

# Chapter 1

## Introduction\*

### 1.1 The Sun: magnetic activity

The Sun is the star closest to Earth and is, therefore, the most and best studied star. Due to the relatively short distance between the Earth and the Sun compared to the distance to other stars, we can reach high spatial resolution. The Swedish 1-m Solar Telescope (Scharmer et al. 2003) at the Roque de los Muchachos on the Canary island of la Palma offers today the best resolution of all solar observatories with an angular resolution element as small as 0.12 arcsec under the best conditions (corresponding to 90 km on the solar surface; Scharmer et al. 2002), which is restricted by the diffraction limit of about 0.1 arcsec (corresponding to 70 km on the Sun). Therefore, we have the opportunity to distinguish small structures on the surface of the Sun and to study many features and processes in detail. This is of great importance because the Sun serves as a prototype for other stars and because of the Sun-Earth connection with the solar impact on space weather and Earth's climate.

Solar activity is the most important set of phenomena, which can be studied in the necessary spatial detail only on the Sun and which is of special interest for the current thesis. Typical active phenomena include sunspots, faculae, network, flares, coronal mass ejections, and cyclic behaviour of all these features. They are an immediate consequence of the existence of magnetic fields (for an overview see Stenflo 1994) which are generated by cyclonic turbulence in the outer convection zone. A convective envelope as relevant ingredient of magnetic activity is also present

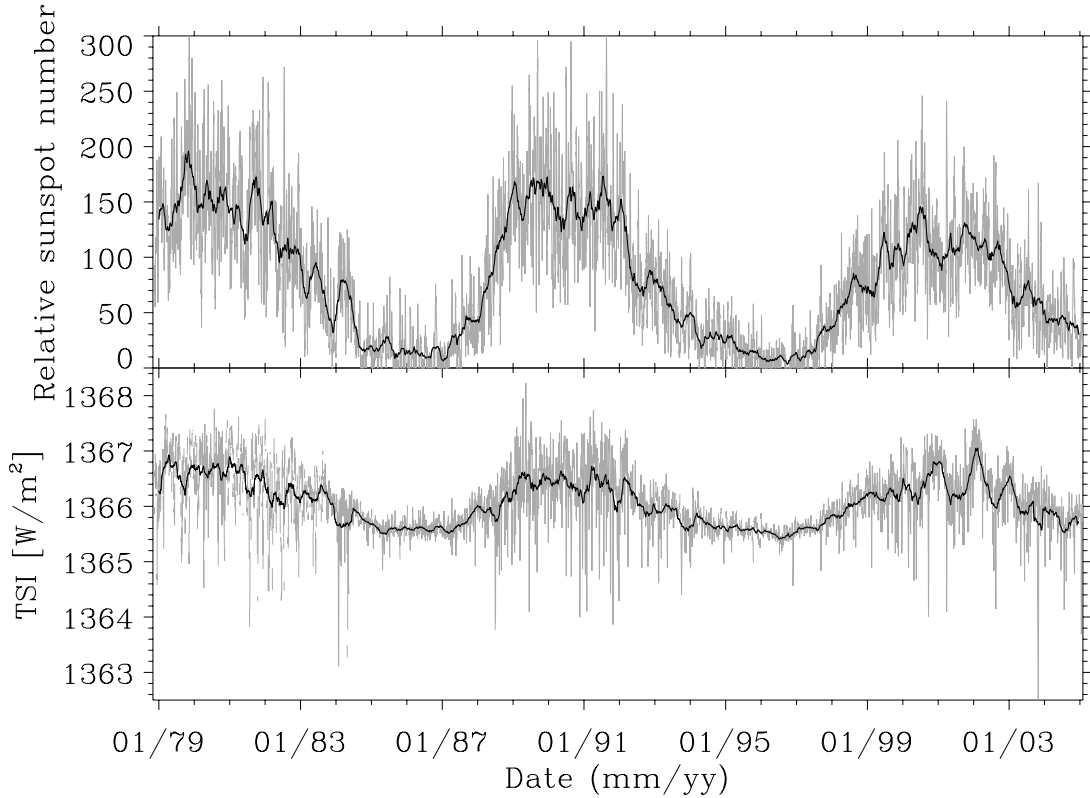
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\* Parts of this chapter, in particular Sect. 1.5, are taken from Solanki, S. K., Krivova, N. A., Wenzler, T., 2005, “*Irradiance models*”, Adv. Space Res., **35**, 376

on other cool stars, which typically exhibit the same activity phenomena (e.g. Schrijver & Zwaan 2000; Berdyugina 2004; 2005). This suggests a common source of the underlying magnetic field in terms of a dynamo (e.g. Schrijver & Zwaan 2000; Berdyugina et al. 2005; Fluri & Berdyugina 2005). The large sample of cool, active stars gives us therefore an ideal testing ground for improving our understanding of magnetic activity, by considering also a wider range of parameters (rotation rate, stellar structure, convection properties, etc.) than available on the Sun.

