Quiescent and Catastrophic Events

In Stellar Atmospheres

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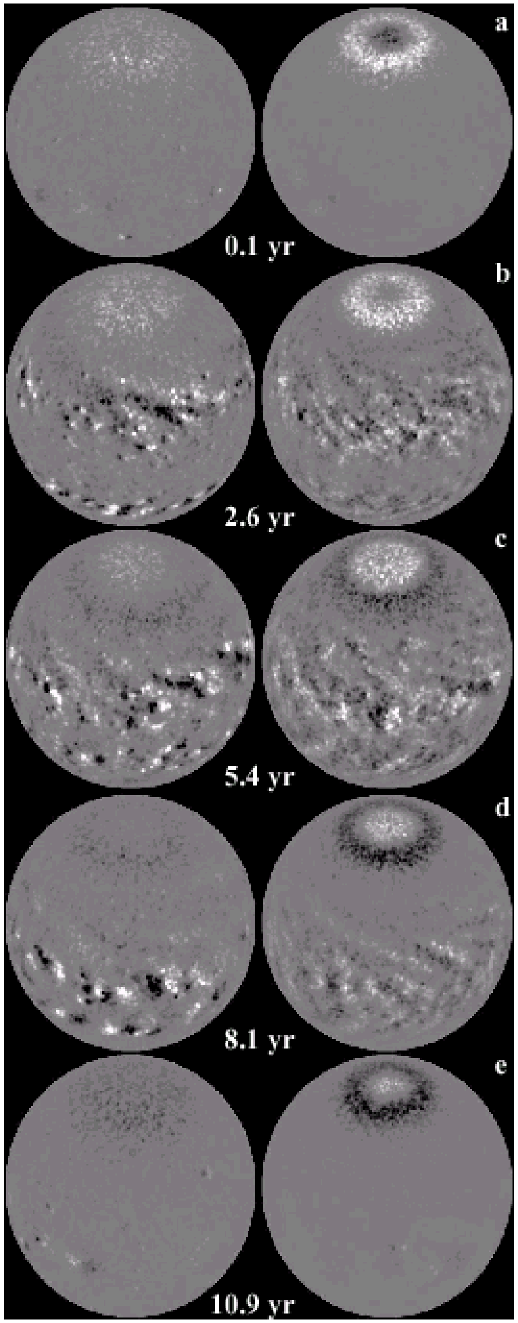
Stellar atmospheres are hot and charged – Much of the observed phenomena are caused by the motion of these charged hot particles (electrons and protons mostly) in Magnetic fields.

Magnetic fields play a key role in the formation of stars (planetary systems) – Control the atmospheres dynamics – the stellar coronae and the stellar winds, the space weather etc.

Stellar magnetic field is generated in the interior of a star like the Sun by a "dynamo mechanism" – still a mystery – rotation and convection are the most important ingredients.

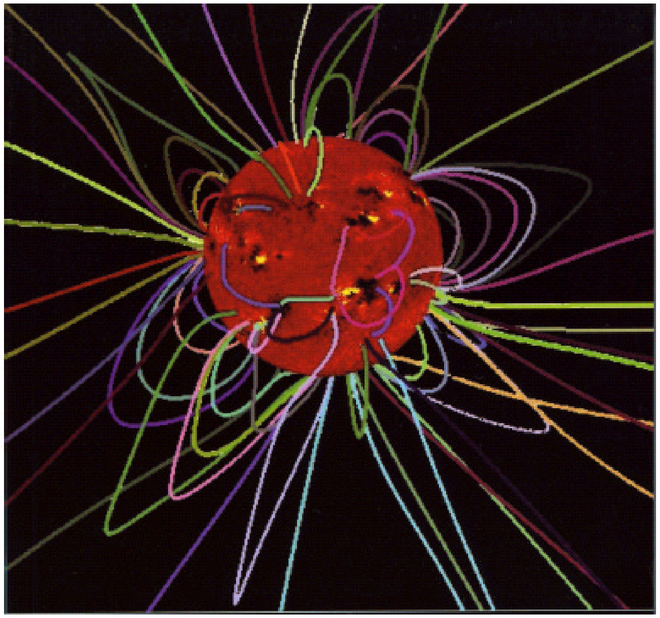
The atmospheric magnetic field continually adjusts to the large-scale flows on the surface, to flux emergence and subduction, and to forces opening up the field into space.



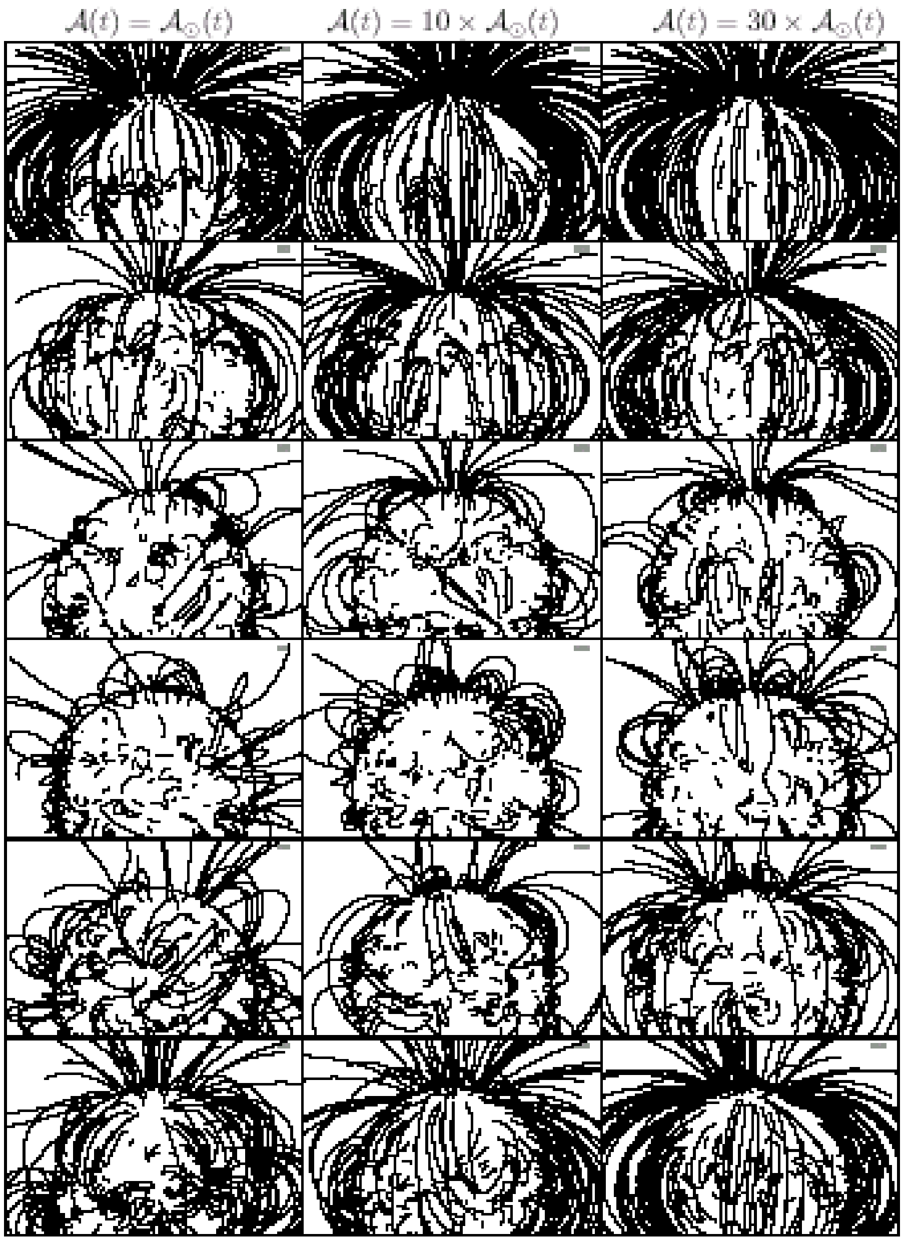
Simulations of stellar magnetic fields for a star like the Sun (left) and for a star with an active-region emergence rate 30 times higher (right)

- The panels show the surface magnetic field, viewed from a position over a latitude of 40^o.
- The gray scale for the Sun-like star saturates at 70 Mx cm^{-2}, and for the active star at 700 Mx cm^{-2}, for a resolution of one square degree.

Potential Field geometry of Active Sun



Dynamic finely structured stellar atmosphere



Potential field geometry of Stellar Coronae

- **Each of the panels shows 500 randomly selected field lines (including in that total field lines behind the sphere).**

- **The columns show: a star of solar activity, and stars with 10 and 30 times the solar active-region emergence rate, respectively.**

- **Six different phases of the 11-year starspot cycles: 0.00 (top, cycle minimum), 0.16, 0.33, 0.49 (near cycle maximum), 0.65, and 0.82 (bottom).** Sample magnetograms for these phases for the simulations of the Sun-like star and of the most active star are shown in Fig. above.

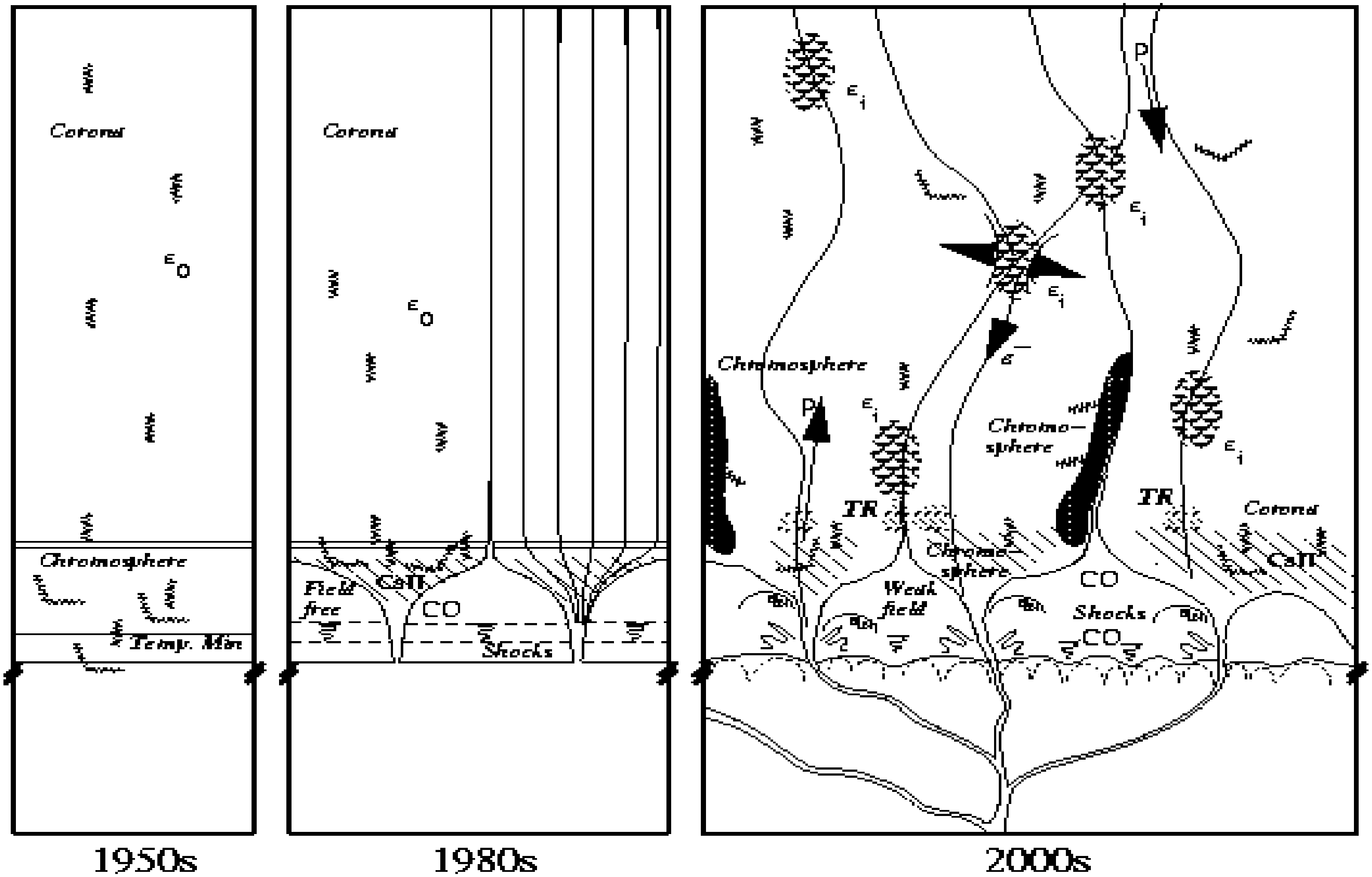
- **The field line density within each panel is statistically proportional to field strength.**

Stellar magnetic activity => wealth of phenomena: starspots, nonradiatively heated outer atmospheres, activity cycles, deceleration of rotation rates, and even, in close binaries, stellar cannibalism.

Key topics : radiative transfer, convective simulations, dynamo theory, outer – atmospheric heating, stellar winds and angular momentum loss.

