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The Flows in the Solar Atmosphere/1

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The Flows in the Solar Atmosphere:

Generation, Acceleration and Escape;

Energy Trasnformation (1)

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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.

In astrophysics, the plasma flow could be assigned at least two distinct connotations:

1) **the flow is a primary object** whose dynamics bears critically on the phenomena under investigation.

The problems of the formation and the original heating of the coronal structure, the creation of channels for particle escape, for instance, fall in this category,

2) **the flow is a secondary feature**, possibly created as a by product and/or used to drive or suppress an instability.

The generation of flows is the theme of this effort — flows are fundamental.

- Recent observations, strongly fortified by improved measuring and interpretive capabilities, have convincingly demonstrated that **the solar corona is a highly dynamic arena replete with multiple–scale spatiotemporal structures.**

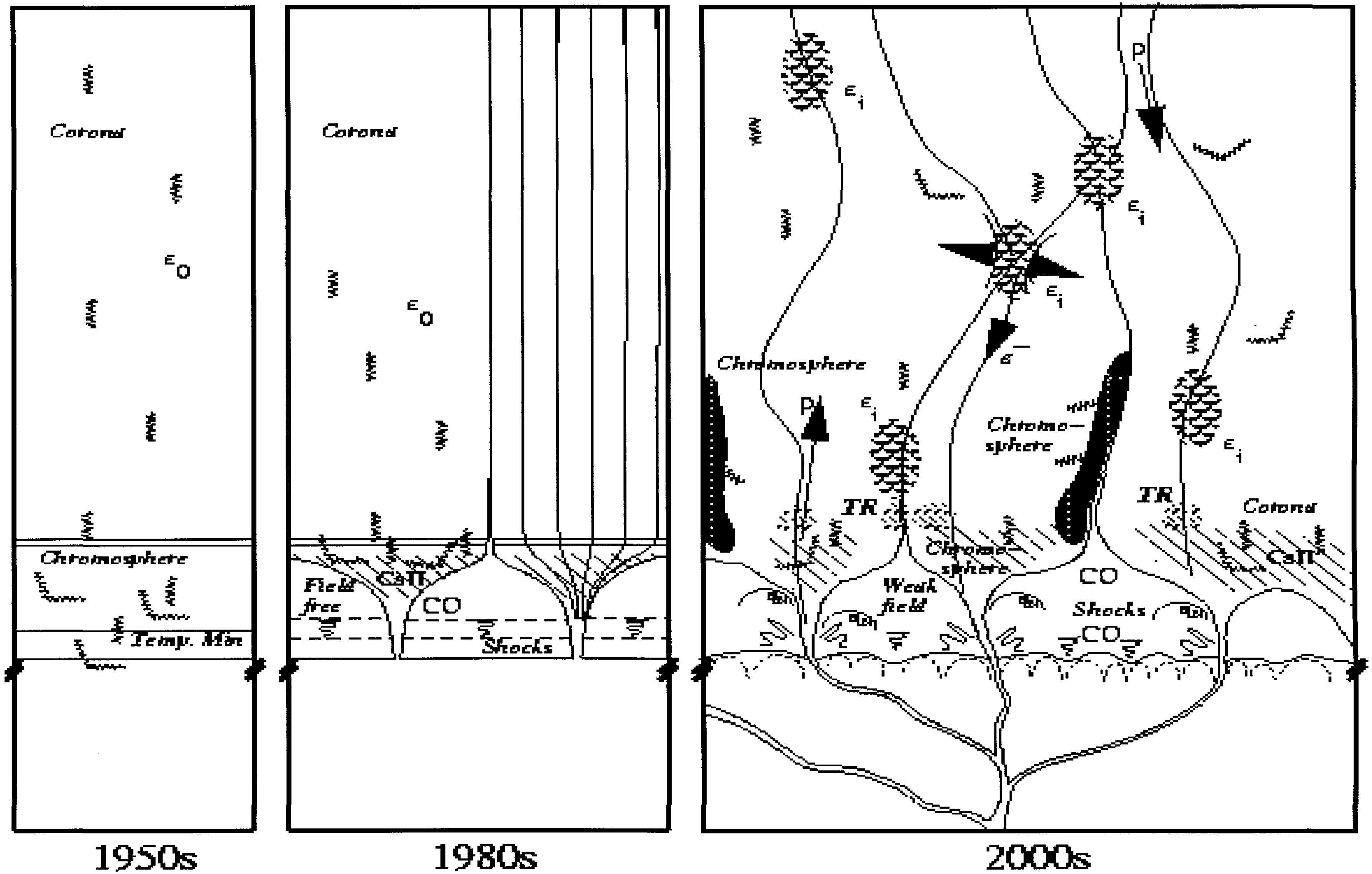
  E.g. Aschwanden, Poland & Rabin, 2001, ARA&A.

- A major new advance is the discovery that **strong flows are found everywhere — in the subcoronal (chromosphere) as well as in the coronal regions.**

  See e.g. Schrijver et al. 1999, Solar Physics; Wilhelm 2000, A&A; Winebarger, DeLuca and Golub 2001, APJ; Aschwanden et al. 2001, ARA&A; Aschwanden 2001, APJ; Seaton e et al. 2001, APJ; Winebarger et al. 2002, APJ and references therein.

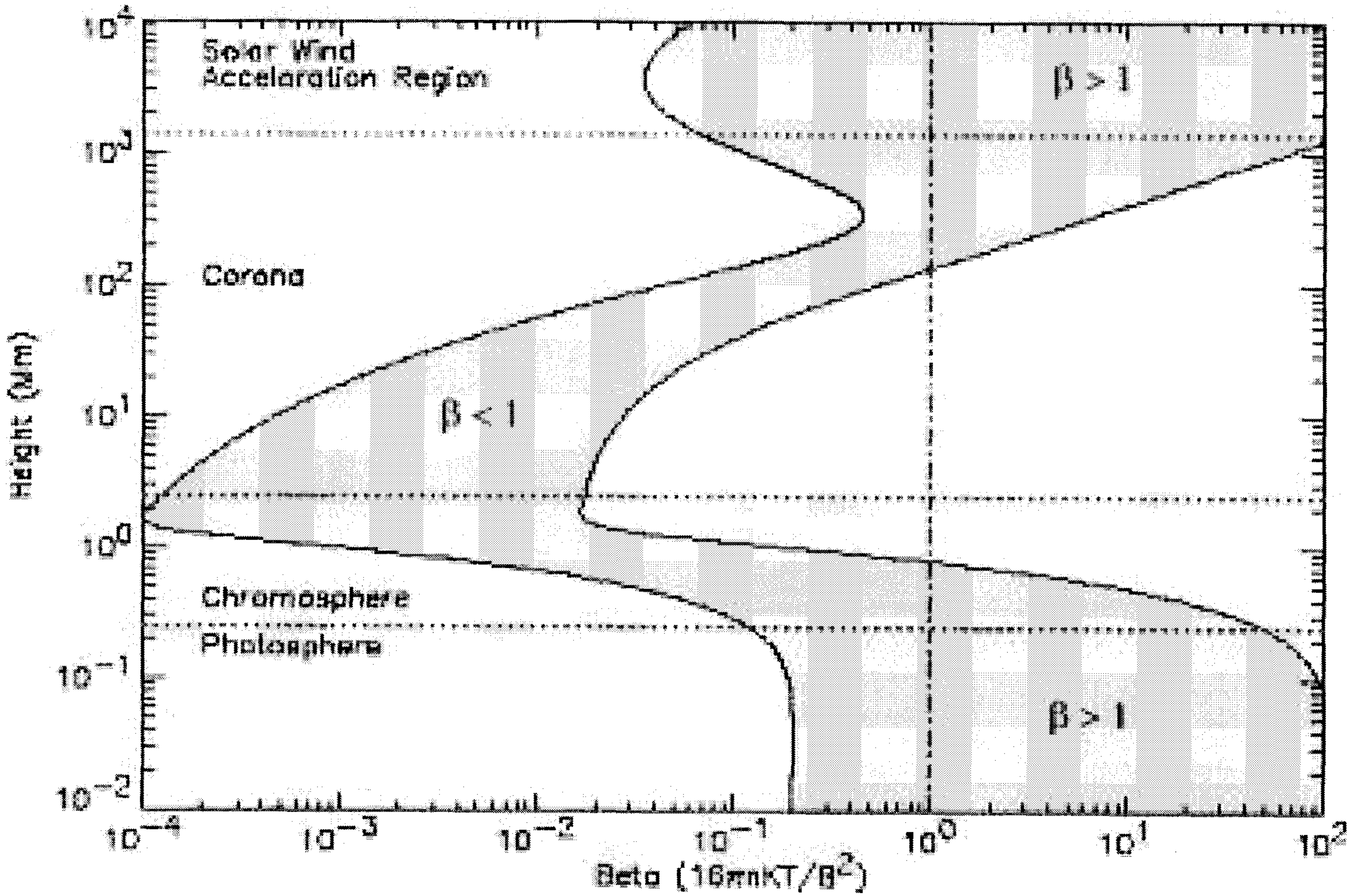
- Equally important: **the plasma flows may complement the abilities of the magnetic field in the creation of the amazing richness observed in the coronal structures.**

  See e.g. Orlando, Peres and Serio 1995, A&A; Nikol'skaya and Valchuk, 1998, Geomagn. Aeron.; Mahajan et al. 1999, 2001, PoP; Adv. Space. Res. Vol.30(3),2002.

