Modelling solar and stellar brightness variabilities

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Abstract. **Total and spectral solar irradiance, TSI and SSI, have been measured from space since 1978. This is accompanied by the development of models aimed at replicating the observed variability by relating it to solar surface magnetism. Despite significant progress, there remains persisting controversy over the secular change and the wavelength-dependence of the variation with impact on our understanding of the Sun's influence on the Earth's climate. We highlight the recent progress in TSI and SSI modelling with SATIRE. Brightness variations have also been observed for Sun-like stars. Their analysis can profit from knowledge of the solar case and provide additional constraints for solar modelling. We discuss the recent effort to extend SATIRE to Sun-like stars.**

1. Introduction

The radiative output from the Sun is described by what is termed total and spectral solar irradiance, TSI and SSI. They are defined, respectively, as the total and wavelength-resolved solar radiative flux as apparent above the Earth's atmosphere and normalized to a distance from the Sun of one AU. Both, SSI in the 120 to 400 nm range (i.e., ultraviolet or UV) and TSI have been monitored from space since 1978. Regular measurement of visible and infrared (IR) SSI started much later, in 2003 with the Spectral Irradiance Monitor instrument (SIM, Harder et al. 2005a,b), covering 200 to 2416 nm, onboard Solar Radiation and Climate Experiment (SORCE, Rottman 2005).

Connections between TSI variations and solar magnetic activity were soon apparent. With this, the tracking of TSI and SSI from space came to be accompanied by the development of models that seek to reconstruct solar irradiance by relating the variability at timescales greater than a day to solar magnetism (Oster et al. 1982; Foukal & Lean 1986). At shorter timescales, variability from acoustic oscillations, convection and flares, excluded from this review, start to dominate (Hudson 1988; Woods et al. 2006; Seleznyov et al. 2011).

Models of solar irradiance, such as the more recent efforts by Bolduc et al. (2012), Chapman et al. (2013) and Yeo et al. (2014b), have been successful in reproducing most of the observed variability in TSI and in certain SSI records. There is growing consensus that solar magnetic activity is responsible for at least most of the solar irradiance variability over the era of satellite observation (Domingo et al. 2009; Solanki et al. 2013; Yeo et al. 2014a).

While the past four decades saw significant progress in the measurement and modelling of solar irradiance variability, there is persistent controversy surrounding the secular trend over this intervening period (Scafetta & Willson 2009; Krivova et al. 2009; Fröhlich 2012) and the spectral-dependence of the solar cycle variability in the UV (see recent reviews by Ermolli et al. 2013; Yeo et al. 2014a, 2015), amongst other issues. As solar radiative flux is by far the most important source of energy into the climate system, these uncertainties have far-reaching implications on our understanding of climate change (Ermolli et al. 2013; Solanki et al. 2013).

In the following, we discuss the controversy related to the secular trend (Sect. 2.2) and solar cycle variability in the UV (Sect. 2.3) in the context of the NRLSSI (Lean et al. 1997; Lean 2000) and SATIRE-S (Fligge et al. 2000; Krivova et al. 2003; Yeo et al. 2014b) models, described briefly in Sect. 2.1. NRLSSI and SATIRE-S are archetypal examples of the two main approaches to modelling solar irradiance variability, what is termed proxy and semi-empirical modelling. At present, these are also the only two models capable of returning TSI and SSI from the UV to the IR over the entire period of satellite observations at daily cadence.

The interest in solar irradiance variability is not limited to the solar and climate communities. In parallel to studies of solar brightness variations, there has been a strong effort to find brightness variations in Sun-like stars (the exact definition of a Sun-like star varies from author to author; we will define a Sun-like star here as a main sequence star of spectral class F, G, or K). A significant milestone was achieved with the start of the synoptic observations of Sun-like stars at the Lowell observatory (Lockwood et al. 1992; Radick et al. 1998). The program, later continued at the Fairborn Observatory (Lockwood et al. 2007, 2013; Hall et al. 2009), revealed decadal photometric variations of Sun-like stars similar to those of the Sun, although with a much wider variety of patterns. The discovery of photometric variations in Sun-like stars posed an intriguing question of whether the Sun is a solar-type variable and prompted a large number of comparative studies of solar and stellar photometric variability.

The interest in solar-stellar comparison is further raised by the new state-of-the-art stellar photometric data, obtained over the last few years. Recent surveys with ground-based automated telescopes have significantly increased the number of stars observed over their activity cycles (Lockwood et al. 2013). In addition, the unprecedented precision of broadband stellar photometry achieved with the CNES CoRoT (Baglin et al. 2006; Bordé et al. 2003) and the NASA Kepler (Borucki et al. 2010) satellites initiated a new era in studying stellar photometric variabilities. Even more data are anticipated from upcoming NASA TESS (Ricker et al. 2014) and ESA PLATO (Rauer et al. 2014) missions as well as from the "Exploring the Transient Optical Sky" program at the 8.4-meter Large Synoptic Survey Telescope (Ivezic et al. 2008). In Sect. 3 we discuss the recent efforts in extending the SATIRE model to Sun-like stars.

2. Solar irradiance variability

The secular trend in solar irradiance over the period of satellite observation is not straightforward to establish. Due to uncertainty in the absolute radiometry and calibration for instrument degradation, the various satellite records exhibit discrepant overall levels and trends. There are three composites of TSI reported in the literature, that by the ACRIM science team (Willson & Mordvinov 2003), IRMB (Dewitte et al. 2004; Mekaoui & Dewitte 2008) and PMOD (Fröhlich et al. 1995, 1997). The three composites differ from each other by which TSI records from individual instrument that they employ, as well as in the way instrumental factors affecting these individual records are treated. With instrumental issues affecting individual records, the three composites indicate conflicting secular trends (Fig. 1a).

Similar instrumental issues afflict UV SSI observations. In this case, they can be severe enough towards longer wavelengths to obscure the underlying solar cycle variability (Yeo et al. 2015), not to mention the secular trend. However, it is still possible to infer information about the secular trend in solar irradiance from UV SSI observations through the Mg II index and the Lyman-α irradiance.

