SOHO 15 Coronal Heating
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Nonlinear Alfvén Wave Model for Solar Coronal Heating and Nanoflares

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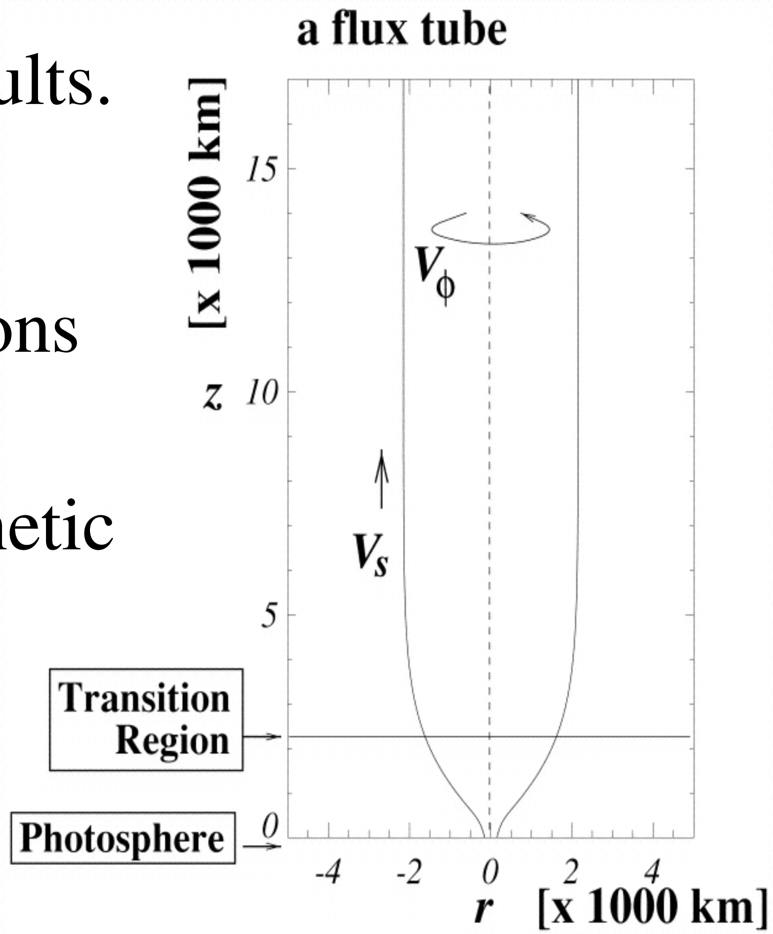
Introduction

“Alfvén wave model of spicules and coronal heating”

Kudoh & Shibata （1999）

Our research is based on their results.

They performed magnetohydrodynamic simulations for torsional Alfvén waves propagating along an open magnetic flux tube.



Introduction

They assumed that the Alfvén waves are generated
by random motions in the photosphere,
which are caused by the convective motions
or the magnetic reconnection in the lower atmosphere.

They found that

if $\sqrt{<V^{2}_{photosphere}>} \geq 1$ km/s ,
the energy flux enough for heating the quiet corona
is transported by **Alfvén waves**.

Introduction

And also,
longitudinal motions are excited by the nonlinear coupling.
The motions propagate upward
as slow- or fast-mode MHD waves.
They grow into shocks.

This suggests that
Alfvén waves may heat the corona via shock dissipation.

Introduction

☆ Our Research

We have applied this model to an emerging flux loop
to examine whether the energy of the Alfvén waves is actually
dissipated in the corona via shock dissipation
or whether such shock heating balances thermal conduction
and radiative cooling.

The aim of this research

We performed 1.5 dimensional MHD numerical simulations to examine whether an initially cool loop is heated to be corona by nonlinear torsional Alfvén wave.

Our simulation includes both thermal conduction and radiative cooling.

Spitzer's classical conductivity

T > 4×10^4 K

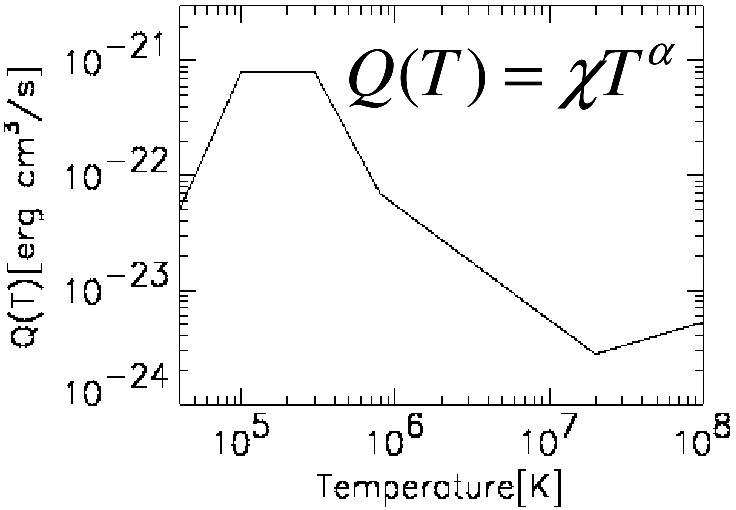
$$R = N_e N_p \chi T^\alpha$$

radiation from the optically thin plasma

T < 4×10^4 K

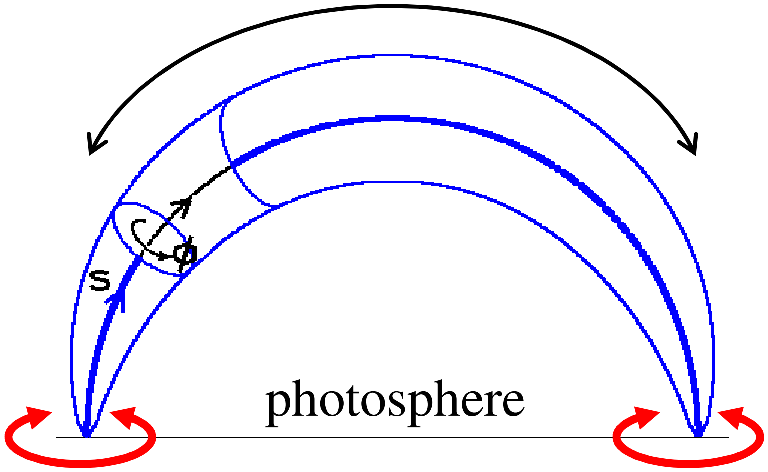
$$R = 4.9 \times 10^9 \rho$$

the empirical model of chromospheric plasma (Sterling et al.1993)



Our model of 1.5 dimensional MHD simulation

100000km emerging flux loop



twisting both foot points at random

We considered a single field line to calculate.
Not only longitudinal motions
 but also azimuthal motions are allowed.
This is meaning of 1.5 dimension.

The ratio of the cross section
 between the loop top and the foot point ～1000
To be
 B@foot point ～ 10^3 gauss
 B@loop top ～ 1 gauss

The basic equations of 1.5 dimensional MHD

- Mass conservation

$$\frac{\partial \rho}{\partial t} + v_s \frac{\partial \rho}{\partial s} = -\rho B_s \frac{\partial}{\partial s}\left(\frac{v_s}{B_s}\right)$$

1.5 dimension means that Vectors have two components, but space is one dimension (s-direction in this case).

