Investigating the magnetic reconnection-condensation model for solar prominence formation

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by

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to

SCHOOL OF PHYSICS
INDIAN INSTITUTE OF SCIENCE EDUCATION AND RESEARCH
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DECLARATION

I, **Abhinav Govindan Iyer (Roll No: MSC21401)**, hereby declare that, this report entitled **"Investigating the magnetic reconnection-condensation model for solar prominence formation"** submitted to Indian Institute of Science Education and Research Thiruvananthapuram towards the partial requirement of **Master of Science** in **Physics**, is an original work carried out by me under the supervision of **Dr. Nitin Yadav** and has not formed the basis for the award of any degree or diploma, in this or any other institution or university. I have sincerely tried to uphold academic ethics and honesty. Whenever a piece of external information or statement or result is used then, that has been duly acknowledged and cited.

Thiruvananthapuram - 695 551 **Abhinav Govindan Iyer**

April 2023

CERTIFICATE

This is to certify that the work contained in this project report entitled **"Investigating the magnetic reconnection-condensation model for solar prominence formation"** submitted by **Abhinav Govindan Iyer** (**Roll No: MSC21401**) to Indian Institute of Science Education and Research, Thiruvananthapuram towards the partial requirement of **Master of Science** in **Physics** has been carried out by him under my supervision and that it has not been submitted elsewhere for the award of any degree.

Thiruvananthapuram - 695 551 Dr Nitin Yadav
April 2023 Project Supervisor

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ABSTRACT

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Thesis title: **Investigating the magnetic reconnection-condensation model for solar prominence formation**

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We investigate the formation of solar prominences by performing 1D radiative hydrodynamic simulations using MPI- Adaptive Mesh Refinement - Versatile Advection Code (MPI-AMRVAC) [1] in a magnetic loop. The loop has a shallow dip and the radiative losses considered are realistic. The localized heating function is steady and decays with height from the chromosphere. We consider both symmetric heating as well as asymmetric heating, where the heating at the two footpoints of the loop is different. In the symmetric case, a single prominence is formed at the midpoint. However, for small values of heating scale length, two prominences were formed which coalesced at the centre to finally form a single prominence. In the asymmetric case, the prominence formed moves towards the less heated side and eventually drains down that side's footpoint. It is seen that this process is repeated throughout. Finally, we also study the effects of heating scale length and amplitude of localized heating on the onset time of the prominence.

Key Words : Solar physics, corona, prominences, localized heating

1 Introduction

In 1875, Angelo Secchi published his landmark text, *Le Soleil* (which translates to "The Sun"). The chapter on prominences began with the following statement,"*The phenomenon of prominences is now so well known by everybody that it may seem unnecessary to retrace the history of their discovery*" [2] . However, nearly 150 years after this statement, our understanding of solar prominences still remains incomplete and not widely known. My current project aims to explore the formation mechanisms of solar prominences, using numerical simulations as the primary tool.

To begin with, what are solar prominences? The word may be used to describe a variety of structures, so a single concise definition cannot do justice. Nevertheless, a crude definition is that prominences are cool and dense plasma structures that are present in the hotter corona of the Sun, suspended through magnetic effects. When these structures are observed by projecting against the solar disk, they show up in absorption spectra looking dark against the bright disk. In this case, the prominences are also known as *filaments*. However, certain short-lived active prominences can show up in emission spectra as well [2] [3]. When seen above the solar limb, they show up as bright structures against the dark sky background.

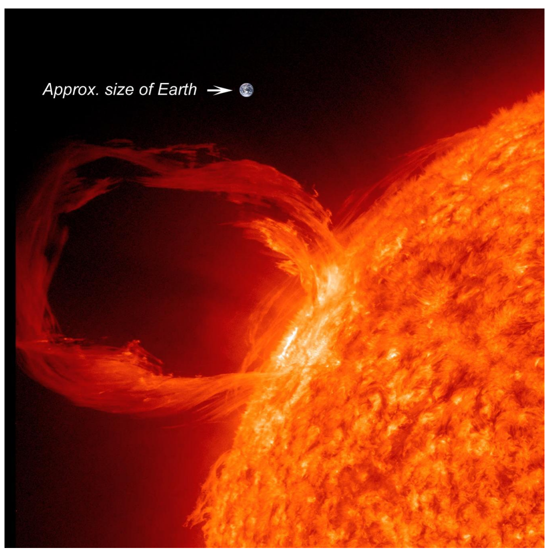


Figure 1: A solar eruptive prominence as seen in extreme UV light on March 30, 2010 with Earth superimposed for a sense of scale. Credit: NASA/SDO

We categorise prominences into two broad types, namely, quiescent and active prominences.

