Are the Signals in the Sun's Mean Magnetic Field Associated With Coronal Mass Ejections?

Wei Liu [1], Yang Liu, Xuepu Zhao, Philip Scherrer

Hansen Experimental Physics Laboratory, Stanford University, Stanford, California 94305-4085

ABSTRACT

A study on time-frequency variability of the solar mean magnetic field (SMMF) using wavelet analysis is presented. The SMMF data of Michelson Doppler Imager (MDI) contain an offset most likely introduced by the random error of the exposure time of MDI. Without the offset correction, the peaks of wavelet power spectra for the full-disk SMMF time series coincide with the onset of coronal mass ejections. It has thus been suggested that the peak of wavelet power spectra is associated with coronal mass ejections [*Boberg and Lundstedt*, 2000]. To localize the source of the peak, the full solar disk has been divided into four quadrants. It turns out unexpectedly that the time series for each quadrant closely resembles that of the full-disk series. In addition, all the five series are nearly in phase. On the other hand, the peaks of wavelet power spectra that coincide with coronal mass ejections disappear for the full-disk SMMF series obtained after the offset correction, suggesting that the signal actually occurs in the offset series. These results give rise to the question – what is the cause of the signals detected in the offset series by the wavelet technique?

1. Introduction

To understand the physical origin of CMEs is a primary goal of both solar physics and space weather forecasting. Studies have shown that CMEs are a part of large-scale coronal magnetic field evolution [e.g., *Luhmann et al.,* 1998; *Zhao et al.,* 1997]. The solar mean magnetic field (SMMF) [*Scherrer et al.,* 1977] is the average field as observed over the entire visible disc (i.e., the Sun seen as a star), which can represent and quantify the global manifestation of the solar magnetism. Long-term changes of SMMF are caused by the rotational modulation and the orientation of the current sheet belt.

[1] Also at Department of Physics, Stanford University (Email: weiliu@sun.stanford.edu).

The non-stationary time-frequency variability of SMMF time series has been investigated more recently, using wavelet analysis [e.g., *Boberg and Lundstedt*, 2000; *Mordvinov and Plyusnina,* 2000]. Based on one minute resolution SMMF data obtained with the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SOHO) spacecraft, it was found that a significant fraction of the wavelet power spectra of SMMF sequences showed a characteristic peak at the time of the coronal mass ejection. A possible interpretation was proposed that the signature in the SMMF, with an average period of 13 minutes, might result from global waves triggered by the CME [*Boberg and Lundstedt*, 2000]. However, the real sources of such signals remain unknown. In the meantime, the previous study was made before the discovery of the offset contained in the MDI data which is most likely introduced by the random error of the CCD exposure time.

In this poster, our task is to localize the source of the signals in the MDI SMMF by considering the presence of the offset. Section 2 describes the data and the wavelet method we use. A comparison of the results achieved without and with considering the offset is shown in section 3. Section 4 gives an interpretation of the offset and its implication. A discussion follows in section 5. Finally, we conclude this poster with section 6.

2. Data and Method

Two data sets are used in this study. The first set is one minute resolution solar mean magnetic field data obtained with SOHO/MDI. With a temporal resolution down to one minute and a spatial resolution 1024×1024 pixels over the whole field of view, the MDI observations have provided researchers with a good opportunity to study the rapid changes in the magnetic field of the sun in much detail.

The second data set is daily Wilcox Solar Observatory (WSO) mean magnetic field data, which have high accuracy with a zero level error less than 0.05 Gauss [*Scherrer et al.,*1977]. We make comparisons between WSO and MDI data to help understand the signals shown in the wavelet power spectra of SMMF time series.

Wavelet analysis is employed in our study which is focused on identifying and localizing the structures in SMMF time sequence data. Traditional Fourier transform is incompetent for this job since it can not recognize variations of power within a time series. Fortunately, wavelet analysis is applicable for searching such localized variations. By decomposing a time series into time-frequency space, one is able to determine both the dominant modes of variability and how those mode vary in time [*Torrence and Compo,* 1998]. In other words, the power of a time series can be localized in both frequency and time domain.

3. Results of Wavelet Analysis of MDI SMMF

As mentioned above in the introduction, there exists an offset in MDI data. In this section, we exhibit what effects are caused by this offset to the results of SMMF wavelet analysis. To do this, an exemplary time interval from 05:24 UT to 09:39 UT on 2 April, 1999, spanning $2^8 = 256$ minutes, is analyzed. In this period, three CMEs are reported in the LASCO CMEs list [http://lasco-www.nrl.navy.mil/cmelist.htm]. At 06:30 UT a narrow ejection occurred in the northwest part of the Sun. Then a bright loop front with a core showed up in the northwest again at 07:31 UT. Finally, a combination of two separate ejections was observed at 08:30 UT, one being an eastern narrow ejection and the other a deformed front in the northwest with a projected speed above 1100 km/s on the sky plane. Using the Morlet wavelet [*Torrence and Compo,* 1998], we analyze the MDI SMMF data before and after offset correction and show the results as follows.