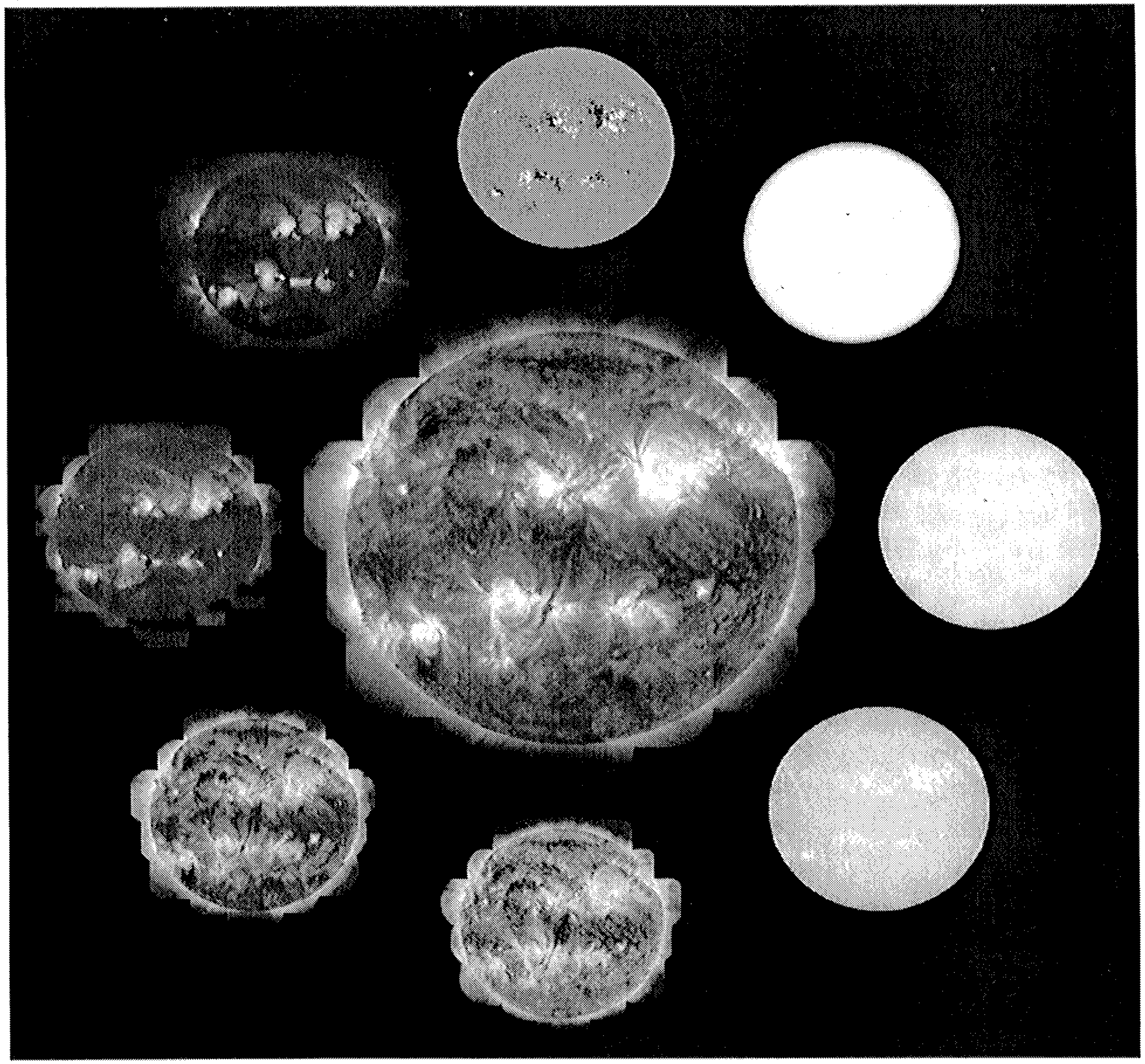


Evolution of corona cartoon: gravitationally stratified layers in the 1950s (left); vertical flux tubes with chromospheric canopies (1980s, middle); fully inhomogeneous mixing of photospheric, chromospheric, TR and coronal zones by such processes as heated upflows, cooling downflows, interminent heating (ε), nonthermal electron beams (e), field line motions and reconnections, emission from hot plasma, absorption and scattering in cool plasma, acoustic waves, shock waves (right). (from Shrijver 2001).

Associating the traditional layers with temperature rather than height is only a little better.

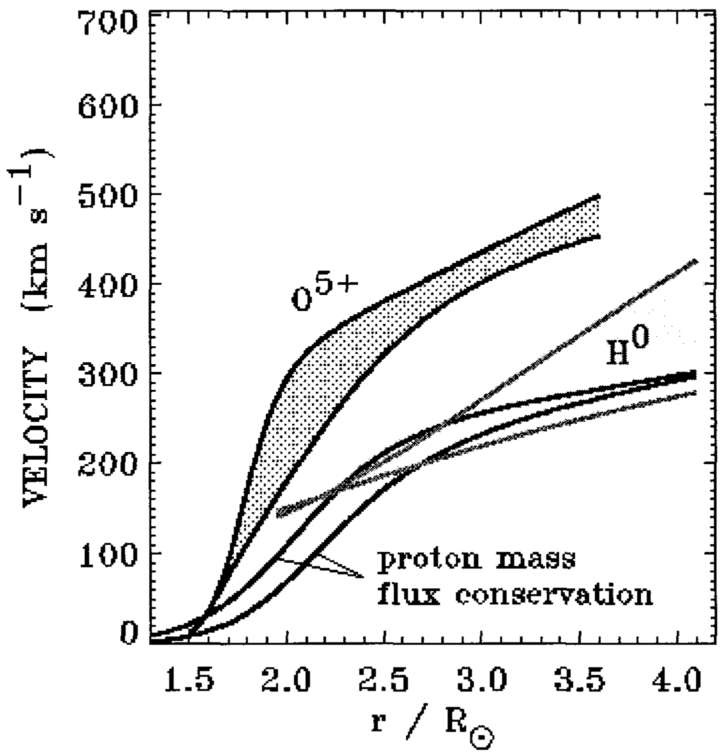


Plasma β in the solar atmosphere for two assumed field strengths, 100 G and 2500 G (Courtesy of G. Allen Gary).



The multitemperature structure of the solar corona is visualized with images in different wavelengths. (Courtesy Lockheed-Martin Solar and Astrophysics Laboratory)

Outflow velocities:



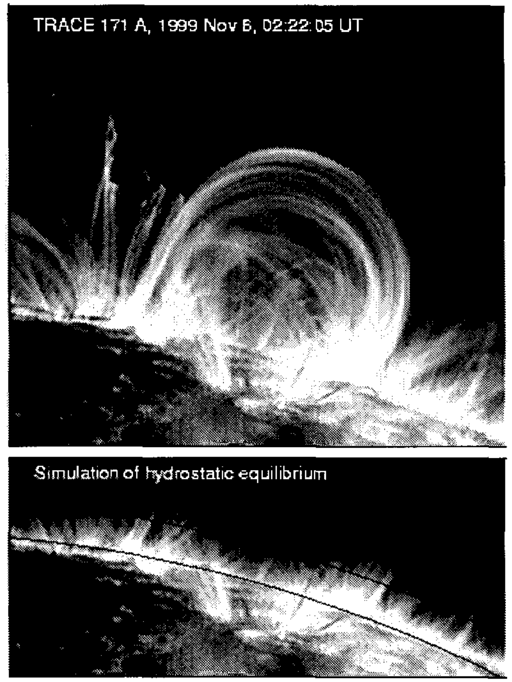
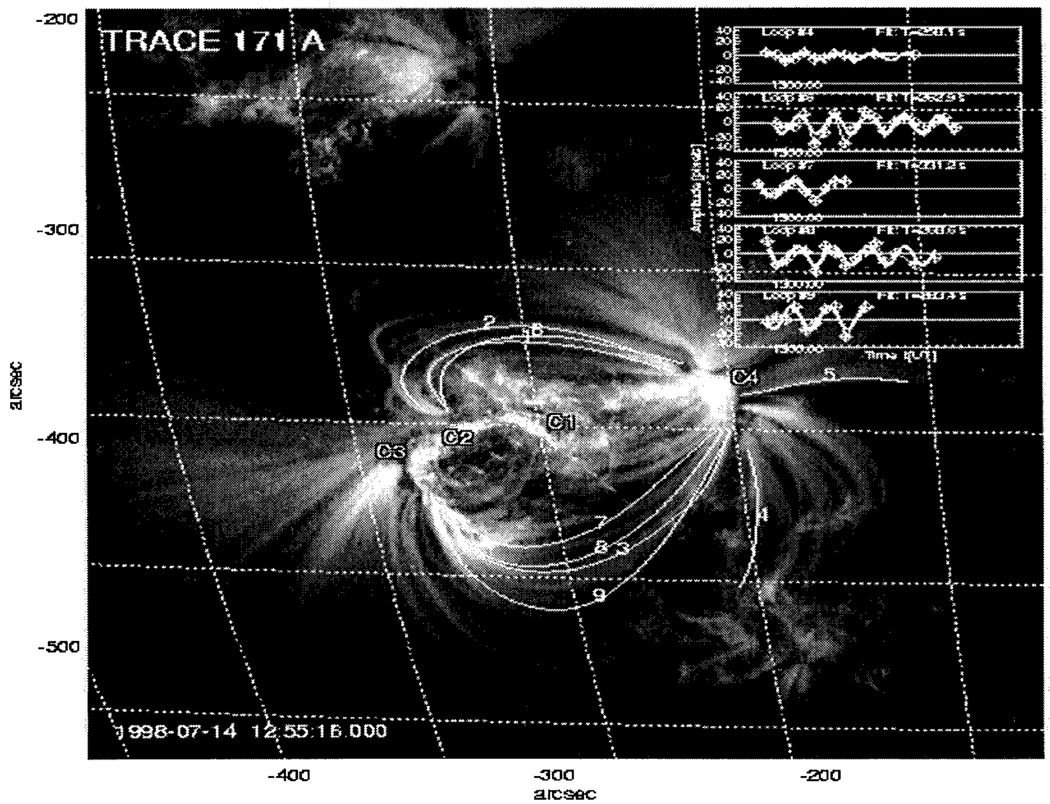


Figure 8v : Aschwanden, Schrijver, and Alexander (2000)



TRACE: A set of coronal loops marked, of which five exhibit transversive oscillations.

