Helmet Streamers with Triple Structures: Stationary States and Dynamics

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Abstract. Recent observations with the LASCO coronagraph on board of SOHO have shown that helmet streamers may have a triple structure even during the solar activity minimum. The streamer regions have been identified as the source regions for the slow solar wind and new observations provide evidence that a stationary slow solar wind may not exist, but that the slow solar wind is produced by many little eruptions leading to an approximately stationary plasma flow on large scales. The observations further show, that the streamer structures occasionally go unstable, leading to huge coronal mass ejections.

We want to undertake a first step towards a better theoretical understanding of these phenomena and present a method to calculate analytically self-consistent stationary helmet streamer configurations with triple structures. We then use these stationary configurations as input for time-dependent MHD simulations to model the generation of the slow solar wind and the occurrence of coronal mass ejections within triple streamers.

Key words: Helmet streamers, MHD equilibria, Coronal Mass Ejections, Solar Wind

1. Introduction

Observations of the solar corona (Schwenn et al., 1997) with the coronagraph LASCO on the SOHO spacecraft showed, that the solar corona can be highly structured even during the solar activity minimum. The observation showed a triple structure in the streamer belt, which exists for several days. The observations further suggest, that the slow solar wind maybe caused by quasistationary small eruptions of the streamers. The observations further show, that these triple helmet streamers occasionally become unstable, which leads to extraordinarily huge coronal mass ejections. The aim of this paper is to make a first step to a better theoretical understanding of these dynamical phenomena. The structure of helmet streamers and their stability has been studied both observationally and theoretically for a long time (e.g. Pneuman and Kopp, 1971; Cuperman et al., 1990; Cuperman et al., 1992; Koutchmy and Livshits, 1992; Wang et al., 1993; Cuperman et al., 1995; Wu et al., 1995; Hundhausen, 1998; Bavassano et al., 1997). A natural association seems to exist between helmet streamer stability and coronal mass ejections (CMEs) and sometimes CMEs are accompanied by erupting prominences or filaments. Coronal streamers are also thought to be the source regions of the slow solar wind and the activity processes discussed above may well contribute to this component of the solar wind.

The paper is outlined as follows. In section 2 we discuss the basic equations. Section 3 contains our model assumptions and their justification. In section 4 we present a method to calculate self-consistent, analytical stationary triple helmet streamer configurations. We use these stationary states as input for numerical experiments with a time-dependent MHD-code in section 5. In section 6 we summarize our results and give an outlook on future work.

2. Basic Equations

Do describe the coronal plasma we use the MHD equations:

$$-\rho\mathbf{v}\cdot\nabla\mathbf{v} - \nabla p + \mathbf{j}\times\mathbf{B} - \rho\nabla\Psi = \rho\frac{\partial\mathbf{v}}{\partial t} \tag{1}$$

$$-\nabla\cdot(\rho\mathbf{v}) = \frac{\partial\rho}{\partial t} \tag{2}$$

$$\mathbf{E} + \mathbf{v}\times\mathbf{B} = \eta\mathbf{j} \tag{3}$$

$$\nabla\cdot\mathbf{B} = 0 \tag{4}$$

$$\mathbf{j} = \frac{1}{\mu_0}\nabla\times\mathbf{B} \tag{5}$$

$$p = \rho RT \tag{6}$$

$$\frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{E} \tag{7}$$

$$\frac{\partial p}{\partial t} + \nabla\cdot(p\mathbf{v}) + (\gamma-1)P\nabla\cdot\mathbf{v} = (\gamma-1)\eta j^2 \tag{8}$$

Here, P stands for the plasma pressure, $\mathbf{B}$ for the magnetic field, ρ for the plasma density, Ψ for the solar gravitational potential, $\mathbf{v}$ for the plasma velocity, $\mathbf{E}$ for the electric field, R is the gas constant, T the temperature, $\mathbf{j}$ the current density, η the resistivity and μ_0 the vacuum permeability. We normalize the magnetic field by a typical value B_0, the plasma pressure p by B_0^2/μ_0, the mass density ρ by $\rho_0 = B_0^2/\mu_0 \mathrm{R}T$, the length L by a solar radius and the current density by $B_0/\mu_0\, L$, the plasma bulk velocity by the Alfven velocity v_A, the electric field by $\frac{B_0^2}{\sqrt{\rho_0}}$, the time by the Alfven time and the resistivity η by $\mu_0 L v_A$.