The Mg II index, given by the line core-to-wing ratio at the Mg II h and k doublet about 280 nm, is relatively robust to instrument degradation as that largely cancels out in the quotient. Nonetheless, perfect stability is extremely hard to achieve. It is therefore not surprising that, similarly to the situation with TSI, the four Mg II index composites available, which differ from one another by the data employed, exhibit discrepant secular trends (Fig. 1b). Contributions to the long-term uncertainty include unaccounted drifts in the wavelength scale (Deland & Cebula 1994), instrumental trends not negated in taking the line core-to-wing ratio (Snow et al. 2014) and uncertainty in the regression of one Mg II index record to another.

The variation in UV SSI over the solar cycle declines with wavelength from about 50% of the overall level at the Lyman-α line to well below 1% above 300 nm. Observations of solar irradiance variability are relatively reliable at the Lyman-α line as the variability and therefore the signal-to-noise ratio is particularly high here. However, when going to longer wavelengths, the observed solar cycle variability is increasingly influenced (and in certain instances, completely obfuscated) by measurement uncertainty.

2.1. Solar irradiance models

As noted in the introduction, NRLSSI and SATIRE-S are archetypal examples of the two main approaches to modelling solar irradiance variability, what is termed proxy and semi-empirical modelling.

Naval Research Laboratory Solar Spectral Irradiance, NRLSSI employs the photometric sunspot index, PSI (Fröhlich et al. 1994; Lean et al. 1998) and the Mg II index (Viereck et al. 2004; Snow et al. 2005) as proxies of the effect of sunspot and faculae on solar irradiance (therefore the term proxy modelling). Above 400 nm, the facular and sunspot contrasts are calculated based on the Solanki & Unruh (1998) model. The TSI variability is given by the regression of the index data to the PMOD TSI composite. UV SSI (120 to 400 nm) variability is determined by matching the rotational variability in the index data to that in UARS/SOLSTICE measurements (Rottman et al. 2001) and assuming the index-to-SSI relationship so derived to apply at solar cycle timescales.

Semi-empirical models such as the Spectral And Total Irradiance REconstruction for the Satellite era, SATIRE-S take a less empirical and more physics-based approach than proxy models, recreating the solar spectrum using the intensity spectra of solar surface features generated from model atmospheres via radiative transfer codes. The solar surface is described as consisting of quiet Sun, faculae and sunspots. In SATIRE-S, the surface coverage by each feature class is determined from full-disc intensity images and magnetograms. The model makes use of the intensity spectra of quiet Sun, faculae and sunspot umbra and penumbra from Unruh et al. (1999). SSI is given by the sum of these spectra, weighted by the surface coverage by each feature class. The integral under the reconstructed spectra yields TSI.

In the interest of brevity, we refer the reader to the recent reviews of the two reconstructions by Ermolli et al. (2013); Yeo et al. (2014a, 2015) for a more complete description.

2.2. Secular variability

While the PMOD TSI composite (red, Fig. 1a) exhibits a solar cycle minimum-to-minimum decline, in agreement with SATIRE-S (black solid), the IRMB composite (green) sees no minimum-to-minimum variation, replicated by the NRLSSI reconstruction (black dash). The scatter between the various Mg II index composites is of similar order as the discrepancy between the NRLSSI and SATIRE-S Mg II index (red, Fig. 1b). The Mg II index, however robust, is evidently not immune to long-term stability issues. The LASP Lyman-α irradiance composite (Woods et al. 2000) indicates a minimum-to-minimum decline, albeit weaker than what is replicated by SATIRE-S (Fig. 1c).

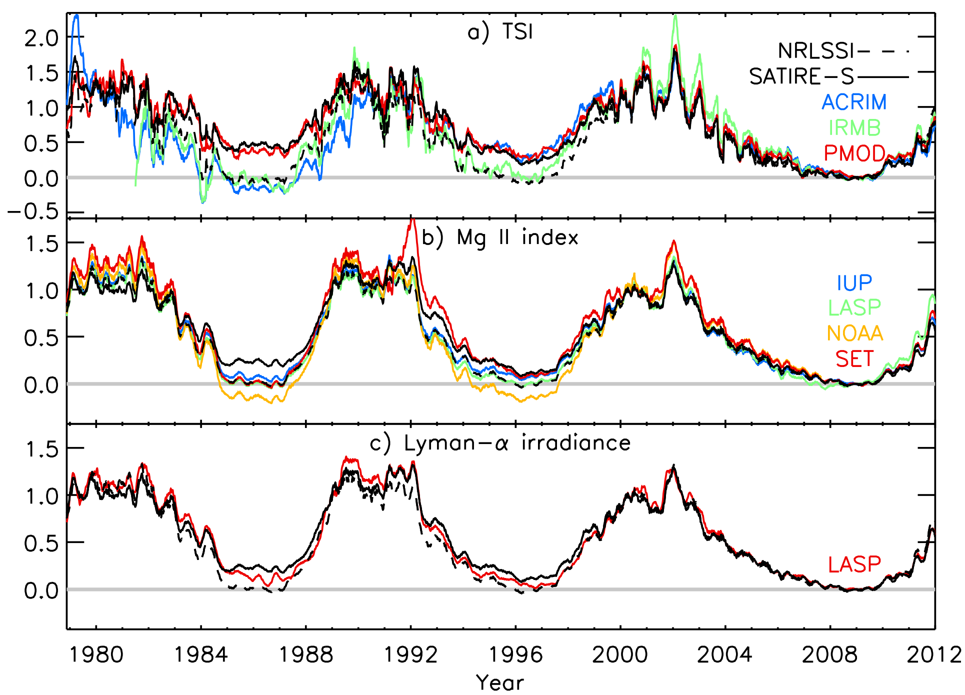

Figure 1. Composite records (colour) and reconstructions (black) of a) TSI, b) Mg II index and c) Lyman-α irradiance. The various time series are smoothed with a 81-day boxcar filter and stretched across null and unity at the 2008 solar cycle minimum (grey lines) and 2000 maximum levels. The NRLSSI and SATIRE-S Mg II index are calculated from the respective SSI reconstructions following the definition of the Mg II index by Heath & Schlesinger (1986). We employed the version of the various data sets available at time of writing.