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.

Heating of the Solar Corona

Solar Wind (SW) — a theoretical constraint where **the hydrodynamical expansion is a source of acceleration** which propels the plasma particles from a velocity of $< 10\,\mathrm{kms}^{-1}$ in the nearby (near the Sun) corona up to several hundred kms^{-1} at 1 AU.
Model requires constant temperature = coronal base one!

Observational evidence suggests that the magnetic fields control, not only the structuring of the corona but also the density and temperature variations in different coronal features.

Another serious difficulty:
the particles in fast component of the solar wind (FSW) have velocities considerably higher than the coronal proton thermal velocity ($> 300\,\mathrm{kms}^{-1}$). Naturally such fast particles could not come from a simple pressure driven expansion.

- the solar wind does originate from the corona,
- the process of wind formation is expansion (acceleration).

Expansion takes place in the regions called the coronal holes where the magnetic field influence can be neglected, i.e., where the field is radial, in fact, very radial. To augment the acceleration process, **additional energy sources were invoked so that the wind could be accelerated to the observed velocities**.

It was shown that wind acceleration grows more rapidly with r so the diverging magnetic field line geometry (non–uniform temperature) of coronal holes should tend to accelerate wind more rapidly than a spherically symmetric expansion.

CONCLUSION:

HEATING TO BE TAKEN INTO ACCOUNT!

Two proposed mechanisms for acceleration:
Electrodynamical approach – developed by Parker and others.
Wave acceleration mechanisms – elaborated in the works of Axford, McKenzie, Marsch and others .
Both these approaches consider the same plasma sources – the plasma jets from microflares caused by magnetic reconnection within the chromospheric network.

Remarkable step: interaction between network magnetic fields and emerging internetwork fields may lead to magnetic reconnection and microflares, which generate fast shocks $\Longrightarrow$ Protons and minor ions are heated and accelerated by fast shocks (local heating). Microflares can be random in space and time $\Longrightarrow$ corona is heated. Fast shocks generated by the magnetic reconnections with a smaller scale in chromosphere (Lee 2000, Wilhelm 2001) can produce Spicules (then they enter the corona!); cascade of shock wave interactions in TR may lead to the acceleration (Ryutova et al., 2000, 2003).

Problem of energy transport mechanisms in the solar atmosphere as well as the channelling of the particles is connected to the challenging problems of solar coronal heating and solar wind origin. A number of recent investigations have made a strong and convincing case that neither the SW "acceleration" nor the numerous eruptive events in the solar atmosphere can be treated as isolated and independent problems; they must be solved simultaneously along with other phenomena, in particular, the plasma heating that, by itself, may take place in different stages.

Parker: SW is a consequence of the hot corona; splits problem in 2:

1) the heating of the corona
2) the acceleration of the solar wind.

The only significant assumption on the solar wind acceleration were the boundary conditions at the coronal base, mainly the density and the temperature.

It took several decades before this problem was tractable.

Assumption: flows are emitted from photosphere continuously with rather significant range of velocity spectrum.

The estimations show that fast flows/jets and spicules generated in the chromosphere carry sufficient energy and material source for hot coronal structure creation.

Outflows detected in the footpoint regions of coronal structures indicate that source comes from below.

The equations that we use will apply in both the open and the closed field regions. The difference between various sub–units of the atmosphere will come from the initial and the boundary conditions.

- We examine the conjecture that the formation and primary heating of the coronal structures as well as the more violent events (possibly flares, erupting prominences and coronal mass ejections (CMEs)) are the expressions of different aspects of the same general global dynamics that operates in a given coronal region.
- It is stipulated that the coronal structures are created from the evolution and re–organization of a relatively cold plasma flow emerging from the subcoronal region and interacting with the ambient solar magnetic field.
- The principal distinguishing component of suggested model is the full treatment accorded to the velocity fields associated with the directed plasma motion.
- The plasma flows, the source of both the particles and energy (part of which is converted to heat), in their interaction with the magnetic field, also become dynamic determinants of a wide variety of plasma states; it is likely that this interaction may be the cause of the immense diversity of the observed coronal structures.

Model and General Equations For the Solar Atmosphere

$\mathbf{V}$ — the flow velocity field of the plasma in a region where the solar magnetic field is $\mathbf{B}_s$.

The processes which generate the flows and the magnetic fields are independent. Total current $\mathbf{j} = \mathbf{j}_f + \mathbf{j}_s$.

$\mathbf{j}_f$ — self-current (generates magnetic field $\mathbf{B}_f$); $\mathbf{j}_s$ — generated by $\mathbf{B}_s$. **Total (observed) magnetic field** — $\mathbf{B} = \mathbf{B}_f + \mathbf{B}_s$.

The solar atmosphere is highly structured.

Corona , SW — the quasineutrality condition: $n_e \simeq n_i = n$

Electron and proton flow velocities are different.

$$\mathbf{V}_i = \mathbf{V}, \qquad \mathbf{V}_e = (\mathbf{V} - \mathbf{j}/en)$$

Fast SW: $T_i \sim 2 \cdot 10^5\,\mathrm{K}$ $\quad T_e \sim 1 \cdot 10^5\,\mathrm{K}$.

For the coronal creation processes, and for the study of the phenomenon related to the SW origin, we will use the assumption of equal temperatures.

The kinetic pressure: $p = p_i + p_e \simeq 2\,nT, \qquad T = T_i \simeq T_e.$

Without primary flows — additional heating mechanism is required.

In present model flows and their viscous dissipation are not ignored in the equations.

We notice that even for incompressible and current-less flows, **heat can be generated from the viscous dissipation of the flow vorticity**:

$$\left[\frac{d}{dt}\left(\frac{m_i \mathbf{V}^2}{2}\right)\right]_{\rm visc} = -m_i n \nu_i \left(\frac{1}{2}(\nabla \times \mathbf{V})^2 + \frac{2}{3}(\nabla \cdot \mathbf{V})^2\right). \qquad (1)$$

Dimensionless variables

$$\mathbf{r} \to \mathbf{r}\ R_\odot; \qquad t \to t\ \frac{R_\odot}{V_A}; \qquad \mathbf{b} \to \mathbf{b}\ b_\odot; \qquad T \to T\ T_\odot;$$

$$n \to n\ n_\odot; \qquad \mathbf{V} \to \mathbf{V}\ V_A; \qquad \mathbf{j} \to \mathbf{j}\ V_A e n_\odot;$$

$$\mathbf{q}_\alpha \to \mathbf{q}_\alpha n_\odot T_\odot V_A; \qquad \nu_i \to \nu_i\ R_\odot V_A \qquad (2),$$

Dimensionless parameters

$$b_\odot = \frac{eB(R_\odot)}{m_i c}; \qquad \lambda_{i\odot} = \frac{c}{\omega_{i\odot}}; \qquad c_s^2 = \frac{2T_\odot}{m_i}; \qquad \omega_{i\odot}^2 = \frac{4\pi e^2 n_\odot}{m_i};$$

$$V_A = b_\odot \lambda_{i\odot}; \qquad r_A = \frac{GM_\odot}{V_A^2 R_\odot} = 2\beta\ r_c; \qquad r_c = \frac{GM_\odot}{2c_s^2 R_\odot};$$

$$\alpha = \frac{\lambda_{i\odot}}{R_\odot}; \qquad \beta = \frac{c_s^2}{V_A^2}, \qquad (3)$$

$R_\odot$ — solar radius, G — gravitational constant,

$M_\odot$ — solar mass. $\nu_i = \nu_i(n,T) = (V_{i,th} T^2 / 12\pi n e^4)$ is local.

$$\frac{\partial}{\partial t}\mathbf{V} + (\mathbf{V}\cdot\nabla)\mathbf{V} =$$

$$= \frac{1}{n}\nabla\times\mathbf{b}\times\mathbf{b} - \beta\frac{1}{n}\nabla(nT) + \nabla\left(\frac{r_A}{r}\right) + \nu_i\left(\nabla^2\mathbf{V} + \frac{1}{3}\nabla(\nabla\cdot\mathbf{V})\right), \tag{4}$$

$$\frac{\partial}{\partial t}\mathbf{b} - \nabla\times\left(\mathbf{V} - \frac{\alpha}{n}\nabla\times\mathbf{b}\right)\times\mathbf{b} = \alpha\beta\,\nabla\left(\frac{1}{n}\right)\times\nabla(nT), \tag{5}$$

$$\nabla\cdot\mathbf{b} = 0, \qquad \frac{\partial}{\partial t}n + \nabla\cdot n\mathbf{V} = 0. \tag{6}$$

$$\frac{3}{2}n\frac{d}{dt}(2T) + \nabla(\mathbf{q}_i + \mathbf{q}_e) = -2nT\nabla\cdot\mathbf{V}$$

$$+2\beta^{-1}\nu_i n\left[\frac{1}{2}\left(\frac{\partial V_k}{\partial x_l} + \frac{\partial V_l}{\partial x_k}\right)^2 - \frac{2}{3}(\nabla\cdot\mathbf{V})^2\right] + \frac{5}{2}\alpha(\nabla\times\mathbf{b})\cdot\nabla T -$$

$$-\frac{\alpha}{n}(\nabla\times\mathbf{b})\nabla(nT) + E_H + E_R. \tag{7}$$

E_R —total radiative loss; E_H — local mechanical heating function.

