ON THE THERMAL STABILITY AND THE STELLAR PLASMAS DYNAMICS

por

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Resumen

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Se llevó a cabo una aproximación al conjunto de ecuaciones obtenidas del análisis de estabilidad de un plasma con abundancias solares, **Ibáñez, Steele, and Higuera** (1995), **Higuera** (1995). Esta consistió en hacer que el coeficiente $\tilde{\mathcal{N}} = 0$ (factor de estabilidad o inestabilidad) en el conjunto de ecuaciones obtenidas sea igual a cero (estado marginal), esto permite ejecutar un algoritmo que soluciona dicho sistema. La integración numérica realizada muestra el comportamiento de la temperatura del centro T_c con respecto a la temperatura de borde T_b, así como la dependencia entre el parámetro ϵ_* con T_c en la estructura laminar bajo estudio.

Palabras clave: hidrodinámica - inestabilidades - plasmas.

Abstract

It was carried out an approximation to the joint of equations obtained from the stability analysis of a plasma with solar abundance **Ibáñez, Steele, and Higuera** (1995), **Higuera** (1995). Theses consisted in make the coefficient $\tilde{\mathcal{N}}$ (stability or instability factor) equal to zero (marginal state) permitting to execute an algorithm that solves the equations derived. The numerical integration shows the behavior of the center temperature T_c with respect to the boundary temperature T_b, as well as the dependency between the parameter ϵ_* with T_c in the laminar structure.

Key Words: hydrodynamics - instabilities - plasmas.

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Introducción

During the past few years, both theoretical models, and numerical codes have substantially modified our knowledge about the thermal stability of a plasma with solar abundance. In a previous paper **Ibáñez, Parravano & Mendoza** (1992). The generalized problem (with cooling and heating terms included at the same time) were analyzed and they have been established that exist steady solutions which depends of three parameters: θ_o, θ_b and λ_*, the central and boundary temperatures and the dimensional parameter, respectively. A non-linear analysis were carried out **Ibáñez, et al** (1993) applying the **Landau** (1944) method, in a slablikes systems. The second order approximation permitted them to derive some general conclusions about the nature and stability of nonhomogeneus thermal structures. On the other hand it was found that the nature of the thermal instability depends on a eigenvalue a_1 (linear approximation) and on a Landau constant a_2, which is equal to $a_2 = \pi(m+n-1-k)/3$, if the system is found nearby marginal state ($a_1 \sim 0$). Furthermore under the no-lineal analysis, they found that the values m, n and k, in conjunction with the direction of the disturbance are determinant to observe the evolution of the system.

In the present paper the above work will be generalized when one introduces dynamics. The object under study is a plasma with solar abundance, enclosed in a slablike thermal structure, which at the same time is affected by a warming-cooling function and a thermal diffusion of heat, dependent both of the temperature and density. The structure will be assumed to be initially in a steady-state at constant pressure with a given boundary temperature. Numerical results for particular cases are obtained.

Dynamic equations

Ideal gases with a ratio of specific heats, γ, and a mean molecular weight, μ are governed by

$$\frac{D\rho}{Dt} + \rho\nabla \cdot v = 0 \, , \tag{1}$$

$$\rho\frac{Dv}{Dt} + \nabla p = 0 \, , \tag{2}$$

$$\frac{R}{\mu}\left(\frac{1}{\gamma-1}\rho\frac{DT}{Dt} - T\frac{D\rho}{Dt}\right) + \rho L(\rho,T) - \nabla\cdot(\kappa\nabla T) = 0, \tag{3}$$

$$p = \frac{R}{\mu}\rho T \, . \tag{4}$$

The previous four relations are the known gas dynamic equations, where ρ, v, p, T, κ, and R are: mass density, velocity, pressure, temperature, coefficient of thermal conductivity, and a gas constant, respectively. On the other hand $L(\rho,T)$ is the heat-loss function per unit mass and time which is defined as

$$\rho L(\rho,T) = \Lambda(\rho,T) - \Gamma(\rho,T) \, , \tag{5}$$

being Γ, the heat liberated per unit volume and time by processes of an irreversible character and/or heat absorbed from and external source, and Λ, the heat loss rate per unit volume and time.

The relationships for the warming and cooling functions are given by,

$$\Gamma(\rho,T) = C\rho^a T^b, \; (erg\ cm^{-3}\ s^{-1}) \, . \tag{6}$$

where C, a, b are constants given (**Rosner it et al.**, 1978; **Dahlburg & Mariska**, 1988); and

$$\Lambda(\rho,T) = \rho^2\Lambda_i(\frac{T}{T_i})^\nu, \; (erg\ cm^{-3}\ s^{-1}) \, , \tag{7}$$

(**Vesecky it et al.**, 1979).

