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The Flows in the Solar Atmosphere/2

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These are preliminary lecture notes, intended only for distribution to participants.

The Flows in the Solar Atmosphere:

Generation, Acceleration and Escape;

Energy Trasnformation (2)

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Based mainly on:

S.M. Mahajan, R. Miklaszewski, K.I. Nikol'skaya & N.L. Shatashvili. Phys. Plasmas, (2001), 8, 1340; ArXiv: astro-ph/0308012 (2003).

S. Ohsaki, N.L. Shatashvili, Z Yoshida & S.M. Mahajan. ApJ (2001), 559, L61; (2002), 570, 395.

S.M. Mahajan, K.I. Nikol'skaya, N.L. Shatashvili & Z. Yoshida. ApJ, (2002), 576, L161.

The observations made in soft X–rays and extreme ultraviolet (EUV), and recent findings from the TRACE show:

1. **the overdensity of coronal loops,**
2. **the chromospheric up–flows of heated plasma**
3. **the localization of the heating function in the lower corona**

Main message — the coronal heating problem may only be solved by including processes (including the flow dynamics) in the chromosphere and the transition region (TR).

The mechanism which transports mechanical energy from the convection zone to the chromosphere (to sustain its heating rate) could also supply the energy to heat the corona, and accelerate the solar wind (SW).

Challenge – to develop a theory of flow generation in these sub–coronal regions.

Generation of Flows

The most obvious process for flow generation could be

- **the conversion of magnetic**
- **and/or the thermal energy**

to plasma kinetic energy.

The magnetically driven transient but **sudden** flow–generation models are:

- **Catastrophic models**,
- **Magnetic reconnection models**,
- **Models based on instabilities**.

Quiescent pathway:

- *we could turn to the Bernoulli mechanism converting thermal energy into kinetic energy, or*
- to the general magnetofluid rearrangement of a relatively constant kinetic energy, i.e, going from an initial high density–low velocity to a low density–high velocity state.

The Double–Beltrami–Bernoulli states (two–fluid systems: the V–field is treated at par with the B–field – Mahajan & Yoshida 1998, PRL) **provide the necessary framework for both pathways.**

Model is based on application of recently developed magnetofluid theory.

Restriction: almost steady state considerations
(for a steady and continuous supply of plasma flows emerging from the sub–coronal regions).

Very near the photospheric surface, the influence of neutrals and ionization (and processes of flux emergence etc.) would not permit a quasi–equilibrium approach.

A little farther distance ($\Delta r \geq 2000\,\mathrm{km}$) from the surface, however, we expect that there exist fully ionized and magnetized plasma structures such that the quasi–equilibrium two–fluid model will capture the essential physics of flow generation.

Recent observational data:

E.g. Goodman (2000); Aschwanden et al. (2001);
Socas-Navarro & Almeida (2002) and references therein
At $\sim (500 - 5000)\, km$

Average plasma density and temperature are:

$n \sim (10^{14} - 10^{11})\mathrm{cm}^{-3};\ T \sim (1-6)\,\mathrm{eV}$

For simplicity we assume $T_e = T_i = T$.

The information about the magnetic field is hard to extract:

Reason — the low sensitivity and lack of high spatial resolution of the measurements coupled with the inhomogeneity and co–existence of small– and large–scale structures with different temperatures in nearby regions.

At these distances we have *different values for the network and for the internetwork fields*

- **The** *network* **plasmas have typically** *short-scale* **fields in the range $B_0 \sim (700 - 1500)$ G, have more or less**
  $n \sim const$ **.**
  Prone to explosive/eruptive analysis — Ohsaki et al. (2001) - APJL, (2002) - APJ.
  B–**energy is converted to flow energy.**

- **The** *internetwork fields* **are generally smaller** (with some exceptions (Socas-Navarro & Almeida (2002)) — $B_o \leq 500\,$G, and are embedded in *larger–scale plasma structures* with
  $n \neq const$
  See Mahajan et al. (2002), APJL.
  General magnetofluid re-arrangement with relatively constant kinetic energy.

Simplest two–fluid equilibria:

$T = \text{const} \longrightarrow \mathrm{n}^{-1}\nabla \mathrm{p} \to \mathrm{T}\nabla \ln \mathrm{n}.$

Generalization to a homentropic fluid: $p = \text{const} \cdot \mathrm{n}^{\gamma}$ is straightforward.