Quiescent prominences usually live for longer periods i.e. days to months and are usually observed away from the active regions of the sun. Active prominences on the other hand are much shorter-lived and are primarily found in the active regions of the Sun.

Given the definition of prominence as a cool and dense plasma structure suspended in the hotter and less dense corona, one might wonder how such objects are able to remain suspended for extended periods, sometimes lasting days or even weeks. The explanation involves a magnetic structure that both provides support against the pull of gravity and thermally isolates the prominence from the surrounding corona. These are thought to be magnetic flux tubes having dips above the magnetic neutral line that are anchored at the chromosphere. The prominence plasma settles along the magnetic dip and remains stable against gravity and thermal interactions [4].

Broadly, there have been three mechanisms put forward to explain prominence formation viz. the chromospheric evaporation plus coronal condensation model, the direct injection model, and the levitation model. In the levitation model, magnetic flux tubes move from the lower depths of the solar atmosphere to the upper regions where chromospheric plasma then levitates to the corona just above the magnetic neutral line. This model has certain drawbacks and lacks observational evidence hence we do not discuss it here [5].

In the direct injection model, as the name suggests, the cold chromospheric plasma is driven by some mechanism to the corona where it then settles along the magnetic dips to form a quasi-static prominence or flows along the other side of the tube to form dynamic prominences [5] [6].

The method we study in this report is the evaporation-condensation model. Here, the plasma in the chromosphere is evaporated through localized heating at the footpoints of the flux tubes, moves to the corona and then condenses to form a prominence. It has been suggested that the condensation is caused by thermal non-equilibrium or "catastrophic cooling". The exact mechanism behind the localized heating in the lower atmosphere is still not fully understood, but one hypothesis is that it could be attributed to magnetic reconnection. Magnetic reconnection is a process where magnetic field lines break and then rejoin in a different configuration, releasing a tremendous amount of energy [5] [6].

To study the formation of prominences, we use a one-dimensional numerical setup representing a magnetic loop and solve the radiative hydrodynamic equations using an MHD simulation code called MPI-AMRVAC. The set of coupled partial differential equations is then solved using various numerical techniques and the plasma dynamics is investigated along the magnetic loop. We include the effects of gravity, thermal conduction, pressure gradients, optically thin radiative losses, and a specified background heating term in the equations. Now, if magnetic reconnection actually were the cause of localized heating, it should be localized in time. However, in most previous studies, a steady heating term is applied that represents a series of magnetic reconnection events, and we will follow this in our work. We study both symmetric and asymmetric localized heating applied to the footpoints of the loop [6].

In the next section, the numerical method used to study the plasma dynamics is briefly outlined. Following this, the results obtained are discussed. Finally, some conclusions are made and future avenues are proposed.

The formation of prominences remains an open problem in solar physics with no definitive explanation till date. Despite years of analysis and observation, there is no broad consensus regarding the underlying mechanisms. Thus, this puzzle requires further exploration and investigation to be solved.

2 Numerical Methods

2.1 Hydrodynamic Equations

We begin with the assumption that the coronal flux tubes are rigid and the flow of plasma is along the magnetic field line in the corona [6]. The 1D radiative hydrodynamic equations governing the plasma motion are as follows

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial s}(\rho v^2 + p) = \rho g_{||}(s) \tag{2}$$

$$\frac{\partial \epsilon}{\partial t} + \frac{\partial}{\partial s}(\epsilon v + pv) = \rho g_{||} v + H(s) - n_H n_e \Lambda(T) + \frac{\partial}{\partial s}\left(\kappa \frac{\partial T}{\partial s}\right) \tag{3}$$

The first of these corresponds to the conservation of mass density, the second to conservation of momentum density and the last to conservation of energy density. The various terms are : ρ - mass density , T - temperature, s - distance along loop, v - velocity of plasma, p - gas pressure, $\epsilon = \rho v^2/2 + p/(\gamma - 1)$ - total energy density, n_H, n_e - number densities of hydrogen and electrons and $g_{||}$ - component of gravity at distance s along loop [6].