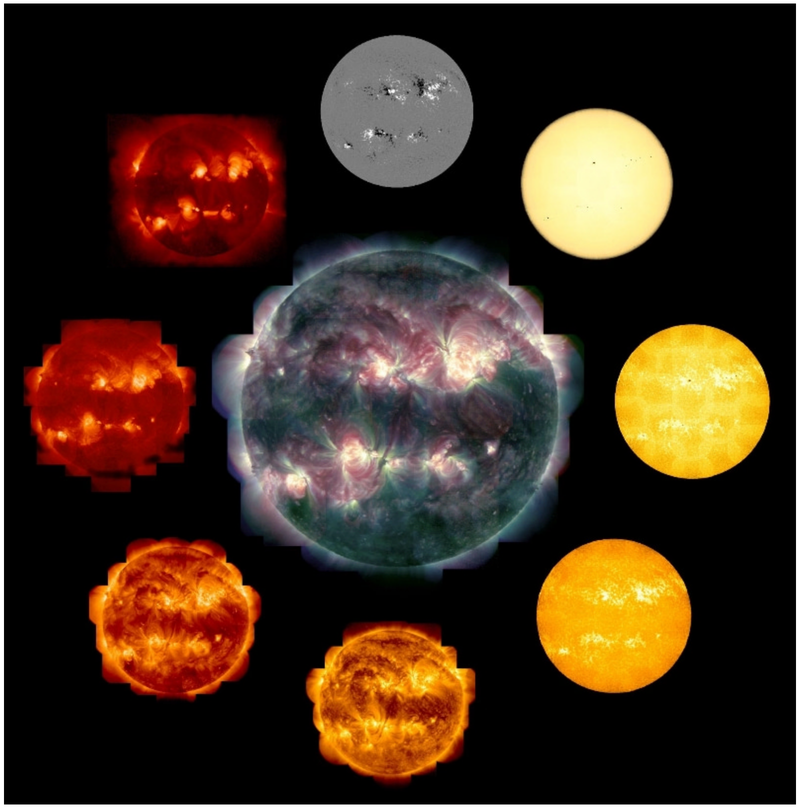
Magnetically active stars shed angular momentum – lose mass through their asterospheric magnetic fields. This process involves the interaction of a topologically complex, evolving coronal magnetic field with embedded plasma, which is heated throughout the corona + accelerated on its way to interstellar space.

Stellar observations suggest: **Sun was magnetically active even before it became a hydrogen-burning star**. Activity smoothly declining over billions of years – angular momentum is lost through a magnetized solar wind (e.g., Schrijver et al. 2003).

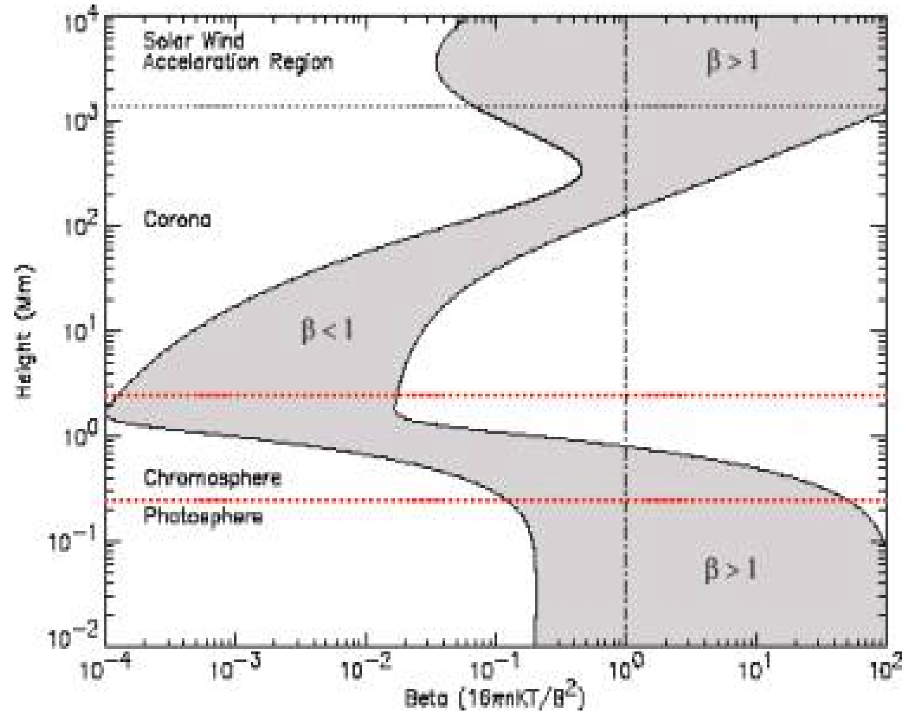


Evolution of corona cartoon: gravitationally stratified layers in the **1950s (left)**; vertical flux tubes with chromospheric canopies **(1980s, middle)**; fully inhomogeneous mixing of photospheric, chromospheric, TR and coronal zones by such processes as heated upflows, cooling downflows, interminent 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) **(Shrijver 2001).**

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



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



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

Processes – Quiescent and Violent

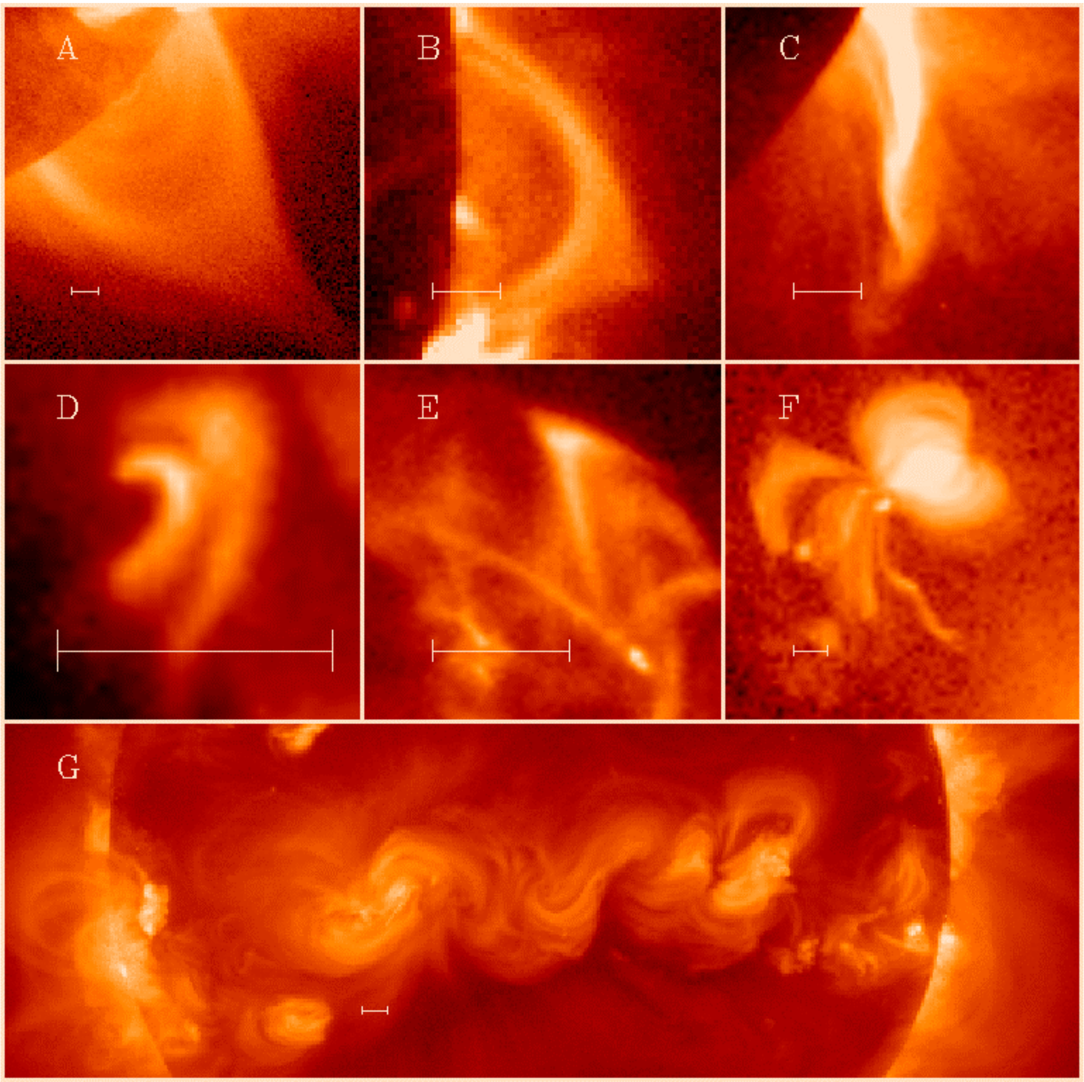
Quiescent: Formation of long lived coronal structures, Heating, Maintenance and Slow dissipation of these structures – solar winds (slow & fast), acceleration, flow generation, waves, Surface turbulence, granulation etc.

Violent – explosive events like blinkers, sudden cell and network brightenings, flares, coronal mass ejection (CME's).

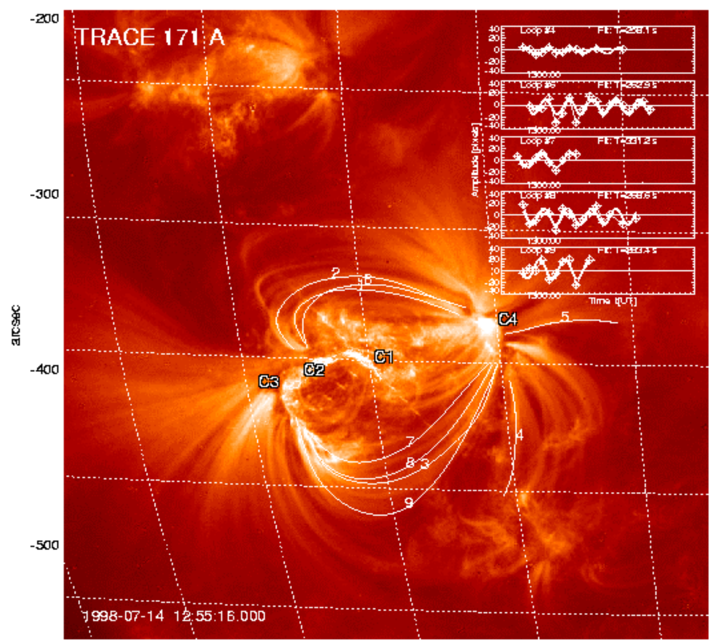
Slow or fast, peaceful or violent – these processes represent conversion of one form of energy into another. And there are really only three forms of energy which play a fundamental role- magnetic, thermal and kinetic – gravity also plays some some role but not a determining one.
Flares convert magnetic energy to heat and motion. CME's destroy magnetic and heat for mass motion – both processes are catastrophic. The latter takes plasma from the low corona into the SW and can disturb the near–Earth space.
Each flux emergence brings helicity to accumulate additively in a coronal structure while excess magnetic energy is flared away.

Catastrophic Events

(Explosive/eruptive events like jet-like outflows, transient brightenings, blinkers, large flares, nano- and micro-flares, eruptions, CME)

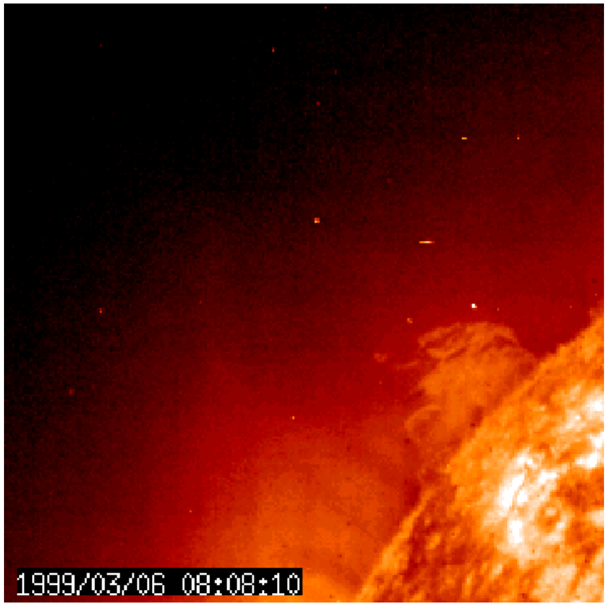


The dynamic, flaring, eruptive and explosive Solar Corona

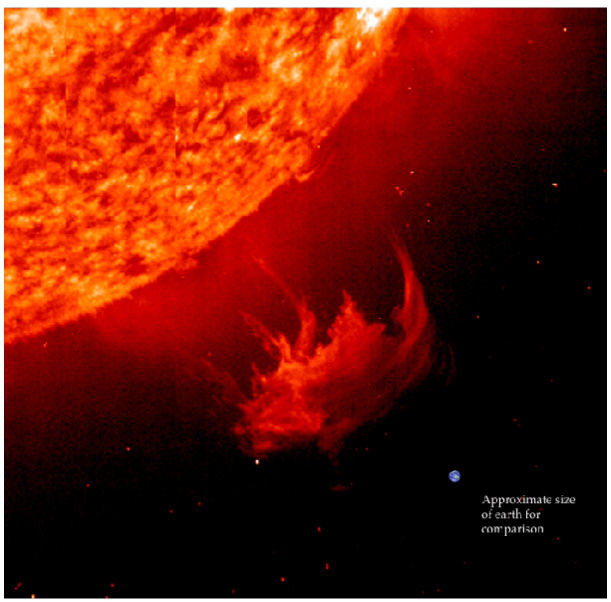


TRACE: A set of coronal loops marked, of which five exhibit transverse oscillations

