MHD Simulation of Filament Formation by Thermal Instability

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Abstract

We propose a new theoretical formation model of a filament and demonstrate it by two-dimensional MHD simulation with anisotropic thermal conduction, radiative cooling and gravity. Our model is based on thermal instability which can generate cool dense plasmas on magnetic field lines. The current theoretical models proposed and confirmed by 1D and 2D simulations with thermal instability (e.g. Xia et al.,2012) do not consider filaments' flux rope structure suggested by observations. We propose the model which accomplishes both generation of cool dense plasmas and formation of a flux rope structure and demonstrate it by 2D MHD simulation. As a result, it is found that the formation of a flux rope plays a significant role to trigger the thermal instability as follows: the effect of thermal conduction is limited in the newly formed flux rope due to the closed geometry of the magnetic filed lines, and the thermal non-equilibrium occurs because the relatively dense plasma at the lower corona is trapped in the flux rope and transported to the upper corona where the heating effect is relatively small. Consequently, the time scale of cooling is smaller than that of conduction in the flux rope, leading to trigger the thermal instability and generate cool dense plasmas.

Introduction

Solar filaments are cool dense plasma clouds in the corona. Their formation mechanism is still unclear. One candidate to explain the generation of high dense plasmas is thermal instability. Recent two-dimensional MHD simulation succeeded in forming condensations of thermal instability by adopting long magnetic field lines (>80Mm) and the heating localized at the footpoints (Xia et al. 2012). The present formation model by thermal instability does not consider the filaments' flux rope structure as suggested by observations. The aim of this study is to propose the model which can explain both of the formation of a flux rope structure and the generation of cool dense plasmas of filaments, and to demonstrate it by 2.5-dimensional MHD simulation including thermal conduction and radiative cooling.

Numerical settings

We set the model of corona which is stratified under a uniform temperature (10^6K) and gravity in a rectangular calculation box. A half of a force-free arcade field is set in the box. The density and the field strength at the bottom is 2x10^9 cm^{-3}, and 3G respectively. The left and right boundaries are symmetric.

We insert the emerging flux into the corona by controlling the magnetic field of the bottom boundary in order to form a flux rope.

The basic equations are the ordinary MHD equations except for the energy equation. We consider the thermal conduction along the magnetic filed lines, radiative cooling and heating as following equations. We use the brief model of radiative cooling function as Fig.2.

$$\frac{\partial}{\partial t}\left(\frac{p}{\gamma-1}+\frac{1}{2}\rho v^2+\frac{B^2}{8\pi}\right)+\nabla\cdot\left(\left(\frac{\gamma}{\gamma-1}p+\frac{1}{2}\rho v^2+\frac{B^2}{8\pi}\right)\mathbf{v}+c\frac{\mathbf{E}\times\mathbf{B}}{4\pi}\right)=\rho\mathbf{g}\cdot\mathbf{v}+\underline{\nabla\cdot(\boldsymbol{\kappa}\nabla T)}-\underline{R}+\underline{H},$$

thermal conduction: $\boldsymbol{\kappa}=\kappa T^{5/2}\mathbf{bb}$ **radiative cooling:** $R=n^2\Lambda(T)$ **heating:** H

The required grid size for a simulation of thermal instability can be computed by the formula in Koyama & Inutsuka (2004). Fig.3 shows the required grid size for our simulation model as a function of temperature. The grid size Δx=0.01 is sufficient to cover whole range of temperature where the cooling function is defined. In order to reduce the computational complexity (to use larger grid size than Δx=0.01), we apply the technical treatment to heating term and make temperature not to be lower than the admissible value which depends on the grid size (see Fig.3). The heating term depends on the local **magnetic pressure (case A)** or the **density (case B)** when the temperature is larger than the admissible temperature T_{adm}. When the temperature is smaller than T_{adm}, the heating term is set to be balanced with the cooling term. We adopt the grid size of 0.4, 0.2 and 0.1 (x300km). T_{adm} of each grid size is 50, 40 and 30 (x10^4K) respectively. Initial condition is in thermal equilibrium.

