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# Magnetic multipoles of the Sun from observations of the mean magnetic field

V. Haneychuk

Crimean Astrophysical Observatory of the Russian Academy of Sciences, Nauchny, Crimea, 298409 Russia

**Abstract.** The data of the mean magnetic field (MMF) of the Sun from the Wilcox Solar Observatory from 1975 to 2023 (49 years, number of daily measurements $N = 14516$) were analyzed to identify the main periodicities over short time intervals. The wavelet-spectrum of these data shows that the MMF has significant rotational harmonics from the first to the third, although sometimes there are higher orders up to the sixth harmonic inclusively. Each of these harmonics corresponds to its own multiplet of the magnetic field (dipole, quadrupole and higher components). Rotation harmonics were identified in the original data series and an approximated time series was built from them. In this case, wavelet-spectrum data and refined parameters of sinusoids obtained using the least squares method were used. The constructed approximated data series contains more than 90% of the power of the original series.

The main components of the Sun's rotation change their amplitude, frequency and phase over time. Changes in the amplitude of oscillations occur depending on solar activity–they are usually maximal in the second half of the cycle. Rotational frequencies change over time, but do not show dependence on solar activity. The maximal amplitude of rotation component most often has a frequency of the main period of about $P \approx 27$ day (55.4% in time), as well as its half value $P/2 \approx 13.5$ day (38.2%); the share of periods $P/3 \approx 9$ day is 6.1%, the rest–no more than 0.3%. This means that the Sun predominantly appears as a magnetic horizontal dipole (≈55% of the time), but the quadrupole component is also very significant and occupies 38% of the time. In general, different multipoles are almost always present on the Sun, but the predominance of one or another component of the multipole does not reveal any patterns and is practically independent on solar activity.

**Keywords:** Sun: magnetic fields, rotation

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## 1 Introduction

The mean magnetic field (MMF) of the Sun as a star is the average value of the magnetic flux from the entire visible solar hemisphere. Its measurements began in 1968 by Severny (1969) at the Crimean Astrophysical Observatory, and then continued in other observatories.

The periodicity of MMF has been studied by different authors, see, for example, Rivin & Obridko (1992), Haneychuk (1999), Chaplin et al. (2003), Haneychuk et al. (2003), Kotov (2020), Haneychuk & Kotov (2021). As has been shown, the main changes in the MMF are associated with the rotation of the Sun. This can be seen directly in the measurement data themselves, and, of course, in the power spectra or periodograms, where peaks in the region of 26–27 days dominate. This main harmonic of the rotation of the MMF is associated with the magnetic horizontal dipole of the Sun. The second harmonic of rotation has a period of about 13.5 days and is associated with the quadrupole component of the magnetic field. Higher harmonics reflect the presence of higher multipoles.

This article analyzes changes in the MMF over 49 years of observations in order to identify the main multipoles or their horizontal components present on the surface of the Sun.

## 2 Observation

To analyze changes in the MMF, an observational data of the Wilcox Solar Observatory (Scherrer et al. 1977) was used, because it is homogeneous, the longest and most numerous. Observations have been carried out on the same instrument since 1975 and continues to this time. One measurement per day is made, taking into account the zero position of the magnetograph. The data is published on the Internet on the observatory website[1].

The observation period from 1975 to 2023 was taken for the study, the number of measurements was $N = 14516$, the total duration of the series $T$ was about 49 years. The measurements cover more than four cycles of solar activity. The original values of the MMF usually do not exceed 1 Gauss in modulus, and at a minimum they are no more than 0.5 Gauss. Positive values correspond to the northern polarity of the magnetic field, negative ones–to the southern polarity.