Furthermore the thermal conduction coefficient is taken under the form

$$\kappa(\rho,T) = \kappa_1\rho^c T^q \, , \tag{8}$$

where κ_1, c and q are given constants (**Parker**, 1953, **Spitzer**, 1962, **Ibáñez & Plachco**, 1991).

If is eliminated from the problem the temporary dependency, that is to say the derivatives with respect to the time are made equal to zero in the relations (1) - (4), is derived the stationary case studied by **Ibáñez, et all** (1992).

The geometry of the problem is a pair of parallel plates to constant pressure, in which the different functions (warming, cooling,) are evaluated point to point. **Higuera** (1995)

If for the thermodynamic variables involved in the problem, are introduced solutions of the form,

$$\Psi(x,y,z,t) = \Psi_o(x,y,z) + \delta\Psi(x,y,z,t), \tag{9}$$

to the joint of equations (1) - (4) (neglects non-linear terms in $\delta\Psi$) the system is reduced to

$$\frac{\partial}{\partial t}(\delta\rho) + \nabla\cdot(\rho_o\delta v) = 0 \, , \tag{10}$$

$$\rho_o\frac{\partial}{\partial t}(\delta v) + \nabla\delta p = 0 \, , \tag{11}$$

$$\frac{R}{\mu}\left[\frac{\gamma}{\gamma-1}\rho_o\nabla T_o\cdot(\delta v)+\frac{\rho_o}{\gamma-1}\frac{\partial}{\partial t}(\delta T)-T_o\frac{\partial}{\partial t}(\delta\rho)\right]$$
$$+[\rho_o L_\rho+L_o-\nabla\kappa_\rho\cdot\nabla T_o-\kappa_\rho\nabla^2 T_o]\delta\rho$$
$$+[\rho_o L_T-\nabla T_o\cdot\nabla\kappa_T-\kappa_T\nabla^2 T_o](\delta T)-\kappa_o\nabla^2(\delta T)$$
$$-\kappa_\rho\nabla\delta\rho\cdot\nabla T_o-(\nabla\kappa_o+\kappa_T\nabla T_o)\cdot\nabla(\delta T)=0\,. \qquad (12)$$

where $Y_\xi = \partial Y/\partial\xi$.

If furthermore they are considered solutions in terms of normal modes (**Chandrasekhar**, 1961), i.e.

$$\frac{\delta\rho}{\rho_o}=\eta(z)\exp[i(k_x x+k_y y)+\mathcal{N}t],$$
$$\frac{\delta T}{T_o}=\theta(z)\exp[i(k_x x+k_y y)+\mathcal{N}t],$$
$$v=v^1(z)\exp[i(k_x x+k_y y)+\mathcal{N}t],$$
$$\frac{\delta p}{p_o}=\beta(z)\exp[i(k_x x+k_y y)+\mathcal{N}t], \qquad (13)$$

where $k_\perp \equiv (k_x, k_y)$ is the wave number normal to z and $\mathcal{N}$is the growth rate, one may simplify the problem into the following three differential equations

$$-\mathcal{N}\Im v_z^1+\mathcal{N}\frac{dv_z^1}{dz}+(\mathcal{N}^2+c_o^2k_\perp^2)\eta+c_o^2k_\perp^2\theta=0, \qquad (14)$$

$$\frac{\mathcal{N}}{c_o^2}v_z^1+\frac{d\eta}{dz}+\frac{d\theta}{dz}=0, \qquad (15)$$

$$v_z^1\Im-c\chi_o\Im\frac{d\eta}{dz}-[2(q+1)-c]\chi_o\Im\frac{d\theta}{dz}$$
$$-\left[\frac{\gamma-1}{\gamma}\mathcal{N}-\frac{\gamma-1}{\gamma c_o^2}(\rho_o L_\rho+L_o)+\right.$$
$$\left.c(q+1-c)\chi_o\Im^2+c\chi_o\delta\Im\right]\eta$$
$$-\chi_o\frac{d^2\theta}{dz^2}+\{\frac{1}{\gamma}\mathcal{N}+\chi_o k_\perp^2+\frac{\gamma-1}{\gamma c_o^2}[T_oL_T-$$
$$(q+1)L_o]\}\theta=0, \qquad (16)$$

where $\Im=\frac{d\ln T_o}{dz}$, $\delta\Im=\frac{d^2\ln T_o}{dz^2}$; $\chi_o\equiv\kappa_o/\rho_o c_p$ (thermometric conductivity), and c_o (the isothermal sound velocity, $c_o^2\equiv RT_o/\mu$).

