Alfvén waves in the solar corona

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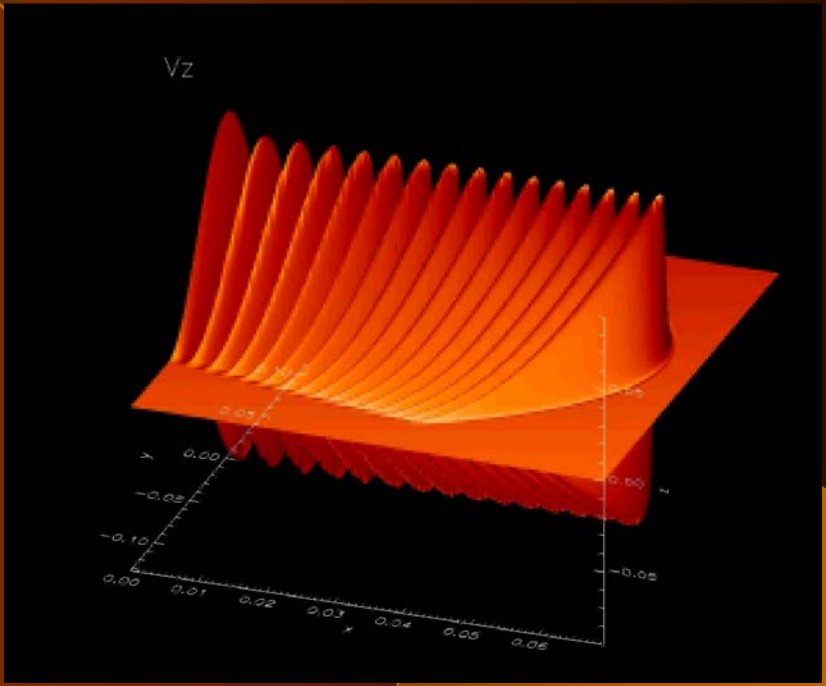


Contents

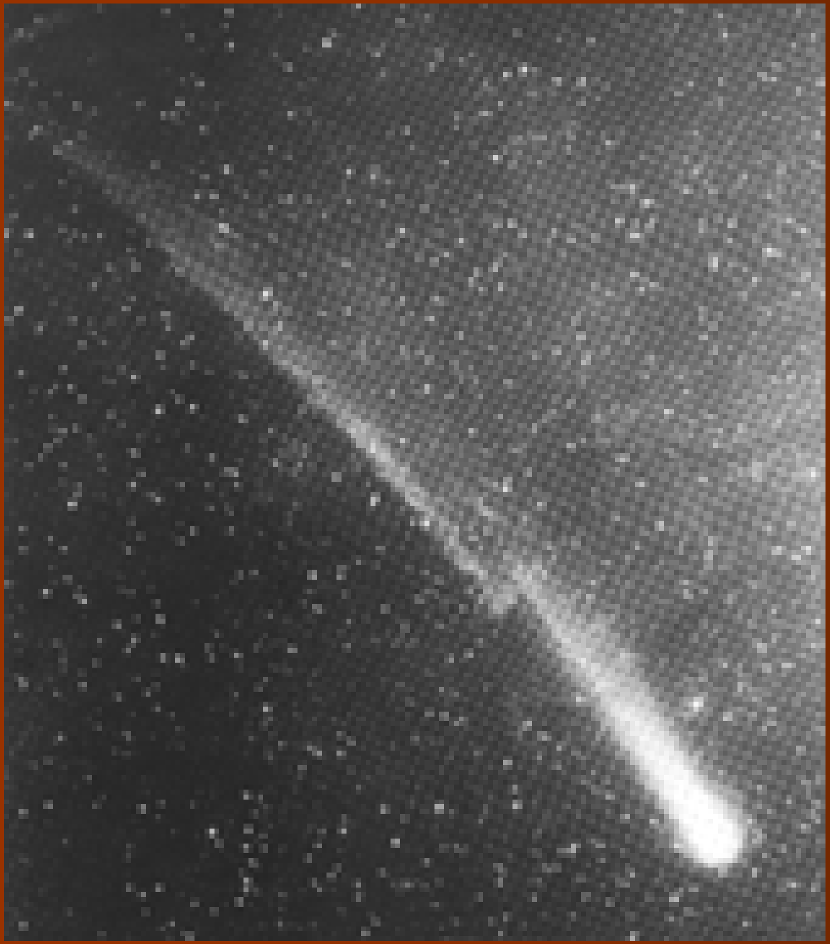
- Overview of my work
- Background
- 1-D simulations
- 2.5-D simulations

My work

- Alfvén waves in coronal holes: 1-D simulations. With *Ulf Torkelsson*
- Alfvén waves in canopy-like topology: 2.5-D simulations. With *Klaus Galsgaard and Ulf Torkelsson*
- Particle accelerations. With *Peter Cargill*, *Loukas Vlahos*, *Klaus Galsgaard*
- History and philosophy of science. Arabic/Islamic Astronomy and the medieval west

- 1731 de Mairan suggested that the aurora was connected to the solar atmosphere

Comet's Tail!



1943 Cuno Hoffmeister
"solar corpuscular radiation"

Chapman Theory

- Static atmosphere.
- Energy transfer by conduction alone.
- Deduced an extended corona to the earth and beyond.

$$4\pi r^2 \kappa \frac{\mathrm{d}T}{\mathrm{d}r} = const$$

$$T = T_0 \left(\frac{R_\circ}{r}\right)^{\frac{2}{7}}$$

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{GM_\circ mn}{r^2}$$

$$p(r) = p_0 \exp\left[\frac{7GM_\circ mn_0}{5p_0R_\circ}\left[\left(\frac{R_\circ}{r}\right)^{\frac{5}{7}} - 1\right]\right]$$

Parker Solution

$$4\pi r^2 \rho v = const,$$

$$\rho v \frac{dv}{dr} = -\frac{dp}{dr} - \frac{GM\rho}{r^2},$$

$$\frac{P}{\rho^\gamma} = K.$$

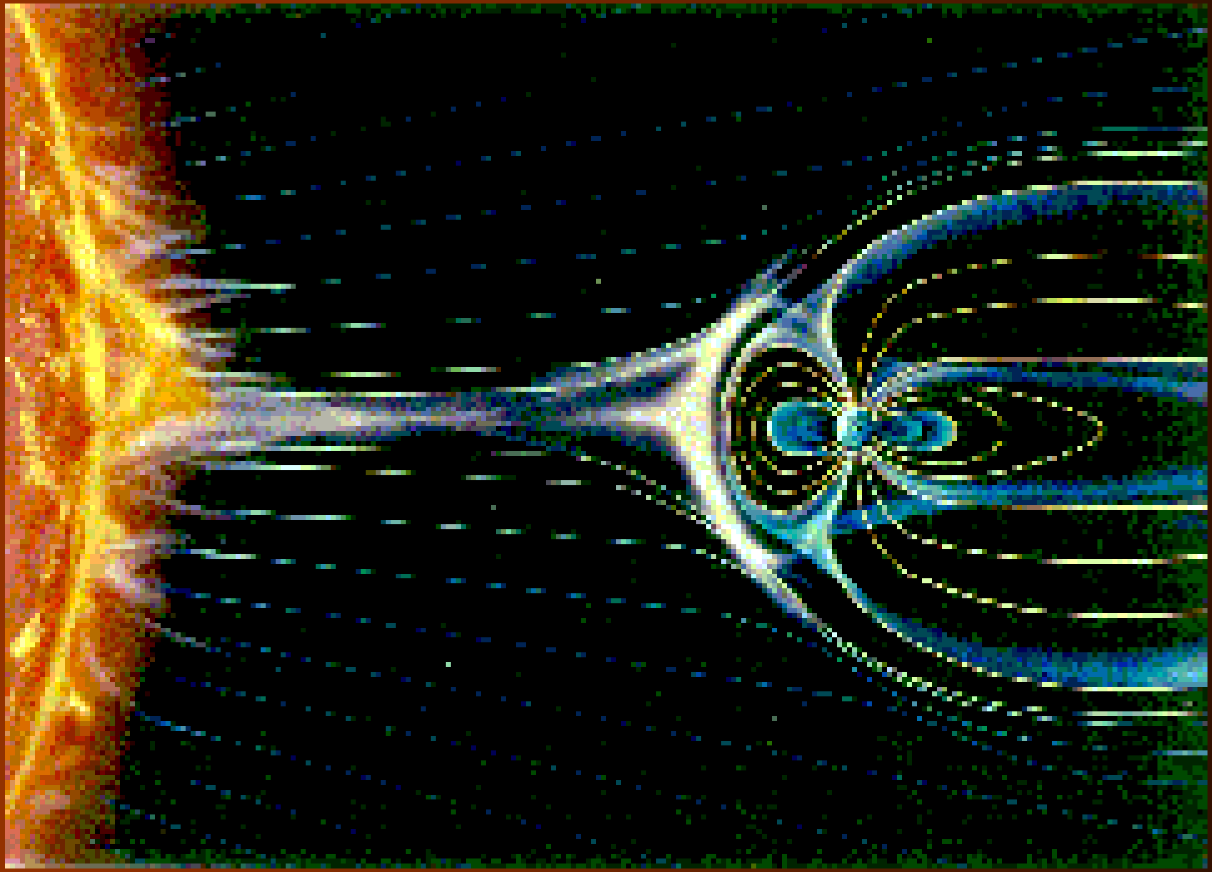
$$p \sim \rho \sim \frac{1}{r^2\sqrt{(\log r)}}$$

- Corona cannot be in static equilibrium, it be continuously expanding outward.