3.1. Before Offset Correction

(1) Coincidence between peaks in wavelet power spectra and CMEs. Fig.1b shows the resulted wavelet power spectrum of the transformed mean field data. The period, representing the characteristic modes in the data, is given on the y-axis. Most of the spectral power is concentrated at the times of the three CMEs events indicated by arrows [*Boberg and Lundstedt*, 2000]. Furthermore, it is seen that all the three power peaks are located at a period of about 13 minutes, which is also shown with a peak standing well above the 95% significance level in Fig.1c. The reconstructed component of the SMMF with a wavelet scale ($\sim$ Fourier period) of 13.5 minutes is plotted in Fig.1a in red. One can see that the reconstructed component undergoes an oscillation with increasing amplitudes around the times of CMEs and dies away gradually afterwards. Again, from Fig.1d, we see that around the CME times, except the first CME, the average power has large values. Although only the peak corresponding to the 3rd CME exceeds the 95% significance level in power (see Fig.1b), the coincidence between the wavelet power peaks and CMEs is really striking.

(2) Coupling between quadrants. To localize the signals corresponding to CMEs, we divide the full solar disk into four quadrants and calculate a mean magnetic field for each quadrant. Then the four mean fields are processed with wavelet transformation. As shown in Fig. 2, the four power spectra exhibit surprising similarity, characterized by the major power peaks and overall structures. In the meantime, the four have all the essential features of the power spectrum of the full disk mean field shown in Fig.1b. Moreover, their reconstructed time sequence components (with a 13.5-minute scale) have almost identical time-dependent variations (Fig. 3).

3.2. After Offset Correction

(1) Coincidence between wavelet peaks and CMEs vanishes! As shown in Fig. 4b, no more distinct spectral power peaks coincide with CMEs. One should note that the absolute value of the power drops dramatically by two orders of magnitude, compared with Fig.1b. All the major features corresponding to CMEs in Fig.1 disappear! This presents a sharp contrast with the results obtained disregarding the existence of the offset.

(2) Correlation between quadrants is partly decoupled. Compared with the results shown in Fig. 2 and 3, the removal of offset from the original SMMF data also decouples the apparent correlation between different quadrants of the solar disk (see Fig. 5 and 6). There still exist correlations between the southern and northern hemispheres, that is to say, the mean fields of the northeast and southeast quadrants are very like, with similar power spectra (Fig. 5) and phases (Fig. 6), and so do the northwest and southwest quadrants. However, much difference show up between the eastern and western hemispheres, especially with anti-phase signals shown in Fig. 6.

4. What is the Offset?

(1) Signals in the offset. To search the sources of the signals corresponding to CMEs discussed above, we perform the same wavelet analysis to the offset during the same time interval on 02 April, 1999. The results are shown in Fig.7, in which it is surprisingly to identify all the major characteristics in Fig.1 related to CMEs, including the three distinct peaks in the wavelet power spectrum (Fig.7b). Associated with the results shown above in section 3.2, this indicates that the correlation between the MDI SMMF data and CMEs essentially comes from the offset, rather than from the real solar mean magnetic field.

(2) The possible origin of the MDI offset. Most likely, the MDI offset error comes from noise in the shutter open time at the part in 10^4 level which introduces noise in each filtergram. 8 filtergrams make each magnetogram. When the noise propagates through the magnetogram calculation it gives a few tenths of gauss noise that is essentially an additive value constant over each magnetogram but different for each.

(3) How is the offset computed? The offset error term is determined by examining the histogram of low field values for all the pixels of a magnetogram. We assume, without such an error, the magnetic field values of all the pixels should take a Gaussian distribution with a zero expectation value. Now, plot the histogram of the field values of all the pixels and make a Gaussian fitting. Then the resulted mean value has an offset from zero and this offset is just the error term. To correct the data, we just subtract this offset from the magnetic field value of each pixel to remove it.

(4) Comparison between MDI and WSO data. The MDI mean field data after offset correction match the WSO mean field very well (Fig. 8d). Whereas before this is done, the MDI mean field is poorly correlated with the WSO field (Fig. 8a). So we are again convinced that most of the signal in the correction term is real noise.

(5) Residual mean field signals in the offset. Inspection to the long-term variation of the offset reveals that there is still some residual mean field signals in the offset. One can see the long-term variability (with a period of about a half Carrington rotation $\sim$ 14 days) of the offset (Fig. 8b) and that of WSO mean field (Fig. 8a) agree quite well. In virtue of the denoising function of wavelet, we extract the residual mean field signals (Fig. 8b) and thus leave behind the pure white-noise offset error (Fig. 8c). Since the residual mean field signals in the offset are of long-period modes, the removal of such signals does not clear the 13-minute signals previously detected in the offset. Obviously, such short-period signals still remain in the pure white-noise offset.

Now, we can conclude that the offset, at least most of it, is real noise, though the source of such noise is not definitely clear so far. We will explore this question further in the following section.

