COLLECTIVE PROCESSES IN THE TRANSITION REGION OF THE SOLAR ATMOSPHERE

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Introduction

Many scientific works are devoted to study of a transitional region between chromosphere and corona in the solar atmosphere. The transition region is characterized by the presence of significant heat flux from the corona into the chromosphere and by the sharp temperature jump. In papers by Bespalov and Savina (2007, 2008) was pointed out that both these properties probably associated with the formation of the developed ion-acoustic turbulence.

There are lots of results on the study of instabilities of waves in space plasma (see e.g. Zhelezniakov, 1997). For ion-acoustic oscillations colleagues usually study instability of particle flux and current (see Rudakov, Korablev, 1966; Galeev, Sagdeev, 1972). Current instabilities were analyzed in connection with of the problem of laboratory plasma heating. It is necessary to consider that ion-acoustic oscillations exist only in nonisothermal plasma.

In this paper we discuss in more detail the conditions of excitation of ion-acoustic oscillations by heat flux. We will show that the instability of ion-acoustic oscillations can be realized in the absence of particle flux by passing through the plasma heat flux. Actually, if in a medium exist heat flux then also exist inhomogeneity. In this paper, we assume that the typical wavelength of ion-acoustic oscillations, often comparable to the Debye radius, is small compared with the scale of inhomogeneity of the medium. Therefore, we can calculate the instability growth rate for locally homogeneous density distribution.

Particular attention will be paid to the study of conditions of ion-acoustic instability threshold and the maximum heat flux, which can be passed through the solar atmosphere in the regime of weak plasma turbulence.

1. Model distribution function

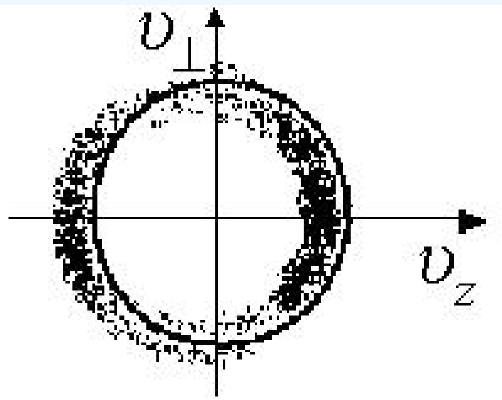
$$f = F(v) + \Phi(x, v).$$

Here $x = v_z / v$ $\quad F(v) = (1/2)\int_{-1}^{1} f dx$

$$F(v) = f_\circ(v) + |f_1(v) + \frac{v}{4}\frac{\partial f_1}{\partial v}|.$$

where $0 \le f_\circ$ ***, and*** $f_1(v)$ ***- the differentiated function***

$$\Phi(x, v) = [f_1(v) + \frac{v}{4}\frac{\partial f_1}{\partial v}]x,$$



Electron flux S_z ***is absent***

$$S_z = -j_z / e = \int_0^\infty \int_{-1}^{1} [f_1(v) + \frac{v}{4}\frac{\partial f_1}{\partial v}] x^2 v^3 dx dv = 0$$

Heat flux q_z ***, which is transferred by the electrons with this distribution function is equal to***

$$q_z = \frac{m}{2}\int_0^\infty \int_{-1}^{1} f x v^5 dx dv = \frac{m}{3}\int_0^\infty [f_1(v) + \frac{v}{4}\frac{\partial f_1}{\partial v}] v^5 dv = -\frac{m}{6}\int_0^\infty f_1(v) v^5 dv.$$

Thus, the selected distribution function corresponds to conditions, when in the plasma there is no electron flux, but there is heat flux.

2. Increment of the ion-acoustic instability

Let us take known expressions for the dispersion equation and the increment of the ion-acoustic oscillations (see Mikhailovsky, 1975) for $v_{Ti} < \omega/k$

Ion-acoustic oscillations have known dispersion relationship. They exist in the nonisothermal plasma $(T_i \ll T)$ ***in the specific range of the phase velocities (see Kadomtsev, 1976***)

$$Re(\varepsilon) = 1 + \frac{1}{k^2 r_D^2} - \frac{\omega_{pi}^2}{\omega^2} = 0, (\qquad \gamma = -\frac{Im(\varepsilon)}{\partial Re(\varepsilon)/\partial\omega}.$$

$$\omega = \frac{kv_s}{(1+k^2 r_D^2)^{1/2}},$$

$$Im(\varepsilon) = -\frac{4\pi^2 e^2}{mk^2}\int \vec{k}\frac{\partial f}{\partial\vec{v}}\delta(\omega - \vec{k}\vec{v})d^3v,$$