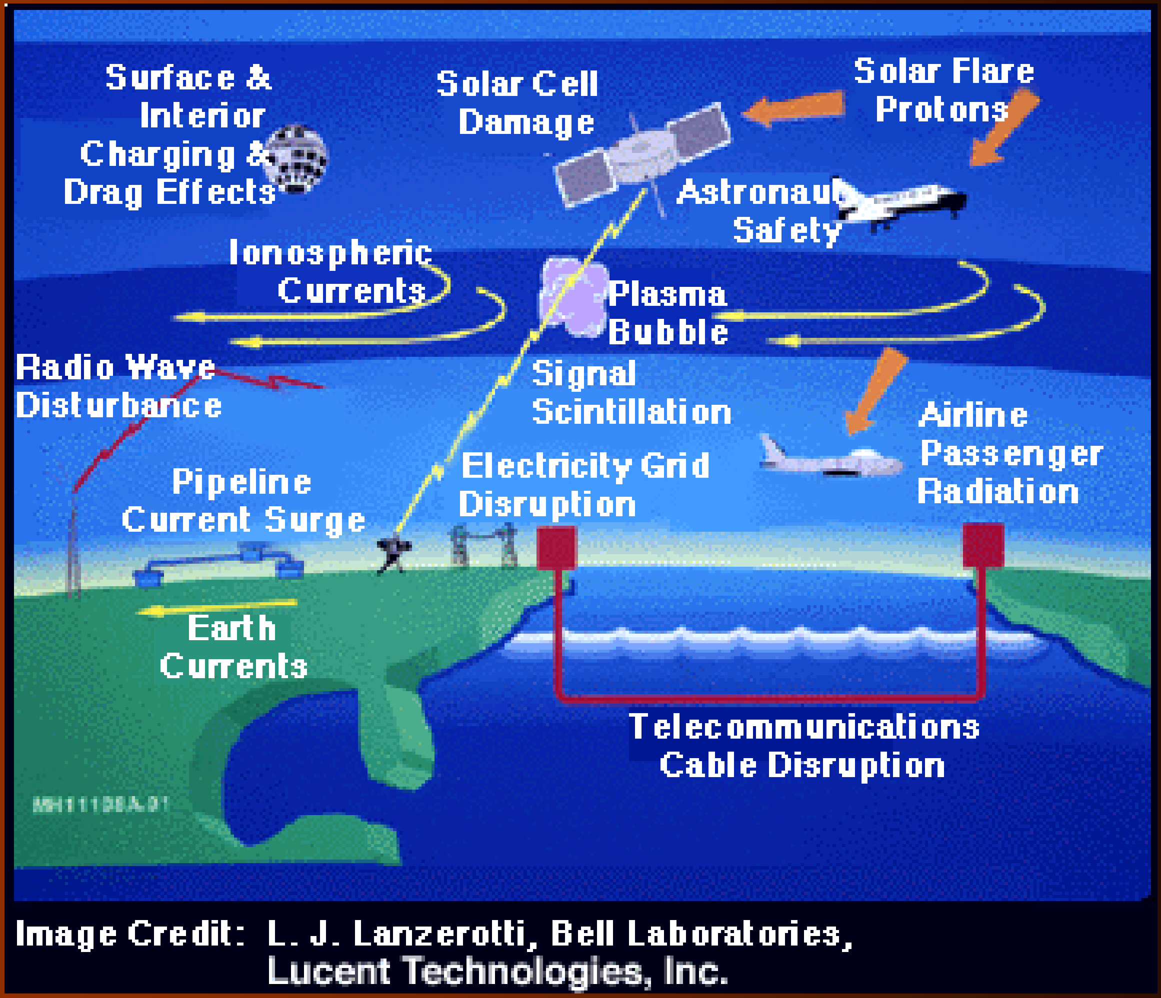
First Evidences

- In 1959 on the soviet Lunik 2 and 3 missions.
- In 1961 on NASA's explorer 10.
- In 1962, when Mariner II flew towards Venus.

The Solar Wind.



