Observational and Data-Driven Magnetohydrodynamic Modeling of the Solar Corona with Bow Shocks of Solar System Objects

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ADVANCING KNOWLEDGE. TRANSFORMING LIVES.

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Abstract

This thesis confronts mainstream astronomy and cosmology on how an electrically-neutral universe still provides the ideological framework. With several studies on the modeling magnetohydrodynamic activities and the effects it has on solar system objects, it will demonstrate how the universe is alive with electromagnetic plasma.

I would like to acknowledge and thank Dr. Stephen E. Zepf for providing sessions for the senior thesis throughout this work. Thankfully, it was with great honour to work with Dr. Marcos Danny Caballero on the electromagnetic phenomenon.

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List of Equations

Maxwell's Equations

$\nabla \cdot E = 0$

$\nabla \cdot B = 0$

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

$\nabla \times B = \mu_0 J$

$$\frac{du}{dt} + (v \cdot \nabla)u = -\frac{1}{\rho}\partial p - \partial \varphi + v\nabla^2 u + \frac{1}{\rho}(J \times B)$$

Fluid Mechanics

$\rho \frac{dv}{dt} = -\nabla p$

$\frac{d\rho}{dt} + p\nabla v = 0$

$$p = R\rho T$$

Shear Alfvén Equation

$$\nabla \frac{\omega^2}{{v^2}_A} \nabla_\perp U + B \cdot \nabla \frac{1}{B^2} \nabla \cdot B^2 \nabla_\perp \frac{1}{B^2} B \cdot \nabla U - \nabla\left(\frac{J_\parallel}{B}\right)$$

$$\cdot \left[\nabla\left(\frac{1}{B^2} B \cdot \nabla U\right) \times B\right] + 2\frac{\kappa \cdot B \times \nabla \delta P}{B^2} = 0$$

I Introduction

Magnetic is magneto, one of the states of matters is hydro, and progress is dynamic. With that, magnetohydrodynamics is the subject of “fluids”. These fluids conduct electricity and its magnetic components. The fundamental concept is that the magnetic fields can induce currents in. Consequently, this polarizes plasma, salt water, or liquid metals. These factors change the magnetic fields itself. Difficultly, the approach for any research is to prove the intended research. Here, it is to prove if it fits a hypothesis of the magnetic interactions that the solar plasma emits. Nevertheless, nothing is completely proven.

Additively, with three decades in their research, there were five cases focused upon. Since the Nobel-Prize winning discovery of magnetohydrodynamics in the sixties, it is unoriginal. Problematically, the kinematics have had a deficiency in updates to rapid calculation. Noting these, the cases differentiate based on advancements and technique variations in modeling. After all, what these studies asked are the observation of the plasma in the Sun will produce as a model. In turn, this will answer where in the corona the location of the energy to heat the plasma. That is where the dissipation of magnetic currents could root out more answers. Mostly, time will tell of the evolution in modeling. It tells if it will attest the magnetic interactions in solar flares. Therefore, will we be aware that the solar corona is magnetically live and well?

Magnetohydrodynamics is the subject of “fluids” that conduct electricity and its magnetic components. The fundamental concept behind this study is that the magnetic fields can induce currents in and consequently polarize plasma, salt water, or liquid metals, changing the magnetic fields itself. One of the earliest experiments with fluids was done by the father of the electric field himself: Michael Faraday. This experiment was on the salt water and its potential difference from its interaction with the Earth’s magnetic field.

Importantly, the Nobel Prize in Physics recipient to bring about the topic of electromagnetism in plasma was a Swedish engineer and plasma physicist named Hannes Alfvén. Hannes Alfvén is regarded as the father of Plasma Physics and Plasma Cosmology. In recognition of his work with Plasma Physics, he was awarded the Nobel Prize in Physics in 1970. While his work with laboratory plasmas is widely recognized. However, his cosmological ideas, and the implications of his work in this field are not as well-known. In his early papers, Alfvén spoke of the magnetic fields being "frozen" into neutral plasma. Astronomers were readily attracted to this notion as the universe could still be explained in terms of gravity alone. Although, this seemed to keep things mathematically simple, Alfvén quickly recognized his error. In fact, he went to great lengths to explain the dangers of this misconception in regards to space plasma. The trouble is, a "frozen-in magnetic field" implies that there is no voltage differential in a plasma. Therefore, there is no electric current. This could only lead to the erroneous notion of electric neutrality in space.

The interest to delve beyond the notion was driven by solar observations made by a solar telescope, with fascinations in the activities of the solar corona (haven for plasma). Also, a hobby is stagecraft, which is scenic designs and forming the structures of a theatrical production. Stagecraft hands me the privilege to be skilled in utilizing a plasma cutter to twist-and-turn unique “artworks” and set-pieces. The scientific papers and reviews read are mostly laboratory practices and applications used to test plasma and its electrical and magnetic aspects to observe whether the experiments can be produced by a low-budget college student.

II Preliminaries

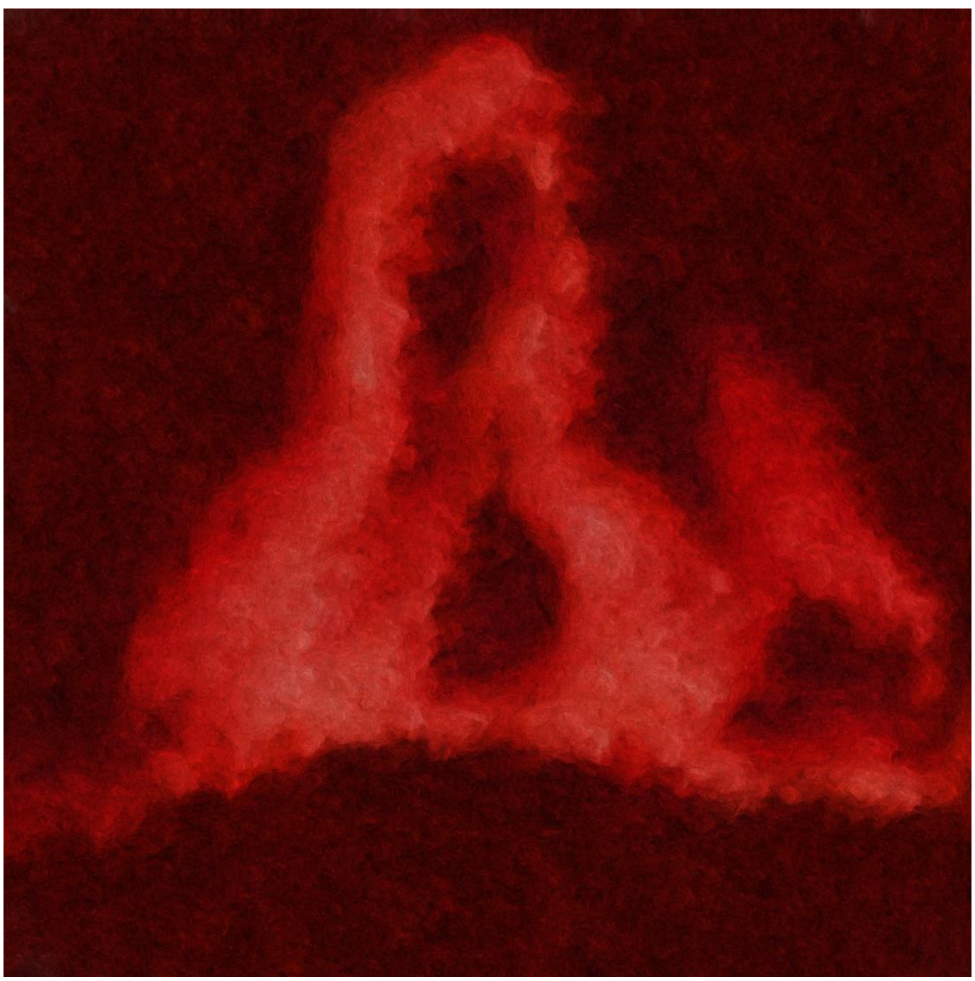
1. Equations

Earlier, in the “List of Equations”, all that is contained are three of Maxwell’s equations. These consist of Ampere’s Law (without the displacement current), Faraday’s Law, and the magnetic divergence. Provided from fluid mechanics was the Navier-Stokes equation. The modification of Maxwell’s equation comes from the assumption that fluids being considered are electrically neutral. In many studied cases, there is no charge-induced electric field, so Gauss’ Law reduces to a statement of zero divergence. The displacement current comes from Gauss’ Law, so that too is discarded. Meanwhile, the Navier-Stokes equation is the governing equation of flow in fluid mechanics. The consequences of these equations via derivation are Alfvén waves.

To describe a single Alfvén wave, “pulse”, it is a series of equally-spaced representative points, called rays. The spatial extent of the pulse is described by the distance covered by the series of rays, and the rays move in the direction of propagation of the wave to describe the motion of the pulse as a whole. The pulse traveled over a one-dimensional grid. Within this grid, various physical values such as plasma and ion densities, and the magnetic field varied. The grid is a discrete-position model of the loop. As each ray moved, researchers kept track of its Poynting flux and use this to determine the heat dissipated into the corona.

2. Coronal Heating

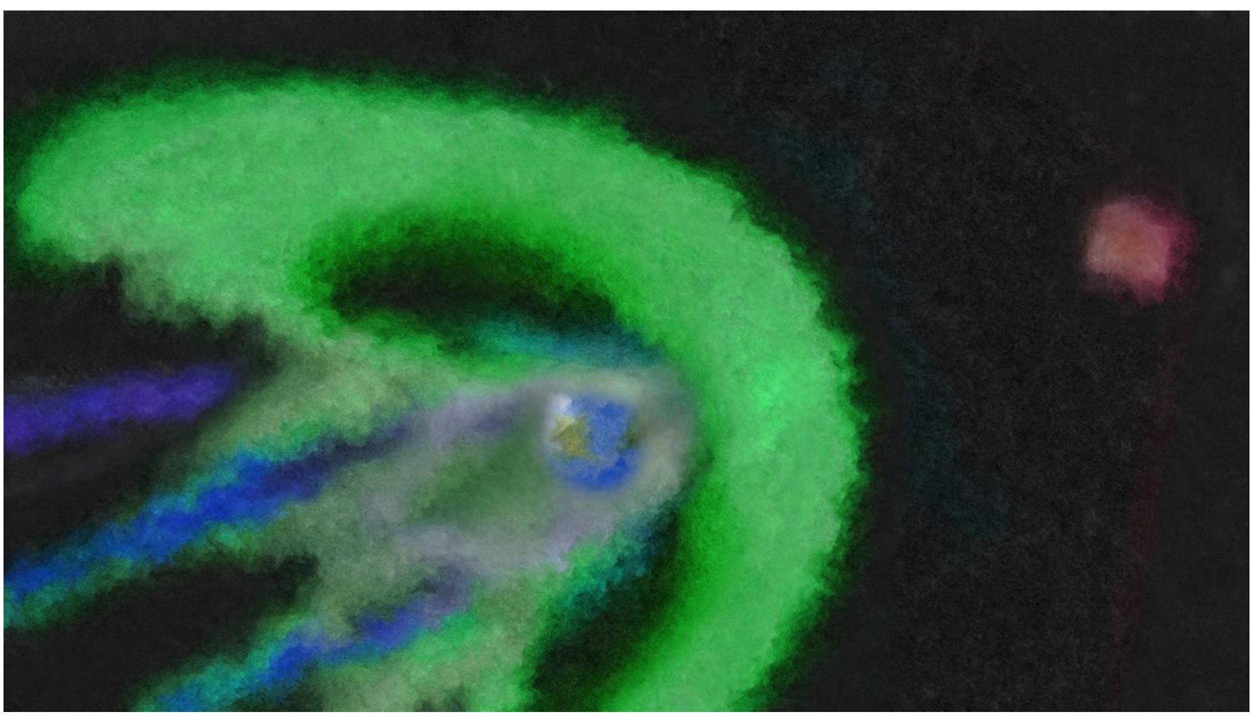
In context of coronal heating, Alfvén waves are proposed travel through structures known as coronal loops, Coronal loops are higher-density regions of plasma in the solar atmosphere, contorted into a loop by magnetic field lines. These magnetic field lines begins and ends at the surface. Alfvén waves travel along these loops. As they move, the energy stored in their fields dissipates by the ways of friction. Also, by other forces which do work. Thus, heating the surrounding corona. This is the system that will be generally modeled.



