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CIMPA/ICTP Geometric Structures and Theory of Control

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Overview of Plasma Flows and Turbulence in the Solar Environment

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Overview of Plasma Flows and Turbulence in the Solar Environment

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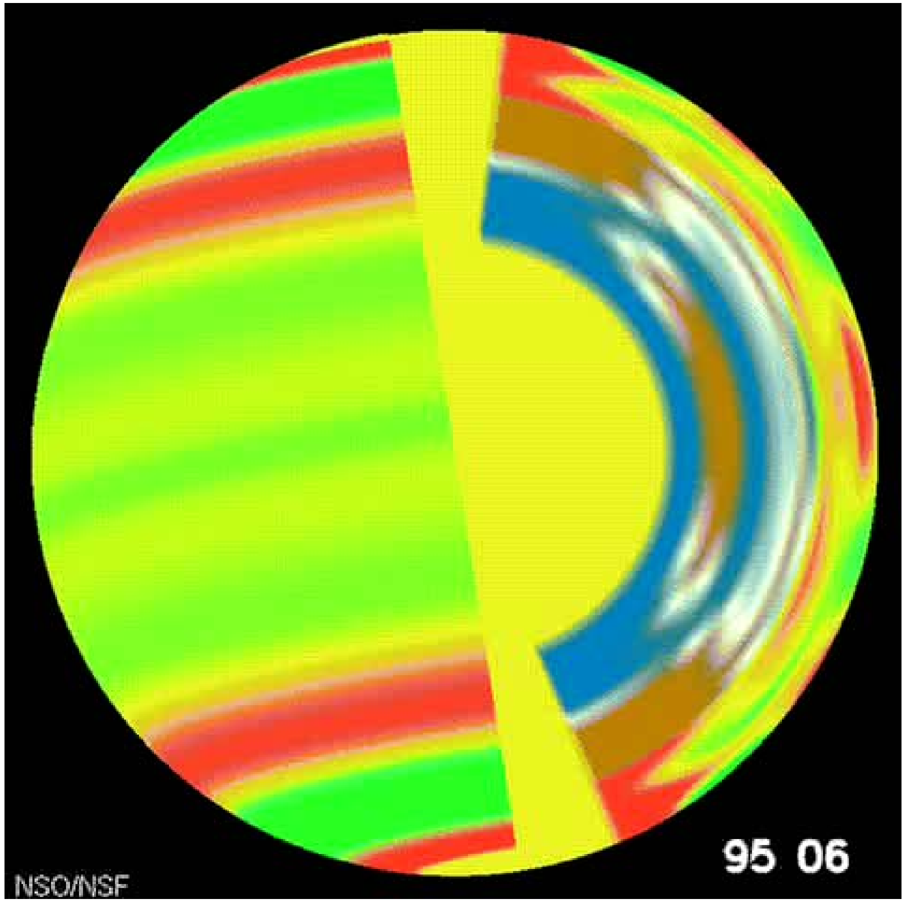
Overview

• Dynamo, Corona, solar wind, magnetosphere, comets, interaction with ISM
•Large scale flow characteristics
• Background in turbulence theory
• Distinctive features of MHD and plasmas
• Applications

-Coronal heating
-Solar wind transport and heating
-Solar modulation of galactic cosmic rays
-Solar energetic particles

Solar convection zone and dynamo

- Data from GONG and SOHO instruments
- Surface differential rotation
- Dynamo at base of convection zone "tachycline"
- Very strong turbulent convection excites millions of seismic modes