- Momentum equation (s-component)

$$\frac{\partial v_s}{\partial t} + v_s \frac{\partial v_s}{\partial s} = -\frac{1}{\rho}\frac{\partial P}{\partial s} - g_s + \frac{v_\phi^2}{r}\frac{\partial r}{\partial s} - \frac{1}{4\pi\rho}\frac{B_\phi}{r}\frac{\partial}{\partial s}\left(rB_\phi\right)$$

- Momentum equation (ϕ -component)

$$\frac{\partial\left(rv_\phi\right)}{\partial t} + v_s \frac{\partial\left(rv_\phi\right)}{\partial s} = \frac{B_s}{4\pi\rho}\frac{\partial}{\partial s}\left(rB_\phi\right) + \underline{L(t,s)}$$

The artificial torque which is source for Alfvén wave.

- Induction equation (ϕ -component)

$$\frac{\partial}{\partial t}\left(\frac{B_\phi}{rB_s}\right) + \frac{\partial}{\partial s}\left(\frac{B_\phi}{rB_s}v_s - \frac{v_\phi}{r}\right) = 0$$

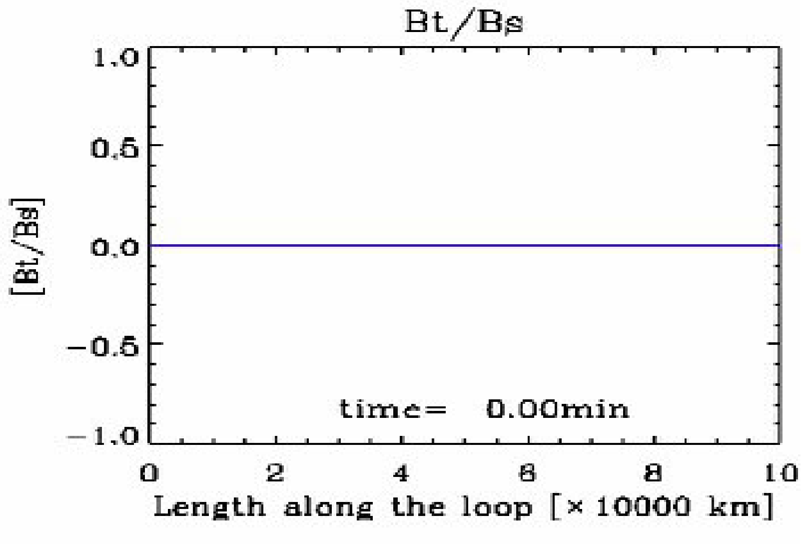
- Energy equation

$$\frac{\partial e}{\partial t} + v_s \frac{\partial e}{\partial s} = -(\gamma - 1)eB_s \frac{\partial}{\partial s}\left(\frac{v_s}{B_s}\right) + \underline{\frac{1}{\rho}\frac{\partial}{\partial s}\left(\kappa_0 T^{5/2}\frac{\partial T}{\partial s}\right) - \frac{1}{\rho}R}$$

The typical results
The heating mechanism

Alfvén wave

nonlinear coupling

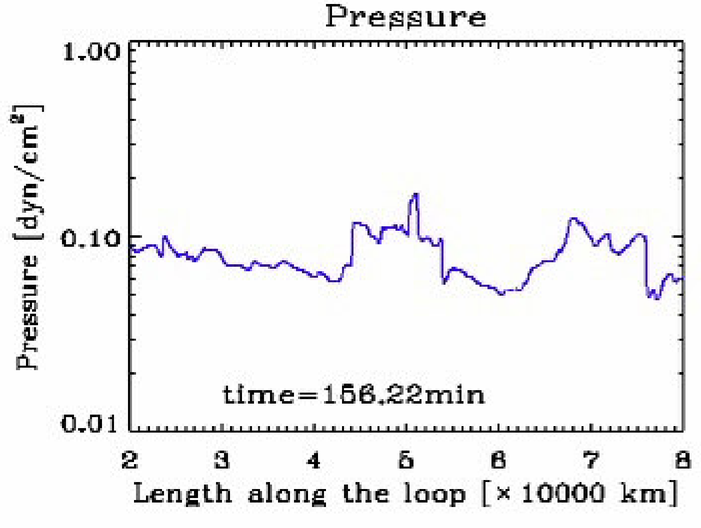


longitudinal motions
(slow- or fast-mode MHD waves)

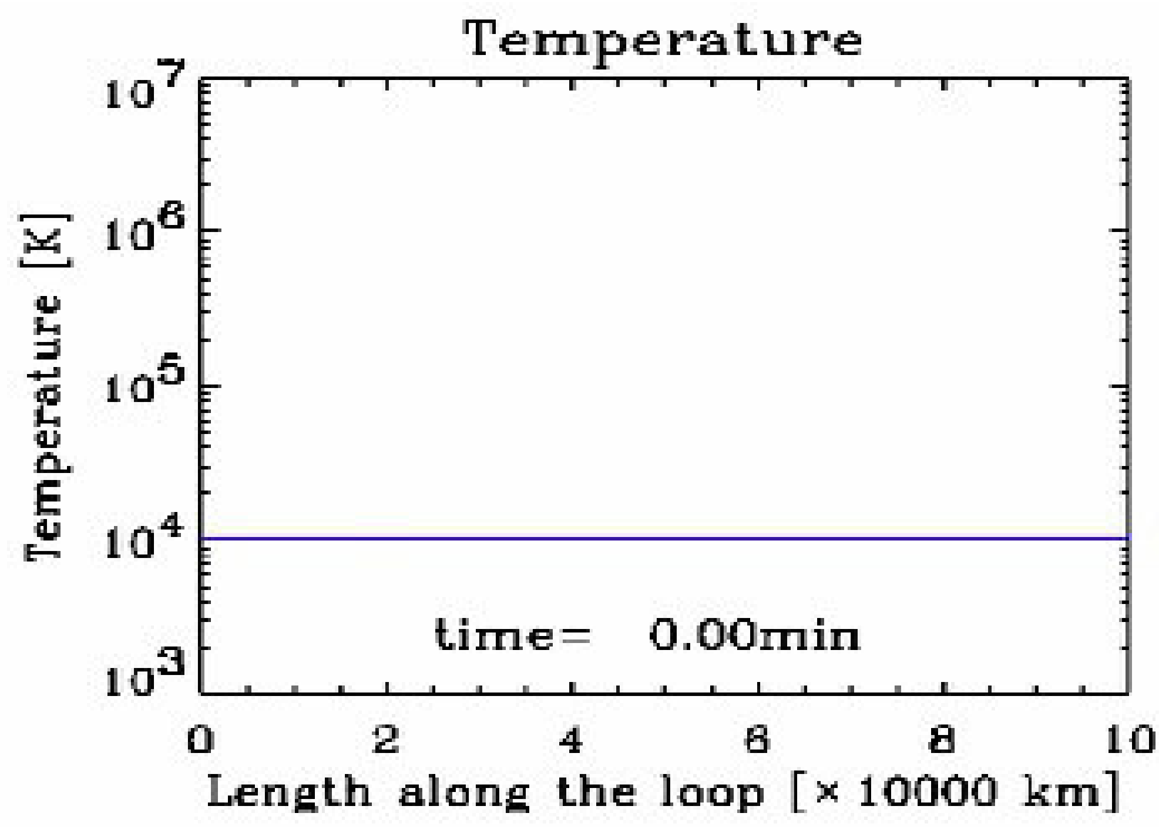
formation of shocks

shock heating

Pressure distribution
around the loop top



The typical result $(\sqrt{<V_{photosphere}^{2}>} \approx 2$ km/s) (heating coronal plasma)



One million K corona is formed.