3. Model assumptions

Throughout the rest of the paper we make the following assumptions:

- The streamer structure is extended in azimuth and varies only very slowly along this direction (Schwenn et al., 1997). Thus we can use a two-dimensional model with rotational invariance.
- The streamers are elongated in the radial direction. Thus we use the method of asymptotic expansion to calculate stationary states.
- The observations (Habbal et al., 1997) show that a stationary slow solar wind might not exist, but that the slow solar wind is produced by many small eruptions. Thus stationary states of helmet streamers should be static equilibria.
- The aim of this work is to investigate the basic physical mechanisms of coronal mass ejections and small eruptions. Therefore we use as a first step a Cartesian geometry and neglect gravity. We are aware of the fact that both gravity and the basic geometry should have influence on the quantitative dynamic evolution of helmet streamers, but we use the correct magnetic field topology and the question whether an instability occurs or not should not be influenced by this model assumption.

4. Stationary States

We use the equations of ideal stationary magnetohydrodynamics, which are a subgroup of the MHD-equations (1 - 8), to calculate stationary state helmet streamer configurations. The equations of stationary ideal MHD are given by equations (1 - 6), where the right-hand side of equations (1-3) is identical zero. With the help of our basic assumptions we simplify the equations of stationary ideal MHD. We illustrate our method in Cartesian geometry without gravitation, magnetic shear and plasma flow. In a two-dimensional Cartesian geometry (x, z) we represent the magnetic field as

$$\mathbf{B}(x,z) = \nabla A(x,z) \times \mathbf{e}_y \tag{9}$$

and find from equation (1) that the flux function $A(x,z)$ has to obey the equation

$$-\Delta A = \frac{\partial p(A)}{\partial A}. \tag{10}$$

Unfortunately it is not possible to derive the function $p(A)$ from the observations. We use the popular choice $p(A) = k\exp(cA)$. To calculate triple streamers, the separatrices between the middle and outer streamers have to be calculated self-consistently with the solution. We label the separatrix field line with a value A_s of the flux function and use $p_1(A) = k_1\exp(-c_1 A)$ for the middle streamer and $p_2(A) = k_1 \cdot \exp(-(c_1 + c_2)A_s) \cdot \exp(c_2 A)$ for the outer streamers $(c_1,\ c_2 > 0)$. This choice ensures, that both pressure function coincide on the separatrices. If we assume that the magnetic field perpendicular to the photosphere (B_z in the Cartesian geometry) is much larger than the parallel component (B_x in the Cartesian geometry), we can use the method of asymptotic expansion (Schindler, 1972) and apply it to Eq. (10). Mathematically stretched configurations are characterized by the ordering

$$\frac{\partial}{\partial x} = O(1) \Rightarrow B_z = O(1) \qquad \frac{\partial}{\partial z} = O(\epsilon) \ll 1 \Rightarrow B_x = O(\epsilon). \tag{11}$$

If we neglect terms of the order ϵ^2 in Eq. (10) we obtain after one integration with respect to x and after solving this differential equation by separation (Birn et al., 1975)

$$A(x,z) = -\frac{2}{c}\log\left\{\cosh\left[c\sqrt{\frac{p_0}{2}}(x - x_0)\right]\right\} + \frac{1}{c}\log\left(\frac{p_0}{k}\right), \tag{12}$$

where $p_0 = p_0(z)$ is an integration constant (total pressure on the z-axis), which depends parametrically on z. One can choose $p_0(z)$ arbitrarily to fit the model to the observations. To derive triple streamers, we use $c = -c_1,\ k = 1,\ x_0 = 0$ in the middle streamer and $c = c_2,\ k = \exp(-(c_1 + c_2)A_s),\ x_0(z) = \operatorname{arctanh}\left(\sqrt{\frac{(p_0 - \exp(-c_1 A_s))}{p_0}}\right)\sqrt{\frac{2}{p_0}}\left(\frac{1}{c_1} + \frac{1}{c_2}\right)$ in the right outer streamer, while the left outer streamer is calculated by a symmetry assumption. Note that p_0 and thus x_0 depends parametrically on z. The separatrix field line x_{sep}, which separates the middle streamer and the right outer streamer is given analytically by $x_{sep}(z) = \sqrt{\frac{2}{p_0}}\frac{1}{c_1}\operatorname{arctanh}\left(\sqrt{\frac{(p_0 - \exp(-c_1 A_s))}{p_0}}\right)$.

Thus we derive selfconsistent, analytical helmet streamer configurations with triple structures. The method works similar in spherical geometry and one can include the solar gravitation, magnetic shear and stationary plasma flow (Wiegelmann et al., 1998).

