PLASMA FLOWS IN THE CHROMOSPHERE-CORONA TRANSITION REGION OF THE SOLAR ATMOSPHERE

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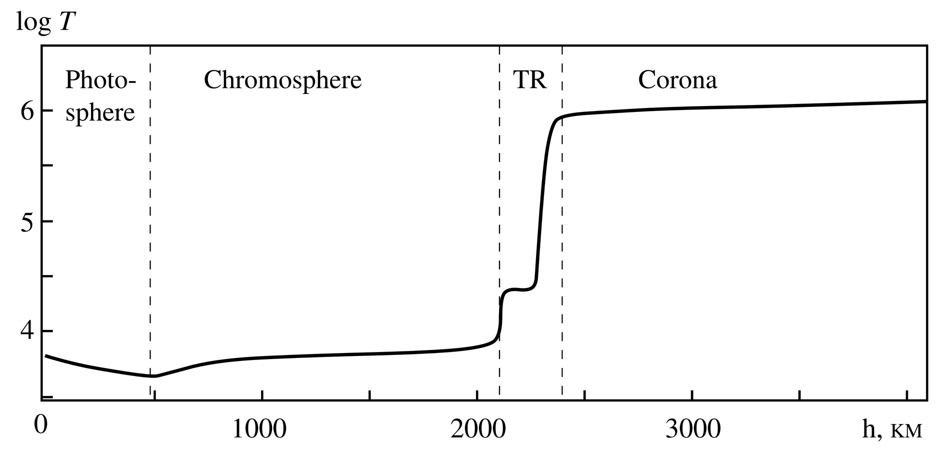
INTRODUCTION

- The structure of solar atmosphere above the photosphere is completely determined by the interaction of magnetic fields.
- The magnetic fields are concentrated in thin tubes.
- Charged particles generally travel along magnetic field lines ⇒ energy transfer also occurs preferentially along magnetic tubes.
- Thus, to study the transition layer, it is important to study the physics of the transfer and losses of energy in the plasma within a magnetic tube.

The **transition region** (TR) between the corona and the chromosphere of the Sun is an area in which temperature drops from $\sim 10^6$ K in the corona to $\sim 10^4$ K at the upper boundary of the chromosphere.



The study of the transition region is interesting, both with respect to energy transfer into the corona (the problem of corona heating) and in itself.

In particular, questions on

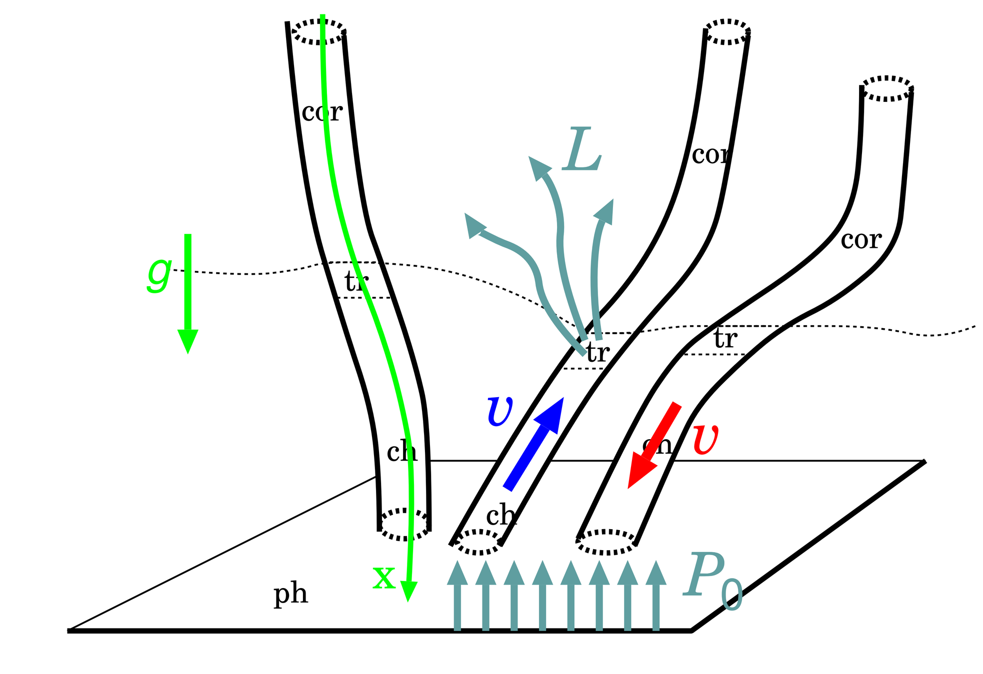
- the general mechanism of heat transfer,
- the role of the stream of runaway electrons,
- and the mechanism of the separation of the plasma into high- and low-temperature plasma