The **dimensionless equations** describing the model equilibrium can be read off from Mahajan et al. Phys. Plasmas (2001)

$$\frac{1}{n}\nabla \times \mathbf{b} \times \mathbf{b} + \nabla \left(\frac{r_{A0}}{r} - \beta_0 \ln\ n - \frac{V^2}{2} \right) + \mathbf{V} \times (\nabla \times \mathbf{V}) = 0, \quad (1)$$

$$\nabla \times \left[\left(\mathbf{V} - \frac{\alpha_0}{n} \nabla \times \mathbf{b} \right) \times \mathbf{b} \right] = 0, \quad (2)$$

$$\nabla \cdot (n\mathbf{V}) = 0, \quad (3)$$

$$\nabla \cdot \mathbf{b} = 0, \quad (4)$$

Normalizations:

$n \to n_0$ – the density at some appropriate distance from the solar surface,
$B \to B_0$ – the ambient field strength at the same distance
$|V| \to V_{A0}$

Parameters:

$r_{A0} = GM_\odot / V_{A0}^2 R_\odot = 2\beta_0\, r_{c0}, \quad \alpha_0 = \lambda_{i0}/R_\odot, \quad \beta_0 = c_{s0}^2/V_{A0}^2,$
c_{s0} — sound speed $\quad R_\odot$ — the solar radius,
$\lambda_{i0} = c/\omega_{i0}$ — the collisionless skin depth

are defined with $n_0,\ T_0,\ B_0.$

The double Beltrami solutions are

$$\mathbf{b} + \alpha_0 \nabla \times \mathbf{V} = d\ n\ \mathbf{V}, \qquad \mathbf{b} = a\ n\ \left[\mathbf{V} - \frac{\alpha_0}{n} \nabla \times \mathbf{b}\right], \quad (5)$$

a **and** d **— dimensionless constants related to ideal invariants:** *The Magnetic and the Generalized helicities* **(Mahajan & Yoshida 1998; Mahajan et al. (2001))**

$$h_1 = \int (\mathbf{A} \cdot \mathbf{b})\ d^3x, \quad (6)$$

$$h_2 = \int (\mathbf{A} + \mathbf{V}) \cdot (\mathbf{b} + \nabla \times \mathbf{V}) d^3x. \quad (7)$$

Substituting (5) into (1)–(2) one obtains the *Bernoulli Condition*

$$\nabla \left(\frac{2\beta_0 r_{c0}}{r} - \beta_0 \ln n - \frac{V^2}{2} \right) = 0, \quad (8)$$

relating the density with the flow kinetic energy, and solar gravity.

- **Uniform density structures:** $n = const$

  May happen practically everywhere in Solar atmosphere.

  Catastrophe leading to sudden eruptive / explosive events:
  $|\mathbf{b}|^2$ **is transformed to heat / kinetic energy of flow.**

- **Varying density structures:** $n \neq const$ — *May happen in Chromosphere.*

  General re–arrangement of a system:
  $|\mathbf{b}|^2 \sim const, \;\; n|\mathbf{V}|^2 \sim const.$

  High density-low velocity $\longrightarrow$ **low density–high velocity.**

Eruptive and exsplosive events, Flaring

Extension of the magneto–fluid theory answering the *questions*:

1. can the basic framework of this model predict the possibility of, and the pathways for the occurrence of sudden, explosive, eruptive, and catstrophic events in the solar atmosphere,
2. does the eventual fate, possibly catastrophic reorganization, of a given structure lie in the very conditions of its birth,
3. is it possible to identify the range and relative values of identifiable physical quantities that make a given structure prone to bulk motion, eruption (flaring),
4. will a fast outflow/eruption be the result of the conversion of excess magnetic energy into heat and bulk plasma motion as is generally believed to happen in the solar atmosphere ?

The parameter change — sufficiently slow = adiabatic:
at each stage, the system can find its local DB equilibrium.
Slow evolution — the dynamical invariants: h_1, h_2, and the total (*magnetic plus the fluid*) energy E are conserved.

The problem reduces to finding the range in which the slowly evolving structure may suffer a loss of equilibrium.

The transition may occur in one of the following two ways:

1. When the roots (λ - large-scale, μ - short-scale) of the quadratic equation, determining the length scales for the field variation, go from being real to complex (implying change in the topology of the magnetic and the velocity fields — boundary separating the paramagnetic from the diamagnetic),
2. Amplitude of either of the 2 states ($C_{\pm}$) ceases to be real.

The three invariants h_1, h_2 and E provide the relations connecting 4 parameters $\lambda, \mu, C_\lambda, C_\mu$ that characterize the DB field.
Large scale λ – the control parameter — the choice motivated by observations.

We study the structure–structure interactions working with simple 2D Beltrami ABC field with periodic boundary conditions:

$$\boldsymbol{G}_{\lambda,\mu} = g_{x\lambda,\mu} \begin{pmatrix} 0 \\ \sin \lambda_{\lambda,\mu} x \\ \cos \lambda_{\lambda.\mu} x \end{pmatrix} + g_{y\lambda\mu} \begin{pmatrix} \cos \lambda_{\lambda,\mu} y \\ 0 \\ \sin \lambda_{\lambda\mu} y \end{pmatrix}, \tag{9}$$

where the ratio of $g_{x\lambda,\mu}$ and $g_{y\lambda,\mu}$ defines the shape of an arcade–magnetic field structure and

$$(g_{x\lambda,\mu})^2 + (g_{y\lambda,\mu})^2 = 1. \tag{10}$$

If λ and μ are complex in (9), the equilibrium solution will have the spatially decaying (or growing) component initially.

