MODELING A SIMPLE CORONAL STREAMER DURING WHOLE SUN MONTH

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ABSTRACT

We model the simplest, most symmetric solar minimum streamer structure observed during the Whole Sun Month (WSM). We first use a Van de Hulst inversion to determine coronal electron density profiles and scale-height temperature profiles using white light coronal images from SOHO/LASCO and the HAO/MLSO coronagraphs. This method is of limited use in understanding coronal force balance, however, so we next apply the axisymmetric magnetostatic model of Gibson, Bagental, and Low (1996). With this model we can quantify a density, temperature, and magnetic field distribution in self-consistent force balance, using both the coronal white light data and photospheric magnetic field data from the Wilcox Solar Observatory as the observational constraints on the model. This magnetostatic model, applied in a regime where solar wind velocities are below the sonic point, is currently the only model of global physical force balance (including MHD simulations) to predict a density distribution in the large scale corona (i.e. 1.2 – 2.5R\(_{\text{sun}}\)) that matches white light observations to within observational error. We present the densities and temperatures attained by the Van de Hulst and magnetostatic models, and compare the magnetic field predicted by the magnetostatic model to a potential field extrapolation from the photosphere.

Key words: Coronal densities; Coronal magnetic fields; Whole Sun Month

1. INTRODUCTION

During solar minimum, the large-scale corona is at its simplest and most stable, maintaining a structure of primarily equatorial helmet streamers and polar coronal holes over several solar rotations. Although the corona does experience dramatic transient changes, such as when a coronal mass ejection blows a huge quantity of mass outwards, it is to this stable background structure that the corona returns. If we consider the large-scale solar minimum corona to be a stable background upon which dynamic events are perturbations, we can take advantage of the stability and simplicity of the solar minimum structure and seek a quantitative global description of steady-state velocities, densities, temperatures and magnetic field in the corona. Such a description is directly relevant to the SOHO mission’s scientific goals. Coronal velocities are obviously relevant to understanding solar wind acceleration, but the large-scale magnetic field structure is also fundamental to solar wind studies. Knowledge of where the coronal field is open and where it is closed, as well as an understanding of how the expansion of the field varies from a purely radial expansion, are essential to studies of how the coronal field is related to fast and slow solar wind passing the earth. Moreover, a well-defined temperature and magnetic field structure would provide clues to coronal heating.

The Whole Sun Month (WSM) campaign coordinated many ground-based and space-based instruments to look at a full rotation (August 10 - September 8, 1996) of the solar minimum corona. One of the main goals of the campaign was to study and quantify the large-scale
physical properties (i.e. densities, temperatures, velocities, and magnetic field) in the solar minimum corona between 1 and 3 solar radii. The WSM rotation turned out not to have the simplest possible solar minimum structure of polar holes and equatorial streamers - in fact, a large equatorial coronal hole extension disrupted one of its hemispheres. However, the other hemisphere was simpler, and coronagraph and magnetograms indicate that there was little variation of the equatorial streamer structure with longitude for 45 degrees on either side of the West limb as observed on August 17, 1996 (see Figure 1). Thus, we chose to begin our analysis by modeling this subset of WSM data with azimuthally symmetric models.

2. THE MODELS

The first model we applied was that of Van de Hulst (Van de Hulst 1950). Coronagraphs such as SOHO/LASCO C2 and HAO/MLSO K-coronameter observed polarized brightness, or $pB$, which is photospheric white light scattered off of coronal electrons. This quantity is directly related to coronal electron density by

$$pB(x, y) = \int_{1.0}^{\infty} C(r) n_e(r, \theta, \phi) ds.$$  (1)

Here $n_e$ is the electron density, $C(r)$ is the Thomson scattering function, and the integral is carried out along the line of sight, $ds$. Van de Hulst showed that if the latitudinal and azimuthal gradients in electron density were weaker than the radial gradients, the equation becomes an invertible Abelian integral. We fit radial power laws to the observed radial profiles of $pB$, and from these deduced radial power laws defining the electron density. We then calculated a scale-height temperature profile, assuming radial hydrostatic equilibrium and the ideal gas law.