Construction of a Typical Coronal structure

Solar Corona — $T_c = (1 \div 4) \cdot 10^6\, K \qquad n_c \leq 10^{10}\,\mathrm{cm}^{-3}$.

3 Heating mechanisms are proposed for the Solar Corona:

- **By Alfven Waves**,
- **By Magnetic reconnection in current sheets**,
- **MHD Turbulence**.

All of these attempts fall short of providing a continuous energy supply that is required to support the observed coronal structures.

Our concept: The heating mechanism is in primary flows. Initial and boundary conditions define the coronal structure characteristics. $\quad T_c \gg T_{0f}$.

Observations $\longrightarrow$ there are strongly separated scales both in time and space in the solar atmosphere.

2 important eras in the life of a coronal structure:

1. A hectic period when it acquires particles and energy **(accumulation and primary heating) — the general set of equations are used.**
Heating takes place while particle accumulation (trapping) in a curved magnetic field.
We show: **that the kinetic energy contained in the primary flows can be dissipated by viscosity, and that this dissipation can be large enough to provide the continuous heating up to observed temperatures.**

2. **Quasistationary period** when it "shines" as a bright, high temperature object — the reduced equations are used; collisional effects and time dependence are ignored.
Equilibrium: each coronal structure has a nearly constant T, but different structures have different characteristic T-s, i.e., bright corona seen as a single entity will have considerable T–variation.

1st Era

Energy losses from corona $F \sim (5 \cdot 10^5 \div 5 \cdot 10^6)$ **erg/cm**^{2} s**.**

If the conversion of the kinetic energy in the PF-s were to compensate for these losses, we would require a radial energy flux

$$\frac{1}{2} m_i n_0 V_0^2 \; V_0 \geq F,$$

For initial $V_0 \sim (100 \div 900)\,\mathrm{km/s}$ $\qquad n \sim 9 \cdot 10^5 \div 10^7\,\mathrm{cm}^{-3}$ – viscous dissipation of the flow takes place on a time:

$$t_{\mathrm{visc}} \sim \frac{L^2}{\nu_i}, \tag{8}$$

For flow with $T_0 = 3\,\mathrm{eV} = 3.5 \cdot 10^4\,\mathrm{K}$, $n_0 = 4 \cdot 10^8\,\mathrm{cm}^{-3}$ creating a quiet coronal structure of size $L = (2 \cdot 10^8 \div 10^{10})\,\mathrm{cm}$, $t_{\mathrm{visc}} \sim (3.5 \cdot 10^8 \div 10^{10})\,\mathrm{s}$.

Note: (8) is an overestimate. $\qquad t_{\mathrm{real}} \ll t_{\mathrm{visc}}$.

Reasons: 1) $\nu_i = \nu_i(t, \mathbf{r})$ will vary along the structure,

2) the spatial gradients of the **V**–field can be on a scale much shorter than L (defined by the smooth part of B–field).