In addition, $\Lambda(T)$ is the radiative loss coefficient for optically thin emission, $H(s)$ is the volumetric heating rate and $\kappa = 10^{-6}T^{5/2}$erg cm^{-1} is the Spitzer heat conductivity. We assume that the plasma is completely ionised and follow a one-fluid model. We also take $\rho = 1.4m_p n_H$ and $p = 2.3n_H k_B T$ due to the helium abundance of $n_{He}/n_H = 0.1$ [5] [6] . The above equations are solved using the MPI-AMRVAC. MPI-AMRVAC is a code developed to solve primarily hyperbolic partial differential equations using a variety of numerical schemes. It is written in FORTRAN 90 and parallelization is achieved using the MPI libraries [1]. The details behind the functioning of AMRVAC are vast and hence will not be discussed in this report.

2.2 Initial and Boundary Conditions

We first describe the structure of the magnetic loop. Consider a symmetric, sinusoidal type magnetic dip that is supported at two ends by a pair of vertical legs. The dip and the legs are connected by two quarter-circle "shoulders". The vertical legs are each 5 Mm (1 Mm = 10^6 m) in length above the footpoint. The quarter-circles are of length 15.7 Mm and the total length of the dipped region is 218.6 Mm. The function $g_{||}(s)$ depends on the structure of the loop and is symmetric about the midpoint. The left half of this function is as follows, with the right half being described in a similar manner [6],

$$g_{||}(s) = \begin{cases} -g_\odot & s \leq s_1 \\ -g_\odot \cos\left(\dfrac{\pi}{2}\dfrac{s-s_1}{s_2-s_1}\right) & s_1 < s \leq s_2 \\ g_\odot \dfrac{\pi D}{2(L/2-s_2)} \sin\left(\pi \dfrac{s-s_2}{L/2-s_2}\right) & s_2 < s \leq L/2 \end{cases} \tag{4}$$

Here $g_\odot$ is the average solar gravity and is equal to $g_\odot = 2.7 \times 10^4$ cm s^{-2}, $s_1 = 5$ Mm, $s_2 = s_1 + 15.7$ Mm, $L = 260$ Mm is the total length of the magnetic loop and $D = 0.5$ Mm is the depth of the magnetic dip. Notice that the dip is not deep and hence the coronal part of the loop is quite flat. The midpoint of the loop is 14.5 Mm above the bottom boundary [6].

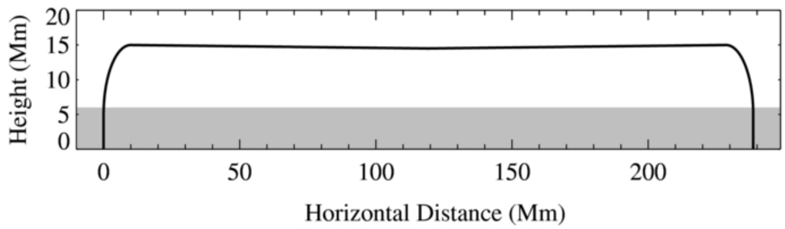


Figure 2: Geometry of the magnetic loop. This shows the magnetic field line across a prominence. The grey region denotes the photosphere and chromosphere [6].

To find the initial equilibrium state, we solve the hydrodynamic equations by only including the steady background heating term. In the energy equation, we take the heating term to be comprised of a steady background term and a localized term, i.e.

$$H(s) = H_0(s) + H_l(s) \tag{5}$$

The temperature as a function of height in the transition region is taken to be

$$T = \tanh(h - h_0) \tag{6}$$

with $T = 10^6$K in the corona and $T = 6000$K in the photosphere [6]. We calculate the density by equating the pressure gradient with gravity. The assumption made is that the background heating decreases exponentially with distance away from the closest footpoint on the loop and is constant in time, i.e.

$$H_0(s) = \begin{cases} E_0 \exp(-s/H_m) & s < L/2 \\ E_0 \exp(-(L-s)/H_m) & L/2 < s < L \end{cases} \tag{7}$$

where the amplitude is $E_0 = 3 \times 10^{-4}$ erg cm^{-3} and the scale length is $H_m = L/2$ [6].