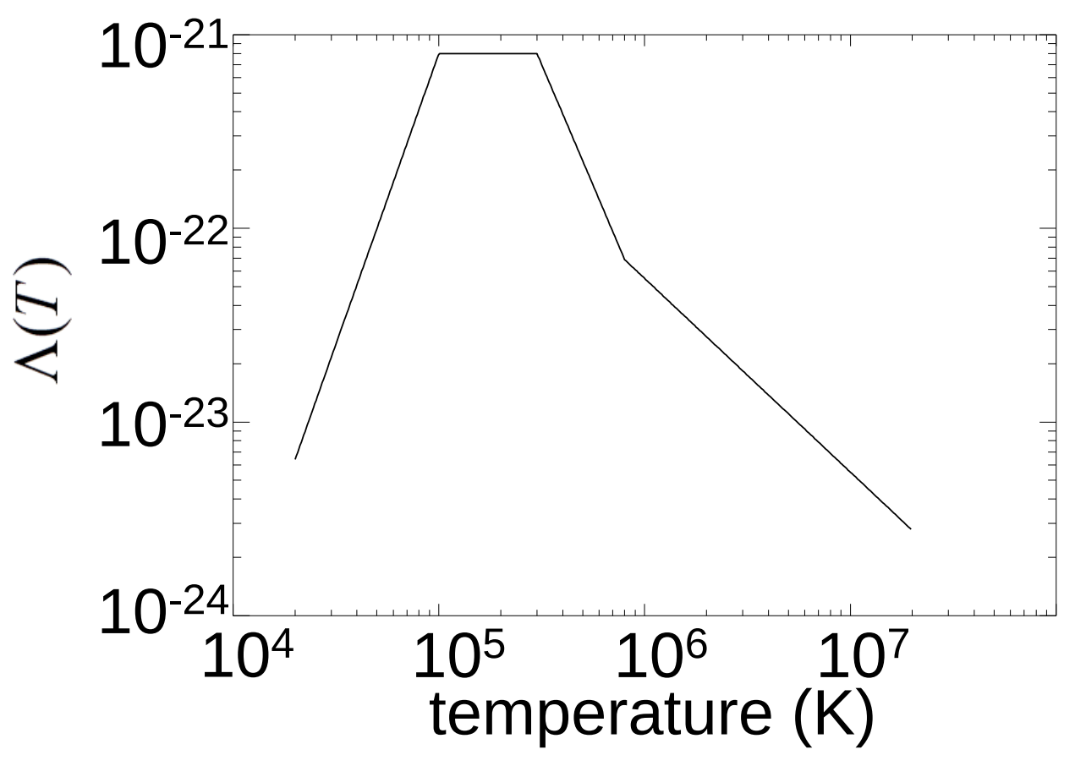

Fig.2. Brief model of the radiative cooling function.