Fig.1 S.M. Mahajan, R. Miklaszewski, K.I. Nikol'skaya and N.L. Shatashvili

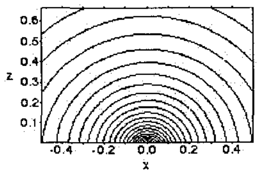


Fig.2 S.M. Mahajan, R. Miklaszewski, K.I. Nikol'skaya and N.L. Shatashvili

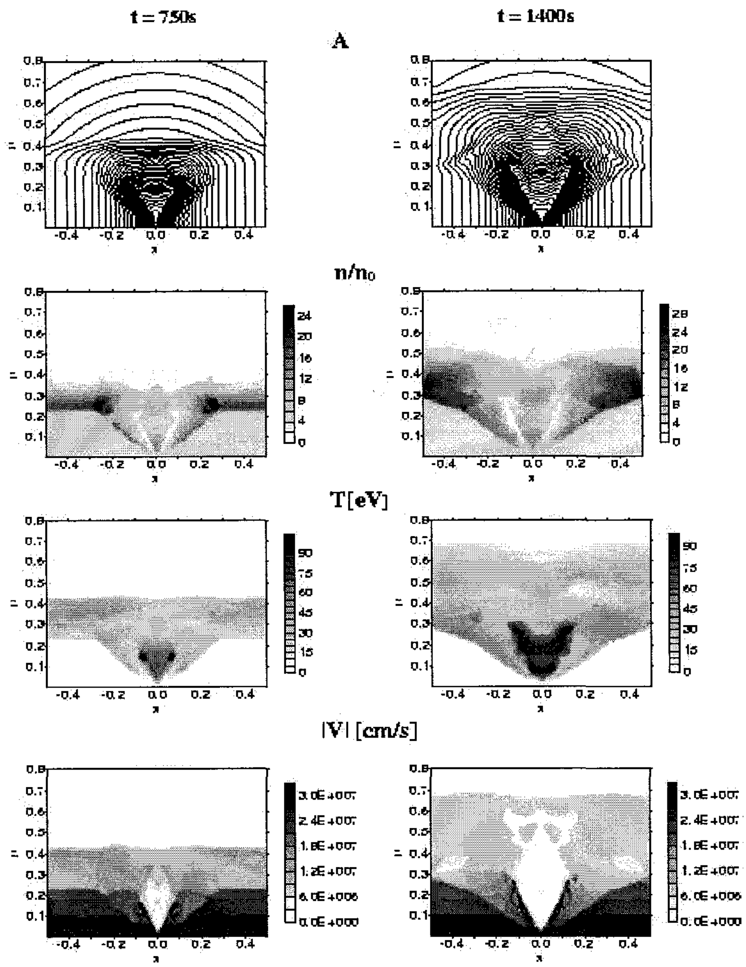


Fig.3a S.M. Mahajan, R. Miklaszewski, K.I. Nikol'skaya and N.L. Shatashvili

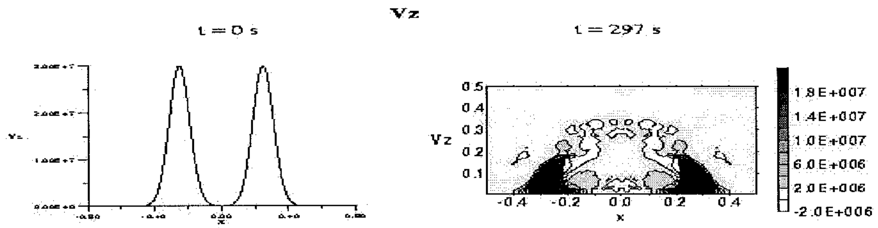


Fig.3b S.M. Mahajan, R. Miklaszewski, K.I. Nikol'skaya and N.L. Shatashvili

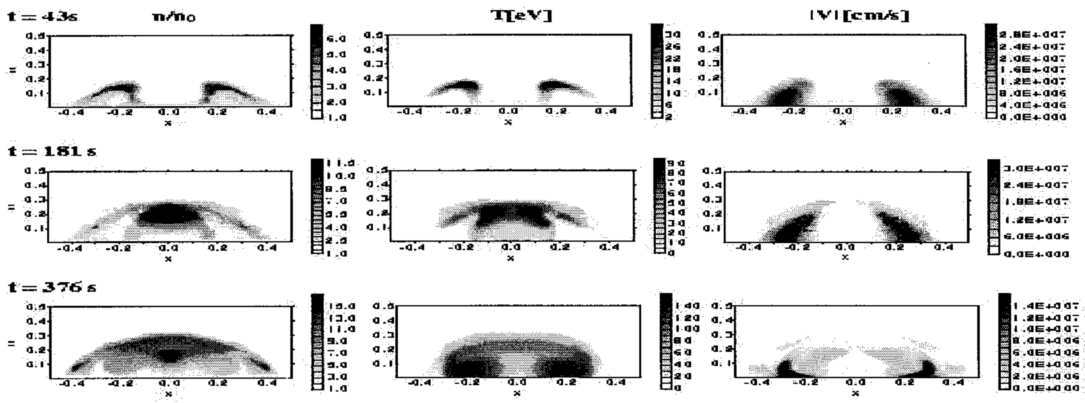


Fig.4 S.M. Mahajan, R. Miklaszewski, K.I. Nikol'skaya and N.L. Shatashvili

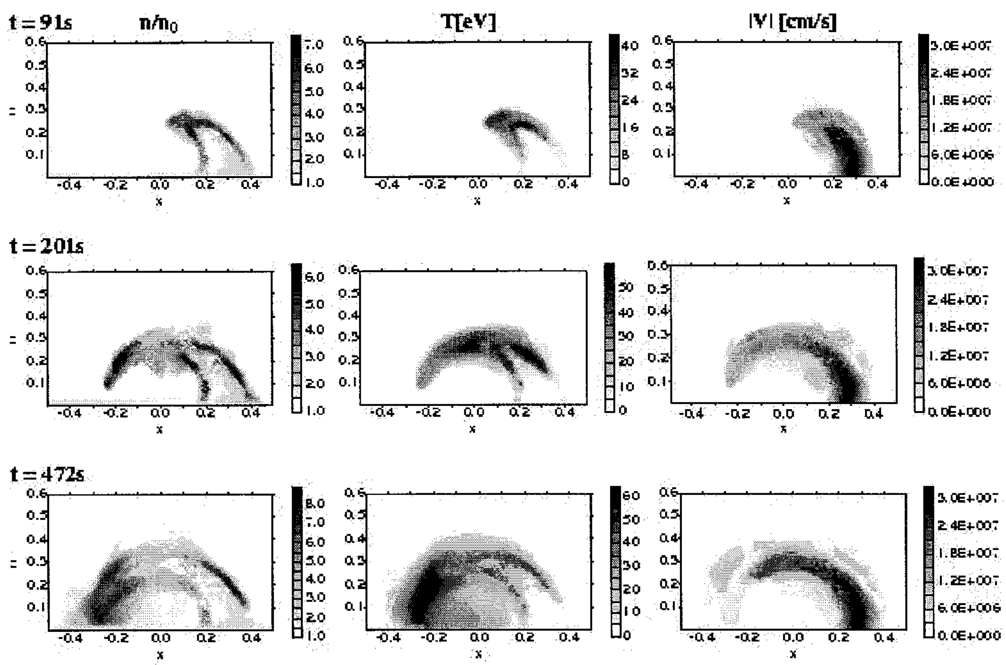
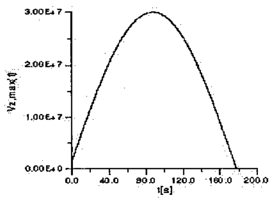
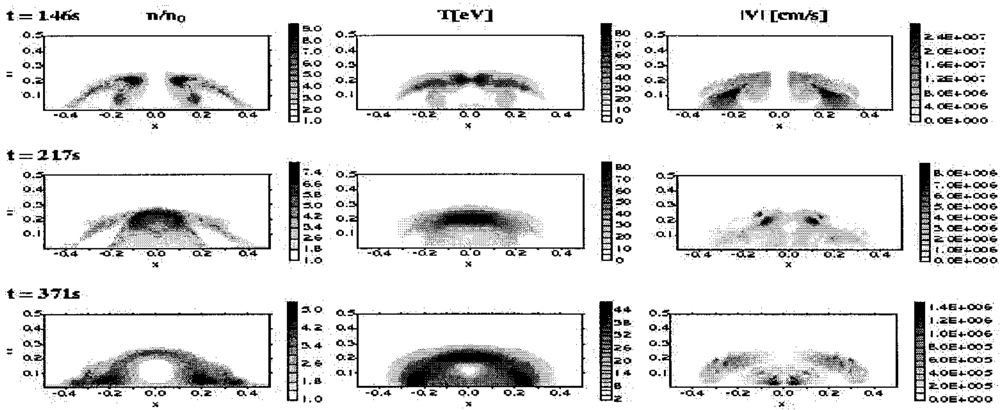


Fig.5 S.M. Mahajan, R. Miklaszewski, K.I. Nikol'skaya and N.L. Shatashvili





2nd Era

The familiar MHD theory (*single fluid*) is a reduced case of the more general *two–fluid* theory. Constrained minimization of the magnetic energy in MHD leads to force–free static equilibrium configurations. Presence of velocity field not only leads to new pressure confining states, but also to the possibility of heating the equilibrium structures by the dissipation of kinetic energy.

Assumption: In the equilibrium state we will use $n \simeq const.$

(i) Primary heating is performed — essential part of flow energy has been converted to heat (exceptions: streamer belt regions!).

(ii) If the rates of kinetic energy dissipation are not very large, we can imagine *the plasma to be going through a series of quasiequilibria before it settles into a particular coronal structure.* At each state we need the velocity fields in order to know if an appropriate amount of heating can take place.

Quasi-equilibrium structure

Normalizing n to some constant coronal base density n_0 (different for different structures!, $\lambda_{i0} = c/\omega_{i0}$ is defined with n_0), our system of equations reduces to:

$$\mathbf{b} + \alpha_0 \nabla \times \mathbf{V} = d\, n\, \mathbf{V} \qquad\qquad \mathbf{b} = a\, n \left[\mathbf{V} - \frac{\alpha_0}{n} \nabla \times \mathbf{b}\right], \qquad (9)$$

where r_{A0}, α_0, β_0 are defined with n_0, T_0, B_0.
a and d are dimensionless constants related to the two invariants:
the magnetic helicity — $h_1 = \int (\mathbf{A} \cdot \mathbf{b})\, d^3x$
and **the generalized helicity** $h_2 = \int (\mathbf{A} + \mathbf{V}) \cdot (\mathbf{b} + \nabla \times \mathbf{V}) d^3x$
Total energy of the system — $E = \frac{1}{2} \int (\boldsymbol{b}^2 + \boldsymbol{V}^2)\, \mathrm{d}\mathbf{r}$.
a and d are fixed by the initial conditions — these are the measures of the constants of motion, the magnetic helicity, and the fluid plus cross helicity or some linear combination thereof — they will be considered as given quantities.

These equations lead to

$$\nabla \left(\frac{r_{A0}}{r} - \beta_0(T) \ln\ n - \frac{V^2}{2} \right) = 0, \qquad (10)$$

giving the **generalized Bernoulli condition** which will determine the density of the structure in terms of the flow kinetic energy, and solar gravity. Equations (9) yield

$$\frac{\alpha_0^2}{n} \nabla \times \nabla \times \mathbf{V} + \alpha_0\ \nabla \times \left(\frac{1}{a} - d\ n \right) \mathbf{V} + \left(1 - \frac{d}{a} \right) \mathbf{V} = 0. \qquad (11)$$

which must be solved with (10) for n and $\mathbf{V}$. Equation (10) is solved to obtain ($g(r) = r_{c0}/r$)

$$n = \exp\left(- \left[2g_0 - \frac{V_0^2}{2\beta_0(T)} - 2g + \frac{V^2}{2\beta_0(T)} \right] \right), \qquad (12)$$

This relation tells us: that the variation in density can be quite large for a low β_0 plasma if the gravity and the flow kinetic energy vary on length scales comparable to the extent of the structure.

Substituting (12) into (11) will yield a single equation for velocity which is quite nontrivially nonlinear.
Numerical solutions of the equations are tedious but straightforward.

Note that temperature can be varying though density we will put constant ($n = 1$) and we will present several classes of the solutions of the following linear equation:

$$\alpha_0^2 \, \nabla \times \nabla \times \mathbf{Q} + \alpha_0 \left(\frac{1}{a} - d \right) \nabla \times \mathbf{Q} + \left(1 - \frac{d}{a} \right) \mathbf{Q} = 0, \qquad (13)$$

where $\mathbf{Q}$ is either $\mathbf{V}$ or $\mathbf{b}$.

We use $\mathbf{b}$ as our basic field to be determined by Eq. (13); the velocity field $\mathbf{V}$ will follow from Eqs. (9) with $n = 1$.

Analysis of the *Curl Curl* Equation, Typical Equilibria

The existence of two, rather than one (as in the standard relaxed equilibria) parameter in this theory is an indication that we may have found an extra clue to answer the extremely important question: **why do the coronal structures have a variety of length scales, and what are the determinants of these scales?**

Parameter $\alpha_0 \sim 10^{-7} - 10^{-8}$ for typical densities of interest ($\sim (10^7 - 10^9\,\mathrm{cm}^{-3})$,

Suppose that we are interested in investigating a structure that has a span $\epsilon R_\odot$, where $\epsilon \ll 1$. For a structure of order 1000 km, $\epsilon \sim 10^{-3}$.

The ratio of the orders of various terms in Eq. (13) are ($|\nabla| \sim L^{-1}$)

$$\frac{\alpha_0^2}{\epsilon^2} : \quad \frac{\alpha_0}{\epsilon}\left(\frac{1}{a} - d\right) : \quad \left(1 - \frac{d}{a}\right) .$$
$$(1) \qquad (2) \qquad (3)$$

The following two principle balances are representative:
(a) The last two terms are of the same order, and the first $\ll$ them:

$$\epsilon \sim \alpha_0 \frac{1/a - d}{1 - d/a}. \tag{14}$$

For our desired structure to exist ($\alpha_0 \sim 10^{-8}$ for $n_0 \sim 10^9\,\mathrm{cm}^{-3}$):

$$\frac{1/a - d}{1 - d/a} \sim 10^5, \tag{15}$$

which is possible if d/a tends to be extremely close to unity.
For the first term to be negligible, we would further need

$$\frac{\alpha_0}{\epsilon} \ll \frac{1}{a} - d \Rightarrow \epsilon \gg \frac{10^{-8}}{1/a - d}, \tag{16}$$

easy to satisfy as long as neither of $a \simeq d$ is close to unity.
Standard relaxed state: flows are not supposed to play an important part. Extreme sub–Alfvénic flows: $a \sim d \gg 1$.

Is the new term as unimportant as it appears to be?

Answer: **no**. It introduces a qualitatively new phenomenon:
Since $\nabla \times (\nabla \times \mathbf{b})$ is second order in $|\nabla|$, it constitutes a singular perturbation of the system; its effect on the standard root (2) $\sim$ (3) $\gg$ (1) will be small, but it introduces a new root for which the $|\nabla|$ must be large (short length scale!)
For a and d so chosen to generate a 1000 km structure

$$d/a \sim 1 + 10^{-4}, \quad d \simeq a = -10, \quad |\nabla|^{-1} \sim 10^2\,\mathrm{cm},$$

an equilibrium root with variation on the scale of 100 cm will be automatically introduced by the flows.
Even if flows are weak ($a \simeq d \simeq 10$), the departure from $\boldsymbol{\nabla} \times \mathbf{B} = \alpha \mathbf{B}$, can be essential: it introduces a totally different (small!) scale solution $\Longrightarrow$ fundamental importance in understanding the effects of viscosity on the dynamics of structures; **dissipation of short scale structures** $\longrightarrow$ **primary heating**.