The hydrostatic state that is reached is then used as the initial condition for the rest of the simulations [6]. The distributions of temperature and density along the loop are shown in figure 3.

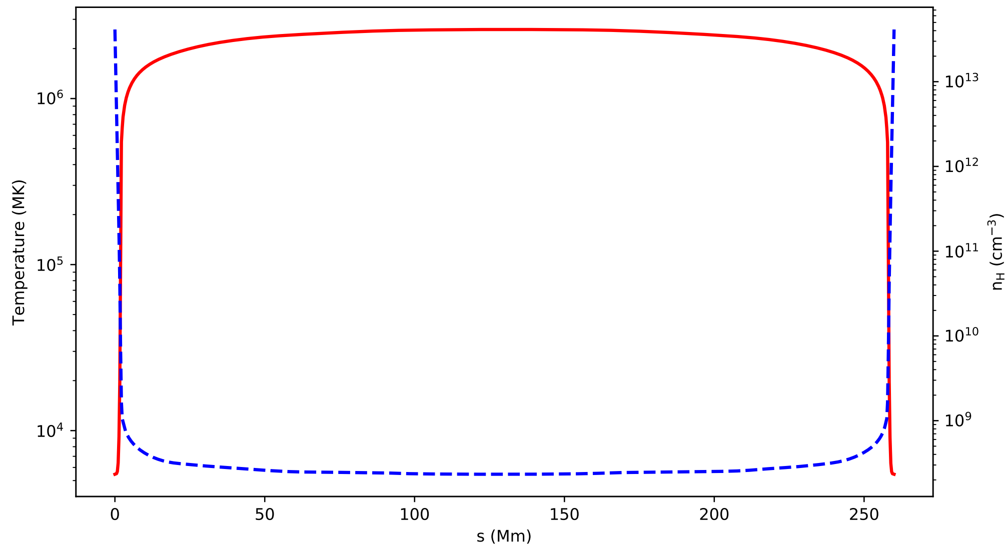


Figure 3: Distribution of temperature (red solid line) and hydrogen number density(blue dashed line) along the magnetic loop in initial state

Temperature and density at the two endpoints of the loop are fixed, setting the required boundary conditions. This assumption is justified, since the density in the photosphere is around 4 orders of magnitude greater than the corona or prominence, and hence the dynamics of the corona will not affect that of the photosphere.

Lastly, to account for the chromospheric evaporation, we consider the localized heating function. As mentioned previously, this evaporation might be caused by magnetic reconnection. In this scenario, we take the heating to be uniform in the chromosphere and photosphere, but exponentially decreasing from the chromosphere with a scale length of λ [6]. The function is as follows.