Wind of change

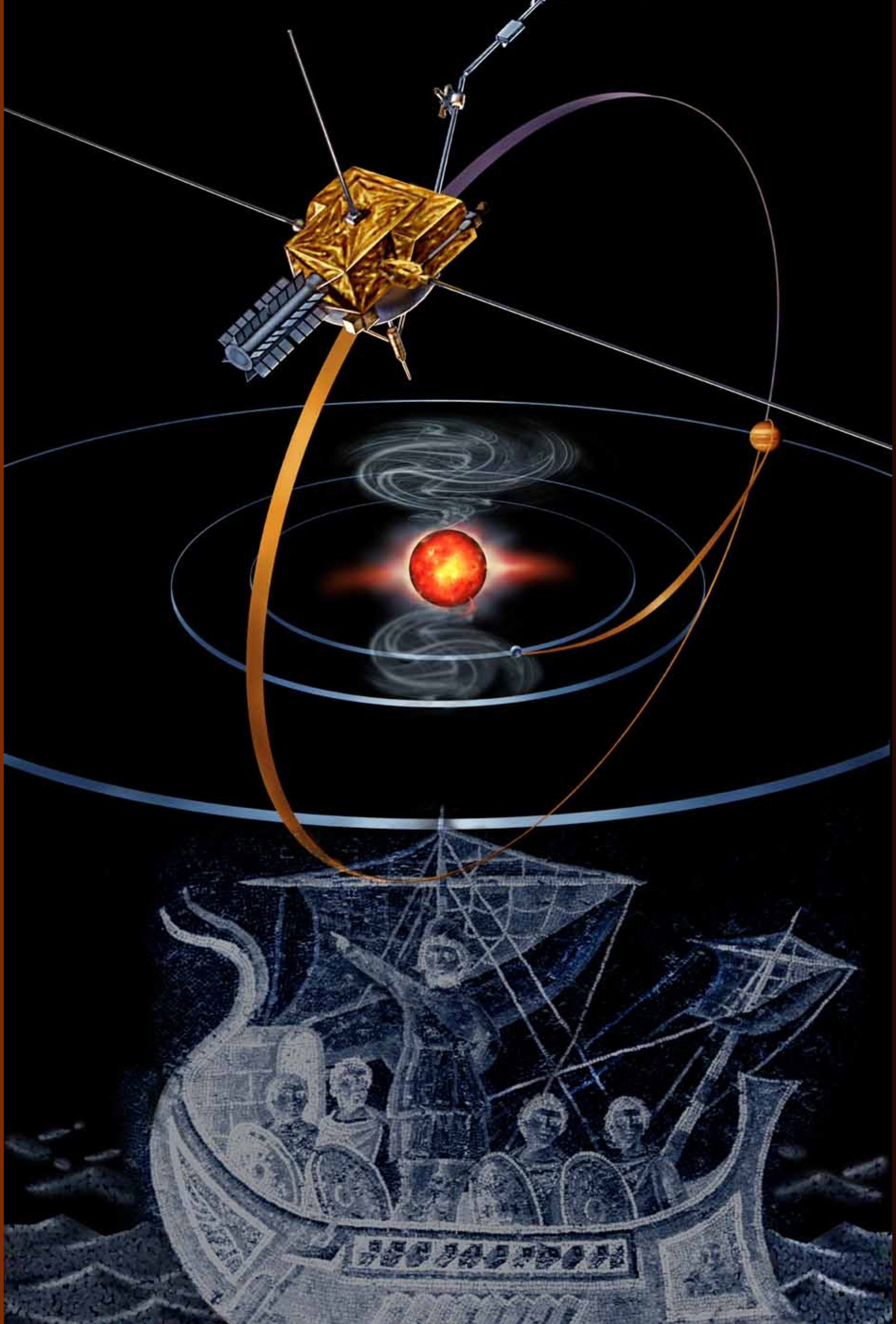


DOCTOR FUN

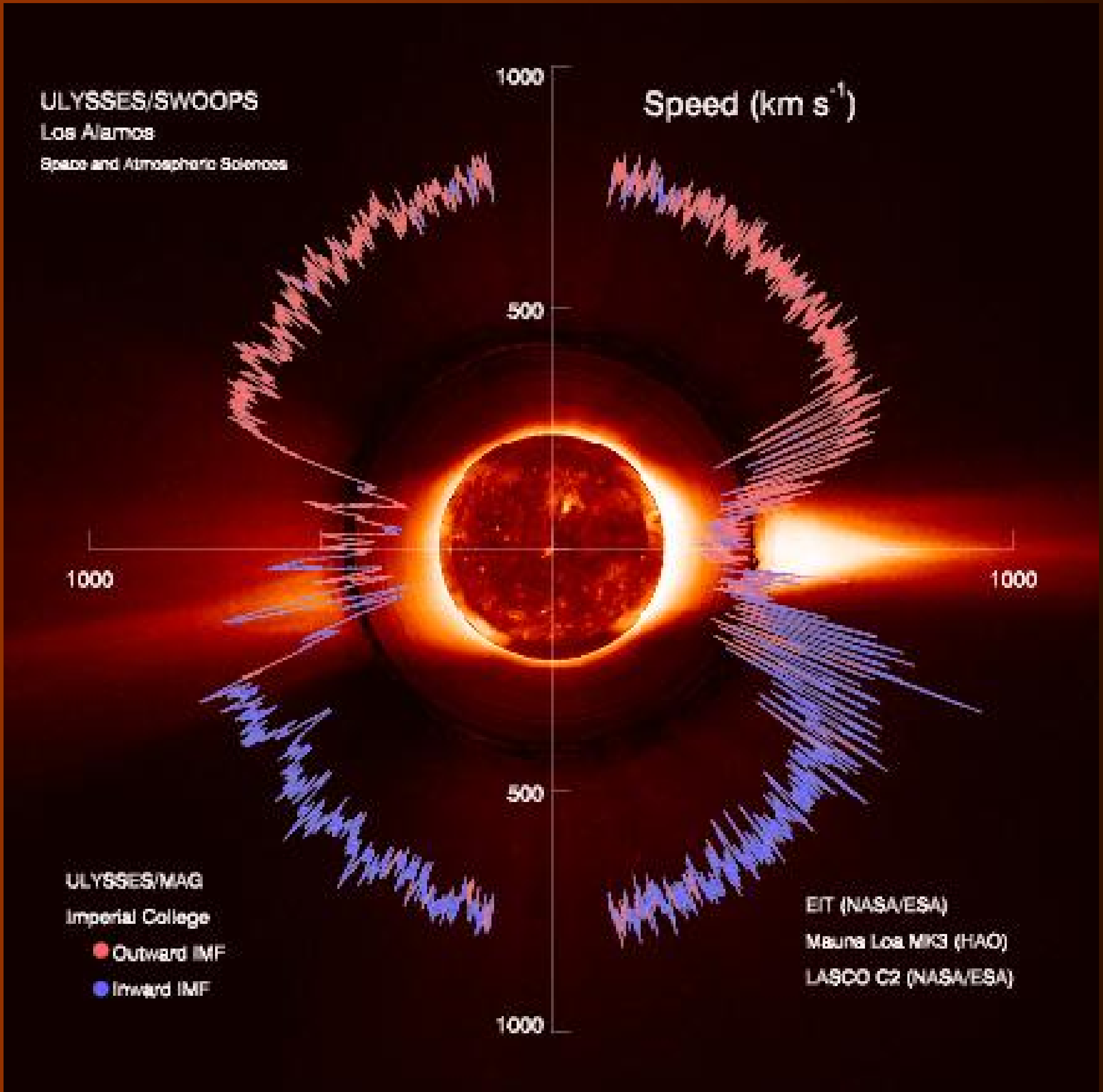
23 May 94

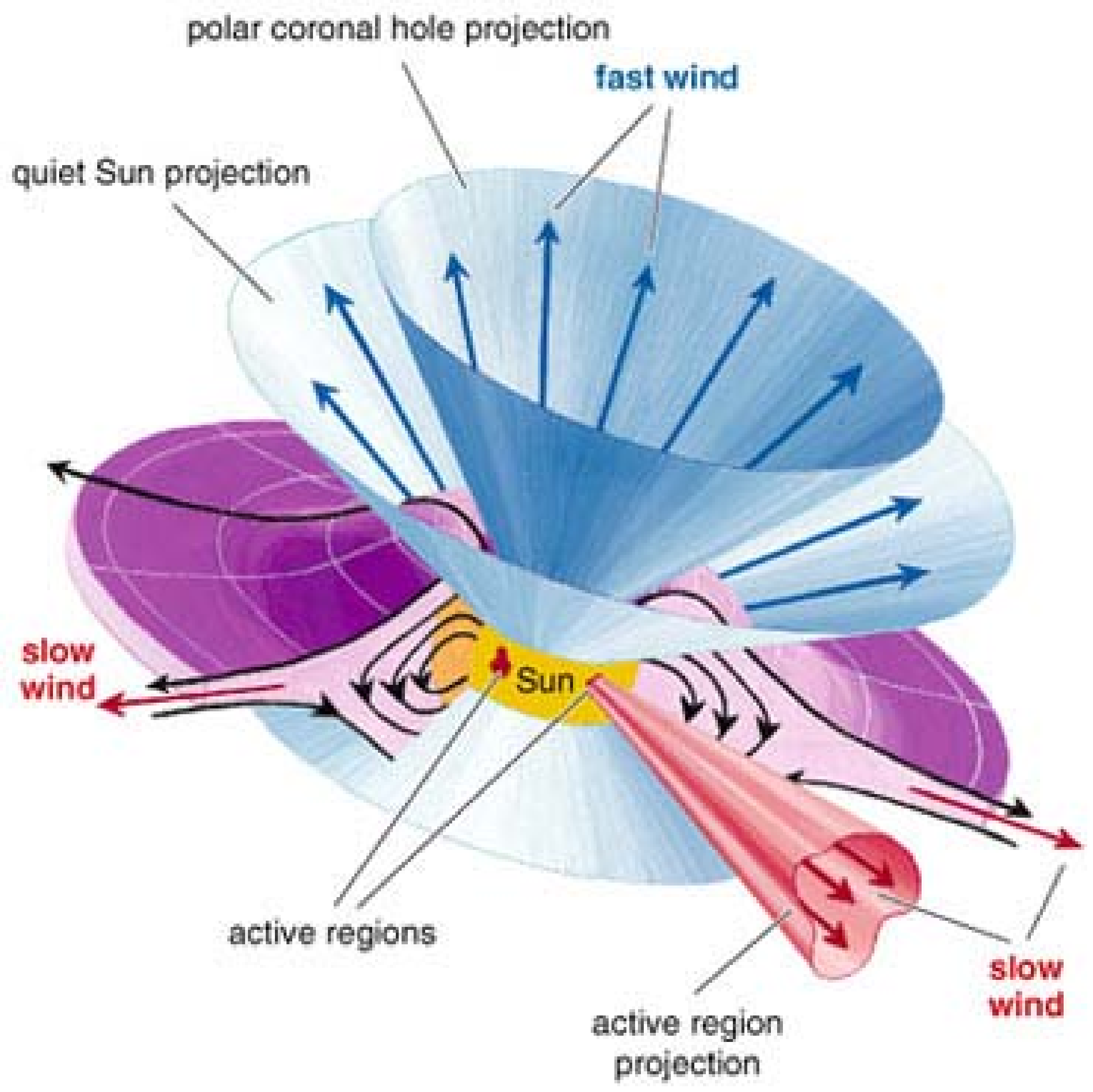
In Space No One Can Hear Ice Cream

Ulysses



From pole to pole!




polar coronal hole projection
fast wind
quiet Sun projection
slow wind
Sun
active regions
active region projection
slow wind

Lower & Extended Corona

Collision rate

Species collisionally coupled

Nearly Collisionless

Magnetic field topology

Complex

Simple

Heat conduction

Strong

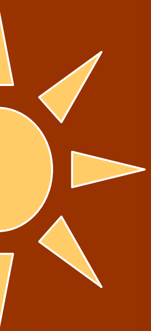
Very low

Heating rate per particle

The same!

The same!