still occupy researchers.

In this work we are interested in how the physical conditions in the transition region change depending on the conditions on the lower boundary of the transition region.

PROBLEM STATEMENT

Let us consider a magnetic tube



- Suppose that classical heat conduction approximation is valid
- Use up-to-date data for energy loss rate due to radiation
- Assume stationary plasma flow in the tube
- Assume the absence of the heat flux from the transition region into the chromosphere

We consider the following system of equations governing the plasma inside the magnetic tube:

$$\begin{cases} p = nk_{\mathrm{B}}T, \\ \dfrac{d(nv)}{dx} = 0, \\ m_i nv\dfrac{dv}{dx} + 2\dfrac{dp}{dx} = g_{\odot}m_i n, \\ \dfrac{d}{dx}\left(-\kappa\dfrac{dT}{dx} + v\left(m_i n\dfrac{v^2}{2} + \dfrac{\gamma}{\gamma-1}2p\right)\right) = \\ \qquad = -(L(T) - L(T_0))n^2 + g_{\odot}m_i nv. \end{cases}$$

Where

* κ – is the electronic thermal conductivity:

$$\kappa \approx \frac{1.84\times 10^{-5}}{\ln\Lambda}T^{5/2}$$

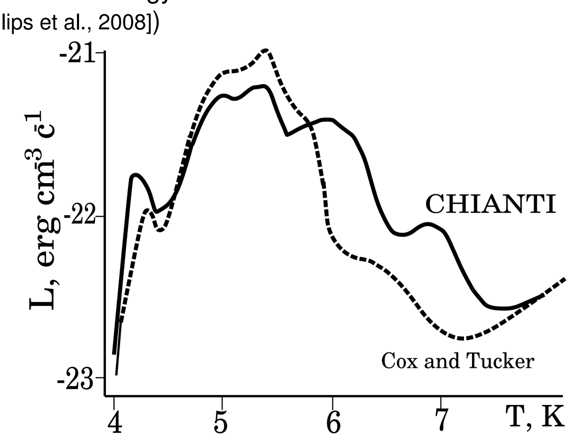
[Braginsky, 1963; Spitzer, 1965]

* $P_0 = L(T_0)n^2$ – is the power of the stationary heating of the chromosphere by an "external" source, in particular, by the flow of waves from the convection zone.

Assume that

- stationary case ($\partial/\partial t = 0$) holds
- plasma is completely ionized ($m_i = 1.44m_H$)
- plasma state is close to local thermodynamic equilibrium that is characterized by the temperature $T(x)$ (at $T = 10^5$ K $\tau_{ee} \sim 10^{-4}$ s, $\tau_{pp} \sim 4\times 10^{-3}$ s, $\tau_{ep} \sim 10^{-1}$ s, $\tau_f \gtrsim (1-10)$ s. ⇒ $T_e = T_p = T$)
- plasma is optically thin at $T > 3x10^4$ K,
- the tube has a constant cross-section,
- viscosity is negligible

* $L = L(T)$ – radiative energy losses function:
(CHIANTI, [Phillips et al., 2008])



Boundary conditions:

$$n\Big|_{T=T_0} = n_0,\quad v\Big|_{T=T_0} = v_0,\qquad T_0 = 10^4\ \mathrm{K},\quad n_0 = 10^{10}\ \mathrm{cm}^{-3},$$

$$T(0) = T_{up}/2,\quad \frac{dT}{dx}\Big|_{x\to\infty} = 0.\qquad T_{up} = 2\times 10^6\ \mathrm{K},\quad v_0 \in [0,\infty) -\ \text{parameter}.$$