$$v_{Ti} < \frac{\omega}{k} < v_{Ti}\left(\frac{T}{T_i}\right)^{1/2},$$

The complete increment expression for the isotropic distribution function of ions and the distribution function of electrons with the isotropic and anisotropic parts is written in the form:

$$\gamma(y,k) = \omega\left(\frac{\omega}{k}\right)^3 \frac{m_i}{m}\frac{\pi^2}{n}\left\{-F\left(\frac{\omega}{k}\right) - \frac{m}{m_i}F_i\left(\frac{\omega}{k}\right) + \frac{1}{\pi}\int_0^\infty\int_{-1}^1\left[\frac{\partial\Phi}{\partial v} + \left(\frac{k}{\omega}y - \frac{x}{v}\right)\frac{\partial\Phi}{\partial x}\right]\times\right.$$

$$\left.\times Re\left[1 - x^2 - y^2 - \frac{\omega}{kv}\left(\frac{\omega}{kv} - 2xy\right)\right]^{-1/2}dxdv\right\},$$

If the anisotropic part of the distribution function of electrons is comparatively small, then expression for the increment can be simplified. In this case the increment can become positive only for the sufficiently small phase velocities ($(\omega/k)^2 \ll \langle v^2\rangle$***)***

$$\gamma(y,k) = \omega\left(\frac{\omega}{k}\right)^3 \frac{m_i}{m}\frac{\pi^2}{n}\left\{-F\left(\frac{\omega}{k}\right) - \frac{m}{m_i}F_i\left(\frac{\omega}{k}\right) + \frac{ky}{\pi\omega}\int_0^\infty\int_{-1}^1\left[f_1(v) + \frac{v}{4}\frac{\partial f_1}{\partial v}\right]Re(1 - x^2 - y^2)^{-1/2}dxdv\right\}.($$

3. Value of the increment maximum

If we in the formula for the increment integrate over x and over v , then increment is simplified and is written by the following form (Bespalov and Savina, 2009)

$$\gamma(y,k) = \omega\left(\frac{\omega}{k}\right)^3 \frac{m_i}{m}\frac{\pi^2}{n}\left[-F\left(\frac{\omega}{k}\right) - \frac{m}{m_i}F_i\left(\frac{\omega}{k}\right) + \frac{3ky}{4\omega}\int_0^\infty f_1(v)dv\right].$$

The maximum in the angular coordinate y increment $\gamma(k) = \max|_y \gamma(y,k)$ exist for $y = 1$, if $\int_0^\infty f_1 dv > 0$, and exist for $y = -1$, if $\int_0^\infty f_1 dv < 0$

$$\gamma(k) = \omega\left(\frac{\omega}{k}\right)^3 \frac{m_i}{m}\frac{\pi^2}{n}\left[-F\left(\frac{\omega}{k}\right) - \frac{m}{m_i}F_i\left(\frac{\omega}{k}\right) + \frac{3k}{4\omega}\left|\int_0^\infty f_1(v)dv\right|\right].$$

For definiteness, assume that the function of the proton distribution is Maxwellian with the temperature T_i , the isotropic part of the electron distribution function at relatively low velocities also assumed Maxwellian with a much higher temperature T. Then

$$F_i = \frac{n m_i^{3/2}}{(2\pi\kappa T_i)^{3/2}}\exp\left(-\frac{m_i v^2}{2\kappa T_i}\right), \qquad F = \frac{n m^{3/2}}{(2\pi\kappa T)^{3/2}}\exp\left(-\frac{m v^2}{2\kappa T}\right),$$

$$\gamma(k) = \pi^2\omega\left(\frac{\omega}{k}\right)^2\left[-\frac{m^{1/2} m_i \omega}{(2\pi\kappa T)^{3/2} k} - \frac{m_i^{3/2}\omega}{(2\pi\kappa T_i)^{3/2} k}\exp\left(-\frac{m_i\omega^2}{2\kappa T_i k^2}\right) + \frac{3m_i}{mn}\left|\int_0^\infty f_1(v)dv\right|\right],$$

where it is considered that $m\omega^2/2\kappa T k^2 < m/m_i$ and so $\exp(-m\omega^2/2\kappa T k^2) \simeq 1$