Lower & Extended Corona



Thought to be heated by a different mechanism than the extended region

- Collisionless MHD fluctuations:
  - Waves
  - Turbulence
  - Shocks

  Thought to dominate heating
- Acceleration region
- Different particles begin to exhibit non-maxwellian velocity distribution with different momentum
- $T_{\perp}/T_{\parallel} \approx 10-100$

Alfvén waves. Why?

- Transverse fluctuations in the magnetic field lines
- Capable of energy transfer to long distances
- They have been observed (low frequency)
- Trigger instabilities
- Wave pressure (transverse magnetic pressure)
- Could be responsible for forming density structures (Spicules, density fluctuations..)
- A signature of:
  - Solar interior → Heliosismology
  - Properties of the solar corona

Questions

- Heating?
- Acceleration?
- Deriving turbulence cascade?
- How can waves reach the solar wind region not completely dissipated? What happens to the waves along the way?
- Which waves?
  - Alfvén waves
  - Slow and fast magneto acoustic wave

Alfvén Waves in Polar Wind

- Alfvén waves are observed in the high speed regions of the solar wind, more outward than inward propagating modes
- They evolve with distance, spectrum steepen and prevalence of outward modes decreases
- Velocity shear has a relevant role in driving turbulence evolution in low-latitude solar wind.
- This should not hold for polar wind, where velocity shear is weak.
- Possible explanations:
  - Effect of overall slow wind expansion
  - Parametric decay of Alfvén waves

Parametric decay

- In this process a parent Alfvénic wave decays into three daughter waves, two Alfvénic (forward and backward propagating) and one compressive. The energy mainly goes to the backward Alfvénic mode and to the compressive mode.
- Parametric decay helps explain:
  - Generating Z- out of Z+
  - Evolving a spectrum
  - Triggering turbulence cascade to get the needed dissipation and heating
  - Generating density fluctuations
  - Turbulence in molecular clouds

Alfvén and his waves

Hannes Alfvén (1908-1995)

'Only infinitely long wave train of circularly polarized Alfvén wave in a homogeneous medium is an exact solution to the MHD equations.'

Circular versus Linear polarization

$$\mathbf{B}_\perp = B_x\hat{x} + B_y\hat{y}$$

$$\mathbf{B}_\perp = B_\perp[\cos(kz-\omega t)\hat{x} + \sin(kz-\omega t)\hat{y}]$$

$$\mathbf{B}_\perp = B_\perp[\cos(kz-\omega t)\hat{x} + \cos(kz-\omega t)\hat{y}]$$

$$P_{mag} = B^2 / 2\mu_0$$

- The same total magnetic field strength everywhere
- No magnetic pressure gradient

- Magnetic field strength varies with position
- Magnetic pressure varies periodically with half the wavelength of the Alfvén wave.

MHD equations

$$\frac{\partial\rho}{\partial t}+\nabla.(\rho v)=0,$$

Lorentz Force

$$\frac{\partial(\rho v)}{\partial t}+\nabla.(v\rho v)=-\nabla p+J\times B+\rho g,$$

$$\frac{\partial B}{\partial t}=\nabla\times(v\times B-\eta\nabla\times B),$$

$$\nabla.B=0$$

$$J\times B=\frac{1}{\mu}(B.\nabla)B-\nabla(\frac{B^2}{2\mu})$$

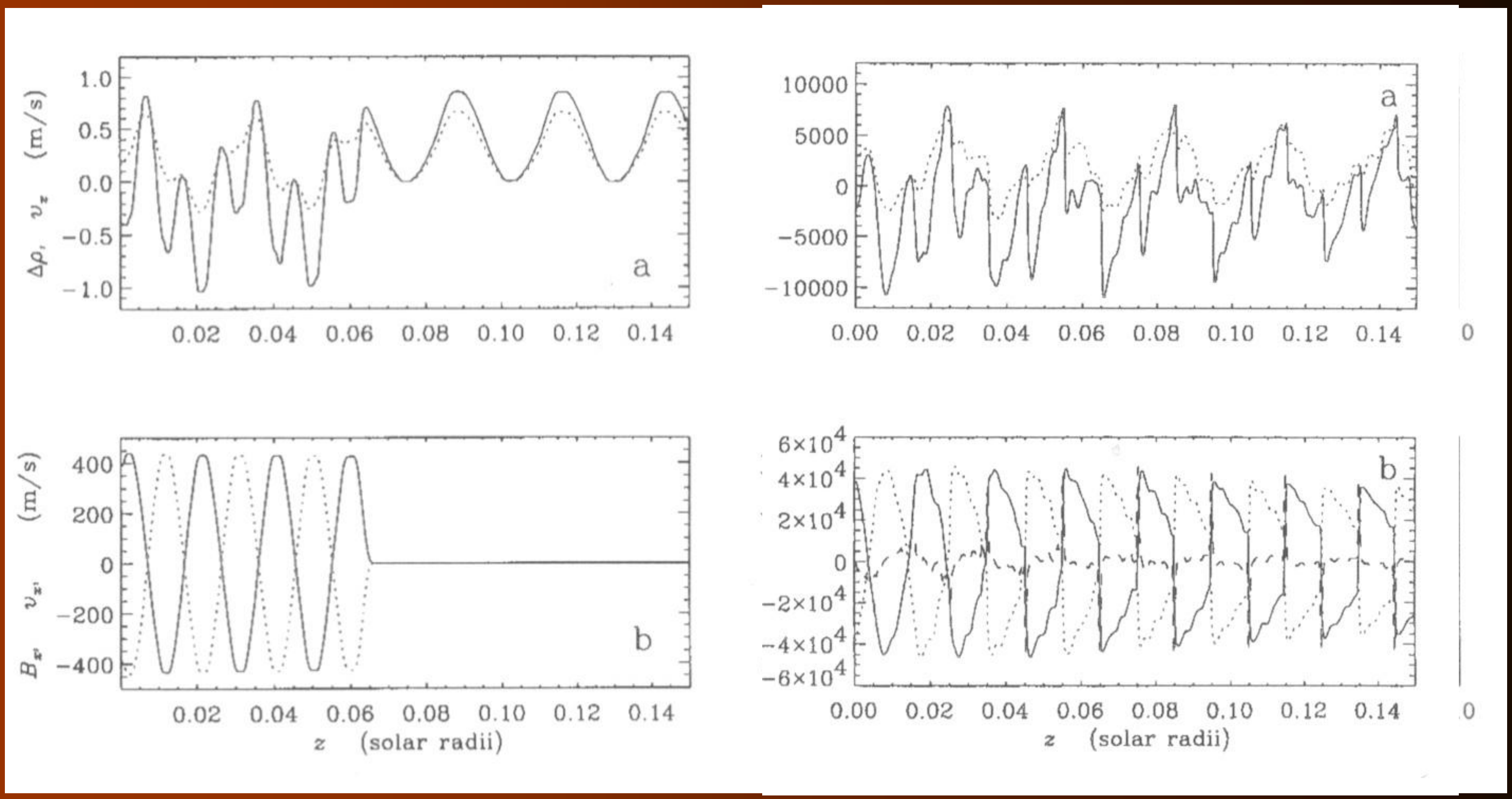
$$P_{mag}=B^2/2\mu_0$$

Magnetic pressure

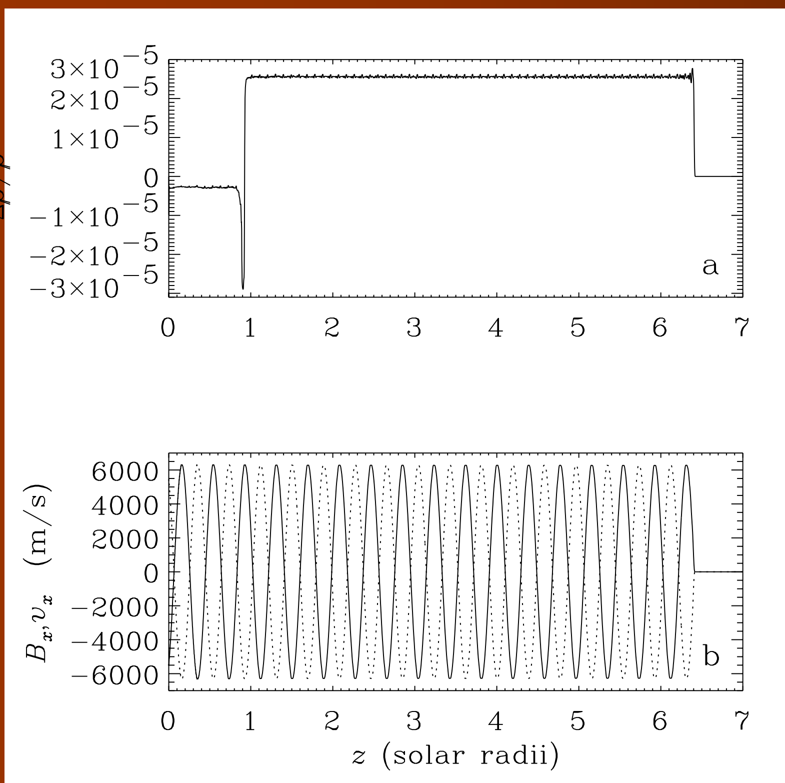
Results for Linearly Polarized Alfvén Waves

