Solar irradiance variability

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The Sun has long been considered a constant star, to the extent that its total irradiance was termed the solar constant. It required radiometers in space to detect the small variations in solar irradiance on timescales of the solar rotation and the solar cycle. A part of the difficulty is that there are no other constant natural daytime sources to which the Sun's brightness can be compared. The discovery of solar irradiance variability rekindled a long-running discussion on how strongly the Sun affects our climate. A non-negligible influence is suggested by correlation studies between solar variability and climate indicators. The mechanism for solar irradiance variations that fits the observations best is that magnetic features at the solar surface, i.e. sunspots, faculae and the magnetic network, are responsible for almost all variations (although on short timescales convection and p-mode oscillations also contribute). In spite of significant progress important questions are still open. Thus there is a debate on how strongly irradiance varies on timescales of centuries (i.e. how much darker the Sun was during the Maunder minimum than it is today). It is also not clear how the solar spectrum changes over the solar cycle. Both these questions are of fundamental importance for working out just how strongly the Sun influences our climate. Another interesting question is how solar irradiance variability compares with that of other cool dwarfs, particularly now that observations from space are available also for stars.

1 Introduction

How strongly the Sun varies is of interest not just for solar physicists, but also for astronomers, for whom the Sun has for many years been the prototype of a constant star; its radiative output, or total solar irradiance, has in the past generally been referred to as the solar constant. This interest has been rekindled with the advent of high precision radiative flux time series of large numbers of stars by the *Kepler* (Borucki et al. 2010) and CoRoT (Baglin et al. 2006) spacecrafts.

However, the strongest and most important reason for interest in solar variability is the Sun's potential influence on climate. As the only serious source of energy from outside Earth, the Sun provides basically all the energy needed to keep the Earth at its present temperature and hence is mandatory for maintaining higher life on Earth.

For us denizens of the Earth, the main quantity of interest from the Sun is its irradiance, i.e. the radiative flux of the Sun measured at 1AU (in space, i.e. without the hindrance of the Earth's atmosphere). The irradiance is a spectral quantity and is often called the spectral irradiance. The spectral irradiance is not that easy to measure reliably, specially over longer times because spectrometers (and in particular their detectors) tend to degrade in sensitivity with time. More reliable to measure is the total solar irradiance (TSI), which is the integral of the spectral irradiance over

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all wavelengths, i.e. the total radiative energy flux from the Sun. Since almost all the energy emitted by the Sun is in the form of radiation, this is basically the total solar energy flux. Averaged over a solar rotation period, the TSI is roughly proportional to the solar luminosity, if we assume that the radiative output seen from the direction of the poles either remains constant or changes in phase with that seen from lower latitude vantage points.

The Sun has been found to be variable on all timescales that we have so far been able to resolve or to cover. In the following we discuss such variability divided between different timescales and consider also briefly similar variability on Sun-like stars.

2 Overview of solar irradiance variability and its causes

To begin, let us briefly discuss the sources of variability at different timescales. Figure 1 shows the power spectrum of total solar irradiance for periods from around one minute to roughly one year. Clearly, power is larger at longer periods and drops rapidly towards shorter timescales. The sources of the power are also quite varied, ranging from p-modes, which give the peak at around 5 min (3000 μHz), granulation (leading to the plateau between 50 and 500 μHz), as well as rotational modulation due to the passage of sunspots and faculae/plages over the solar disk (the rotation frequency of the Sun lies at 0.45 μHz). No significant peak
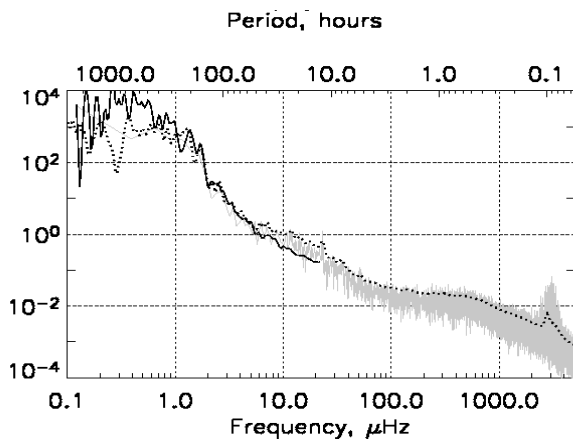
Fig. 1   Power spectrum of solar total irradiance showing the Fourier (grey line) and global wavelet (black dotted line) power spectra (in ppm^2/60μHz) of the VIRGO data set for the year 2002, sampled at a 1-min cadence (Fröhlich et al. 1995). The black solid line shows the global wavelet spectrum of the SORCE TIM data (Kopp, Lawrence & Rottman 2005) for the year 2003 sampled every 6 h (from Seleznyov et al. 2011).