(b) The other balance: we have a complete departure from conventional relaxed state: all three terms are of the same order

$$\epsilon \sim \alpha_0 \, \frac{1}{1/a - d} \sim \alpha_0 \, \frac{1/a - d}{1 - d/a} \tag{17}$$

which translates as:

$$\left(\frac{1}{a} - d\right)^2 \sim 1 - \frac{d}{a}, \qquad \frac{1}{a} - d \sim \alpha_0 \, \frac{1}{\epsilon}. \tag{18}$$

For a 1000 km structure, $\alpha_0 \cdot 1/\epsilon \sim 10^{-5}$ and $a \sim d \sim 1$
we would need the flows to be almost perfectly Alfvénic!

Structures of the 1 km or 10 km size, $\longrightarrow \alpha_0 \cdot 1/\epsilon \sim 10^{-2}$ or 10^{-3}: the flows needed are again Alfvénic.
At a density of $(1-4) \cdot 10^8\,\mathrm{cm}^{-3}$, and a speed $\sim (200-300)\,\mathrm{km/s}$, the flow becomes Alfvénic for $B_0 \sim (1-3)\,\mathrm{G}$. Such flow conditions may pertain only in the weak magnetic field regions.

Following are the obvious characteristics of this class of flows:

(1) Alfvénic flows are capable of creating entirely new kinds of structures, which are quite different from the ones that we normally deal with. Notice that here we use the term flow to denote not the primary emanations but the plasmas that constitute the existing coronal structures, or the structures in the making.

(2) Though they also have two length scales, these length scales are quite comparable to one another: This is very different from the extreme sub–Alfvénic flows where the spatial length–scales are very disparate.

(3) In the Alfvénic flows, the two length scales can become complex conjugate, i.e., which will give rise to fundamentally different structures in $\mathbf{b}$ and $\mathbf{V}$.

Definitions: $p = (1/a - d)$ and $q = (1 - d/a)$. Eq. (13) $\Longrightarrow$

$$(\alpha_0 \nabla \times -\lambda)(\alpha_0 \nabla \times -\mu)\mathbf{b} = 0 \tag{19}$$

where $\lambda(\lambda_+)$ and $\mu(\lambda_-)$ are the solutions of the quadratic equation

$$\alpha_0 \lambda_\pm = -\frac{p}{2} \pm \sqrt{\frac{p^2}{4} - q}. \tag{20}$$

If $\mathbf{G}_\lambda$ is the solution of the equation (a_λ and a_μ are constants)

$$\nabla \times \mathbf{G}(\lambda) = \lambda \mathbf{G}(\lambda), \qquad \textit{then} \tag{21}$$

$$\mathbf{b} = a_\lambda \mathbf{G}(\lambda) + a_\mu \mathbf{G}(\mu), \tag{22}$$

is the general solution of the double *curl* equation. Velocity field is:

$$\mathbf{V} = \frac{\mathbf{b}}{a} + \alpha_0 \boldsymbol{\nabla} \times \mathbf{b} = \left(\frac{1}{a} + \alpha_0 \lambda\right) a_\lambda \mathbf{G}(\lambda) + \left(\frac{1}{a} + \alpha_0 \mu\right) a_\mu \mathbf{G}(\mu). \tag{23}$$

Thus a complete solution of the double *curl* equation is known if we know the solution of Eq. (23).

2–dimensional solutions:

Cartesian geometry, z representing the radial coordinate and x representing the direction tangential to the surface $(\partial/\partial y = 0)$.

Sub–Alfvénic: $a \sim d \gg 1 \quad \Longrightarrow \quad \lambda \sim (d-a)/\alpha_0\, d\, a, \quad \mu = d/\alpha_0.$

The velocity field is:

$$\mathbf{V} = \frac{1}{a}\, a_\lambda \mathbf{G}_\lambda + d a_\mu \mathbf{G}(\mu) \tag{24}$$

revealing that, while, the slowly varying component of velocity is smaller by a factor $(a^{-1} \simeq d^{-1})$ as compared to the similar part of the magnetic field, the fast varying component is a factor of d larger than the fast varying component of the magnetic field!

Result: for an extreme sub–Alfvénic flow (e.g. $|\mathbf{V}| \sim d^{-1} \sim 0.1$),

$$\left| \frac{V_z(\mu)}{V_z(\lambda)} \right| \simeq 1; \tag{25}$$

velocity field is equally divided between slow and fast scales.

Viscous damping of this substantially large as well as fastly varying flow component may provide the bulk of primary heating needed to create and maintain the bright, visible Corona.

- Neglecting viscous terms may not be a good approximation until a large part of the kinetic energy has been dissipated.
- The solution of the basic heating problem may have to be sought in the pre–formation rather than the post–formation era.
- Extreme sub–Alfvénic flows: the magnetic field, unlike the velocity field, is primarily smooth.
- Strong flows: the magnetic fields may also develop a substantial fastly varying component $\Longrightarrow$ the resistive dissipation can also become a factor to deal with.

Dynamical Escape Channel Creation

Two possible modes of escape from the magnetic field:
1) the passive mode in which the particles find a region of open field lines and escape without affecting the ambient field,
2) the active mode: the particle flows are strong enough to distort/ modify the local magnetic field to create their own escape channels.

- Habbal and Woo (2001), e.g, have shown that the fast solar wind detected by ULLYSES seems to arrive (mostly radially) from all latitudes of the so-called quiet Sun.
- TRACE — the diffuse quiet Sun seems to be studded with a gamut of loop–like structures; no open magnetic field lines can be distinguished in these images.
- Even in the so called coronal holes (low temperature regions originally believed to have open field lines) there is no direct evidence for open magnetic field lines.

Genesis of Solar Wind may lie in active mode of particle escape.

- If a given stream of particles were to punch out its own channels of escape in a short–lived, dynamic process, we could explain the emergence of the wind from regions of the solar surface with no observable long–lived (quasi–static) open–field line structures.
- The flow enters a closed field line region (preferably with weak fields), distorts it, creates a channel, escapes and leaves the field lines to mend themselves.
- This phenomenon will happen with statistical uniformity over the entire solar surface and the wind would appear to come from the regions permeated by primarily closed field line structures.

Studies using multi–fluid, multi–dimensional descriptions (e.g. Tu & Marsch (1997, 2001), Hollweg (1999)) include the self–consistent effects of MHD waves on minority ions.

A high–speed flow in/or near the TR must overcome both gravity and the magnetic field to emerge as the SW.
Overcoming gravity imposes a lower bound on the flow velocity.

Negotiating the magnetic field is hard.

Preliminary studies show that flows with reasonable TR densities and velocities $\leq 400\, km/sec$ can not destroy or deform closed magnetic fields structures sufficiently to meet escaping conditions.
Estimates based on the observed magnetic field strengths show that even in weak field regions ($\sim (1-5)\, G$) flows must be rather strong to punch holes in the structure.

If the up–flow creation and acceleration mechanisms were operative somewhere below the hot corona, the flow–magnetic field interaction could lead to conditions more favorable to particle–escape.

Assumption: the high speed flows are already there below the coronal base where they begin to interact with the closed field regions; they provide the initial conditions in our numerical work.

Simulation of two distinct representative problems will be presented:
1) the flow interacting with a single structure providing the simplest example of field–deformation,
2) the flow passing through a multiple structure region creating escape–channels under specific conditions.

Note 1: 2D cartesian nature of code does not allow us to explore large distances from the surface due to interference with the boundaries.

Note 2: Asymmetric situations is straightforward.

Habbal, Woo & Arnaud (2001) — coexistence of strong– and weak–field components in the quiet–Sun photospheric field.

The observed predominance of quiet coronal magnetic field radial component is defined by the weak–field component.

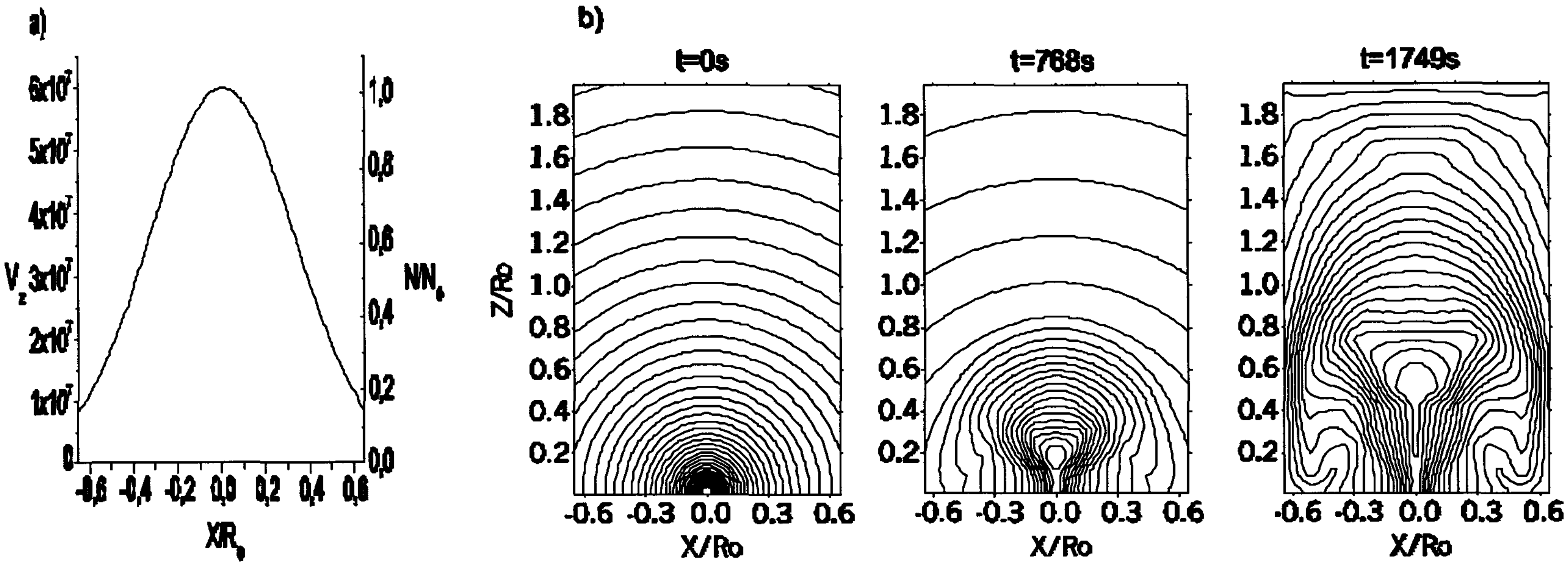
1. Spatially localized flow entering an arcade–like single closed field line structure. *2 scenerios emerge*:

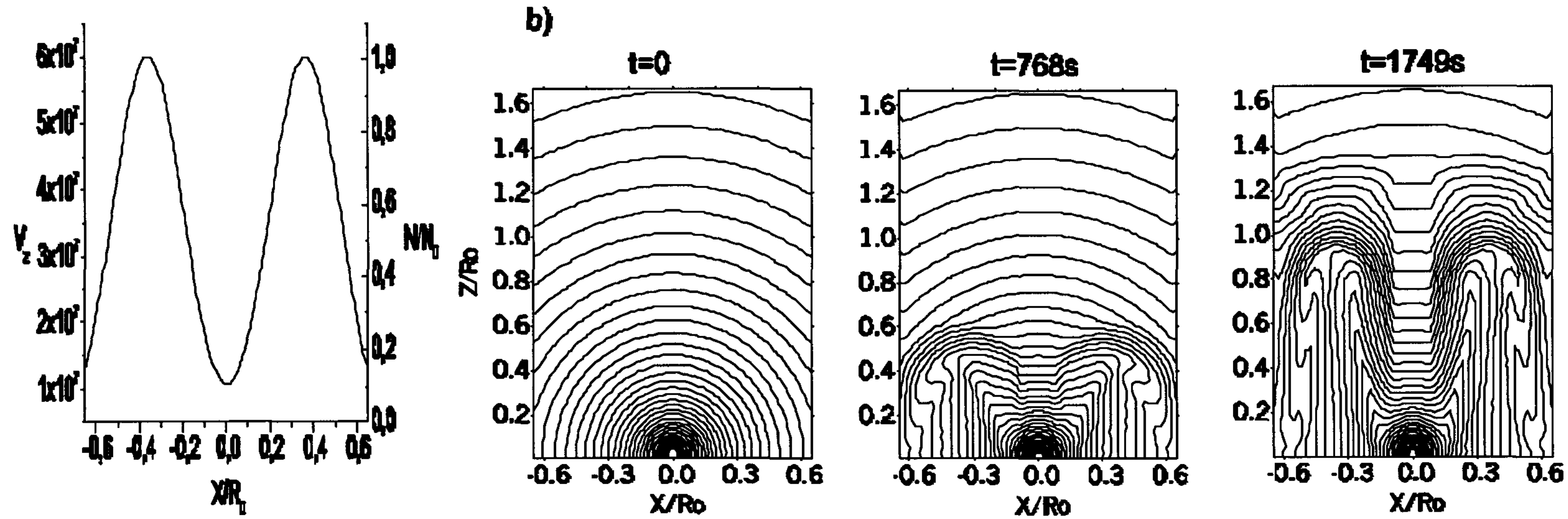
i) strong flow – $|\mathbf{V}|_{max} \sim 600\,km/sec$ + arcade: $B_{max} = 5\,G$.
Strong deformation: narrower the flow pulse, the sharper the shear created; stronger the flow, the faster is the deformation process.

ii) several flow pulses arrive simultaneously towards the single arcade structure. *In the central region the sheared narrow sub–regions is created with opposite polarity.*

Assumption: diffusion time of magnetic field is longer than the duration of the interaction process (would require $T \leq$ a few eV–s.)

Result: flows are not able to escape regardless deformation.


a)
b)
t=0s
t=768s
t=1749s
Z/Ro
X/Ro
X/R0
NN0
Vz


b)
t=0
t=768s
t=1749s
Z/Ro
X/Ro
X/R0
NN0
Vz

2. Observations + the models of high–speed up–flow generation in the chromosphere/corona $\Longrightarrow$ reasonable to study the passage of a strong flow through multi–arcade B–field structures.

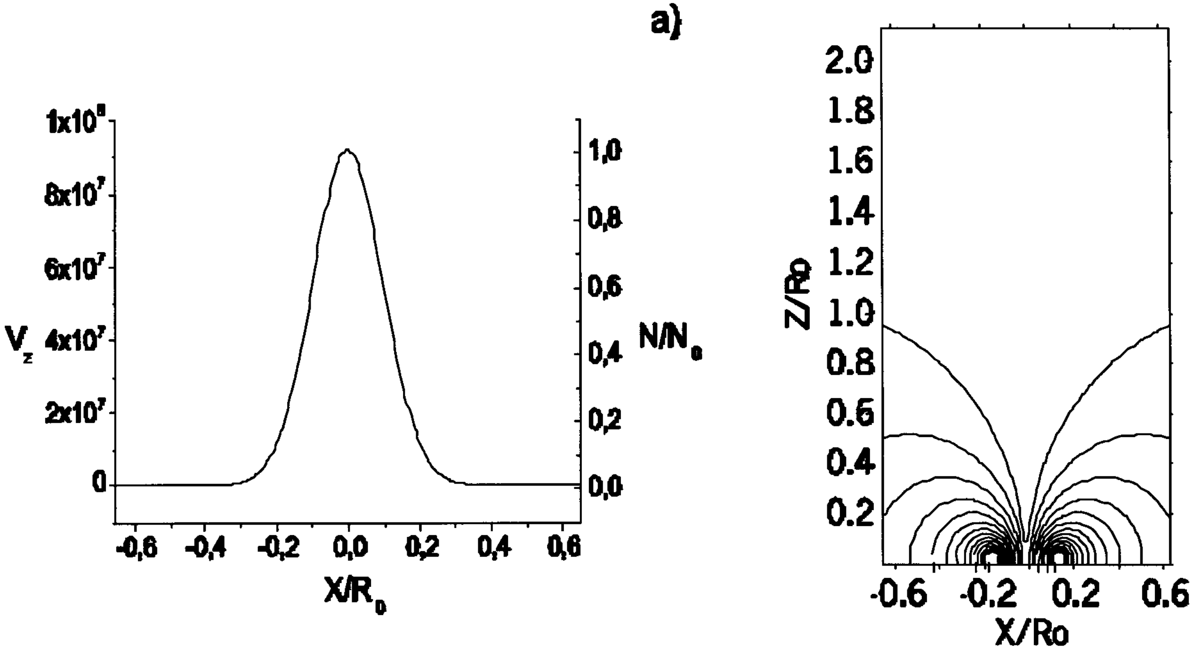
i) flow + two neighboring arcade–structures: one channel is created in $\sim 50\,min$

Sharp decrease in density along channel (after the usual shock front area due to the interaction of flow with background plasma) with a clearly distinguishable ballistic deceleration of the flow.

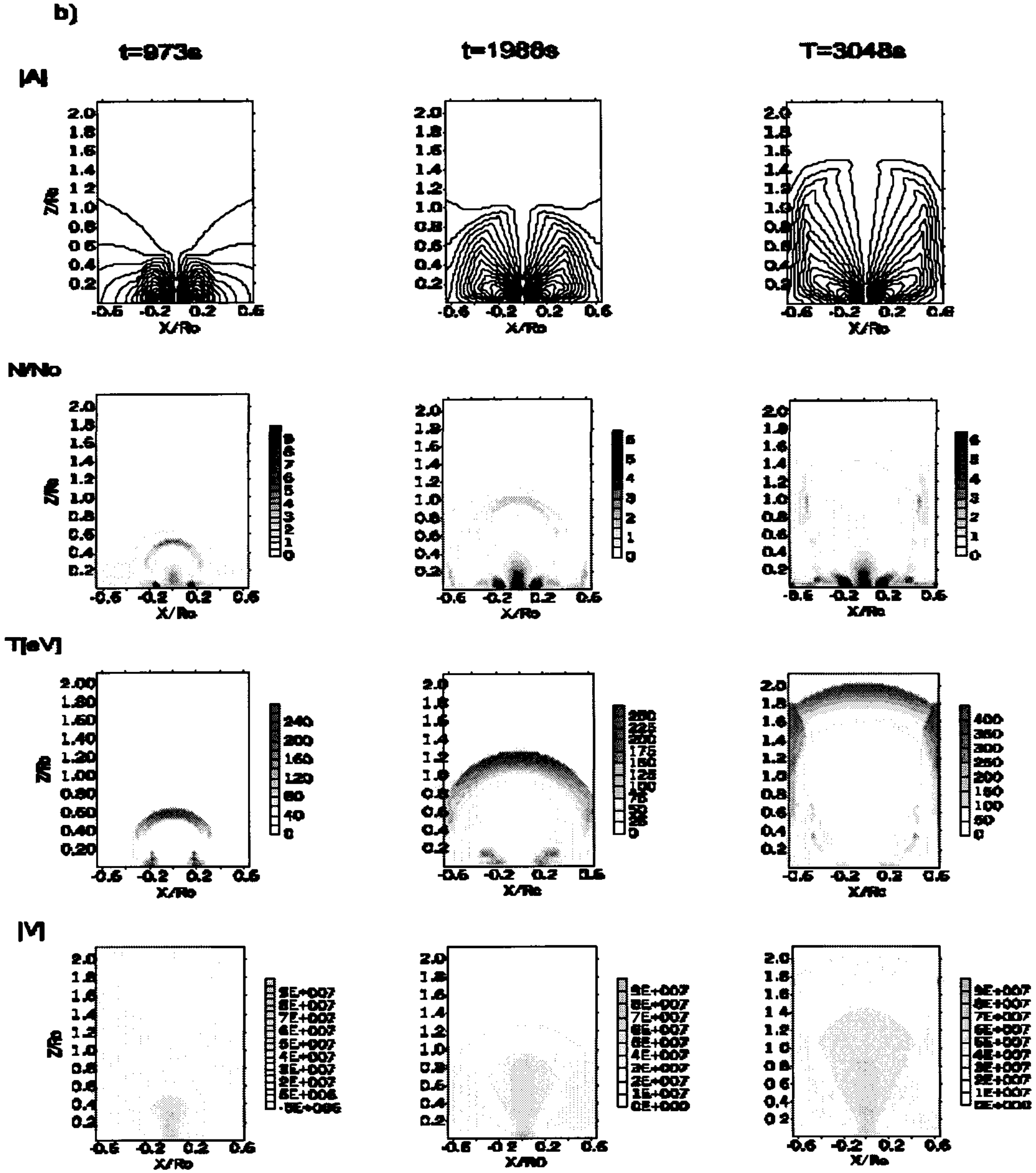
At heights $\geq 2\,R_{\odot}$ the flow speed $\sim 800\,km/sec$.