In this study we choose real λ, μ for quasi–equilibrium structures in atmosphere. Assuming

$$L = n_\lambda \frac{2\pi}{\lambda} = n_\mu \frac{2\pi}{\mu}, \tag{11}$$

($n_{\lambda,\mu}$ are integers)

$\boldsymbol{G}_{\lambda,\mu}$ of (9) satisfy the following relations ($\int \mathrm{d}\mathbf{r} = \int_0^L \int_0^L \mathrm{d}x\mathrm{d}y$),

$$\int \boldsymbol{G}_{\lambda,\mu}^2 \mathrm{d}\mathbf{r} = L^2 \left[(g_{x\lambda,\mu})^2 + (g_{y\lambda,\mu})^2 \right] = L^2,$$

$$\int \boldsymbol{G}_\lambda \cdot \boldsymbol{G}_\mu \mathrm{d}\mathbf{r} = 0.$$

The constants of motion h_1, $\tilde{h}_2$ $(= h_2 - h_1)$ and E read $(\tilde{a} = 1/a\ )$

$$h_1 = \frac{L^2}{2}\left[\frac{C_\lambda^2}{\lambda} + \frac{C_\mu^2}{\mu}\right], \tag{12}$$

$$\begin{aligned}\tilde{h}_2 = \frac{L^2}{2}\{&[2+\lambda\,(\lambda+\tilde{a})]\,(\lambda+\tilde{a})\,C_\lambda^2 \\ &+[2+\mu\,(\mu+\tilde{a})]\,(\mu+\tilde{a})\,C_\mu^2\}\,,\end{aligned} \tag{13}$$

$$\begin{aligned}E = \frac{L^2}{2}\Big\{&\left[1+(\lambda+\tilde{a})^2\right]C_\lambda^2 \\ &+\left[1+(\mu+\tilde{a})^2\right]C_\mu^2\Big\}\,.\end{aligned} \tag{14}$$

Next, let's derive general relations of equilibrium.

$$d = \frac{\tilde{h}_2 + \lambda\mu h_1}{E} \quad \text{or} \quad d = \frac{h_2}{E + h_1\tilde{a}} \tag{15}$$

$$\frac{L^2}{2} C_\lambda^2 = D^{-1}\left\{E - \left[1 + (\mu + \tilde{a})^2\right]\mu h_1\right\}\lambda, \tag{16}$$

$$\frac{L^2}{2} C_\mu^2 = -D^{-1}\left\{E - \left[1 + (\lambda + \tilde{a})^2\right]\lambda h_1\right\}\mu, \tag{17}$$

$$\begin{aligned} D &= \left[1 + (\lambda + \tilde{a})^2\right]\lambda - \left[1 + (\mu + \tilde{a})^2\right]\mu \\ &= (\lambda - \mu)\, d\,(d + \tilde{a}) \end{aligned} \tag{18}$$

Naturally, D diverges at the coalescence of the roots (when $\lambda = \mu$). For an acceptable equilibrium we must always have $C_{\lambda,\mu}$ and μ real as λ goes over real values — $C^2_{\lambda,\mu} > 0$ must remain.

Then, there are two scenarios of losing equiliubrium:
(1) Either of $C_\pm$ becomes zero (starting from positive values) for real $\lambda_\pm$,
(2) The roots $\lambda_\pm$ coalesce ($\lambda_- \leftrightarrow \lambda_+$) for real $\lambda_\pm$ and $C_\pm$.

Solar atmosphere: the equilibria with vastly separated scales (for a variety of sub–alfvénic flows).
The second possibility is not of much relevance.

Note: for λ and μ vastly separated one must have $(d+\tilde{a})^2 \gg 4$.
There are two distinct cases:
(i) Both a and d are small and very near ($\tilde{a} = a^{-1} \gg 1$).
(ii) Both a and d are large and very close to one another ($a \sim b \gg 1$).

Let's find a condition for the catastrophic behavior using (15).
These equations represent a curve for given $h_1, \tilde{h}_2$ (or h_2) and E (all real). We must investigate the nature of this curve.

Questions:

1) Does this curve intersect the line $\lambda = \mu$? i.e. does it allow the possibility of the root–coalescence? This will be a critical point.

2) Does this curve have any extrema, for instance, as, $\lambda(\mu)$, i.e. λ as a function of μ ?

Notice, that there is a perfect symmetry – if we find $\lambda(\mu)$ we can readily deduce the properties of $\mu(\lambda)$.