is seen at the rotation period itself, because most sunspots live less long than a full rotation and larger active regions (which do live longer) evolve in this time period and are rarely present on their own (the steep rise between 1 and 10 μHz is due to the combined effect of rotational and evolutionary effects).

Thus irradiance variability on timescales of minutes to hours is driven by granulation and p-mode oscillations, from hours to days by the evolution and rotational modulation of magnetic features (specifically sunspots), with a contribution by granulation (and possibly supergranulation). Between days and the solar rotation period the main contributors are sunspots, whose darkness is rotationally modulated (but also faculae). From the solar rotation period to the solar cycle the variability is determined mainly by active region evolution, the appearance and disappearance of active regions and their remnants, and finally the solar cycle itself. On centuries to millennia the long-term evolution of the magnetic field, produced by the solar dynamo, displays secular changes (including marked changes on time scales of 70–100 years – the so-called Gleissberg cycle) that are expected to give rise to secular variations in the irradiance. On still longer timescales up to 10^5 years, the thermal relaxation timescale of the convection zone, the energy blocked by sunspots is released again, while beyond 10^6 years solar evolution leads to a slow brightening of the Sun.

Most of the causes of irradiance variations listed above are associated more or less directly with the Sun's magnetic field (with the exception of the very shortest and the very longest timescales), mainly via the influence of sufficiently strong magnetic fields on the thermal structure of the solar surface and atmosphere.

Magnetic concentrations on the solar surface can be dark (e.g. large magnetic features, sunspots, pores) or bright (the small magnetic features forming faculae and

the network). Since magnetic flux concentrations are well described by flux tubes (Yelles Chaouche, Solanki & Schüssler 2009), the question arises why some flux tubes are bright while others are dark.

Two counteracting processes determine the surface brightness of solar magnetic features. The strong magnetic field within both small and large magnetic flux tubes reduces the convective energy flux, which leads to a cooling of the magnetic features, since the vertical radiative energy flux in the convection zone is comparatively small and cannot fully compensate the reduction in convective flux.

The large magnetic pressure in the interiors of magnetic flux concentrations and horizontal pressure balance implies that magnetic features are evacuated. Consequently, the evacuated magnetic structures are heated by radiation flowing in from their dense and generally hot walls. This radiation heats flux tubes narrower than about 250 km sufficiently to make them brighter than the mainly field-free part of the photosphere, especially when seen near the limb where the bright interfaces of the flux tubes with their surroundings are best visible (Spruit 1976; Keller et al. 2004). For larger features the radiation flowing in from the sides penetrates only a very small part of the volume of the magnetic feature (the horizontal photon mean free path is roughly 100 km), so that features greater than roughly 400 km in diameter remain dark (pores and sunspots), cf. Grossmann-Doerth et al. (1994).

According to Spruit (1982), the energy blocked by sunspots gets redistributed in the solar convection zone and is re-emitted again slowly over the convection zone's Kelvin-Helmholtz timescale, i.e. around 100 000 years. Similarly, the excess radiation coming from small flux tubes is also taken from the heat reservoir of the convection zone. In this sense these small, evacuated magnetic features act as leaks in the solar surface, by increasing the solar surface area.