3. Bow Shock

If one is invested in boating, they will be able to make out what a magnetosphere of Earth rippled by solar winds would be called. Beyond one dimension of a bow wave, the solar bow shocks occur in three.

The solar wind forms a bow shock in front of Earth's magnetosphere. As it flies through the less-dense cloud of plasma that is the bigger cluster it forms a bow shock. Scientists study such cluster shocks to deduce their velocity in the plane of the sky. And the fine structure of the shocks reveals a lot about the interesting, complicated physical processes in the plasmas present in clusters as well as in many other astrophysical objects across the universe.



III Annotated Bibliography

1. Key Findings

The key findings from “Observationally driven 3D magnetohydrodynamics model of the solar corona above an active region” by Bourdin, Bingert, and Peter was the thermal structure of the plasma and of the magnetic field in the coronal structures. Prominently, these findings are important as the description sets the pressure of the coronal structure within the limitations of the spatial resolution in the models computed. Initially, the models cannot resolve the actual dissipation length scale based on precision, but it has taken into account the energy input, redistribution, and radiative losses to get a proper coronal energy balance. Specifically, the coronal energy balance is the redistribution of energy by heat conduction along the magnetic field . Also, these assisted in the comparison of observations to test the field-line braiding mechanism. Routinely, what led to this finding is that the implementation of the field-aligned heat conduction together with the optically thin radiative losses allows the researcher to properly describe the energy cycle between the chromosphere and corona.

What is necessary to understand the matter is Ohmic heating, which is a process wherein an electric current is passed through materials with the primary purpose of heating them. Mathematically, Ohmic dissipation of induced currents is $E \cdot E$. How they initialized the magnetic field configuration with a potential field extrapolation is from the observed photospheric magnetogram. A magnetogram refers to a photographic representation of the spatial variations in the strength of the solar magnetic field. An interesting notion to run the numerical experiments is utilizing the Pencil Code, due to its modular structure. The Pencil Code are codes utilized to solve partial differential equations and prominent in magnetohydrodynamics.

To summarize, the central idea behind this study are to compare synthesized emission from a forward three-dimensional magnetohydrodynamics coronal model driven by photospheric observations to actual coronal observations. The goal was to employ a three-dimensional magnetohydrodynamics model to illustrate the corona in an observed solar active region.

The key findings from “Three-Dimensional Magnetohydrodynamics of the Emerging Magnetic Flux in the Solar Atmosphere” by Matsumoto, Tajima, Shibata, and Kaisig was that nonlinear instability does not exist in the pure interchange instability and that the pure interchange instability alone cannot create emerging magnetic loops. The figure that supports these key findings was by studying the three-dimensional nonlinear evolution of the magnetic buoyancy instability, a concept by which magnetic fields from within the Sun might come to the surface and contribute to its magnetic activity.

Significantly, there is much to learn before delving into this article. This article is a follow-up on their previous paper on two-dimensional magnetohydrodynamic code and 2.5D simulations, a necessary read. To state, 2.5D means that we include the vector components in the third dimension, but removes the variation in the third direction. The main aspects to take into account when thinking of the magnetic components from this article are two ideas. The rise velocity of the magnetic field saturates in a short time when it reaches the Alfvén speed evaluated at the initial conditions. If an isolated flux tube has the same temperature as the external medium, it cannot be in magnetostatic equilibrium. In discussion, they use the term "collimated expansion" for an expansion in the $x - z$ plane, but which is restricted in the y-direction.

To summarize, the study is towards the case in which the unperturbed magnetic flux tube is in magnetostatic equilibrium with the external medium that has the same density distribution. "The overall nature of the magnetic flux expansion is characterized by the properties of the undular mode."

2. Magnetohydrodynamic Definition

The definition of "Magnetohydrodynamics" from "MHD modeling of the interaction between the solar wind and solar system objects" by Ekenbäck and Holmström, is that magnetohydrodynamics is the description of the average properties of a plasma by using the basic conservation laws for a fluid. This considered that plasma is conducting, so the effects of electric and magnetic fields and currents are added to ordinary hydrodynamics. Therefore, that makes it magneto.

How the phenomenon of magnetohydrodynamics works is kinematic relationships between plasma and fluids. Without several assumptions of position, densities, velocities of the fluid, magnetic fields, vacuum accountability, plasma pressure, internal energy, and external forces such as gravity, there would be no validation for most simulations of magnetohydrodynamic models.

Systematically, the ways that the models are used to understand the magnetohydrodynamics content of solar winds is by vector fields. The vector fields utilized by the 2004 study is that velocity shifted right while magnetic field vectors centrally shift right then diverge in either side of the y-axis. The demonstration of the simulation is to present the effects of the magnetic properties of solar wind from a plasma-entity with a solidified comet.

The meaning of “Magnetohydrodynamics” from “Magnetohydrodynamic modeling of the global solar corona” by Lionello, Mikić, Schnack, and Tarditi, is that it is a tool utilized for the exploitation of direct comparisons between observations and scientific models of the solar corona.

Significantly, magnetic reconnection is the strong evidence of conduction of plasma. The coronal magnetic reconnection not only defines the structure of the solar corona, but the position of the heliospheric current sheet, and the regions of fast and slow solar winds.

With that, the models utilized to understand the solar corona are the observational photos and the implanted field lines on a three-dimensional model and the heliospheric current sheets. These improved magnetohydrodynamics models confronts the limitations of the polytropic models. Polytropic models are graphical representations of the radius of the observed star to its dependence on density. Precisely, what links the phenomena in the solar wind back to their origin in the solar corona is the measurement established from probes' observations, which in this case is Ulysses.

IV Research

Coronal loop oscillations were studied analytically, but these studies are unfortunately applicable only onto highly idealized situations. The numerical simulations are often used for solutions of more complex problems – these studies are based on numerical solution of the full set of MHD equations. These mentioned studies of coronal loop oscillations are very important in connection with the problem of coronal heating, solar wind acceleration and many unsolved problems in solar physics. Magnetohydrodynamic coronal seismology is one of the main reasons for studying waves in solar corona.

1. Numerical Solution

The MHD equations (1) – (4) are transformed into a conservation form.

$$\frac{\partial u_i(x,t)}{\partial t} = -\sum_{j=1}^{3} \frac{\partial F_{i,j}(u_i(x,t))}{\partial x_j}$$

$$\partial_t \mathbf{\Psi} + \partial_x \mathbf{F}(\mathbf{\Psi}) = 0 \qquad \mathbf{\Psi} = (\varrho, \varrho v, B, U)$$

$$\frac{\partial \rho v_i}{\partial t} = -\nabla_j \left[\rho v_i v_j - \frac{B_i B_j}{\mu_0} + \delta_{ij} \left(\frac{B^2}{2\mu_0} + p \right) \right]$$

There exist a lot of numerical methods used for the solution of equations in conservation form in numerical mathematics. Generally, we can use the two types of numerical methods. First, the explicit methods calculate the state of a system at a later time from the state of the system at the current time. Second, the implicit methods find the solution by solving an equation involving both the current state of the system and the later one. Positively, the implication of utilizing explicit methods to modelling is ease in programming, while utilizing implicit methods is stable data. Contrarily, the positive and negative roles switch roles for these methods.

We will use only explicit methods in our calculations for this reason we must use the artificial smoothing for the stabilization of the numerical scheme. Some mathematical definitions of numerical methods for partial differential equations are:

- *Consistency* – the numerical scheme is called consistent if

$$\lim_{h \to 0} \tau_j^n = 0, \quad \text{for } x_j \in G_h, \ 1 \leq n \leq T/\tau$$

- *Convergence* – the numerical method is called convergent if

$$\lim_{h \to 0} \max_{x_j \in G_h} |e_j^{T/\tau}| = \lim_{h \to 0} \max_{x_j \in G_h} |f(T, x_j) - w_j^{T/\tau}| = 0$$

For the solution of the magnetohydrodynamic equations in a conservation form the methods of so-called *flux limiters* are used. These numerical methods are able to jump down the oscillations near sharp discontinuities and jumps. Generally, for the solution of partial differential equation in conservation form in one dimension, we can write:

$$q_i^{n+1} = q_i^n + \lambda(q_i^n - q_{i-1}^n) - \frac{\lambda(1-\lambda)}{2}[\phi(\theta_{i+1/2}^n)(q_{i+1}^n - q_i^n) - \phi(\theta_{i-1/2}^n)(q_i^n - q_{i-1}^n)]$$

$$\lambda \equiv \frac{\mathrm{d}t}{\mathrm{d}x}$$

$$\theta_{i-1/2}^n = \frac{q_{i-1}^n - q_{i-2}^n}{q_i^n - q_{i-1}^n}$$

Many authors often use the linear methods

- upwind scheme

$$\phi(\theta) = 0$$

- Lax-Wendroff scheme (downwind slope)

