Comparison of Magnetohydrodynamics Simulation And Observasional Result to Solar Coronal Helmet Streamer

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Abstract. This research is compare of magnetohydrodynamics (MHD) simulation and observational product to solar coronal helmet streamer (SCHS). Magnetohydrodynamics simulation is performed to construct evolution of a solar coronal helmet streamer attaining magnetohydrodynamics stability in solar corona. The dynamical evolution is satisfied by implementing numerical approach to reach complete self-consistent solution through modified general equation of Lagrangian-Navier-Stokes time-dependent. The density profile resulting from numerical solution is compared to the real data derived from large-angle solar coronagraph data taking by a coronagraph satellite. The research product show range of error is 10% with using measure of differential emission. We conclude that the plasma electron density distribution derived from simulation is in accordance with observational data.

1. Introduction

Helmet streamers are cusp structures seen in the corona by a coronagraph or during the total solar eclipse. They are usually situated above active regions or above remnant of old active regions [1]. These helmet streamers can be seen in white light because the electron density are about ten times higher than in the quiet corona (see fig. 1) [2]. The lower parts (arcade base) are about the scale of active regions or even larger as observed in the green line emitted by FeXIV (λ = 5303Å) [3].

The plasma is a quasi-neutral gas consisting of positive ion and negative charged particles (electrons) [4]. Despite plasma having similar properties as a gas, it may form structures such as filaments, beams and double layers when in the presence of a magnetic field [1]. The presence of a charge non-negligible carriers makes the plasma electrically conductive so that it responds strongly to electromagnetic fields. Due to its attributes, plasma is sometimes considered the fourth state of matter.

The coronal plasma density distribution is not isotropic as a result of the penetration by the helmet streamer magnetic structure [1,3,4]. Figure 1 is making image of the process white light data with several helmet streamers structure (A and B) [2,3].

Below the cusp structure of the helmet streamers are frequently become inflated and all the structure seem to loss their equilibrium [1]. Study of the helmet streamers formation in the solar corona is very important to have some plausible physical condition prior a launch of energetic solar CMEs since the CMEs mostly emerge from the helmet streamers [3,5].
The idea of research is magnetic fields can induce currents in a moving conductive fluid, which create forces on the fluid. The set of equations which describe this condition are combination of the Navier-Stokes equations of fluid dynamics and Maxwell’s equations of electromagnetism [3,6,7]. Magnetohydrodynamics equation was used in reference to the transfer of momentum from the Sun to the planets, but it’s eventually expanded upon to include the current field. These differential equations can be solved simultaneously, either analytically or numerically.

In this paper, simulate the formation of a helmet streamer under gravitationally stratified and isothermal atmosphere. The helmet streamer formation closely to a realistic helmet streamer formation in the real solar corona. The atmosphere is initially in hydrostatic balance and has an isothermal temperature distribution at $2 \times 10^6$ K [3].

The simulation to this project was run up to 1000 time-steps to obtain a numerically initial hydrostatic balance and isothermal condition. The arcade magnetic field structure is then permeates the atmosphere most instantly as a result of penetration of the arcade magnetic fields from a remnant, of an old active region [2,4,8]. The comparison is made in a situation when “dynamical equilibrium” is satisfied by the simulated helmet streamer.

2. Basic MHD Equations

Magnetohydrodynamics transport equation used to study process the helmet streamer formation [4,6,7]. The equations is

Mass transport:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0$$

Momentum transport:

$$\frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla P + \left( \nabla \times \mathbf{B} \right) \times \mathbf{B} + \rho \mathbf{g}$$

Magnetic transport:

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{V} \times \mathbf{B}) = 0$$

Pressure transport:

$$\frac{\partial P}{\partial t} + \nabla \cdot (P \mathbf{V}) = -\gamma \left( \nabla \cdot \mathbf{V} \right)$$

And the gas ideal relation

$P = \rho T$
These equations are solved numerically in a rectangular two-dimensional space by the Shasta-FCT algorithm [6,8]. Equations (1) to (4) can be solved in GLNS as invented and implemented by [6]. We solve in a way such that the solution has second order accuracy in space and in time. Adiabatic environment ($\gamma = 5/3$) is assumed during the helmet streamer formation [7,9]. The plasma pressure $P$ and plasma density $\rho$ are directly computed through equations (1) and (4), while the plasma temperature $T$ is derived from equation (5). Since we assumed the plasma is non-degenerate material such that the Maxwell-Boltzman statistics is not violated then the relation in equation (5) is presumably held.

**Initial conditions**

Computational domain is a rectangular which represents a region in the corona. The base of the corona lies along the horizontal $x$-axis which runs parallel to the solar surface. The vertical $y$-axis is perpendicular to the solar surface and points upwards such that $y=0$ represents the solar surface. The solar gravitation vector runs parallel with the $y$-axis and points downward. We assume that gravitation is due to the whole body of the sun so that we do not taken into account the self-gravity of the plasma.

