Title: Rotation of the photospheric magnetic field through solar cycles 21, 22, 23.

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Abstract

Rotation of the large scale solar magnetic field has a great importance for the understanding of solar dynamic, for the search of longitudinal structure and for the study of solar-terrestrial relations. 30-year long observations taken at the Wilcox Solar Observatory (USA) in 21-23 cycles have been analyzed carefully to deduce magnetic field rotation rate at different latitudes in both hemispheres and its variability in time.

The WSO data appear to indicate that additionally to the differential rotation along the latitudes there are running waves of fast rotation of the magnetic field. These torsional waves are running from the poles to the equator with a period of 11 years.

The rotation of the magnetic field (RMF) is almost rigid at latitudes above 55 degrees in both hemispheres. The rotation rate in the sub-polar regions is slower when the magnetic field is strong there (during minima of solar activity), and faster when the magnetic field changes polarity (during maxima of solar activity).

Keywords: Sun; solar variability; magnetic field; rotation; solar cycle; torsional waves.

1 Introduction

The characteristics of the solar magnetic field and their variability have been studied over the years by many authors (see Gavryuseva (2018) and references there). The rotation of the magnetic field is extremely important for the solar dynamo theory.

This paper is focused on the study of the rotation of the large scale photospheric magnetic field (SMF) and its variability through solar activity cycles. Rotation rate of solar plasma was measured over many years. Sunspot spectroscopic observations provide the information on the mid and low latitudes.

The Wilcox Solar Observatory (WSO) data from [http://wso.stanford.edu/](http://wso.stanford.edu/) have been used because they provide the sets of the large scale photospheric solar magnetic field (SMF) observations at different latitudes. The rotational grid of the available data is made of 30 equal steps in sine of latitude $\theta$ ($\sin(\theta)$) where $\theta \pm 39.3, \pm 34.5, \pm 30.0, \pm 25.7, \pm 21.5, \pm 17.5, \pm 13.5, \pm 9.6, \pm 5.7, \pm 1.9$ degrees, and of 5 degree steps in heliographic longitude. The observations were taken by the WSO’s Babcock solar magnetograph using the Zeeman splitting of the 525.02 nm Fe I spectral line (Scherrer et al., 1977; Hoeksema, 1984). The results of the study of the rotational rate of the SMF data sets since May 27, 1976 over 21, 22, 23 cycles are presented in this paper.
2 Rotation of the Solar Magnetic Field Through the Cycles

We have used two independent methods to evaluate the period of the rotation of the solar magnetic field: spectral analysis (fast Fourier transform – FFT) and autocorrelation. The periods of the differential rotation at each latitude were deduced for the whole 29 years long data sets and for sub-sets of shorter duration with step of 1 CR. The differential rotational period was also estimated as a mean of the rotational periods calculated for the shorter series at each latitude.

The results obtained by the FFT method for the sub-sets of 40 CR (about 3 years) long are presented in Fig. 1. On the upper plot the sideral period of the magnetic field rotation as a function of time and latitude is shown. Blue (yellow) colors correspond to the shorter (longer) periods. Contours correspond to the periods of 27, 28, 29, 30 and 31 days. The well known differential rotation appears also for the large scale solar magnetic field. Additionally in the sub-polar zones there is a clearly visible decrease of the rotational rate in 1985 and 1994 during solar activity minima and an increase of the rotation rate approximately in 1990 and in 1991 after the polarity inversion. This happens with the 11-year periodicity (Gavryuseva, 2005, 2006, 2006d, 2008a,b). This result provides the panoramic understanding of the variability of the magnetic field rotation and complete the earlier studies performed by Gilman and Howard (1984), Stenflo (1977, 1990), Obridko and Shelting (2001). An attempt of modeling 11-year variations in sub-polar regions was done by Tikhomolov (2001).