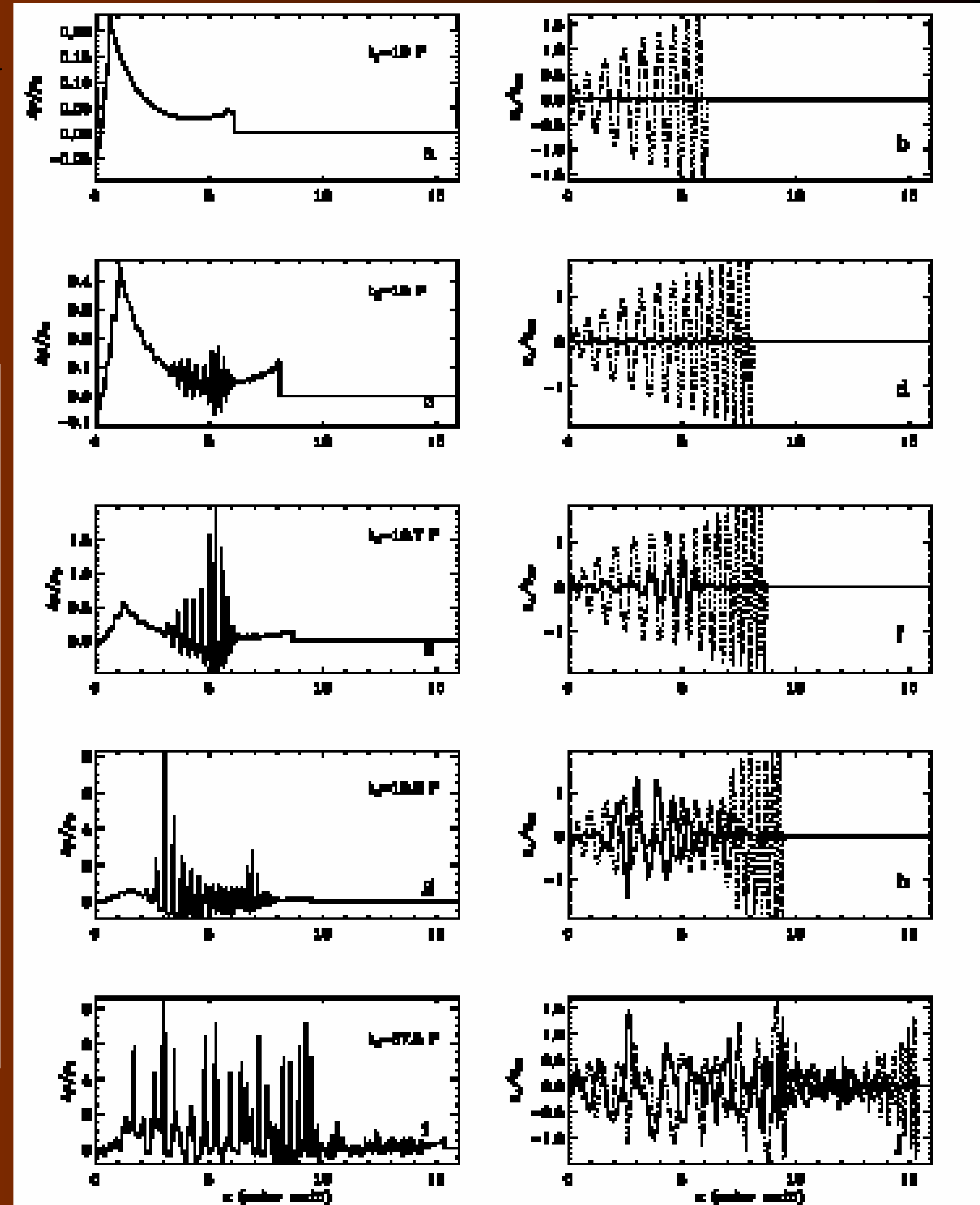
- Non linear polarized Alfvén waves can steepen to form current sheets at magnetic pressure minima.
- These current sheets enhance the dissipation rate of the Alfvén waves by several orders of magnitude
- The energy lost from the Alfvén waves depending on whether the medium is dominated by gas or magnetic pressure may.
  - Go into heating of the medium via joule dissipation.
  - Do mechanical work on the medium via Lorentz force.

Results for Linearly Polarized Alfvén Waves

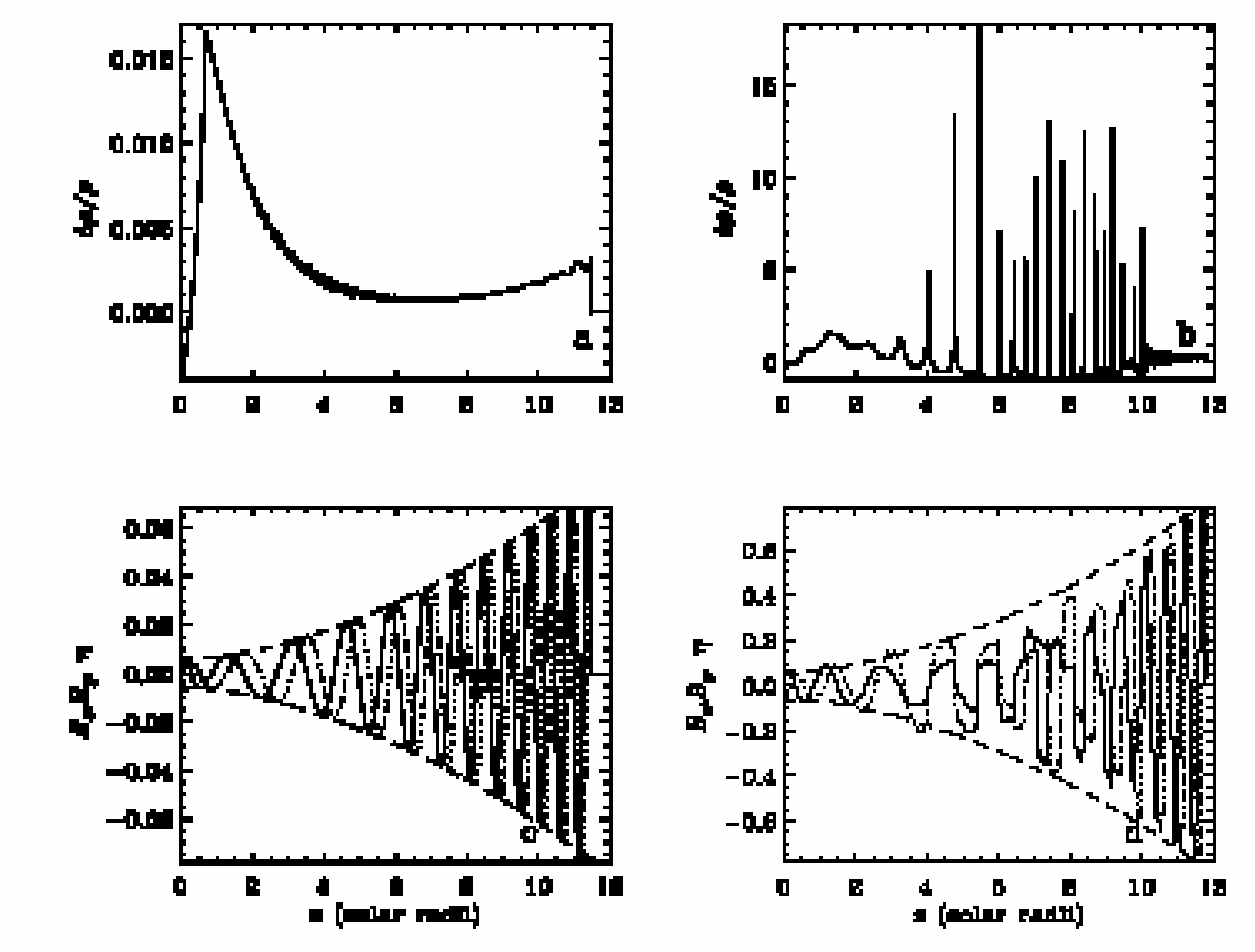


Results from Circularly polarized waves (plain parallel models)