The typical results

$\left(\sqrt{<V^{2}_{photosphere}>} \approx 2\text{km/s} \right)$

The loop comes into quasi-steady state after about 150 minutes.

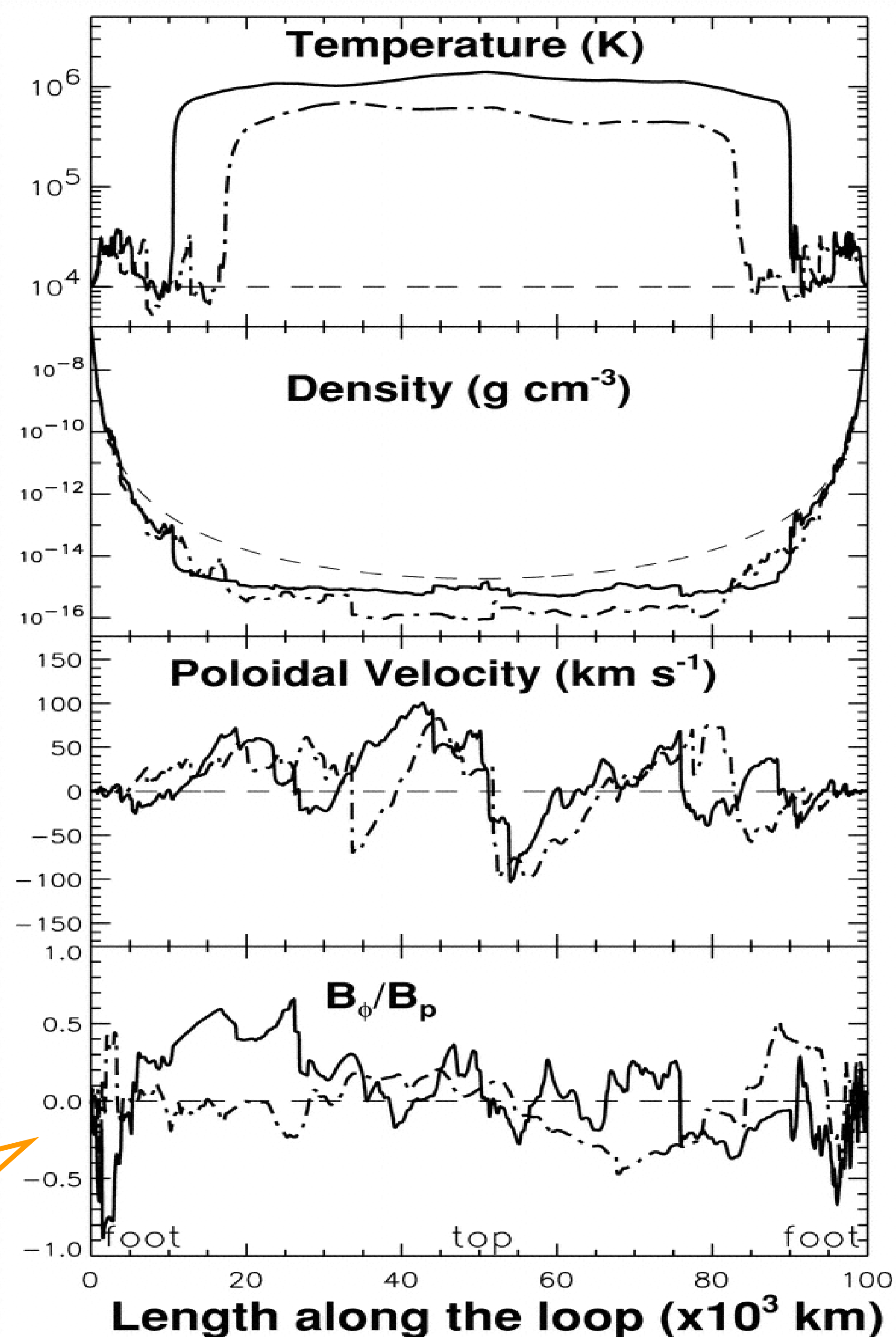
average temperature and number density at the loop top while quasi-steady state

$T = 1.26 \times 10^{6}$ K

$N = 3.70 \times 10^{8}$ /cm^{3}

→ typical values for the corona

→fit the RTV scaling law



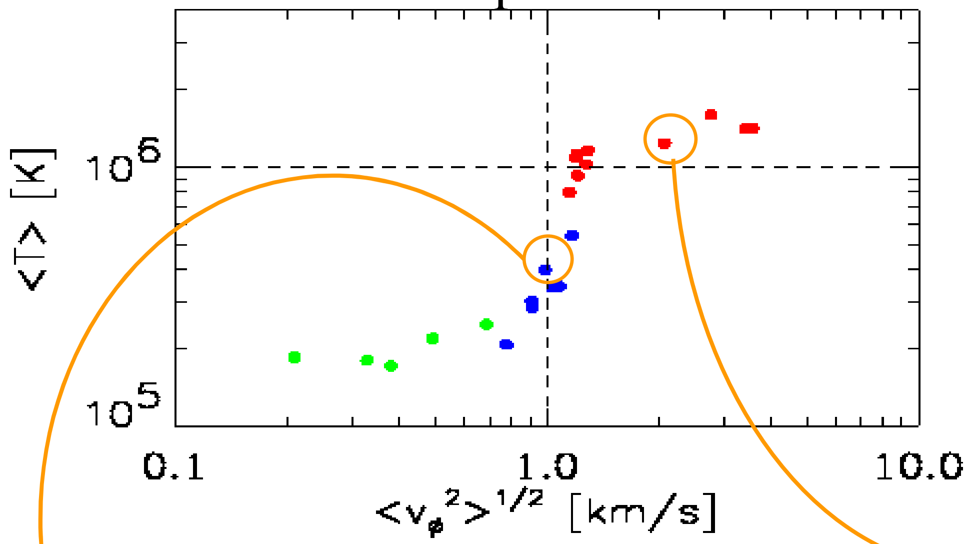
—— 156 min.

— · — · · 48 min.

- - - - - 0 min.

Results for various amplitudes of photospheric velocity field

the average temperature of the atmosphere
of uniform temperature distribution

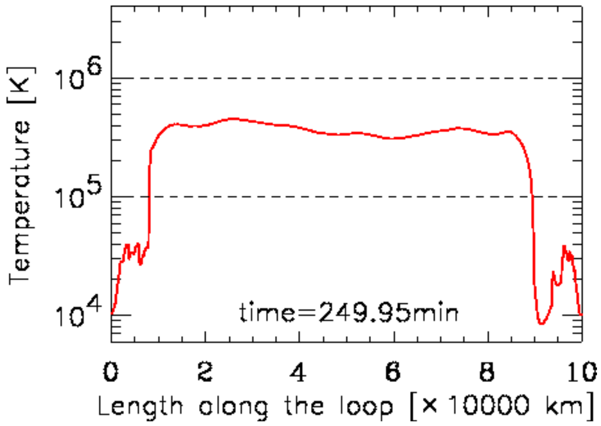


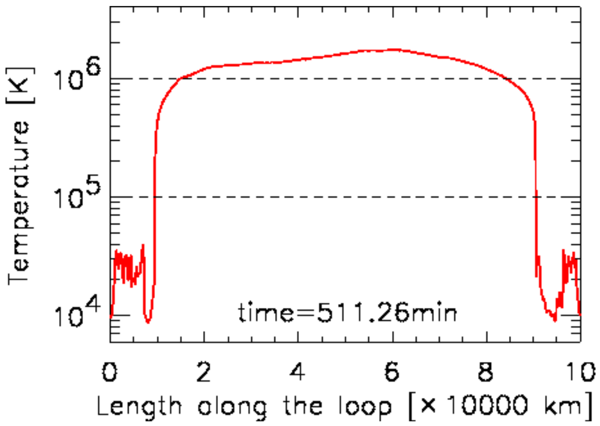
the average amplitude of photospheric velocity field

