f_{smin} - f_{smax})$, then we would see only a low amplitude of photometric variability with $\Delta F/F_{star} \ll 1$.

This counterintuitive result is due to the offsetting effects of a high filling factor of relatively brighter faculae in the presence of cool spots. Does such a special case exist in reality? Perhaps there is evidence for its occurrence in the developing work of Bastien *et al.* (2015, in preparation). These investigators find in their Ca II survey of solar-type stars in the *Kepler* field a population of objects with normalized chromospheric emission $\sim 3-6$ times that of the mean Sun but with a range in photometric variability < 1 mmag. This combination of relatively high chromospheric activity with very low photometric variability could equally arise from a homogeneous surface distribution of spots and plages. In contrast to the homogeneous case, however, the asymmetric surface distribution represented in equation (3) when $f_{fmin} \gg f_{fmax}$ (and the second term becomes approximately equal to $-\epsilon$) would give rise to strong rotational modulation of the Ca II H & K lines but in the presence of only a small amplitude of broad band photometric variability. In our differential analysis, it was, of course, not necessary to invoke non-solar facular contrasts to account for the range of photometric variability in active, solar-type stars.

4. Summary

Our simple three-component model suggests that photometric variability in the visible band is dominated by spots (consistent with what we see in the Sun-as-a-star) characterized by a strong longitudinal asymmetry. However, special cases exist where the facular contrast can play a critical role in determining the range of photometric variability. In the case of active solar-type stars, our schematic representation of the normalized variability indicates the possible presence of high facular contrasts that may be non-solar. But this interpretation assumes that the observed, uncalibrated light-curves represent an excursion from a relatively quiet photosphere in their minimum–maximum range of variation.

In this preliminary analysis, we did not consider inclination effects nor did we include the wavelength dependence of facular contrast in the visible band. Shapiro *et al.* (2015) find that the viewing angle with respect to the stellar rotation axis can determine whether the observed variability is spot-dominated or faculae-dominated on rotational time scales, at least at solar-like activity levels. The relative amplitude of the rotational modulation also declines at low inclinations due to foreshortening effects on the spot coverage as well as reduced spot contrasts as seen toward the limb (Shapiro *et al.* 2015). Further progress will require calibrated, multi-color photometry in conjunction with spectroscopic observations of key diagnostics, such as the Ca II resonance lines, the G band, and the He I lines at 5876 Å and 10830 Å, respectively (Andretta *et al.* 2015), which are sensitive to bright magnetic elements extending from the photosphere to the high chromosphere.

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