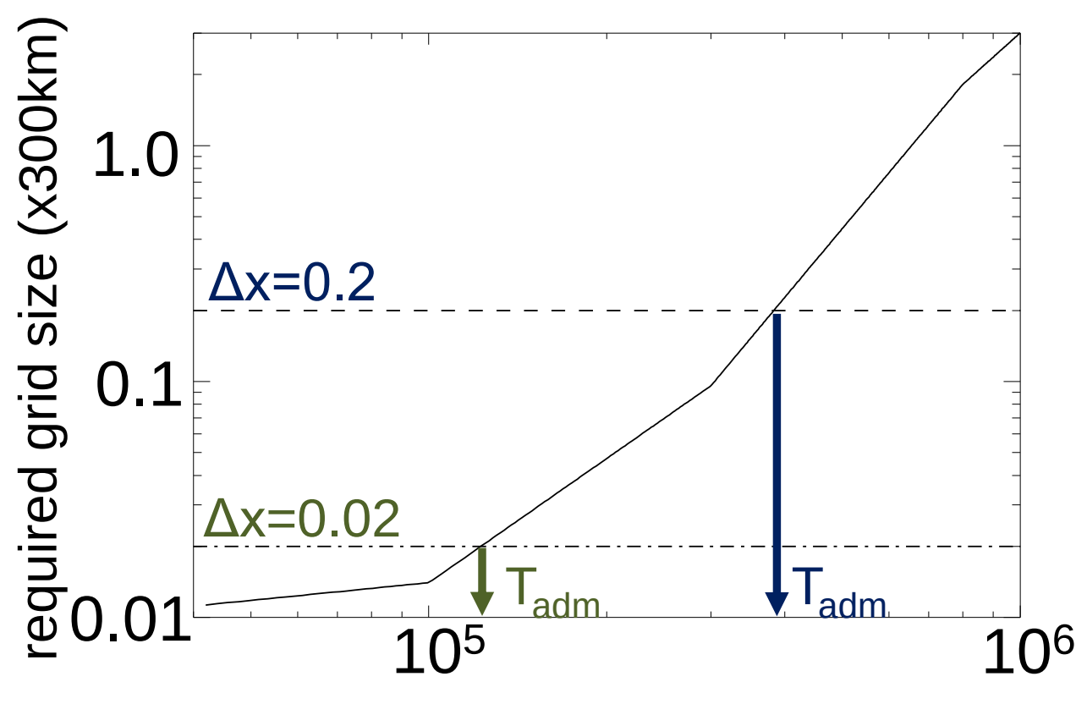

Fig.3. Required grid size as a function of temperature.