These extrema, could be again critical points of the system and we could find them what they are. Naturally, they must correspond to one of the $C^2_{\lambda,\mu} \to 0$ for them to be physically relevant.

1) Condition $\lambda = \mu = \lambda_o$ leads to

$$d = \lambda_o \pm 1, \quad \tilde{h}_2 = E\,(\lambda_o \pm 1) - \lambda_o^2 h_1$$

solving to

$$\lambda_o = \frac{1}{2}\left[E \pm \sqrt{E^2 - 4h_1(\tilde{h_2} \pm E)}\right].$$

For λ_o to be real one must have:

$$E^2 > E_o^2, \qquad E_o^2 = 4\left(h_1 \pm \sqrt{h_1 h_2}\right)^2. \qquad (19)$$

2) The condition of critical point $\mathrm{d}\lambda/\mathrm{d}\mu = 0$ demands to have

$$h_1 h_2 = \left[(\mu + \tilde{a})\,(E + h_1\tilde{a})\right]^2 \geq 0, \qquad (20)$$

when h_1 and h_2 have opposite signs there is no loss of equilibrium.

Investigating the process at the critical point: $d\lambda/d\mu = 0$ from eq.(15) one arrives to the basic relation:

$$E = \lambda h_1 \left[1 + (\tilde{a} + \lambda)^2\right], \tag{21}$$

i.e., if (21) is satisfied, the curve $\lambda(\mu)$ has an extremum.

Notice, that this is precisely the condition for $C_\mu^2 = 0$ (see (17)).
Thus, at extremum point $C_\mu^2 \to 0$.
Since it starts from a positive value *the extremum point represents a transition point: if* the system is pushed beyond this point, $C_\mu^2 < 0 \longrightarrow C_\mu$ becomes imaginary $\longrightarrow$ the loss of equilibrium.
$\lambda = \lambda^{\rm crit}$ can be determined from a simultaneous solution of (15) and (21) — both equations being curves in $\lambda - \mu$ space for given h_1, h_2 and E:

$$\lambda^{\rm crit} = \frac{1}{2h_1}\left(E \pm \sqrt{E^2 - E_o^2}\right) . \tag{22}$$

where E_o has been defined earlier by (19).

Using the value of $\lambda^{\rm crit}$, we find from eq.(17) that coefficient C_μ (measure of short scale field strength) $\longrightarrow 0$ identically.
The equilibrium changes from DB to SB state defined by $\lambda = \lambda^{\rm crit}$ and $\boldsymbol{b} = C_\lambda \boldsymbol{G}_\lambda$ $(\nabla \times \boldsymbol{b} = \lambda \boldsymbol{b})$ with $\boldsymbol{V} || \boldsymbol{b}$.
$C_\lambda = \lambda^{\rm crit} h_1$ and hence we are taking the (i) scenario.
The transition leads to a magnetically more relaxed state with $|b|^2$ reaching its minimum with appropriate gain in the flow $E_{kinetic}$.
For (i) scenario at the critical point $(b^2/V^2) \sim 1/(\tilde{a}+\lambda)^2 \ll 1$.
Other conditions to be satisfied:
(i) scenario: $-D^{-1}\mu \sim 1/d\tilde{a}$ and $D^{-1}\lambda \simeq (1/d\tilde{a}) \cdot (d-a)/\tilde{a}$.
Well–separated lenghts–scales: $b\tilde{a} > 0$ (d and a have same signs):

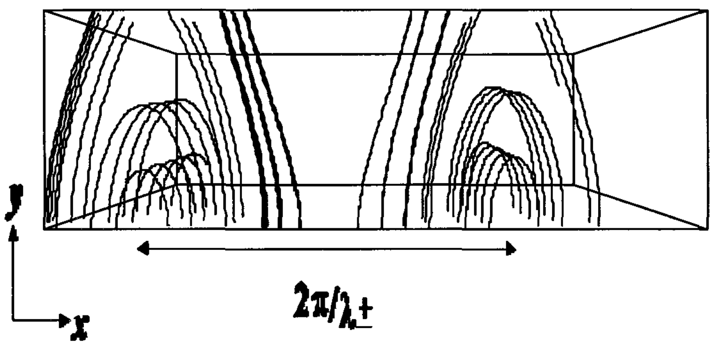
$$C_\mu^2 \simeq \frac{1}{d\tilde{a}} \left[E - (d-a)h_1[1+(\tilde{a}+\lambda)^2]\right],$$

