



Three Cycles of the Solar Toroidal Magnetic Field and This Peculiar Minimum

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Abstract

Thirty-four years of WSO (Wilcox Solar Observatory) and thirteen years of SOHO/MDI (Michelson Doppler Imager) magnetograms have been studied to measure the east-west inclination angle, indicating the toroidal component of the photospheric magnetic field. This analysis reveals that the large-scale toroidal component of the global magnetic field is antisymmetric around the equator and reverses direction in regions associated with flux from one solar cycle compared to the next. The toroidal field revealed the first early signs of cycle 24 at high latitudes, especially in the northern hemisphere, appearing as far back as 2003 in the WSO data and 2004 in the MDI data. As in previous cycles, the feature is moving gradually equatorward. Cycles overlap and the pattern associated with each cycle lasts for about 17 years. Even though the polar field at the current solar minimum is significantly lower than during the three previous minima, the toroidal field pattern is largely the same.

Toroidal Field

The solar dynamo model predicts that the toroidal and poloidal components of the global magnetic field are regenerated from one other. The poloidal field is transformed into the toroidal field from differential rotation (the Ω -effect), and the toroidal field is twisted into the poloidal field (the α -effect). These alternate and repeat in a 22 year cycle.

This toroidal field component was previously measured by Shrauner and Scherrer using WSO data over the period of 1977-1992, and provided evidence for an extended activity cycle of 16-18 years. Ulrich and Boyden also measured the toroidal field using Mount Wilson data from 1986-2004 and verified the dynamo model for the creation and reversal of the toroidal field.

Why Now?

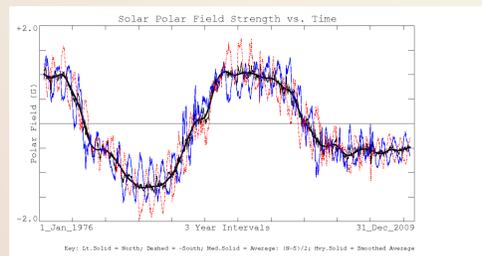


Fig 1 - The poloidal field strength measured from WSO data from 1976-2009. The first complete cycle has a trough of -1.3 gauss, and the second one has a peak of +1.0 gauss. The latest cycle, which we are still experiencing, has a magnitude of 0.6 gauss, which is significantly less than the previous two.

Since we are facing a peculiar solar minimum, we want to investigate whether there is also some peculiar activity in the toroidal fields leading up to the minimum. Three solar cycles of WSO data are available to us now, as well as a complete cycle of MDI data.

Inclination Angle

We first generated maps of the inclination angle for both the positive and negative field polarities using the WSO magnetograms and the MDI synoptic maps. This is done by tracking the line of sight B for a given Carrington coordinate as it crosses the disk.

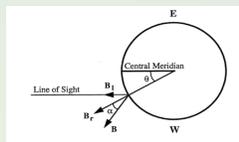


Fig 2 - Diagram of the field components and angles as viewed from the north pole. The east-west inclination field angle α is the angle between B and B_r . We measure BI as it crosses the disk over various θ 's.

We can fit the measurements of BI for different longitudes to the following equation to calculate the average east-west inclination angle of the field, α :

$$B_l(\theta) = A \cos(\theta + \alpha)$$

Where A is proportional to the true magnetic field. A derivation of this fit gives the following formula:

$$\tan \alpha = \frac{(\sum_i B_i^2 \cos \theta_i)(\sum_i \sin \theta_i \cos \theta_i) - (\sum_i B_i^2 \sin \theta_i)(\sum_i \cos^2 \theta_i)}{(\sum_i B_i^2 \cos \theta_i)(\sum_i \sin^2 \theta_i) - (\sum_i B_i^2 \sin \theta_i)(\sum_i \sin \theta_i \cos \theta_i)}$$

Example

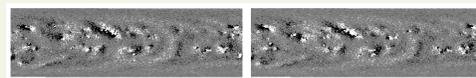


Fig 3 - MDI synoptic maps for Carrington rotation 1975 taken at 30°E (left) and 30°W (right). The magnetic field values (in gauss) in these two maps are very similar, but the differences are important. These differences allow us to calculate the east-west inclination angle.

We fit the values of BI and θ taken from the synoptic maps into the equation for α to generate maps of the inclination angles. We generate two separate maps for each Carrington rotation based on the sign of BI. One is for BI's with positive polarity and one for the negative polarity. Finally, we take the difference of these two maps to get the net inclination plots for each Carrington rotation.

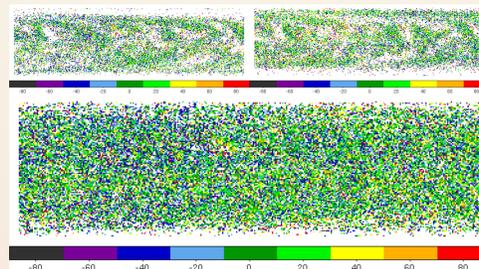


Fig 4 - Inclination angle maps for Carrington rotation 1975 (in degrees). The difference is taken between the positive polarity map (top-left) and the negative polarity map (top-right) in order to create the inclination difference map (bottom). This inclination difference map tells us the east-west direction of the magnetic field at each point on the sun for this Carrington rotation.

Results

The inclination difference maps are then combined to create summary averages of inclination over time, using both WSO and MDI data. From these averages we then made contour plots, as well as line plots for each hemisphere. The WSO data spans 34 years, which gives us three solar cycles of data.

