MAGNETIC CONFIGURATION OF CORONAL STREAMERS AND THREADS

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Abstract. We give a short account of the most prominent structures of the intermediate corona. Then we propose an axially symmetrical model for coronal streamers, according to which charged particles move along magnetic surfaces whose sources are electrical currents situated in the vicinity of the photosphere. The simplest current configuration is a pair of coaxial, coplanar, circular, and oppositely directed currents parallel to the photosphere. Magnetic surfaces for this current distribution exhibit a helmet-shaped separatrix and a saddle point. The temperature profile along the streamer can be predicted qualitatively if one takes into account the conservation of an adiabatic invariant in the drift theory of the charged particle motion.

1. Introduction

The structure of coronal streamers observed during a solar total eclipse (Koutchmy, 1992) poses many theoretical problems that are still unsolved: i) the origin of the typical helmet with a cusp or onion shape, ii) the origin of the confinement of streams at distances from the surface exceeding the solar diameter and/or in the intermediate corona, iii) the large excess density of particles on the visible surface of the streamer, etc.

The classical approach for solving these problems is to start with a simple magnetostatic configuration around the Sun, similar to a dipole field, and to try to solve the full MHD equations, assuming a strictly radial flow presumably due to the thermally driven “wind”. Then the magnetic field lines are stretched out and the neutral sheet could be a streamer, although some additional forces are needed to maintain a significant density enhancement in a neutral sheet. See Koutchmy and Livshits, (1992) for a recent review of “classical” models. Another empirical method for computing the magnetic configuration of the corona in 3D is to introduce a so-called “source surface”, which considerably simplifies the computation, but leads to an artificial concept that does not have a physically plausible counterpart in the case of streamers.

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Moreover, a modern approach for analyzing the coronal structures convincingly shows that the intermediate corona is filled with tiny and elongated structures like rays or threads as in Fig. 1. Some threads have obviously a circular cross-section that they keep over many solar radii; they extend along a direction that is never exactly radial: sometimes the deviation from the radial direction is as large as 60° (Koutchmy, 1969). Furthermore, these structures were seen outside eclipses: YOHKOH images taken in SXR show that the intermediate corona, above the inner corona made of loops, is also filled with rays, especially in the vicinity of active regions. A beautiful example is given in Shibata et al. (1992). In SXR images, time sequences show that threads are jets, although the magnetic features channeling the jet may persist. The rays often have the shape of threads rising above a loop-like structure; sometimes a cusp is well identified. YOHKOH images show more inner corona than eclipse images, but the fundamental loop-cusp-ray structure seems general. As to more quantitative aspects, little can be said from the observations of the temperature inside a range of 1 to 3 MK, but the density enhancements are at least one order of magnitude about the average background corona.

Fig. 1. Processed WL coronal eclipse image of July 31, 1990 using the “MadMax” algorithm; note the long threads.
2. Topological modelling and energy

Some of the above questions lead to the following model. We assume that charged particles from the Sun flow mainly along the separatrix magnetic surface, which has a singular X-point on the vertical axis. This magnetic surface with a sharp top (cusp) is interpreted as the visible surface of the coronal streamer. The required magnetic configuration could be due to the superposition of a circular current-carrying prominence, or facula, surrounding the spot and having a field of the opposite sign. The simplest current distribution is a pair of circular, oppositely directed, coaxial, and coplanar currents.

Let \( A_\rho, A_\phi, A_z \) be the components of the vector potential in cylindrical coordinates \((\rho, \phi, z)\). The axial symmetry provides magnetic surfaces that are contour lines of \( \Psi(\rho, z) = \rho A_\phi(\rho, z) \). Then the poloidal components of the magnetic field are \( B_z = \frac{1}{\rho} \frac{\partial \Psi}{\partial \rho}, \quad B_\rho = -\frac{1}{\rho} \frac{\partial \Psi}{\partial \phi}, \quad B_\phi = 0 \).