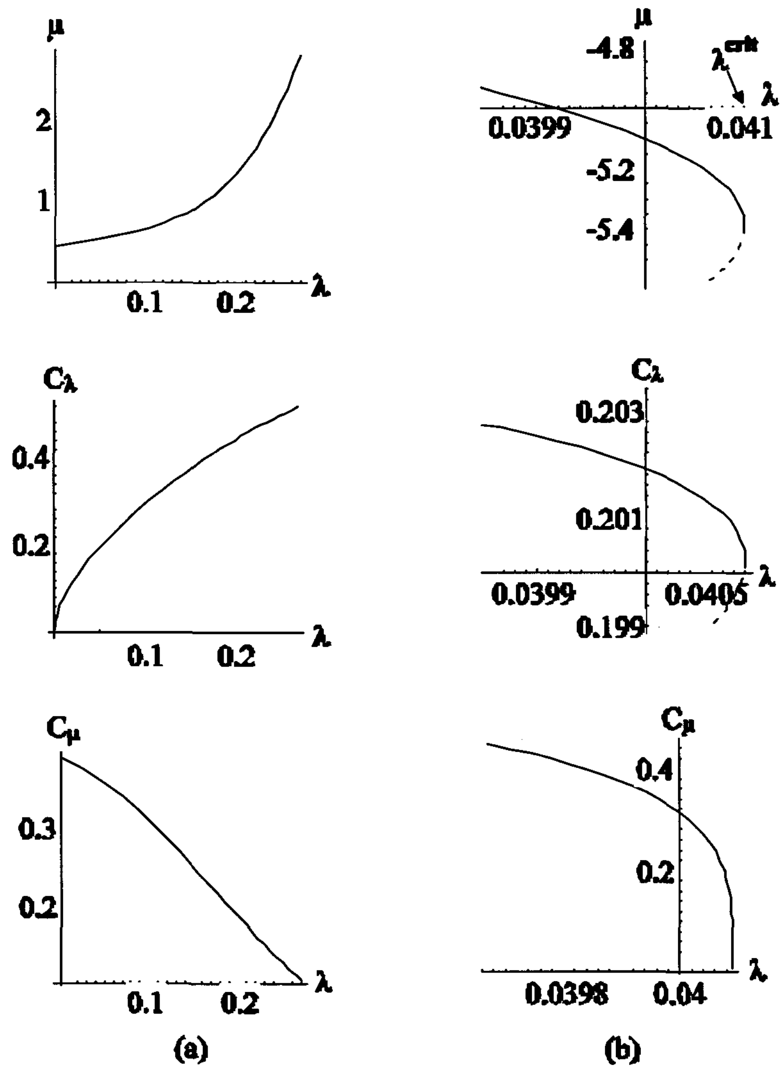
$$C_\lambda^2 \simeq \frac{d-a}{\tilde{a}} \frac{1}{d\tilde{a}} \left[E + \tilde{a}h_1[1+(\tilde{a}+\mu)^2]\right]$$

and if C_μ^2 has to go to zero one must have $(d-a)h_1 > 0$.

Fig3: "Energy Transformation Mechanism in Solar Atmosphere Associated with ....
S.Ohsaki, N.L.Shatashvili, Z.Yoshida and S.M.Mahajan

Fig2: "Energy Transformation Mechanism in Solar Atmosphere Associated with ...."
S.Ohsaki, N.L.Shatashvili, Z.Yoshida and S.M.Mahajan





For $h_1 > 0$, $(d-a) > 0$, $C_\mu^2 > 0$ is guaranteed if $a > 0$, $d > 0$.

The system is invariant to $d \to -\tilde{a}$ and $\tilde{a} \to -d$.

Applying to the **solar atmosphere** one can find the *conditions* for formation **of explosive/eruptive events.**
Consider
$|\lambda| \ll |\mu|, \quad C_\lambda \sim O\left(\lambda_\lambda/\lambda_\mu\right) \ll 1 \quad C_\mu \sim O\left(\lambda_\mu/\lambda_\mu\right) \sim 1$.

If any interaction increases λ – *the size of the structure shrinks* – $\lambda = \lambda^{\text{crit}}$ will be reached at which $C_\mu = 0$.
$|B|^2 \propto C_\lambda^2 + C_\mu^2$ decreases to a very small value since $C_\lambda^2 \ll 1$.

$E = const \Longrightarrow$ almost all the initial magnetic energy (SHORT–SCALE) is transfered to the flow causing an eruption.

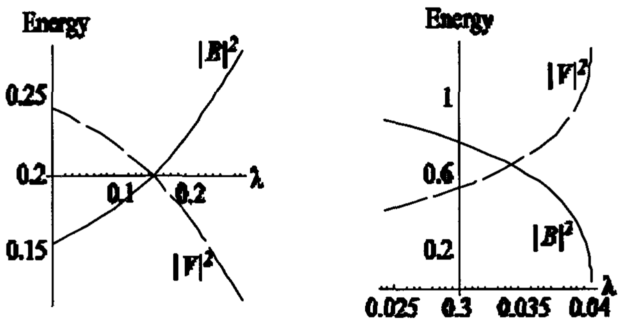
Notice that for coronal plasma, the skin depth l_i is small $\sim$ 100cm ($l_i/\lambda \sim 10^3$km), for a typical density of $\sim 10^9\,\mathrm{cm}^{-3}$.

