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Rieger-type periodicity in the total irradiance of the Sun as a star during solar cycles 23–24

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ABSTRACT

Context. Total solar irradiance allows for the use of the Sun as a star for studying observations of stellar light curves from recent space missions.

Aims. We aim to study how the mid-range periodicity observed in solar activity indices influences the total solar irradiance.

Methods. We studied periodic variations of total solar irradiance based on SATIRE-S and SOHO/VIRGO data during solar cycles 23–24 on timescales of Rieger-type periodicity. Then we compared the power spectrum of oscillations in the total solar irradiance to those of sunspot and faculae data to determine their contributions.

Results. Wavelet analyses of TSI data reveal strong peaks at 180 days and 115 days in cycle 23, while cycle 24 showed periods of 170 days and 145 days. There are several periods in the sunspot and faculae data that are not seen in total solar irradiance as they probably cancel each other out through simultaneous brightening (in faculae) and darkening (in sunspots). Rieger-type periodicity is probably caused by magneto-Rossby waves in the internal dynamo layer, where the solar cyclic magnetic field is generated. Therefore, the observed periods in the total solar irradiance and the wave dispersion relation allow us to estimate the dynamo magnetic field strength as 10–15 kG.

Conclusions. Total solar irradiance can be used to estimate the magnetic field strength in the dynamo layer. This tool can be of importance in estimating the dynamo magnetic field strength of solar-like stars using light curves obtained by space missions.

Key words. Sun: activity – Sun: magnetic fields – Sun: faculae, plages – sunspots

1. Introduction

The recent NASA space missions *Kepler* (Borucki et al. 2010) and Transiting Exoplanet Survey Satellite, (TESS, Ricker et al. (2014)), along with ESA's Convection, Rotation and planetary Transits mission (CoRoT, Baglin et al. 2008) collected a huge store of information on the basic properties of stars and exoplanets. These missions have provided the light curves for hundreds of thousands of stars, which allows us to gain new insights into stellar interiors using asteroseismology, as well as into stellar activity based on the time modulation of the curves. Stellar light curves may reveal stellar rotation periods (Nielsen et al. 2013; Reinhold et al. 2013; McQuillan et al. 2014) and short-term activity cycles (Ferreira Lopes et al. 2015; Reinhold et al. 2017). To understand stellar rotation and activity, it is of fundamental importance to use the Sun as a star analog since it provides much more detailed information on solar rotation and activity variations.

The analog for stellar light curves is the total solar irradiance (TSI). The variability of solar irradiation was first found after the launch of the Nimbus 7 mission in 1978. Subsequently, radiometers on board different satellites, such as Solar Maximum Mission (SMM) ACRIM-I, NOAA-9, NOAA-10, SOHO/VIRGO, and SORCE/TIM continuously measured the solar bolometric flux (Hathaway 2010). The variations in the proxies for solar activity (sunspot number; total sunspot area) from the Maunder minimum up through today has been reconstructed using different methods (Krivova et al. 2009, 2010; Yeo et al. 2014, 2017; Dasi-Espuig et al. 2016; Wu et al. 2018). Using solar full-disc magnetograms and continuum images, Yeo et al. (2014) reconstructed the daily variation of the solar irradiance from 1974 to 2013, using the Spectral And Total Irradiance REconstructions model (SATIRE).

The irradiance observations show that solar brightness changes over different timescales, ranging from several minutes to years. The temporal variation of the TSI is mainly caused by solar magnetic field effects, including sunspot darkening and faculae brightening.

It is important to study the relation between sunspots and faculae, as it has the potential to deliver vital knowledge of how the TSI changes, which can be used to better understand the stellar light curves observed by *Kepler*. Sunspots and faculae are the most significant contributors to solar activity. Sunspots appear as dark spots on the solar surface, where the temperature is significantly lower. In contrast, faculae are brightest structures where the temperature is higher and they can be easily observed at the solar limb and almost invisible in the center of the disk. At the maximum of the solar cycle, the contribution from faculae dominates the sunspot contribution, making the Sun appear brightest at the maximum.

The Rieger-type periodicity of 150–200 days was discovered by Rieger et al. (1984) more than 30 yr ago. This periodicity is seen in many indices of solar activity (Bai & Sturrock 1987; Bai & Cliver 1990; Lean 1990; Ballester et al. 2002, 1999; Oliver et al. 1998; Zaqarashvili et al. 2010). Lean & Brueckner (1989) showed that the Rieger period of 155 days is seen in the sunspot blocking function, 10.7 cm radio flux, and the Zürich sunspot number during solar cycles 19–21, but it is absent in plages, where the magnetic field is weak. This may indicate that the periodicity is related to the solar interior, namely with the solar tachocline, where the solar magnetic field is thought to be generated. Zaqarashvili et al. (2010) suggested that the periodicity can be explained by unstable magnetic Rossby waves in the tachocline owing to the latitudinal differential rotation and the toroidal magnetic field, which may lead to the quasi-periodic eruption of magnetic flux towards the surface. It has also been shown that the Rieger-type periodicity is anti-correlated with the solar cycle strength, such that stronger cycles exhibit shorter Rieger periods (Gurgenashvili et al. 2016, 2017). Therefore, the observed periodicity and dispersion relation of magnetic Rossby waves can be used to estimate the magnetic field strength in the dynamo layer (Zaqarashvili & Gurgenashvili 2018). Rieger-type periodicity can also be observed in the activity of other stars; therefore, the method may allow for the probing of the dynamo magnetic field on the stars at different stages of evolution.