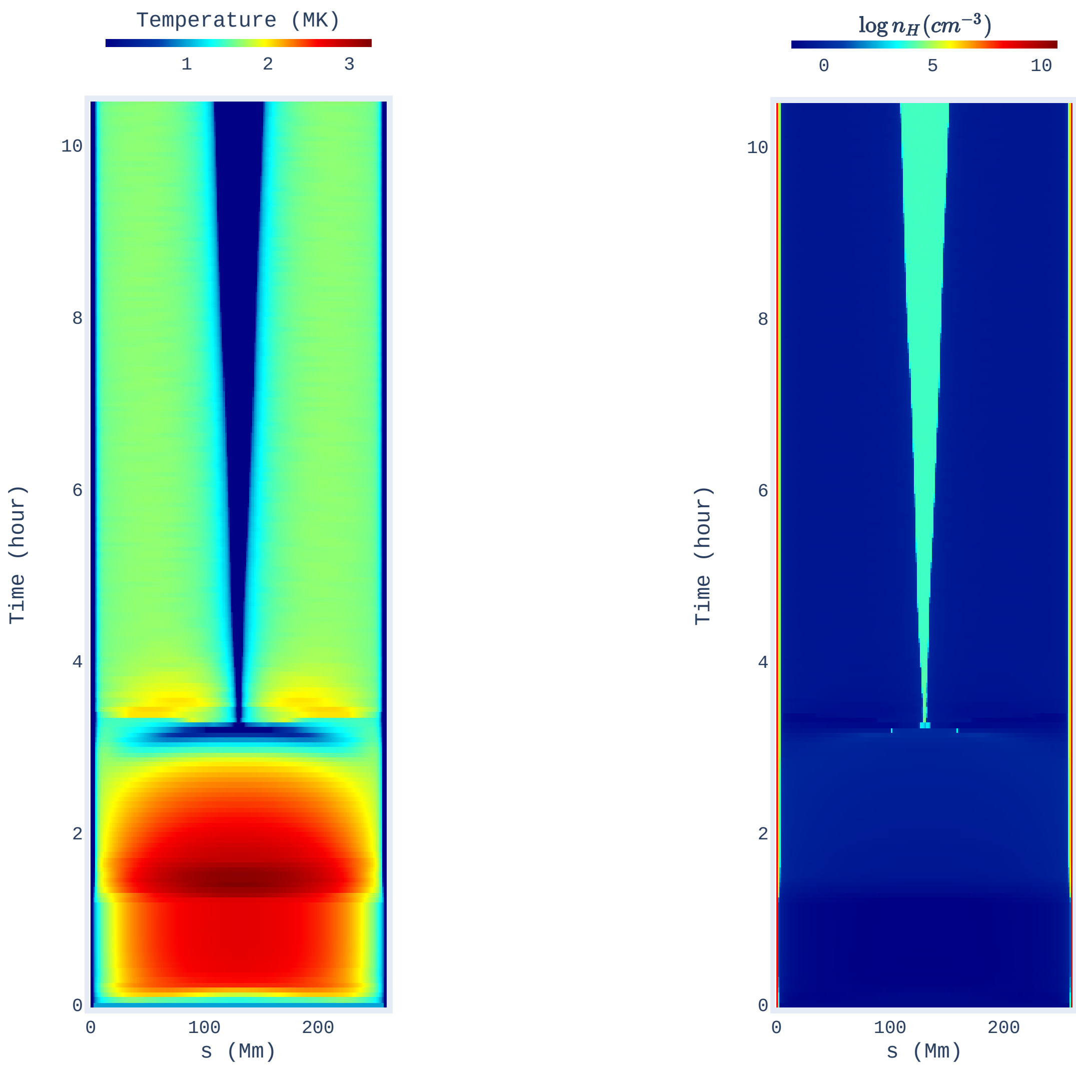
$$H_l(s) = \begin{cases} E_1 & s < s_{tr} \\ E_1 \exp(-(s - s_{tr})/\lambda) & s_{tr} < s < L/2 \\ fE_1 \exp(-(L - s_{tr} - s)/\lambda) & L/2 < s < L - s_{tr} \\ fE_1 & s > L - s_{tr} \end{cases} \tag{8}$$

where the amplitude is $E_1 = 10^{-2}$ erg cm^{-3}, the height of transition region is $s_{tr} = 6$ Mm and the factor f is the ratio of heating between the right and left footpoints. The heating function is linearly increased over 1000s and then kept fixed. When $f = 1$, we have the symmetric heating case and when $f < 1$, we get the asymmetric case [6] [7].

3 Results

3.1 Symmetric Heating

When symmetric heating is added, chromospheric plasma evaporates and moves up towards the corona. The contour plots of temperature and density as a function of time along the loop are shown below. It is seen that around $t = 3.08$ hours, near the midpoint, the temperature decreases drastically. This creates a low pressure and cold region near the midpoint. The density is low and only increases slowly. Due to the pressure gradient created by the low pressure region, coronal plasma surrounding the midpoint rapidly moves towards the centre. Then, the density rapidly increases due to the flow of plasma from both sides. The inflows collide near the centre, creating a high-pressure peak. This, in turn, causes two rebound shock waves to move away from the centre towards the sides. Following this, we can see the small region where the condensation forms and evolves with time. The size of the condensation increases linearly with time. The shock waves are reflected multiple times before they dissipate. These waves heat the surrounding plasma to higher temperatures, by dissipating their energy [6].