In NRLSSI, the solar cycle minimum-to-minimum trend is given mainly by the Mg II index and is therefore not independent of the long-term uncertainty in the latter

(Fig. 1b). The minimum-to-minimum decline produced by SATIRE-S came from the palpable differences in prevailing magnetic activity at the 1986, 1996 and 2008 minima apparent in full-disc magnetograms (see Fig. 11 in Yeo et al. 2014b). It is supported by the PMOD TSI composite (Fig. 1a) and the LASP Lyman-α irradiance composite (Fig. 1c). Consensus on the secular variation in solar irradiance over the period of satellite observation is still wanting. Present evidence does suggest however that a secular decline over this interval, as apparent in the PMOD TSI composite, the LASP Lyman-α irradiance composite and the SATIRE-S reconstruction, is likely.

2.3. Solar cycle variability in the UV

In a recent review of UV SSI measurements and models, Yeo et al. (2015) examined all the extended UV SSI records available and matched them against NRLSSI, SATIRE-S and the UV SSI reconstruction reported by Morrill et al. (2011). The Morrill et al. (2011) reconstruction is given by the regression of the Mg II index to the UARS/SUSIM record (Brueckner et al. 1993; Floyd et al. 2003). This is in contrast to NRLSSI, where UV SSI variability is based on matching the rotational variability in the Mg II index and PSI to that in the UARS/SOLSTICE record. Yeo et al. (2015) demonstrated that excluding measurements where the reported long-term uncertainty exceeds solar cycle variability, the various records and reconstructions examined are actually in reasonable agreement, with the following exceptions.

- The decline in 240 to 400 nm SSI between 2003 and the 2008 minimum recorded by SIM (version 22) is five to ten times that in reconstructions and concurrent measurements from other instruments. This has been similarly noted for earlier revisions of the data set and numerous studies have concluded that it is likely instrumental in origin (DeLand & Cebula 2012; Lean & DeLand 2012; Unruh et al. 2012; Ermolli et al. 2013; Solanki et al. 2013; Morrill et al. 2014; Yeo et al. 2014b).

- Solar cycle variability in the NRLSSI reconstruction is palpably weaker than that in SATIRE-S above 240 nm. In particular, between 300 and 400 nm, the solar cycle amplitude in NRLSSI is only about half that indicated by the SATIRE-S and Morrill et al. (2011) reconstructions and the SUSIM record, the only SSI record stable enough to reveal solar cycle modulation in this wavelength range.

Lean (2000) suggested that the weaker solar cycle variability replicated by NRLSSI towards longer wavelengths might be from assuming the apparent relationship between indices and SSI at rotational timescales applies at solar cycle timescales.

Yeo et al. (2015) applied the NRLSSI method to the SUSIM record. The resulting reconstruction aligned with the SUSIM record only up to about 300 nm, above which it became as weak as NRLSSI. The authors noted that the agreement between the regression of the rotational variability in the Mg II index and PSI to that in the UARS/SOLSTICE and SUSIM records deteriorates with wavelength and is especially poor longwards of 300 nm, about where the solar cycle variability in NRLSSI and the test reconstruction based on the SUSIM record starts to diverge from the SATIRE-S and Morrill et al. (2011) reconstructions and the SUSIM record. (As with the variation over the solar cycle, rotational variability weakens with wavelength with the consequence that observed rotational variability is increasingly affected by measurement noise.) The authors went on to argue that the relatively weak solar cycle variability produced by

NRLSSI above 300 nm is a consequence of measurement noise in UARS/SOLSTICE rotational variability.

To test the assertion of Yeo et al. (2015), we conducted two experiments where we applied the NRLSSI method to the SSI records from the UARS and SORCE missions but with certain modifications.

- In the first experiment, denoted here as test A, we matched the rotational variability in the index data to that in SSI records by orthogonal distance regression, ODR instead of OLS. The idea behind ODR is to minimize the orthogonal distance between the data and the function fit, weighted by the user-specified variance in both the predictor and the response. In comparison, OLS seeks to minimize the distance between the data and the fit along the response coordinate axis, assuming the predictor to be perfect.

- In the second experiment, denoted here as test B, we identified 13-day periods corresponding to the transit of active regions across the solar disc. At each wavelength bin, we averaged the 13-day SSI segments from these periods to yield a single 13-day profile where noise is suppressed as compared to the original time series. The index time series were similarly sampled. Finally, we fit the index transit profiles to the SSI transit profiles via OLS.

The idea here is to examine the result of taking measurement noise into account either in the regression (test A) or by denoising SSI data prior to regression (test B) on the result of applying the NRLSSI approach. Both experiments will be detailed in an upcoming publication (Yeo et al., in preparation). In both instances, the replicated solar cycle variability is in excellent agreement with SATIRE-S (Fig. 2). This indicates that the relatively weak solar cycle variability reproduced by NRLSSI towards longer wavelengths is dominantly from noise in the referenced SSI record not being taken into account in the derivation (i.e., in accordance with the assertion of Yeo et al. 2015) and not from index data relating to SSI differently at rotational and solar cycle timescales as claimed by Lean (2000).

3. Solar variability in the stellar context

Until very recently modelling of the irradiance variability was limited to the solar case. Consequently, the models have only been tested against and constrained by the solar data, which represent a single point in a wide parameter space of the possible magnetic activities, effective temperatures, metallicities, inclinations of stellar rotation axes, etc. At the same time, joint study of solar and stellar variations has a potential to simultaneously constrain solar models over a much wider space of stellar parameters and to gain more insights into the physical causes of stellar variability.

