A Model of Coronal Helmets with Prominences

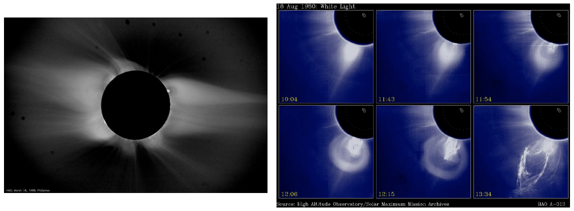
E. Greenfield, Y. Fan, B. C. Low
National Center for Atmospheric Research, High Altitude Observatory

Abstract

The process by which coronal mass ejections are accelerated from the surface of the sun is not well understood. A possible explanation is that a solar prominence may serve to anchor the magnetic field associated with a coronal helmet allowing magnetic energy to grow beyond the open field limit. Once this limit is surpassed the helmet may relax to a less energetic open field state and be expelled as the CME. In order to analyze this situation, a partially open magnetic field representing an idealized 2D coronal helmet is constructed based on the conditions required of a potential magnetic field. A prominence is then introduced as a vertical sheet along the equator extending from the surface to some height r_{sh}. Some amount of magnetic flux is then set to thread through the prominence sheet. The magnetic energy resulting from this partially open magnetic field configuration is then calculated using the Virial Theorem. The amount of flux set to thread through the prominence is directly related to the energy of the overall field as well as the mass contained along the prominence. The calculated energy E is then compared to the energy of the completely open field E_{open}. If the ratio E/E_{open} is greater than 1, the helmet is energetically capable of opening completely. If the mass required to meet the condition $E/E_{open} > 1$ is within observational limits, we can conclude that this is a viable mechanism for storing the magnetic energy needed to drive a CME.

Coronal Helmets and Coronal Mass Ejections (CME's)

Coronal helmet streamers are large scale structures in the solar corona seen above the solar limb during a solar eclipse or with a coronagraph. They correspond to regions of closed magnetic field surrounded by the open field stretched out by the solar wind. Prominences are often situated beneath helmet streamers. The magnetic field of a coronal helmet can spontaneously erupt, resulting in a coronal mass ejection. Besides opening up the previously closed magnetic field, a CME typically eject a mass of 5.e15 g at a median speed of 450 km/s. Free magnetic energy stored in the helmet magnetic field is believed to be the energy source for driving the CME.



Source: High Altitude Observatory/Solar Maximum Mission Archives

Images courtesy of the NCAR High Altitude Observatory

Methodology: Modeling a Coronal Helmet

We construct an idealized 2D axisymmetric magnetic field model for a coronal helmet that reflects its basic partially-open field configuration. The magnetic field is assumed to be in the (r, θ) plane and thus can be written in the following form which guarantees that the field is divergence free:

$$\vec{B} = \vec{\nabla}\times\left(\frac{A}{r\sin\theta}\hat{\phi}\right)$$

where *A* is a function of (r, θ) and contours of constant *A* correspond to magnetic field lines. Furthermore, the magnetic field is assumed to be everywhere potential except the possible presence of two current sheets along the equatorial plane: an outer current sheet gives rise to the open field configuration outside of the helmet dome, and an inner current sheet provides support for a prominence sheet. North-south symmetry is assumed for the global magnetic field and we solve for *A*(r, θ) in the northern hemisphere domain in which the field satisfies the potential field equation:

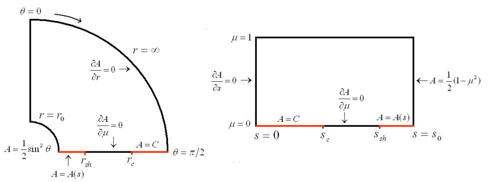
$$\vec{\nabla}\times\vec{B} = 0 \Rightarrow$$

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

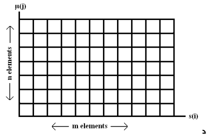
By performing a change of the independent variables, the domain is transformed from the infinite (r, θ) domain into a finite, rectangular domain of (s,μ) , and we instead solve the following transformed equation:

$$s^2\frac{\partial^2 A}{\partial s^2} + 2s\frac{\partial A}{\partial s} + (1-\mu^2)\frac{\partial^2 A}{\partial\mu^2} = 0 \qquad \text{where} \quad s = r_0^2/r, \quad \mu = \cos\theta$$

The following diagram helps to visualize the transformation of the domain and describes the imposed boundary conditions for the field.