Let us consider two opposite cases:

- the **tube is oriented horizontally**
  $v \neq 0,\ g = 0$
  (in this case we can see **the influence** of the presence **of plasma flows** on the physical conditions in the TR)
- the **tube is oriented vertically**
  $v \neq 0,\ g = g_{\odot}$
  (the influence of the presence of **gravitation**)

$n(T), p(T), v(T)$ DISTRIBUTIONS

- In the case of horizontally oriented tube the first three equations of the system can be **solved analytically**:

$$\begin{cases} n = \dfrac{n_0T_0}{T}\cdot\dfrac{1}{2}\cdot(1+r)(1\pm f(T)), \\ p = \quad p_0 \quad\cdot\dfrac{1}{2}\cdot(1+r)(1\pm f(T)), \\ v = \quad v_0 \quad\cdot\dfrac{1}{2r}\cdot(1+r)(1\mp f(T)). \end{cases}$$

For $v_0 < v_s(T_0)$ we have $(+,+,-)$,
for $v_0 > v_s(T_0)$ we have $(-,-,+)$.

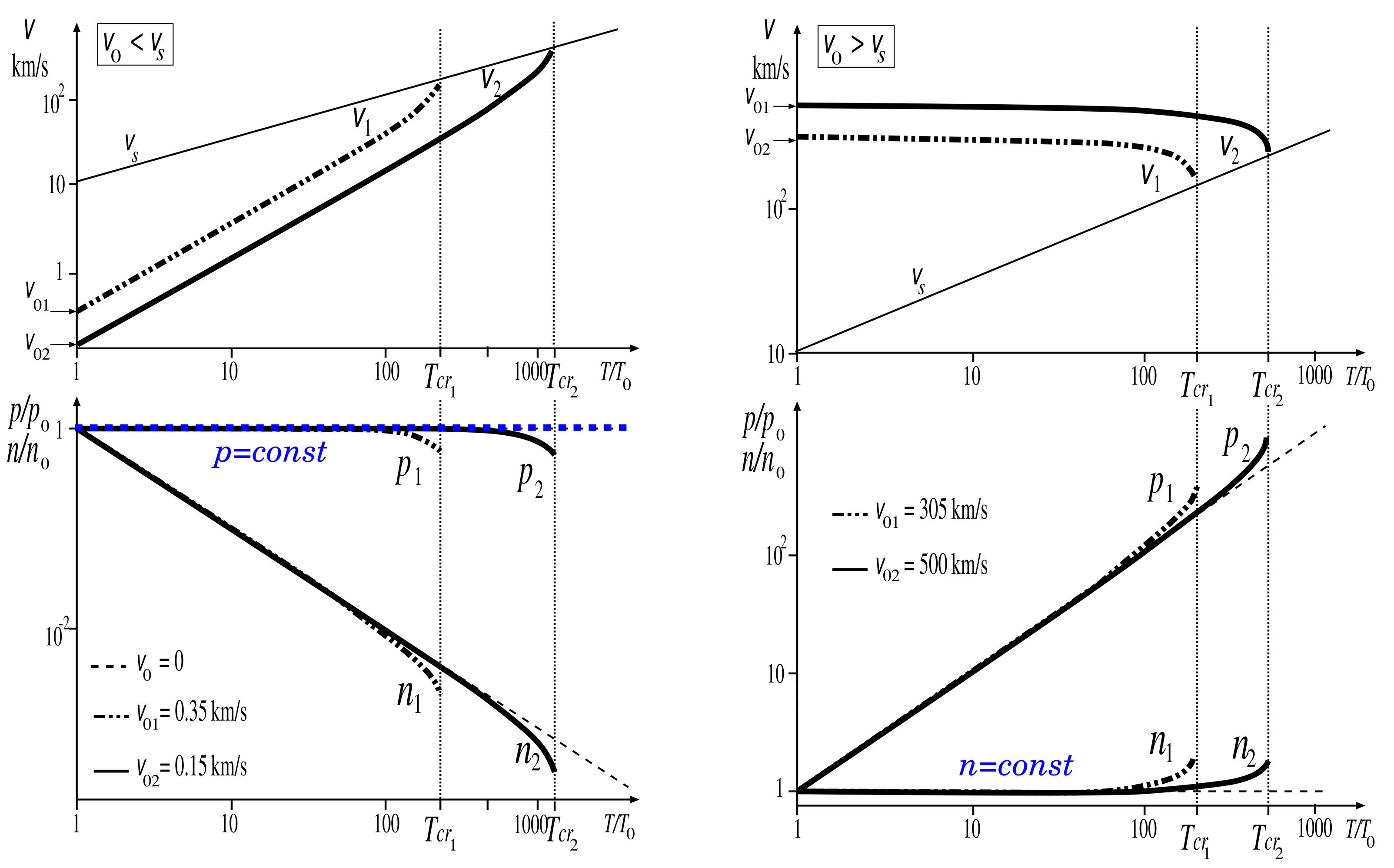
Here

$$r = \frac{m_i n_0 v_0^2}{2\,p_0} = \left(\frac{v_0}{v_s(T_0)}\right)^2,$$

$$f(T) = \sqrt{1 - \frac{4rT}{(1+r)^2T_0}}.$$

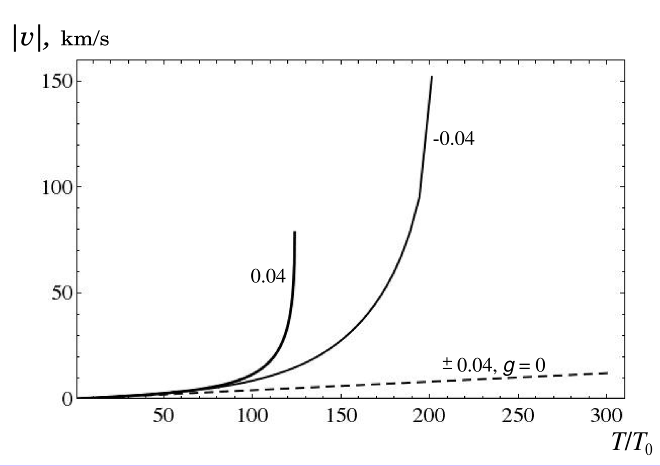
From the condition of the nonnegativity of the expression under the root sign we can see that

$$T \in (0, T_{cr}],\quad T_{cr} = \frac{(1+r)^2T_0}{4r}$$



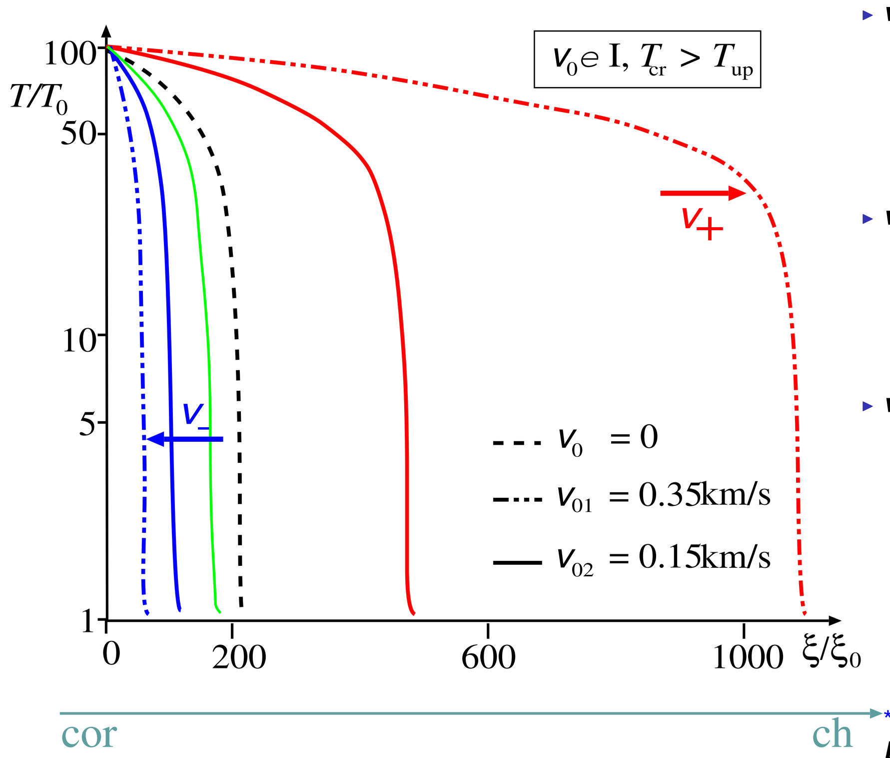
For $v_0 < v_s(T_0)$ one can see that n, p remain equal to $n_{v=0}, p_{v=0}$ for the temperatures below T_{cr}. Here the case $p = const$ applies.