The Van de Hulst method provides information about electron density in the corona, and even some information about coronal temperature. However, it says nothing about the coronal magnetic field. Unfortunately, the coronal plasma is so tenuous that it is not generally possible to measure its magnetic field. A determination of the coronal field therefore requires some sort of physical model. One approach to modeling the coronal field is to assume that it is force free or potential, and to extrapolate the observed photospheric field. This approach is inconsistent with observations of coronal white light: without magnetic forces, no latitudinal gradients in density would be possible and the white light corona would appear spherically symmetric. Thus the Van de Hulst method describes the density variation but no field, while a potential field extrapolation describes a field but no density variation.

Our second model allows us to model both the field and the density variation in self-consistent force balance. Because of the high conductivity of the corona, we expect the coronal electron density to follow magnetic field lines. We therefore used the white light images to constrain the coronal magnetic field. We did this via a model that finds a solution to the axisymmetric magnetostatic force balance equations (Gibson, Bagenal, & Low 1996 (GB&L)). This model allows both volume currents throughout the corona and current sheets surrounding the helmet streamer and above the streamer at the equator. Magnetic field, density, and temperature are all expressed in terms of model parameters. We chose parameters which simultaneously reproduced a $pB$ distribution matching the combined HAO/MLSO and SOHO/LASCO C2 data and matched the dipole magnetic field strength observed on August 17, 1996 by the Wilcox Solar Observatory. GB&L has shown that current sheets around the helmet streamer can balance the coronal density gradients observed, and that bulk currents are a secondary effect. This is consistent with 3-D numerical MHD simulations of the corona (Linker et al. 1990, Pneummann & Kopp 1971).

3. RESULTS

Figure 2 shows the modeled $pB$ corresponding to the observations of Figure 1. The basic polar coronal holes and equatorial streamer are reproduced by both the Van de Hulst and GB&L models. Since the GB&L model is symmetric about the equator, it does not reproduce the slight observed asymmetry (we have fit this model to the southwest quadrant data only.) The GB&L model, however, can model the sharp boundary of the coronal streamer as seen in Figure 1, because of the jump in density across the current sheet surrounding the streamer (necessary to keep total pressure continuous across the boundary). The VdH model, since it assumes no large gradients in the latitudinal direction, cannot model this.

Figure 3 shows radial profiles of $pB$ at the west limb equator, south-west mid-latitude, and south pole. The actual observations are shown by the symbols (MLSO: green diamonds; LASCO: purple diamonds), and the model fits are shown by the lines (Van de Hulst: blue; GB&L: red). The Van de Hulst fit can match the radial variation of the $pB$ very well, since this variation is directly modeled by a four parameter power law fit to each radial profile of $pB$ - thus, a total of 4 X 180 = 720 parameters are used to fit radial profiles along the west limb at one degree intervals, resulting in the fit shown in Figure 2. The GB&L model depends on only five parameters, and
so not surprisingly cannot match the data as well. In particular, it creates a $pB$ radial profile at the pole that appears somewhat too low for heights less than $1.3R_{\odot}$, and somewhat too flat for heights above $2.2R_{\odot}$. We would expect the model to break down where the magnetostatic assumption is invalid, and recent work (Habbal et al. 1994) finds a critical point as low as $3.16R_{\odot}$ at the poles. Moreover, this model depends on only one scale length for currents, so we do not necessarily expect it to model the brightening in the lower corona. However, while taking these points under consideration, we point out that the GB&L $pB$ model profiles match the Van de Hulst model extremely well at the equator, and still lie within observational error bars at the pole and mid-latitude. (See Gibson & Bagenal 1995 for discussion of MLSO error bars and model scale lengths.)

Figures 4 and 5 show the electron density and temperatures corresponding to the $pB$ model fits of Figure 3. The densities vary somewhat at mid-latitude and the poles: this is reflected in the difference in temperature also (note that the density profiles are plotted on log-linear plots, but the temperatures are plotted on linear plots.) We need to emphasize here that neither model solves the energy equations. As stated above, the temperatures from the Van de Hulst are calculated assuming that the electron density is in radial hydrostatic equilibrium. This, along with the ideal gas law and an assumption that the temperature is zero at infinity allows us to predict a temperature distribution. Radial hydrostatic equilibrium is probably not a very good assumption at the poles where wind velocity becomes important, and at the mid-latitudes where a significant current sheet may exist. The GB&L model temperatures are a product of a simplified analytic form of the equations of magnetostatic force balance (see Bogdan & Low 1995 for discussion). Since both models depend on the ideal gas law, they assume a single fluid and so predict an average temperature of the coronal gas rather than a true electron temperature. Recent work (Habbal et al. 1994) implies significant differences between electron and proton temperature as low as $1.2R_{\odot}$ in coronal holes.