5. Discussion

We note that there is still some correlation to times of CME for the 13-minute wavelet power spectrum peaks, although it is due to the offset. This leads us to speculate on conceivable sources for such signals.

(1) Why Signals in Phase? As we have seen above, before the offset correction, the mean field data of all quadrants of the solar disk have almost identical phases. Assuming they are real solar signals, a plausible explanation is that the whole sun undergoes a global oscillation. However, if the oscillation were due to some waves propagating throughout the whole sun, generated by CMEs, there should be some phase delay for different parts on the disk with different distances from the site where the CME occurred. This conclusion is in contrast with the result we obtain. No disturbance can propagate with a infinite speed to generate a global oscillation on the whole sun like a standing wave. We even calculate the mean field time series of small regions (down to 200×200 pixels) in each quadrant and it turns out that those signals are still coupled, having similar wavelet spectra and in-phase reconstructed time series. In the presence of the offset and its possible source, such in-phase signal phenomena are readily to be understood. Namely, if the interpretation of the offset as the MDI shutter open time error works, such error can be imposed to every pixel of the CCD so that every pixel has an in-phase variation, thus naturally producing the results we obtain in wavelet analysis.

(2) Statistically random coincidence? Paradoxically, there is still some coincidence in time between MDI offset wavelet peaks and CMEs? So we doubt there might exist some statistical coincidence. We randomly shuffle the SMMF time series for the 02 April, 1999 case. It turns out that no matter how the data are shuffled, there are always some wavelet peaks between scales of 4 and 32 minutes. Also, we have checked some other CME-free time intervals and found that there exist some wavelet power spectrum peaks too, not necessarily with a scale of 13 minutes. Without doing a systematic statistical study, we can not make any definite conclusion on this point, but leave this open to further study.

(3) Instrumental error? As shown in the study of Boberg and Lundstedt [2000], 27 CMEs out of 74 show good coincidence with a wavelet power spectrum peak at a scale of 13 minutes. It seems above a statistically random level. Could it be any instrument response to high energy particles hitting MDI from flares associated with CMEs? It might be due to a source of 14 minute signal in the SOHO pointing, which once occurred in 1996. Unfortunately, after examining the SOHO fine pointing data for the time interval in question, we find no correlation to the 13-minute signals in the offset. However, some unknown instrumental errors could be responsible for such 13-minute signals, which also needs further exploration.

6. Summary

(1) Results of data analysis. By examining the MDI solar mean magnetic field data we have the following results.

(a) Before the offset correction, the peaks of wavelet power spectra of the full-disk SMMF time series coincide with the onset times of coronal mass ejections. The reconstructed mean fields of the four quadrants of the solar disk have almost identical phases and very similar time-dependent variations.

(b) After the offset correction, the coincidence between the peaks in wavelet power spectra and CMEs vanishes. It turns out that the signals related to CMEs are in the offset error term.

(c) The offset error most probably comes from noise in the MDI shutter open time, but not likely related to the SOHO pointing error.

(2) Remaining questions. Through our discussion above, there are still several open questions.

(a) Could the fraction of those CMEs coincident with wavelet peaks be on a statistically random level?

(b) How can the CME-related signals be enciphered in the offset?

(c) Is there any instrument response to CMEs which is in part introduced to the offset?

Acknowledgments. MDI research is supported by NASA contract NAG5-3077 at Stanford University. Wavelet software was provided by C. Torrence and G. Compo, and is available at URL: http://paos.colorado.edu/research/wavelets/. Also, the authors are grateful to the SOHO/LASCO team for providing CME lists, and to Dr. Sasha Kosovichev, Dr. Yi-Hua Yan, and Dr. Lundstedt Henrik for enlightening discussions.

REFERENCES

Boberg, F. and H. Lundstedt, Coronal mass ejections detected in solar mean magnetic field, *Geophys. Res. Lett., 27,* 3141-3143, 2000.

Luhmann, J. G., J. T. Gosling, J. T. Hoeksema, and X. P. Zhao, The relationship between large-scale solar magnetic field evolution and coronal mass ejections, *J. Geophys. Res., 103,* 6585-6593, 1998.

Mordvinov A. V. and L. A. Plyusnina,Cyclic changes in solar rotation inferred from temporal changes in the mean magnetic field, *sol. Phys., 197,* 1-9, 2000.

Scherrer, P. H., J. M. Wilcox, V. Kotov, A. B. Severnyi, and R. Howard, The mean magnetic field of the sun: Method of observation and relation to the interplanetary magnetic field, *sol. Phys., 52,* 3-12, 1977.

Torrence, C. and G. P. Compo, A practical guide to wavelet analysis, *Bulletin of the American Meteorological Society, 79,* No. 1, 61-78, 1998.

Zhao, X. P., J. T. Hoeksema, and P. Scherrer, Application of SOI-MDI images: 1. Changes of large-scale photographic magnetic field and the 6 January 1997 CME, April 8-9, 1997, ISTP Workshop 1997.

This preprint was prepared with the AAS LaTeX macros v5.0.