Recently Shapiro et al. (2014) extended the SATIRE model to stars with different levels of magnetic activities, attributing the variability of stellar brightness to the imbalance between the contributions from dark starspots and bright faculae. They showed that the solar paradigm is remarkably successful in explaining the stellar variability on the activity cycle timescale. In particular, assuming that solar facular contrasts employed in SATIRE model are also valid for other Sun-like stars, Shapiro et al. (2014) solved a long-standing puzzle in the study of stellar activity: the observation that whereas the stars with a relatively low level of activity become photometrically brighter

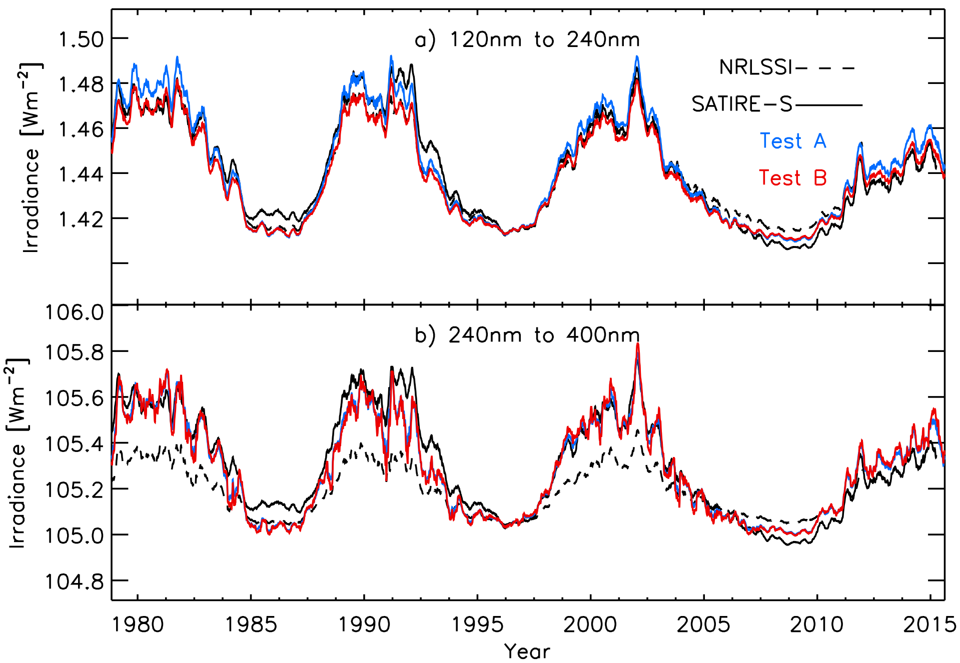

Figure 2. Integrated SSI between a) 120 and 240 nm, and b) 240 and 400 nm in NRLSSI (black dash), SATIRE-S (black solid) and the test reconstructions based on applying the NRLSSI approach to UARS and SORCE SSI either taking measurement noise into account either in the regression (test A) or by denoising SSI data prior to regression (test B). See Sect. 2.3 for details. The time series from SATIRE-S and the test reconstructions are at many times barely distinguishable from one another due to the close agreement.

as their activity level increases, more active stars display the opposite behaviour, becoming darker with rising activity level (see Fig. 3). According to SATIRE the solar variability is faculae-dominated in the visible spectral domain (i.e. SSI changes are in phase with solar activity) independently on the position of the observer relative to the ecliptic plane. However, the Sun has been found to be very close to the threshold between two these regimes of the variability so that the stars which are a bit more active than the Sun are already observed as spot-dominated. This to some extend construes the ongoing controversy on the phase of the SSI variability in the visible spectral domain (Ermolli et al. 2013; Solanki et al. 2013; Yeo et al. 2014a). We note that extrapolating from the Sun to more active stars was proposed by Foukal (1994), although at a more qualitative level than in Shapiro et al. (2014).

Figure 4 presents a comparison between stellar photometric variabilities measured by Lockwood et al. (2007) and calculated by Shapiro et al. (2014). While the calculations byShapiro et al. (2014) are in a reasonably good agreement with the data for the high activity stars, the calculated variabilities of the stars with near-solar activity are significantly below the Lockwood et al. (2007) observations. This is not surprising, since the SATIRE model is known to accurately reproduce solar irradiance variability (see, e.g. Yeo et al. 2014b, and references therein), which is known to be low compared to Sun-like stars with near-solar magnetic activity (Lockwood et al. 2007, 2013; Judge et al. 2012; Shapiro et al. 2013).