In Fig. 2 the SMF mean sideral rotational period deduced from the full sets of 29 year long (composed of 27721 points) are plotted as a function of latitude deduced by auto-correlation method (continuous line) as well as by the FFT method for 3-years long subsets (dashed-dotted line) with corresponding error bars. There is a 0.5–0.7-day decrease of the period at latitudes higher than 56-60 degrees in both hemispheres, corresponding to the 1.7–2.3% range. The accuracy of the autocorrelation method for the full data sets is limited by the longitudinal resolution of 5 degrees, and its accuracy is equal to 1.3% at most. This result coincides with the latitudinal dependence of the rotation rate calculated by the FFT method for the full data sets, and with the rotation rate calculated by both methods as the mean of the rotation rates corresponding to the shorter subsets. The accuracy of the mean rotation rate is at least 10 times better.

The sideral SMF rotational period agrees with the results of the spectroscopic measurements of the solar rotation in the interval of latitudes $\theta$ from -40 to 40 degrees (Howard and Harvey, 1970; Howard et al., 1991), see also, for example, (Stenflo, 1974; Godoli and Mazzuconi, 1979, 1983; LaBonte and Howard, 1981, 1982b; Snodgrass, 1983; Howard et al., 1984; Bumba and Heina, 1987; Ulrich et al., 1988; Snodgrass and Ulrich, 1990; Beck, 1999; Ivanov et al., 2001; Ossendrijver, 2003).

On the contrary at the latitudes between 40 and 55 degrees the SMF rotates faster than other tracers and the photospheric plasma. This result of Gavryuseva (2006, 2006d, 2008) and Gavryuseva & Godoli (2006) well agrees with the latitudinal dependence of the rotational period of magnetic field data from the Mount Wilson and Kitt Peak National Observatories taken in 1959-1985, reported by Stenflo, (1989). It was noted also by Obridko and Schelting (2001)
that the solar magnetic field rotates more rigid at high latitudes. The decrease of the SMF rotational period at latitudes above 55-60 degrees (deduced from the 25-30 years long data sets of the SMF) has never been found for other tracers or in spectroscopic measurements of shorter duration (Beck, 1999). This interesting result can be explained by the replenishing of surface magnetic field ‘over a time scale of weeks by new flux emitted from the source region, which is probably near the bottom of the convection zone’ (Stenflo, 1989) (the rotation of the plasma at the bottom is faster than at the surface in high latitudes). The rigid SMF’s rotation at high latitudes can explain the fact of slow rigid rotation of coronal holes.

The radial and latitudinal dependence of the rotational rate was obtained by helioseismological methods, see for example, (Rhodes et al., 1990; Howe et al., 2000; Gavryuseva et al., 2000; Di Mauro, 2003). The higher rotation rate at the latitudes above the 55 degrees corresponds to the rate of the rotation at a deeper layer. This is an evidence that the solar magnetic field rotation at latitudes above 55 degrees follows the rotation of the deeper layers where it is originated from.

Such latitudinal dependence of the rotation would also support the theoretical model of Snodgrass (1986, 1987a) and Wilson (1988) of the solar cycle based on the existence of a system of latitude- and time-dependent toroidal convective rolls in which the rotation rate is alternately faster or slower than the time averaged differential rotation at that latitude (Rabin et al., 1991). This model was suggested to describe the observed torsional oscillations.

On the bottom plot of Fig. 1 the mean North-South deviation of the rotational period, obtained by the FFT method for the 3 years long sub-sets, from the mean period over 1976-2004 years for each latitude $\theta$ is shown as a function of time and latitude. This interval corresponds to the cycles No 21 and No 22 (two complete cycles have been chosen in order to avoid possible influence of the variability through cycles). Blue (yellow) colors correspond to negative (positive) deviation. Contours correspond to the deviations of 0, ±0.5, ±1.0 days.

