Simulating Cyclic Evolution of Coronal Magnetic Fields using a Potential Field Source Surface Model Coupled with a Dynamo Model

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Introduction and Motivation

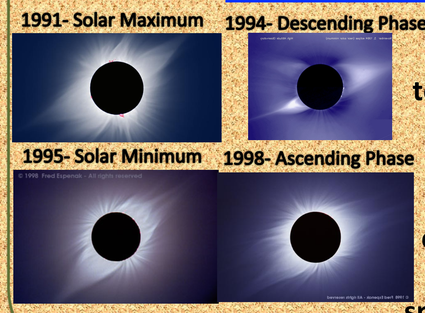


Figure 1

Shown here are composite images of the corona during total solar eclipse in 4 different phases of solar cycle 22. The Sun's corona is governed by magnetic fields. Why do the coronal fields change through the solar cycle, from a spherically symmetric maximum to a dipole minimum?

Mathematics

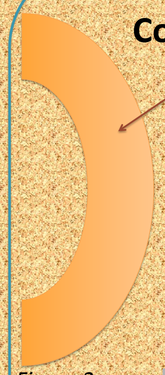


Figure 2

Dynamo Equation

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B}\right) + \eta \nabla^2 \vec{B} + S \qquad \vec{B} = \nabla \times A\hat{e}_\phi$$

- We use axisymmetry (no ϕ dependence)
- Above photosphere (r=R) we take free-space assumptions, i.e. η=∞
- v=0 at r>R
- Thus, large-scale coronal fields are determined by Laplace's Equation

$$\left(\nabla^2 - \frac{1}{r^2 \sin^2\theta}\right)A = 0$$

Solutions ⇨

$$\sum_{m=1}^{\infty} \frac{a_m^1}{r^{m+1}} P_m^1(x) = A$$

Some Examples of Associated Legendre Polynomials of the First Order

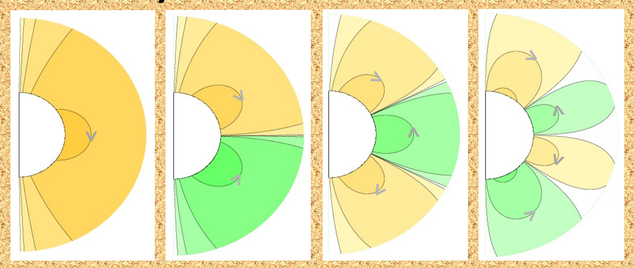


Figure 3 Field lines for m=1,2,3,and 4.

Results

Taking linear combinations of these $P^1_m(x)$ gives solutions that can match more complex structures of the solar corona.

$$A = \frac{1.3P_1^1}{r^2} - \frac{5P_2^1}{r^3} + \frac{10P_3^1}{r^4} \qquad A = \frac{1.6P_1^1}{r^2} - \frac{5P_2^1}{r^3} + \frac{32P_3^1}{r^4} - \frac{200P_4^1}{r^5}$$

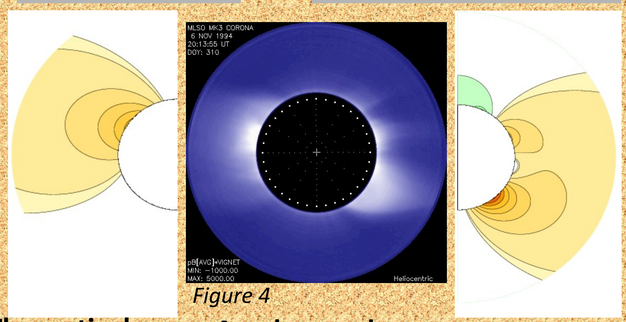


Figure 4

Theoretical potential field solutions for west limb | An observed corona from MLSO Data | Theoretical potential field solutions for east limb