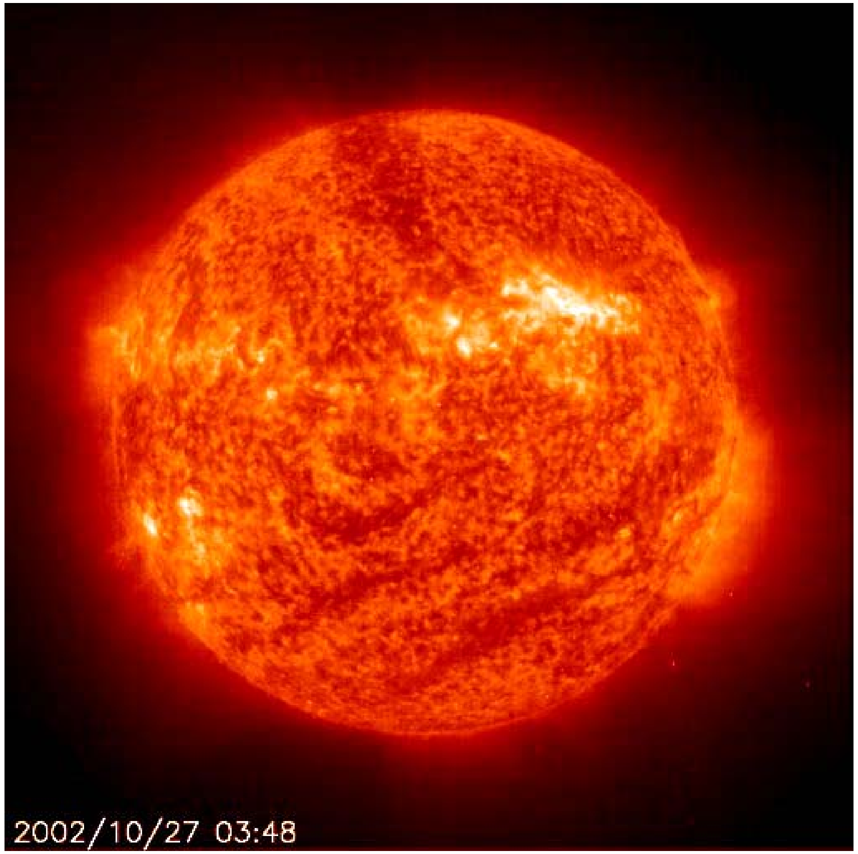
Courtesy National Solar Observatory

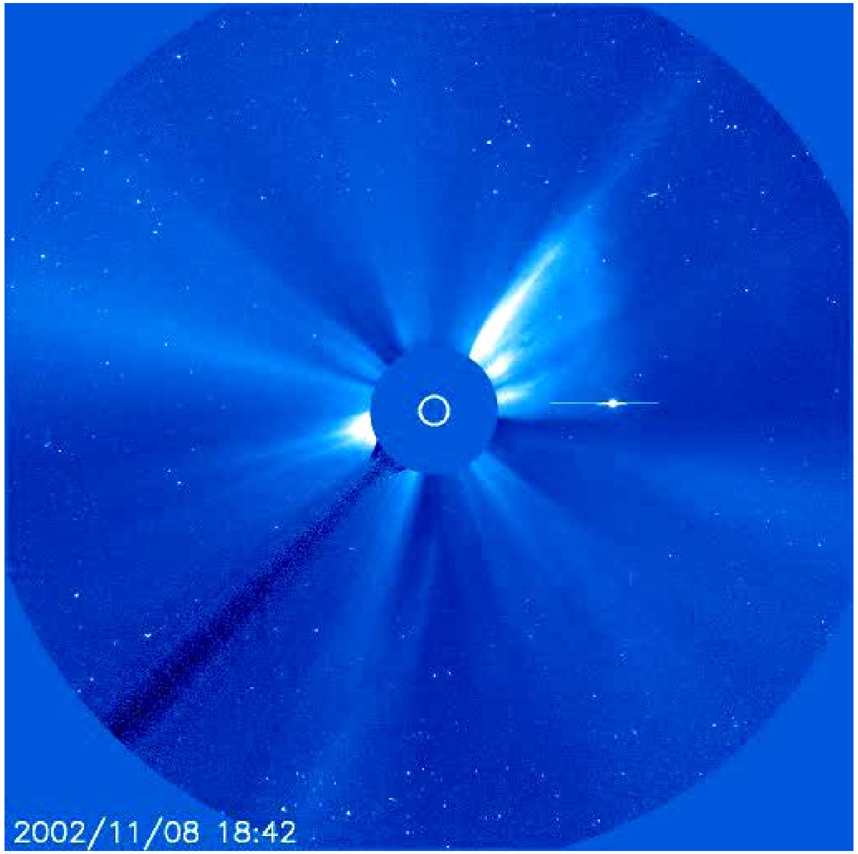
Activity in the solar chromosphere and corona