With the help of equation (15) the velocity may be eliminate, and reduce the set of equations (14)-(16) to two coupled ordinary differential equations. These equations can be written in a dimensional form as

$$\frac{d^2\eta}{d\tilde z^2}-\left(\frac{\tilde{\mathcal{N}}^2}{\tilde T_o}+\tilde k_\perp^2\right)\eta+\frac{d^2\theta}{d\tilde z^2}-\tilde k_\perp^2\theta=0, \qquad (17)$$

$$\Im\left\{[2(q+1)-c]\tilde\alpha\tilde T_o^{q-c}\tilde{\mathcal{N}}+1\right\}\frac{d\theta}{d\tilde z}$$
$$+\tilde{\mathcal{N}}\left[\frac{\gamma-1}{\gamma}\frac{\tilde{\mathcal{N}}}{\tilde T_o}-\tilde\alpha\epsilon_*(2\tilde T_o^{n-1}-a\tilde T_o^{m-1})+\right.$$
$$\left.c(q+1-c)\tilde\alpha\tilde T_o^{q-c}\Im^2+c\tilde\alpha\tilde T_o^{q-c}\delta\Im\right]\eta$$

$$\Im\left(c\tilde\alpha\tilde T_o^{q-c}\tilde{\mathcal{N}}+1\right)\frac{d\eta}{d\tilde z}+\tilde\alpha\tilde T_o^{q-c}\tilde{\mathcal{N}}\frac{d^2\theta}{d\tilde z^2}+$$
$$-\tilde{\mathcal{N}}\left\{\frac{1}{\gamma}\frac{\tilde{\mathcal{N}}}{\tilde T_o}+\tilde\alpha\tilde T_o^{q-c}\tilde k_\perp^2+\tilde\alpha\epsilon_*[(\nu-q-1)\tilde T_o^{n-1}-\right.$$
$$\left.(b-q-1)\tilde T_o^{m-1}]\right\}\theta=0, \qquad (18)$$

where

$$\tilde z=\frac{z}{l}\quad,\quad \tilde T_o=\frac{T_o}{T_*}\quad,\quad \tilde k_\perp^2=(lk_x)^2+(lk_{and})^2\,,$$
$$\tilde{\mathcal{N}}=\tau_*\mathcal{N}\quad,\quad\tau_*=\frac{l}{c_*}\quad,\quad\tau_\chi=\frac{l^2}{\chi_*}\quad,\quad\tilde\alpha=\frac{\tau_*}{\tau_\chi},$$
$$\epsilon_*=\frac{l^2\Gamma_1T_*^{m-1}}{\kappa_*}=\frac{l^2\Lambda_1T_*^{n-1}}{\kappa_*}. \qquad (19)$$

In the above equations the subindex ($_*$) refers to the respective quantity evaluated at the temperature T_*. In particular, c_* is the isothermal sound speed at T_* Additionally, due to the fact that the steady pressure is a constant p_o, the heating and cooling functions were expressed in identical form as in **Ibáñez, et al** (1992), i.e. $\Gamma=\Gamma_1T^m$, $\Lambda=\Lambda_1T^n$, Γ_1 and Λ_1 being constants, and $m=b-a$, $n=\nu-2$.

At this stage, the problem at hand has been reduced to finding the functions $\eta(z)$, $\theta(z)$ and the eigenvalues $\tilde{\mathcal{N}}$ for which the two equations (17) and (18) are compatible to each other for a given steady solutions $\tilde T_o(z)$ and for particular plasma conditions (i.e. for given values of c, q, a, b, and ν). Obviously, appropriate boundary conditions for free, or rigid bounding surfaces also have to be provided. Generally, the above problem has to be solved numerically. However, analytical solutions are possible for the steady trivial solution $\tilde T_o=1$ which physically corresponds to the solution for thermal equilibrium. ($L_o=0$). **Higuera.G.M.A** (1994)