● $\sqrt{<V_\phi{}^2>}$ > 1 km/s
10^6 K steady corona

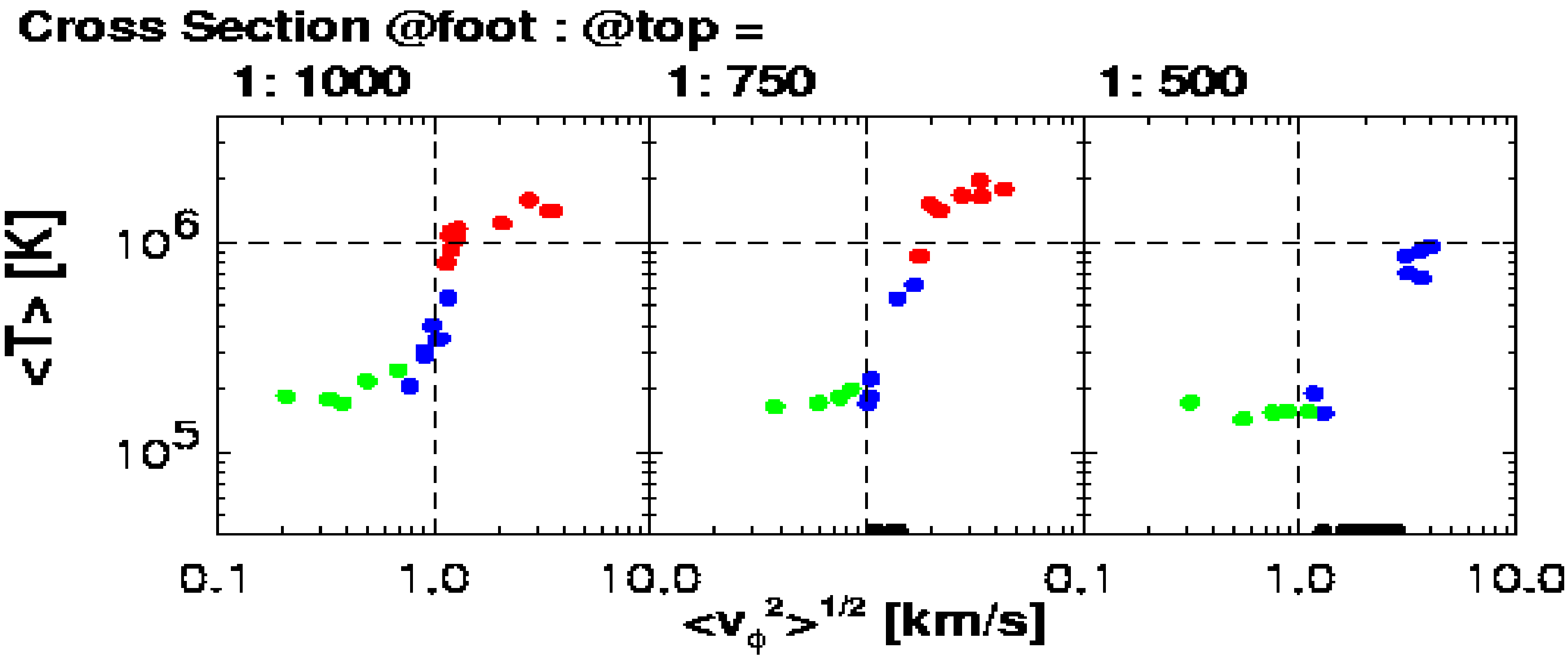
● $\sqrt{<V_\phi{}^2>}$ ~ 1 km/s
several 10^5 K
unstable atmosphere

● $\sqrt{<V_\phi{}^2>}$ < 1 km/s
2×10^5 K
unsteady atmosphere
to be cooling gradually





Results of various situation
amplitude of velocity field/
cross section



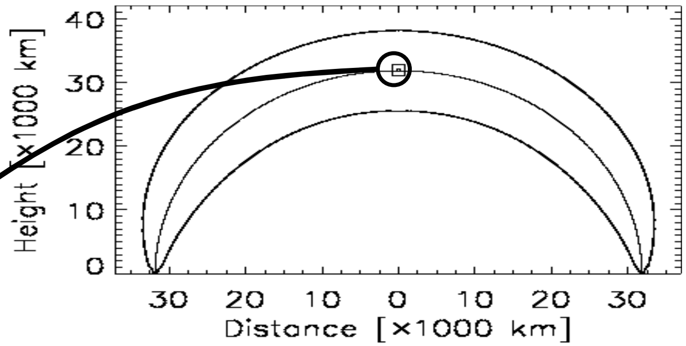
🔴 10^6 K steady corona

🔵 several 10^5 K
unstable atmosphere

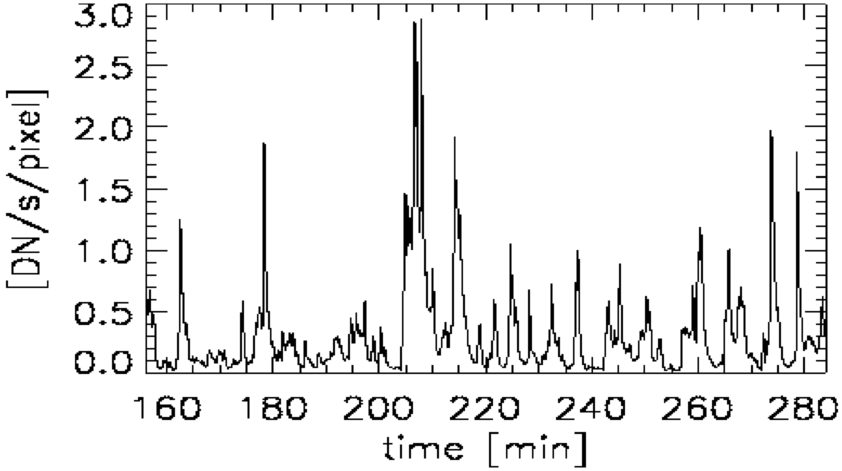
🟢 2×10^5 K
unsteady atmosphere
to be cooling gradually

⚫ Any structures are not formed.