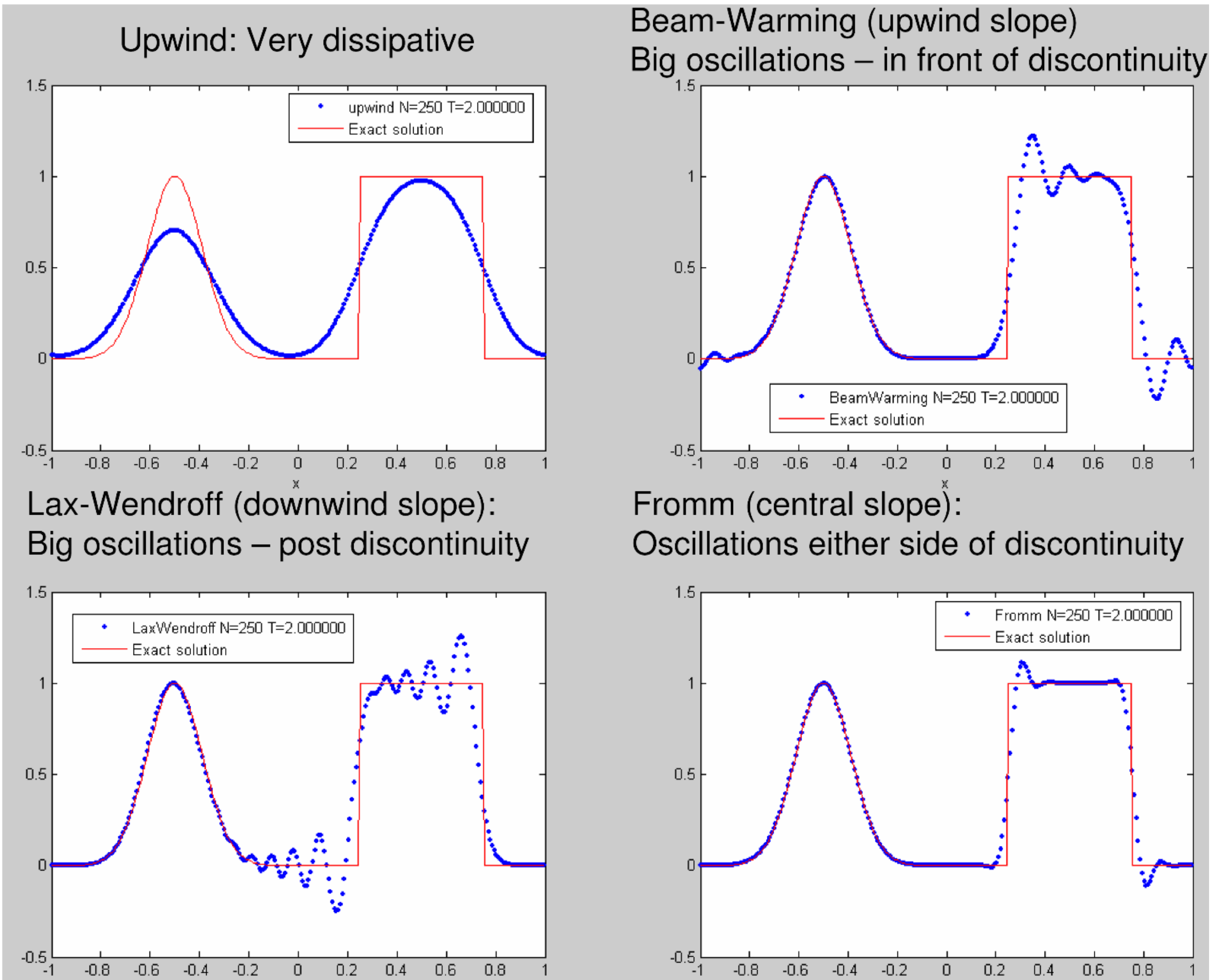
$$\phi(\theta) = 1$$

- Beam-Warming scheme (upwind slope)

$$\phi(\theta) = \theta$$

- Fromm scheme (centered slope)

$$\phi(\theta) = \frac{1}{2}(1+\theta)$$



To avoid the "overshoots" we limit the slope by flux limiter methods

- Minmod

$$\phi(\theta) = \mathrm{minmod}(1, \theta)$$

- Superbee

$$\phi(\theta) = \max(0, \min(1, 2\theta), \min(2, \theta))$$

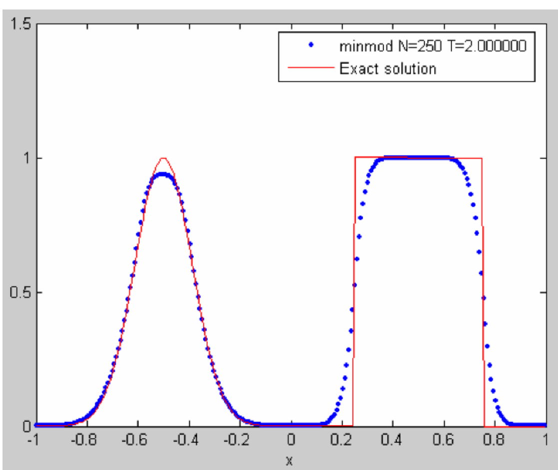
- MC

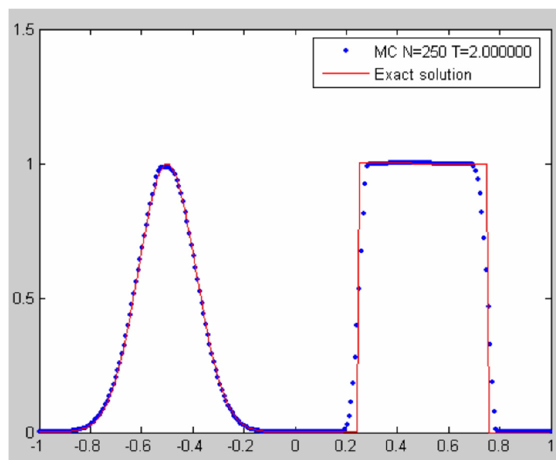
$$\phi(\theta) = \max\left(0, \min\left(\left(\frac{1+\theta}{2}\right), 2, 2\theta\right)\right)$$

- van Leer

$$\phi(\theta) = \frac{\theta + |\theta|}{1 + |\theta|}$$

- And many others – van Albada, OSPRE, UMIST, MUSCL schemes





2. One Dimension

There exists a lot of types of oscillations in solar coronal loop. This includes acoustic oscillations, kink and sausage oscillations, and fast and slow propagating waves. Acoustic oscillations are easy to simulate, they can be modelled in one dimensions, without magnetic field, etc. Kink and sausage oscillations were directly observed (SOHO, TRACE) and there are many unanswered questions – excitation and damping mechanisms, etc. We focused on the impulsively generated acoustic standing waves in coronal loops.

The initial conditions are:

$$p_0 = c_s^2 \varrho_0 / \gamma = \mathrm{const.}$$

$$\varrho(x) = \varrho_0 \left\{ \frac{d}{2} [\tanh(s(x - x_t)(x - L + x_t)) + 1] + 1 \right\}$$

$$\varrho_0 = 10^{-12}\ \mathrm{kg} \cdot \mathrm{m}^{-3}$$

The length of the coronal loop was L = 50 Mm which corresponds to loop radius about 16 Mm. The loop footpoints were settled at positions x = 0 and x = L.

In the view of our interest to study impulsively generated waves in the solar coronal loops, a pulse could be installed in the pressure and mass density. The pulse has the following form:

$$\delta f(x,0) = A_f \cdot \exp\{-[(x - x_0)/w]^2\}$$

$$f(x,0) = f_0(x,0) + \delta f(x,0)$$

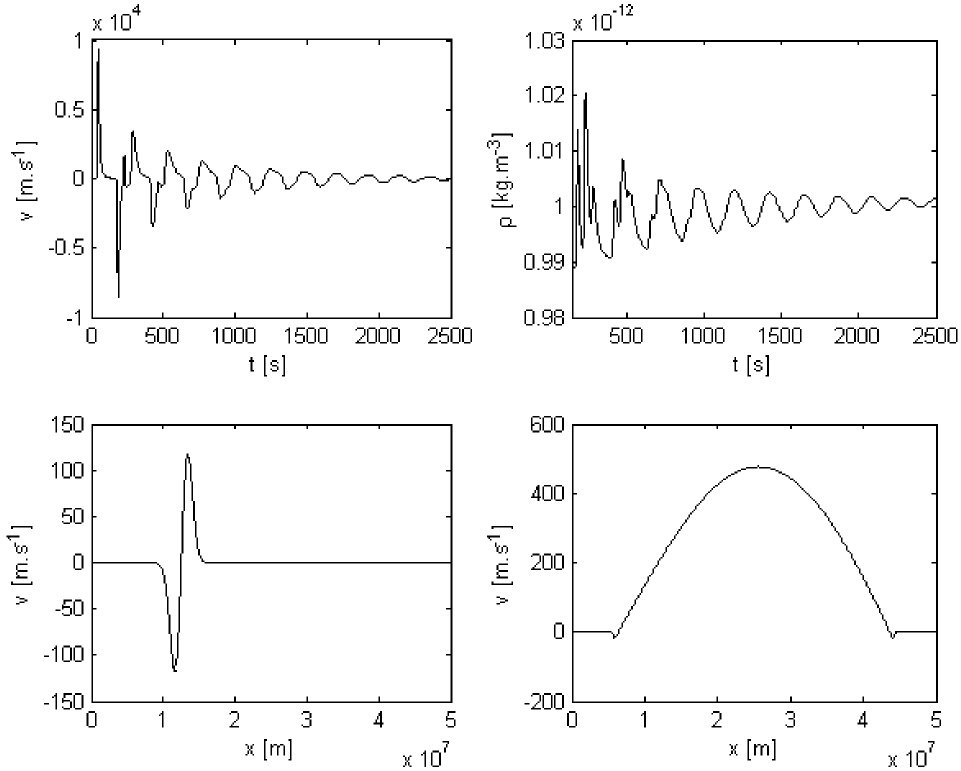
A_p	A_ϱ	$w[m]$	$x_0[m]$
$0.25p_0, 0.5p_0$	$0.125\varrho_0(x_0), 0.250\varrho_0(x_0)$	$L/40$	$L/2, L/4$

The numerical region were covered by a uniform grid with two thousand cells and open boundary conditions that allow a wave signal freely to leave the region were applied. The time step used in our calculations satisfied the Courant-Friedrichs-Levy stability condition in the form:

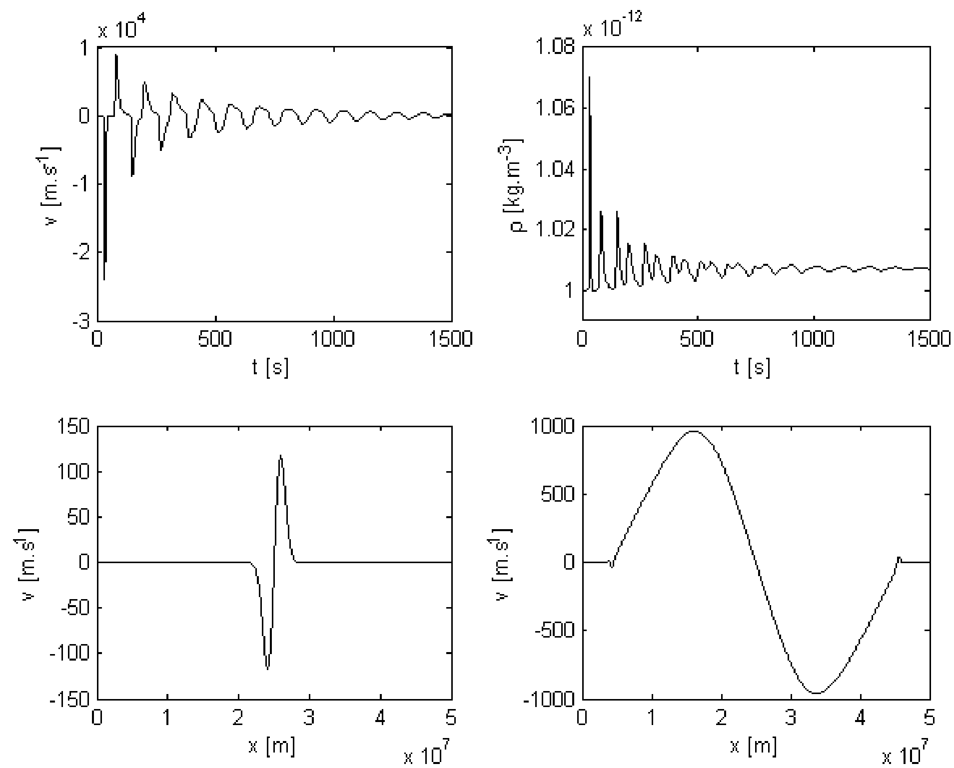
$$\Delta t \leq \frac{\mathrm{CFL} \cdot \Delta x}{\max(c_s + |v|)}$$

In order to stabilize of numerical methods we have used the artificial smoothing as the replacing all the variables at each grid point and after each full time step as

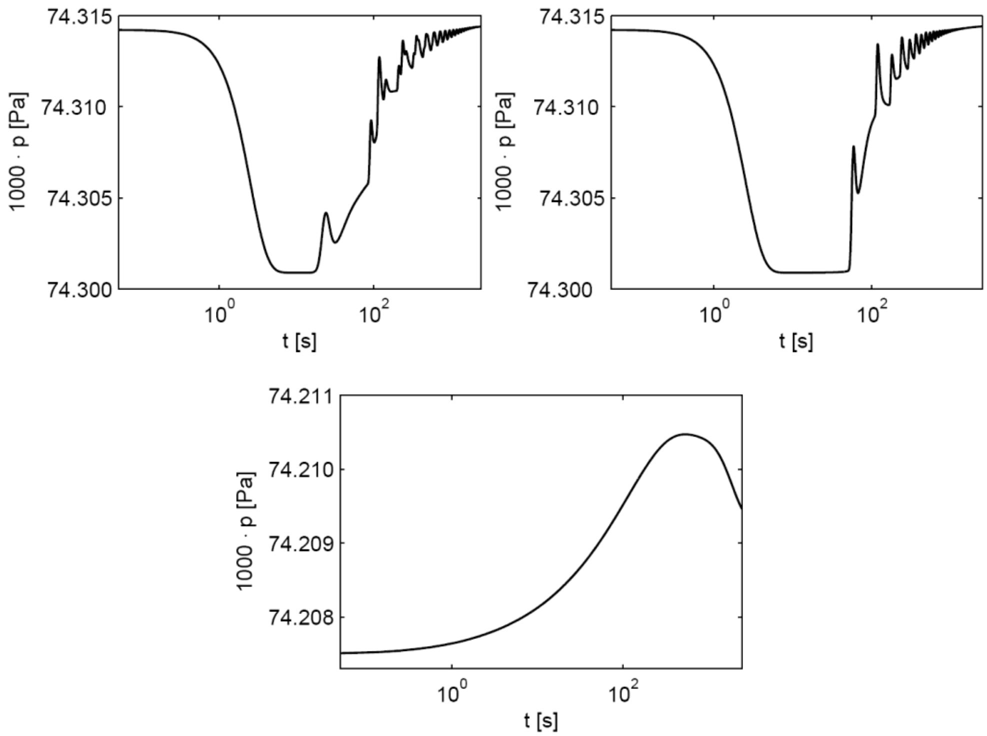
$$\mathbf{\Psi}_i^n \longrightarrow \mathbf{\Psi}_i^n + \frac{1-\lambda}{2}(\mathbf{\Psi}_{i+1}^n + \mathbf{\Psi}_{i-1}^n)$$



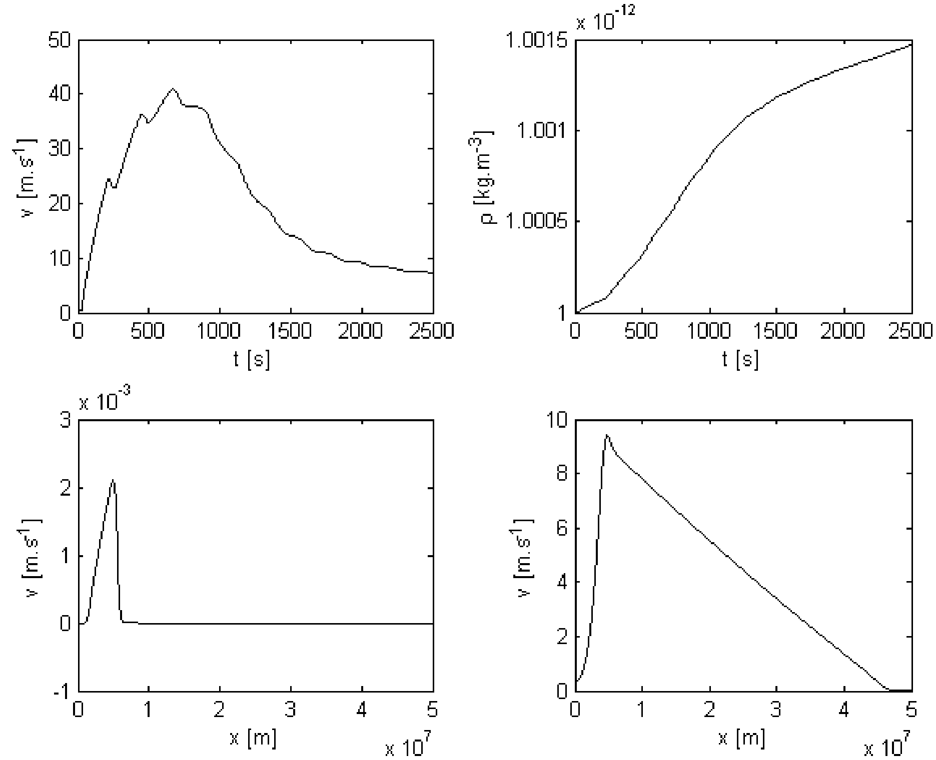
Time evolution of velocity $v(x = L/4,t)$, mass density $r(x = L/4,t)$ (top panels) and spatial profiles of velocity $v(x,Dt)$, $v(x,7.12T_1)$ (bottom panels); all for mass density contrast $d = 10^8$, pulse width $w = L/40$, and initial pulse position $x_0 = L/4$.



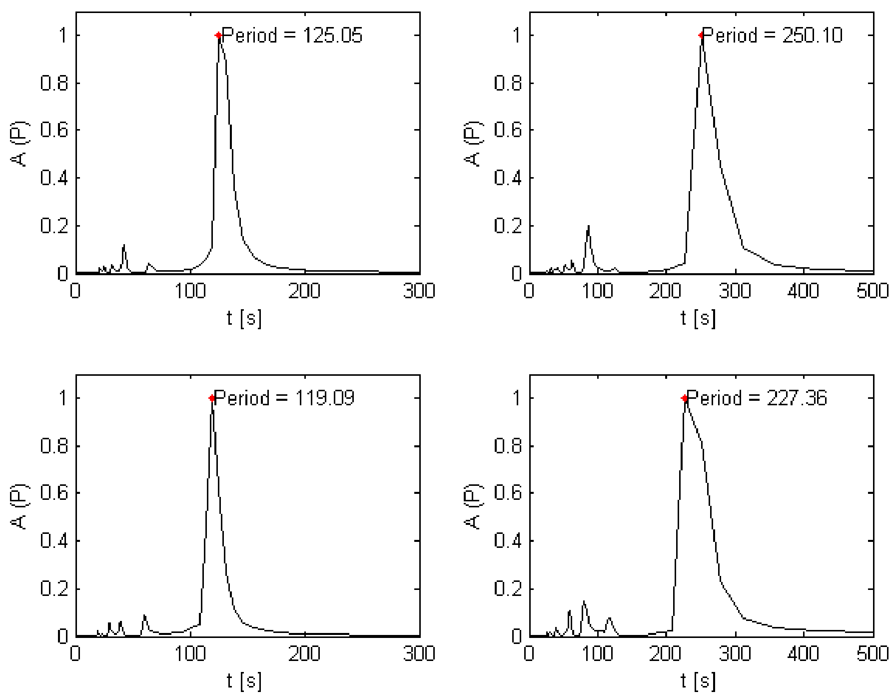
Time evolution of velocity $v(x = L/4,t)$, mass density r(x = $L/4,t$) (top panels) and spatial profiles of velocity $v(x,Dt)$, $v(x,7.89T_2)$ (bottom panels); all for mass density contrast d = 10^8, pulse width w = $L/40$, and initial pulse position x_0=$L/2$.



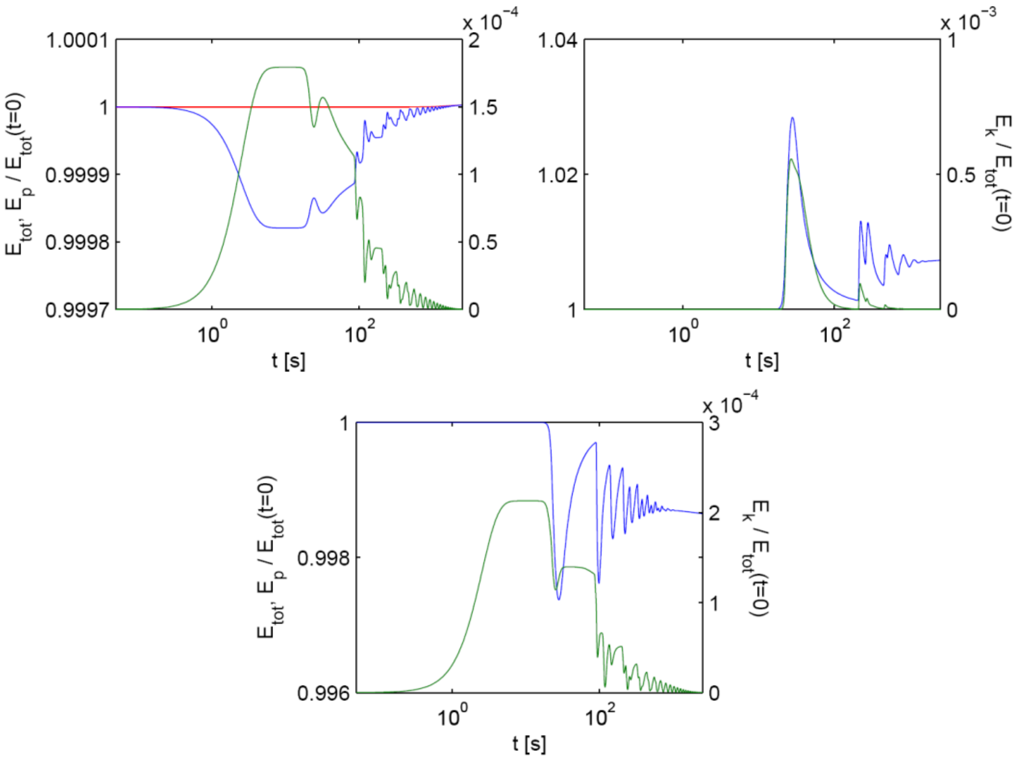
Time evolution of average pressure, increased by the factor 10^3, initial pulse position x_0 = L/4 (left top panel), x_0 = L/2 (right top panel) and x_0 = L/50 (bottom panel), mass density contrast $d = 10^8$ and pulse width w = L/40; note that x-axis is in the logarithmic scale.