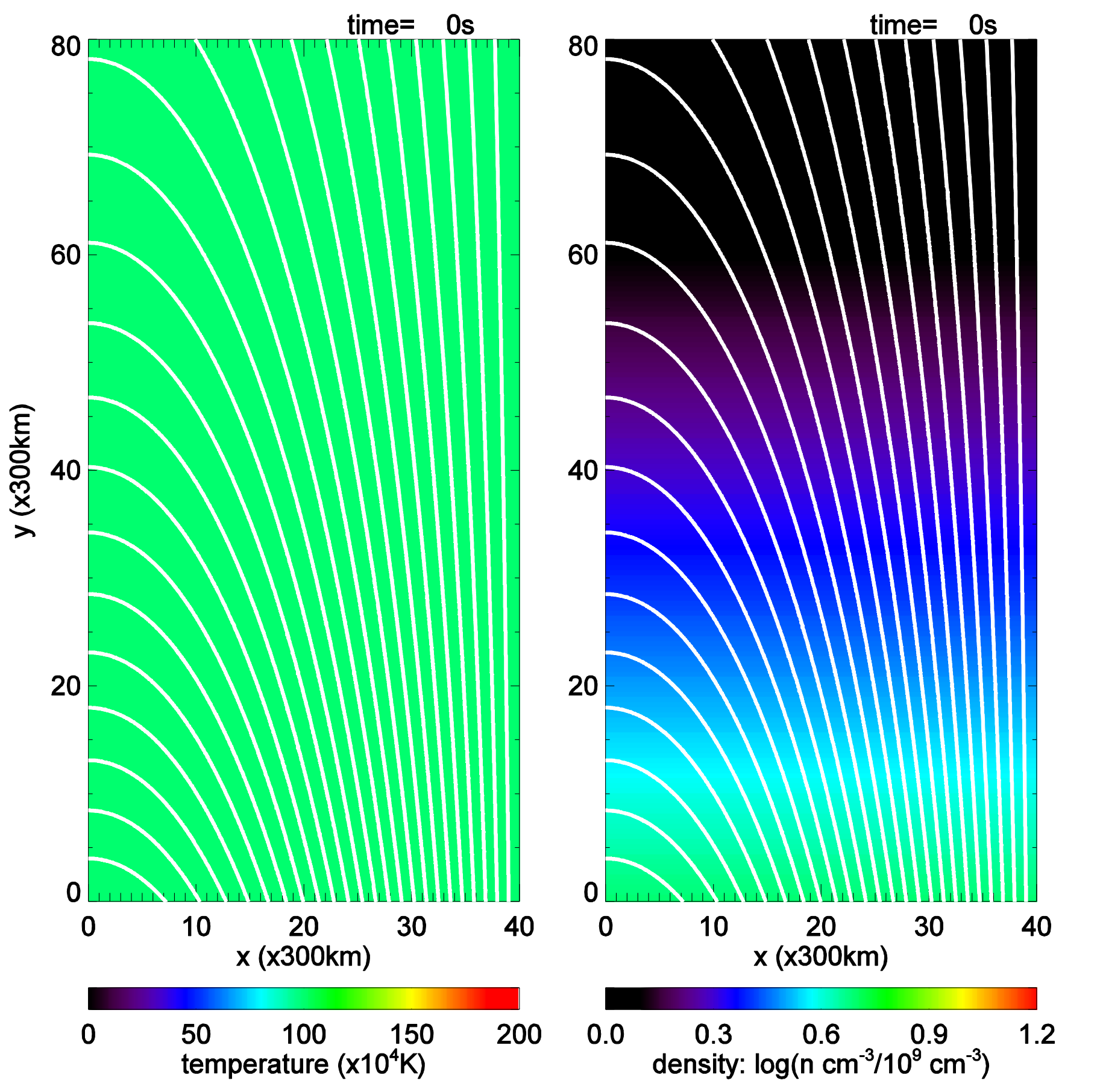

Fig.1 Initial condition. Colors are temperature (left) and density (right). White lines are magnetic field lines.

Case A $\begin{cases} H=\alpha P_m & (T>T_{\mathrm{adm}}) \\ H=R & (T<T_{\mathrm{adm}}) \end{cases}$ Case B $\begin{cases} H=\alpha\rho & (T>T_{\mathrm{adm}}) \\ H=R & (T<T_{\mathrm{adm}}) \end{cases}$

Results & Discussion

Fig.4 shows the time evolution of the formation of a flux rope and the generation of cool dense plasmas inside the flux rope. The flux rope is formed by the reconnection between the emerging flux and the arcade field. The relatively dense plasmas at the bottom of the corona are trapped inside the flux rope and are transported to the upper region of the corona as the flux rope goes upward. The radiative cooling overwhelms the heating in the flux rope due to its higher density than the surroundings, causing thermal non-equilibrium. Because the thermal conduction across the field lines is forbidden, the thermal non-equilibrium in the closed field lines can not be suppressed by the conduction, leading to thermal instability. Once thermal instability is triggered, rapid cooling causes pressure gradient, and the cool dense condensation appears as a result of convergence along the field line. The condensation is accumulated at the lower side of the flux rope by the gravity. Table. 1 shows the maximum density in each heating case and resolution. Higher resolution allows the lower admissible temperature in our simulations. The radiative cooling increases as temperature decreases until T>3x10^5K (Fig.2). The strong radiative cooling causes steeper pressure gradient, and generates denser condensations.

resolution Δx (x300km)	Case A maximum density (x 2x10^9cm^{-3})	Case B maximum density (x 2x10^9cm^{-3})	T_{adm} (x10^4K)
0.4	2.8	3.4	50
0.2	3.3	3.4	40
0.1	4.2	5.0	30

Table.1 Maximum density in each heating case and resolution. Heating depends on magnetic pressure in Case A and density in Case B.