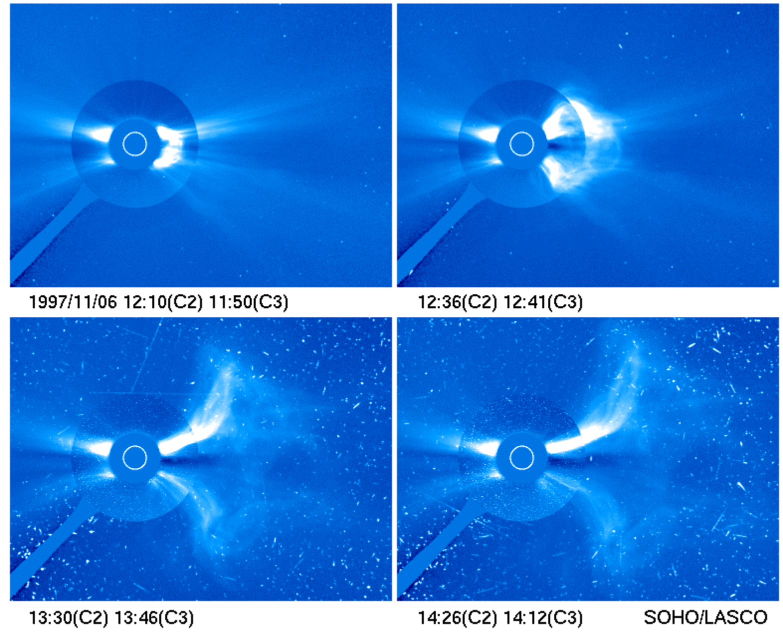
Coronal Mass Ejection



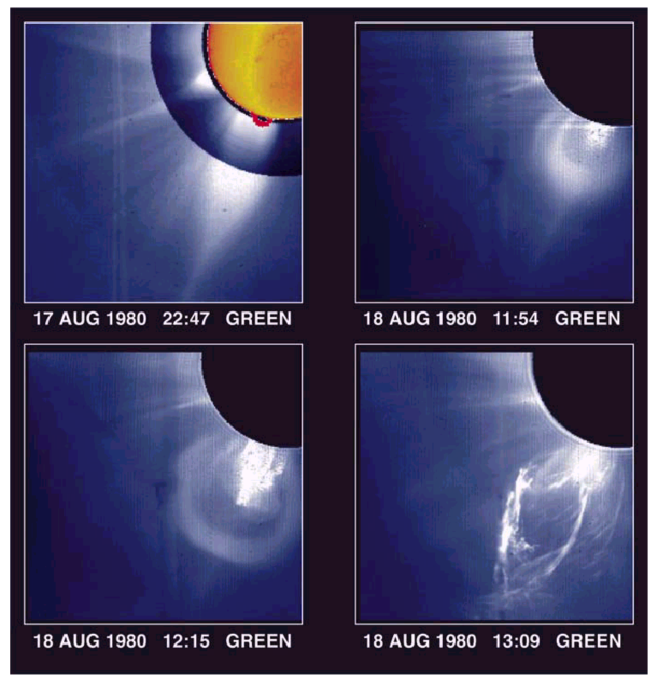
Eruption from Solar Surface



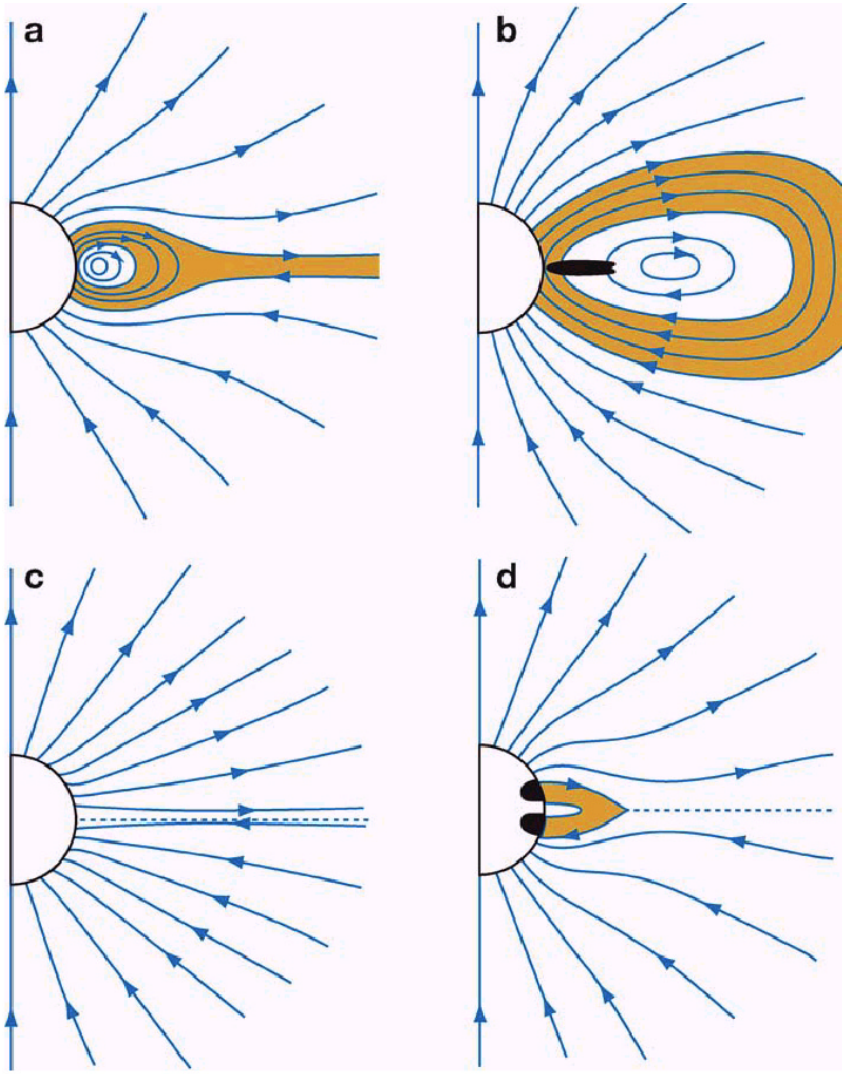
Sun and Earth

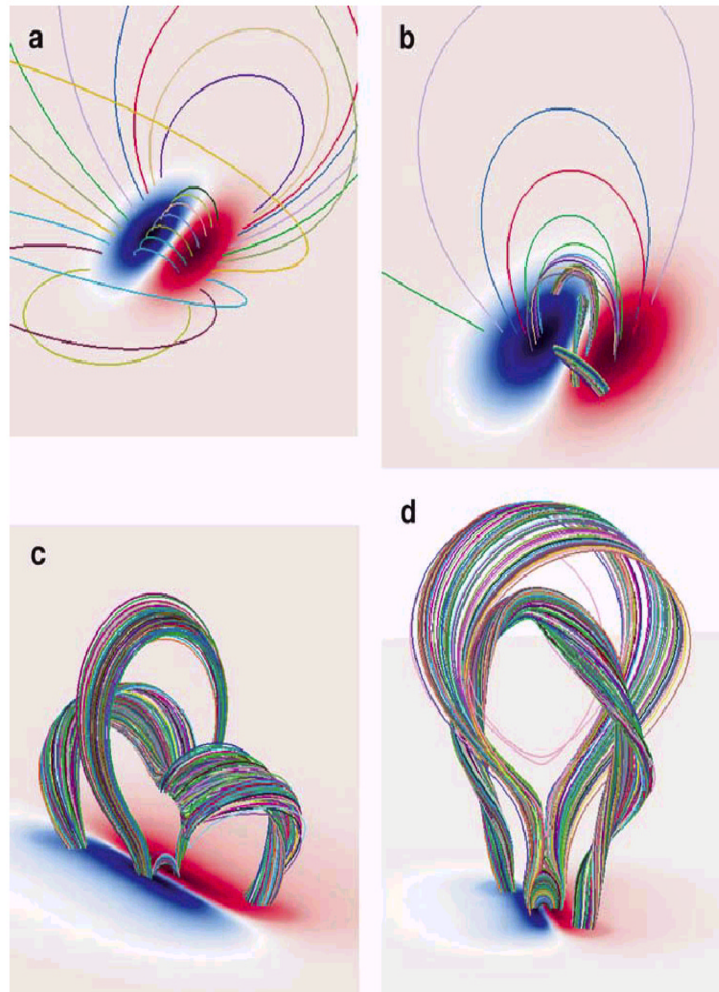


SOHO/LASCO images of a coronal mass ejection on 6 November 1997



A time sequence of *Solar Maximum Mission* coronagraph images showing a CME on August 18, 1980 (from Hundhausen (1999))

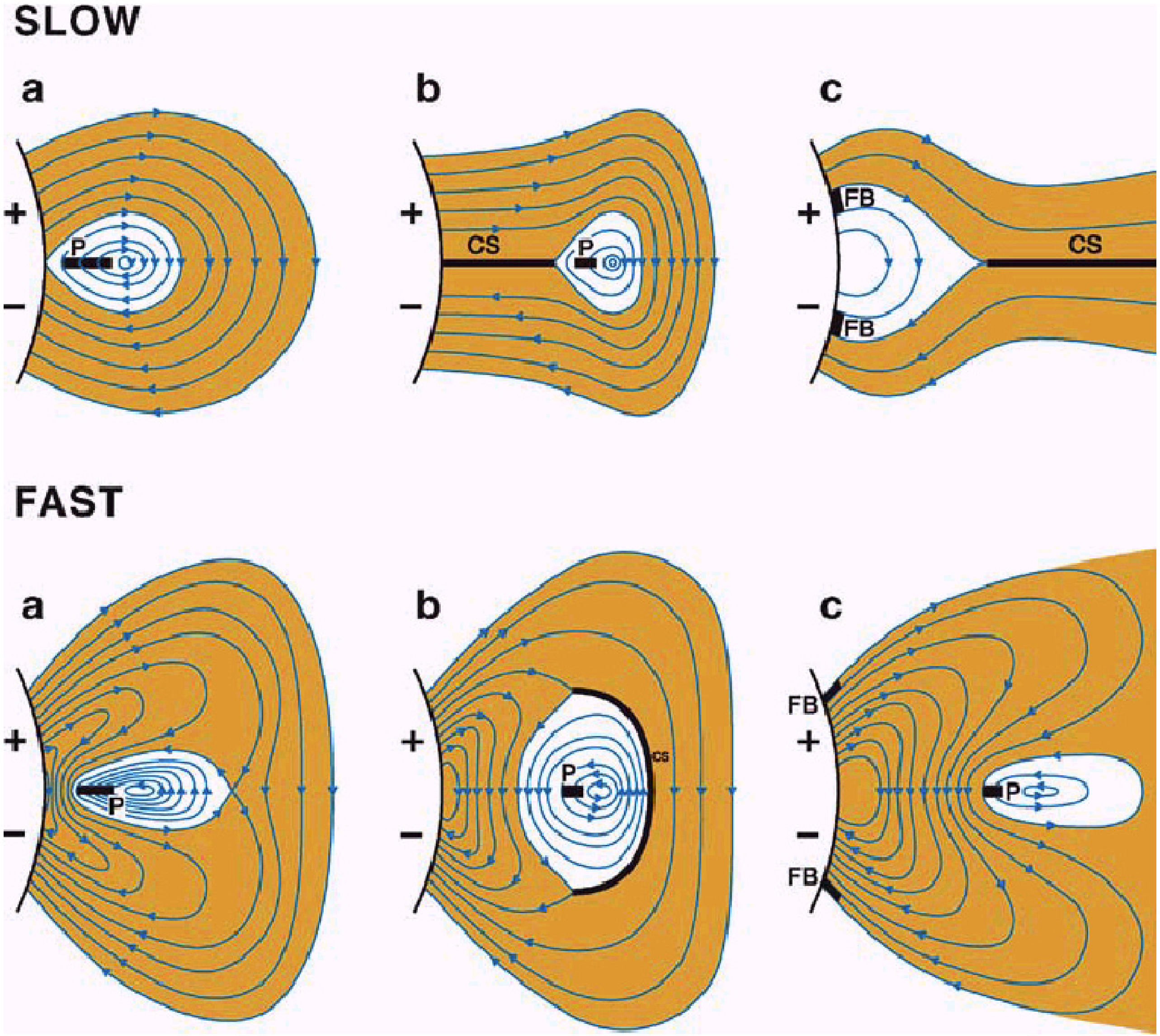




Field lines showing magnetic configurations in a numerical simulation, from Amari et al. (2003a)

Coronal mass ejections *(*a) pre-eruption, *(b* and c) eruption, and *(d*) post-eruption states depicted by the mass-loading model, from Low (2001)

Magnetic energy is built up by twisting foot points of initial bipolar potential field (a). After this building (b), twisting is stopped, field is allowed to relax to force-free equilibrium. Flux ropes may form (c) either by imposing further foot-point converging motions of the bipolar field or by imposing a slow diffusion of the normal field at the boundary. Eruption may occur: by flux cancellation at the boundary, by further imposing foot-point converging motions, or by imposing the diffusion of the boundary normal field beyond a certain threshold; the rising flux rope resembles a three-part CME (d).



Evolution of magnetic configurations for the slow *(top panels)* and fast *(bottom panels)* coronal mass ejections cases (from Low & Zhang 2002). During the eruption, the dissipation of the current sheet (CS) produces foot-point brightenings (FB) in newly reconnected fields as the prominence (P) travels out with the ejected magnetic flux rope.

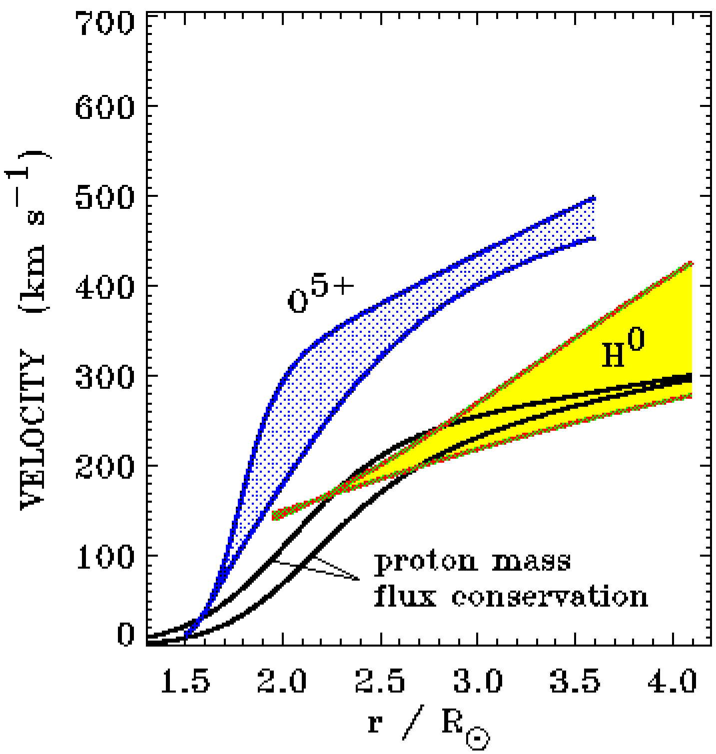
Quiescent events

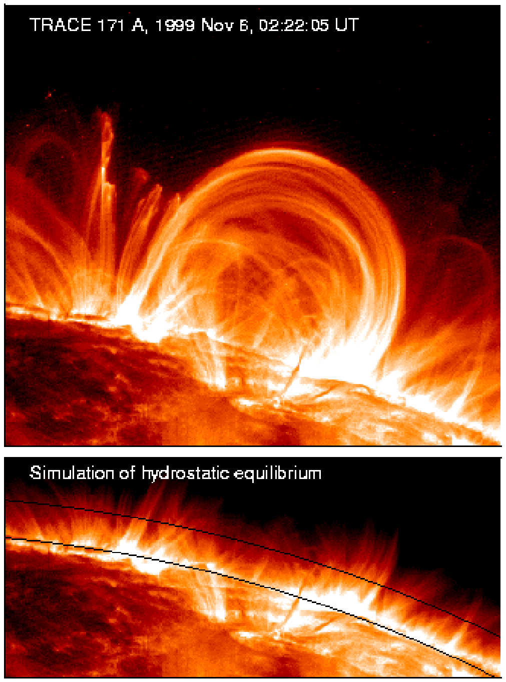
(Fast and slow SW, quasi-static loops, polar and transient CH-s, spicules)

Quasi-steady Solar Wind

Different dynamical behavior of constituting species

Outflow velocities:





Fine structure of Solar Atmosphere:

Quiescent solar coronal loops over active regions - co-existed varying scale different temperature closed field structures (Aschwanden, Schrijver & Alexander (2000)).