Time evolution of velocity $v(x = L/4,t)$, mass density $r(x = L/4,t)$ (top panels) and spatial profiles of velocity $v(x,Dt)$, $v(x,11.00T_1)$ (bottom panels); all for mass density contrast $d = 10^8$, pulse width $w = L/40$, and initial pulse position $x_0 = L/50$.



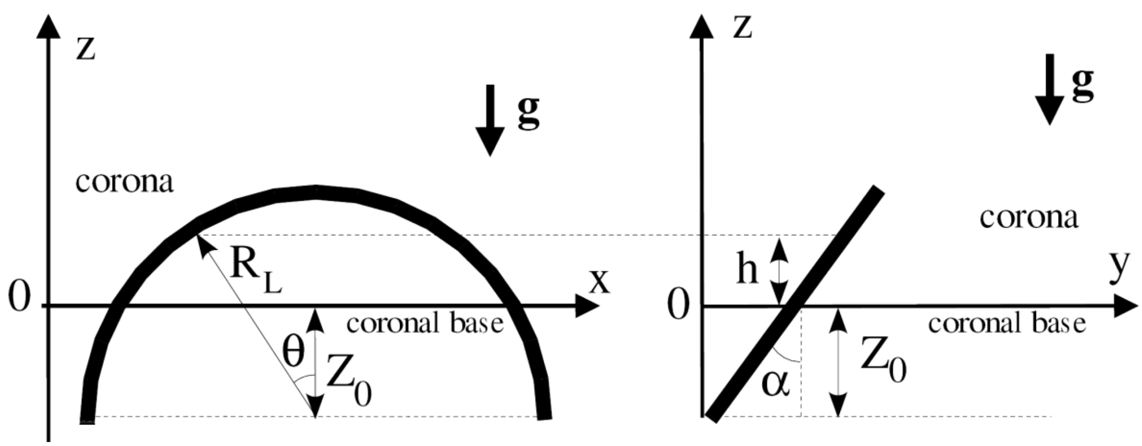
Fourier power spectra of velocities v for initial pulse position x_0 = L/2 (left) and x_0 = L/4 (right), mass density contrast $d = 10^5$ (top panels) and $d = 10^8$ (bottom panels) and pulse width w = L/40. The amplitude of the power spectrum $A(P)$ is normalized to 1.



There exists a lot of types of oscillations in solar coronal loop acoustic oscillations kink and sausage oscillations fast and slow propagating waves, … Acoustic oscillations are easy to simulate, they can be modelled in 1D, without magnetic field, etc. Kink and sausage oscillations were directly observed (SoHO, TRACE) and there are many unanswered questions – excitation and damping mechanisms, etc. We focused on the impulsively generated acoustic standing waves in coronal loops.

3. Stratified Flow

Stratified flow is used solely to create more realistic models. Here is semi-circular loop with the curvature radius R_L, in this model we incorporate the effect of loop plane inclination the shift of circular loop center from the baseline was omitted.



The magnetohydrodynamic equation of motion has the following form:

$$\varrho \partial_t \vec{v} + \varrho(\vec{v} \cdot \nabla)\vec{v} = -\nabla p + \frac{1}{\mu_0}(\nabla \times \vec{B}) \times \vec{B} + \varrho g$$

The gravitational acceleration at a distance *s* measured from the footpoint along the loop, is:

$$g(s) = \frac{GM_\odot}{R_\odot^2} \frac{\left[\frac{X_0}{R_L}x - \frac{Z_0}{R_L}h\right] \cos\,\alpha}{\left[1 + \frac{R_L}{R_\odot}\left(\frac{X_0}{R_L}h - \frac{Z_0}{R_L}(1-x)\right) \cos\,\alpha\right]^2}$$

$$x = \cos(s/R_L) \qquad h = \sin(s/R_L) \qquad X_0/R_L = (1 - Z_0^2/R_L^2)^{1/2}$$

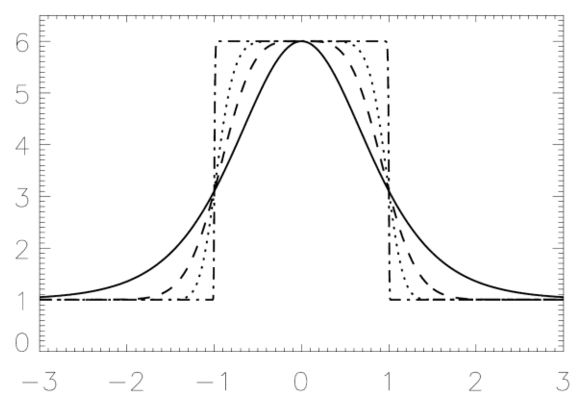
For the plasma pressure in the loop, we can write:

$$0 = -\frac{dp}{dz} - \rho g \qquad \Longrightarrow \qquad p = p_0 \exp - \int_0^z \frac{1}{\Lambda(z)} dz$$

$$\Lambda(z) = \frac{k_B T(z)}{mg}$$

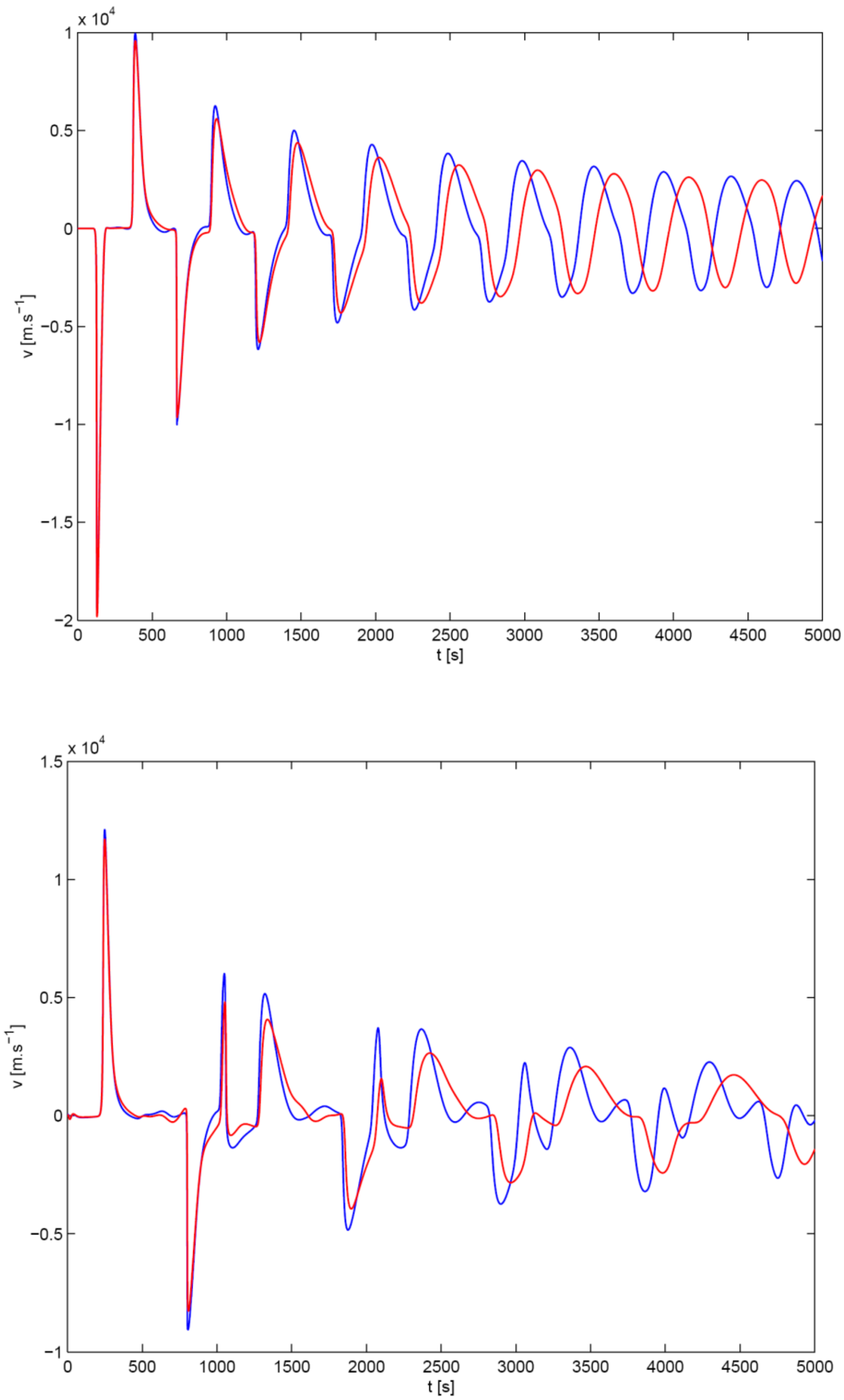
The temperature profile should be calculated by means of this formula:

$$T(x) = T_{\mathrm{ph}} + (T_{\mathrm{cor}} - T_{\mathrm{ph}})\mathrm{sech}^2\left[\left(\frac{x}{a}\right)^n\right]$$



The mass density should be calculated from:

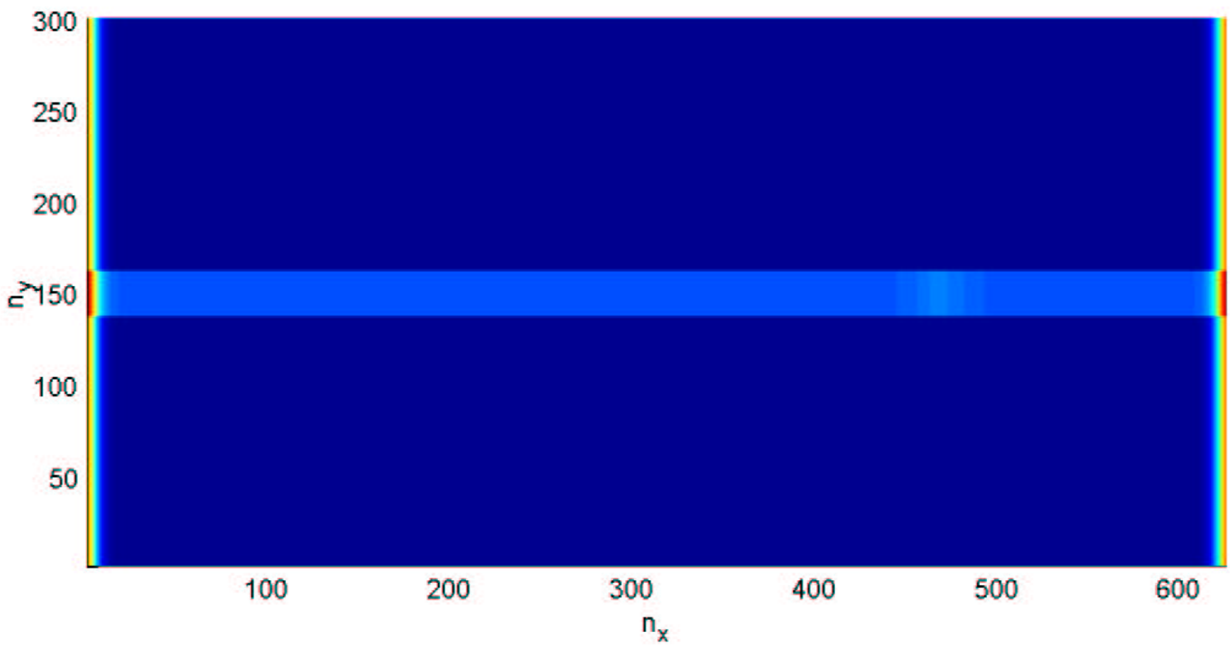
$$\varrho = \frac{mp}{k_{\mathrm{B}} T}$$



Time evolution of velocity $v(x = L/4, t)$, mass density contrast $d = 10^2$, pulse width $w = L/80$, and initial pulse position $x_0 = L/4$ and $x_0 = L/2$, inclination angle $a = 0°$ (blue line) and $a = 45°$ (red line).

4. Two Dimensions

We consider a coronal slab with a width w = 1Mm and mass density r_i, embedded in an environment of mass density r_e



The pressure, mass density, temperature and initial pulses in pressure and mass density are calculated similarly as in one-dimensional model.

For the solution of two-dimensional magnetohydrodynamic equations, the Lax-Wendroff numerical scheme was used, this method is often used for the solutions of magnetohydrodynamic by many authors.

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{f}}{\partial x} + \frac{\partial \boldsymbol{g}}{\partial y} = 0$$

Step 1

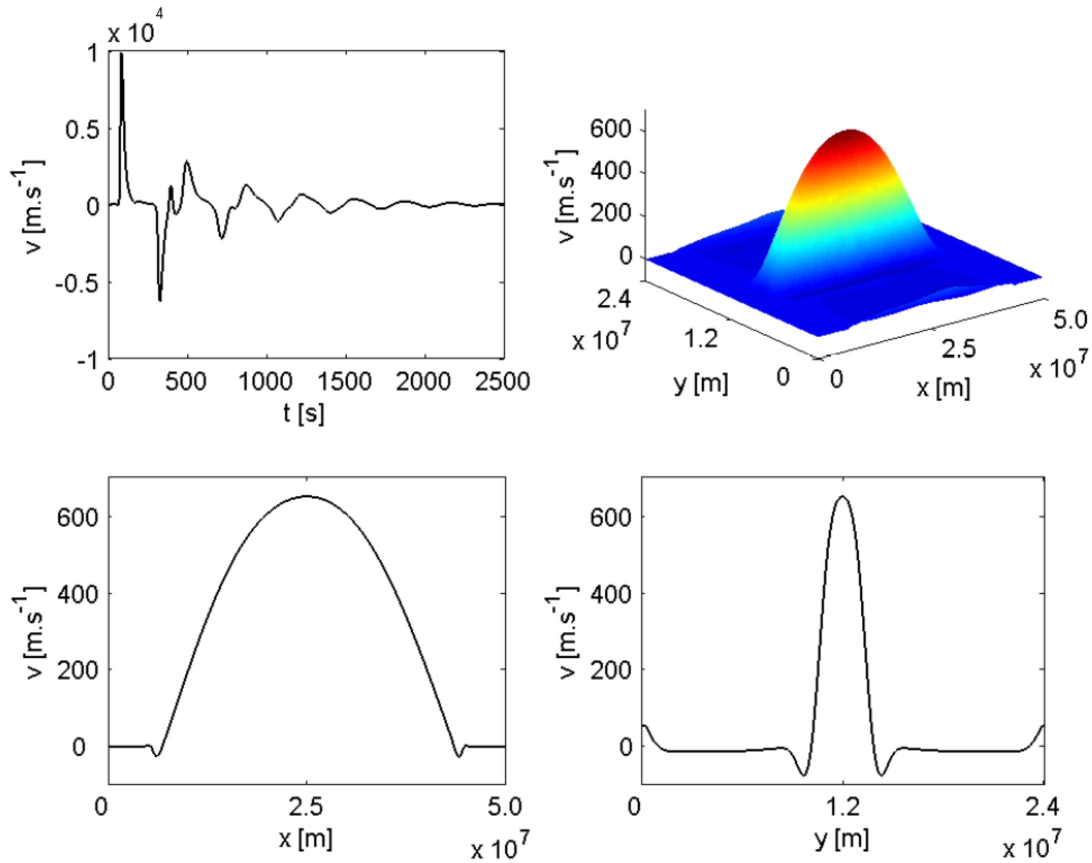
$$\boldsymbol{U}_{i,j}^{n+\frac{1}{2}} = \frac{1}{4}(\boldsymbol{U}_{i+1,j}^{n} + \boldsymbol{U}_{i-1,j}^{n} + \boldsymbol{U}_{i,j+1}^{n} + \boldsymbol{U}_{i,j-1}^{n}) + \frac{\Delta t}{2\Delta x}(\boldsymbol{f}_{i+1,j}^{n} - \boldsymbol{f}_{i-1,j}^{n}) + \frac{\Delta t}{2\Delta y}(\boldsymbol{g}_{i,j+1}^{n} - \boldsymbol{g}_{i,j+1}^{n})$$

Step 2

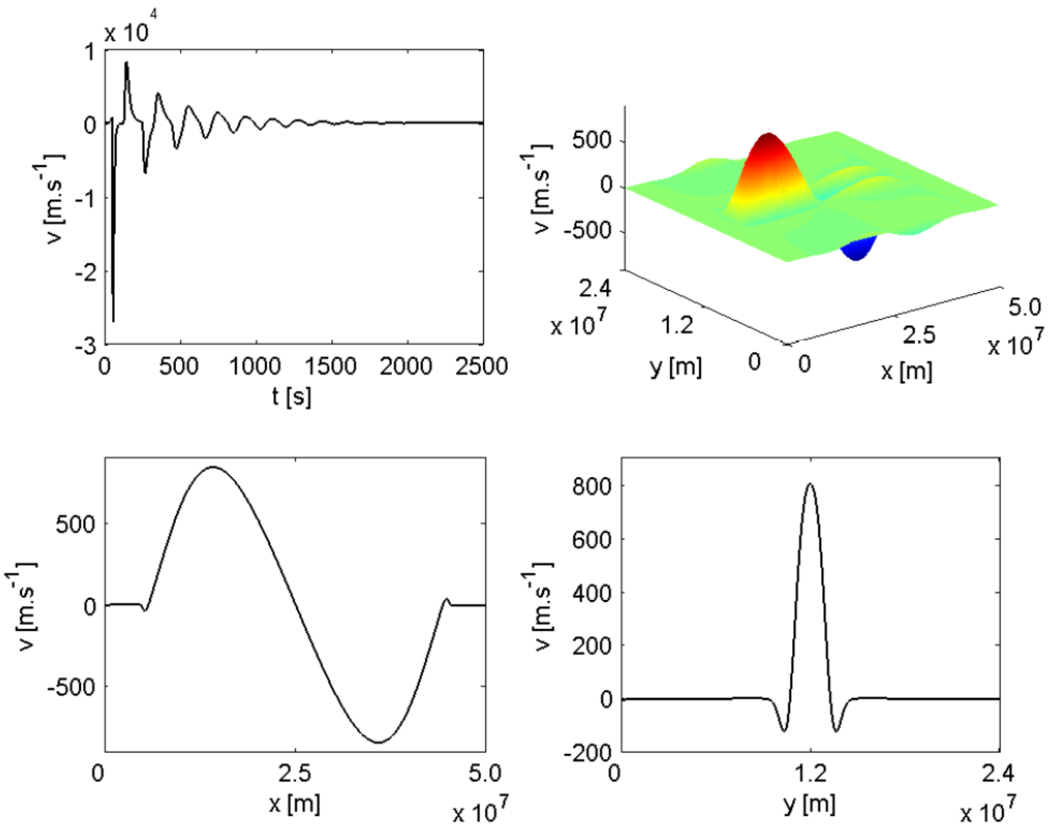
$$\boldsymbol{U}_{i,j}^{n+1} = \boldsymbol{U}_{i,j}^{n} - \frac{\Delta t}{\Delta x}(\boldsymbol{f}_{i+1,j}^{n+\frac{1}{2}} - \boldsymbol{f}_{i-1,j}^{n+\frac{1}{2}}) - \frac{\Delta t}{\Delta y}(\boldsymbol{g}_{i,j+1}^{n+\frac{1}{2}} - \boldsymbol{g}_{i,j-1}^{n+\frac{1}{2}})$$