Caution: approaching the critical point, the quasi–equilibrium considerations are just an indicator of what is happening – they must be replaced by a full time–dependent treatment to capture the dynamics; the changes are no longer slow.

Root coalescence: E_o becomes the critical E, λ_o – the critical λ.

At the transition we can not distinguish between C_μ^2 and C_λ^2; $b^2/V^2 = (\tilde{a} + \lambda)^{-2} =? \sim O(1)$ — no separation between the roots!

Fig4: "Energy Transformation Mechanism in Solar Atmosphere Associated with ...."
S.Ohsaki, N.L.Shatashvili, Z.Yoshida and S.M.Mahajan



(a) (b)

Fig6: "Energy Transformation Mechanism in Solar Atmosphere Associated with ....
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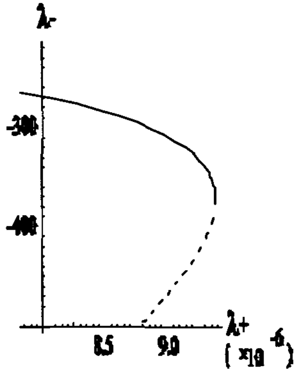

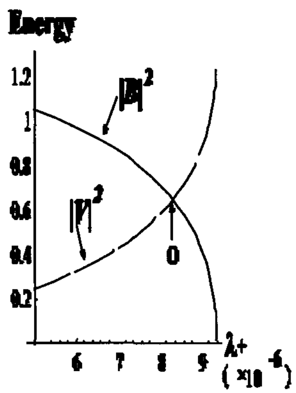

Fig7: "Energy Transformation Mechanism in Solar Atmosphere Associated with ....
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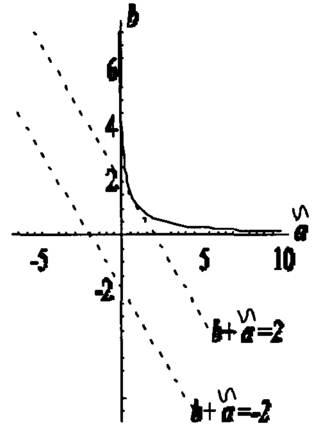
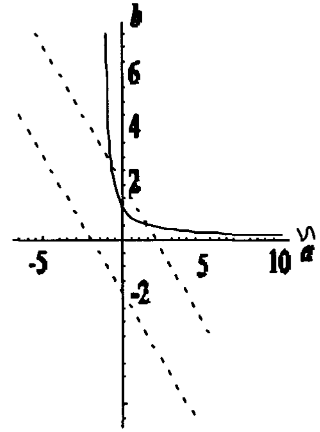


(a)



(b)

Conclusions for uniform density case

- By modelling quasi–equilibrium, slowly evolving solar atmosphere structures as a sequence of DB magnetofluid states the conditions for catastrophic changes leading to a fundamental transformation of the initial state are derived.
- When the total energy exceeds a critical energy the DB equilibrium suddenly relaxes to a single Beltrami state corresponding to the large macroscopic size.
- All of the short–scale magnetic energy is transformed to the flow kinetic energy.
- The proposed mechanism for the energy transformation work in all regions of Solar atmosphere with different dynamical evolution depending on the initial and boundary conditions for a given region.

Non–uniform density case

Equations (1), (5) and (8) represent a close system.

They may be easily manipulated to yield $(g(r) = r_{c0}/r)$

$$\frac{\alpha_0^2}{n}\nabla \times \nabla \times \mathbf{V} + \alpha_0 \, \nabla \times \left[\left(\frac{1}{a\,n} - d\right) n\,\mathbf{V}\right] + \left(1 - \frac{d}{a}\right)\mathbf{V} = 0, \quad (39)$$

$$\alpha_0^2 \nabla \times \left(\frac{1}{n}\nabla \times \mathbf{b}\right) + \alpha_0 \, \nabla \times \left[\left(\frac{1}{a\,n} - d\right)\mathbf{b}\right] + \left(1 - \frac{d}{a}\right)\mathbf{b} = 0. \quad (40)$$

$$n = \exp\left(-\left[2g_0 - \frac{V_0^2}{2\beta_0} - 2g + \frac{V^2}{2\beta_0}\right]\right), \quad (41)$$

Caution: this time–independent set is not suitable for studying chromospheric *primary* heating processes at lower heights.

The main thrust is to uncover mechanisms that create *flows* in the sub-coronal regions — that *could supply matter and energy needed to create the coronal structures, and provide their primary heating.*

The creation and heating problem requires a fully time–dependent (Mahajan et al. Phys.Plasmas, 2001) treatment with multi–species.