On the other hand,the equations (17)-(18) also can be expressed in a matricial way:

$$\begin{pmatrix} \frac{d^2}{d\tilde{z}^2} & \frac{d^2}{d\tilde{z}^2} \\ E\frac{d}{d\tilde{z}} & F\frac{d}{d\tilde{z}} \end{pmatrix} \begin{Bmatrix} \eta \\ \theta \end{Bmatrix} + \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{Bmatrix} \eta \\ \theta \end{Bmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \tag{20}$$

where

$$A = -\left(\frac{\tilde{\mathcal{N}}^2}{\tilde{T}_o} + \tilde{k}_\perp^2\right) \tag{21}$$

$$B = -\tilde{k}_\perp^2 \tag{22}$$

$$C = \tilde{\mathcal{N}}\left[\frac{\gamma}{\gamma-1}\frac{\tilde{\mathcal{N}}}{\tilde{T}_o} - \tilde{\alpha}\epsilon_{*(2\tilde{T}_o^{n-1} - \alpha\tilde{T}_o^{m-1})+} c\tilde{\alpha}\tilde{T}_o^{q-c} \left\{(q+1-c)\Im^2 + d\Im\right\}\right] \tag{23}$$

$$D = -\tilde{\mathcal{N}}\left[\frac{1}{\gamma}\frac{\tilde{\mathcal{N}}}{\tilde{T}_o} + \tilde{\alpha}\tilde{T}_o^{q-c}\tilde{k}_\perp^2 + \tilde{\alpha}\epsilon_*\left\{(\gamma-q-1)\tilde{T}_o^{n-1} - (b-q-1)\tilde{T}_o^{m-1}\right\}\right] \tag{24}$$

$$E = \Im\left(c\tilde{\alpha}\tilde{T}_o^{q-c}\tilde{\mathcal{N}} + 1\right) \tag{25}$$

$$F = \tilde{\alpha}\tilde{T}_o\tilde{\mathcal{N}} + \Im\left[(2(q+1)-c)\tilde{\alpha}\tilde{T}_o^{q-c}\tilde{\mathcal{N}} + 1\right] \tag{26}$$

Marginal states

Independently of the boundary conditions, exists a non-trivial solution for the equation system (20) that corresponds to $\tilde{\mathcal{N}} = 0$. This root identifies a shift of the static equilibrium values at constant pressure, where the change in density just equalizes the change in temperature.

If is replaced the value $\tilde{\mathcal{N}} = 0$ in the equation (17) we obtain,

$$\begin{aligned} \frac{d^2\eta}{d\tilde{z}^2} + \tilde{k}_\perp^2\eta &= -\left[\frac{d^2\theta}{d\tilde{z}^2} + \tilde{k}_\perp^2\theta\right] \\ \eta &= \theta \end{aligned} \tag{27}$$

On the other hand, if is replaced the previous resulted in the equation (18) and are reorganized the remaining terms, one obtained,

$$\frac{d^2\theta}{d\tilde{z}^2}\left(\tilde{\alpha}\tilde{T}_o^{q-c}\right) + \frac{d\theta}{d\tilde{z}}\left[2(q+1-c)\tilde{\alpha}\tilde{T}_o^{q-c}\right]\Im + \theta\left\{\begin{array}{l} -\left[\frac{1}{\gamma}\frac{\tilde{\mathcal{N}}}{\tilde{T}_o} + \tilde{\alpha}\tilde{T}_o^{q-c}\tilde{k}_\perp^2 + \tilde{\alpha}\epsilon_*[(\nu-q-1)\tilde{T}_o^{n-1} - (b-q-1)\tilde{T}_o^{m-1}]\right] \\ -\left[\frac{\gamma-1}{\gamma}\frac{\tilde{\mathcal{N}}}{\tilde{T}_o} - \tilde{\alpha}\epsilon_*(2\tilde{T}_o^{n-1} - a\tilde{T}_o^{m-1}) + c\tilde{\alpha}\tilde{T}_o^{q-c}\left[(q+1-c)\Im^2 + \delta\Im\right]\right] \end{array}\right\} = 0, \tag{28}$$

now if $\tilde{\mathcal{N}} = 0$ finally one obtain,

$$\frac{d^2\theta}{d\tilde{z}^2}\left(\tilde{\alpha}\tilde{T}_o^{q-c}\right) + \frac{d\theta}{d\tilde{z}}\left[2(q+1-c)\tilde{\alpha}\tilde{T}_o^{q-c}\right]\Im + \theta\left\{\begin{array}{l} \left[-\tilde{\alpha}\tilde{T}_o^{q-c}\tilde{k}_\perp^2 - \tilde{\alpha}\epsilon_*[(\nu-q-1)\tilde{T}_o^{n-1} - (b-q-1)\tilde{T}_o^{m-1}]\right] \\ +\left[\tilde{\alpha}\epsilon_*(2\tilde{T}_o^{n-1} - a\tilde{T}_o^{m-1}) - c\tilde{\alpha}\tilde{T}_o^{q-c}[(q+1-c)\Im^2 + \delta\Im]\right] \end{array}\right\} = 0 \tag{29}$$

Table 1
HEATING FUNCTIONS

Case	*Description*	*a*	*b*
A	*Constant per unit volume heating*	0	0
B	*Constant per unit mass heating*	1	0
C	*Heating by coronal current dissipation*	1	1
D	*Heating by Alfvén mode/mode conversion*	7/6	7/6
E	*Heating by Afvén mode anomaluos conduction damping*	1/2	−1/2

Five dominant heating processes in astrophysical plasmas.