4. Estimation of heat flux on the threshold of the ion-acoustic instability

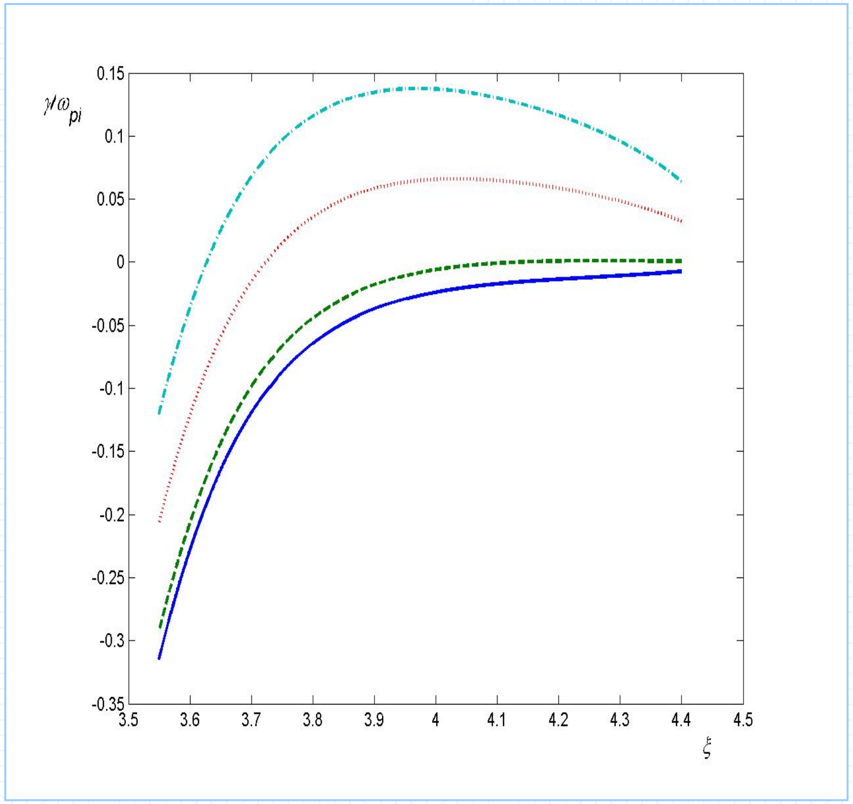
Replace approximately . $\int_0^\infty f_1 dv \approx -(6q_z)/(mv_T^5)$

Consider the dimensionless growth rate $\gamma(k)/\omega_i$ ***as a function of the dimensionless phase velocity*** $\xi = \omega/kv_{Ti}$ ***within the permitted phase velocities interval. Dimensionless growth rate can be written as***

$$\frac{\gamma(k)}{\omega_{pi}} = \xi^2(1-\pi^{-1/2}B^{2/3}C^{1/3}\xi^2)^{1/2}[A - B\xi - C\xi\exp(-\xi^2)].$$

Here $A = \frac{9\pi^2 m^{1/2} T_i |q_z|}{2^{5/2} n\kappa^{3/2} T^{5/2}}, B = (\pi\frac{m}{m_i})^{1/2}(\frac{T_i}{T})^{3/2}, C = \pi^{1/2}\frac{m_i}{m}.$

Let us consider now that $0 \le A$, $B \approx 1.3 \cdot 10^{-3}$, $C \approx 3.3 \cdot 10^3$.
If $B < A \ll C$ ***, that for*** $\sqrt{\ln(C/\sqrt{2}A)} \le \xi$ ***function in RHS has a maximum, which corresponds to the instability of ion-acoustic oscillations. The increment maximum grows with an increase in the parameter*** A ***, proportional to the heat flux.***



Let us determine condition to the critical heat flux, which corresponds to the threshold of instability, which is realized with simultaneous satisfaction of two conditions:

$$\frac{\gamma}{\omega_{pi}} = 0, \quad \frac{\partial}{\partial \xi}\left(\frac{\gamma}{\omega_{pi}}\right) = 0.$$

Carrying out simple computations, we obtain that these conditions are satisfied, if $A/B = 2\xi^3/(2\xi^2 - 1)$ **.**
The instability threshold corresponds to the condition