1D simulation — for a variety of boundary conditions.

The relevant dimension — the height "Z" from Sun's center.

Boundary conditions are applied to the surface $Z_0 = R_\odot + \Delta r$.

$Z_0 > (1 + 2.8 \cdot 10^{-3})\, R_\odot$ — *the influence of ionization can be neglected.*

For all runs the following boundary conditions were imposed:
$|b_0| = 1, \quad V_0 = 0.01\, V_{A0} \quad$ (with $V_{x0} = V_{y0} = V_{z0}$).

Choice: $d \sim a \sim 100$ *and* $(a-d)/a^2 \sim 10^{-6}$ *for the DB parameters* — a sub–Alfvénic flows with a very small α_0 (Mahajan et al. 1999).

Code limitations: α_0–s chosen for the simulation are much larger than their actual values ($\leq 10^{-8}$ for corona and smaller for sub–coronal regions).
Special assumptions simplifying the equations may help in overcoming the difficulties connected to smallness of α_0.

Plots clearly show that the essential features of the final results are not sensitive to changes in α_0.

Figs. 1-2: plots of n; b; b_x $|V|$; V_x; V_z as functions of $Z-1$. The parameters defining different frames are $(n_0;\ B_0;\ T_0;\ V_{A0})$**:**

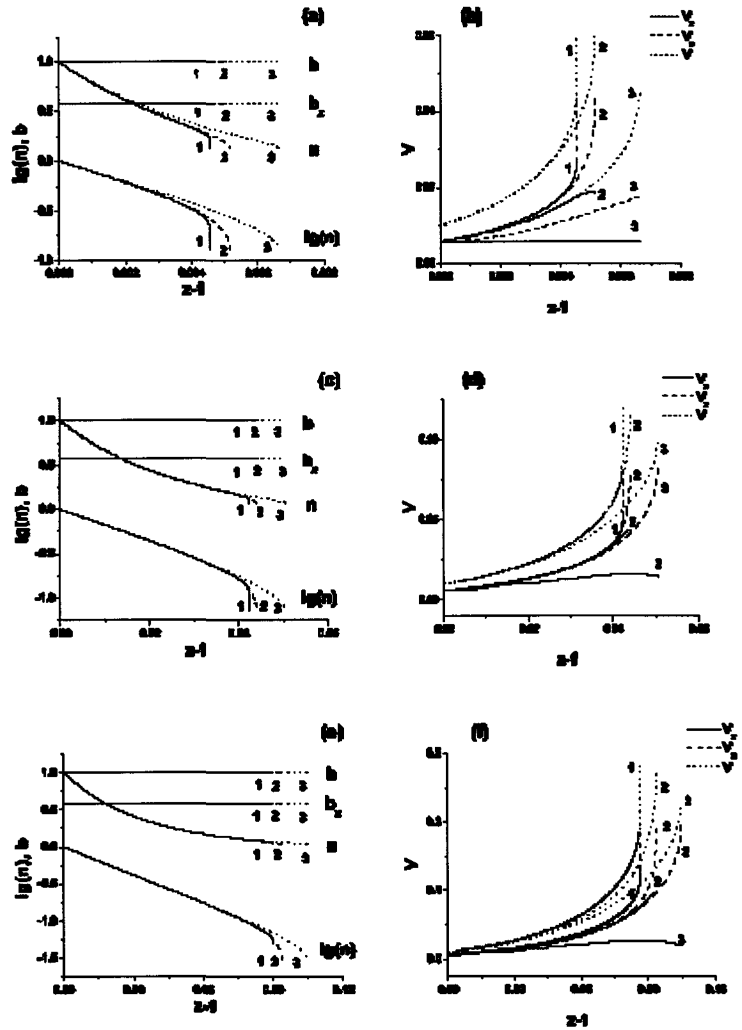
(a-b): $(10^{12}\,\mathrm{cm}^{-3};\ 200\,\mathrm{G};\ 2\,\mathrm{eV};\ 440\,\mathrm{km/s})$; $\beta_0 \sim 0.002 \ll 1$, $r_{c0} = 225$

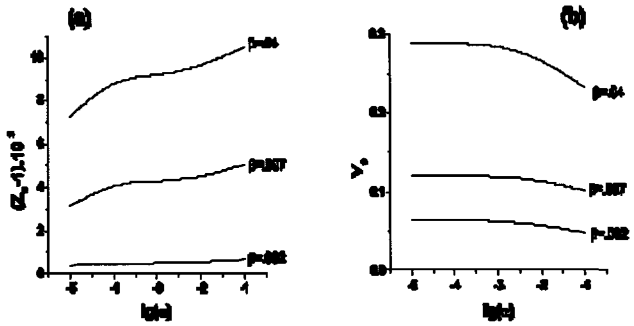
(c-d): $(10^{11}\,\mathrm{cm}^{-3};\ 100\,\mathrm{G};\ 5\,\mathrm{eV};\ 600\,\mathrm{km/s})$ $\beta_0 \sim 0.007 \ll 1$, $r_{c0} = 40$

(e-f): $(10^{11}\,\mathrm{cm}^{-3};\ 50\,\mathrm{G};\ 6\,\mathrm{eV};\ 330\,\mathrm{km/s})$ $\beta_0 \sim 0.04 < 1$, $r_{c0} = 30$.