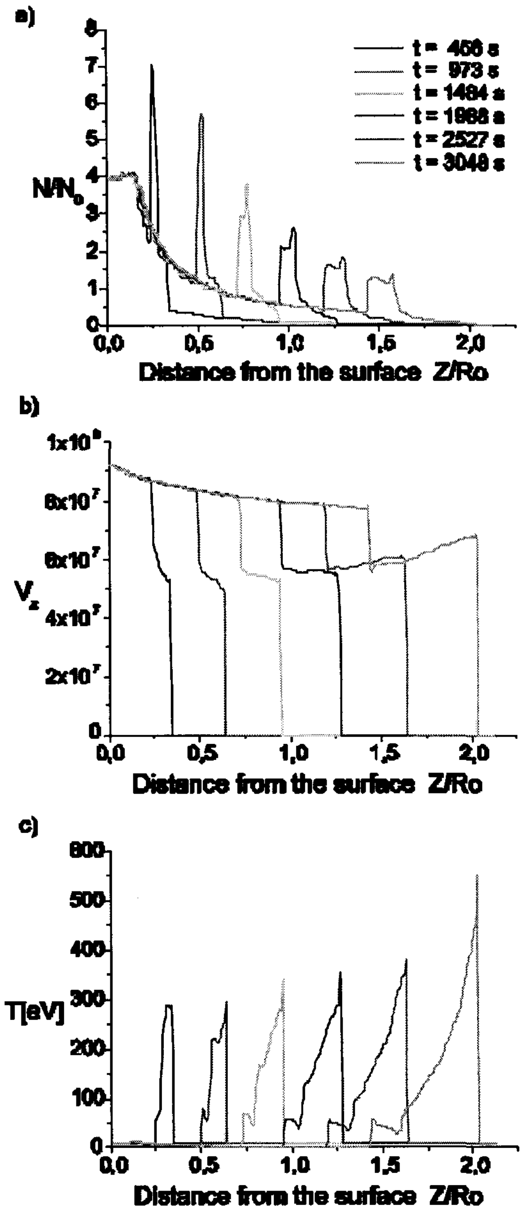
Fast flow expends a negligible fraction of its energy in creating a channel for its escape.

a)



1x10^8
8x10^7
6x10^7
4x10^7
2x10^7
0
V_z
1,0
0,8
0,6
0,4
0,2
0,0
N/N_0
-0,6 -0,4 -0,2 0,0 0,2 0,4 0,6
X/R_0
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Z/Ro
-0.6 -0.2 0.2 0.6
X/Ro

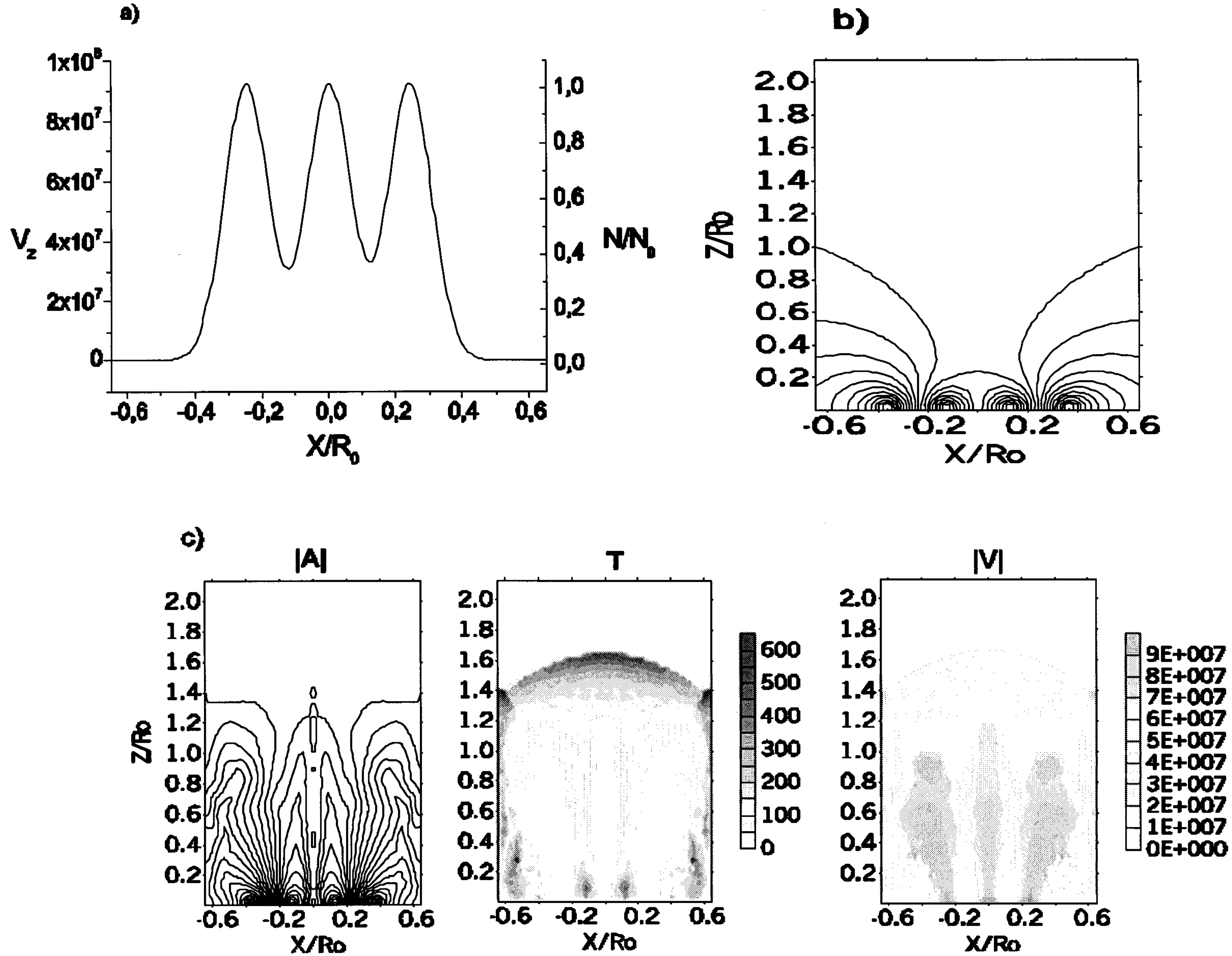

b)
t=973s
t=1988s
T=3048s
|A|
N/No
T[eV]
|V|
Z/Ro
X/Ro


a)
N/No
Distance from the surface Z/Ro
b)
Vz
Distance from the surface Z/Ro
c)
T[eV]
Distance from the surface Z/Ro

ii) flow + four neighboring arcade–structures: several channels are created in the region of the flow. At longer times the 3 structures will be permeated by flows.
For optimum effect we located the maxima of the flow pulses in the weak–field region in between the neighboring arcades.

For this study, the arcade structure is taken to be symmetric.
Inhomogeneous initial conditions lead to different evolutions, but colorred channel creation remains a common feature.

Caution: initial flows were assumed to be constant in time.
Up–flows from the chromosphere or TR have finite life times $\Longrightarrow$ the channel creation process will last for the time dictated by the duration and other characteristics of the impinging flow–pulse.



a)
b)
c)
1x10^8
8x10^7
6x10^7
V_z 4x10^7
2x10^7
0
1,0
0,8
0,6
0,4
0,2
0,0
N/N_0
-0,6 -0,4 -0,2 0,0 0,2 0,4 0,6
X/R_0
Z/Ro
X/Ro
|A|
T
|V|
600
500
400
300
200
100
0
9E+007
8E+007
7E+007
6E+007
5E+007
4E+007
3E+007
2E+007
1E+007
0E+000

List of omissions of this preliminary effort: anisotropies of velocities and temperature (source of wave generation and instabilities), ionization, multi–species dynamics, flux emergence etc. are not included. Either of these could influence the channel–creation dynamics.

Result: sufficiently strong flows are capable of engineering their escape (self–induced transparency) from a variety of closed field line structures prevalent in the solar atmosphere.

The intense re–arrangement of the magnetic field lines needed for the formation of escape channels is a consequence of the magneto–fluid coupling — the ability of a strong flow to deform and distort the field lines. During this highly dynamical phase, viscous dissipation leads to heating (preferentially of ions) of what would eventually become the solar wind.