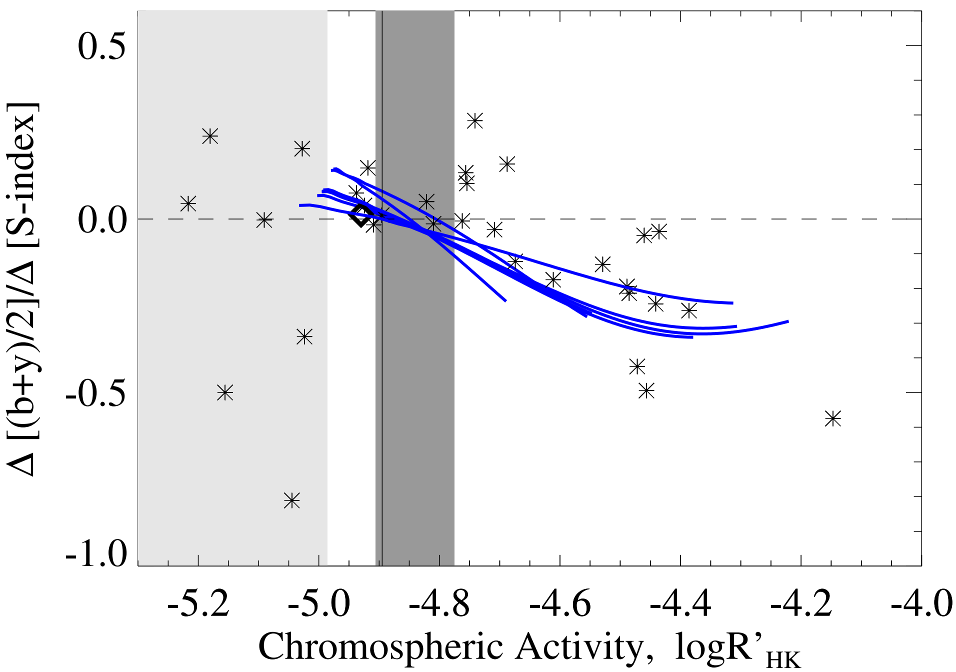

Figure 3. The photometric brightness variation normalised to the HK emission variation plotted vs. mean chromospheric activity. The blue curves represent the values calculated with SATIRE for various combinations of distributions of magnetic features on stellar surfaces and inclinations of stellar rotation axis. The asterisks indicate the observed stellar values from Lockwood et al. (2007). The diamond points to 18 Scorpii (the data are taken from Hall et al. 2009). The light shaded areas represent the activity levels for which $\Delta[(b+y)/2]/\Delta S$ cannot be reliably constrained. The solid vertical line denotes the mean level of solar chromospheric activity. The dark shaded bands indicate the range of the chromospheric activities for which the stars can be observed as either faculae or as spot- dominated.

Recently Shapiro et al. (2015a) demonstrated that low photometric variability of the Sun in Strömgren filters *b* and *y* is associated with almost total compensation of the spot and facular contributions to solar brightness measured in these filters (see Fig. 5). Furthermore, they showed that the solar variability measured in Strömgren filters *b* and *y* is even lower by a factor of three than was thought before (cf. Lockwood et al. 2007; Hall et al. 2009) and it would be very difficult to detect solar photometric variability degraded to the precision and time coverage of the ground-based photometry.

Nevertheless, Lockwood et al. (2013) pointed out that there is a large group of Sun-like stars with near-solar level of magnetic activity whose photometric variability is unambiguously confirmed and is an order of magnitude larger than that of the Sun (see their Fig. 1). One of the possible explanations for such an anomaly is that the compensation between facular and spot contributions to brightness variability, which happens in the solar case, does not occur in these high-variability star. One can expect that the facular contrast in Sun-like stars depends on the stellar effective temperature (cf. Beeck et al. 2015a,b) and on the stellar metallicity (since the facular contrast is strongly affected by the weak atomic and molecular lines, see Shapiro et al. 2015b). A small change of the facular contrast might break a delicate balance between facular and spot

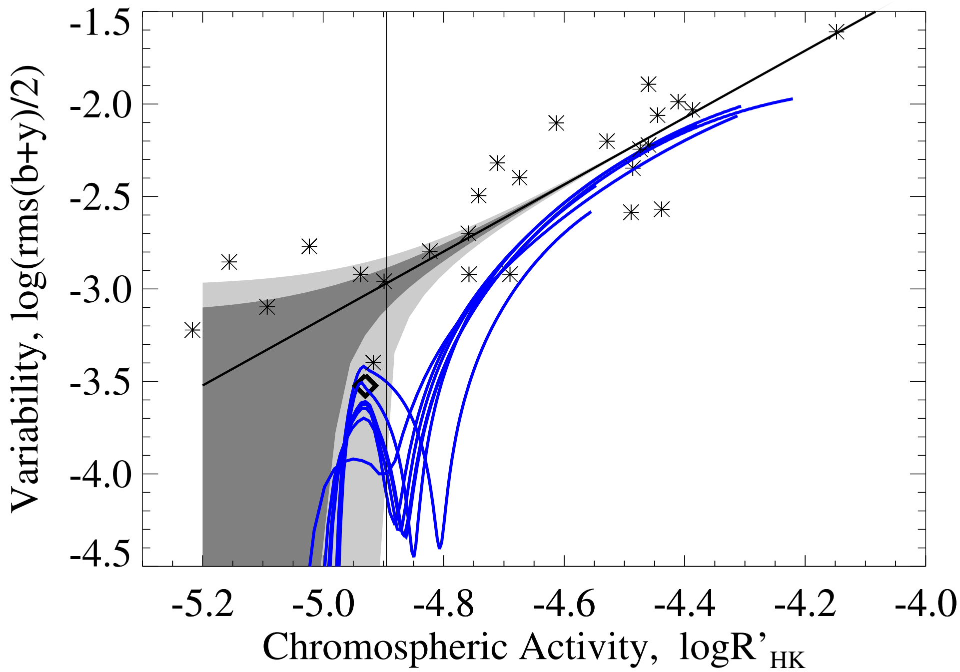

Figure 4. The photometric brightness variation plotted vs. mean chromospheric activity. The blue curves represent the photometric variability calculated with SATIRE for various combinations of distributions of magnetic features on stellar surfaces and inclinations of stellar rotation axis. The black line and asterisks indicate regression and stars with observed variability from Lockwood et al. (2007). The diamond points to 18 Scorpii (the data are taken from Hall et al. 2009). The solid vertical line shows the mean level of solar chromospheric activity. The dark and light shaded areas indicate estimated 1σ and 2σ uncertainty in the Lockwood et al. (2007) data, respectively.

contributions (see Fig. 5) to Strömgren *b* and *y* photometry and significantly increase the stellar brightness variability. Hence it is possible that stars with slightly different parameters show brightness variability significantly stronger than that of the Sun. This would imply that low 11-year variability of the Sun in Strömgren *b* and *y* photometry can be explained by the incidental combination of solar fundamental parameters and spectral location of the Strömgren *b* and *y* passbands.

Recent Kepler and CoRoT data provide a way for testing this hypothesis. In contrast to the activity cycle timescale, there is no compensation of the facular and spot contributions to stellar brightness variability on the timescale of stellar rotation. Therefore if the photometric variabilities of Sun-like stars are governed by the same physical processes as those acting on the Sun, one would not expect that the variability of solar brightness on the rotational timescale is anomalous to that of Sun-like stars.