- In the case of vertically oriented tube we solve the system numerically.



- Positive and negative velocities are growing with different gradients.
- Velocities growing with the temperature much faster than in the case $g = 0$.

TEMPERATURE DISTRIBUTION



$\xi = \int_0^x n(x)\,dx$, cm^{-2}.

All lines except for the green one correspond to the case $g = 0$.
Green line corresponds to the case $v_0 = 0, g = g_{\odot}$.

- $v = 0, g = 0$ This case can be solved analytically

$$\begin{cases} F = -\kappa\dfrac{dT}{dx}, \\ F = \left(\displaystyle\int_{T_0}^{T} 2\,(L(T') - L(T_0))\,\kappa n^2 dT'\right)^{1/2}. \end{cases}$$

- $v \neq 0, g = 0$

$$\begin{cases} y = \dfrac{dT}{dx}, \\ \dfrac{dy}{dT} = f(y,T) = \dfrac{L(T)n^2 - P_0}{\kappa}\dfrac{1}{y} - \dfrac{1}{\kappa}\dfrac{d\kappa}{dT}y + \dfrac{1}{\kappa}\dfrac{dF_v}{dT}. \end{cases}$$

- $v \neq 0, g = g_{\odot}$

$$\begin{cases} \dfrac{dT}{dx} = w, \\ \dfrac{dv}{dx} = f_1(T,v,w), \\ \dfrac{dw}{dx} = f_2(T,v,w). \end{cases}$$

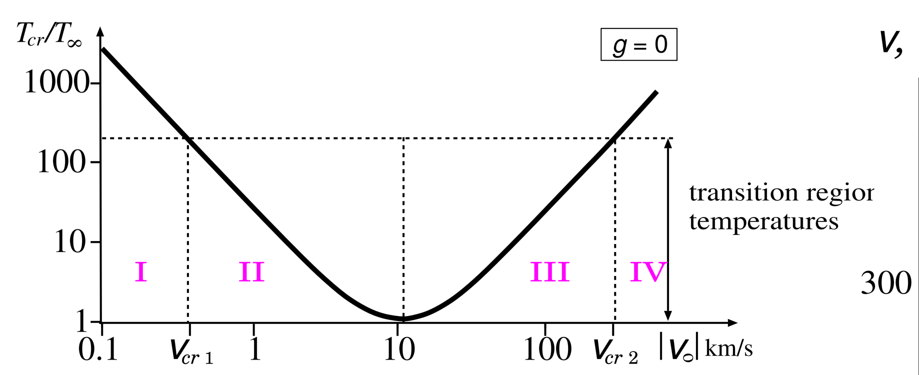
* Plasma is divided into high- and low-temperature parts (because of the $L(T)$ form).
* Plasma flow from the corona in the chromosphere "promotes" heat propagation from the corona in the TR; the chromosphere is heated more deeply than in the case $v = 0$.
* Plasma flow from the chromosphere in the corona "prevents" the heat propagation. A part of the heat energy returns into the corona together with the plasma stream.
* The gravitational force compresses temperature distributions (makes gradients of temperature and other variables bigger).
* Classical collisional approximation is valid only for distributions obtained with $v_0 \in$I, II, III.