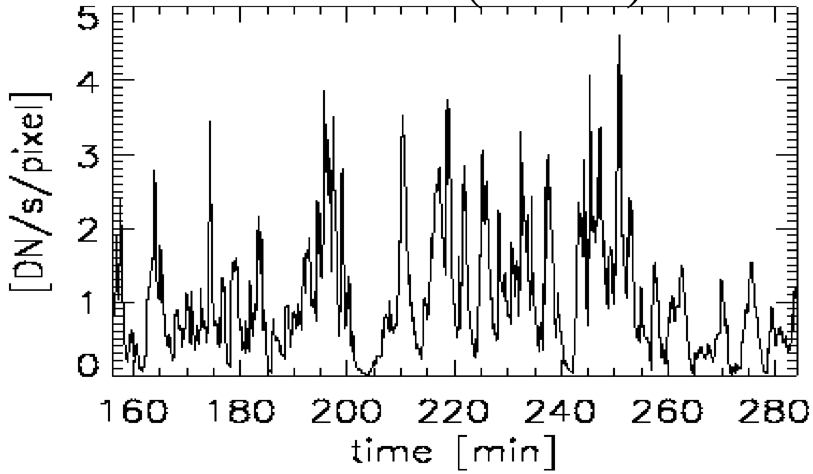
Trying to observe the result of the simulation



Yohkoh/SXT

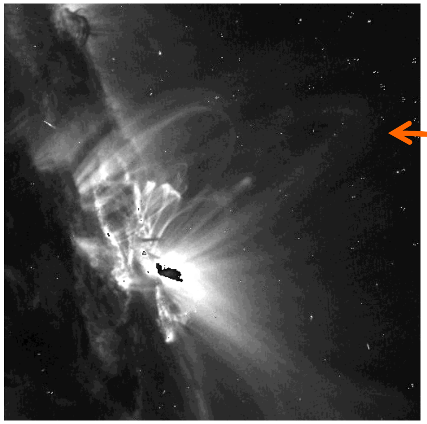


TRACE (171Å)



intermittent transient brightenings
= flare-like behavior

EUV intensity (lower panel)
is the same order of
the actual observation of 10^5km loop.



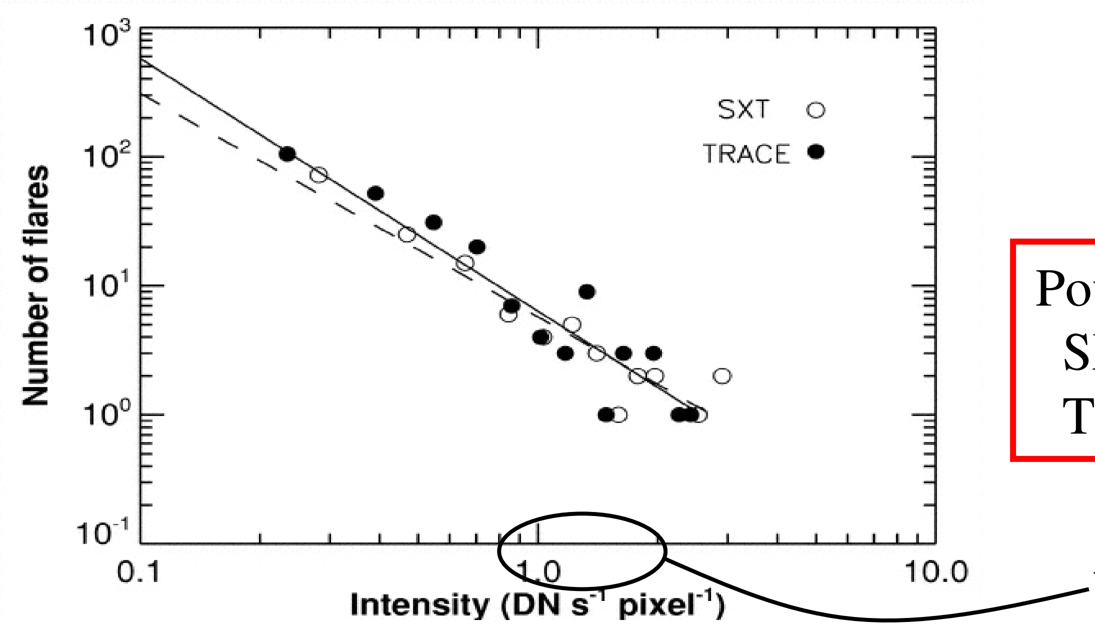
1998/6/4
TRACE (171Å)

The statistics of “flares”

The occurrence frequency of theoretical “flares” shows power-law which is similar to that of actual observed flares, power-law index is also similar to observed one.

↓

The observed nanoflares may not be a result of reconnection, but in fact may be due to nonlinear Alfvén wave heating.



typical nanoflare

Power-law index
SXT : −1.7
TRACE : −1.9

Summary

- The corona is episodically heated by fast- and slow-mode MHD shocks generated by nonlinear Alfvén waves via nonlinear coupling.
- Our model is consistent with actual coronal loops of 10^5km.
- The shock heating is the intermittent heating mechanism, so that it can be observed as small-scale flares.
- This suggests that nanoflares cannot easily be distinguished from Alfvén wave heating on observations.
- The upcoming Solar-B mission will test whether Alfvén waves are efficiently produced and whether the nanoflares are actually MHD shocks.

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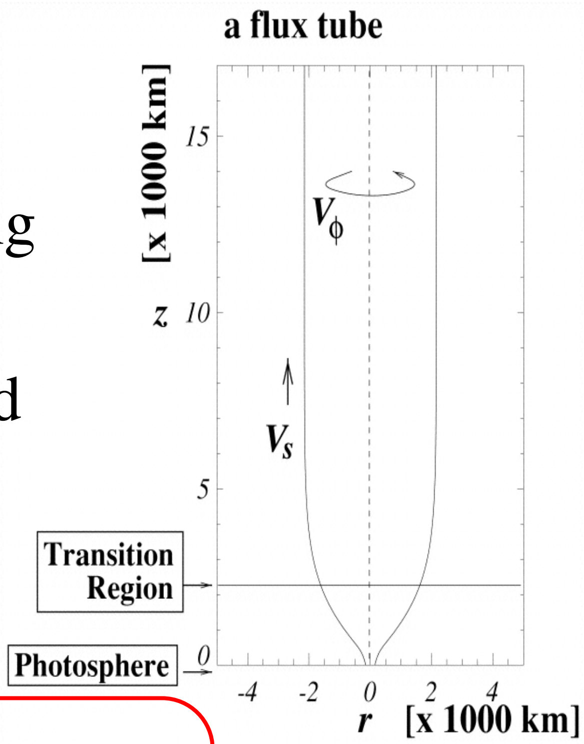

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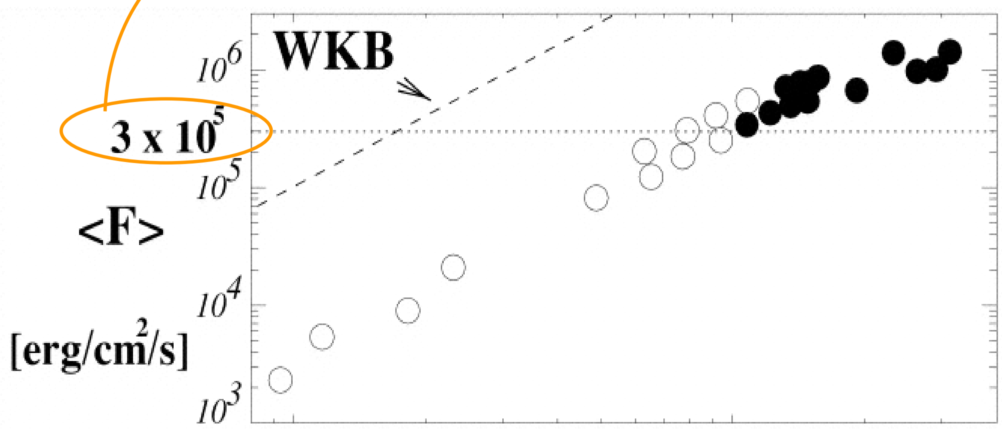
energy flux enough for heating the corona

Withbroe & Noyes (1977)



From Kudoh & Shibata (1999),

if $\sqrt{< V_{photosphere}^2 >} \geq$ 1 km/s ,

the energy flux enough for heating the quiet corona is transported by **Alfvén wave**.