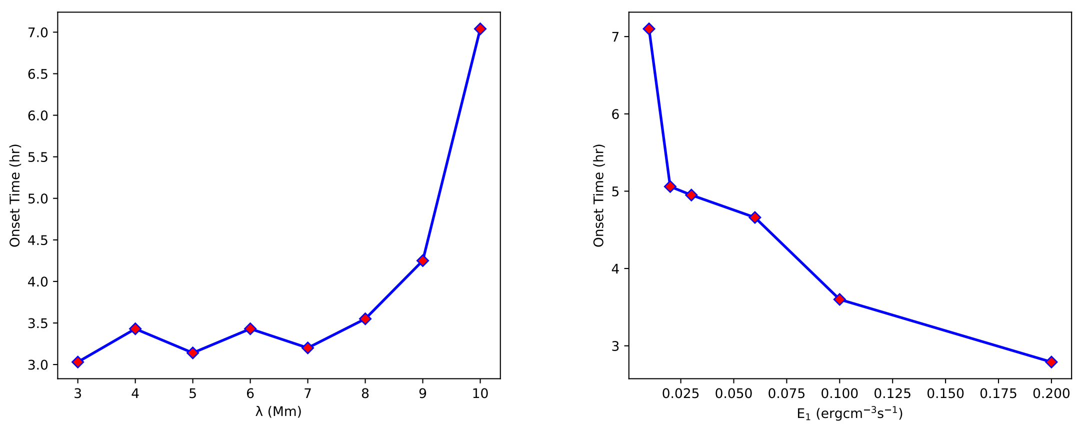


(a) Temperature (MK) along loop as a function of time

(b) log n_H (cm^{-3}) along loop as a function of time

Figure 4: Symmetric heating with $f = 1$ and $\lambda = 3$ Mm

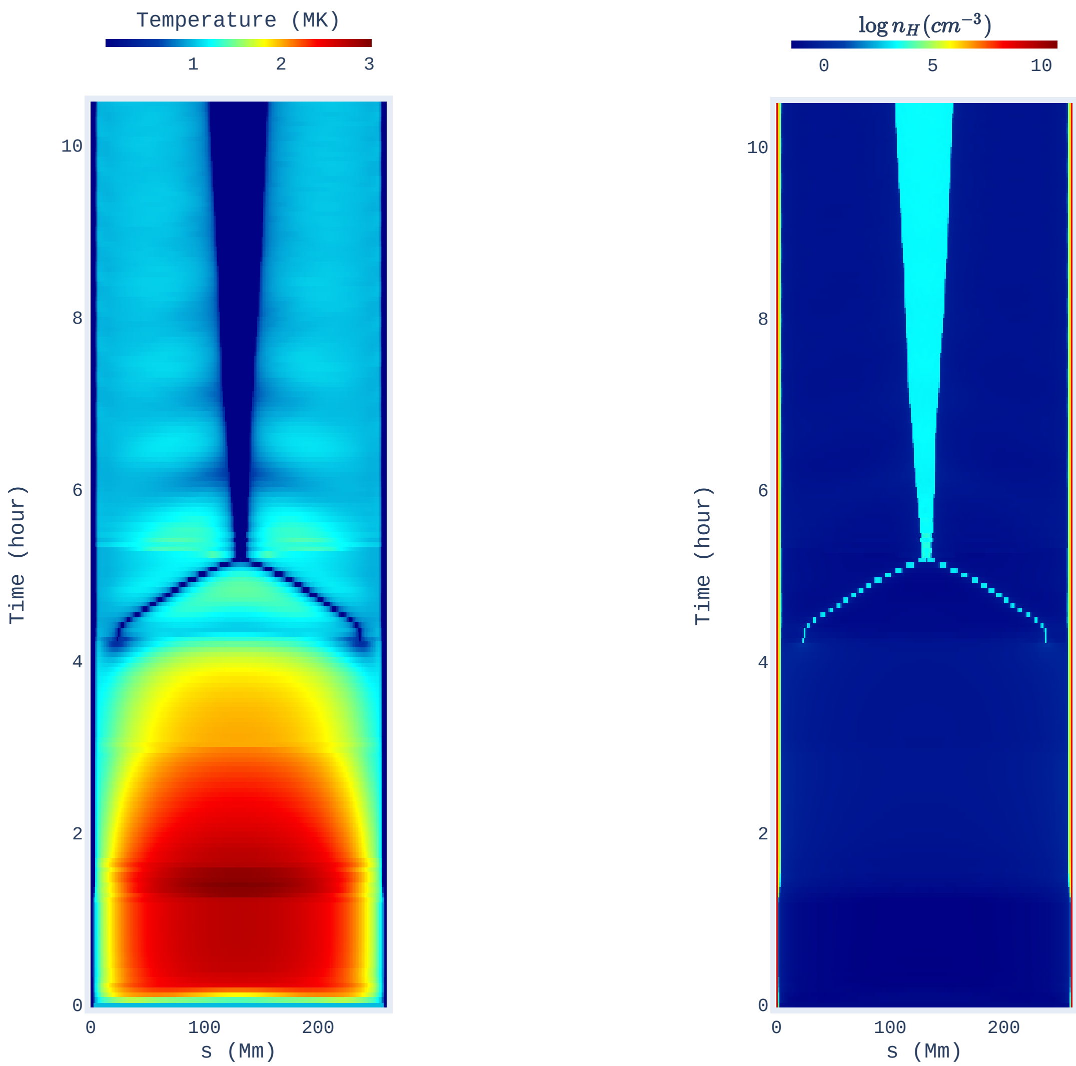
We also looked at the effect of the localized heating scale length λ on the onset time of the prominence. It was found that the onset time generally increases with increase in λ. For small values of λ it was seen that two prominences were formed on either side of the dip and moved towards the centre. The area between these two saw a decrease in T and p. Again, a pressure gradient is created and the two prominences accelerate towards the centre and coalesce. Below a critical value of λ, no prominence formation was observed.