The Stability Condition

$$\frac{\Delta t}{\Delta x}(c_s + |v|) \leq \frac{1}{\sqrt{2}}$$

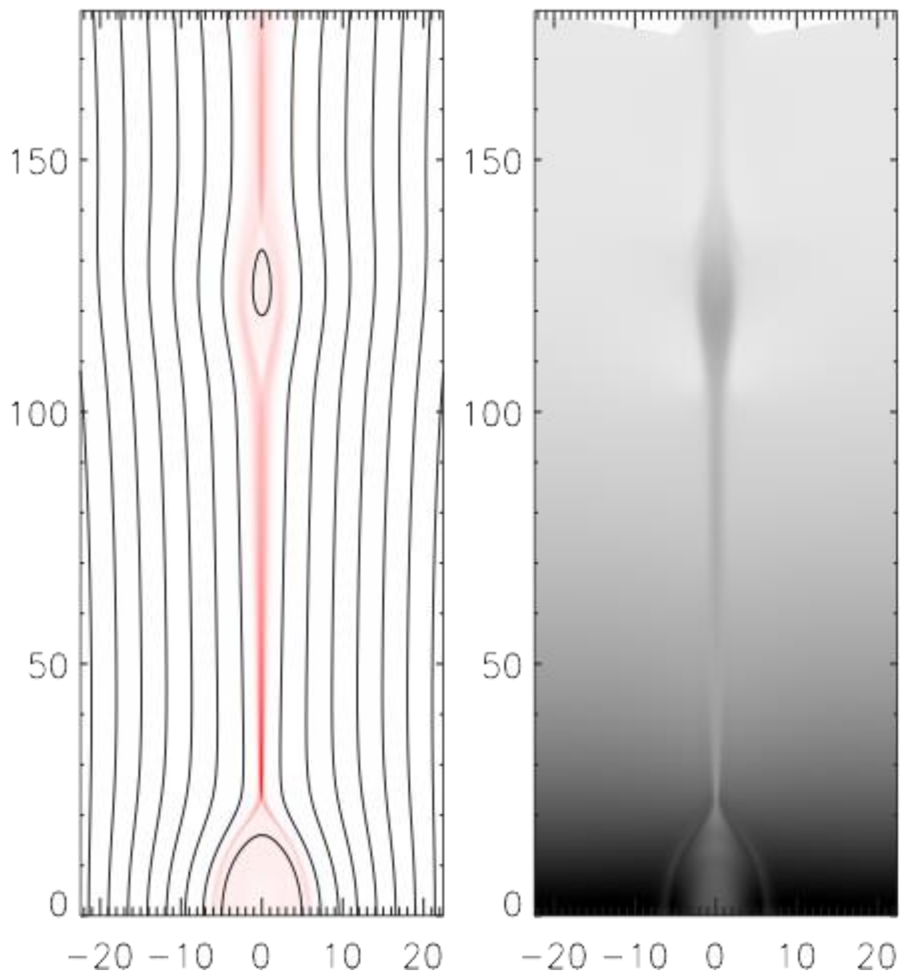


Time evolution of velocity $v(x = L/4, y = 0, t)$ (left top panel). Spatial profile of x-component of velocity – vx at time t = 8.17 $T1$ (right top panel) and the corresponding slices of vx along y = $H/2$ ($x = L/2$) – bottom left (right) panel; all for mass density contrast d = 108, pulse width $w = L/40$, and initial pulse position $x0 = L/2$.



Time evolution of velocity v(x = L/4, y = 0, t) (left top panel). Spatial profile of x-component of velocity – vx at time t = 6.15 T2 (right top panel) and the corresponding slices of vx along y = H/2 (x = L/4) – bottom left (right) panel; all for mass density contrast d = 108, pulse width w = L/40, and initial pulse position x0 = L/4.

5. Pseudo-3D



2.5D MHD modelling of solar flare. Formation of raising magnetic arcade above the bottom boundary – photosphere and plasmoid ejection are clearly visible. Left panel:magnetic field lines (black contours) and the current density (red area); right panel: the density structure in gray-scale (black means higher value).

The system is numerically solved in the 2.5D geometry (2D symmetry with z-component of vectors allowed) inside a rectangular box with the fixed boundary condition (simulating the solar photosphere) on the bottom and free outer boundaries. We used a vertical Harris type current sheet that was perturbed around the point [x = 0LA, y = 20LA] for a finite time by anomalous resistivity as an initial state.

6. Three Dimensions

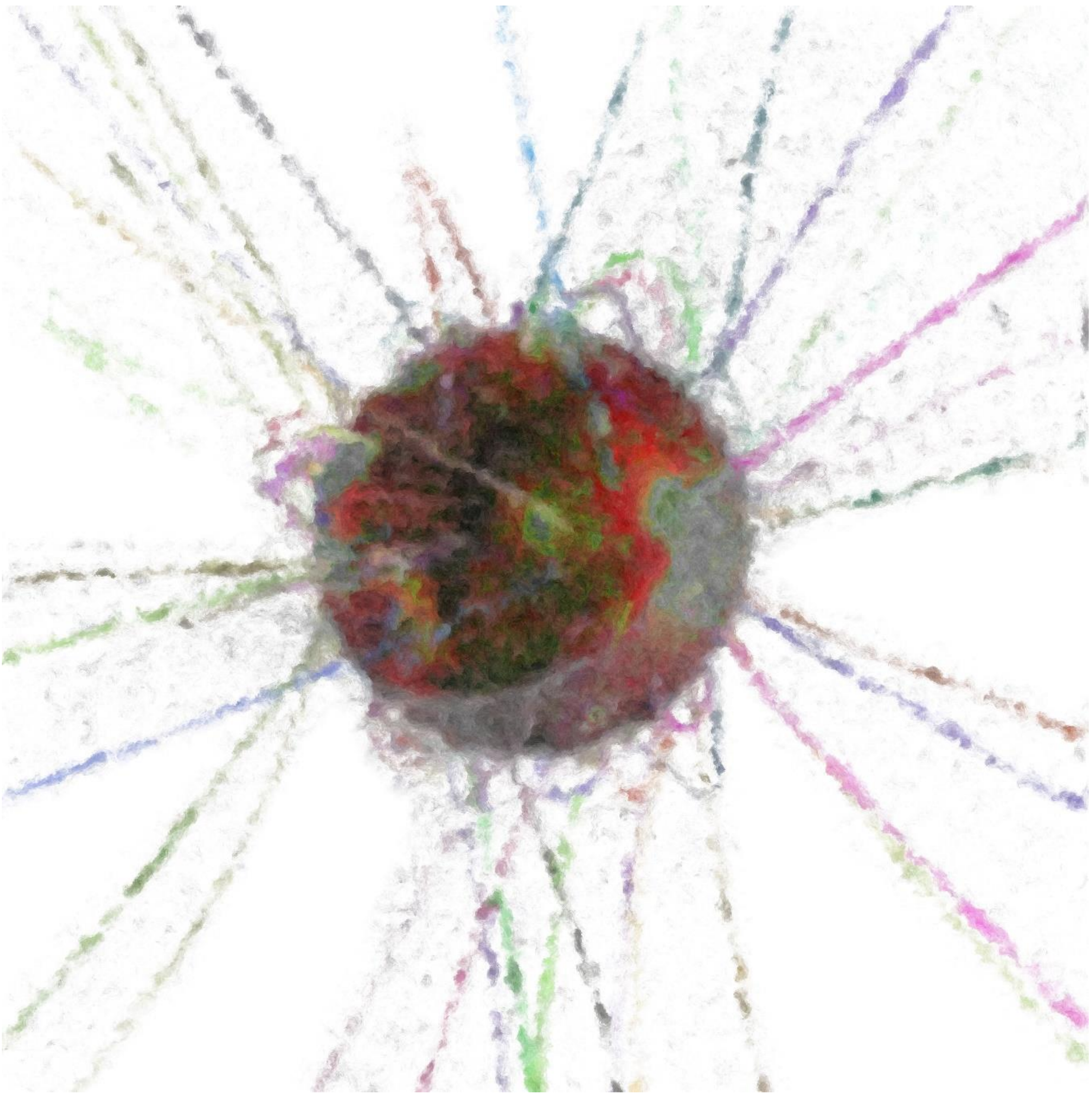
These researchers span three decades, building upon each other from a shift of observation to advances in modeling. Generally, what is asked by these studies are what will the observation of the plasma in the Sun produce as a model. In turn, this will answer where the energy of the corona is located to heat the plasm. That is where the dissipation of magnetic currents could root out the answers. When it comes to addressing magnetohydrodynamics, the Max-Planck-Institut discovered that the coronal loops examined are heated predominantly by Ohmic heating, which is induced by the braiding of field lines through the photospheric motions. Additively, the research from the NASA Astrophysics Data System focused on the footprints of the magnetic loops in the corona that determines the speed of the downflow from its expanding loops. Contrary, the Swedish Institute of Space Physics focuses on the interaction between the solar wind and solar system objects and its ejections. The Science Applications International Corporation takes in the observations of the coronal structure and three-dimensional magnetohydrodynamic model, which would direct these other studies. Overall, what taken into my study was the agreement goes to the deliver of sufficient amount of energy at the base of the corona to heat the plasma based on the magnetic flow of the Sun, expelling solar flares. Generally, what was fascinating was the modelling utilized to elevate beyond observations. Focusing on the study done in Germany, three-dimensional model is not enough to resolve the dissipation length scales done with precision, but it provides the redistribution of energy. What I learnt that it is not necessary to obscure sunspots though, but utilizing x-ray imaging from telescopes, hot loops can be seen by its connection of two extended regions showing opposite polarity. Therefore, there is a strong magnetic field in the Sun. These objective place my concentration of three-dimensional modeling to the topic of solar magnetohydrodynamics. It shifted far from 1992's study done by the American Astronomical Society by non-linear 2.5D simulation. This model was the inclusion of three-dimensional vector components without its variation. Also, it advanced beyond kinematic-oriented work done by 1998's study in California on coronal holes. Regardless, these two studies have increased sophistication since the idealized models. What intrigued me is the scale of the polytropic model that requires the interaction of forces by plasma, magnets, and solar gravity. What this adds in the German study is a self-consistent description of the thermal structure of the plasma and of the magnetic field in the coronal structure. All the model had to do was include heat conduction by gravitational force which has done. Specialized, the Swedish studied the interaction of solar winds to solar system objects. This study utilized Flash Code. Essentially, Flash Code is a software with modules that mesh hydrodynamic code to model astrophysical thermonuclear flashes. This method is used to scale magnetohydrodynamic aspects on a smaller scale which is fundamental to classify plasma overall. To conclude this summarization, what I picked up from the studies is the processes of modeling to identify the global magnetic structure of the Sun. Predictively, for the future studies done on the corona would reproduce the magnetic connections if this magnetosphere still loops. Problematically, what I look forward to is studying the Flash Code and what I still question is what observational methods can be done to study the coronal loops that done in this year's modeling with advancements in telescopes and coding.

In reiteration, these various cases spanned three decades of modeling to clarify the plasma's interaction. Particularly, the interactions of the solar flare and solar system objects. In addition to these researchers, there was a study of the gasdynamic models of this planet's magnetosheath from Stanford in 1994 and data-driven modeling magnetohydrodynamic modelling done by the SIGMA Weather Group from the Chinese Academy of Sciences. Additively, Stanford shapes the work of the Swedes on the interaction between the solar wind and solar system objects. Stanford did so by focusing on the terrestrial magnetosheath rather than comets. Contrarily, SIGMA builds from the other three studies, with the new emphasis on the modeling of solar eruption. Fundamentally, these studies build on the idea of where the energy of the corona is located to heat the plasma and its effects on the solar system objects.