Figure 1 is a plot of the previous heating mechanisms. In all cases the value of density was $\rho = 4.96$

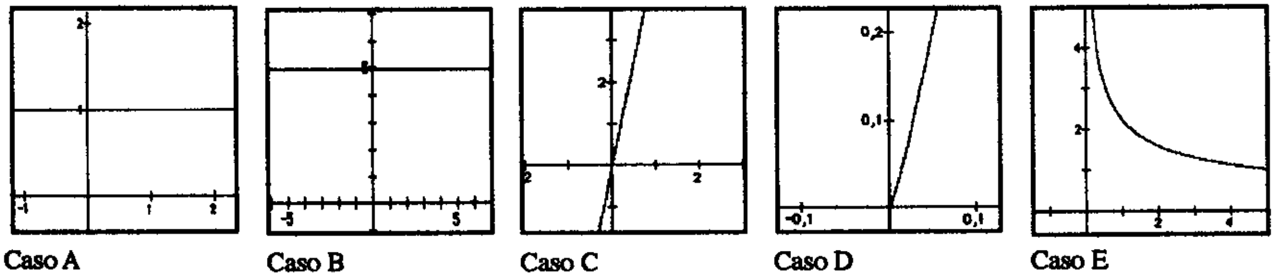

Figure 1. The heatings functions for five kinds of mechanisms, $\Gamma(\rho,T)=C\rho^aT^b$, see Table 1.

The steady state distributions of temperature are obtained through the equation,

$$\frac{d}{d\tilde{z}}\left(\tilde{T}_o^{q-c}\frac{dT}{d\tilde{z}}\right) = \varepsilon_*\left[\tilde{T}_o^{\nu-2} - \tilde{T}_o^{b-a}\right], \qquad (30)$$

where $\nu - 2 = n$ and $b - a = m$.

The cooling and heating functions

There are five heating processes, of particular importance in astrophysics, see for instance, Rosner, Tucker, & Vaiana (1978), Dahlburg & Mariska (1988) and references therein. Notice that the index m may only have two values, -1, or 0 for the five heating mechanisms under consideration.

The Table 2 shows the different values for the terms of the cooling function.

Table 2
Radiated Loss Function

$T_i(K)$	Λ_i	ν
$1.00\ x\ 10^2$	$1.85\ x\ 10^{17}$	+0.4000
$1.00\ x\ 10^4$	$2.42\ x\ 10^{24}$	+7.1700
$1.56\ x\ 10^4$	$5.88\ x\ 10^{25}$	−0.8390
$3.16\ x\ 10^4$	$3.25\ x\ 10^{25}$	+1.4300
$1.00\ x\ 10^5$	$1.68\ x\ 10^{26}$	−0.0307
$2.51\ x\ 10^5$	$1.63\ x\ 10^{26}$	−1.7400
$6.31\ x\ 10^5$	$3.28\ x\ 10^{25}$	−0.0792
$2.00\ x\ 10^6$	$2.99\ x\ 10^{25}$	−0.6640
$3.16\ x\ 10^7$	$4.78\ x\ 10^{24}$	+0.2930
$4.00\ x\ 10^7$	$5.13\ x\ 10^{24}$	+0.500

Ten diferrent values of the loss functions

Figure 2 shows the graphics relationed with the former table.