In order to observe Rieger-type periods on other stars, we can look into light curves provided by *Kepler*, CoRoT, and TESS. The existence of short-term cycles, which are similar to the Rieger periods, was previously reported based on the CoRoT (Lanza et al. 2009) and *Kepler* (Bonomo & Lanza 2012; Lanza et al. 2019) observations. However, more observations and detailed analysis of stellar light curves are needed to improve on these results. Prior to a stellar light curve analysis, it is clearly of vital importance to study the periodicity in the total irradiance of the Sun in detail. In this paper, we analyze the TSI data for cycle 23 and 24 and we look for quasi-periodic variations on timescales of Rieger-type periodicities, using the Morlet wavelet transform (Torrence & Compo 1998).

2. Data

We used three different data sets, including both observations and reconstructions. For the TSI measurements, we used data from Variability of solar IRradiance and Gravity Oscillations (VIRGO) on board Solar and Heliospheric Observatory (SOHO), combining two radiometers (Diarad and PMO6-V) and two sun-photometers, which measure the spectral irradiance at 402, 500, and 862 nm with 5 nm passbands. To make comparisons with the SOHO/VIRGO TSI data, we used the SATIRE-S reconstruction model (here “S” stands for the Satellite era) from the Max Planck web page[1], which includes the data of the TSI and Spectral Solar Irradiance (SSI) starting from 1947 (Yeo et al. 2014). It combines the contributions of faculae brightening and sunspot darkening.

The VIRGO data has much higher quality than the other older radiometers, however, an almost seven-month gap in the data appears during the ascending phase of cycle 23 (Fröhlich et al. 1995). In order to search periodicities in VIRGO data, we filled the gap with the SATIRE-S reconstruction. For sunspot data, we use the U.S. Air Force/National Oceanic and Atmospheric Administration (USAF/NOAA) sunspot area (SA) data[2], that has continuous data for cycles 23–24, without any gaps; however, the data ends in September 2016 and therefore does not cover the most recent years of cycle 24.

3. Results

Figure 1 shows TSI data using the SATIRE-S reconstruction. Total solar irradiance includes the contributions from different sources, mainly from faculae and sunspots. Faculae brightening (FB) leads to an increase in TSI, while sunspot darkening (SD) reduces it. Figure 1 shows that the faculae contribution has almost twice as much amplitude as the sunspots in both cycles. Several different timescales are seen in the TSI. First of all, there is a clear modulation of TSI with the 11-year solar cycle. In particular, TSI mainly follows the FB curve, which shows that the solar irradiance is faculae dominated. The second timescale is on the order of 0.5–1.5 yrs (from the range of the Rieger periodicity to that of the quasi-biennial oscillation) and the third timescale is on the order of solar rotation (~27 d). Here we are interested in searching for the mid-range periodicity in the total irradiance of the Sun.

Figure 2 shows the Morlet wavelet analysis of TSI and sunspot area during cycles 23–24 in 100–220 day period window (the periods are defined with close to 5-day accuracy). The hatched regions on the figure (and on all wavelet figures) show the cone of influence (COI), which means that the wavelet transform is not reliable in these areas (Torrence & Compo 1998). First of all, we note that the VIRGO (left panel) and SATIRE (middle panel) data show almost identical spectra; therefore, SATIRE data can be safely used for detailed analysis. The wavelet spectra are significantly different in the cycles 23 and 24; thus, we consider the periodicities in both cycles separately.

3.1. Cycle 23

Two strong periodicities are seen in both the power spectra of the TSI data and the SATIRE-S model, namely: 180 days and 115 days. The peak at 180 days is in the range of typical Rieger-type periodicity (150–180 days) found previously in the sunspot area data (Gurgenashvili et al. 2016). On the other hand, the peak at 115 days is relatively shorter compared to the typical Rieger periodicities, therefore it is probably related with another branch of periodicity (the shorter period can be explained by another harmonic of Rossby waves; see discussion in Sect. 4). There is also a weak power near the period of 140 days. In order to compare the TSI variations with the sunspot area, we plot the wavelet spectrum of USAF/NOAA data on the right panel of this figure. A strong peak is clearly seen at 115 days, however, the strong power is absent at the period of 180 days. Instead, there is a strong peak near the period of 165 days. We can note the weak peak at 180 days, but it has much less power than the one shown at 165 days. Gurgenashvili et al. (2017)

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[1] `http://www2.mps.mpg.de/projects/sun-climate/data.html`.

[2] `http://solarscience.msfc.nasa.gov/greenwch.shtml`.