In top, left, and right of the computational domain we apply free boundaries where the plasma can pass the boundaries freely. The bottom boundary is hard boundary which makes the coronal magnetic fields in line-tied condition. The plasma can penetrate the bottom boundary from below as a result of ever escaping plasma from the photosphere and the chromospheres [6,7,9].

The solar corona is initially in hydrostatic equilibrium with the temperature is uniform everywhere (or isothermal) and takes a value of 2 x10$^6$ K [8]. In the initial configuration the pressure is derived from the equation of hydrostatic balance as follows [6],

$$\nabla_y P(y) = \rho(y) g_y(y)$$ \hspace{1cm} (6)

where we assign that

$$\rho(y) = \rho_0 \exp\left[-\left(\frac{g_0 R_0^2}{RT}\right)\frac{y}{(R_0 + y)^2}\right]$$ \hspace{1cm} (7)

And

$$g_y(y) = g_0 \frac{R_0^2}{(R_0 + y)^2}$$ \hspace{1cm} (8)

All symbols have their usual meanings. This initial analytical condition is tested to 1000 cycles to check whether this solution can reach (numerical) equilibrium before penetrated by a magnetic field. Equations (6) and (7) express that our initial model is held as our planet’s atmosphere with the exception that the material is purely electron plasma. While equation (8) indicates the gravitational scale exceeds great height from the solar surface into interplanetary space extension.

A remnant but still evolving old active region then penetrates this initial atmosphere almost instantly by a magnetic field of the following type [1],

$$B_x(x,y) = B_0 \cos\left(\frac{\pi x}{2x_0}\right)\exp\left(-\frac{\pi y}{2x_0}\right)$$ \hspace{1cm} (9)

and

$$B_y(x,y) = -B_0 \sin\left(\frac{\pi x}{2x_0}\right)\exp\left(-\frac{\pi y}{2x_0}\right)$$ \hspace{1cm} (10)

where $B_0$ is arbitrary coronal base magnetic strength. In this case we put a value of 10 Gauss. The $2x_0$ is the length of the helmet streamer’s arcade base. The negative value of $B_y(x,y)$ will result in a total inward force.

This force is necessary to balance the pressure gradient force. The magnetic fields structure in equations (9) and (10) exhibit that initially a primitive helmet streamer structure penetrates lower corona and attains equilibrium with exponential decreasing magnetic strength [3,6].
3. Results and Discussion

After the magnetic field structure penetrated the hydrostatic and isothermal atmosphere, we run simulation up to 2,000 cycle or about 11.13 minutes of real time. Before cycle 1,000 (or about 6.35 minutes of real time) was attained a noticeable variation of the physical parameters could be seen easily at every 100 cycles (see Fig. 2). After cycle 1,000 up to the last of cycle 2,000 there was no much change on the pressure, density, and magnetic pressure profiles as well. It can be inspected in the Fig. 2 that the profiles in the axis of symmetry superimposed each other. Evolution of the pressure and the density of plasma along axis of symmetry. The superimpose profiles are obvious after cycle 1000.

![Figure 2](image1.png)

**Figure 2.** This is The Signature of New Equilibrium Onset In The Helmet Streamer Structure In The Solar Corona.

In the last cycle 2,000 it can be seen on Fig. 3 that the pressure contour and the density contour resemble nicely the cusp type helmet streamers as observed in white light with a coronagraph. We concluded that the system satisfied new dynamical equilibrium. The term "dynamical" means that even the helmet streamer attained its new equilibrium state, there were still plasma flow upward in the neighboring regions [1,5].

From Fig. 2 we can see that, on the axis of symmetry, the superimposing profiles in general satisfied approximately the profiles of the magnetohydrostatic balance as derived by Setiahadi et al. (1998). Even though, it should be noted that we did not include the solar gravitational acceleration formally in the previous work. Nevertheless, within a scale height smaller than that of the corona (<50,000 km), these profiles (with and without gravitation) should approach each other.

During the first 1000 cycles, along the axis of symmetry, a relatively high plasma speed was blown upward. After cycle 1,000 the plasma speed at the symmetrical axis ceased and at the last cycle 2,000 the speed distribution was much less than that of the quiet corona (< 140 km s⁻¹). Though, there were relatively high speeds of plasma still persisted around the axis of symmetry.

This high speed of plasma came from below and flew along the boundaries of the helmet streamer structure (see Fig. 3). At the last of cycle 2,000 the cusp type of the pressure distribution and the density distribution are clearly reproduced. Note the density output matches with the density calculated from the real data using differential emission measure equation. If we continue the simulation this situation will not change much and the flow will exist for a long time. From the observational works, it is suggested that the continuous radio burst of type III may be originated from the boundaries of the helmet structure [2].