Torsional waves firstly discovered by Howard and LaBonte by “the analysis of 12 years of full disk Doppler velocity observations” LaBonte and Howard, (1982a), Howard and LaBonte, (1980); are present in the magnetic field rotation rate as well Snodgrass, (1985, 1987b); Gilman and Howard, (1984;) Makarov et al., (1997) up to high latitudes as it is seen on the bottom plot of Fig. 1. The 11-year variability of the deviations of the period from the mean one in the sub-polar zones correspond to the torsional waves. The rotational rate of the pre-equatorial zones varies in time with a periodicity of 55–60 CR about (4 – 5 years) Gavryuseva and Godoli, (2006). Results obtained by both methods entirely agree with each other.

This is better illustrated by Fig. 3 where the correlation between the deviations at the different latitudes in the northern and in the southern hemispheres from the mean rotational rate corresponding to each latitude is plotted. The 11-year variability of the rotational rate at high latitudes is synchronized in both the hemispheres. The 5-year periodicity is common for pre-equatorial zones and active belts Gavryuseva and Godoli, (2006).

This result confirms the increase of the rotational rate in those latitudinal zones where, in in some intervals of time, the magnetic field is weak. This result agrees with the conclusions of Stenflo (1977, 1990); Makarov et al. (1997) and Obridko and Shelting (2001) that the pre-equatorial SMF rotation rate depends
on the phase of the solar cycle and is higher during minimum of the activity.

Interesting investigations have been performed using helioseismological approach to study how rotation varies with radius and latitude within the solar interior. Frequency splittings of acoustic modes confirm that the variation of rotation rate with latitude seen at the surface carries through the convection zone. At the base of the convective envelope (outer 30% by radius) there is the tachocline zone. R. Howe et al. (2000) have detected changes in the rotation of the Sun near the base of its convective envelope, including a prominent variation with a period of 1.3 years at low latitudes. Inversion of the global-mode frequency splittings reveals that the largest temporal changes in the angular velocity are of the order of 6 nanohertz and occur above and below the tachocline that separates the Sun’s differentially rotating convection zone from the nearly uniformly rotating deeper radiative interior beneath. This result agrees with the revealed variability of the SMF at low latitudes. S. V. Vorontsov et al. (2002) confirm the presence of the bands of slower and faster rotation observed at the Sun’s surface and migrated in latitude over the 11-year solar cycle. The entire solar convective envelope appears to be involved in the torsional oscillations, with phase propagating poleward and equatorward from midlatitudes at all depths throughout the convective envelope.

3 Summary

1. The differential rotation of the large scale magnetic field and its temporal dependence have been investigated. The WSO data appear to indicate that the differential rotation of the magnetic field differs from that of the plasma at latitudes above 55 degrees in both hemispheres.

2. The 11-year periodicity of the rotational rate has been found at high latitudes. An 11-year periodicity and a 5-year quasi-periodicity of the rotational rate have been found in the near-equatorial zones and in the activity belts.

This magnetic field topology, highly-organized over the solar surface and over time, must be considered as a basic structure with a major influence on the solar corona and solar wind propagation, and is fundamental for the understanding of the heliospheric structure and for the prediction of the magnetospheric perturbations.

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Figure 1: On the upper plot the sidereal period of the magnetic field differential rotation calculated by auto-correlation method for subsets of 3-year long is shown as a function of time and latitude. Blue (yellow) colors correspond to the shorter (longer) periods. Contours correspond to the sidereal rotational periods of 27, 28, 29, 30 and 31 days. On the bottom plot the mean North-South deviation of the time dependent rotational period from the differential rotational period averaged over 22 years is plotted as a function of time and latitude. Blue (yellow) colors correspond to negative (positive) deviations. Contours correspond to the deviations of 0, ±0.5, ±1.0 days.
Figure 2: The SMF mean rotational periods deduced from the full sets are plotted as a function of latitude as it is deduced by auto-correlations method (continuous line) and by FFT method (broken line) and as a mean for sub-sets with corresponding error bars (dashed-dotted line).
Figure 3: Correlation between the deviation of the rotational period from the mean one for each latitude on the northern and on the southern hemispheres as a function of time shift expressed in Carrington rotation number.