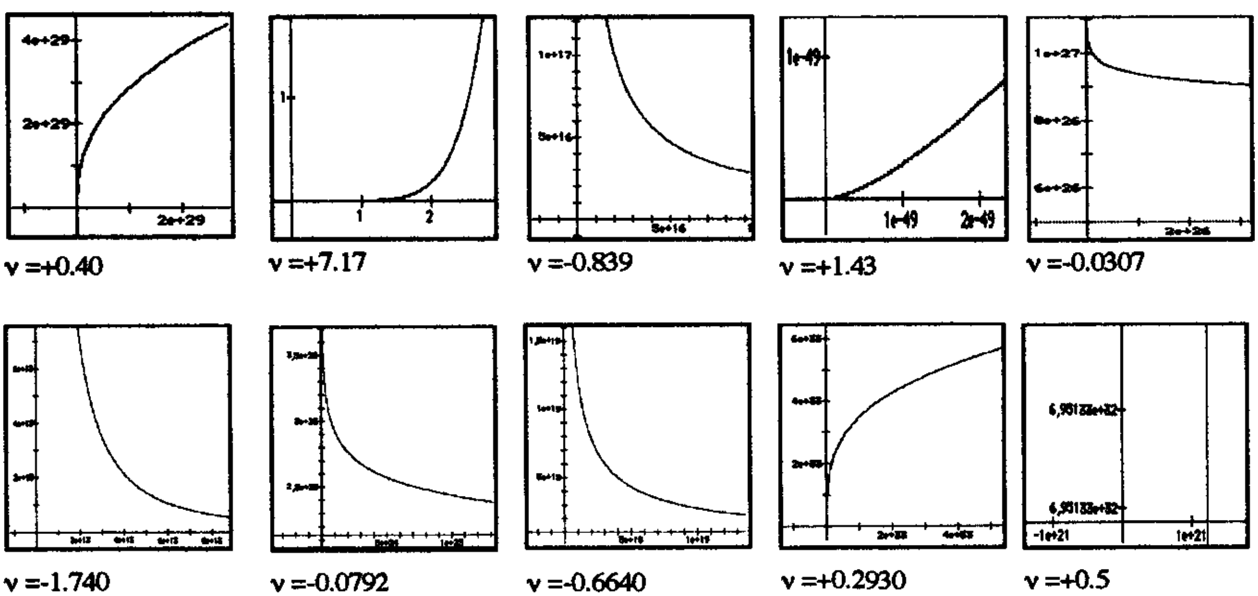

Figure 2.The cooling functions for the all diferents values shown in Table2, and ρ =4.96.

Astrophysical Applications

For context, the case $n = -3/2$, $m = -1$ studied in paper I will be analyzed. This case corresponds to a slab of plasma with solar abundance heated at a rate constant per unit mass (case B), and cooled by free-free radiation (ν=1/2). Additionally, under the above conditions, the heat diffusion is dominated by electrons and the well known relation of Spitzer (1962) holds (i.e. $c = 0$, $q = 5/2$)

The equations (29) and (30) represents the condition for $\tilde{N} = 0$. i.e. $\tilde{N}_r = 0$, $\tilde{N}_i = 0$. The boundary conditions are that $\theta = 1$, $\frac{d\theta}{d\tilde{z}} = 0$ when $\tilde{z} = 0$, and $\theta = 0$ when $\tilde{z} = 1$. As the system is oversuscribed by one quantity, ϵ_* plays the role of an eigenvalue.

Under this context the expression,

$$I = \int_o^1 \frac{1}{T} \left| \frac{dT}{d\tilde{z}} \right| d\tilde{z}, \qquad (31)$$

defines de inhomogeneity of the system.