Initial condition

The temperature distribution is uniform: $T = 10^4$ K .

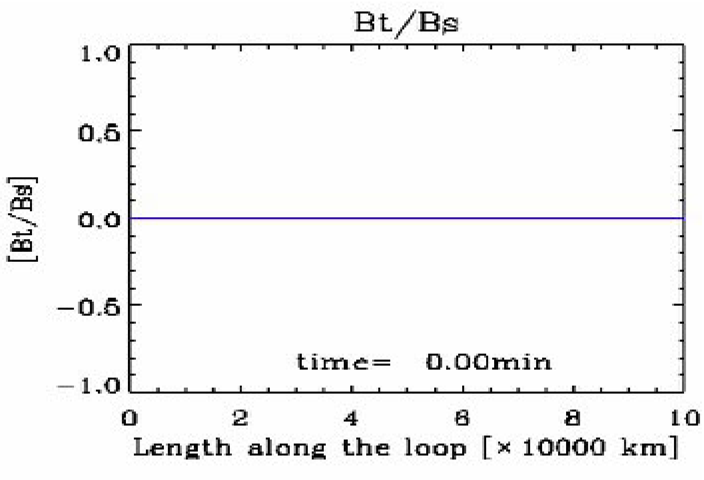
The density distribution mimics that of the emerging flux.

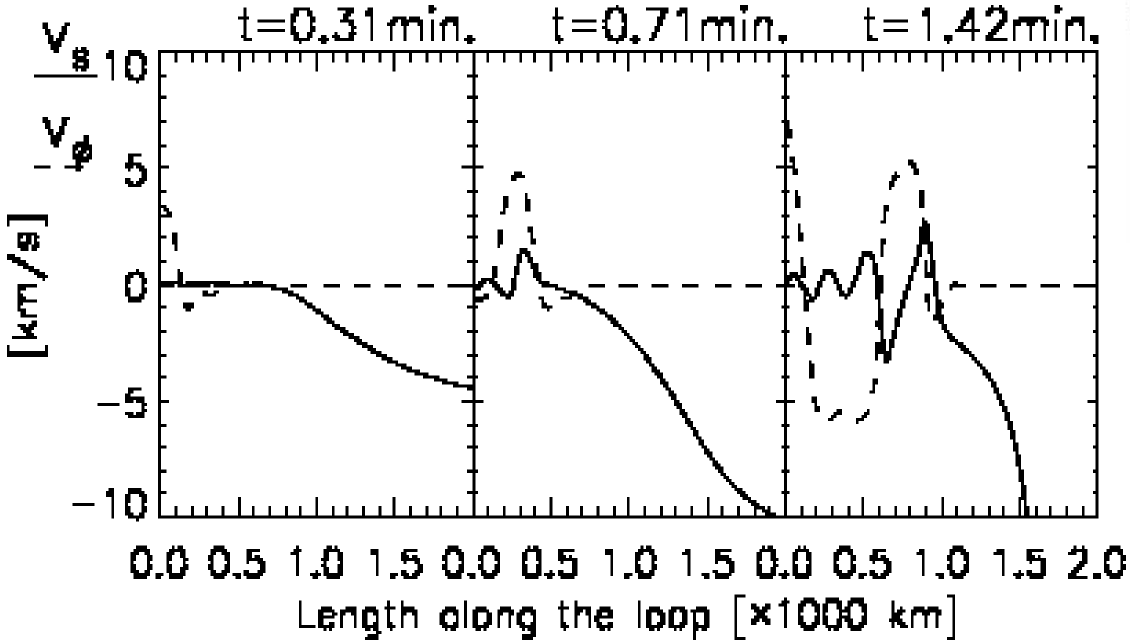
$$\rho \propto \mathrm{height}^{-4}$$

From two dimensional numerical simulation of an emerging flux.

（Shibata et al.1989)

The nonlinear coupling





Initially, only azimuthal motions are imposed.
(That is torsional Alfvén waves: dashed-line)
Then longitudinal motions are excited by nonlinear coupling. (solid line)

RTV scaling law

average physical values at loop apex while quasi-steady state

$$\begin{cases} T = \underline{1.26 \times 10^{6}\ \mathrm{K}} \\ N = 3.70 \times 10^{8}\ /\mathrm{cm}^{3} \\ P = 9.93 \times 10^{-2}\ \mathrm{dyn/cm}^{2} \end{cases}$$

RTV scaling law (Rosner, Tucker, & Vaiana 1978)

$$T \approx 1.4 \times 10^{3} (Pl)^{1/3}\ \mathrm{K}$$

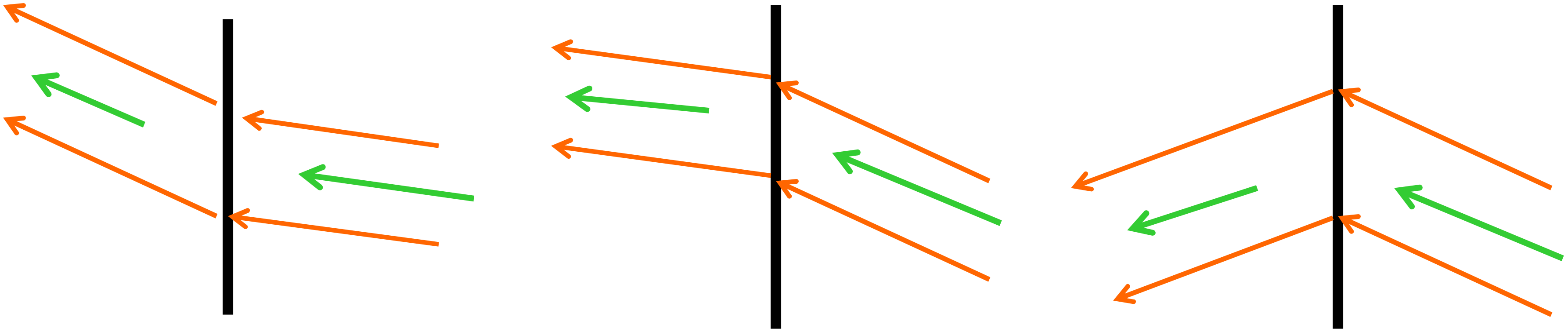
$$\approx \underline{1.29 \times 10^{6}\ \mathrm{K}} \qquad (\ l \sim 8 \times 10^{4}\ \mathrm{km\ \ in\ this\ case})$$