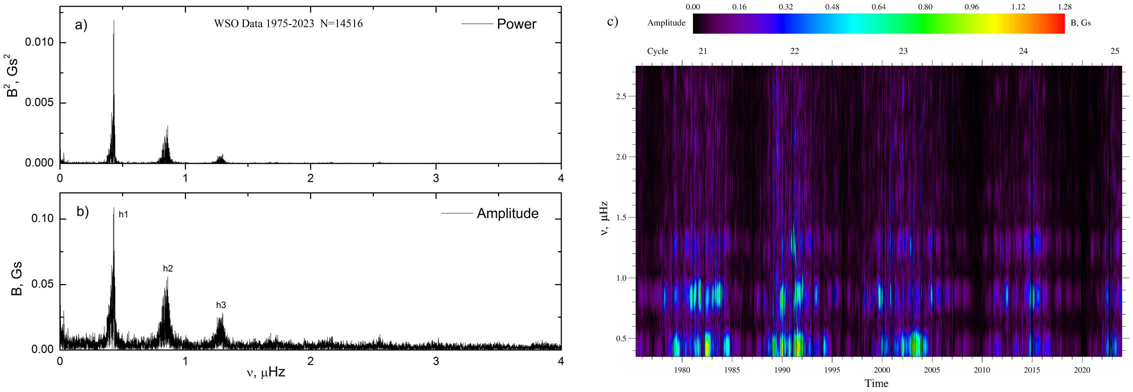

**Fig. 1.** a) Power spectrum of the MMF, along the $x$ axis–frequency in $\mu$Hz, along the $y$ axis–power in Gs$^2$. b) Amplitude spectrum of the MMF, along the $x$ axis–frequency, along the $y$ axis–amplitude in Gs. c) Wavelet spectrum of the MMF, along the $x$ axis–time in years, along the $y$ axis–frequency in $\mu$Hz, the horizontal bar at the top shows the oscillation amplitude in Gs.

## 3 Spectra of observational data

Figure 1(a) shows the power spectrum of the studied series of the MMF. Three groups of peaks associated with the rotation of the Sun are clearly visible on it. The highest peak corresponds to the main rotation harmonic with a period $P$ of about 27 days. The second most powerful group of peaks corresponds to the second harmonic of rotation with periods in the region of $P/2 \approx 13.5$ day. The third, smallest in power, group of peaks in the region of $P/3 \approx 9$ day is also noticeable. No higher rotation harmonics are observed. For a more detailed search for high harmonics, the amplitude spectrum of this series of MMFs was constructed (Fig. 1(b)). The first three fundamental harmonics of rotation are marked on the graph. Higher harmonics do not show themselves here either.

Figure 1(c) shows the wavelet spectrum of the studied series, which shows the change in the amplitude of MMF oscillations with time. The window width was taken to be 60 days. The graph clearly shows that the maximum amplitudes of oscillations are observed during the maximum of solar activity, which can be seen also directly from observational data. It can also be seen that there are three horizontal bands of increased power, which correspond to the first three harmonics of rotation. Here, however, it is noticeable that there is a certain oscillation power in the region of higher frequencies, which corresponds to harmonics from the fourth to the sixth.

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[1] http://wso.stanford.edu/

They are not preserved in the spectra of the entire data series (Fig. 1(a, b), since they have a random phase and small amplitudes.

From Fig. 1 it follows that the studied MMF series contains mainly the first three harmonics of rotation. This means that we can try to approximate the original data with sinusoids of these harmonics. In this way they can be separated and then examined in detail.

## 4 Approximation of the original data series

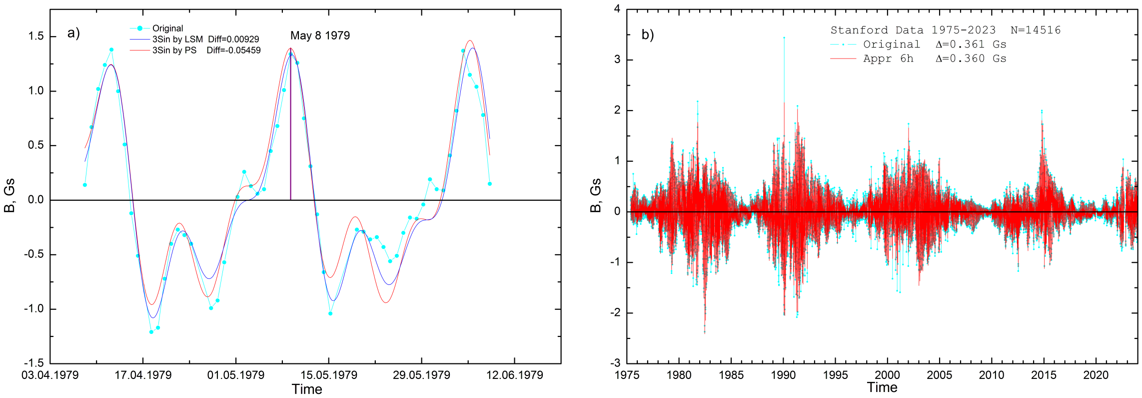

**Fig. 2.** a) An example of approximation of the original data series for May 8, 1979: cyan color–original data, red color–approximation by sum of three sinusoids from the power spectrum, blue–sum of three sinusoids calculated by the least squares method; the vertical line marks the point for which the approximation was carried out. b) Comparison of the original data series (cyan color) and the artificial series constructed from the main harmonics of rotation (red color).