THE ORIGIN OF THE CRITICAL TEMPERATURE

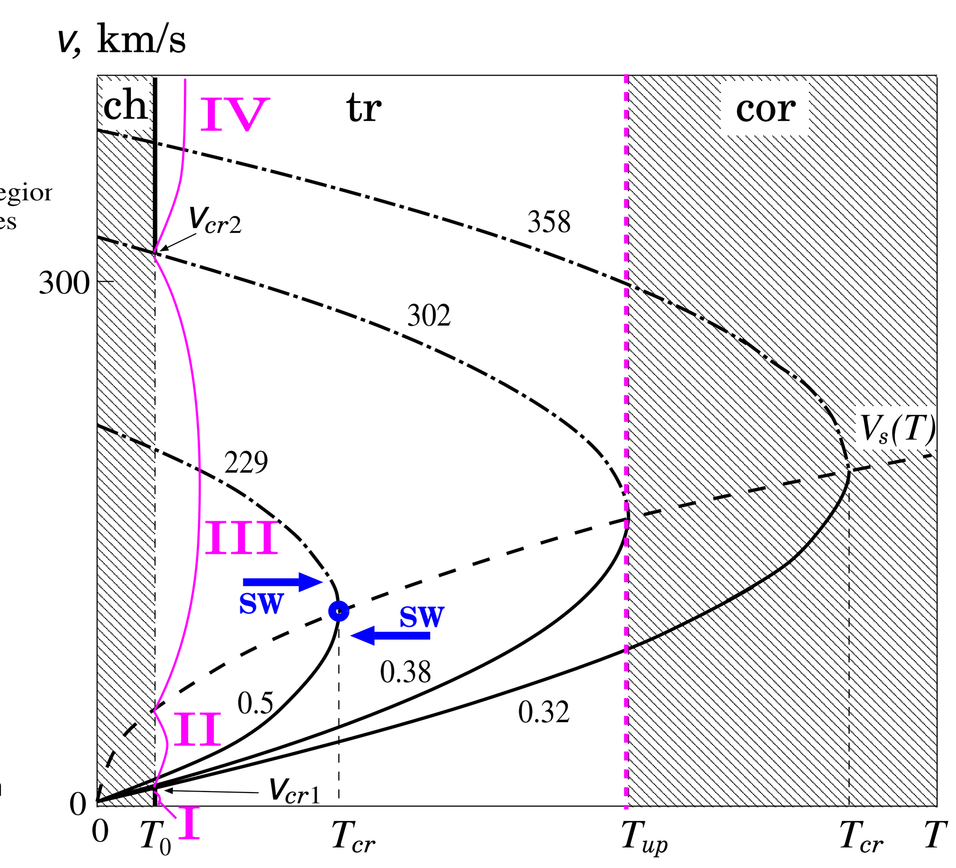
From the mathematical point of view T_{cr} is the boundary of the allowed temperature range.

From the physical point of view T_{cr} is the temperature at which plasma flow velocity is equal to the local sound velocity. $\boxed{v(T_{cr}) = v_s(T_{cr})}$

From the two following figures one can see that T_{cr} can be reached in the transition region or in the corona depending on the velocity at the lower boundary of the transition region.



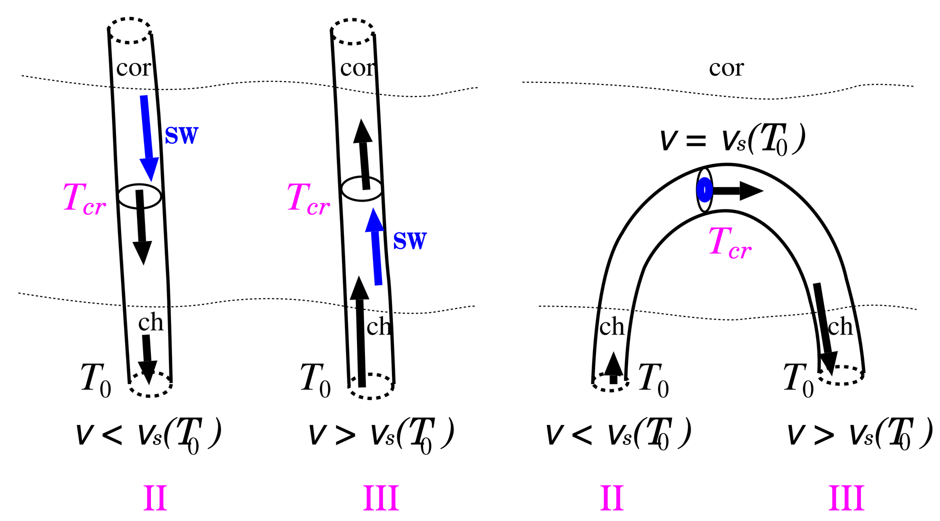
$V_{cr\,1} = 0.38$ km/s,
$V_{cr\,2} = 302$ km/s.