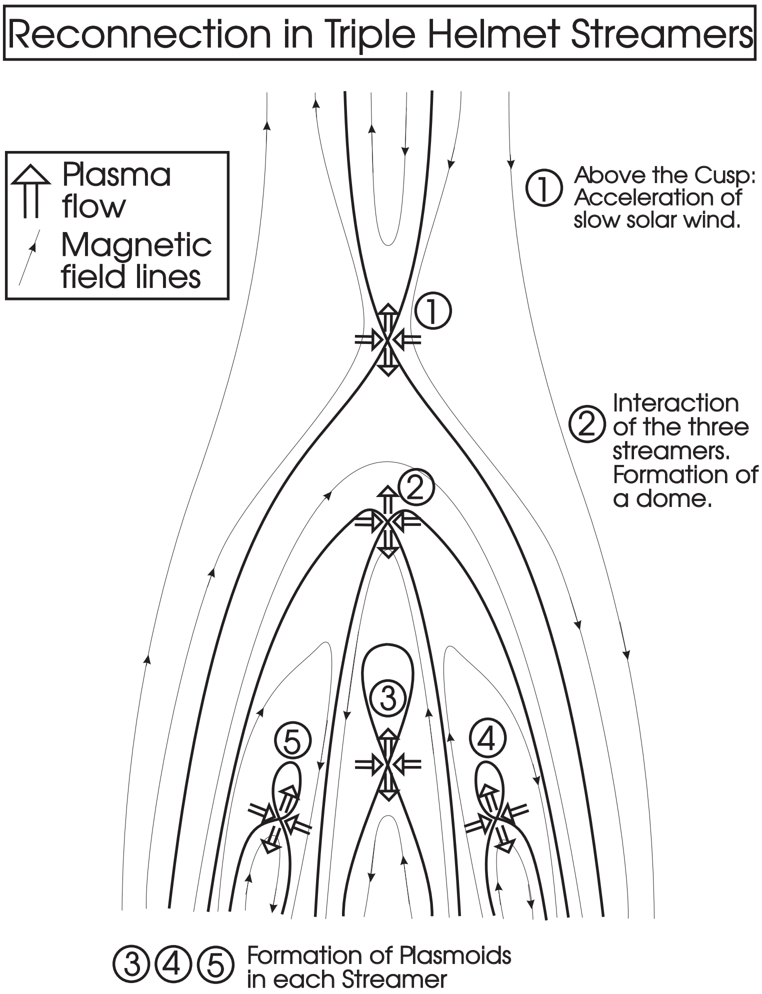

Figure 1. Reconnection processes in triple helmet streamers. (see text)

5. Dynamics

To study the dynamical evolution of triple helmet streamers we solve the time dependent resistive MHD equations (1-8) with the help of a numerical MHD-code. As start configurations we use the stationary state triple helmet streamer configurations calculated in the last section. This equilibrium structure has a thin current sheet above the helmet streamer cusp. This cusp is a radial boundary for the last closed field line of the streamer configuration. The current distribution on the closed field lines in the helmet streamers is much smoother. We remark, that during a quasistatic evolution thin current sheets may form within each streamer, analogous to the formation of thin current sheets in the Earth's magnetotail (Wiegelmann and Schindler, 1995). One difficulty is to choose the resistivity profile η. The easiest choice is a constant resistivity in whole space. More realistic is to use a current dependent resitivity profile $\eta = \eta(|\mathbf{j}|)$ or to localize the resistivity at the equilibrium current sheets.

The results of our numerical experiments are presented schematically in figure 1. We find different regions where reconnection processes occur:

- (1) The helmet streamer cusp transforms to an X-point and very small plasmoids are ejected into space. This process is a possible mechanism for the acceleration of the slow solar wind.
- (2) Interaction of the outer streamers lead to the formation of a dome above the three streamers.
- (3-5) Within each streamer we find the formation of plasmoids. If we consider only one streamer, the acceleration of these plasmoids leads to a coronal mass ejection. But the two outer streamers and the dome have a stabilising effect and make it more difficult for a plasmoid to leave the configuration. One finds that triple streamers are more stable than a single streamer. The acceleration of the plasmoids in each streamer may cause an slow growth of the whole configuration and lead to a huge coronal mass ejection.

We remark that the process (1) occurs on a much shorter timescale than the other processes. A streamer configuration which emits the slow solar wind in the helmet streamer stalk above the cusp and stays nearly stationary elsewhere seems to be the common state of the streamer belt.

6. Conclusions

We have developed a method to calculate stationary triple helmet streamer configurations in a self-consistent analytical model. We used these stationary states as input for numerical experiments with a time-dependent MHD-Code. These simulations show that a possible source for the slow solar wind is the helmet streamer cusp. We found that this cusp transforms into a X-point and small plasmoids are accelerated due to reconnection. We further investigated reconnection processes in each streamer and between the streamers and discussed the role of this processes for the generation and development of coronal mass ejections.

Thus we developed a self-consistent model, which explains the origin of the slow solar wind and the generation of CMEs in one model.

As a next step we plan to extend our model to three dimensions. This extension is necessary to model helmet streamers in the solar activity maximum, where an azimuthally extended streamer belt might not exist.

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