Corona - Observations - Inferences

- **The solar corona – a highly dynamic arena replete with multi-species multiple–scale spatiotemporal structures**.

- Magnetic field was always known to be a controlling player.

- Enters a major new element – discovery that **strong flows are found everywhere in the low atmosphere — in the sub-coronal (chromosphere) as well as in coronal regions**.

- Directed kinetic energy has to find its rightful place in dynamics: **the plasma flows may, in fact, do complement the abilities of the magnetic field in the creation of the amazing richness observed in the coronal structures**.

Challenge – to develop a theory of energy transformations for understanding the quiescent and eruptive/explosive events.

How does the Solar Corona get to be so hot?

The temperature of the solar corona is a million K (100eV) (Grotrian 1939; Edlen 1942) – so much hotter than the photosphere (less than an eV for the Sun and other cool stars. How does it get to be so hot – still an unsolved problem!

Models galore – never a lack of suggestions – **the problem is how to prove or disprove a model with the help of observations.** Is it the ohmic or the viscous dissipation? or is it the shocks or the waves that impart energy to the particles – And do the observations support the "other consequences" of a given model?

– Recently developed notions that formation and heating of coronal structures may be simultaneous and directed flows may be the carriers of energy within a broad uniform physics framework opens a new channel for exploration.

The Solar Wind (SW) – History

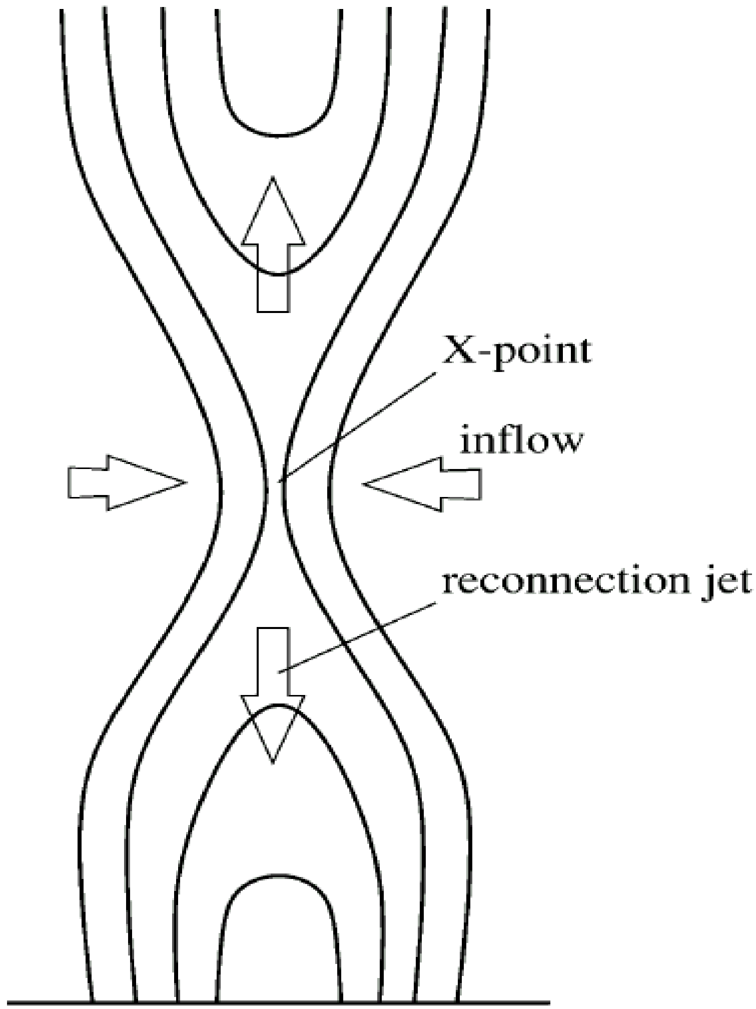
Hydrodynamical expansion of the corona makes the wind.

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.

Rescue: **additional energy sources for accelerating the wind to observed velocities**. Birth of a new acceleration industry. Myriad mechanisms

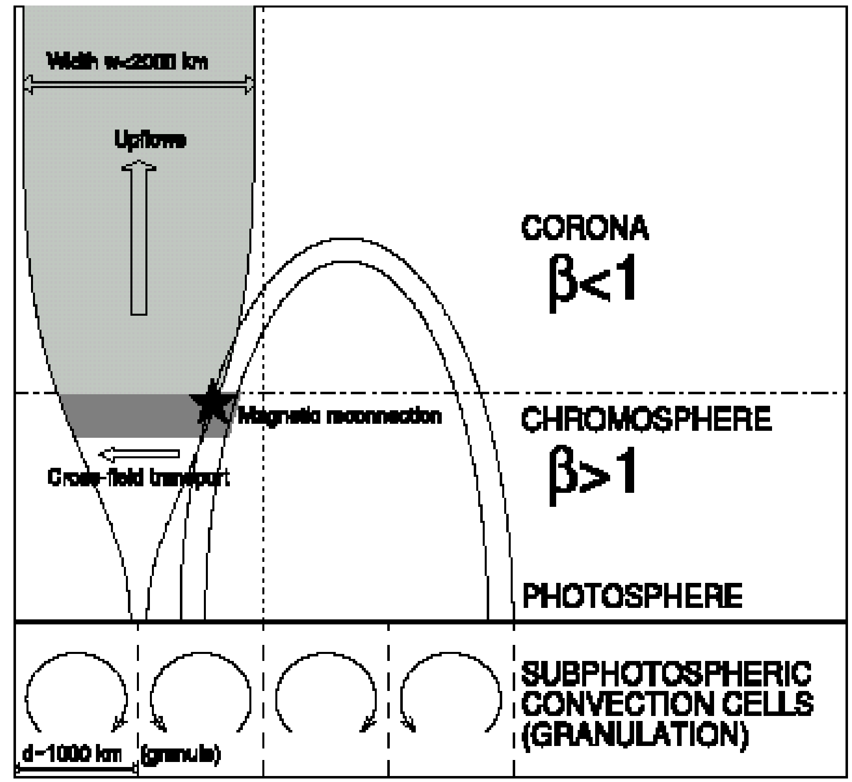
Expansion/acceleration takes place in the regions called the coronal holes where the magnetic field influence can be neglected. But the wind comes from everywhere – How so? How do the charge particles beat the closed line magnetic fields?

Reconnection – A digression



Schematic illustration of the reconnection model of a solar flare for the simplest bipole case.

Thick solid lines show the magnetic field. Arrows indicate the plasma bulk flow.



Sketch of a theoretical model that explains the thermal homogeneity of coronal loops for widths of ≤ 2000 km, based on the magnetic field expansion from intergranular photospheric locations.

The heated plasma is uniformly spread over the entire loop cross section at a height where the plasma parameter exceeds the value of unity - in the upper chromosphere / lower transition region.

A sample of models

Magnetic reconnection and microflares $\Longrightarrow$ 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 can produce Spicules.

Cascade of shock wave interactions in TR may lead to acceleration. Here are typical observational constraints on the theory:

- **Acceleration must be completed very near the Solar surface.**
- Large anisotropy in the electron and proton temperatures – the real mechanism must preferentially heat ions.

Present State of Art:

Energy transport and particle channeling mechanisms in the stellar atmosphere are connected to the challenging problems of coronal heating and stellar wind origin.
Neither the SW "acceleration" nor the numerous eruptive events in the stellar atmosphere can be treated as isolated and independent problems; they must be solved simultaneously along with other phenomena like the plasma heating (may take place in different stages). Any particular mechanism may be dominant in a specific region of parameter space.

For the solar wind there is another serious problem. What is the source of matter and energy – the corona or the sub coronal regions (chromosphere, photosphere, more directly from the sun).

Growing consensus: the same mechanism that transports mechanical energy from convection zone to chromosphere to sustain its heating rate also supplies the energy to heat corona and accelerate SW.

Towards a General Unifying Model:

Need for a theory for general global dynamics that operates in a given region of solar atmosphere.

In addition to the magnetic field, the plasma flows are also accorded a place of honour. Both of these have origins in the sub-atmospheric region and will jointly participate in the creation of a rich variety of coronal structures..

The magneto-fluid equations should cover 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.

Conjecture: the formation and primary heating of the coronal structures as well as the more violent events (flares, erupting prominences and CMEs) are the expressions of different aspects of the same general global dynamics that operates in a given coronal region.

The plasma flows, the source of both the particles and energy (part of which is converted to heat), interacting with the magnetic field, become dynamic determinants of a wide variety of plasma states $\Longrightarrow$ the immense diversity of the observed coronal structures.

Magneto-fluid Coupling

$\mathbf{V}$ — the flow velocity field of the plasma
Total current $\mathbf{j} = \mathbf{j}_0 + \mathbf{j}_s$. $\mathbf{j}_s$ – self-current (generates $\mathbf{B}_s$).
Total (observed) magnetic field — $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_s$.

The stellar atmosphere is finely structured.
Multi-species, multi-scales. Simplest – two-fluid approach.
Quasineutrality condition: $n_e \simeq n_i = n$
The kinetic pressure: $p = p_i + p_e \simeq 2\,nT$, $T = T_i \simeq T_e$.

Electron and proton flow velocities are different.

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

Nondissipative limit: electrons frozen in electron fluid; ion fluid (finite inertia) moves distinctly.
Heating due to the viscous dissipation of the flow vorticity:

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

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

Parameters:
$r_{A0} = GM/V_{A0}^2 R_0 = 2\beta_0\, r_{c0}, \quad \alpha_0 = \lambda_{i0}/R_0, \quad \beta_0 = c_{s0}^2/V_{A0}^2,$
c_{s0} — sound speed $\quad R_0$ — the characteristic scale length,
$\lambda_{i0} = c/\omega_{i0}$ — the collisionless ion skin depth
are defined with $n_0,\ T_0,\ B_0.$

Hall current contributions are significant when
$\alpha_0 > \eta,$ $\qquad$ (η - inverse Lundquist number).
Important in: interstellar medium, turbulence in the early universe, white dwarfs, neutron stars, stellar atmosphere.
Typical solar plasma: condition is easily satisfied.

Construction of a Typical Coronal structure

Solar Corona — $T_c = (1 \div 4) \cdot 10^6\, K \qquad n_c \leq 10^{10}\,\mathrm{cm}^{-3}$.
Standard picture – Corona is first formed and then heated.
3 principal heating mechanisms:

- **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.

New concept: Formation and heating are contempraneous – the primary flows are trapped and a part of their kinetic energy dissipates during their trapping period. It is the Initial and boundary conditions that define the characteristics of a given structure . $T_c \gg T_{0f}\ 1eV$.

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

A coronal structure – 2 distinct eras:

1. **A hectic dynamic period** when it acquires particles and energy **(accumulation + primary heating) – Full description needed: time dependent dissipative two-fluid equations are used.** Heating takes place while particles accumulate (get trapped) in a curved magnetic field.

Simulations show that 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 — a reduced equilibrium description suffices; 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 – Fast dynamic

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

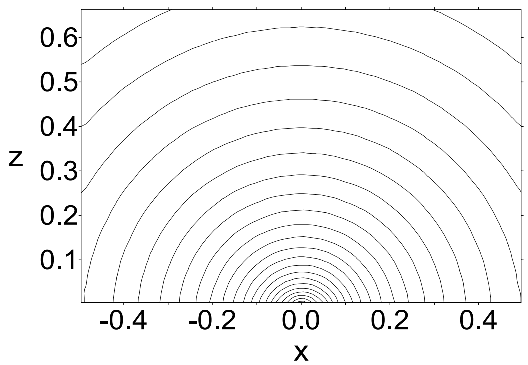
$$t_{\mathrm{visc}} \sim \frac{L^2}{\nu_i}, \tag{2}$$

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 $L = (2 \cdot 10^8 \div 10^{10})\,\mathrm{cm}$, $t_{\mathrm{visc}} \sim (3.5 \cdot 10^8 \div 10^{10})\,\mathrm{s}$.

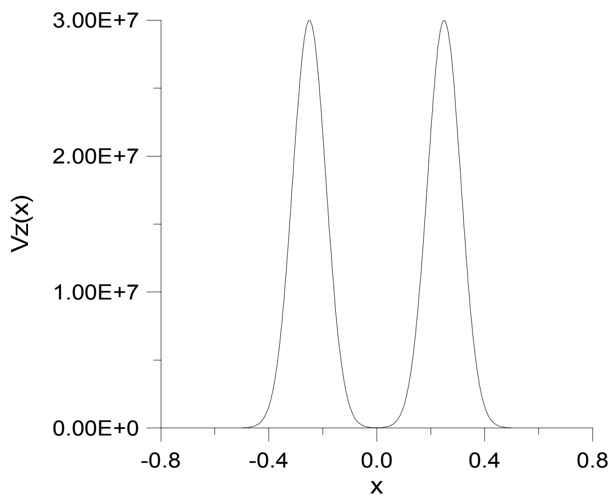
Note: (2) is an overestimate. $t_{\mathrm{real}} \ll t_{\mathrm{visc}}$.