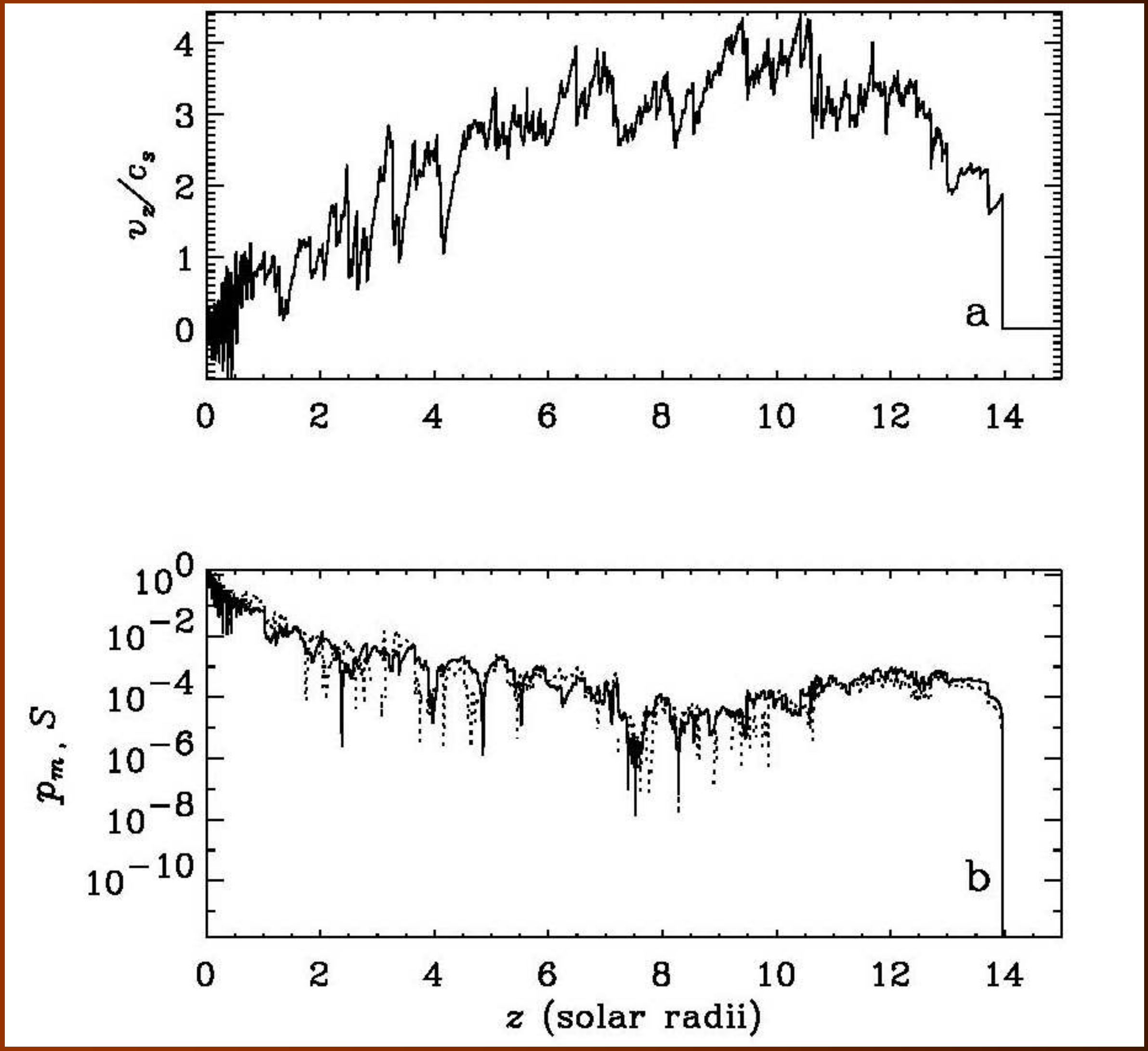




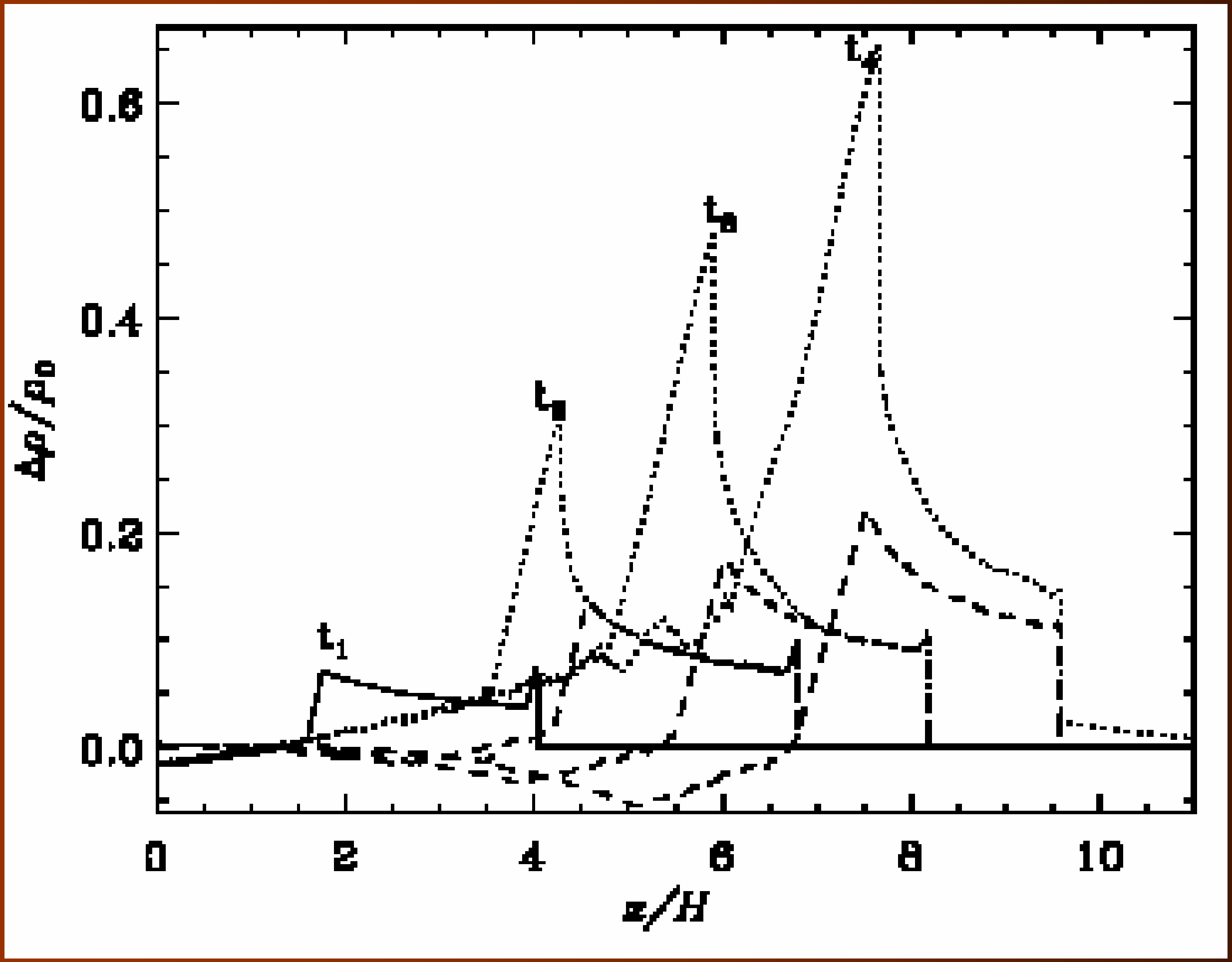
Wave Amplitude (spherical models)