Figures 5a and 5b

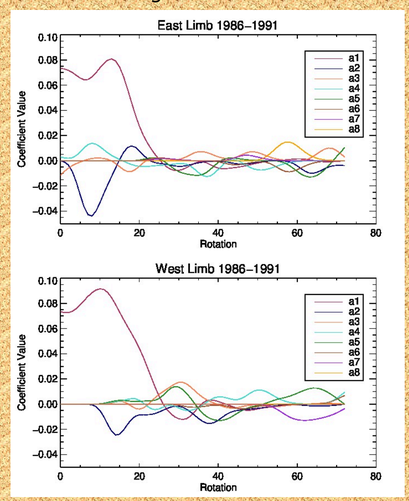


Figure 6

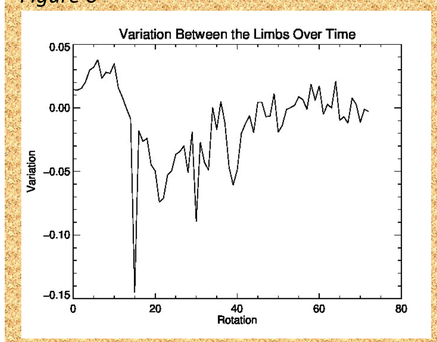


Figure 7a

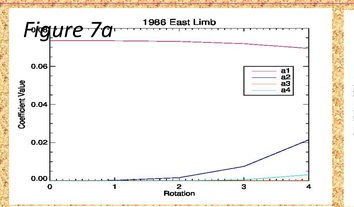


Figure 7e

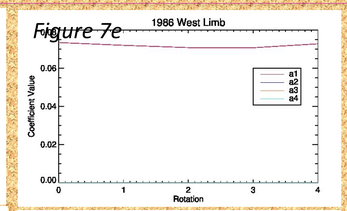


Figure 7b

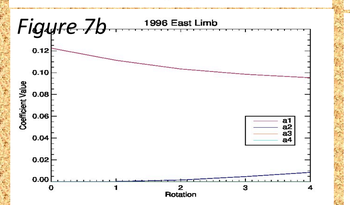


Figure 7f

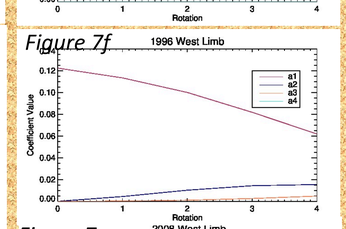


Figure 7c

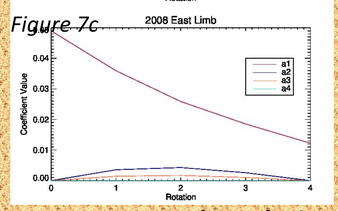
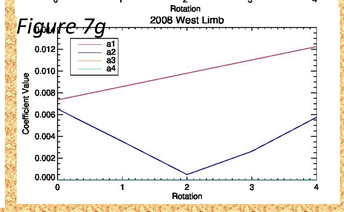
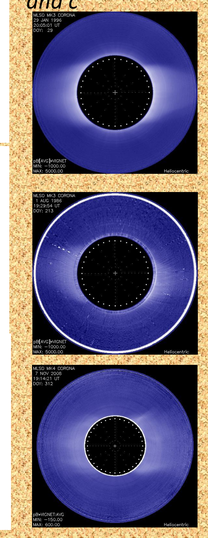


Figure 7g



Figures 8a,b, and c



Using the same technique as above, we computed solutions to corona images from 1986 to 1991, where each image was one Carrington rotation apart, and plotted the relative amplitude of each polynomial term as a function of time. We see in Figures 5a and b:

- during minimum, both limbs are dominated by the dipole term, as was reported by previous authors (Wang and Sheeley, 2003)
- over time, this term begins to fade and higher order multipoles become dominant
- furthermore, computing the difference between east limb and west limb coefficients, we see in Figure 6 the two limbs are not perfectly symmetric, with the difference being greatest at minimum, showing a ϕ dependence that changes with time