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

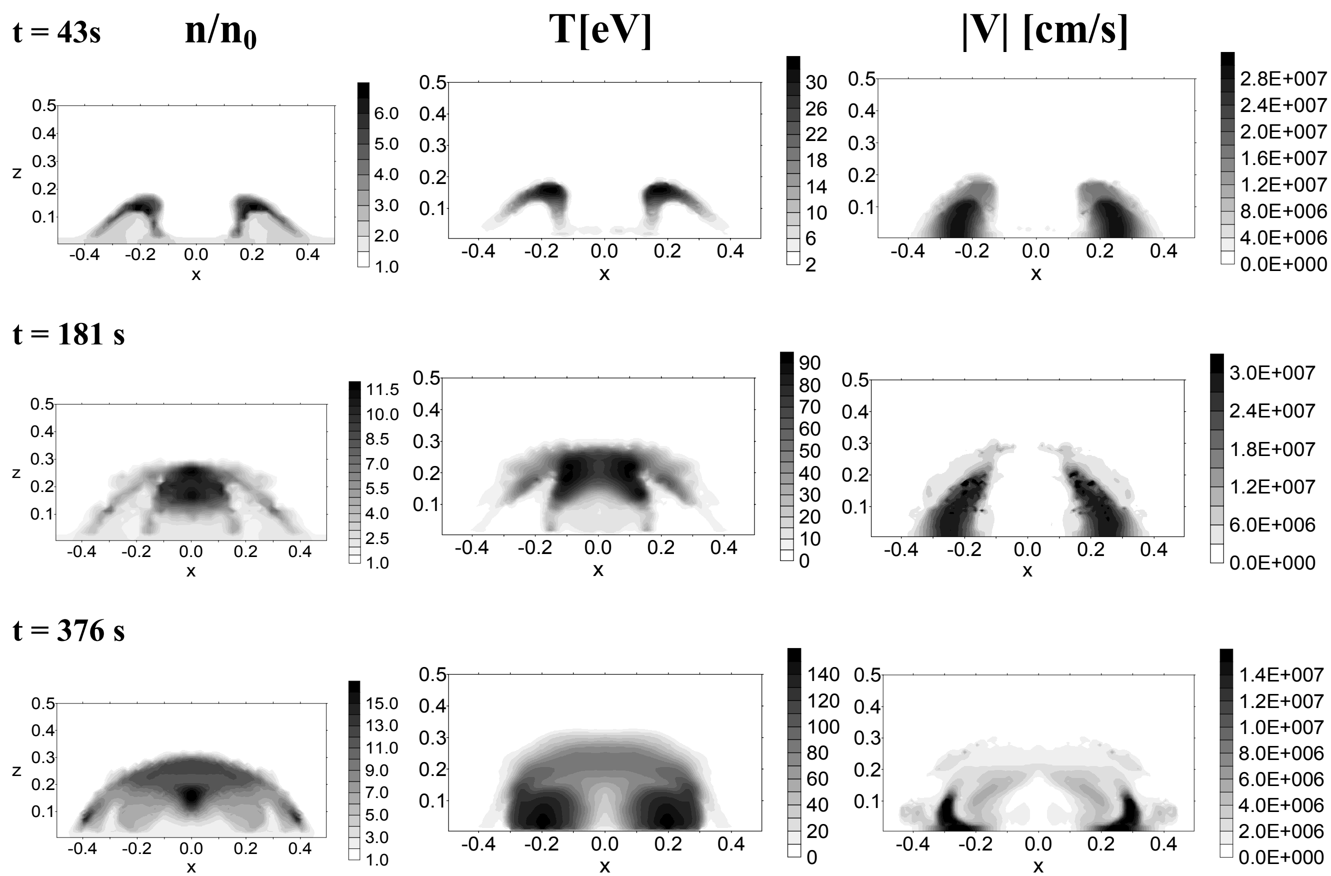
2) the spatial gradients of the $\mathbf{V}$–field can be on a scale much shorter than L (defined by the smooth part of B–field).



Contour plots for the vector potential **A** *(flux function)* in the $x - z$ plane for a typical arcade-like solar magnetic field.



The distribution of the radial component **Vz** (with a maximum of 300 km/s at t=0) for the symmetric, spatially nonuniform velocity field.

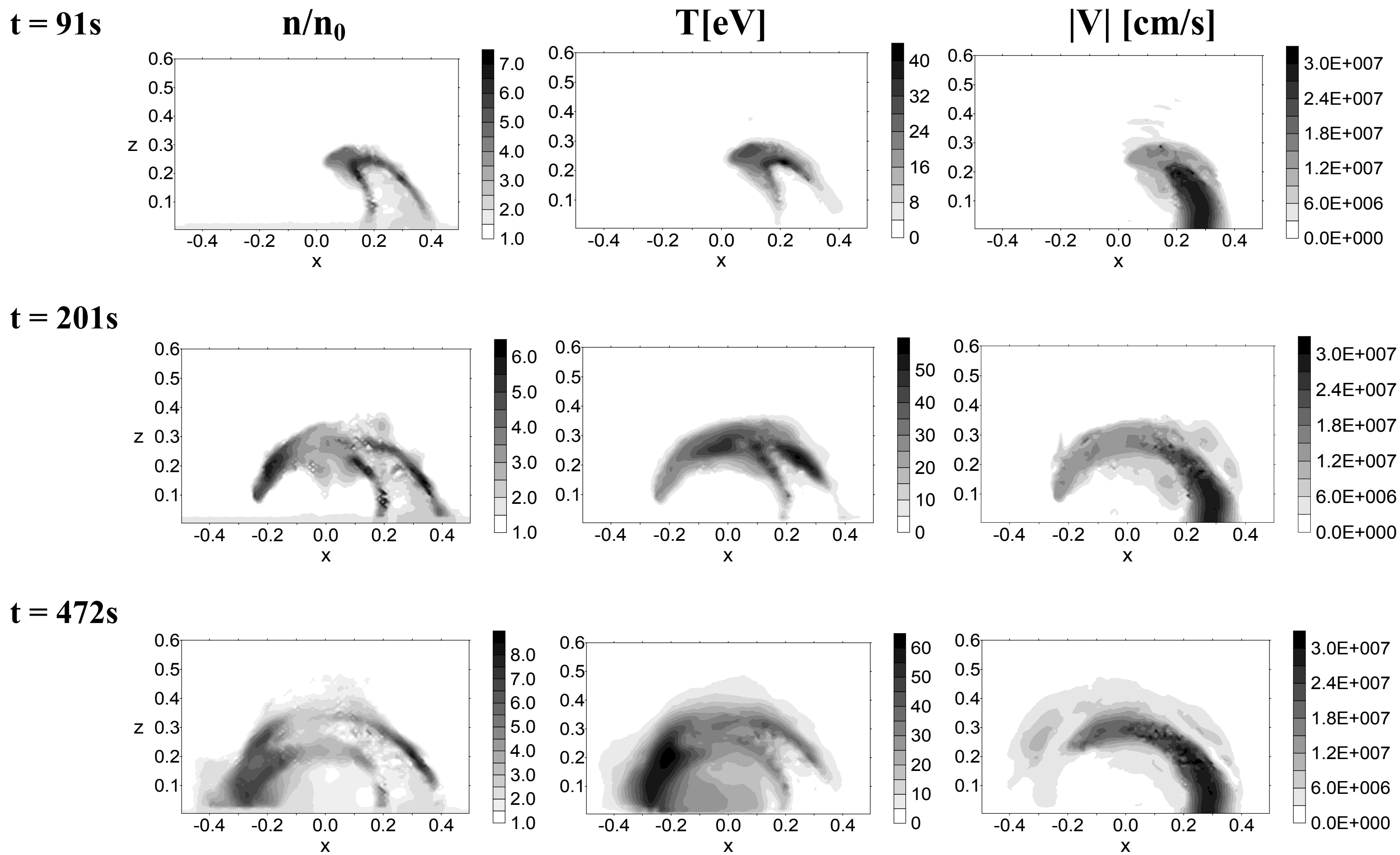


Hot coronal structure formation.

Initial parameters: the flow T_0 =3 eV and n_0 $=4\bullet10^{8}$ cm^{-3} , the initial background density $=2\bullet10^{8}$ cm^{-3} , B_{max} $(x_0 , z_0=0)$=20 G.

The primary heating is completed in ~(2 – 3) min on distances ~10 000 km.

The heating is symmetric and the resulting hot structure is heated to $1.6\bullet10^{6}$ K. Much of the primary flow kinetic energy has been converted to heat via shock generation.



Hot Coronal Structure Creation

The interaction of an initially asymmetric, spatially nonuniform primary flow (just the right pulse) with a strong arcade-like magnetic field B_{max} $(x_0, z_0=0)=20$ G.

Downflows, and the imbalance in primary heating are revealed

2nd Era – Quasi Equilibrium

- The familiar magneto hydrodynamics (MHD) theory (*single fluid*) is inadequate – The fundamental contributions of the velocity field do not come through.

- Equilibrium states (relaxed minimum energy states) encountered in MHD do not have enough structural richness.

In a two-fluid description, the velocity field interacting with the magnetic field provides:

- new pressure confining states
- the possibility of heating these equilibrium states by dissipation of short scale kinetic energy.

Let us now construct a simple equilibrium theory.

A Quasi-equilibrium Structure

Model: recently developed magnetofluid theory.

Assumption: at some distance there exist fully ionized and magnetized plasma structures such that the quasi–equilibrium two–fluid model will capture the essential physics of the system.

Simplest two–fluid equilibria: $T = \mathrm{const} \longrightarrow \mathrm{n}^{-1}\nabla \mathrm{p} \rightarrow \mathrm{T}\nabla \ln \mathrm{n}.$
Generalization to homentropic fluid: $p = \mathrm{const}\cdot \mathrm{n}^{\gamma}$ is straightforward.
The **dimensionless equations**:

$$\frac{1}{n}\nabla \times \mathbf{b} \times \mathbf{b} + \nabla \left(\frac{r_{A0}}{r} - \beta_0 \ln\, n - \frac{V^2}{2} \right) + \mathbf{V} \times (\nabla \times \mathbf{V}) = 0, \quad (3)$$

$$\nabla \times \left[\left(\mathbf{V} - \frac{\alpha_0}{n} \nabla \times \mathbf{b} \right) \times \mathbf{b} \right] = 0, \quad (4)$$

$$\nabla \cdot (n\mathbf{V}) = 0, \quad (5)$$

$$\nabla \cdot \mathbf{b} = 0, \quad (6)$$

The system allows the following relaxed state solution

$$\mathbf{b} + \alpha_0 \nabla \times \mathbf{V} = d\ n\ \mathbf{V}, \qquad \mathbf{b} = a\ n\ \left[\mathbf{V} - \frac{\alpha_0}{n} \nabla \times \mathbf{b}\right], \tag{7}$$

augmented by the Bernoulli Condition

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

a **and** d **— dimensionless constants related to ideal invariants: The Magnetic and the Generalized helicities**

$$h_1 = \int (\mathbf{A} \cdot \mathbf{b})\ d^3x, \tag{9}$$

$$h_2 = \int (\mathbf{A} + \mathbf{V}) \cdot (\mathbf{b} + \nabla \times \mathbf{V}) d^3x.. \tag{10}$$

The system is obtained by minimizing the energy $E = \int (\mathbf{b} \cdot \mathbf{b} + n\mathbf{V} \cdot \mathbf{V})\ d^3x$ **keeping** h_1 **and** h_2 **invariant.**

Equations (7) 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 (8) for n and $\mathbf{V}$.
Equation (8) is solved to obtain $(g(r)=r_{c0}/r)$

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

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.

Model calculation – temperature varying but density constant ($n=1$); The following still holds (where $\mathbf{Q}$ is either $\mathbf{V}$ or $\mathbf{b}$):

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

Curl Curl Equation – Double-Beltrami states

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

$$(\alpha_0 \nabla \times -\lambda)(\alpha_0 \nabla \times -\mu)\mathbf{b} = 0 \tag{14}$$

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

$$\alpha_0 \lambda_\pm = -\frac{p}{2} \pm \sqrt{\frac{p^2}{4} - q}. \tag{15}$$

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

$$\nabla \times \mathbf{G}(\lambda) = \lambda \mathbf{G}(\lambda), \qquad then \tag{16}$$

$$\mathbf{b} = a_\lambda \mathbf{G}(\lambda) + a_\mu \mathbf{G}(\mu), \tag{17}$$

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

$$\mathbf{V} = \frac{\mathbf{b}}{a} + \alpha_0 \boldsymbol{\nabla} \times \mathbf{b} = \left(\frac{1}{a} + \alpha_0 \lambda\right) a_\lambda \mathbf{G}(\lambda) + \left(\frac{1}{a} + \alpha_0 \mu\right) a_\mu \mathbf{G}(\mu). \tag{18}$$

Double *curl* equation is fully solved in terms of the solutions of Eq. (21).

Double Beltrami States

- There are two scales in equilibrium unlike the standard case.
- A possible clue for answering the extremely important question: why do the coronal structures have a variety of length scales, and what are the determinants of these scales?
- The scales could be vastly separated – are determined by the constants of the motion – the original preparation of the system. These constants also determine the relative kinetic & magnetic energy in quasi-equilibrium.
- The scales could be a complex conjugate pair – the fields will be obtained by an appropriate real combination – change in the topological character of the flow and magnetic fields.
- The short scale is a result of a singular perturbation on the standard MHD system – introduces classes of states inaccessible to MHD.
- It is all a consequence of treating flows and magnetic field co-equally.
- These vastly richer structures can and do model the quiescent solar phenomena rather well – construction of coronal arcades fields, slow acceleration, spatial rearrangement of energy etc.

An Example of structural richness

In a coronal structure, the magnetic field is relatively smooth but the velocity field must have a considerable short – scale component if its dissipation were to heat the plasma. Can a Double Beltrami state provide that?

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

$$\mathbf{V} = \frac{1}{a}\, a_\lambda \mathbf{G}_\lambda + d a_\mu \mathbf{G}(\mu) \tag{19}$$

$$\mathbf{b} = a_\lambda \mathbf{G}_\lambda + a_\mu \mathbf{G}(\mu) \tag{20}$$

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

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

$$\frac{|\mathbf{V}(\mu)|}{|\mathbf{V}(\lambda)|} \simeq 1; \tag{21}$$

the velocity field is equally divided between slow and fast scales.

Acceleration of Plasma Flows

The most obvious process for acceleration (rotation is ignored):

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

to plasma kinetic energy.