3   Irradiance variations at timescales up to the solar cycle

Reliably measured changes in the TSI were first reported in the early 1980s and soon attributed to sunspots and faculae (e.g., Willson 1982). TSI has been monitored continuously since 1978, and a number of TSI composites that combine measurements from a sequence of different instruments are available (see, Domingo et al. 2009 for a discussion). These composites agree well with each other on timescales ranging from days to years, though the stability of the instruments contributing to the composites is not yet good enough to unambiguously detect changes (or indeed the absence of changes) between subsequent cycle minima.

Just as for Sun-like stars, rotational variability on the Sun is dominated by cool spots; these typically produce dimmings of the order of 1000 ppm that can be clearly seen on Fig. 2 where TSI is plotted for the last three solar cycles. Some large spot groups can lead to more dramatic effects, such as the decrease of approximately 4000 ppm that was produced by the passage of the sunspot group that gave rise
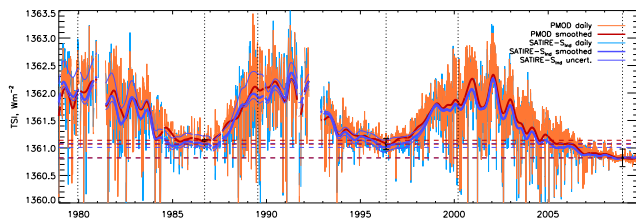
Fig. 2 (online colour at: www.an-journal.org) Modelled and observed total solar irradiance from 1978 to 2010. The thin orange and light-blue lines are daily values from the PMOD composite (Fröhlich 2000) and SATIRE-S (Ball et al. 2012), respectively. The thick lines show the smoothed PMOD and SATIRE-S values. Figure kindly provided by W. Ball.

to the 2003 'Halloween storm'. In addition to the spot dimmings, the Sun also shows brightenings due to faculae; a typical active region leads to an increase of about 200 ppm in the TSI (e.g., Fligge, Solanki & Unruh 2000).

As the Sun goes from sunspot minimum to maximum, more flux emerges on the solar surface, and the area coverage of bright flux tubes initially increases more rapidly than that of the spots. This is illustrated in Fig. 3 (top) where the sunspot and facular filling factors are plotted as a function of the solar S-index, a measure of the solar activity. Combined with the longer life times of the faculae, their larger area coverage results in the Sun being "activity-bright" on cyclical timescales, i.e., the Sun is (on average) brighter during sunspot maximum than during sunspot minimum. Sunspot darkening and facular brightening are in a delicate balance on the Sun; indeed, there are good indications that the Sun is darker during times of higher activity in some wavelength bands (Unruh et al. 2008).

A number of empirical and semi-empirical irradiance models have been developed. The empirical models generally are simple regressions between one or more activity indicators and the TSI, while the semi-empirical models make use of model atmospheres to compute the full solar spectrum and determine the TSI from the surface distribution of magnetic (or brightness) features on the solar surface. The models successfully reproduce TSI changes on timescales ranging from days to years and show that more than 90% of the TSI changes on timescales of weeks to years can be explained as being due to changes in the solar surface flux (Krivova et al. 2003; Wenzler et al. 2006; Preminger et al. 2010; Ball et al. 2012). An example is shown in Fig. 2 where the TSI modelled with SATIRE-S is plotted alongside the PMOD composite (Fröhlich 2000).