In summary, Stanford addressed magnetohydrodynamic components through gasdynamics. Gasdynamics is compressible flow or the branch of fluid mechanics that deals with flows having significant changes in fluid density. Topically, it shares elements of how the corona is live and shifts its magnetic field as its plasma. Conclusively, the magnetosheath of Venus is influenced by the effects of newly ionized neutral atmospheric atoms or molecules and is displayed by modeling bow shocks where the plasma properties from solar flares change from one equilibrium to another. Illustratively, this study is unique for the attention on shockwaves and connection of the bow shocks from observing terrestrial planets to the amount of sunspots. Effectively, the sunspots' magnitude is proportional to the intensity of plasmic solar flares. Interestingly, they degenerate the magnetosheath of the Moon or any objects like it that they neither have a magnetic field to stop the solar wind plasma before it reaches the surface. Previously, each magnetohydrodynamic solution was time-consuming using a Cray YMP computer. Including the American Astronomical Society's study, it acknowledges the difficulty of computation. Problematically, this is due to the enormous number of values that must be output to represent a single solution. Advancing, that is where the SIGMA study addresses the data. The computational work was carried out in the National Supercomputer Center in Tianjin, China. Their simulation started with a magnetohydrodynamic model that is almost current-free and then focused on the photospheric field in a low plasma condition. The HMI of the supercomputer provided routine vector data of the photosphere with precisional resolution of 1 arc second for any formations of solar eruption. The data are driven by supplying the bottom boundary derived from the Poynting flux. Descriptively, the Poynting is the directional energy flux of an electromagnetic field. Conclusively, the models exemplified that the magnetic free energy continuously increase due to the uninterrupted injection of energy into the volume with graphic models that free energy is proportional to time. This fits the topographic models of evolution in the magnetic field of the coronal as it loops.

Captivatingly definitive, SIGMA explained that the methods to modeling was numerical calculations of time-dependent kinematics with the bottom boundary conditions being proportional to what is observed of the photosphere. Sparingly, the researchers did not consider the physics of the chromosphere to the transition region. Quantumly, this is due to the overall unknown of how the coronal heating is mechanized where temperatures sour from a few to several magnitudes of degrees. Significantly, SIGMA coloured the magnetic loops of previous studies. Relatively, SIGMA traces the German study by observing the active regions of sunspots and its redistribution of energy by graphing the free energy from the solar plasma. Reevaluating the 2013 study, they would define magnetohydrodynamic components in their models by its projections of field lines crossing the maximum of the synthesized emission of the respective loop in the three-dimensional computational domain. For Stanford's then innovative gasdynamic convected magnetic field model, it was derived as a tractable approximation to the magnetohydrodynamic model, using a workstation. The corresponding magnetohydrodynamic solutions and the Earthly and other solar system's observation demonstrate its accuracy and compare it with the solar wind data. Simply, if the field is aligned with the flow, the magnetohydrodynamic equations can be transformed into a simpler set of equations that resemble those of gasdynamic. Mathematically, it adds to the phenomenon portrayed by the Swedish study by the characteristic weak bow shock in all simulations. From the stand-point of bow shocks when observing these models again, the phenomenon of magnetohydrodynamics is based on the drape of the magnetic field from the nucleus of the observed solar system object as it is impacted by the solar wind.

In conclusion to this portion of the study, the two papers elevated the comprehensions of the solar active region and its magnetic loops by the details of free energy, and drift the focus off of the Flash Code towards the bow shock trends of the models from the Swedish research team. What was garnered was the models' field lines being what would be mentally ingrained when the phenomenon of magnetohydrodynamics comes to mind. Personally, it builds on the impact that computational modeling has advanced far. Earlier, it started from the studies of the solar atmospheric magnetic flux. Later, studies from supercomputers would factor out the entirety of the chromosphere. Phenomenally, the study and models of magnetohydrodynamic will continue to do so.



V Solar Explanation

When it came to addressing magnetohydrodynamics, one of the earliest experiments with fluids was done by the father of the electric field himself: Michael Faraday. Formulaically, this experiment was on the salt water. There was a focus on its potential difference from its interaction with the Earth's magnetic field. Eventually, the Max-Planck-Institut discovered that the examined coronal loops heated. Predominantly, Ohmic heating heated these loops. The braiding of field lines through the photospheric motions induced Ohmic heating. Additively, the NASA Astrophysics Data System focused on the magnetic loops' footprints in the corona. This determines the speed of the downflow from its expanding loops. Contrarily, the Swedish Institute of Space Physics placed attention on the interactions between the solar wind ejections upon solar system objects. In addition, Stanford studied the gasdynamic models of this planet's magnetosheath. Lately, the contemporary case has been the data-driven modeling magnetohydrodynamic modeling. The SIGMA Weather Group from the Chinese Academy of Sciences provided this study.

Previously, each magnetohydrodynamic solution was time-consuming using a Cray YMP computer. Stanford's and the American Astronomical Society's study acknowledges the difficulty of computation. Problematically, this is due to the enormous number of values that must be output to represent a single solution.

Critically, Flash Code is a difficult software. It utilizes modules that mesh hydrodynamic code to model astrophysical thermonuclear flashes. The Stanford paper elevated the comprehensions of the solar active region and its magnetic loops. By the details of free energy, focus drifted off of the Flash Code towards the bow shock trends of the models from the Swedish research team. Advancing, that is where the SIGMA study addresses the data. The National Supercomputer Center in Tianjin, China carried out the computational work. Their simulation started with a magnetohydrodynamic model that is almost current-free. Then, they focused on the photospheric field in a low plasma condition. Precisely, the HMI of the supercomputer provided routine vector data of the photosphere. This had a resolution of one arc second for any formations of solar eruptions. By supplying the bottom boundary derived from the Poynting flux, the data was driven. Descriptively, the Poynting is the directional energy flux of an electromagnetic field. Conclusively, the models exemplified that the magnetic free energy continuously increase due to the uninterrupted injection of energy into the volume with graphic models that free energy is proportional to time. This fits the topographic models of evolution in the magnetic field of the coronal as it loops.

Overall, there was an agreement for the delivery of sufficient amount of energy at the base of the corona to heat the plasma. The magnetic flow of the Sun bases this agreement, expelling solar flares. Regardless, these studies have increased sophistication since the idealized models. What intrigued me is the scale of the polytropic model that requires the interaction of forces by plasma, magnets, and solar gravity. What this adds in the German study is a self-consistent description of the thermal structure of the plasma. Also, it added the magnetic field in the coronal structure. All the model had to do was include heat conduction by gravitational force. Specialized, the Swedes studied the interaction of solar winds to solar system objects. This Flash Code method scaled magnetohydrodynamic aspects on a smaller scale. Overall, this is fundamental to classify plasma. Additively, Stanford shapes the work of the Swedes on the interaction between the solar wind and solar system objects. Stanford did so by focusing on the terrestrial magnetosheath rather than comets. Contrarily, SIGMA's latest observation builds from the other three studies. There is the new emphasis on the modeling of solar eruptions. Fundamentally, these studies build on the curiosity of location for the energy of the corona to heat the plasma. Also, its effects on the solar system objects. Stanford addressed magnetohydrodynamic components through gasdynamics. Gasdynamics is the compressible flow or the branch of fluid mechanics. This deals with flows having significant changes in fluid density. Topically, it shares elements of how the corona is live and shifts its magnetic field as its plasma. Conclusively, the newly ionized neutral atmospheric molecules influenced Venus' magnetosheath. It modeled bow shocks where the plasma properties from solar flares change from one equilibrium to another. Illustratively, this study is unique for the attention on shock waves and connection of the bow shocks from observing terrestrial planets to the amount of sunspots. Effectively, the sunspots' magnitude is proportional to the intensity of solar flares. Interestingly, they degenerate the magnetosheath of the Moon or any objects like it that they neither have a magnetic field. There is nothing to stop the solar wind plasma before it reaches the surface.

Fascinatingly, the modeling was utilized to elevate beyond observations. Focusing on the German study, three-dimensional model is not enough to resolve the dissipation length scales done with precision. But, it provides the redistribution of energy. What was learnt is that it is unnecessary to obscure sunspots. Though, utilizing x-ray imaging from telescopes, connection of two extended regions showing opposite polarity notices the hot loops. Therefore, there is a strong magnetic field in the Sun. This objective placed the concentration of three-dimensional modeling to the topic of solar magnetohydrodynamics. It shifted far from 1992 American Astronomical Society's study by non-linear 2.5D simulation. This model was the inclusion of three-dimensional vector components without its variation. Also, it advanced beyond kinematic-oriented work done by 1998's study in California on coronal holes. Captivatingly and definitively, SIGMA's modeling methods were numerical calculations of time-dependent kinematics with the bottom boundary conditions. The boundary conditions were proportional to the photosphere's observations. Sparingly, the researchers did not consider the physics of the chromosphere to the transition region. Quantumly, this is due to the unknown of how the coronal heating mechanized itself. This is where temperatures soar from a few to several magnitudes of degrees. Significantly, SIGMA coloured the magnetic loops of previous studies. By graphing the free energy from the solar plasma, SIGMA traces the German study. They observed the active regions of sunspots and its redistribution of energy. Reevaluating the 2013 study, they would define magnetohydrodynamic components in their models by its projections of field lines crossing the maximum of the synthesized emission of the respective loop in the three-dimensional computational domain. For Stanford's then innovative gasdynamic convected magnetic field model, a workstation derived a tractable approximation to the magnetohydrodynamic model. The corresponding magnetohydrodynamic solutions as well as the Earthly and other solar system's observation demonstrate its accuracy. Just compare it with the solar wind data. If the field aligned with the flow, the magnetohydrodynamic equations can transform into a simpler set of equations. These equations would resemble those of gasdynamic. Mathematically, it adds to the phenomenon portrayed by the Swedish study. It integrated the characteristic weak bow shock in all simulations. From the stand-point of bow shocks when observing these models again, the phenomenon of magnetohydrodynamics is based on the drape of the magnetic field from the nucleus of the observed solar system object as the solar wind impacts it.

VI Conclusion

In conclusion, the fundamental concept behind this study is that the magnetic fields can induce currents in. Consequently, this polarizes plasma, salt water, or liquid metals. In turn, this changes the magnetic fields itself. With the processes of modeling, there is an identification of the global magnetic structure of the Sun. Predictively, the future corona studies would reproduce the magnetic connections if this magnetosphere still loops. The models' field lines garnered this. This would be mentally ingrained when the phenomenon of magnetohydrodynamics comes to mind. Personally, it builds on the impact that computational modeling has advanced far. Earlier, it started from the studies of the solar atmospheric magnetic flux. Later, studies from supercomputers would factor out the entirety of the chromosphere. Phenomenally, the study and models of magnetohydrodynamic will continue to do so. Before computation, many scientists believed that there was a magnetic connection. A magnetic connection was in the solar flare as it pummels our world. This was once done by observing the Sun. Currently, we can see to believe by believing in supercomputer calculations and its computer models.

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