Magnetically driven transient but **sudden** flow–generation models:

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

Quiescent pathway:

- *Bernoulli mechanism converting thermal energy into kinetic*
- General magnetofluid rearrangement of a relatively constant kinetic energy: going from an initial high density–low velocity to a low density–high velocity state.

Eruptive and Explosive events, Flaring

What happens when the parameters of the DB field change? Assume

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

Can such a slowly evolving structure suffer a catastrophic loss of equilibrium? The General equilibrium solution was shown to be

$$\boldsymbol{b} = C_\mu \boldsymbol{G}_\mu(\mu) + C_\lambda \boldsymbol{G}_\lambda(\lambda), \tag{22}$$

$$\boldsymbol{V} = \left(\frac{1}{a} + \mu\right) C_\mu \boldsymbol{G}_\mu(\mu) + C_\lambda \left(\frac{1}{a} + \lambda\right) \boldsymbol{G}_\lambda(\lambda). \tag{23}$$

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.
2. Amplitude of either of the 2 states ($C_{\mu/\nu}$) ceases to be real.

The three invariants h_1, h_2 and E (quantum nmbers) provide three relations connecting 4 parameters $\lambda, \mu, C_\lambda, C_\mu$ that characterize the DB field.

Large scale λ – control parameter — observationally motivated choice.

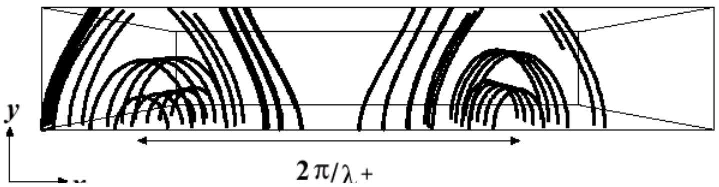
Study the structure–structure interactions working with simple 2D Beltrami ABC field with periodic boundary conditions.

Choose real λ, μ for quasi–equilibrium structures in atmospheres.

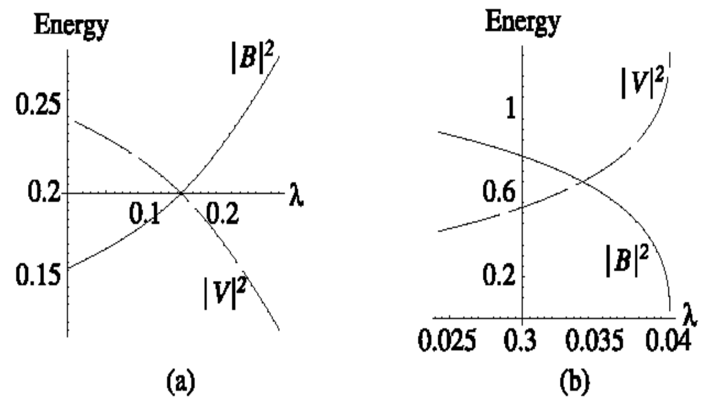
There are two scenarios of losing equiliubrium:
(1) Either of $(C_{\mu/\nu})^2$ becomes zero (starting from positive values) for real $\lambda_{\mu/\nu}$,
(2) The roots $\lambda_{\mu/\nu}$ coalesce ($\lambda_\mu \leftrightarrow \lambda_\nu$) for real $\lambda_{\mu/\nu}$ and $C_{\mu/\nu}$.

Solar atmosphere: equilibria with vastly separated scales (for a variety of sub–alfvénic flows). (2) possibility is not of much relevance.

Flow Acceleration (n=const)

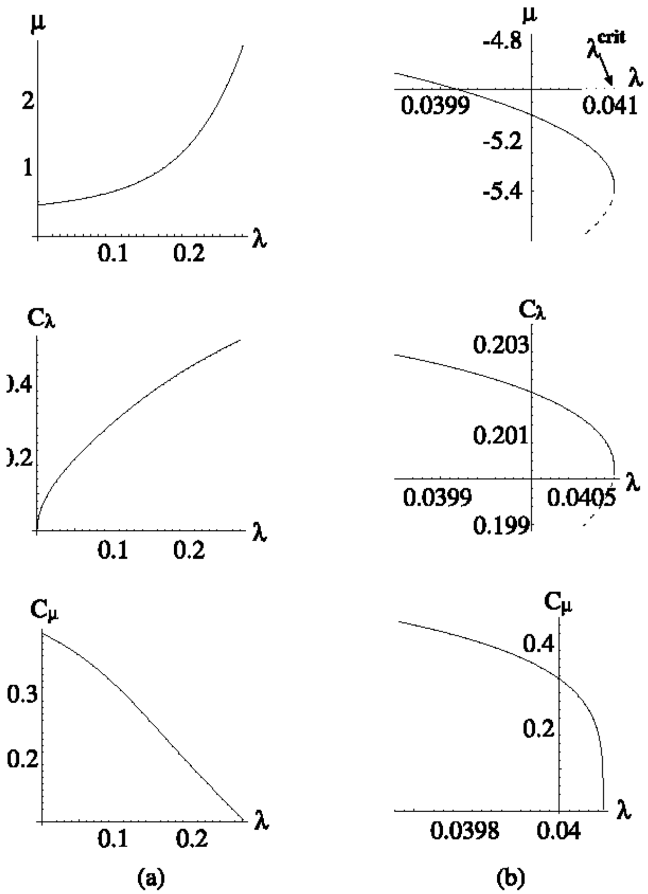


2D Beltrami ABS Field with periodic boundary conditions

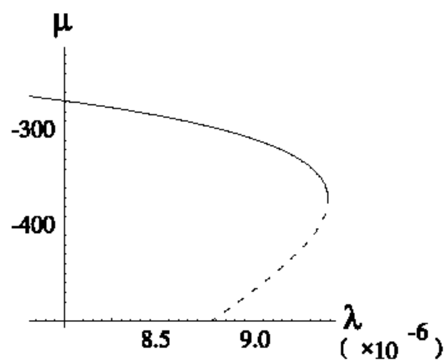


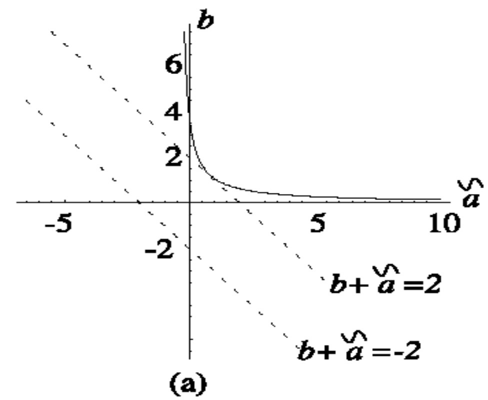
a) No catastrophe initial conditions

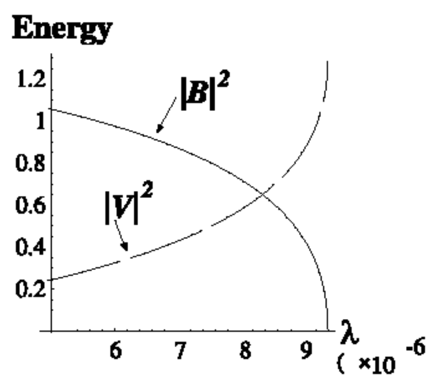
b) Catastrophe initial conditions

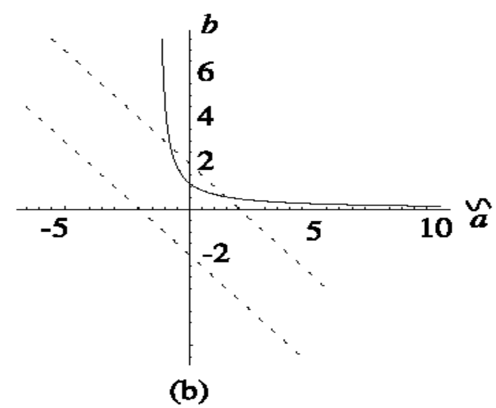


a) No catastrophe initial conditions
b) Catastrophe initial conditions









Solar Atmosphere:
Almost all initial magnetic energy (short scale) is transferred to flow

Root coalescence:
No separation between roots at the transition!

Summary of Results

- Conditions for catastrophic changes in Slowly evolving solar structures (sequence of DB magnetofiuid states) leading to a fundamental transformation of the initial state, are derived.

- **For $E > E_c = 2\left(h_1 \pm \sqrt{h_1 h_2}\right)$, the DB equilibrium suddenly relaxes to a single Beltrami state corresponding to the large macroscopic size.**

- **All of the short–scale magnetic energy is catastrophically transformed to the flow kinetic energy. Seeds of destruction lie in the conditions of birth**

- **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

Variational Principle $\Longrightarrow$ One can deal with any case:
constant density, constant temperature, or a given equation of state.

Closed system (3), (7),(8) with $g(r) = r_{c0}/r \quad \Longrightarrow$

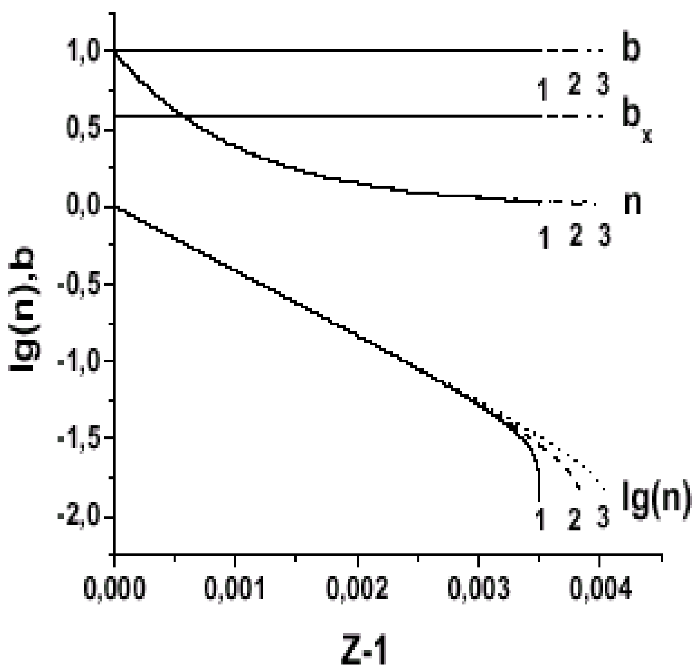
$$\frac{\alpha_0^2}{n}\nabla \times \nabla \times \mathbf{V} + \alpha_0 \nabla \times \left[\left(\frac{1}{a\,n} - d\right) n\,\mathbf{V}\right] + \left(1 - \frac{d}{a}\right)\mathbf{V} = 0, \quad (24)$$

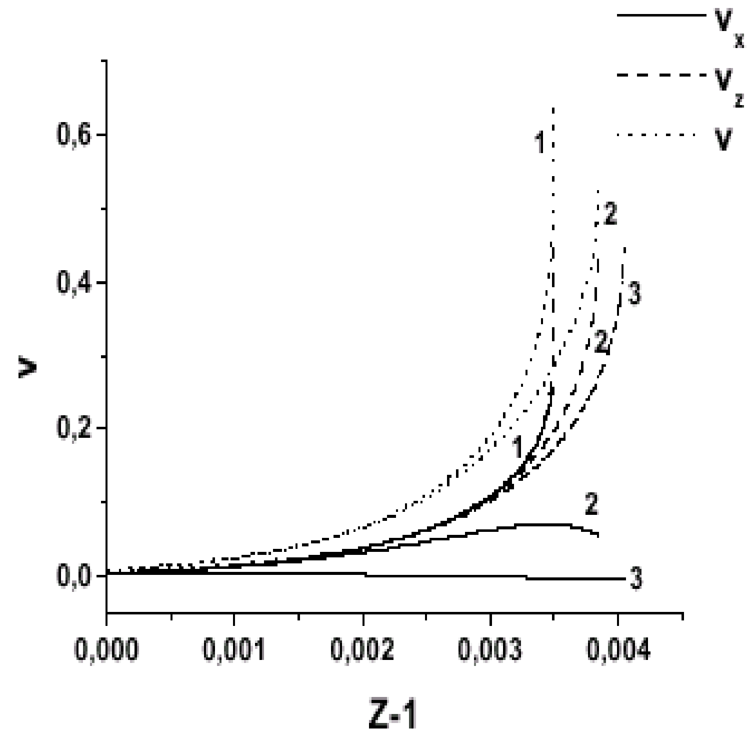
$$\alpha_0^2 \nabla \times \left(\frac{1}{n}\nabla \times \mathbf{b}\right) + \alpha_0 \nabla \times \left[\left(\frac{1}{a\,n} - d\right)\mathbf{b}\right] + \left(1 - \frac{d}{a}\right)\mathbf{b} = 0. \quad (25)$$

$$n = \exp\left(-\left[2g_0 - \frac{V_0^2}{2\beta_0} - 2g + \frac{V^2}{2\beta_0}\right]\right), \quad (26)$$

Caution: this time–independent set is not suitable for studying **primary heating** processes at lower heights (Mahajan et al. PoP 2001).

Flow Acceleration (n≠const) 1D





Sub-Alfvénic flows: Boundary conditions at:

$Z_0>(1+2.8\bullet10^{-3})R_s$ – the influence of ionization can be neglected

$|b_0| = 1$, $V_0= 0.01V_{A0}$ (with $V_{x0} =V_{yo} =V_{z0}$)

DB parameters:

d ~a ~100, $(a- d)/a^2$ ~10^{-6}

3 sets of curves labeled by α_0 for parameters versus height (Z- 1).