Following Landau and Lifshits (1985), the function \( \Psi \) for a pair of coils with radii \( a \) and \( A \), and currents \(-\mathcal{I}_a\) and \( \mathcal{I}_A \), can be written as

\[
\Psi(\rho, z) = \frac{4 A \mathcal{I}_A}{C} \left[ G_A(\rho, z) - \frac{a \mathcal{I}_a}{A \mathcal{I}_A} G_a(\rho, z) \right], \tag{1}
\]

where

\[
G_x(\rho, z) = \frac{1}{k_x} \left( \frac{\rho}{x} \right)^{1/2} \left[ \left( 1 - \frac{k_x^2}{2} \right) K(k_x) - E(k_x) \right],
\]

with \( k_x^2 = 4 x \rho ((x + \rho)^2 + z^2)^{-1} \), \( K(k_x) \) and \( E(k_x) \) full elliptic integrals of the 1st and 2nd kind respectively, and \( C \) a constant.

The magnetic field on the axis \( z \) can be described using elementary functions:

\[
B_z(0, z) = \frac{2 \pi A^2 \mathcal{I}_A}{C} \left\{ \frac{1}{(A^2 + z^2)^{3/2}} - \frac{a^2 \mathcal{I}_a}{A^2 \mathcal{I}_A} \frac{1}{(a^2 + z^2)^{3/2}} \right\}. \tag{2}
\]

The following expansion in even powers of \( \rho \) is valid for an arbitrary axially symmetrical configuration (Morozov and Solov’iev, 1963):

\[
\Psi(\rho, z) = \frac{\rho^2}{2} b(z) - \frac{\rho^4}{16} b''(z) + \ldots = \rho J_1(\rho \hat{b}'(z)), \tag{3}
\]

where \( b(z) = \hat{b}'(z) = B(0, z) \) is the field on the \( z \)-axis and \( J_1(x) \) is Bessel function of the first kind.

The cross-section of a magnetic surface for the configuration (1) has a hyperbolic singular point \( z_s \) on the \( z \)-axis if the magnetic field (2) is zero at \( z_s \), with

\[
\frac{z_s^2}{A^2} = \frac{(a/A)^{2\lambda/3} - a^2/A^2}{1 - (a/A)^{2\lambda/3}} = \frac{(m_a/m_A)^{2/3} - a^2/A^2}{1 - (m_a/m_A)^{2/3}}. \tag{4}
\]
Here \( m_a/m_A \equiv (a/A)^\lambda \) is the ratio of the magnetic moments of the rings and \( m_a/m_A = a^2 I_a/(A^2 I_A) \). The singular point can exist if \( 0 < \lambda < 3 \).

When \( \lambda \to 0 \), \( z_s \to \infty \) and, when \( \lambda \to 3 \), \( z_s \to 0 \). When \( \lambda \to 0 \), the magnetic moments and magnetic fields of both coils become equal, \( m_A \to -m_a \), \( B_A \to -B_a \), and the ratio of the fields at the origin tends to the third power of \( A/a \):

\[
\frac{B_a(0,0)}{B_A(0,0)} = \frac{a^2 I_a}{A I_A} \left( \frac{A}{a} \right)^3 \to \left( \frac{A}{a} \right)^3.
\]

With \( \lambda \) small enough, the top of a helmet corresponding to the point \( \rho = 0 \), \( z = z_s \) occurs at an arbitrarily height above the surface of the photosphere.

The magnetic surfaces \( \Psi(\rho, z) = \text{const} \) in the vicinity of the singular point \( \rho = 0 \), \( z = z_s \) can be drawn using expansion (3). Assuming that

\[
b(z) = \frac{C}{2 \pi A^2 I_A} \left( \frac{\mu}{(A^2 + z^2)^{3/2}} - \frac{\mu}{(a^2 + z^2)^{3/2}} \right),
\]

so that \( \mu = (a^2 + z_s^2)^{-3/2} (A^2 + z_s^2)^{3/2} \), we obtain, to an accuracy of \( \rho^4 \),

\[
\Psi = \frac{\rho^2}{2} \left[ \frac{1}{(A^2 + z_s^2)^{3/2}} - \frac{\mu}{(a^2 + z_s^2)^{3/2}} \right] - \frac{3\rho^4}{16} \left[ \frac{4z^2 - A^2}{(A^2 + z^2)^{7/2}} - \frac{\mu(4z^2 - a^2)}{(a^2 + z^2)^{7/2}} \right].
\]

In the vicinity of \( \rho = 0 \) and \( z = z_s \), \( \Psi = P \rho^2 \zeta \), with \( \zeta = z - z_s \) and \( P \) a constant.