Changes in the solar irradiance show a strong wavelength dependence and measuring solar spectral irradiance (SSI) changes accurately is challenging. For wavelengths below 400 nm, a reasonably long data train is available from a succession of instruments, the longest being from the SUSIM and SOLSTICE instruments onboard the Upper Atmosphere Research Satellite, UARS (see DeLand & Cebula (2008) for a compilation of UV irradiances up to 2005). With the exception of measurements in three narrow wavelength bands, data above 400 nm only became avail-
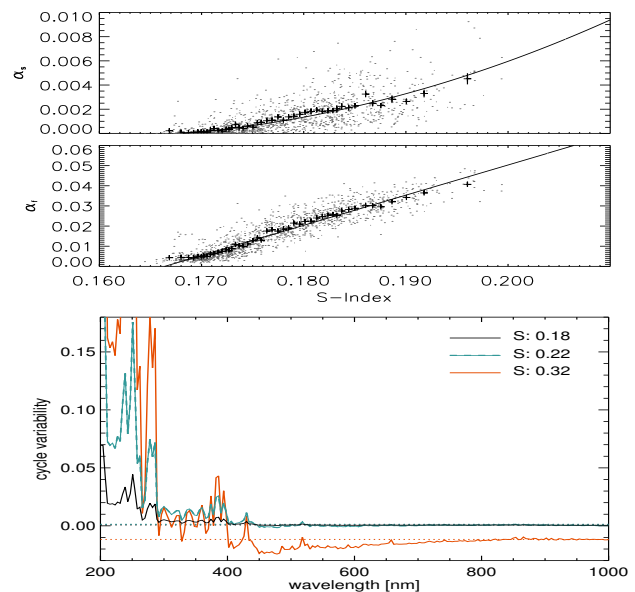

Fig. 3 (online colour at: www.an-journal.org) *Top:* solar facular and spot filling factors as a function of the Ca S-index (filling factors are from Wenzler et al. 2006; the S-index has been computed from the Kitt Peak Ca data). Figure kindly provided R. Knaack. *Bottom:* Cyclical variability as a function of wavelength for hypothetical Sun-like stars with maximum S-indices of 0.18 (black), 0.22 (dashed blue) and 0.32 (orange). The S-index at minimum is 0.167 in all three cases. The dotted lines indicate the wavelength-integrated variability (on this scale the total variability for S = 0.18 and S = 0.22 can not be distinguished).
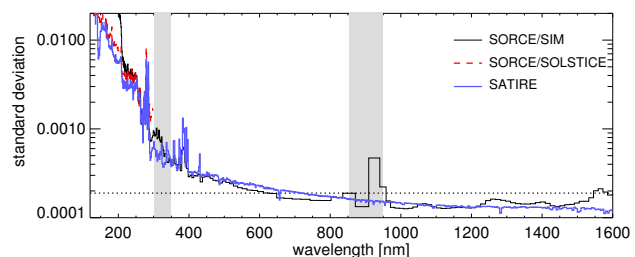

Fig. 4 (online colour at: www.an-journal.org) Normalised standard deviation of the SSI for 3 solar rotations in 2005 for SORCE/SOLSTICE (v11 release; dashed black line), for SORCE/SIM (v17 release; black line) and for SATIRE-S (blue line). The grey shading indicates the location of the SORCE/SIM detector edges.

able with SCIAMACHY onboard ENVISAT (since August 2002, Skupin et al. 2005) and SIM onboard SORCE (since April 2004, Rottman et al. 2005).

On rotational timescales, there is good agreement between the SSI changes measured with different instruments and models. We can quantify the spectral variability in terms of the normalised standard deviation (Johns & Basri 1995) which is given by $\sigma_\lambda / \bar{f}_\lambda$, where $\bar{f}_\lambda$ is the average irradiance at a given wavelength and σ_λ is the standard deviation, $[\sum_{j=1}^{N} (f_\lambda(t_j) - \bar{f}_\lambda)^2 / (N-1)]^{1/2}$. This quantity is plotted in Fig. 4 for three solar rotations in 2005 for the SATIRE-S model (blue line, Krivova et al. 2003, Krivova, Solanki & Wenzler 2009) SORCE/SOLSTICE (dashed black line)

and SORCE/SIM (solid black line). The variability generally decreases with increasing wavelength. The spectral variability is comparable to that of the TSI for wavelengths above 400 nm, but exceeds it by a factor of almost 10 below 240 nm, and can reach very high values in some individual lines, as, e.g., in the Mg II line at 280 nm. The character of the variability also changes with wavelength. In the UV below approximately 290 nm, variability is mostly due to faculae; faculae and spots contribute roughly equally between 290 and 400 nm, while spots dominate in the visible and NIR (Unruh et al. 2008).