There have been a number of studies (Basri et al. 2010, 2011, 2013; Gilliland et al. 2011; McQuillan et al. 2012, 2014; García et al. 2014) aimed at understanding whether solar brightness variability on the rotational timescale is typical or rather weak compared to the majority of Sun-like stars observed by the Kepler satellite. While there is still some discussion in the literature, the latest studies tend to agree that solar

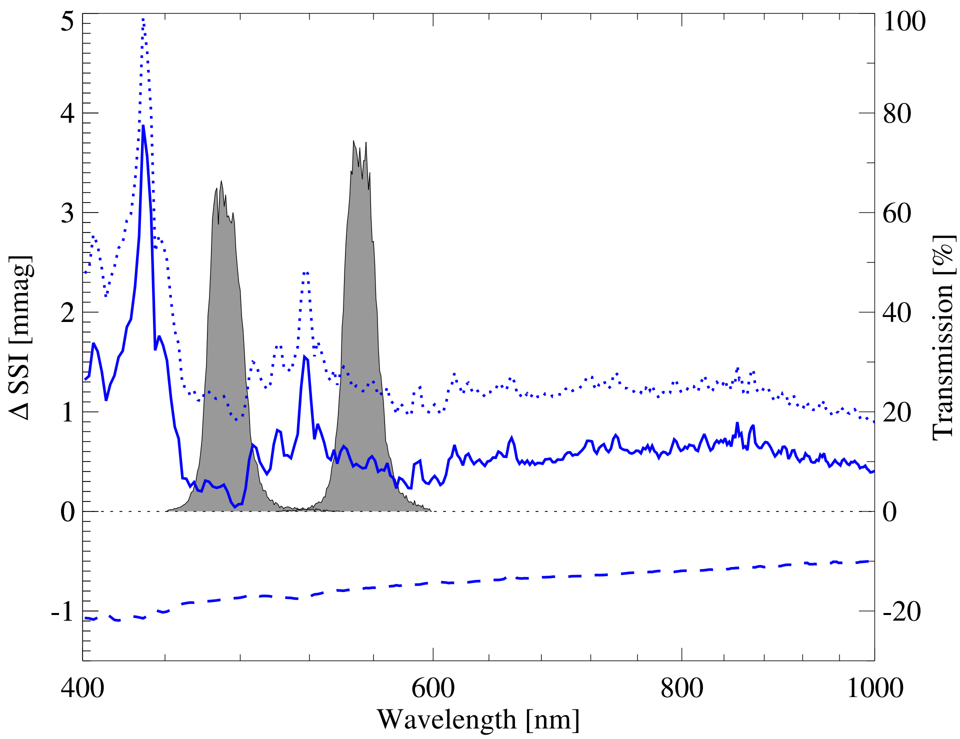

Figure 5. The amplitude of the 11-year solar brightness variability and its facular and spot components (solid, dotted, and dashed curves, respectively). The shaded contours represent the transmission curves of the Strömgren filters *b* and *y* (centred at 467 and 547 nm, respectively).

variability is comparable to that of the Sun-like stars. In particular, while Gilliland et al. (2011) and McQuillan et al. (2012) concluded that about 60% of G Dwarfs in the Kepler field have larger variability than the Sun and consequently the Sun appears to be unusually quiet, Basri et al. (2013) argued that after accounting for the change of solar rotational variability over the activity cycle the Sun exhibits roughly the same level of variability as most Kepler stars. This observation supports our explanation of low solar 11-year variability in Strömgren *b* and *y* photometry.

4. Summary

NRLSSI and SATIRE-S are archetypal examples of the two main approaches to modelling solar irradiance variability, what is termed proxy and semi-empirical modelling.

While the PMOD composite of TSI exhibits a solar cycle minimum-to-minimum decline, supported by SATIRE-S, the IRMB composite sees no minimum-to-minimum variation, replicated by NRLSSI. Similar to TSI, the various Mg II index composites available exhibit discrepant secular variability, suggesting that the long-term uncertainty is sufficient to obscure the underlying secular trend. Evidently, this limits the reliability of the secular trend replicated in proxy models relying on the Mg II index such as the NRLSSI. The minimum-to-minimum decline between the successive solar cycle minima of 1986, 1996 and 2008 replicated by SATIRE-S comes from the different levels of magnetic activity at the three minima apparent in full-disc magnetograms. It is also supported by the LASP Lyman-α composite.

In the UV, solar cycle variability in the NRLSSI reconstruction is palpably weaker than that in SATIRE-S above 240 nm. In proxy models such as NRLSSI, solar cycle variability is given by the apparent relationship between activity indices and measured SSI at rotational timescales, determined by regression. It has been suspected that the relatively weak solar cycle variability reproduced by NRLSSI towards longer wavelengths is due to activity indices relating to SSI differently at rotational and solar cycle timescales. Here, we demonstrated that if measurement uncertainty is taken into account, either during regression or by denoising the data prior to regression, the resultant solar cycle variability actually agrees with that from SATIRE-S. That is to say, the discrepant solar cycle variability in the UV in NRLSSI and SATIRE-S is dominantly from NRLSSI not treating measurement noise properly in its derivation.

After demonstrating that the SATIRE-S model is successful in replicating most of the available solar observations we have been expanding it to modelling brightness variations of Sun-like stars. This allows us to constrain SATIRE-S over a wide range of fundamental stellar parameters, and, thus, along with interpreting the stellar data, it helps to better understand the general concepts of solar and stellar variability.

The Sun exhibits roughly the same level of the rotational variability as most Kepler stars. However, it appears to be anomalously quiet on the 11-year activity cycle timescale. We attribute this to the incidental combination of solar fundamental parameters and spectral location of the Strömgren *b* and *y* passbands, where the measurements of stellar brightness variability are made.