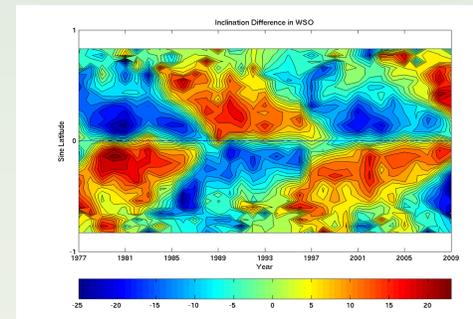


Fig 5 - Contour plot of the summary averages of inclination differences from 1977-2009 using WSO data. There are almost three complete cycles of inclination differences, and the extended solar minimum can be seen in both the duration of cycle 23 near the equator, as well as in the rate at which cycle 24 moves equatorward. Cycle 24 first emerges in 2003 in the north at high latitudes, and looks almost identical to the last two cycles.

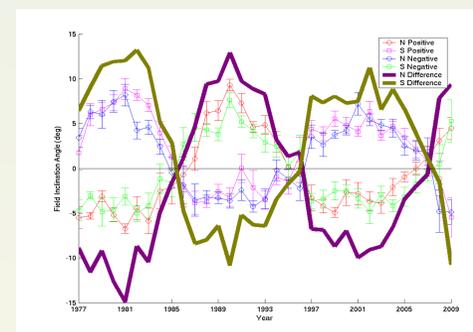


Fig 6 - Line plot of the summary averages of inclination differences for each hemisphere from 1977-2009 using WSO data. Again, we can see nearly three full cycles. Another indication of cycle 24's emergence is in 2007, when the average northern and southern field angles cross zero. This is when most of the weak field regions in each hemisphere have reversed their toroidal field component. Oddly enough, the extended minimum does not appear in this figure, as the time between zero crossings this cycle is the same as in the last cycle.

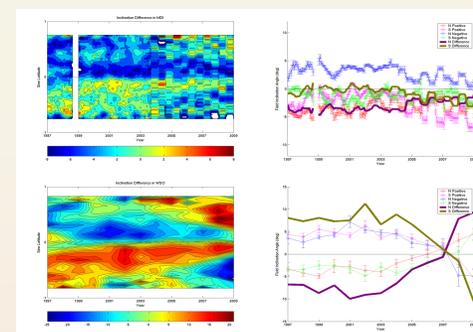


Fig 7 - The plots generated from MDI (top) were only for one cycle, spanning from 1997-2009. The general shape of the contour map matches WSO's for this time period (below). Just like in the WSO data, we see the extended cycle 23, and the emergence of cycle 24 in 2004 in the north at high latitudes. The line plot is not as clear for MDI, but we do see an intersection between the northern and southern field angles around 2007, which matches the WSO data.

However, the values from MDI are significantly different from WSO, and is most apparent in the southern hemisphere. This is due to the calibration of the CCD. Much of the data after 2003 had to be removed due to SOHO's three month rolling period, which is why the data appears irregular.

Problems with MDI Data

After creating the summary averages of the inclination differences over the life cycle of the MDI data, we noticed a regular disturbance in the signal after 2003. We concluded that this was a result of SOHO periodically rolling from 0° to 180°. Our solution was to remove the data from when SOHO was rotated 180° (Fig 8). We believe that these differences come from a noise gradient in the bottom half of the CCD, which is due to the relative alignment of the filters that introduce cross talk between the Doppler signal and the magnetic signal. This gradient in sensitivity might be related to the offset in the inclination angles we see (Fig 7).

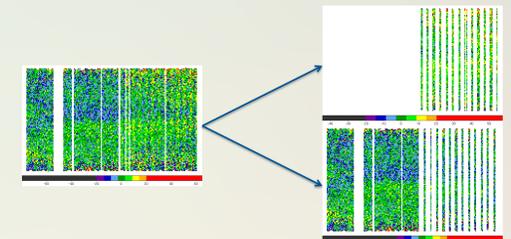


Fig 8 - The summary averages for the inclination differences using MDI data from 1997-2009 (left). About halfway through, we find a regular disturbance in the data, starting in July 2003. After determining that this was from SOHO's periodic rolling, we removed the data from when SOHO was upside down (top-right) and kept the data from when SOHO was right side up (bottom-right) to use in our plots.



Fig 9 - Noise plot of a large number of averaged magnetograms from one of the dynamics runs. We believe that the noise gradient in the bottom half causes some distortions in our inclination angle measurements.

Conclusion

From the inclination difference summary averages, we detected the emergence of cycle 24 some time during 2003-2004. This emergence pattern is very much like the pattern observed in the previous two cycles. The emerging inclination angles, which are related to the toroidal fields, are consistent with those from the previous cycles, indicating that the toroidal field has little effect on both the duration of the following solar minimum and the generation of the poloidal fields at the concurrent minimum. However, if the toroidal field is generated from the preceding poloidal field, the next cycle's toroidal field will be weak. Also, the inclination angle that indicates the toroidal field at the sun's surface is only a distant reflection of the toroidal field that is present wherever the true solar dynamo is acting. Particularly in the MDI data, the weak field regions that contribute to the analysis may also reflect the spatially averaged characteristics of a surface dynamo process whose connection to the solar cycle dynamo is uncertain. Further work needs to be done to solve the calibration issues of MDI.

References

- Shrauner, J. A., & Scherrer, P. H. 1994, Sol. Phys., 153, 131.
- Ulrich, R. K., & Boyden, J. E. 2005, ApJ, 620, 123.