![Figure 3](image2.png)

**Figure 3.** The Density Inside of This Structure Is, on The Average, Ten Times Higher Then In The Outside.
Though we started with a comparable plasma $\beta = 1$ as an initial state, the plasma $\beta$ became higher at all points in the helmet streamer at the last of cycle 2,000. We suggest that the evolution to higher plasma $\beta$ is due to plasma flow-trapping by the magnetic field of the helmet streamer during its way to reach a new equilibrium [2,5]. Outside the helmet streamer the plasma is freely to flow along the boundaries and forms a high speed solar wind. Thus, finally we have a helmet streamer which is dominated by plasma pressure. Evolution to other state is then controlled by the plasma pressure evolution in the helmet streamer [9].

The only way for validation with real physical world is accomplished through density output from computation with the density provided from observational data, since the helmet streamer from real corona is nothing than the electron density scattered by Thomson electron scattering mechanism. The formula to convert from intensity data to density data is written as [7]

$$\rho = k I$$

(11)

Where $\rho$ is the plasma density derived from observation, $k$ is the conversion that accommodates the surface electron intensity to plasma density, and $I$ is the electron intensity due to the Thomson electron scattering mechanism in solar corona. Through the above formulation we may eventually compare the density from MHD output with electron density in a real helmet streamer.

From Fig. 3 it is noted the density output matches with the density calculated from the real data using differential emission measure equation (1). The electron scattering data is very important since it provides us a gate to compare indirectly the MHD computation output with real physical world.

4. Conclusion

Helmet streamers are seen unchanged during several days and even weeks before they loss their equilibrium to launch the solar CMEs. It means that the magnetic field in the helmet streamers structure may have a unique physical condition which are able to resist their stability against disturbances from below [1]. The most probably stabilizing mechanism is the magnetic line-tied condition. Any change of the line-tied condition by some process may change the stability on the magnetic field.

The line-tied condition may change due to shearing motion on the base of the helmet streamer [5]. The change should result as increasing magnetic energy in the helmet streamers and should attain a critical state so that the helmet streamers will loss their equilibrium and will release the magnetic energy almost instantly. Research on the problem is still uncertain now. Some authors concluded that after the magnetic field of the helmet streamers attain their critical state they will loss their equilibrium [4]. In the other hand, some authors found that after attaining a critical state, the magnetic field of the helmet streamers will not loss their equilibrium but attain other equilibrium sequence as discussed by [6] and [12]. Other possibility of losing equilibrium may be caused by plasma pressure evolution in the base of the helmet streamers as a result of ever escaping plasma flow from the photosphere and the chromosphere. Results of ideal MHD numerical experiments [9,10,11] pointed out that the loss of equilibrium may be caused by pressure evolution on the coronal base.

References

[1] Zuccarello, F. Balmaceda, L. Cessateur, G. Cremades, H. Guglielmino, S. Lilensten, J. Kretzschmar, M. Fernando M. Lopez, Mierla M, Parenti S. Pomoell, S. Romano, P., (2013), Solar activity and its evolution across the corona: recent advances, J. Space Weather Space Clim A18, 10. 1051/swsc/201303 9
[2] Setiahadi, B., Anwar, B., Sakurai, T. (1995), 2D MHD Simulation of CME Generated Interplanetary Shock Waves, The Ninth International Symposium on Equatorial Aeronomy (ISEA), Bali, Indonesia, March 20-24, p. D-10, 1995
[3] F. Goryaev1, V. Slemzin1, L. Vainshtein1, and David R. Williams, (2014), Study of Extreme-Ultraviolet Emission And Properties Of A Coronal Streamer From Proba2/Swap, Hinode/Eis And Mauna Loa Mk4 Observations, The Astrophysical Journal, Volume 781, Number 2. The American Astronomical Society
[4] Jokers, K. (2008), Solar Physics, 56, p. 37.
[5] Setiahadi, B., Anwar, B., Akioka, M., Sakurai, T. (1998), Non-linear Evolution of Erupting Coronal Magnetic Fields, Proceedings of Yohkoh 5th Anniversary Symposium, p. 345.
[6] Fan, Y. and Gibson, S., E. (2004), Numerical Simulations of Three-dimensional Coronal Magnetic Fields Resulting from the Emergence of Twisted Magnetic Flux Tubes, The Astrophysical Journal, Volume 609, Number 2, The American Astronomical Society.

[7] Madhavan, S., Gandhinagar, M., V., Majalee, A., (2005), Two-Dimensional MHD Simulation of Quasi-Spherical and Cylindrical Metallic Liner Acceleration. Pulsed Power Conference, 2005 IEEE Inst. for Plasma Res.,

[8] Priest, E.R. (1982), Solar Magnetohydrodynamics, D. Reidel, Dordrecht, Holland, p. 149.

[9] Kliem, B. Van Ballegooijen, and Deluca, E. (2013), Magnetohydrodynamic Modeling of The Solar Eruption On 2010 April 8, Astro-Phy.SR