3 sets of curves labelled by α_0 — the measure of the strength of the two–fluid Hall currents — 1–2–3 correspond to $\alpha_0 = 0.000013;\ 0.005;\ 0.1$).

Result: for small α_0 there exists some height where the density begins to drop precipitously with a corresponding sharp rise in the flow speed. The effect is stronger for low beta plasmas.


(a)
(b)
(c)
(d)
(e)
(f)
lg(n), b
z-1
V


(a)
(b)

At very short distances, the stratification is practically due to gravity but as we approach the velocity "blow–up" height, the self–consistent magneto-Bernoulli processes take over and control the density (and hence the velocity) stratification.
Bernoulli condition (41) yields an indirect estimate for the height at which the observed shock–formation may take place (for all α_0):

$$|\mathbf{V}|^2 - V_0^2 > 2\,\beta_0. \tag{42}$$

At $\beta_0 = 0.04$ it occurs at $|\mathbf{V}|^2 > 0.08$, $|V| \sim 0.28$ (simulation confirms)
Simulation: the velocity blow–up distance depends mainly on β_0; the final velocity is greater for greater T_0.
Magnetic energy remains practically uniform over the distance — sharp decrease in density with a corresponding sharp rise in the flow–speed the expression of Bernoulli constraint imposed by the magneto-fluid equilibrium.

Fixing β_0 is quite difficult due to complications like ionization.
Flows tend to be mostly radial only for large α_0.
The situation could change considerably when we deal with time–dependent dynamical model with dissipation. Plasma heating, then, could result from the dissipation of the perpendicular energy so that at larger distances, the flows would have larger radial components.
Heating would also keep $\beta(\mathbf{r}, t)$ large at upper heights shifting the velocity blow–up distance further or eliminating it all together.

β_0 goes up — the density fall (V–amplification) smoother.
Notice, that final velocities go up with $V_0[km/s] \sim d^{-1} V_{A0}$.

Initial flow with speed $3.3\,\mathrm{km/s}$ ends up acquiring speed $\sim 100\,\mathrm{km/s}$ at the height $(Z - Z_0) \sim 0.09\,R_\odot$ but at a lower density $\sim 10^{9.5}\,\mathrm{cm}^{-3}$.

- The general nature of the solution is determined by the values of dimensionless input parameters.
- Since β_0 determines whether the density fall (velocity amplification) will be sharp or smooth, lowering the magnetic field and keeping other parameters fixed will drive the system towards a smoother change.
- If density is adjusted to bring the system back to the same β_0, the results will be exactly like that of the high field cases we have discussed above — region of sharp changes will persist.
- **Ignoring the flow term in (8) we will end up finding essentially radial flows. The magnitude of these flows remains small;** there is no region of sharp rise (42), and the **generated flows achieve reasonable energies at heights typically 10 times greater than the heights at which the correct Bernoulli condition would do the trick.**

Comment: as the flows reach the blow–up distance the parameters cease to be slowly varying — the time–independent approach is no more valid.

- The connection of flows with explosive/eruptive events is direct: it depends on their ability to deform (distort) the ambient magnetic field lines to temporarily stretch (shrink, destroy) the closed field lines so that the flow can escape the local region with a considerable increase in kinetic energy in the form of heat/bulk motion.
- We believe that the chromospheric mass outflows, spicules, explosive events in chromosphere, micro– and nano-flares, large coronal flares, erupting prominences and CMEs may happen separately but can also be parts of a more global dynamic process of coronal specific region formation.

- Results reproduce several features of typical loops: the structure creation and primary heating are simultaneous – the heating takes place in a few minutes, is non-uniform, base is hotter than the rest.
- From a general framework describing a plasma with flows, it has been able to "derive" several of the essential characteristics of the coronal structures including particle escape channels (CH-s).
- High speed primary solar outflows interacting with neighboring closed magnetic field structures create channels for escape.
- We have shown the possibility of, and derived the conditions for catastrophic changes leading to a fundamental transformation of the initial quasi-equilibrium state. When the total energy exceeds a critical energy the DB equilibrium suddenly relaxes to a single Beltrami state (large macroscopic size). All of the short–scale magnetic energy is transformed to the flow energy.
- We have shown the possibility of fast flow generation in the lower Solar Atmosphere.