The (s,μ) plane is then divided into a grid so the differential equation can be discretized and solved numerically.



The derivatives in the equation are replaced by centered finite differences based on the general forms given below:

$$\frac{\partial^2 y}{\partial x^2} = \frac{y(x+\Delta x) - 2y(x) + y(x-\Delta x)}{\Delta x^2}$$

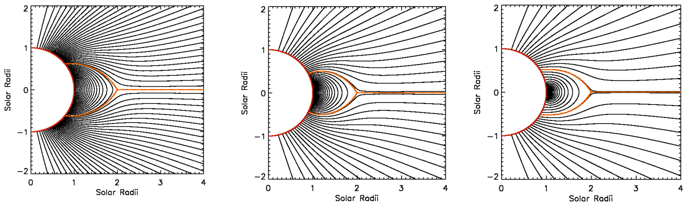
$$\frac{\partial y}{\partial x} = \frac{y(x+\Delta x) - y(x-\Delta x)}{2\Delta x}$$

The above discretization converts the linear partial differential equation together with the imposed boundary conditions given in the above diagram into a system of linear algebra equations, which is then solved using the conjugate gradient method for sparse linear systems.

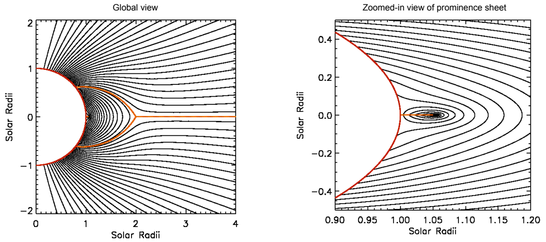
Results

Having solved the resulting matrix equation for A(s,μ) we remapped the solution back to (r, θ). The solution is then plotted as a contour map of A which shows the magnetic field lines. The top of the helmet dome is a triple point where **B** → 0 in this idealized model. The following figures show three different solutions illustrating how the shape of the helmet dome can change due to the change of normal flux distribution on the solar surface:

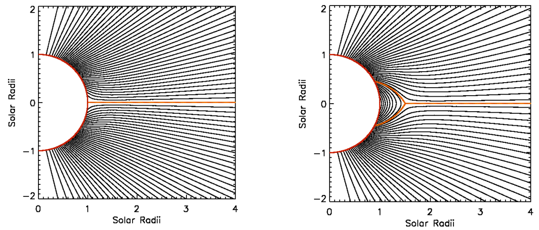
Left: Dipole Distribution
Middle: Dipole with moderately concentrated flux at equator
Right: Dipole with extremely concentrated flux at equator



To achieve magnetic energy storage beyond the open field limit, we introduce an additional inner current sheet representing a thin sheet of prominence. A set amount of closed magnetic flux detached from the solar surface thread through this inner current sheet and are anchored in equilibrium by the weight of the prominence mass. Such a solution is shown below:



In the case above, the amount of flux threading through the sheet is 15% of the total flux through the solar surface. This amount of flux threading through the inner current sheet directly affects the prominence mass and the total magnetic energy: the greater the amount of flux, the greater the prominence mass and the magnetic energy. As the mass of the prominence sheet grows, the energy built up in the helmet structure can exceed the open field limit. We envision a scenario where the prominence equilibrium supported by the magnetic field becomes unstable such that most of the prominence mass drains to the solar surface. As a result the detached inner field loses its anchor and erupts, opening up the helmet field and expelling the mass of the helmet dome as a CME. In the extreme case, the helmet magnetic field opens up completely during a CME, before it again returning to a usually smaller partially open helmet configuration due to magnetic reconnection.



Required Prominence Mass

In this specific model, we find that In order for the magnetic energy to exceed the open field limit, the flux threading through the inner current sheet needs to be > 5% of the total surface flux and it requires a minimum of **1.31 e16 g** prominence mass to anchor the field in equilibrium. This value is within the range of the observed prominence masses.

Resources

Fong, B., B. C. Low, and Y. Fan. "Quiescent Solar Prominences and Magnetic-Energy Storage."

Low, B. C., B. Fong, and Y. Fan. "The Mass of a Solar Quiescent Prominence."

Low, B. C. "Models of Partially Open Magnetospheres with and without Magnetodisks."

William, Press H., and Brian P. Flannery. Numerical Recipes in Fortran 77. 2nd ed. 1992.

Acknowledgements

Greenfield is supported by the Laboratory of Atmospheric and Space Physics summer REU program. The National Center for Atmospheric Research is sponsored by the National Science Foundation