If the Larmor radii of the particles are small compared to the characteristic size of the configuration, then the drift approximation applies (Morozov and Solov’ev, 1963). If \( B_\varphi = 0 \), then the drift trajectories of particles lie on the magnetic surfaces \( \Psi(\rho, z) = \text{const} \). Particles drift in the azimuthal direction, and some of them are reflected from regions of strong magnetic field, which act as magnetic mirrors. Using the adiabatic invariant \( I = v_\perp^2 / B = \text{const} \), the transverse and longitudinal energies of the particles are:

\[
\epsilon_\perp = \epsilon_\perp^0 + \frac{mI}{2} (B - B_0), \quad \epsilon_\parallel = \epsilon_\parallel^0 - \frac{mI}{2} (B - B_0).
\]

When a particle moves into a strong field, its transverse energy, which determines the temperature, increases, but the longitudinal energy decreases, and vice versa. Now the dependence of the magnetic field on \( z \) has a characteristic profile and Eq. (7) provides the radial temperature dependence in the corona. The deduced behavior can be considered to be the result of the conservation of the transverse adiabatic invariant in the drift motion of charged particles.
To summarize, the coronal streamer in our model is the separatrix of an axially symmetric configuration, which arises as a result of the superposition of the magnetic fields of a facula surrounding the spot or of a filament surrounding the facula. The tendency of charged particles to escape along the separatrix magnetic surface was established by Auerbach and Boozer (1980) and by Gribkov et al. (1984).

In order to simulate an inclined streamer, while keeping the possibility of describing the system with the function $\Psi$, we consider also a two-dimensional problem in cartesian coordinates with $\partial \Psi / \partial y = 0$. We replace the system of circular currents by a pair of linear conductors with oppositely directed currents. Then

$$\Psi = P_y(x, z) = \frac{2}{C} \sum_i J_i \ln \left[ \frac{(x - x_{i1})^2 - (z - z_{i1})^2}{(x - x_{i2})^2 - (z - z_{i2})^2} \right]^{1/2},$$

where $(x_{i1}, z_{i1})$ and $(x_{i2}, z_{i2})$ are the coordinates of the conductors of the $i$-th pair.

Fig. 2. $B$-lines for $\lambda = 0.03$, $a/A = 0.1$  
Fig. 3. $B$-lines in the plane configuration

3. Results and Discussion

Fig. 2 shows the magnetic configurations calculated for selected parameters $a/A$ and $\lambda$ from Eq. (4). The magnetic surface cross-sections shown in Fig. 2 have the helmet shape. With increasing height, magnetic surfaces in the vicinity of the separatrix become onion-shaped (cusp). The shape of the magnetic surfaces may vary in the vertical direction.

A magnetic configuration with two saddle points in the plane $z = 0$ is possible. This configuration can be considered for modelling the coronal
polar rays or plumes and possibly also corresponds to the quiet Sun field in the corona. Fig. 3 shows an inclined ray in the plane approximation. Its behaviour at infinity is determined by superposing a uniform and a weak background magnetic field $B^0_2 = \text{const.}$ The calculated and observed structures of Fig. 1 are similar. From the general appearance of helmets we can conclude that $0.001 < \lambda < 1$ in these configurations, and the best value for real structures is $\lambda \approx 0.03$. This includes straight, very long, and slightly inclined “rays”.

4. Conclusion

The “separatrix model” of coronal streamers rests on the assumption of negligible influence of the proper currents on the motion of charged particles along magnetic surfaces. Magnetic surfaces are assumed to be created by external sources placed on the solar surface. The smallness of the magnetic fields does not prevent, in principle, the existence of a singular X-point on the axis where the magnetic field tends to zero. The boundaries of the helmets and cusps are mathematically isolated separatrix surfaces. The problem of the filling of the boundary with charged particles or plasma requires further work. The geometry of the magnetic field lines of the helmet configuration is analogous to that of streamlines around a sphere in a stream of fluid. In our case the non-existing lower hemisphere can be considered as a reflection of the MHD-configuration in equilibrium in the perfectly conducting plane of the photosphere. The nested meridional cross-sections of the toroidal magnetic surfaces observed inside the helmets are typical of the equilibrium MHD-configurations in TOKAMAKS inside the separatrix surface.

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