Figure 6 shows the magnetic field lines for our fit to the white light structure. Figure 7 shows the coronal field calculated from a potential field extrapolation of the photospheric field and assuming a source surface where the field lines are radial as an upper boundary condition (observations are from August 19, 1996, which is within our $\pm 45$ degrees of symmetry). The dipole field strengths of the two magnetic fields are the same. The closed field region of the potential extrapolation intersects the photosphere at latitudes consistent with the lower streamer boundary seen in the lower corona (seen in the EIT and lower HAO/MLSO data of Figure 1). Since the GB&L model is limited to a single scale length, we do not expect it to be able reproduce the low down, smaller scale structures seen in the photospheric extrapolation. Instead we have concentrated on modeling the large-scale field in the helmet streamer of the outer corona ($>1.2R_{\odot}$). Only a magnetic dipole term, coupled with current sheets around the closed field region, is needed to reproduce this white light structure. The potential extrapolation closed field region cannot match the helmet shape of the outer corona (seen particularly in the LASCO/C2 data of Figure 1) as well as the GB&L model partly because it uses a source surface at $2.5R_{\odot}$ as its upper boundary condition. The GB&L model has a current sheet at the equator as an upper boundary condition, which pulls the field into a cusp matching the white light structure. The current sheets surrounding the helmet streamer then introduce a magnetic pressure jump which requires a gas pressure jump to maintain a continuous total pressure, creating the density gradient to match white light observations.
4. CONCLUSIONS

Using two models, the Van de Hulst and GB&L, we have quantified density and temperature in the corona between approximately 1.2 $R_{\odot}$ and 2.5 $R_{\odot}$. We have used coronal white light observations as the main constraint for both models. The electron densities predicted by the two models are basically comparable, although the GB&L model can reproduce sharp gradients in density across the helmet streamer boundaries. The temperatures predicted by the models are based on assumptions which can be tested by directly comparing these predictions to UVCS, SUMER, and CDS observations of coronal temperatures.

The GB&L model predicts a density distribution in magnetostatic force balance with a dipolar magnetic field. We plan to test the magnetostatic assumption of the GB&L model by comparing to wind velocities predicted from UVCS observations. The closed magnetic field lines predicted by the GB&L model are defined to overlay the white light helmet streamer. We do not attempt to match the magnetic structure in the lower corona emphasized by a potential field extrapolation. The potential field extrapolation, however, is inconsistent with white light latitudinal gradients that are observed. The GB&L model creates these gradients with current sheets at the open field/closed field interface.

For this simple solar minimum streamer, the GB&L model predicts a magnetic field that is predominantly dipolar, and that is kept in force balance with the white light density distribution through current sheets around the helmet streamer. In this sense it agrees with MHD models of coronal streamers (Linker et al. 1990, Pneuman & Kopp 1971). On the other hand, the GB&L model predicts densities which quantitatively match observations of the white light corona to within observational error bars. Current MHD models are unable to do this. Even though the magnetostatic approximation will eventually break down as solar wind velocities become significant in coronal force balance, below approximately 3$R_{\odot}$, it predicts a force balance between coronal densities and the magnetic field which is unlikely to be greatly affected by dynamic forces (for example, the log of the density of an isothermal static corona is only changed by approximately 10% at the sonic point by the addition of an isothermal Parker wind (Parker 1958)). The GB&L model is thus a good technique for understanding the physical force balance between coronal electron density and magnetic fields in the large-scale, simple solar minimum structure observed during the “quiet half” of the Whole Sun Month.

REFERENCES

Figure 5. Radial profiles of temperature from Van de Hulst fit to data (blue line), and GBB&L (red line) model inversions of combined HAO/MLSO and SOHO/LASCO C2 pB data. Profiles are seen at the equator, mid-latitude, and pole of the southwest quadrant.

Figure 6. Coronal magnetic field lines determined from GBB&L model fit to white light. Field shown is due to a dipole magnetic field of strength 2.78 Gauss (same as photospheric field), with an upper boundary condition of a current sheet positioned at 2.8 Rsun at the equator.

Figure 7. Coronal magnetic field lines determined from a potential field extrapolation of photospheric field observations from Stanford Wilcox Solar Observatory. Extrapolation assumes a potential field and a source surface at a height of 2.5Rsun.