$$\xi_{th} = \frac{A}{3B} + \frac{1}{G}\left(\frac{A}{3B}\right)^2 + G, ($$

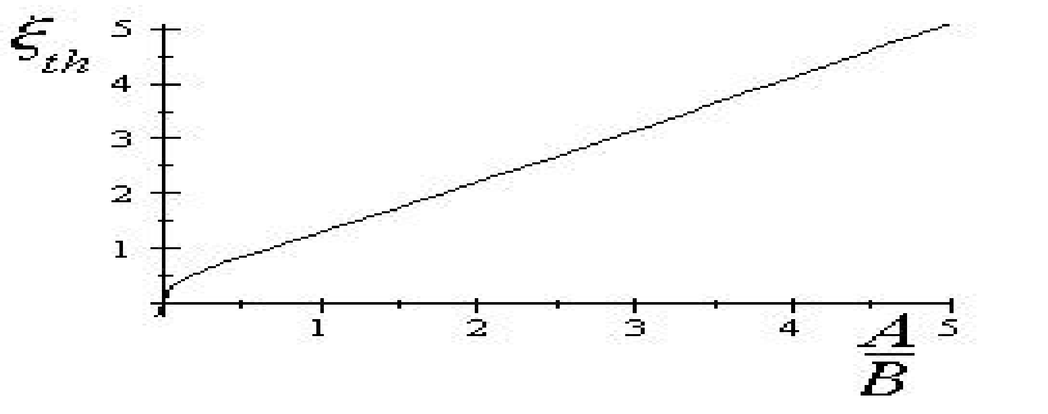
where

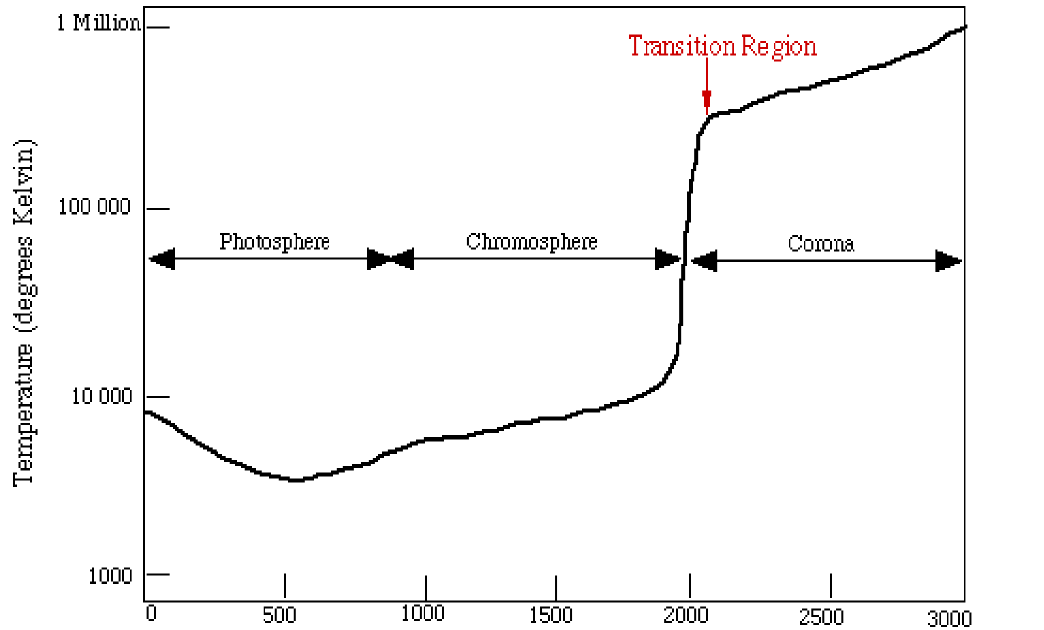
$$G = \{\frac{A}{4B} + (\frac{A}{3B})^3 + [(\frac{A}{4B})^2 + \frac{1}{3}(\frac{A}{2B})^4]^{1/2}\}^{1/3}.$$

Local critical heat flux is given by

$$|q_z| = \delta \frac{n(\kappa T)^{3/2}}{m_i^{1/2}},$$

Where $\delta = (2^{5/2} T_i^{1/2} \xi_{th})/(9\pi^{3/2} T^{1/2}) \approx 1$ ***. This result practically coincides with the expression, obtained in the paper by (Bespalov, Savina, 2008) by another method. It is important that, if in the heterogeneous layer of plasma heat flux constant, then the maximum of increment is realized in a certain intermediate region, where is minimal*** $nT^{3/2}$ **.**





The experimental data about the altitude distributions of the electron density and their temperature in solar atmosphere (Ashvanden, 2004) are known. As a result of the analysis of these data it is obtained, that the increment can become positive first of all in the transition layer, where with $q_z \approx 5 \cdot 10^5$ $erg \cdot cm^{-2} \cdot s^{-1}$ ***the electron density*** $n \approx 10^{10} cm^{-3}$ ***much less than in the chromosphere, and the temperature*** $T \approx 10^5 K$ ***much less than in the corona.***