On timescales of years and longer the uncertainty of the instrumental degradation corrections are of a similar order of magnitude as the expected long-term SSI changes at many wavelengths, particularly for wavelengths greater than 300 nm. Measurements taken with SORCE/SIM during the declining phase of cycle 23 suggest that the decline in the UV irradiance (integrated over a wavelength range of 200 to 400 nm) exceeds the decline in the TSI, and that this excess decline is compensated by an anti-cyclic increases in the irradiance for wavelengths between 400 and 800 nm and 1000 and 1600 nm. This scenario is at odds with modelling results (e.g., Ball et al. 2011; Lean & DeLand 2012) and does not agree with previous measurements such as UARS/SUSIM where Morrill et al. (2011) estimate the UV contribution to the TSI to be approximately 60 % (see Ermolli et al. 2012 for further discussion).

4 Irradiance variations on longer timescales: secular change

One of the most contentious questions in current solar irradiance research deals with the magnitude of secular variations in solar irradiance on time scales of centuries up to millennia. Do such variations exist and how strong are they? This question is particularly important, because this magnitude partly decides on the effect of the Sun on climate and whether the Sun has contributed to global warming.

The only direct evidence for secular variations in irradiance comes from the TSI record and the slightly lower brightness during the just completed activity minimum between cycles 23 and 24 (see Fig. 2). However, there is also other, more indirect evidence. In Fig. 5 we display the open magnetic flux of the Sun since 1900 (measured values from Lockwood et al. 2009a,b in black, modelled values from Vieira & Solanki 2010 in blue). In addition to the clearly visible cyclic changes, an increase in the first half of the record is seen: the Sun's open magnetic flux roughly doubled between 1900 and the middle of the 20th century. Then, during the deep and long minimum between cycles 23 and 24, the open flux dropped back to the level it had over a century ago. This is a large and rapid change. However, it is not clear to what extent and how strongly such variations in open flux convert into variations of the irradiance. Remarkably the model reproduces the observed variations rather well.
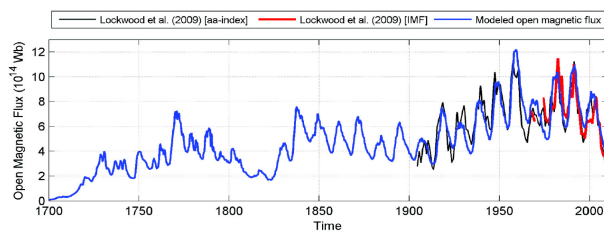

Fig. 5 (online colour at: www.an-journal.org) Evolution of the Sun's reconstructed and modelled open magnetic flux since the end of the Maunder minimum. The flux reconstructed from the measured interplanetary magnetic field is plotted in red, the reconstruction of the open flux from the geomagnetic aa-index is plotted black (Lockwood et al. 2009a,b) while the open flux computed by the SATIRE-T model by Vieira & Solanki (2010) is in blue (adapted from Vieira et al. 2011).

Therefore one of the major uncertainties in our knowledge of solar irradiance is how strongly the solar irradiance varied since the Maunder minimum, with the extreme values being 0.7 W m^{-2} (Schrijver et al. 2011) and 6 W m^{-2} (Shapiro et al. 2011). Most reconstructions and estimates lie between these extremes (e.g. Krivova, Balmaceda & Solanki 2007), i.e. roughly between 1 and 2 W m^{-2} (e.g. the upper limit set by Schnerr & Spruit 2011, although they only considered continuum brightness of magnetic features in the visible and thus underestimate the total brightness excess due to magnetic fields in the quiet Sun).