1- 2- 3 correspond to: α_0 = 0.000013; 0.005; 0.1

(a) (b)

Following are the (n_0 ; B_0 ; T_0 ; V_{A0}):

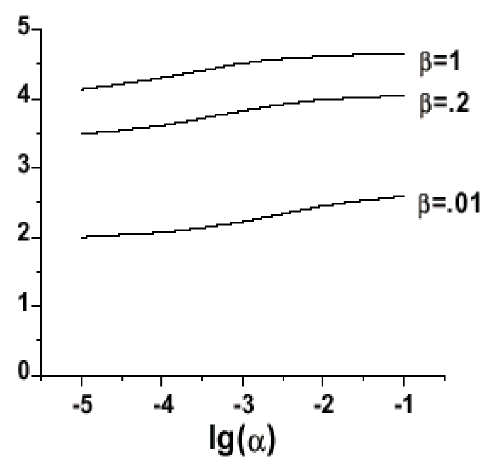
$10^{11}cm^{-3}$; 100G; 5eV; 600km/s; β_0~0.007<<1

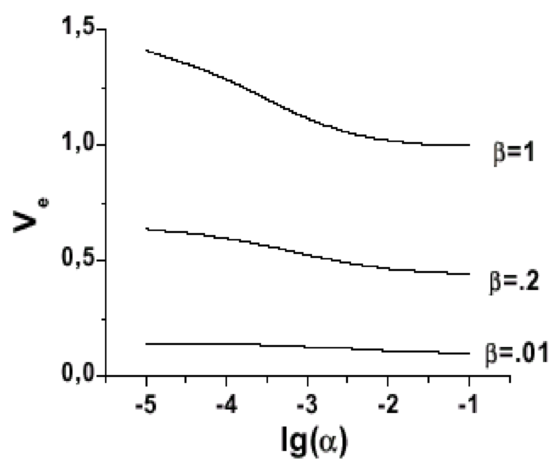
$|b|^2$~const; Density fall → Velocity increase

(a) Blowup distance

(b) velocity

vs.. α_0





Catastrophe!

Acceleration is determined by local β_0

Where do the flows come from?

The Dynamo mechanism is the generic process of generating macroscopic magnetic fields from an initially turbulent system. It is biggest industry in plasma astrophysics; is highly investigated in a variety of fusion devices.

Standard Dynamo – generation of macroscopic fields from (primarily microscopic) velocity fields. The relaxations observed in the reverse field pinches is a vivid illustration of the Dynamo in action. The Myriad phenomena in stellar atmospheres (heating, field opening, wind) impossible to explain without knowing the origin/nature of magnetic field structures. **In the so called kinematic dynamo, the velocity field is externally specified and is not a dynamical variable**. **In "higher" theories – MHD, Hall MHD, two fluid etc, the velocity field evolves just as the mag. field does – the fields are in mutual interaction**.

Short-scale turbulence → macroscopic magnetic fields. Will turbulence, under appropriate conditions => macroscopic plasma flows?

Reverse Dynamo – Flow generation

If the process of conversion of short–scale kinetic energy to long–scale magnetic energy is termed "dynamo" (D) then the mirror image process of the conversion of short–scale magnetic energy to long–scale kinetic energy could be called "Reverse dynamo" (RD).

Extending the definitions:

- **Dynamo(D) process** - Generation of macroscopic magnetic field from any mix of short–scale energy (magnetic and kinetic).
- **Reverse Dynamo(RD) process** - Generation of macroscopic flow from any mix of short–scale energy (magnetic and kinetic).

Theory and simulation show

(1) D and RD processes operate simultaneously — whenever a large scale magnetic field is generated there is a concomitant generation of a long scale plasma flow.

(2) The composition of the turbulent energy determines the ratio of the macroscopic flow/macroscopic magnetic field.

Reverse Dynamo relationship — Theory

Minimal two fluid model – incompressible, constant density HMHD-gravity is ignored

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \Big[[\boldsymbol{V} - \boldsymbol{\nabla} \times \boldsymbol{B}] \times \boldsymbol{B} \Big], \qquad \boldsymbol{V}_e = \boldsymbol{V} - \boldsymbol{\nabla} \times \boldsymbol{B} \tag{27}$$

$$\frac{\partial \boldsymbol{V}}{\partial t} = \boldsymbol{V} \times (\boldsymbol{\nabla} \times \boldsymbol{V}) + (\boldsymbol{\nabla} \times \boldsymbol{B}) \times \boldsymbol{B} - \boldsymbol{\nabla} \left(P + \frac{V^2}{2} \right) \tag{28}$$

The total fields are broken into ambient fields and perturbations

$$\boldsymbol{B} = \boldsymbol{b}_0 + \boldsymbol{H} + \boldsymbol{b}$$

$$\boldsymbol{V} = \boldsymbol{v}_0 + \boldsymbol{U} + \boldsymbol{v}$$

$\boldsymbol{b}_0$, $\boldsymbol{v}_0$ - equilibrium; $\boldsymbol{H}$, $\boldsymbol{U}$ - macroscopic; $\boldsymbol{b}$, $\boldsymbol{v}$ - microscopic fields.

Equilibrium fields are taken to be the DB pair

obeying Bernoulli condition $\boldsymbol{\nabla}(p_0 + \boldsymbol{v}_0{}^2/2) = const$

$$\frac{\boldsymbol{b}_0}{a} + \boldsymbol{\nabla} \times \boldsymbol{b}_0 = \boldsymbol{v}_0, \quad \boldsymbol{b}_0 + \boldsymbol{\nabla} \times \boldsymbol{v}_0 = d\boldsymbol{v}_0, \tag{29}$$

which may be solved in terms of the SB fields ($\nabla \times \boldsymbol{G}(\mu) = \mu \boldsymbol{G}(\mu)$)

Inverse scale lengths λ, μ are fully determined in terms of a, d (hence, initial helicities). As a, d vary, λ, μ can range from real to complex values of arbitrary magnitude.

Below: λ - micro-scale; μ - macro-scale structures; $|b| \ll b_0, |v| < v_0$ **at the same scale;** $\boldsymbol{v}_{e0} \equiv \boldsymbol{v}_0 - \nabla \times \boldsymbol{b}_0$.

See for the details of closure model of Hall MHD Mininni et al, ApJ, 2003, 2005.

Evolution Equations of the macrofields:

$$\partial_t \boldsymbol{U} = \boldsymbol{U} \times (\nabla \times \boldsymbol{U}) + \nabla \times \boldsymbol{H} \times \boldsymbol{H} + \langle \boldsymbol{v}_0 \times (\nabla \times \boldsymbol{v}) \rangle$$
$$+ \langle \boldsymbol{v} \times (\nabla \times \boldsymbol{v}_0) + (\nabla \times \boldsymbol{b}_0) \times \boldsymbol{b} + (\nabla \times \boldsymbol{b}) \times \boldsymbol{b}_0 \rangle$$
$$- \langle \nabla (\boldsymbol{v}_0 \cdot \boldsymbol{v}) \rangle - \nabla \left(p + \frac{\boldsymbol{U}^2}{2} \right) \tag{30}$$

$$\frac{\partial \boldsymbol{H}}{\partial t} = \nabla \times \langle [\boldsymbol{v}_e \times \boldsymbol{b}_0] + \boldsymbol{v}_{e0} \times \boldsymbol{b} \rangle + \nabla \times [(\boldsymbol{U} - \nabla \times \boldsymbol{H}) \times \boldsymbol{H}] \tag{31}$$

where the blue terms are nonlinear and the ensemble averages of the black terms have to be found after solving for $\boldsymbol{v}$ and $\boldsymbol{b}$.

Equations for the microfields

The evolution of the short scale fields $\boldsymbol{v}$ and $\boldsymbol{b}$ follows:

$$\frac{\partial \boldsymbol{v}}{\partial t} = -(\boldsymbol{U} \cdot \boldsymbol{\nabla})\boldsymbol{v}_0 + (\boldsymbol{H} \cdot \boldsymbol{\nabla})\boldsymbol{b}_0 \tag{32}$$

$$\frac{\partial \boldsymbol{b}}{\partial t} = (\boldsymbol{H} \cdot \boldsymbol{\nabla})\boldsymbol{v}_{e0} - (\boldsymbol{U} \cdot \boldsymbol{\nabla})\boldsymbol{b}_0 \tag{33}$$

Since one can, in principle, solve the above set for $\boldsymbol{v}$ and $\boldsymbol{b}$ in terms of $\boldsymbol{U}$ and $\boldsymbol{H}$, one can go back to (8-9) and have a closed set of equations for the macroscopic fields.

This closure model of the Hall MHD equations is rather general – two essential features :
1) a closure of full set of equations – feedback of the micro-scale is consistently included in the evolution of $\boldsymbol{H}$, $\boldsymbol{U}$
2) role of the Hall current (especially in the dynamics of the micro–scale) is properly accounted.

Short Scale Initial Fields

The model calculation is best done by assuming that the original equilibrium is predominantly short-scale. Thus from the $\boldsymbol{D}$B fields we keep only the λ part. Following relations, then, follow:

$$\boldsymbol{v}_0 = \boldsymbol{b}_0 \left(\lambda + a^{-1}\right) \tag{34}$$

leading to

$$\boldsymbol{v}_{e0} = \boldsymbol{v}_0 - \boldsymbol{\nabla} \times \boldsymbol{b}_0 = \boldsymbol{b}_0 \; a^{-1} \tag{35}$$

yielding the system:

$$\dot{\boldsymbol{b}} = \left(a^{-1}\boldsymbol{H} - \boldsymbol{U}\right) \cdot \boldsymbol{\nabla}\boldsymbol{b}_0 \tag{36}$$

$$\dot{\boldsymbol{v}} = \left(\boldsymbol{H} - \left(\lambda + a^{-1}\right)\boldsymbol{U}\right) \cdot \boldsymbol{\nabla}\boldsymbol{b}_0. \tag{37}$$

Carrying out appropriate averages over the short scale ambient fields (all expressed in terms $\boldsymbol{b}_0$) will give us the time behavior of the macro fields $\boldsymbol{U}$ and $\boldsymbol{H}$.

Spatial averages with isotropic ABC flow yield:

$$\ddot{U} = bN_1 + \frac{\lambda}{2}\frac{b_0^2}{3}\boldsymbol{\nabla} \times \left[\left(\left(\lambda + \frac{1}{a}\right)^2\right)\boldsymbol{U} - \lambda\boldsymbol{H}\right] \tag{38}$$

$$\ddot{H} = bN_2 - \lambda\frac{b_0^2}{3}\left(1 - \frac{\lambda}{a} - \frac{1}{a^2}\right)\boldsymbol{\nabla} \times \boldsymbol{H}. \tag{39}$$

where $\boldsymbol{N}_1$ and $\boldsymbol{N}_2$ are the time derivatives of the nonlinear terms displayed earlier - they will not change on short-scale averaging. b_0^2 **measures the ambient micro scale energy**.

***H* evolves independently of *U* but evolution of *U* does require knowledge of *H*.**

Neglecting the nonlinear terms and writing (52),(53) formally as

$$\ddot{\boldsymbol{H}} = -r(\lambda)(\boldsymbol{\nabla} \times \boldsymbol{H}), \qquad \ddot{\boldsymbol{U}} = \boldsymbol{\nabla} \times [s(\lambda)\boldsymbol{U} + q(\lambda)\boldsymbol{H}], \tag{40}$$

Fourier analyzing we find the **growth rate** at which $\boldsymbol{H}$, $\boldsymbol{U}$ increase,

$$\omega^4 = r^2k^2 \qquad \omega^2 = -|r|(k). \tag{41}$$

The growing Macro-fields are related as

$$\boldsymbol{U} = \frac{q}{(s+r)}\boldsymbol{H}. \tag{42}$$

A Nonlinear Solution in Linear Clothing

The linear solution has a few remarkable features:

Since a choice of a, d (and hence of λ) fixes relative amounts of microscopic energy in ambient fields, it also fixes the relative amount of energy in **the nascent macroscopic fields $\boldsymbol{U}$ and $\boldsymbol{H}$.**

The linear solution makes nonlinear terms strictly zero – it is an exact (a special class) solution of the nonlinear system and thus remains valid even as $\boldsymbol{U}$ and $\boldsymbol{H}$ grow to larger amplitudes.

(This behavior appears again and again in Alfvenic systems: MHD - nonlinear Alfvén wave: Walen 1944,1945; in HMHD - Mahajan & Krishan, MNRAS 2005).

Analytical Results — An Almost straight dynamo

Explicit connections for mix in the ambient turbulence to the mix in the macro fields.:
(i) $a \sim d \gg 1$, inverse micro scale $\lambda \sim a \gg 1 \Longrightarrow \boldsymbol{v}_0 \sim a\, \boldsymbol{b}_0 \gg \boldsymbol{b}_0$, i.e, the ambient micro-scales fields are primarily kinetic. The Generated macro-fields have opposite ordering, $\boldsymbol{U} \sim a^{-1} \boldsymbol{H} \ll \boldsymbol{H}$.

An example of the straight **dynamo mechanism** – super-Alfvénic "turbulent flows" generate magnetic energy far in excess of kinetic energy – super-Alfvénic "turbulent flows" lead to steady flows that are equally sub–Alfvénic.

Important: the dynamo effect must always be accompanied by the generation of macro-scale plasma flows.

This realization can have serious consequences for defining the initial setup for the later dynamics in the stellar atmosphere. The presence of an initial macro-scale velocity field during the flux emergence processes is, for instance, always guaranteed by the mechanism exposed above.

Analytical Results — An Almost Reverse dynamo

(ii) $a \sim d \ll 1$ the inverse micro scale $\lambda \sim a - a^{-1} \gg 1 \Longrightarrow \boldsymbol{v}_0 \sim a\,\boldsymbol{b}_0 \ll \boldsymbol{b}_0$. **The ambient energy is mostly magnetic.** (Photospheres/chromospheres)

Micro-scale magnetically dominant initial system creates macro-scale fields $\boldsymbol{U} \sim a^{-1}\boldsymbol{H} \gg \boldsymbol{H}$ that are kinetically abundant.

From a strongly sub-Alfvénic turbulent flow, the system generates a strongly super-Alfvénic macro–scale flow [**reverse dynamo**].

Initial Dominance of fluctuating/turbulent magnetic field + magneto-fluid coupling = efficient/significant acceleration. Part of the magnetic energy will be transferred to steady plasma flows – a steady super–Alfvénic flow; a macro flow accompanied by a weak magnetic field.
RD → observations: fast flows are found in weak field regions (Woo et al, ApJ, 2004).

D, RD Summary:

- Dynamo and "Reverse Dynamo" mechanisms have the same origin – are manifestation of the magneto-fluid coupling;

- ***U*** and ***H*** are generated simultaneously and proportionately.

  Greater the macro-scale magnetic field (generated locally), greater the macro-scale velocity field (generated locally);

- **Growth rate of macro-fields** is defined by DB parameters (by the ambient magnetic and generalized helicities) and **scales directly with ambient turbulent energy** $\sim b_0^2\ (v_0^2)$.