5. On the influence of magnetic field to the calculation results

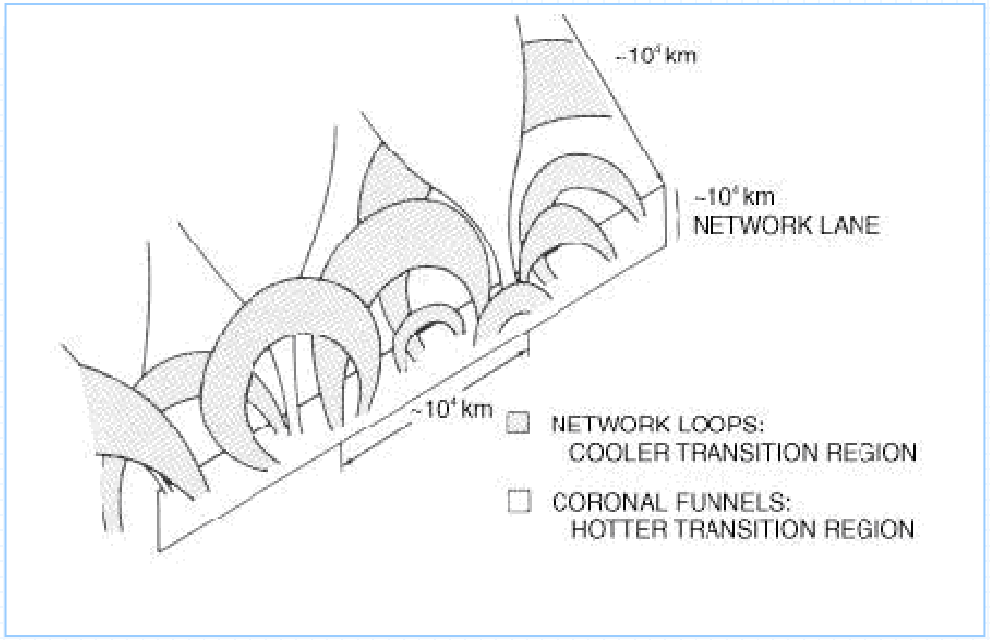
For clarification of the applicability of the results it is important to know the degree of application of the magnetic field. The obtained results are stored in a weak magnetic field, if the following three inequalities (see Mikhailovsky, 1975)

$$T_i \ll T,\ \omega_{Bi}^2 \ll \omega^2,\ \omega_B^2 \ll k^2 v_T^2.$$

The first of these inequalities must be satisfied for the ion-acoustic waves in a plasma without a magnetic field to. The second inequality provides a weak magnetic field effect on the dispersion relation, and the last inequality ensures that the expression for the growth rate. In the case of interest $\omega \approx \omega_{pi},\ k^2 \approx 0.1(\omega_{pi}/v_{Ti})^2$ ***. Therefore, the desired inequality on the magnetic field has the following form:***

$$B < (4\pi nmc^2)^{1/2} \min[(\frac{m_i}{m})^{1/2}, 0.1(\frac{T}{T_i})^{1/2}]$$

These inequalities are known to be carried out in the transition region of the solar atmosphere, and if $B < (4\pi nmc^2)^{1/2} \approx 100G$ ***and*** $n \approx 10^9 cm^{-3}$ ***Recall you that the typical values of the magnetic field in the transition region of the solar atmosphere outside active regions of the order of several Gauss. Consequently, outside of active regions and even in the active regions not with the strongest magnetic fields ion-acoustic turbulence can be responsible for the formation of a sharp temperature jump.***



6. Conclusion

- *The possibility of instability of ion-acoustic oscillations in the plasma without current and particle fluxe, but with the anisotropic distribution function corresponding to the heat flux, is shown. Model distribution function was chosen taking into account the conditions imposed on the fluxes of matter and heat.*
- *The increment of ion-acoustic oscillations is investigated as a functional of the distribution function parameters. As a result, set the threshold condition for the anisotropic part of the distribution function under which begins the growth of ion-acoustic waves with wave vectors against the heat flux. Local critical heat flux corresponding to the threshold of ion-acoustic instability is defined.*
- *In quiet regions of the solar atmosphere local critical heat flux was close to the magnitude of the known heat flux from the corona into the chromosphere on the altitude of the transition region.*
- *Our estimates show that out of the active regions and even in the active regions not with the strongest magnetic fields ion-acoustic turbulence can be responsible for the formation of a sharp temperature jump.*