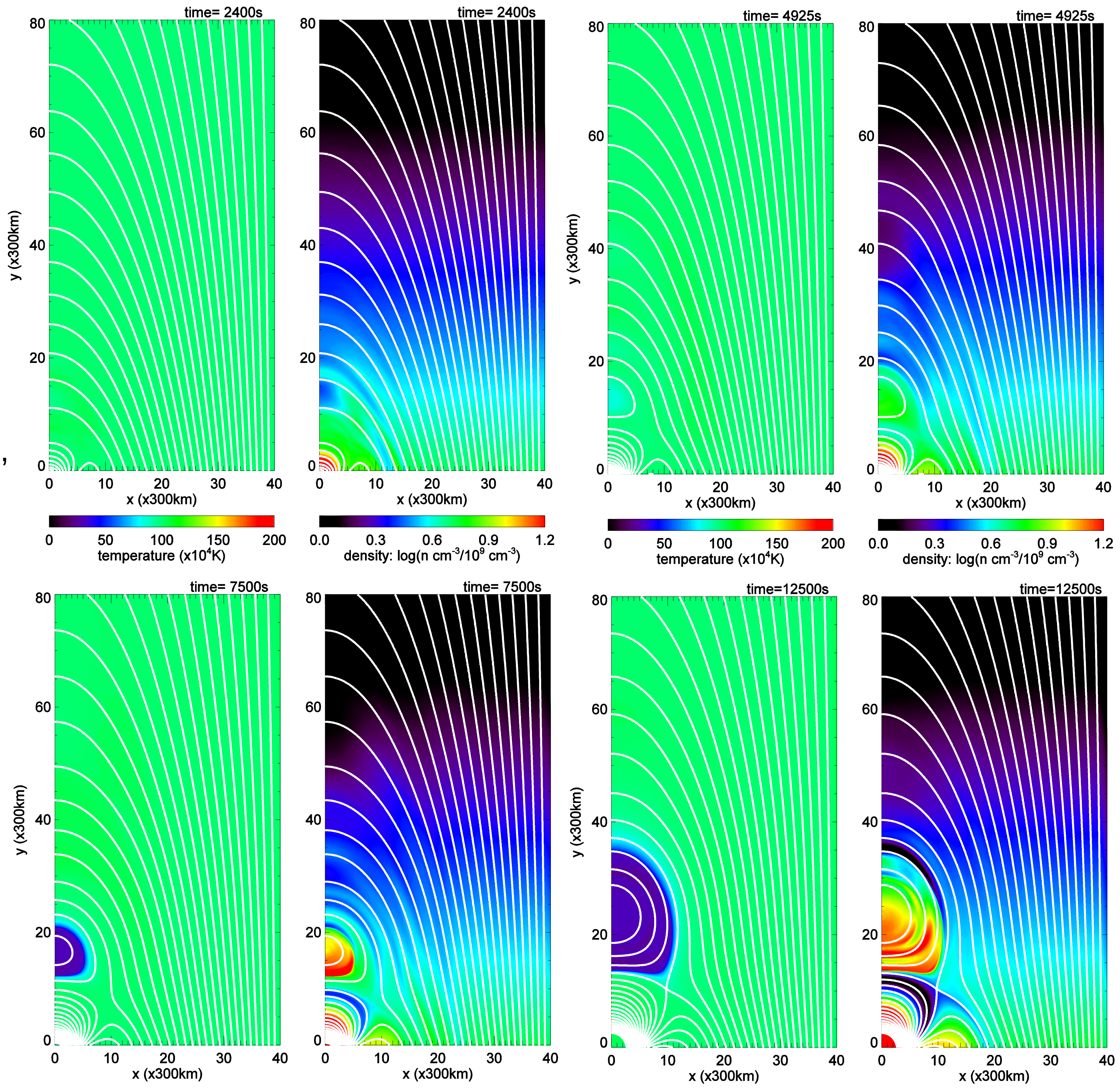

Fig.4. Time evolution of formation of the flux rope and the condensation. Colors are temperature and density. White lines are magnetic field lines

Summary

We propose the model which can explain both of the formation of a flux rope and the generation of cool dense plasmas of filaments and demonstrate it by two-dimensional MHD simulation including thermal conduction along magnetic field lines and radiative cooling. In our model, the flux rope is formed by the reconnection between the emerging flux and the arcade filed. Because the radiation inside the flux rope is larger than surroundings due to the relatively dense plasma and the thermal conduction between the inside and outside of the flux rope is forbidden by the closed geometry , thermal instability is triggered and the cool dense plasmas are accumulated inside the flux rope.

Reference: Xia et al., 2012 , ApJL, 748, 26
Koyama and Inutsuka, 2004, ApJL, 602, 25