Acknowledgments. The published data sets featured in this review are available at the following: ACRIM TSI composite, http://acrim.com/; IRMB TSI composite, ftp://gerb.oma.be/steven/RMIB_TSI_composite/; IUP Mg II index composite, http://www.iup.uni-bremen.de/gome/gomemgii.html; LASP Mg II index and Lyman-α composites and NRLSSI, http://lasp.colorado.edu/lisird/; NOAA Mg II index, ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_UV/NOAAMgII.dat; PMOD TSI composite, http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant; SATIRE-S, http://www2.mps.mpg.de/projects/sun-climate/data.html; SET Mg II index composite, http://www.spacewx.com/About_MgII.html. The research leading to this paper has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA grant agreement No. 624817.

References

Baglin, A., Auvergne, M., Boisnard, L., Lam-Trong, T., Barge, P., Catala, C., Deleuil, M., Michel, E., & Weiss, W. 2006, in 36th COSPAR Scientific Assembly, vol. 36 of COSPAR Meeting, 3749

Basri, G., Walkowicz, L. M., Batalha, N., Gilliland, R. L., Jenkins, J., Borucki, W. J., Koch, D., Caldwell, D., Dupree, A. K., Latham, D. W., Marcy, G. W., Meibom, S., & Brown, T. 2011, Astron. J., 141, 20. 1008.1092

Basri, G., Walkowicz, L. M., Batalha, N., Gilliland, R. L., Jenkins, J., Borucki, W. J., Koch, D., Caldwell, D., Dupree, A. K., Latham, D. W., Meibom, S., Howell, S., & Brown, T. 2010, Astrophys. J. Lett., 713, L155. 1001.0414

Basri, G., Walkowicz, L. M., & Reiners, A. 2013, Astrophys. J., 769, 37

Beeck, B., Schüssler, M., Cameron, R. H., & Reiners, A. 2015a, Astron. Astrophys., 581, A42. 1505.04739
— 2015b, Astron. Astrophys., 581, A43. 1505.04744
Bolduc, C., Charbonneau, P., Dumoulin, V., Bourqui, M. S., & Crouch, A. D. 2012, Sol. Phys., 279, 383
Bordé, P., Rouan, D., & Léger, A. 2003, Astron. Astrophys., 405, 1137. astro-ph/0305159
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 977
Brueckner, G. E., Edlow, K. L., Floyd, L. E., IV, Lean, J. L., & Vanhoosier, M. E. 1993, J. Geophys. Res., 98, 10695
Chapman, G. A., Cookson, A. M., & Preminger, D. G. 2013, Sol. Phys., 283, 295
Deland, M. T., & Cebula, R. P. 1994, Sol. Phys., 152, 61
DeLand, M. T., & Cebula, R. P. 2012, J. Atmos. Sol.-Terr. Phy., 77, 225
Dewitte, S., Crommelynck, D., Mekaoui, S., & Joukoff, A. 2004, Sol. Phys., 224, 209
Domingo, V., Ermolli, I., Fox, P., Fröhlich, C., Haberreiter, M., Krivova, N., Kopp, G., Schmutz, W., Solanki, S. K., Spruit, H. C., Unruh, Y., & Vögler, A. 2009, Space Sci.Rev., 145, 337
Ermolli, I., Matthes, K., Dudok de Wit, T., Krivova, N. A., Tourpali, K., Weber, M., Unruh, Y. C., Gray, L., Langematz, U., Pilewskie, P., Rozanov, E., Schmutz, W., Shapiro, A., Solanki, S. K., & Woods, T. N. 2013, Atmos. Chem. Phys., 13, 3945
Fligge, M., Solanki, S. K., & Unruh, Y. C. 2000, Astron. Astrophys., 353, 380
Floyd, L. E., Cook, J. W., Herring, L. C., & Crane, P. C. 2003, Adv. Space Res., 31, 2111
Foukal, P. 1994, Science, 264, 238
Foukal, P., & Lean, J. 1986, Astrophys. J., 302, 826
Fröhlich, C. 2012, Surv. Geophys., 33, 453
Fröhlich, C., Crommelynck, D. A., Wehrli, C., Anklin, M., Dewitte, S., Fichot, A., Finsterle, W., Jiménez, A., Chevalier, A., & Roth, H. 1997, Sol. Phys., 175, 267
Fröhlich, C., Pap, J. M., & Hudson, H. S. 1994, Sol. Phys., 152, 111
Fröhlich, C., Romero, J., Roth, H., Wehrli, C., Andersen, B. N., Appourchaux, T., Domingo, V., Telljohann, U., Berthomieu, G., Delache, P., Provost, J., Toutain, T., Crommelynck, D. A., Chevalier, A., Fichot, A., Däppen, W., Gough, D., Hoeksema, T., Jiménez, A., Gómez, M. F., Herreros, J. M., Cortés, T. R., Jones, A. R., Pap, J. M., & Willson, R. C. 1995, Sol. Phys., 162, 101
García, R. A., Ceillier, T., Salabert, D., Mathur, S., van Saders, J. L., Pinsonneault, M., Ballot, J., Beck, P. G., Bloemen, S., Campante, T. L., Davies, G. R., do Nascimento, J.-D., Jr., Mathis, S., Metcalfe, T. S., Nielsen, M. B., Suárez, J. C., Chaplin, W. J., Jiménez, A., & Karoff, C. 2014, Astron. Astrophys., 572, A34. 1403.7155
Gilliland, R. L., Chaplin, W. J., Dunham, E. W., Argabright, V. S., Borucki, W. J., Basri, G., Bryson, S. T., Buzasi, D. L., Caldwell, D. A., Elsworth, Y. P., Jenkins, J. M., Koch, D. G., Kolodziejczak, J., Miglio, A., van Cleve, J., Walkowicz, L. M., & Welsh, W. F. 2011, Astrophys. J. Supp., 197, 6. 1107.5207
Hall, J. C., Henry, G. W., Lockwood, G. W., Skiff, B. A., & Saar, S. H. 2009, Astron. J., 138, 312
Harder, J., Lawrence, G., Fontenla, J., Rottman, G., & Woods, T. 2005a, Sol. Phys., 230, 141
Harder, J. W., Fontenla, J., Lawrence, G., Woods, T., & Rottman, G. 2005b, Sol. Phys., 230, 169
Heath, D. F., & Schlesinger, B. M. 1986, J. Geophys. Res., 91, 8672
Hudson, H. S. 1988, ARA&A, 26, 473
Ivezic, Z., Tyson, J. A., Abel, B., et al. 2008, ArXiv e-prints
Judge, P. G., Lockwood, G. W., Radick, R. R., Henry, G. W., Shapiro, A. I., Schmutz, W., & Lindsey, C. 2012, Astron. Astrophys., 544, A88
Krivova, N. A., Solanki, S. K., Fligge, M., & Unruh, Y. C. 2003, Astron. Astrophys., 399, L1
Krivova, N. A., Solanki, S. K., & Wenzler, T. 2009, Geophys. Res. Lett., 36, 20101
Lean, J. 2000, Geophys. Res. Lett., 27, 2425
Lean, J. L., Cook, J., Marquette, W., & Johannesson, A. 1998, Astrophys. J., 492, 390
Lean, J. L., & DeLand, M. T. 2012, J. Climate, 25, 2555