For each point of the original time series, a region around it was selected in an interval of ±30 days (two rotation periods), in which the data were approximated by sinusoids $y(t) = A_0 + A\cos(\omega t - \varphi)$. The initial values of the sinusoid parameters $A_0, A, \omega, \varphi$ were determined from the spectrum of this section for the maximum oscillation power. Then the first component was subtracted from the original series and the parameters of the second component were determined from the spectrum of residuals, etc. In this way, this region of the time series was approximated. Figure 2(a) shows an example of approximation for data on May 8, 1979. The sum of three sinusoids determined from the power spectrum is shown in red. To refine the parameters of the sinusoids, the least squares method (LSM) was used. The blue curve shows the LSM sinusoids approximation. For most points in the series, three sinusoids quite satisfactorily describe changes in the MMF. However, for some points this was not enough, and then higher components were used–up to the sixth inclusive. The final criterion for selecting the approximation curve was the minimum deviations of the constructed curve from the original point.

Figure 2(b) shows a comparison of the approximated MMF series (red) with the original (cyan). The standard deviation of the two series is almost the same: $\Delta_o = 0.361$ Gs for the original series and $\Delta_a = 0.360$ Gs–for the approximated one. The original series in peak field values is larger than the approximated one. However, there are few such points. More than 90% of the power of the original data is contained in the approximated series.

## 5 Basic multipoles of the Sun

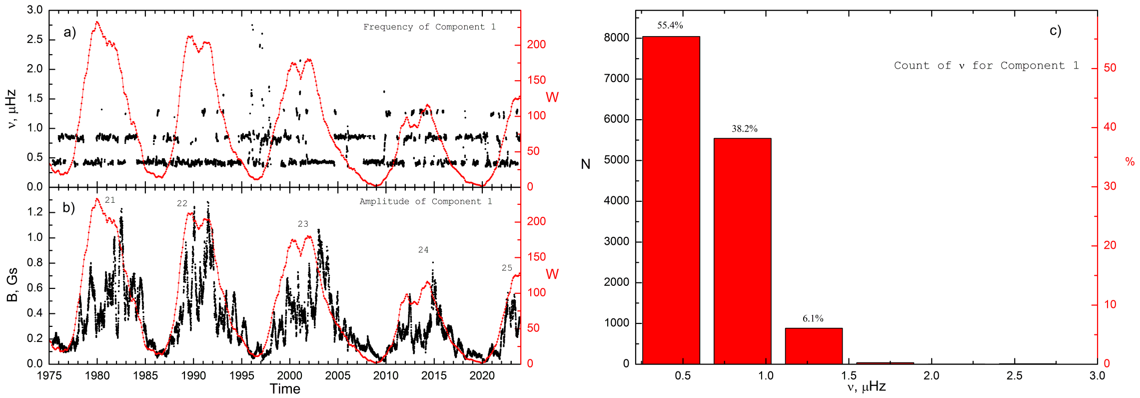

**Fig. 3.** a) Frequency of the first rotation component (black, left scale) as a function of time; red color–Wolf numbers curve (right scale). b) Amplitude of the first rotation component (black, left scale); red color–Wolf numbers curve (right scale). c) Frequency distribution histogram for the first rotation component: $N$–number of occurances, left scale; percentage–right scale.

Figure 3(b) shows the time course of the amplitude of the main (first) component of the rotation of the MMF (black color) in comparison with changes in the Wolf numbers $W$ (red color). It can be seen that the amplitude follows the course of solar activity. It can be noted, however, that it lags somewhat behind $W$, especially in odd cycles 21 and 23, and has its maximum closer to the beginning of the decline phase of solar activity. Figure 3(a) shows the change over time in the frequency of the first component of rotation of the MMF (black color) and the Wolf number $W$ (red color). Three horizontal stripes are noticeable here, which correspond to the main harmonics of rotation or multipoles of the MMF. The lowest band is the basic harmonic (dipole), the second is the quadrupole, the third, weakest, corresponds to the period $P/3$. The change in the frequency of the main oscillation (or change in the multipole) occurs in an indefinite manner and does not depend on solar activity.

In the 21st cycle of activity on the Sun, both dipole and quadrupole components were present approximately equally in time, but at its end–in 1984–the longest interval of the dipole field began until the end of 1995. After that, at a minimum of 1996–1998 a predominance of high multipole components was observed, up to the sixth harmonic inclusive, which is very unusual for the Sun. In subsequent cycles 23–25, the Sun appeared alternately as a dipole and quadrupole with some more noticeable proportion of the octupole component. In general, different multipoles are almost always present on the Sun, but the predominance of one or another component of the multipole does not reveal any patterns and is independent on solar activity.

Figure 3(c) shows a histogram of the frequency distribution for the first rotation component. Each vertical bar shows the number $N$ of occurrences of the main rotation components or multipoles (left red scale in percentage). The frequency of the basic rotation period $P \approx 27$ day occurs in 55.4% of cases, the second harmonic–in 38.2% of cases; the share of periods with $P/3 \approx 9$ days is 6.1%, the rest–no more than 0.3%. This means that the Sun appears predominantly as a magnetic horizontal dipole ($\approx 55\%$ of the time), but the quadrupole component is also very significant and occupies 38% of the time.

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