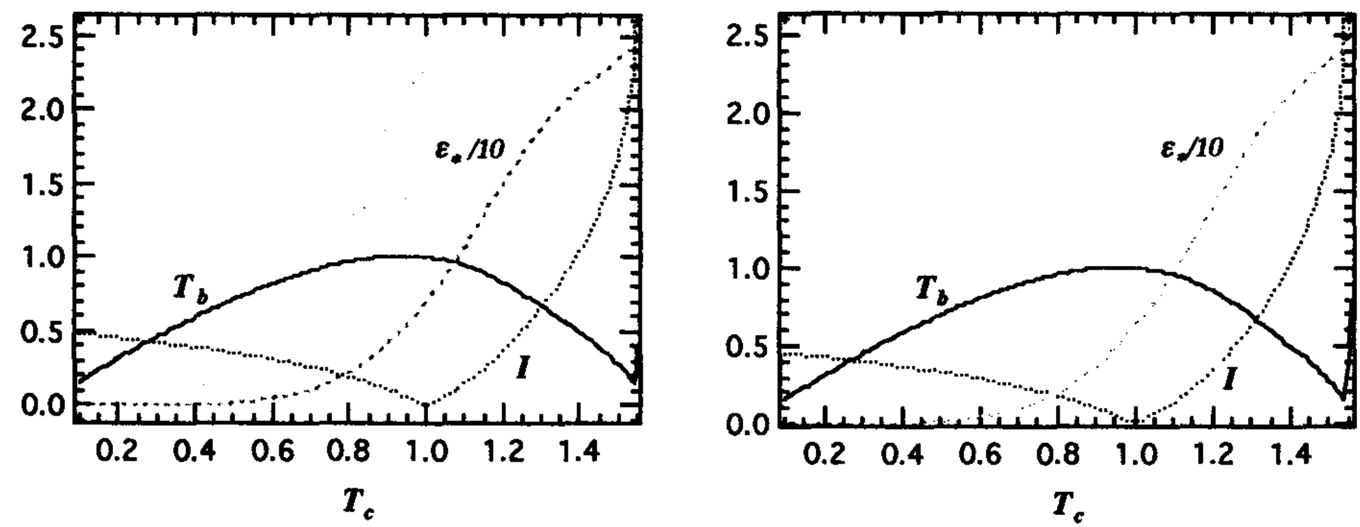

Figure 3. Constant heating per unit mass (Case B). Left picture corresponds to K=1.0, and right picture corresponds to K=π/4

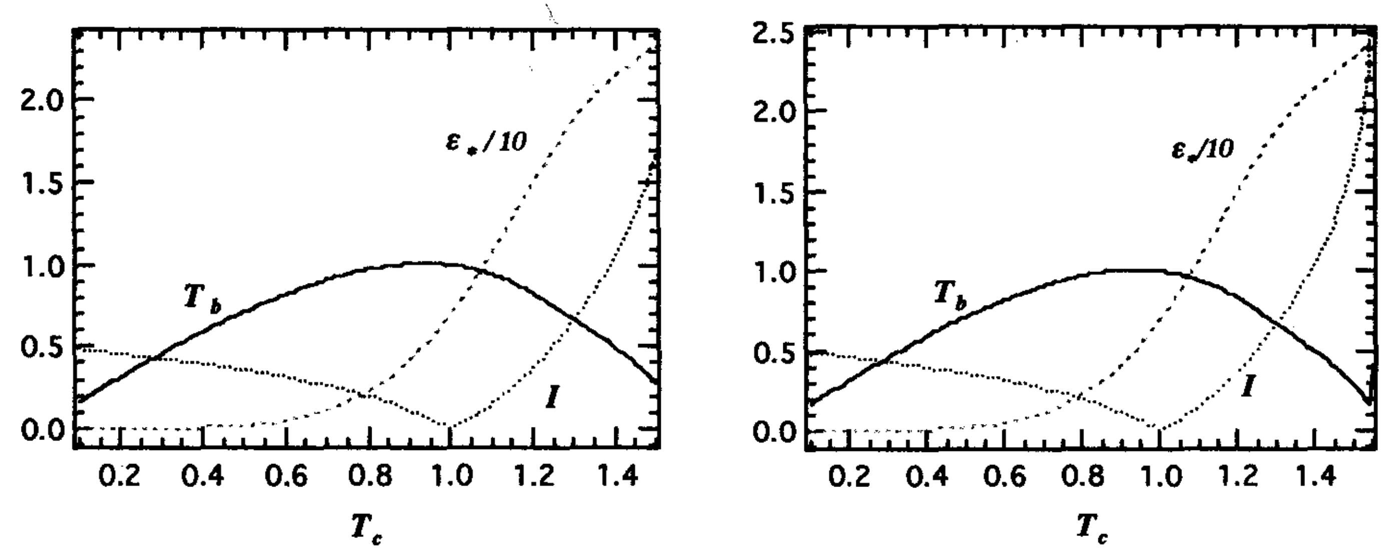

Figure 4. Constant heating per unit mass (Case B). Left picture corresponds to α=1.0, and right picture corresponds to α=10

With the help of a numerical code one can resolve this equations and obtain the dependency among the central temperature T_c and the frontier temperature T_b. On the other hand one can be derived the dependency among the parameter ϵ_* and T_c, as well as the factor of inhomogeneity I with T_c

Figure 3 shows ϵ_* varying with $\tilde{T}_c$, also are plotted the parameter I and the outer temperature $\tilde{T}_b$ for Case B. Left picture corresponds to $K = 1.0$ and right to $K = \pi/4$. The behavior of the edge temperature T_b as compared to the center temperature T_C in the laminar system, shows that for values of T_c less than 1, T_b grows in equal proportion, meanwhile for values of T_c greater than 1, T_c growing while T_b reduces. On the other hand for values of T_c greater than 1.45, T_b grows strongly. It is interesting to note that the parameter ϵ_* for values of T_c between 0,0 and $\sim$ 0,1 stays constant, however above 0,5 grows in direct proportion to the central temperature. On the other hand the factor of inhomogeneity I for values of T_c among 0,0 and 1,0 decreases until a value of zero, however above this value grows in function of T_c.