Lean, J. L., Rottman, G. J., Kyle, H. L., Woods, T. N., Hickey, J. R., & Puga, L. C. 1997, J. Geophys. Res., 102, 29939

Lockwood, G. W., Henry, G. W., Hall, J. C., & Radick, R. R. 2013, in New Quests in Stellar Astrophysics III: A Panchromatic View of Solar-Like Stars, With and Without Planets, edited by M. Chavez, E. Bertone, O. Vega, & V. De la Luz, vol. 472 of Astronomical Society of the Pacific Conference Series, 203

Lockwood, G. W., Skiff, B. A., Baliunas, S. L., & Radick, R. R. 1992, Nature, 360, 653

Lockwood, G. W., Skiff, B. A., Henry, G. W., Henry, S., Radick, R. R., Baliunas, S. L., Donahue, R. A., & Soon, W. 2007, Astrophys. J. Supp., 171, 260. arXiv:astro-ph/0703408

McQuillan, A., Aigrain, S., & Roberts, S. 2012, Astron. Astrophys., 539, A137. 1111.5580

McQuillan, A., Mazeh, T., & Aigrain, S. 2014, Astrophys. J. Supp., 211, 24. 1402.5694

Mekaoui, S., & Dewitte, S. 2008, Sol. Phys., 247, 203

Morrill, J. S., Floyd, L., & McMullin, D. 2011, Sol. Phys., 269, 253

— 2014, Sol. Phys., 289, 3641

Oster, L., Schatten, K. H., & Sofia, S. 1982, Astrophys. J., 256, 768

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

Rauer, H., Catala, C., Aerts, C., et al. 2014, Experimental Astronomy, 38, 249

Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9143, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 20

Rottman, G. 2005, Sol. Phys., 230, 7

Rottman, G., Woods, T., Snow, M., & DeToma, G. 2001, Adv. Space Res., 27, 1927

Scafetta, N., & Willson, R. C. 2009, Geophys. Res. Lett., 36, 5701

Seleznyov, A. D., Solanki, S. K., & Krivova, N. A. 2011, Astron. Astrophys., 532, A108

Shapiro, A., Solanki, S. K., Krivova, N. A., Yeo, K. L., & Schmutz, W. 2015a, Astron. Astrophys.. Submitted

Shapiro, A. I., Schmutz, W., Cessateur, G., & Rozanov, E. 2013, Astron. Astrophys., 552, A114. 1303.2245

Shapiro, A. I., Solanki, S. K., Krivova, N. A., Schmutz, W. K., Ball, W. T., Knaack, R., Rozanov, E. V., & Unruh, Y. C. 2014, Astron. Astrophys., 569, A38. 1406.2383

Shapiro, A. I., Solanki, S. K., Krivova, N. A., Tagirov, R. V., & Schmutz, W. K. 2015b, Astron. Astrophys., 581, A116. 1507.05437

Snow, M., McClintock, W. E., Woods, T. N., White, O. R., Harder, J. W., & Rottman, G. 2005, Sol. Phys., 230, 325

Snow, M., Weber, M., Machol, J., Viereck, R., & Richard, E. 2014, J. Space Weather Space Clim., 4, A4

Solanki, S. K., Krivova, N. A., & Haigh, J. D. 2013, ARA&A, 51, 311

Solanki, S. K. & Unruh, Y. C. 1998, Astron. Astrophys., 329, 747

Unruh, Y. C., Solanki, S. K., & Fligge, M. 1999, Astron. Astrophys., 345, 635

Unruh, Y. C., Ball, W. T., & Krivova, N. A. 2012, Surveys in Geophysics, 33, 475

Viereck, R. A., Floyd, L. E., Crane, P. C., Woods, T. N., Knapp, B. G., Rottman, G., Weber, M., Puga, L. C., & Deland, M. T. 2004, Adv. Space Res., 2, 10005

Willson, R. C., & Mordvinov, A. V. 2003, Geophys. Res. Lett., 30, 1199

Woods, T. N., Kopp, G., & Chamberlin, P. C. 2006, J. Geophys. Res., 111, 10

Woods, T. N., Tobiska, W. K., Rottman, G. J., & Worden, J. R. 2000, J. Geophys. Res., 105, 27195

Yeo, K. L., Ball, W. T., Krivova, N. A., Solanki, S. K., Unruh, Y. C., & Morrill, J. 2015, J. Geophys. Res., 120, 6055

Yeo, K. L., Krivova, N. A., & Solanki, S. K. 2014a, Space Sci.Rev., 186, 137

Yeo, K. L., Krivova, N. A., Solanki, S. K., & Glassmeier, K. H. 2014b, Astron. Astrophys., 570, A85