When we compute the relative amplitude of each polynomial term in three successive solar minima at the end of cycles 21, 22, and 23, we should expect predominantly dipolar structure with small amounts of multipoles that increase as we enter the ascending phase. We found a sustained dipole structure over 5 Carrington rotations in both 1986 and 1996, with high a1 coefficients for both east and west wings; higher multipole coefficients were very small. However, near the end of 2008 multipoles were present with significant amplitudes. The corona never went into a perfectly dipolar configuration in both limbs for any rotation. The corona behaved in a different way from the other minima. There were indications of such different behavior in polar coronal holes, solar wind, and cosmic rays (e.g. Gibson et. al 2009, deToma 2011, Dikpati 2013). In order to understand why the corona behaved in this way in the last minimum, we explore whether north south asymmetry in the surface source has any impact.

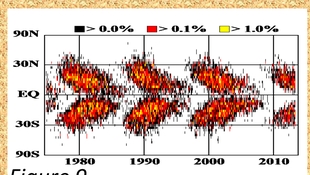


Figure 9

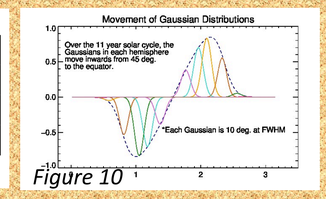


Figure 10

Figure 9 shows that cycle 23 had asymmetric butterfly wings in the north and south compared to cycles 21 and 22. A typical surface source for the dynamo can be represented as a migrating Gaussian band, as shown in Figure 10.

We simulate the coronal magnetic field from the coupled model (dynamo coupled with a potential field source surface model, Altschuler and Newkirk 1969) using a symmetric surface source and find that this produces a typical spherically symmetric solar maximum corona and a typical dipolar solar minimum corona (see Figure 11). However, for a surface source with a large north-south asymmetry, our simulation produces a solar maximum and minimum corona as shown in Figure 12.

Figure 11

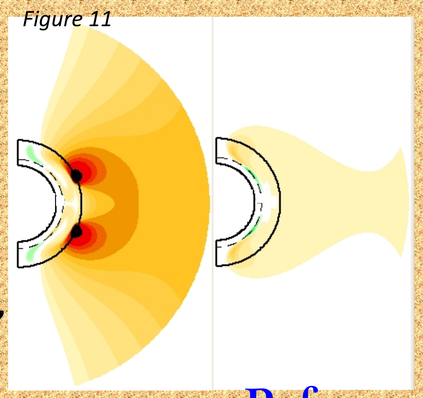
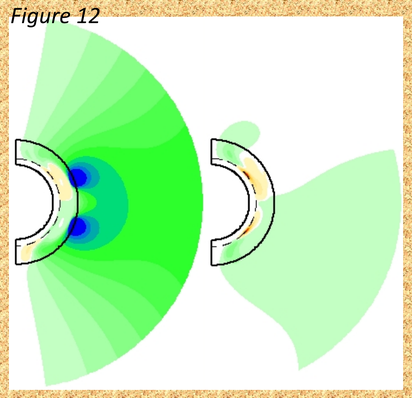


Figure 12



Limitations of the Model

- Axisymmetric models cannot explain the difference between east and west limbs
- Reproducing more complex coronal structures such as helmet streamer is beyond the scope of this model

Conclusions

- By matching the theoretical solution from the potential field model with the MLSO observations, we first reproduce previous results that the solar minimum corona is primarily dipolar whereas higher multipoles come in during solar maximum
- The difference between east and west limbs is greatest during solar minimum and smallest during solar maximum
- Comparing the three past minima (1986, 1996, and 2008), we find that for five rotations in 1986 and 1996 the corona remained in a dipolar state, but that in 2008 there was no single rotation in which both limbs exhibited dipolar structure
- Simulating the evolution of the solar corona using a potential field source surface model by implementing the dynamo generated cyclic field as the boundary condition, we find that north-south asymmetry could be one of the sources for the departure from dipole corona during the end of cycle 23

References

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