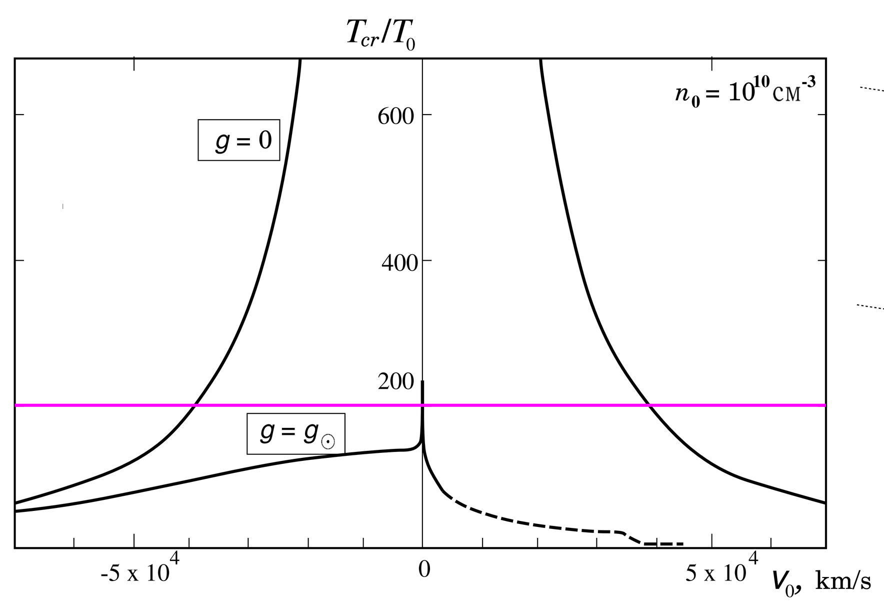


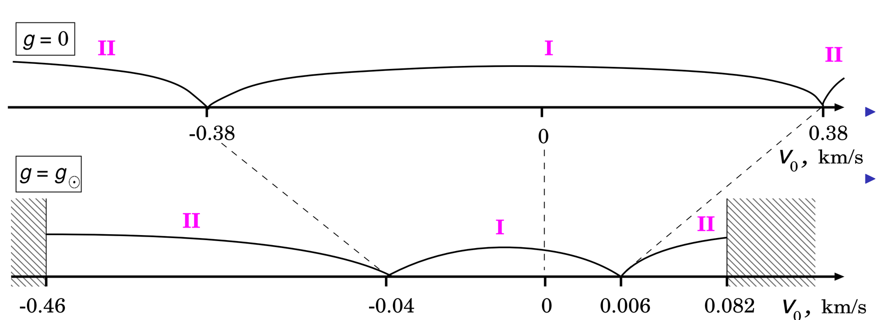
We can separate out 4 different velocity ranges:

- $v_0 \in$ **I** : $T_{cr} > T_{up}$ => $v < v_s$ in the transition region. Regime $p = const$ applies, concentration and pressure temperature distributions don't " feel" plasma flow. Quiet transition region.
- $v_0 \in$ **II** : $T_{cr} \leq T_{up}$ => $v(T_{cr})$ reaches $v_s(T_{cr})$ in the transition region. Shock waves can occur.
- $v_0 \in$ **III** : $T_{cr} \leq T_{up}$ => $v(T_{cr})$ drops to $v_s(T_{cr})$ in the transition region. Shock waves can occur.
- $v_0 \in$ **IV** : $T_{cr} > T_{up}$ => => $v < v_s$ in the transition region. Regime $n = const$ applies.