The solar magnetic activity changes on various time scales (Sonett et al. 1991; Knaack et al. 2005). The lifetime of sunspots, e.g., varies from hours to months (Solanki 2003) whereas the lifetimes of the Sun's faculae and their magnetic fields are always substantially larger (on average by about a factor of three) than the lifetime of the associated sunspots or sunspot groups (Scheffler & Elsässer 1990). The number of sunspots and their areas follow a cycle, called the solar, sunspot or activity cycle, with a periodicity of about 11 years. The sunspots also exhibit longer term periodicities such as the Gleissberg cycle with a period of about 80 years (Gleissberg 1939). Particularly intriguing are the long periods with strongly reduced sunspot numbers such as the Wolf (1280–1340), Spörer (1409–1551) and Maunder (1645–1715) minima that seem to occur quasi-periodically every few centuries. Note that the corresponding time scales for stellar variability are of the same order (Radick et al. 1998; Giampapa 2005).

The longest running direct record of solar activity is clearly the sunspot number. Consistently calibrated sunspot numbers were collected over the last approximately 160 years, but the 11-year activity cycle (discovered by M. Schwabe in 1843; Schwabe 1844) could be retraced back to the beginning of the telescopic observations in the early 17th century (Eddy 1976; Hoyt & Schatten 1998). In the upper panel of Fig. 1.1 the 11-year solar cycle is clearly evident in the variation of the relative sunspot numbers, which are proportional to the total area of the visible sunspots. The relative sunspot number is defined as  $R = k(10g + f)$ , where  $g$  is the number of sunspot groups and  $f$  is the total number of distinct spots. The scale factor  $k$  (usually less than unity) depends on the observer, the seeing, and the observatory (location and instrumentation) and serves as conversion factor to the scale originally introduced by R. Wolf. The time series of the relative sunspot number is now com-



**Figure 1.1:** Relative sunspot number between November 16, 1978, and December 31, 2004 (*top panel*). The lower panel shows the newest total solar irradiance PMOD composite time series (version 41) compiled from multiple, cross-calibrated independent radiometric measurements (Fröhlich 2004). The grey lines are daily values and the black lines are their 3-month running means.

piled and reported by the National Geophysical Data Center (NGDC) of the NOAA Satellite and Information Service and by the Solar Influences Data analysis Center (SIDC) at Brussels. Nowadays, the characterisation of solar activity by the sunspot number is complemented by the observation of many other magnetic phenomena, which became possible in particular since the advent of space missions with satellites.

## 1.2 Solar irradiance variations

The electromagnetic energy emitted by the Sun is strongly related to solar magnetic activity. It is quantified in terms of the total solar irradiance (TSI), which is defined as the solar constant  $S$ , i.e. the total

electromagnetic energy flux, integrated over all wavelengths, that is radiated by the Sun in the direction of Earth and measured at a distance  $R = 1$  AU from the Sun, where one astronomical unit (AU) is the annual mean Sun-Earth distance (for an overview see Lean 1991; Fröhlich & Lean 2004). With the TSI being primary energy source of Earth, it is interesting to study its variations.

On the very long time scale of solar evolution irradiance variations are well understood. The solar luminosity,  $L_{\odot} = 4\pi R^2 S$ , which is the power radiated by the Sun from its entire surface, was at the beginning of its tenure on the hydrogen-burning main sequence 4.6 Gyr ago roughly 30% lower than its current value, i.e.  $\approx 0.7L_{\odot}$ . Since then the Sun's luminosity has slowly increased and will continue to do so. In 6.5 Gyr from now it will reach about  $2.2L_{\odot}$  and will then increase rapidly (Sackmann et al. 1993). As a consequence higher life forms and plants on Earth are doomed to die out already in approximately 1 Gyr (Caldeira & Kasting 1992).

At time scales of days up to the solar cycle the TSI variations show a close relation to the temporal magnetic activity variations. Over the 11-year cycle the TSI varies by approximately  $1 \text{ Wm}^{-2}$  (e.g. Fröhlich 2003) and by larger amounts on shorter time scales. The lower panel of Fig. 1.1 shows the newest composite record (version 41) of the total solar irradiance constructed by Fröhlich (2004), who has compiled measurements by five independent space-based radiometers that started measuring in 1978 (see Sect. 1.4 for details). Note the good correlation between the solar brightness variations and the variations of the sunspot number, which itself is a measure of magnetic activity (Fig. 1.1). This indicates that the TSI variations and magnetic activity are strongly related to each other. Thus, motivated by this good correlation, the general aim of the current thesis is to increase our understanding of the physical mechanisms responsible for solar brightness variations. The general idea is to reconstruct the total solar irradiance employing a model that is based on surface magnetic fields (Sect. 1.5.2).