Once the magnitude of the variations has been determined, the variation with time can be found from a proxy of solar activity available for a sufficiently long period of time. Two important directly measured proxies are the sunspot area, available since 1874 (Balmaceda et al. 2009) and sunspot number that is available since 1610 (Hoyt & Schatten 1998). For many purposes it is important to know the evolution of solar activity over an even longer period of time, e.g. in order to study the long-term development of the solar dynamo (how often do grand minima such as the Maunder minimum take place?) and in order to have better statistics on whether solar activity influences climate.

Past solar activity can be reconstructed from cosmogenic isotopes, such as ^{10}Be (Beer et al. 1990) or ^{14}C (Solanki et al. 2004). The former can be gleaned from ice cores drilled in Greenland or Antarctica, the latter is obtained from tree trunks (and dated via dendrochronology; Stuiver et al. 1998; Reimer et al. 2004). Recently, evidence has been presented that also nitrate in certain antarctic ice cores carries information on past solar activity (Traversi et al. 2012).

Reconstructions of, e.g., open magnetic flux or sunspot number from such data (e.g. Usoskin et al. 2004; Steinhilber, Beer & Fröhlich 2009) reveal that there have been regular episodes of extremely low solar activity (grand minima) as well as equally common periods of particularly high solar activity (grand maxima), e.g. Usoskin et al. (2007). Particularly striking is that during the last roughly 70 years the Sun has been in a prominent grand maximum, although

it is agreed that the Sun is now leaving this phase (Lockwood et al. 2009c; Solanki & Krivova 2011).

Once an appropriate solar activity proxy has been determined, it can be used to compute the solar total irradiance (Steinhilber et al. 2009; Vieira et al. 2011). Such irradiance data sets display ups and downs associated with grand minima and maxima. The exact temporal variation depends mainly on the data set underlying the solar activity reconstruction (and to a smaller extent on the model used), while the amplitude of the irradiance variations must be set independently.

5 Comparison with other stars

Historically, ground-based stellar variability studies tended to focus on the most active stars with clear rotational cycles and dominated by large spots, some of them covering as much as 50 % of the visible stellar hemisphere (see, e.g., Berdyugina 2005 for an overview).

An important step in understanding stellar variability for less active stars was the establishment of the Mt Wilson Ca II H&K survey (Wilson 1978; Baliunas et al. 1995) that showed that activity cycles are ubiquitous on Sun-like stars with typical cycle lengths of 2.5 to 20 years. The cores of Ca II H&K are good tracers of the magnetic field and scale with the magnetic field strength. A further milestone was the start of a photometric program in 1984 that monitored a large fraction of the Mt. Wilson targets in the b and y filters (Lockwood et al. 1997, 2007; Radick et al. 1998). This has produced almost two decades of simultaneous chromospheric and photospheric variability data, allowing the Sun to be placed in the stellar context. Note that the photometric program measures the radiation arising in the photosphere, in contrast to the chromospheric information carried by the Ca II H&K line cores.

Considering first the short-term variability that is thought to be largely due to stellar rotation, Lockwood et al. (1997) and Radick et al. (1998) showed that stars with larger chromospheric emission (as measured by the mean $\log R'_{HK}$ or the S-index) were generally more variable with larger photometric $(b+y)$ amplitudes. Almost all stars show Sun-like rotational variability in the sense that chromospheric and photospheric brightness are anticorrelated, pointing to spots as the main causes of short-term variability.

Lockwood et al. (1997) found that variability was more likely for later spectral types; approximately 40 % of the G and K-type stars in their sample were variable. This dependence was confirmed by Basri et al. (2011) who used the exquisite precision offered by *Kepler* to investigate stellar variability. They found that approximately half of all Sun-like stars showed rotational variability (the slightly higher variability fraction is to be expected for the higher precision of the space-based *Kepler* observations).