Acceleration

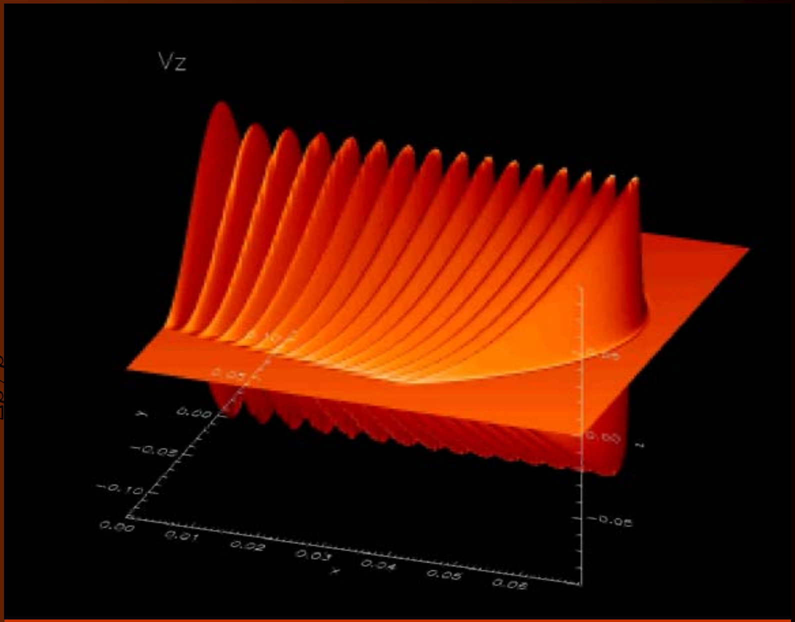


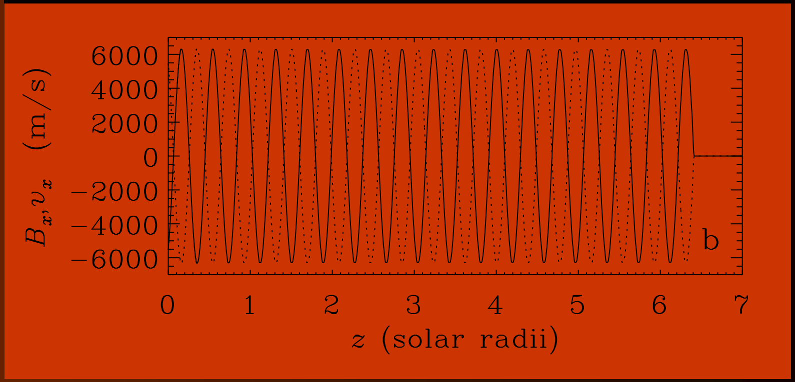
Density enhancements driven by Alfvén wave



1-D to 2.5-D

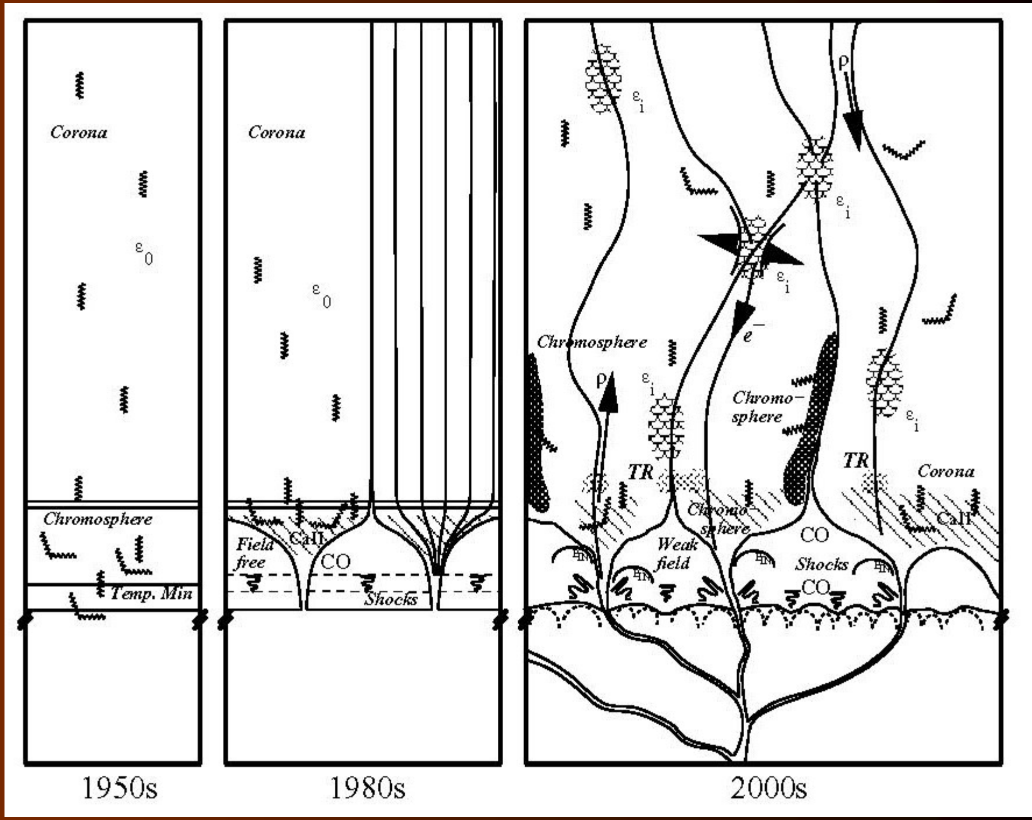
- Upgrading to higher dimensions give rise to more mechanisms to take place
- 1-D simulations can be good to study isolated mechanisms
- Many mechanisms acting together in higher dimensions make it difficult to interpret results





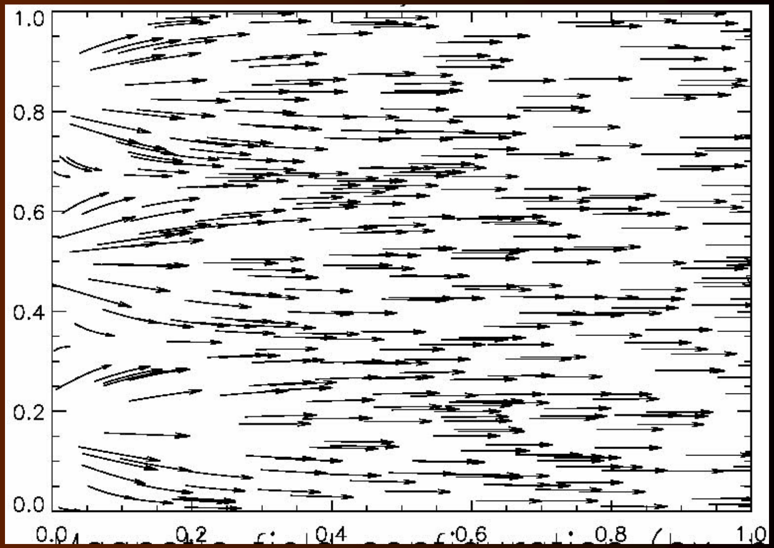
2.5-D Simulations

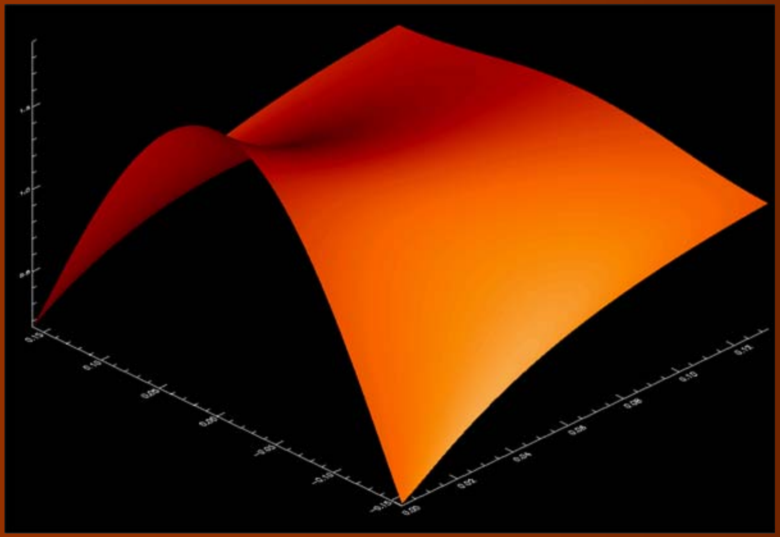
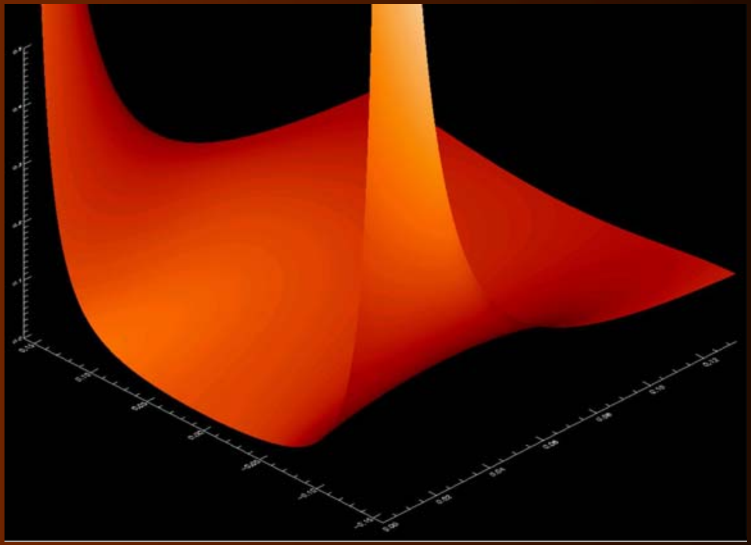
- How the topology of the network region affect the propagation of waves generated at the atmospheric base
  1. How magnetic effect comes into play
  2. How density stratifications in addition to the magnetic effect come into play