(a) Variation of onset time with heating scale length λ (b) Variation of onset time with heating amplitude E_1

Figure 5: Variation of onset time with heating scale length (a) and heating amplitude (b)

The explanation for the two condensation formation is as follows. Initially, the midpoint has warmer and less denser plasma than at the shoulders, and hence radiative loss is stronger at the shoulders. When λ is large enough, the heating at the shoulders reduces the cooling and hence the centre becomes the fastest cooling area, leading to only one prominence. When λ is smaller, it cannot prevent cooling from taking place at the shoulders, and hence two prominences are formed.



(a) Temperature (MK) along loop as a function of time

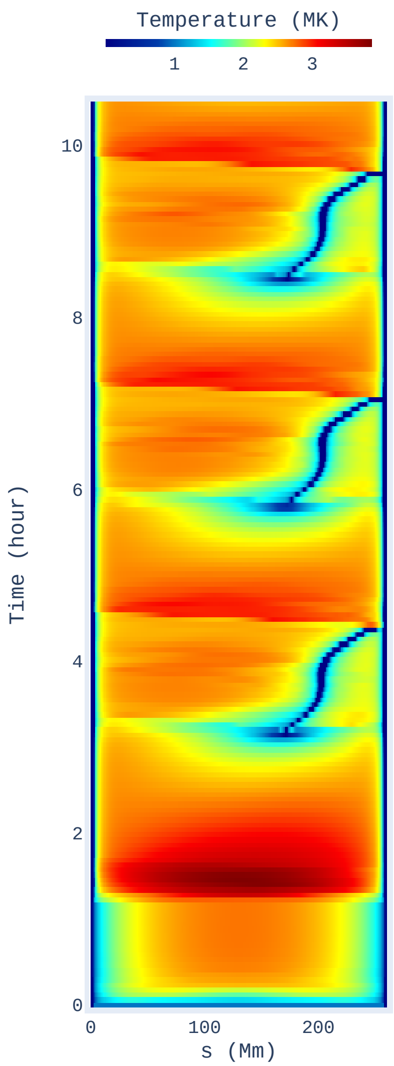
(b) log n_H (cm^{-3}) along loop as a function of time

