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Sunspot group tilt angle measurements from historical observations

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Abstract

Sunspot positions from various historical sets of solar drawings are analyzed with respect to the tilt angles of bipolar sunspot groups. Data by Scheiner, Hevelius, Staudacher, Zucconi, Schwabe, and Spörer deliver a series of average tilt angles spanning a period of 270 years, additional to previously found values for 20th-century data obtained by other authors. We find that the average tilt angles before the Maunder minimum were not significantly different from the modern values. However, the average tilt angles of a period 50 years after the Maunder minimum, namely for cycles 0 and 1, were much lower and near zero. The normal tilt angles before the Maunder minimum suggest that it was not abnormally low tilt angles which drove the solar cycle into a grand minimum.

Keywords: Sun: sunspots; Tilt angles; Cycle-averaged tilt angle

1. Introduction

The long-term study of solar cycle properties using historical observations has provided mainly the sunspot number (Clette et al., 2014). However, we can also access other properties more directly related to the solar dynamo through historical sunspot drawings. The tilt angle of sunspot groups is among those parameters and can be included in certain types of dynamo models. Bipolar sunspot groups exhibit an axis through the two main magnetic polarities. The tilt angle is the angle at which this axis is orientated with respect to the solar equator. It is an important property in flux-transport dynamos (Babcock-Leighton dynamos, see e.g. Charbonneau, 2010, Section 4.8) in which it provides the source term for the poloidal magnetic field which in turn correlates with the strength of the next cycle. The tilt angles are widely believed to be the result of buoyantly unstable magnetic flux tubes at the bottom of the convection zone, rising under the influence of rotation, internal twist, and magnetic tension.

According to results of the thin flux tube approximation, tilt angles are either due to writhing of rising flux loops by the Coriolis force or the pitch angle of the subsurface field wound up by the differential rotation (D'Silva and Choudhuri, 1993). The combination of magnetic buoyancy and the Coriolis force generates the correct latitudinal distribution of tilt angles, according to numerical simulations in the thin flux tube framework (e.g. D'Silva and Choudhuri, 1993; Caligari et al., 1995; Fan and Fisher, 1996; Weber et al., 2013). These computations can also reproduce the correlation between the magnetic field strength and the tilt angle which is seen in some observational studies (Tian et al., 2003; Dasi-Espuig et al., 2010). The average tilt angle and the amplitude of the corresponding cycle appears to be anti-correlated, while the product of the average tilt angle with the cycle amplitude is well correlated with the strength of the following cycle (Dasi-Espuig et al., 2010, 2013).

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In thin flux tube models, the tilt angles are even useful in constraining the strength of initial magnetic flux. The strength of the toroidal magnetic field at the bottom of the convection zone has to be in the range of 40–50 kG in order to obey the observed Joy's law (Weber et al., 2011).

Observational studies by Kosovichev and Stenflo (2008) show that the tilt angles of sunspot groups change gradually over their lifetime except in the beginning of emergence. While the tilt angles are random in the earliest phase of emergence, they adjust towards Joy's law during the rest of the emergence phase, i.e. as long as the magnetic flux is growing. It is not straight-forward to draw a direct link between the tilt angles and the emergence of flux tubes in simulations. The average tilt angles are also fairly independent of the cycle phase within fixed latitudinal zones (Li and Ulrich, 2012).

The study of tilt angles derived for several centuries helps us understand their origin and their relation to the solar cycle. The true tilt angles of sunspot groups are available only from magnetic data of the solar surface for the second half of the 20th century, while pseudo-tilt angles are measured without the polarity information and have a 180°ambiguity. Pseudo-tilt angles can be computed whenever individual spot positions in sunspot groups are available from drawings or images. They have recently been calculated for the period of 1825–1867 using the sunspots observations by Schwabe (Senthamizh Pavai et al., 2015).

In this paper, we present the tilt angle measurements from further historical sunspot observations, namely the observations by Christoph Scheiner (1618, 1621–1622, 1625–1627), Johannes Hevelius (1642–1644), Johann Caspar Staudacher (1749–1796), Ludovico Zucconi (1754–1760), and Gustav Spörer (1861–1894).

The details of different solar observations and the methods used in data extraction from those sunspot drawings are described in Section 2. The comparison of mean tilt angles and cycle-mean tilt angles from various data are discussed in Section 3.

2. Data set

Christoph Scheiner started his sunspot observations from Ingolstadt, Germany, in the early 17th century. His first known sunspot drawing was made on 21 October 1611. Most of his data, however, were recorded from Rome. He published observations only for a few days during each of the years of 1611, 1612, 1618, 1621, 1622, and 1624. In the period 1625–1627, the observations are fairly continuous (drawings covering 342 days in 1625, 163 days in 1626, and 55 days in January–June 1627). His drawings show the sunspot groups traversing the solar disk in a single full-disk drawing (Scheiner, 1630). The positions and areas of the sunspots were measured using 13 circular cursor shapes with areas between one and 364 pixels. The data before 1618 were not included in the tilt angle distribution, because they are extremely coarse and show highly exaggerated sizes of sunspot groups.

Johannes Hevelius recorded his observations of the Sun from Gdańsk, Poland, during the period of 1642–1644 (15 days in October–December 1642, 110 days in May–December 1643, and 98 days in January–October 1644). These sunspot drawings were published by Hevelius in an appendix of his book *Selenographia* (Hevelius, 1647). His drawing style is very similar to Scheiner's style, and the positions and area information were obtained in the same way. It is important to note that these sunspot drawings were made just before the Maunder minimum, a period of reduced solar activity from 1645 to 1715 approximately (Spörer, 1889; Usoskin et al., 2015).

During the second half of the 18th century Johann Caspar Staudacher (or Staudach) recorded his observations of the Sun from Nuremberg, Germany, and made drawings in 1749–1796. Detailed information about the drawings and the data extraction methods can be found in Arlt (2008, 2009). Various methods of estimating the orientation of the drawings had to be employed to measure the sunspot positions. From the data base derived, we use only the spots with quality flags 1 and 2. This basically excludes drawings for which the orientation was estimated using a typical tilt angle for bipolar regions. Quality-3 observations use the tilt as an input in many cases and are therefore not used.

For a rather short time from April 1754 to May 1758 and a short spell in June 1760, Ludovico Zucconi observed the Sun from Venice, Italy, contemporaneously with Staudacher. The positions and areas of individual sunspots were extracted by Cristo et al. (2011) using the HSUNSPOTS tool. The orientation of these drawings were clearly marked by the observer, and we consider them fairly precise.

The drawings of sunspot observations made by Samuel Heinrich Schwabe from Dessau, Germany, in the period 1825–1867, and the extraction of data from them were explained in detail by Arlt (2011) and Arlt et al. (2013). A description of the method that was employed to compute all the tilt angles in the present paper is given by Senthamizh Pavai et al. (2015), where it was applied to the Schwabe data.

Friedrich Wilhelm Gustav Spörer observed sunspots from Anklam and Potsdam, Germany, during 1861–1894. He drew the sunspot groups while they crossed the central meridian, so the evolution of sunspot groups is not available. The details of the drawings and the technique used in the extraction of positions and areas of sunspots were given by Diercke et al. (2015).

3. Tilt angle distributions

Based on the positions of the individual spots, a tangential plane is adopted touching the solar surface in the group center in order to minimize curvature effects in determining the tilt angle. The groups are divided into two polarities

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