2.5-D Simulations

- Magnetic field from oblique to parallel
- Non-zero plasma
- Six coupled first order ODEs
    - Including gravity (*Zugzhda & Dzhalilov 84*)
    - Zero gravity (*Nakariakov et al 97*)
- The three wave modes, fast, Alfvén and slow are no longer distinct.
- They are coupled to one other and are subject to mixing and conversion



- High beta plasma →
  - Fast mode is mainly longitudinal acoustic wave
  - Slow mode is mainly transverse wave

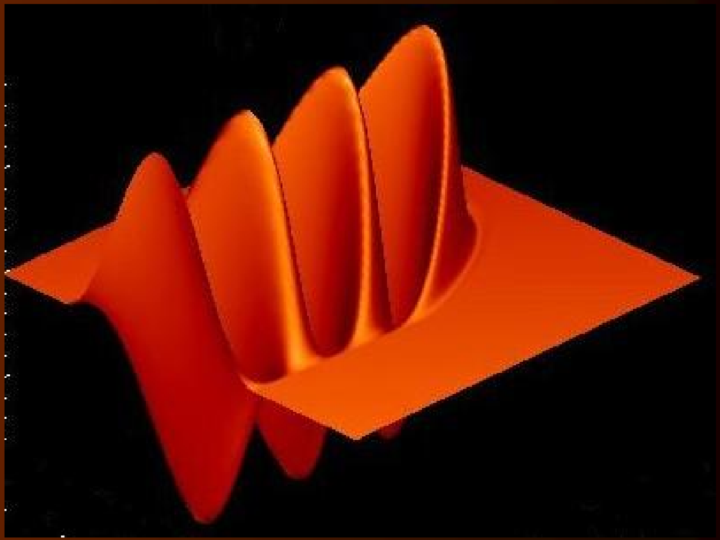
Mixing layer: Alfvén speed = sound speed →
Mode conversion, transmission and reflection

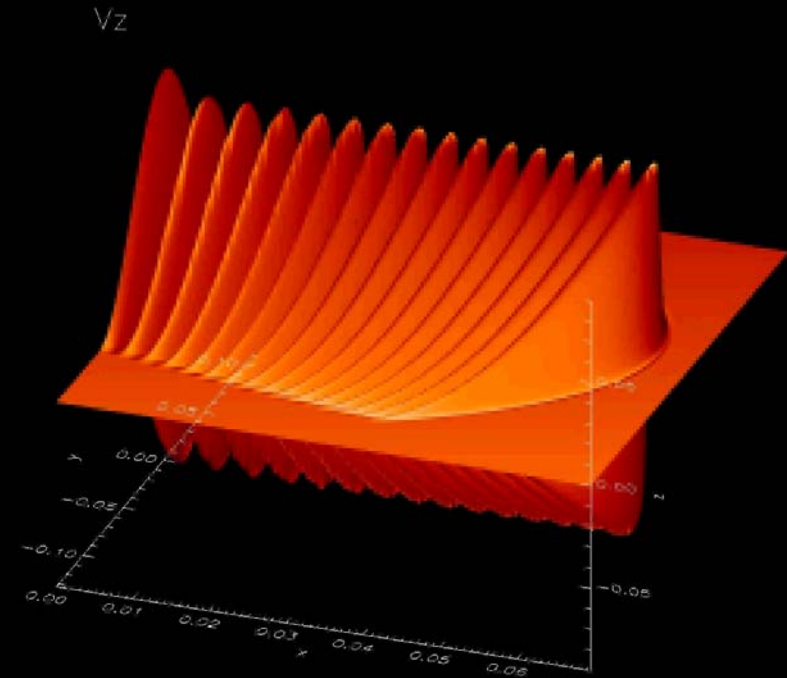
- Low beta plasma →
  - Fast mode is mainly transverse wave
  - Slow mode is mainly longitudinal wave

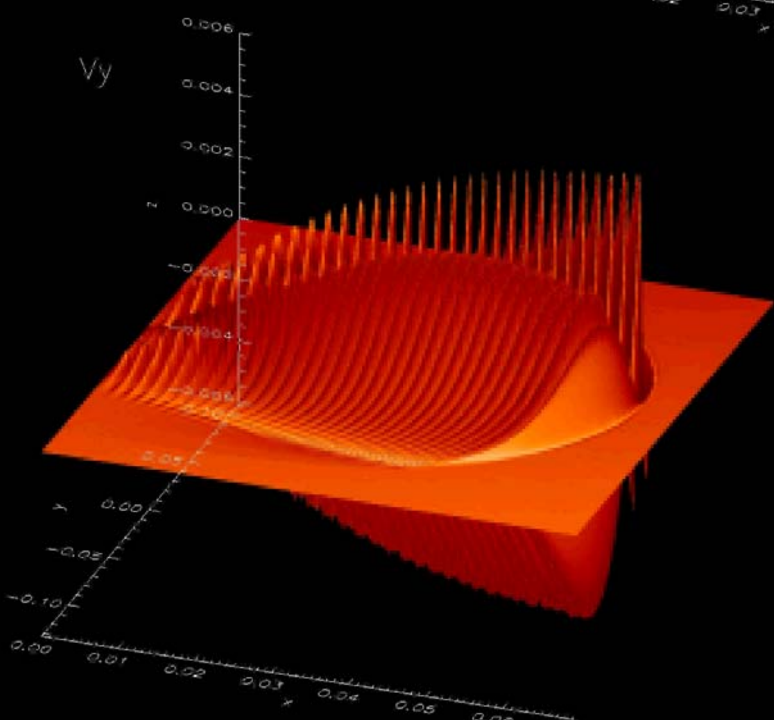
Model

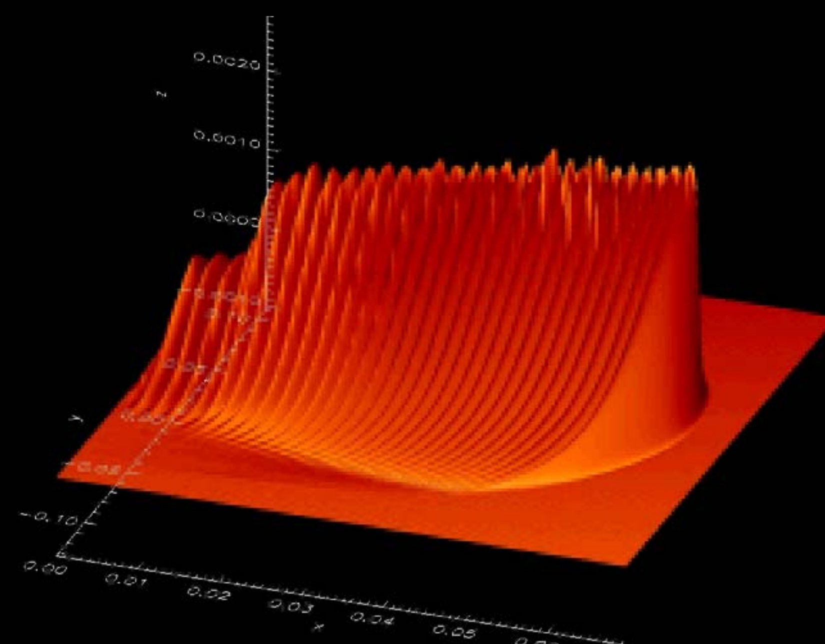
The wave is driven on the boundaries in two main models:

1. *The wave is perpendicular to the plane of the magnetic field (perturbing the y-direction) → the Alfvénic mode is predominant. Presented in model A where the initial wave amplitude =0.1*
2. *The wave is polarised in the plane of the magnetic field (perturbing the x-direction) → the magneto acoustic solution is predominant. Presented in models B and C where the initial wave amplitude is taken to be 0.1, 0.5 respectively*




Vz
y
0.05
0.00
−0.05
−0.10
0.00
0.01
0.02
0.03
x
0.04
0.05
0.06
z
0.00
−0.05


Vy
0.006
0.004
0.002
z
0.000
y
0.00
−0.05
−0.10
0.00
0.01
0.02
0.03
x
0.04
0.05
0.06


z
0.0020
0.0010
y
−0.10
0.00
0.01
0.02
0.03
x
0.04
0.05
0.06

The End!

"Everything is ok at the end...
if it is not ok, it's not the end."