Collating two decades of photospheric and chromospheric measurements, Lockwood et al. (2007) were able to show that stars fall into two groups in terms of their cyclical behaviour. The most active stars (as traced by their Ca II H&K emission) tend to be "activity dark", i.e., they become fainter as their magnetic activity ramps up, while less active stars tend to follow the solar "activity-bright" pattern.

Considering the Sun's total irradiance, the Sun is activity bright on the solar-cycle timescale, though it is located not far from the activity dark/bright boundary. Comparing the Sun to other Sun-like stars is not entirely straightforward, as we do not yet have long-term solar spectral measurements that are equivalent to the b and y filters. In addition, we monitor the Sun from a somewhat special "equator-on" position, while the stellar sample will present a mix of inclination angles (see Knaack et al. 2001).

To shed more light on the expected spectral behaviour of Sun-like stars, we consider the case of hypothetical Suns by extrapolating the observed facular and spot filling factors shown in the top two plots of Fig. 3 to higher activity levels. The fits to the binned data (solid lines) suggest that the total area covered by faculae increases linearly with the S-index, while the spot areas increase as the square of the S-index. Taking the typical mean S-index during solar maximum to be approximately 0.18, the solid line in the bottom plot of Fig. 3 shows the expected solar-cycle variability for a simple 3-component model of faculae, sunspots and quiet-Sun. The active-region contrasts used here are derived from disk-integrated fluxes and thus neglect the location of the active regions. Nevertheless, the resulting spectrum is in good agreement with the more detailed SATIRE-S model discussed earlier (see also Ball et al. 2011). Note that in this model the Sun is clearly activity bright in the UV; in the visible, it shows very little variability, and remains marginally activity bright (though see Preminger et al. 2011). In the NIR (not shown here) it reverses sign (see also Solanki & Unruh 1998) and becomes activity dark.

Extrapolating the facular and spot filling factors to more extreme values, we find that the behaviour of the hypothetical Suns switches from activity bright to activity dark in the visible while remaining activity bright at most UV wavelengths. The wavelength-integrated variability is not necessarily a good tracer of the spectral variability: regardless of the very different spectral shape shown by the black and dashed blue curves, the integrated change is almost the same (≈ 1000 ppm) for S = 0.18 and S = 0.22. At S = 0.32 (shown in orange), the star becomes clearly activity dark with a total irradiance change of -1.2 %.

6 Conclusions

Solar irradiance variability has been mainly studied under the aspect of the Sun's possible influence on the evolution of the Earth's climate. However, it is also becoming important for comparison with and to help in the interpretation of the microvariability of other cool stars, that has become a lot more accessible through the CoRoT and *Kepler* missions.

Solar total irradiance has been measured since 1978 and we now have a reasonable understanding of the causes of TSI variations on different time scales. In particular, on the

prominent timescales of solar rotation and the solar activity cycle, it is now clear that the TSI variations are caused by magnetic fields at the solar surface. Regarding the solar spectral irradiance variations the situation remains less clear. Models and the measurements by the SIM instrument on the SORCE spacecraft diverge rather strongly, even showing opposite phases of evolution in the visible part of the spectrum. The cause of this discrepancy remains one of the major open questions in solar irradiance research.

Thanks to the breakthroughs of the last decade in the reconstruction of solar activity, there have been multiple reconstructions of solar total irradiance over the Holocene. These differ from each other in various aspects, but most strongly in the amplitude of the TSI changes from the Maunder minimum to the present day, with extreme estimates of this value diverging by an order of magnitude from each other. This quantity is a key to deciding how large the influence of solar irradiance variations on climate change has been and is expected to be in the future. Consequently, the uncertainties in this quantity constitute the second major unknown in our knowledge of solar irradiance variations.

Besides these two major open questions, the main missing ingredient from the solar side in Sun-climate research is our inability to predict the course of future irradiance variations, or solar activity as a whole for that matter.

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