  Larger the initial turbulent magnetic energy, the stronger the acceleration of the flow.

  Impacts: on the evolution of large-scale magnetic fields and their opening up with respect to fast particle escape from stellar coronae; on the dynamical and continuous kinetic energy supply of plasma flows observed in astrophysical systems.

  Initial and final states have finite heliciies (magnetic and kinetic). The helicity densities are dynamical parameters that evolve self-consistently during the flow acceleration.

A simulation Example for Dynamical Acceleration

2.5D numerical simulation of the general two-fluid equations in Cartesian Geometry.

Code: Mahajan et al. PoP 2001, Mahajan et al, 2005, arXiv: astro-ph/0502345

Simulation system contains:

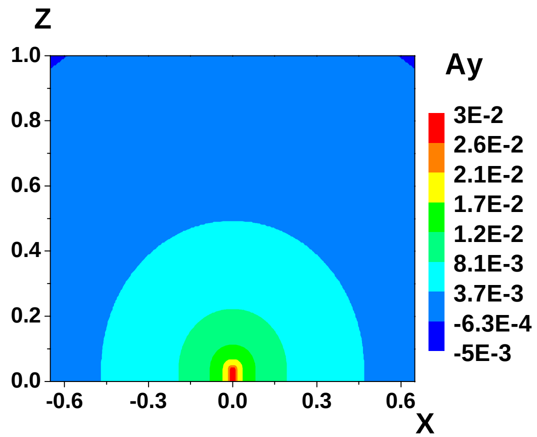
- an ambient macroscopic field
- effects not included in the analysis:
  1. dissipation and heat flux
  2. plasma is compressible embedded in a gravitational field $\rightarrow$ extra possibility for micro-scale structure creation.

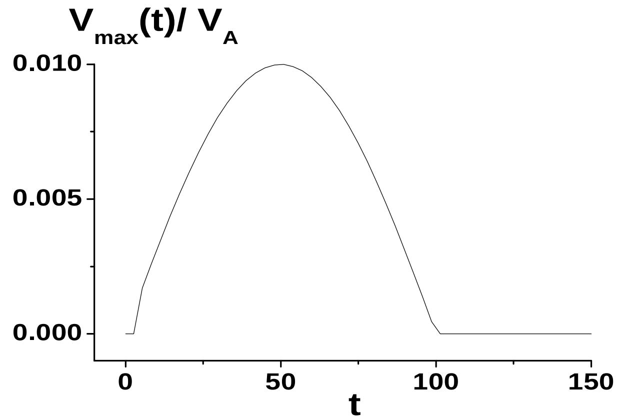
Transport coefficients are taken from Braginskii and are local.

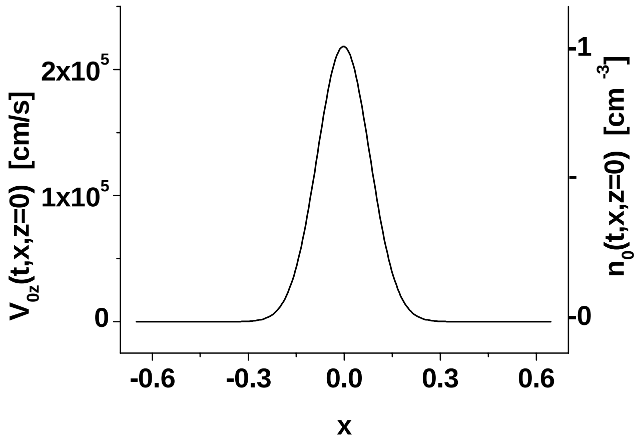
Diffusion time of magnetic field > duration of interaction process (would require $T \leq$ a few eV-s).

Trapping and amplification of a weak flow impinging on a single closed-line structure.

Initial characteristics of magnetic field and flow







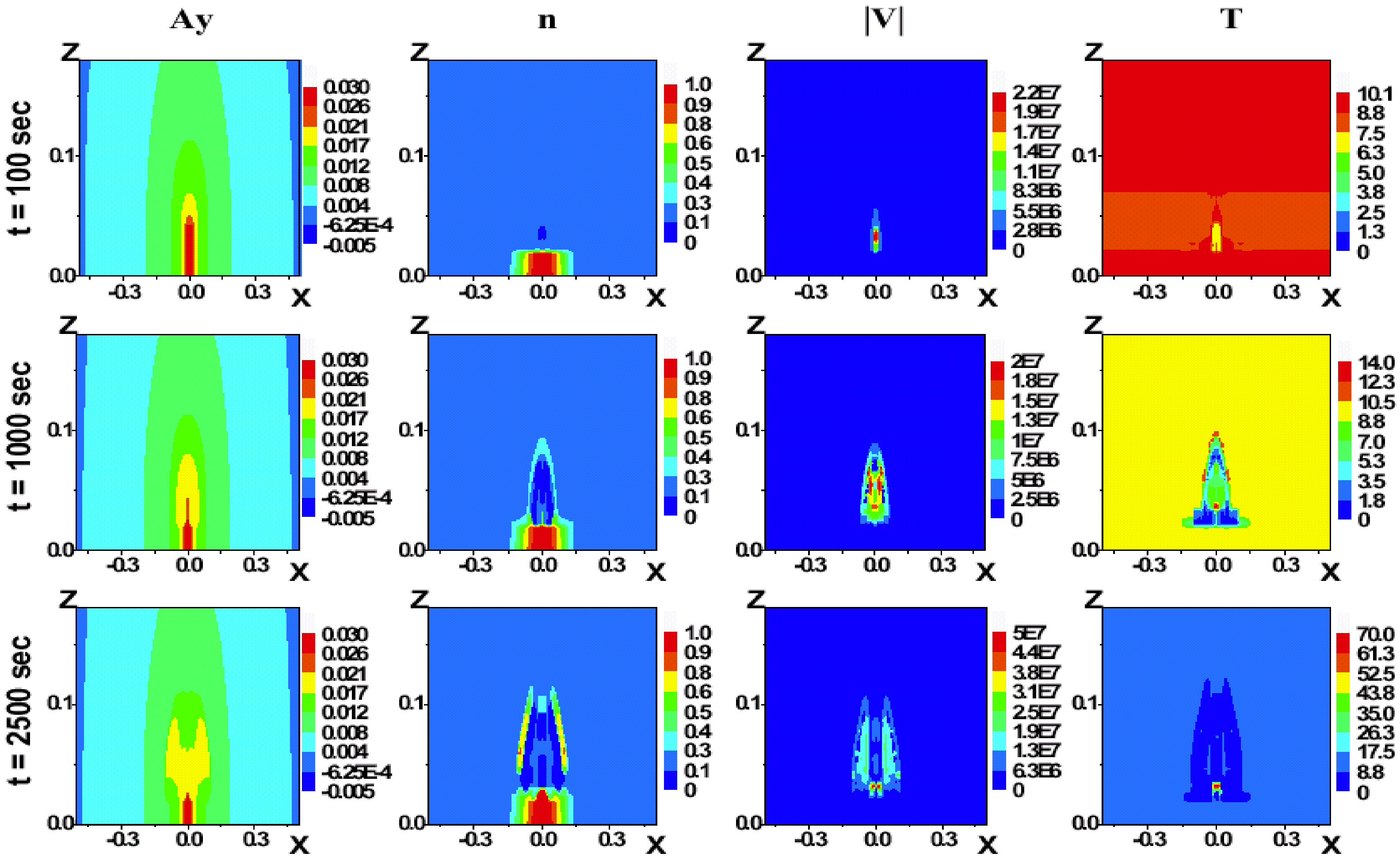
$\mathbf{B} = \nabla \times \mathbf{A} + B_z \hat{\mathbf{z}}$ $\mathbf{A}(0; A_y; 0)$; $\mathbf{b}=\mathbf{B}/B_{0z}$; $b_x(t, x, z \neq 0) \neq 0$ $B_{0z}=100G$ - uniform it time.

Weak symmetric up-flow (pulse-like): $|V|_{0max} << C_{s0}$ C_{s0} - initial sound speed; time duration - $t_0=100s$

Initially Gaussian; peak is located in the central region of a single closed magnetic field structure.

Initial flow parameters: $V_{0max}(x\_o, z=0)=V_{0z}=2.18 \bullet 10^5 cm/s$; $n_{0max}=10^{12} cm^{-3}$; $T(x,z=0)=const=T_0=10, eV$

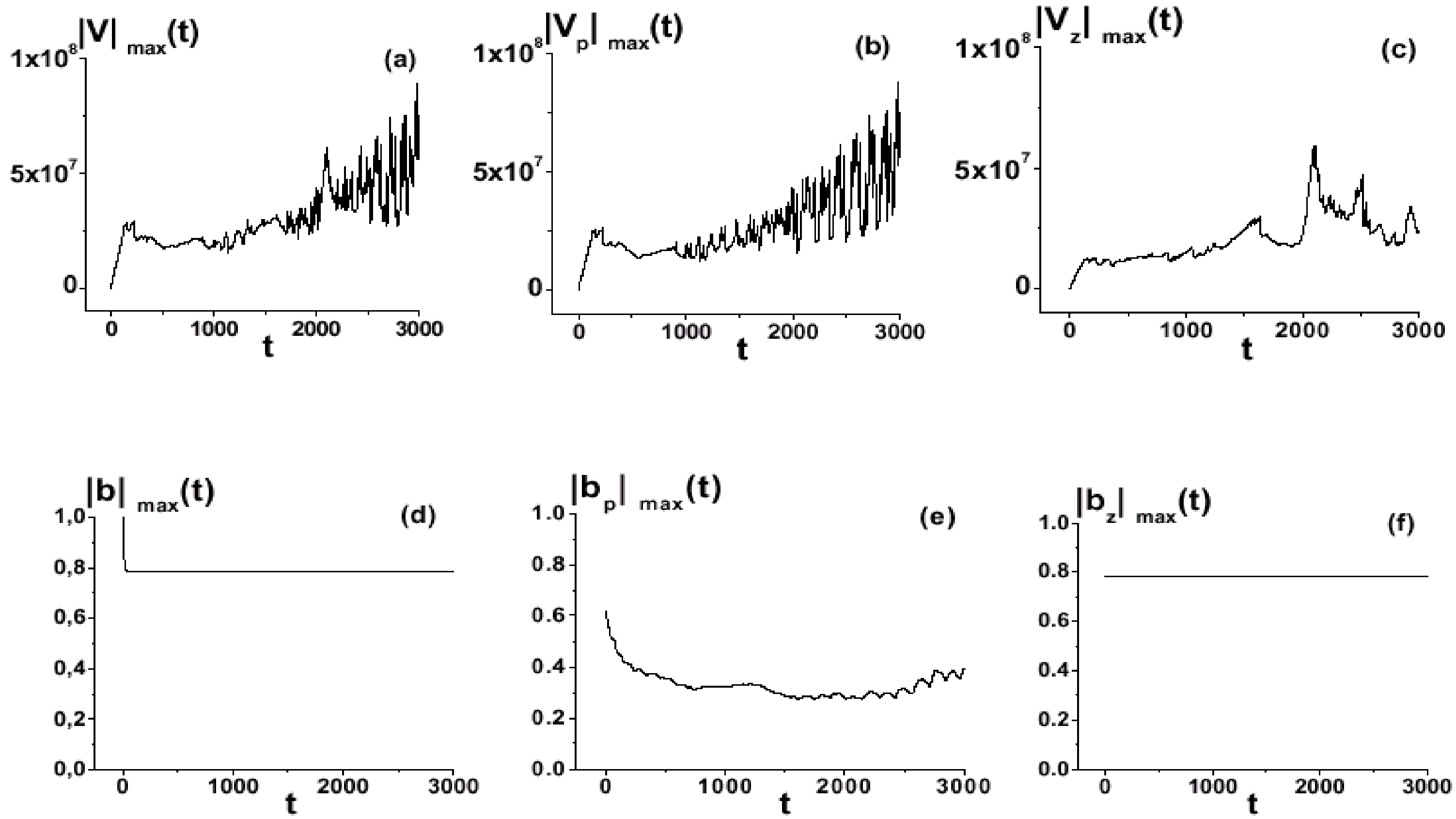
Acceleration of plasma flow due to Magneto-fluid coupling - RD



- **Acceleration is significant in the vicinity of magnetic field-maximum with strong deformation of field lines + energy re-distribution due to MFC+dissipation**
- **A part of flow is trapped in the maximum field localization area, accumulated, cooled and accelerated. The accelerated flow reaches speeds greater than 100km/s in less than 100s**
- **Accelerated flow follows to the maximum magnetic field localization areas - RD**

Then the flow passes through a series of quasi-equilibria. In this relatively extended era ~1000s of stochastic/oscillating acceleration, the intermittent flows continuously acquire energy → bifurcation

Flow starts to accelerate again - acceleration highest in strong field regions (newly generated!)



Initial stage of acceleration: macroscopic magnetic energy → macroscopic flow energy

Second stage of acceleration after the quasi-equilibrium: microscopic magnetic energy is converted to macroscopic flow energy

Simulation Summary:

- Dissipation present: Hall term ($\sim \alpha_0$) (through the mediation of micro-scale physics) plays a crucial role in acceleration/heating processes

- Initial fast acceleration in the region of maximum original magnetic field + the creation of new areas of macro-scale magnetic field localization with simultaneous transfer of the micro-scale magnetic energy to flow kinetic energy = manifestations of the **combined effects of the D and RD phenomena**

- Continuous energy supply from fluctuations (dissipative, Hall, vorticity) $\rightarrow$ maintenance of quasi-steady flows for significant period

- Simulation: **actual h_1, h_2 are dynamical**. Even if they are not in the required range initially, their evolution could bring them in the range where they could satisfy conditions needed to efficiently generate flows $\rightarrow$ **several phases of acceleration**

Summing up:

- A two fluid theory in which the velocity field is treated at par with the magnetic field has the potentials of creating an excellent theory for the structures present and phenomena observed in the solar atmosphere.

- Quasi-steady, fast, and even catastrophic phenomena have an underlying unified description.

- Simple analysis can capture essential and qualitative aspects of both the quiescent and the violent processes. A violent fate of a given structure is underwritten right at its moment of birth.

- Simulations are needed to capture what actually happens near the catastrophe.