Figure 6: Symmetric heating with $f = 1$ and $\lambda = 1$ Mm

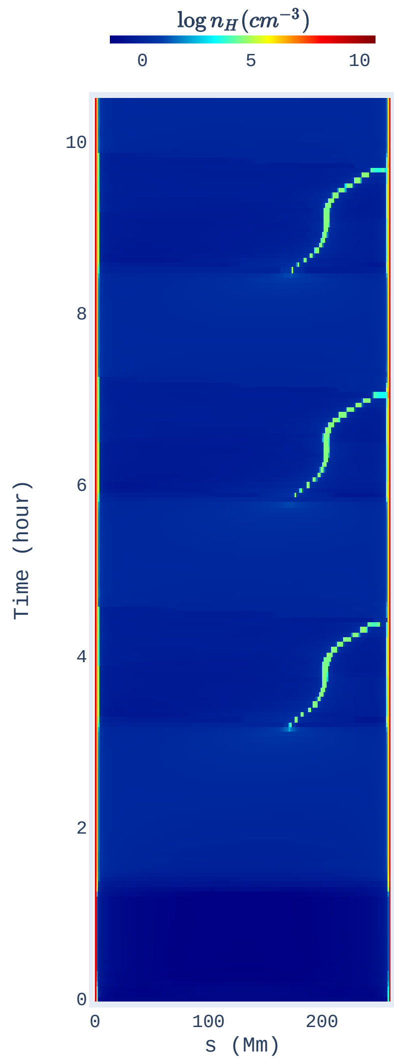
Further, the effect of heating amplitude E_1 on onset time was also measured, keeping λ and other quantities fixed. It was seen that the onset time of the prominence decreased with increase in E_1. This is easily explained, since if E_1 is greater, chromospheric heating is stronger leading to the prominence being formed earlier.

3.2 Asymmetric Heating

In general, the heating at the two footpoints of the loop is not equal and we must hence consider the asymmetric heating case. This is done by choosing f in the localized heating function to be $f < 1$. The formation of the prominence is similar to the symmetric case, except now the condensation is towards the right side of the centre. This is because the right side is less heated compared to the left. As the condensation is forming, two shock waves are generated that move towards the left and right footpoints. These waves collide and get reflected between the footpoints and condensation repeatedly before dissipating. Unlike the symmetric heating, the prominence now moves with a velocity to the right. The pressure gradient accelerates the condensation to the right, but at a certain point, it decelerates. This is because there is a pressure gradient inversion at this point. The reason for this is that the condensation interacts with a reflected right side shock wave, when the left side wave has not yet been reflected at the footpoint. Once the left side wave reaches the condensation, the pressure gradient is back to normal, and the prominence gets pushed to the right. Finally, the prominence drains down the right footpoint of the loop and gives rise to a rebound shock wave which also bounces back and forth [6]. This process of formation and drainage is repeated multiple times throughout the simulation as seen from the figure 7.



(a) Temperature (MK) along loop as a function of time



(b) log n_H (cm^{-3}) along loop as a function of time

Figure 7: Asymmetric heating with $f = 0.75$ and $\lambda = 5.0$ Mm

4 Conclusions

We studied the formation of prominences through localized heating by simulating the 1D radiative hydrodynamic equations in a particular magnetic loop. We saw that when localized heating was symmetric, a single prominence was formed near the midpoint and grew linearly with time. Below a certain value of λ, two prominences were formed which coalesced at the midpoint to give one. The dependence of onset time on λ and E_1 was also measured. We also studied the asymmetric heating case, where the prominence moved towards the less heated side and eventually drained down the footpoint.

There are various future possibilities to better understand the formation of prominences. Firstly, the assumption of completely ionised plasma and optically thin radiative cooling is not valid for actual prominences, which are dense and partially ionised. Secondly, a multidimensional study, including magnetohydroynamic effects will give a far more realistic picture of prominences. Lastly, the localized heating may be caused by different phenomena, such as MHD waves or oscillatory reconnections. A detailed analysis of these functions might lead to a better explanation for the formation of prominences.

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