→fitting to theoretical model very well

MHD shocks

← B field

← Plasma flow



fast shock

slow shock

intermediate shock

$B_{behind} > B_{ahead}$

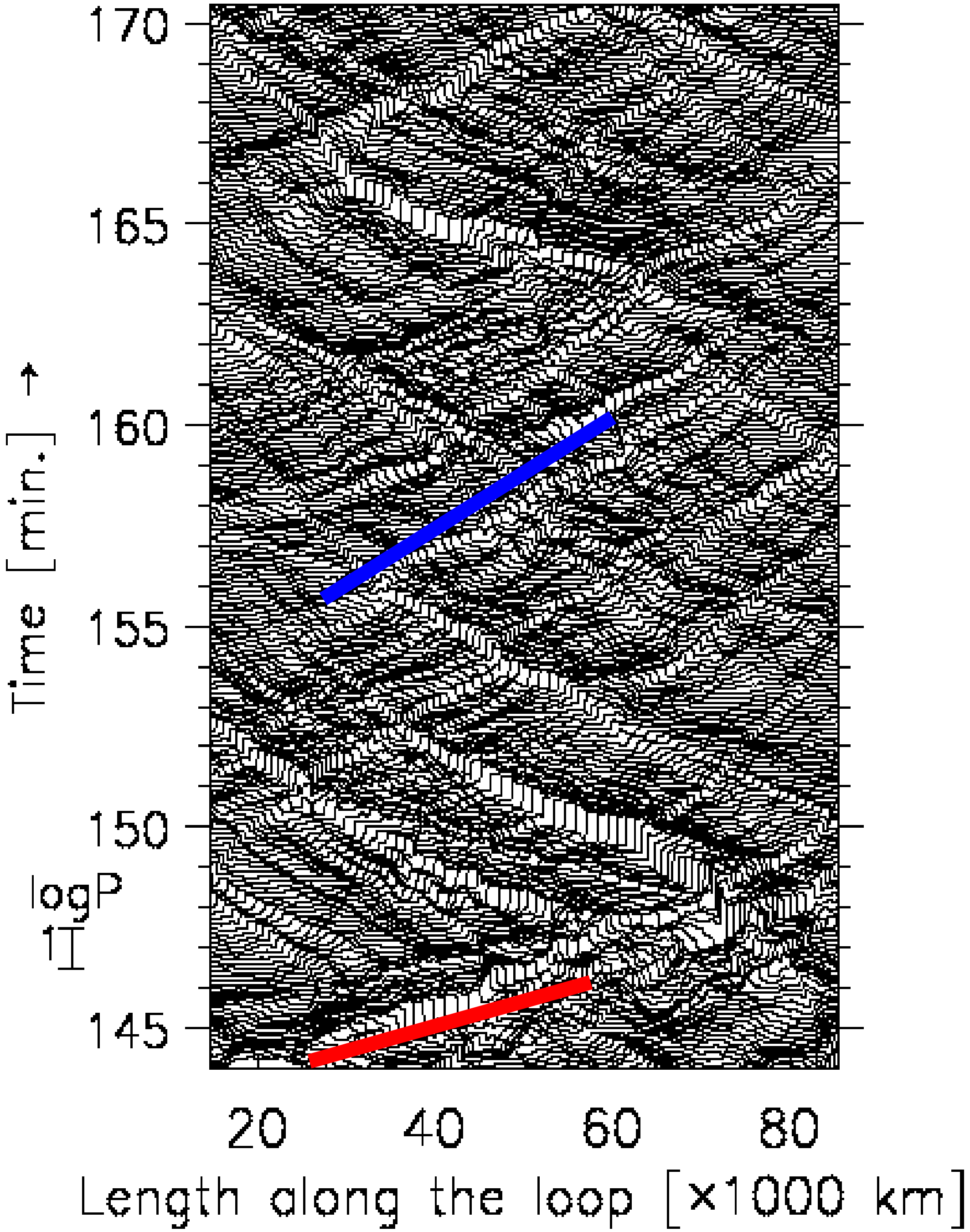
$B_{behind} < B_{ahead}$

fast shocks & slow shocks

🟥 Va ~ 250 km/s

🟦 Cs ~ 120 km/s

If shock heating is real,
future mission will observe
propagation of shock waves
like this figure.



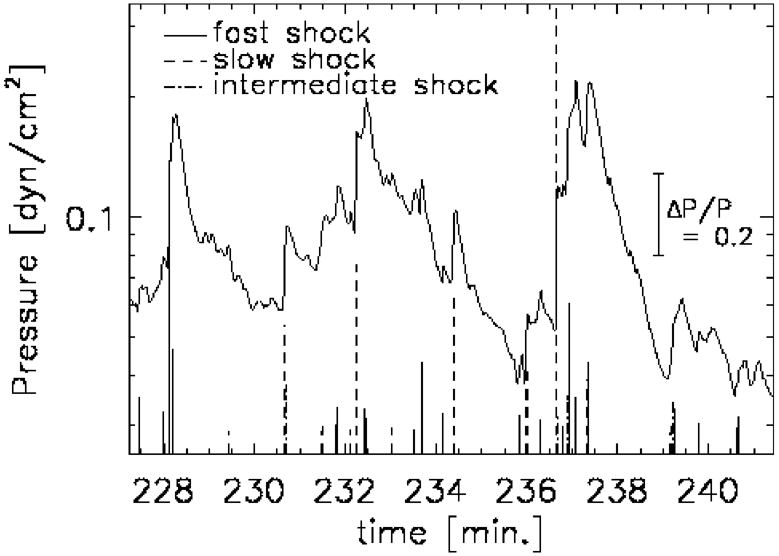
estimate of heating rate

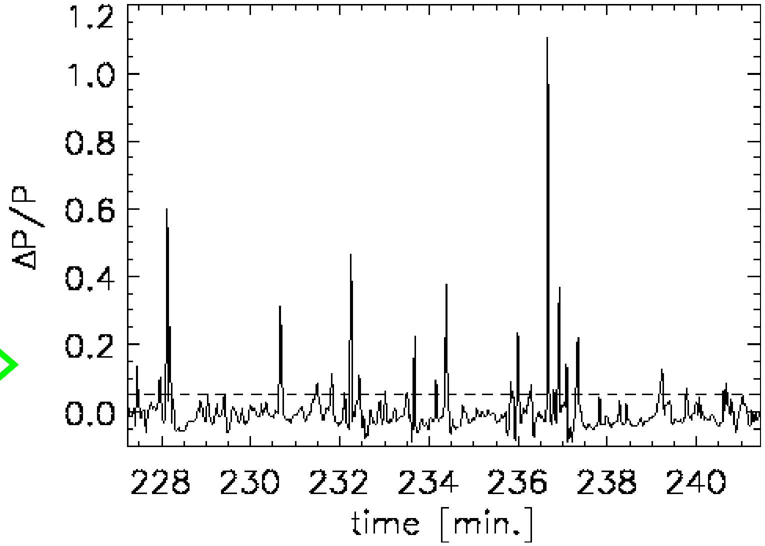
To estimate heating rate,
summing up every increment
of inertial energy by shocks.
↓

$$\text{heating rate} \equiv \frac{1}{\Delta t}\sum \frac{\Delta P}{\gamma - 1}$$