Figure 4 shows the same variables as figure 3 but in this case it was maintained constant the value of K and was modified the parameter $\tilde{\alpha}$ between 0.1 and 10. Of course it does not exist any dependency of the variables with this parameter.

In the Figure 5, the parameter ϵ_*, the outer temperature $\tilde{T}_b$ and the inhomogeneity I are plotted for Case A. The boundary temperature increases quickly with respect to the center temperature (for values of $T_c < 0,3$), above this temperature, T_c grows while T_b decreases slightly. On the other hand the parameter ϵ_* grows slowly with T_c. The factor I for values of $T_c > 1,0$ is resembled to show in the case B, however for $T_c < 1,0$ I grows strongly until $T_c \sim 0,2$ below of which these factor tends to reduce.

Conclusions

Such as in the previous work (Higuera, 1995), the general problem of own values was reduced to two coupled differential equations of second order those which should be solved numerically. It was made carry out the approximation $\tilde{N} = 0$ (marginal state) and was solved the set of corresponding equations.

Such as is observed in the Figure 4, and derived of the obtained equations, for the marginal state ($\tilde{N} = 0$) does not exist dependency of the variables involved with the parameter $\tilde{\alpha}$. The behavior of the center temperature versus the boundary temperature in the two cases (A and B) shows considerable differences. For example while for the range $0,0 < T_c < 0,3$ in the Case A, the frontier temperature increases more quickly than the central temperature, in the Case B grow proportionally. Now for the range $0.3 < T_c < 1.0$ in the Case A, T_b

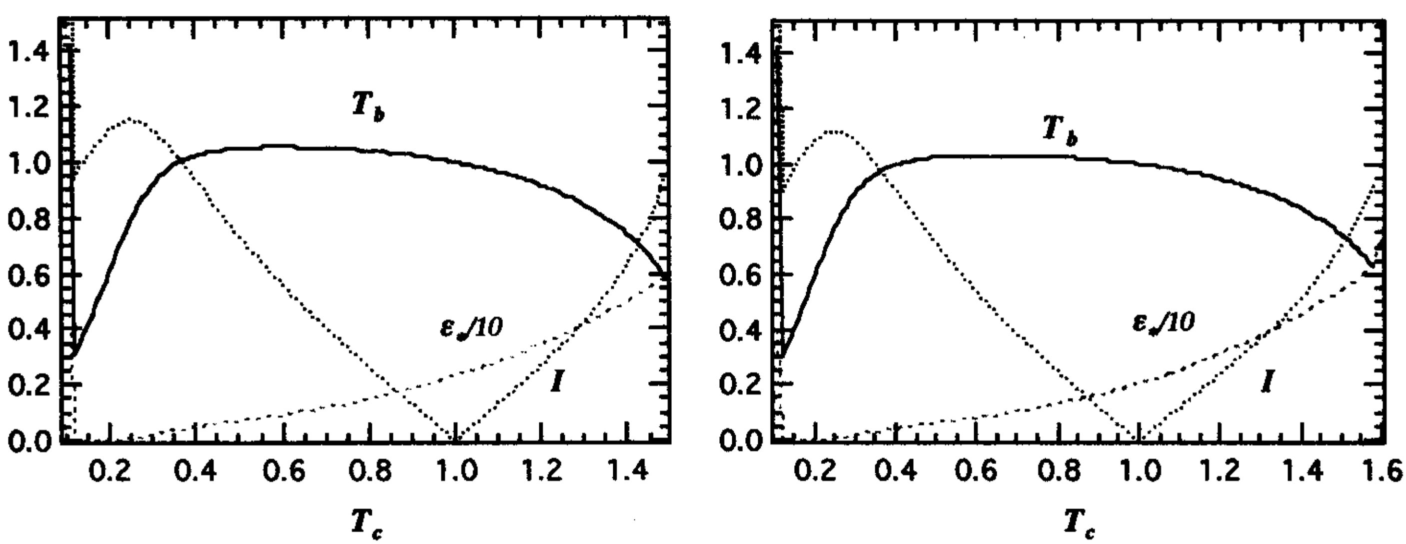

Figure 5. Constant heating per unit volume (Case A). Left picture corresponds to K=1.0, and right picture corresponds to K=π/4

stays approximately constant, while in the Case B, the two temperatures stay proportional. Finally for values $T_c > 1,0$ in the Case A, T_b decreases slowly while in the Case B decreases more quickly. Of the previous analysis can be concluded that for the Case A in the range $0.0 < T_c < 0.3$ this present an instability.

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