Possible interpretation $v_0 \in$ II,III:



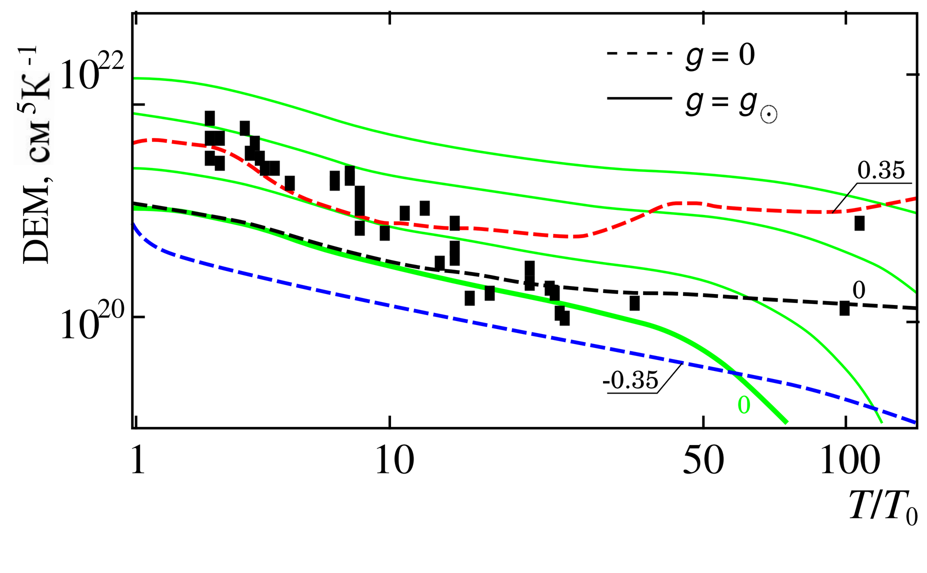




- In the case $g = g_{\odot}$ range I, for which there are no shock waves in the TR, become smaller than in the case $g = 0$,
- and it becomes asymmetric with respect to zero: it's shifted towards the negative velocities (the ones directed towards the corona).

COMPARISON WITH THE OBSERVATIONS

Obtained DEM distributions:



Differential emission measure DEM $= \frac{d\,\mathrm{ME}}{d\,T} = |ME = \int_0^x n_e^2\,dl| = n_e^2 dx/dT = n_e\,d\,\xi/d\,T$

Points correspond to observational data obtained by SUMER/SOHO, 1997. [Landi et al.,2008;Curdt et al.,2001] (differential emission measure, which is averaged over the entire disk of the quiet Sun, for a spectral line excited at a given temperature).

Green lines – $g = g_{\odot}$, $v_0 = 0$km/s, $n_0 \in [10^{10} - 10^{11}]$cm^{-3} – TR concentrations.

- When n_0 is bigger, then DEM is bigger (because with increase of concentration, the amount of emitting material is growing).
- The influence of gravitation becomes noticeable only in the upper part of the TR.
- Results obtained for $v_0 \in$ I and for the TR concentrations are consistent with the observational data.

The observations correspond to the average velocity of the plasma on the Sun. Therefore, the observed differential emission measure cannot be identified with the specific plasma velocity within a single magnetic tube. When observations with the resolution more than 100 km/pix will appear, it would be possible to obtain new information regarding boundary conditions in the chromosphere using obtained DEM profiles.

RESULTS

For horizontally and vertically oriented magnetic tubes:

- For various plasma flux velocities specified on the lower boundary of the chromosphere-corona transition region, we found temperature dependencies of plasma concentration, velocity and pressure along magnetic tube with one end immersed in the chromosphere and the other end located in the corona.
- We also obtained stationary temperature distributions along the magnetic tube. At each point of the distribution, there is a balance between the heating by the classical heat flux, the energy losses through the radiation of optically thin plasma and the energy transport associated with plasma flow.
- We then determined:
  (a) the range of velocities at the lower boundary of the chromosphere-corona transition region (v_0) for which generation of shock waves in the transition region is possible;
  (b) the range of v_0 for which transition region can be considered in the classical collisional approximation,
  (c) and the range v_0 for which the heating regime is close to p = const and computed radiation values are consistent with the results of satellite observations of extreme ultraviolet (EUV) radiation from the transition region.