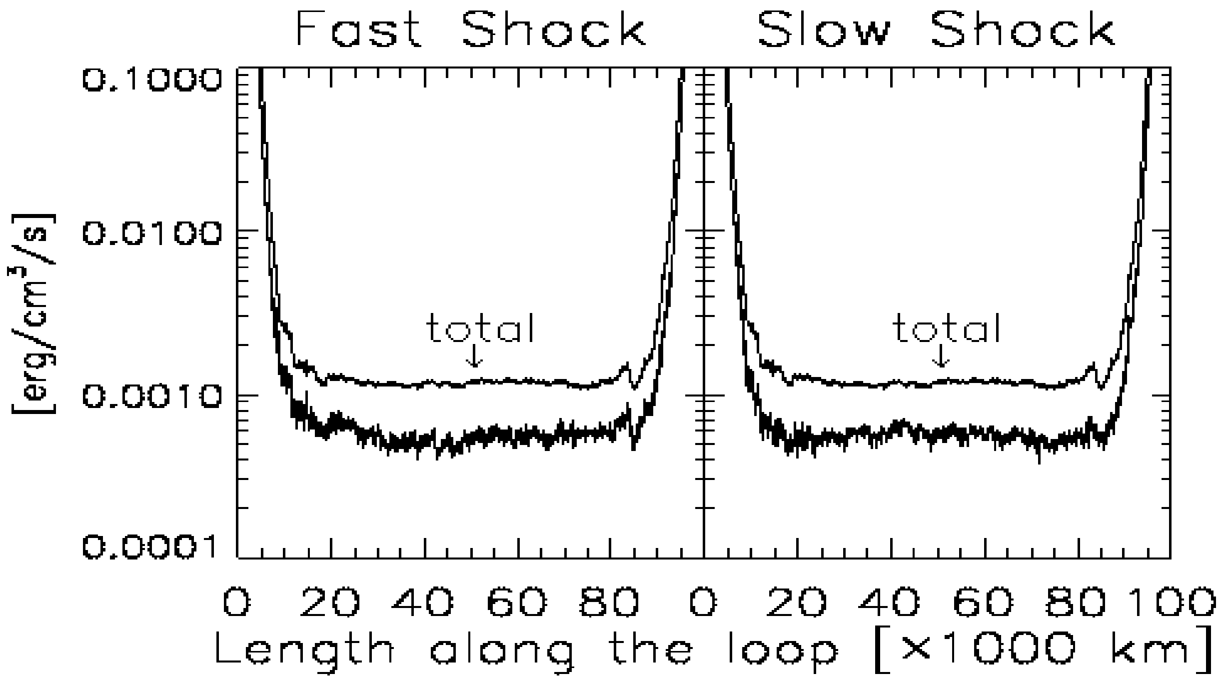
But, shocks of $\frac{\Delta P}{P} \geq 0.05$ are summed.
(Very small shocks are neglected.)

time variation of pressure
at loop apex

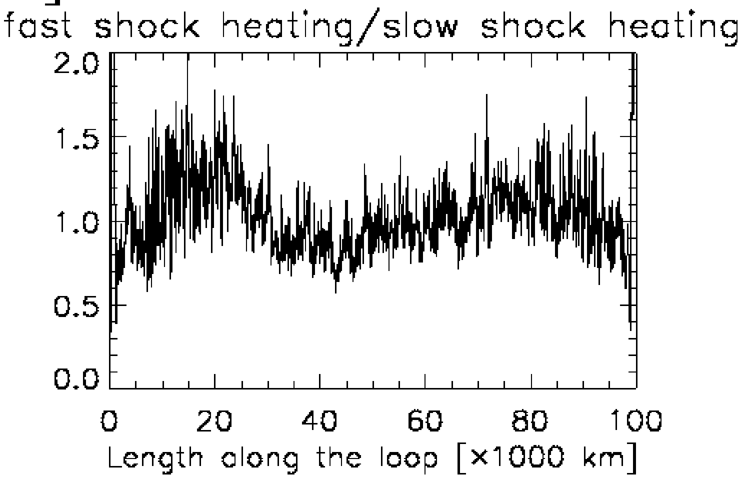




heating rate
(comparison of fast/slow shock contribution)



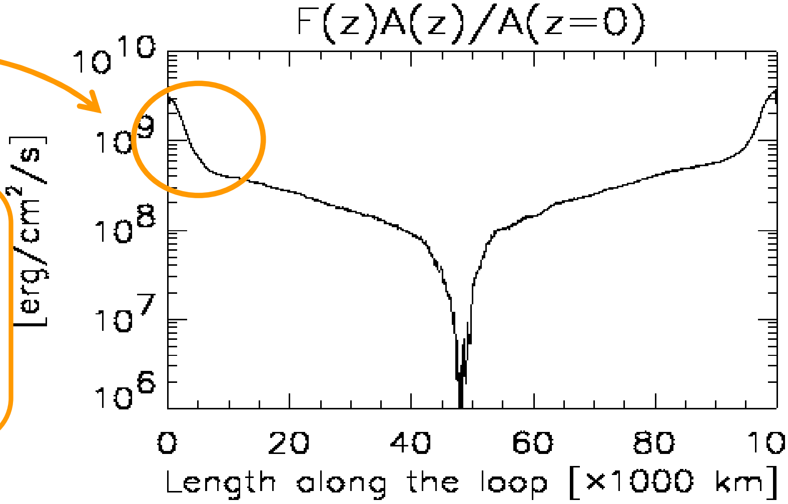
ratio of fast-shock heating
to slow-shock heating



equal amount of heating rate

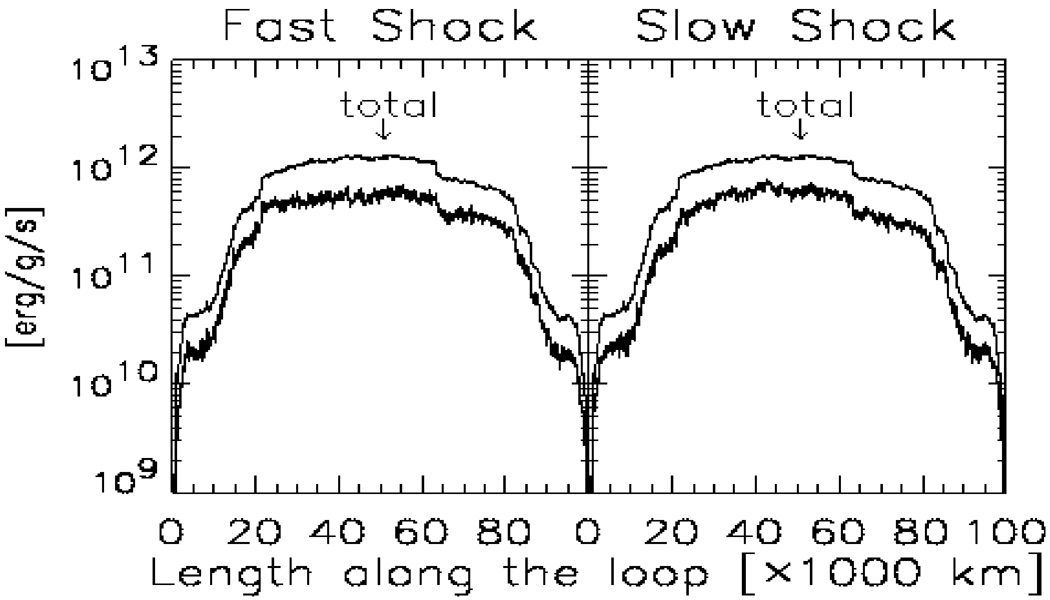
heating rate

time average of the energy flux



chromospheric heating
80% of energy flux is dumped
for high density plasma

heating rate per unit mass



Heating for corona is
the most efficient.

The numerical scheme

CIP scheme (cubic interpolated propagation)
developed by Japanese; Yabe (Yabe & Aoki 1991)
This has advantage to solve contact discontinuity
like the transition region or shock wave.

MOC-CT scheme (method of characteristic-constrained transport)
solving the propagation of Alfven waves
(Evans & Hawley 1988; Stone & Norman 1992)

The magnetic induction equation is solved by MOC-CT,
and the other equations are solved by CIP.

Observational evidence favorable to our model

The mean speed of the turbulent convection in the photosphere is observed to be ~ 1 km/s.

The observational results of the photospheric power spectrum shows a nearly flat spectrum. Tarbell et al.(1990)

A simulated observation with Yohkoh/SXT