SOHO spacecraft

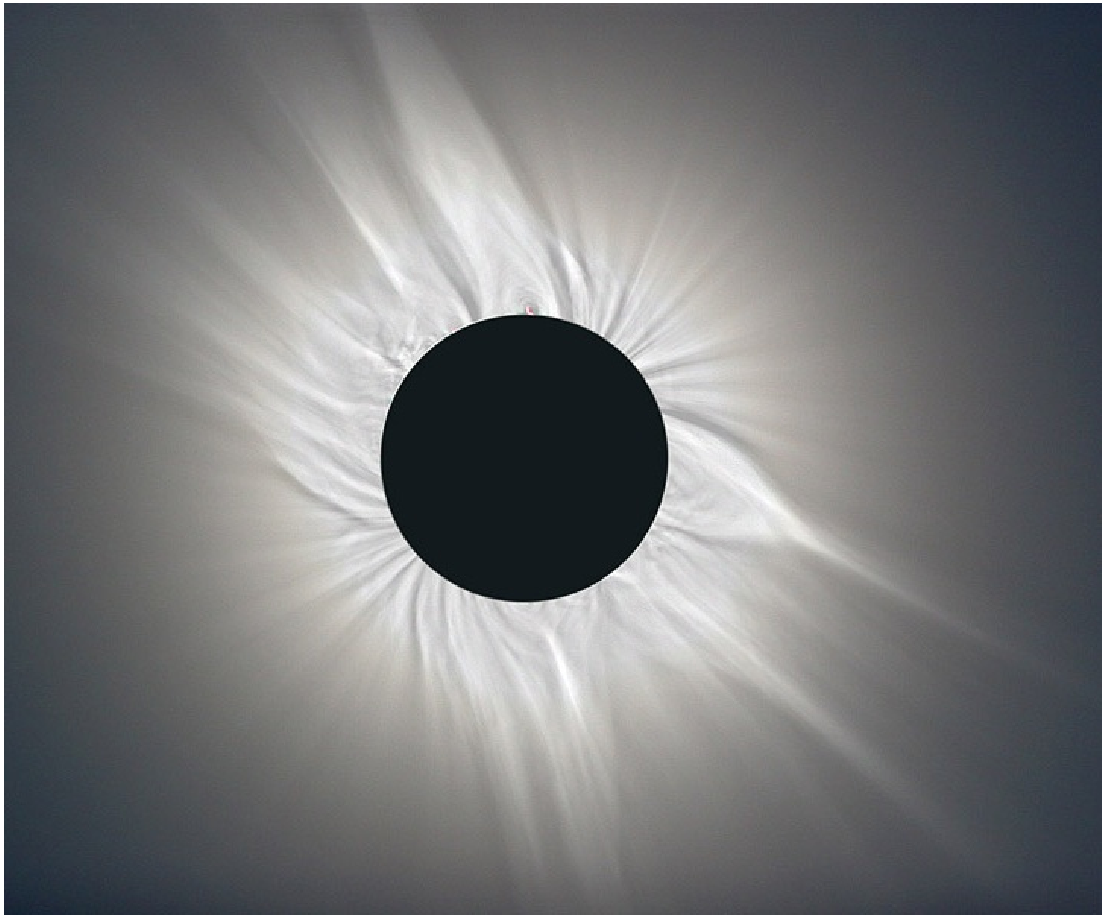
UV spectrograph: EIT 340 A

White light coronagraph: LASCO C3





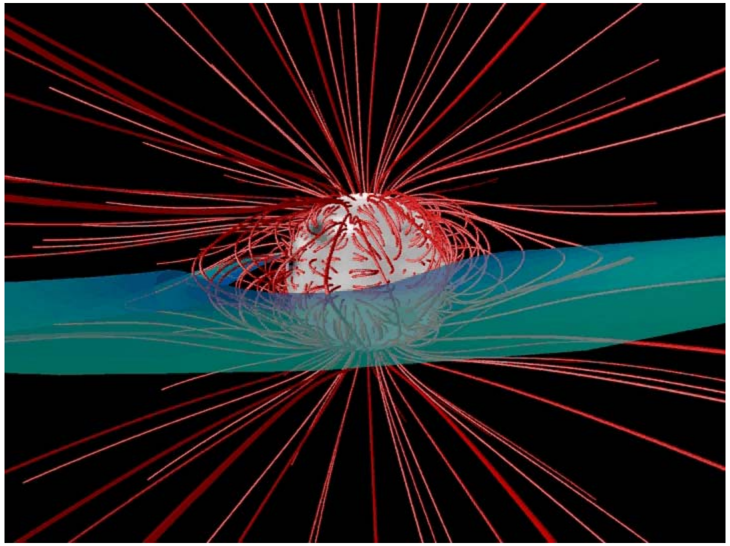
Coronagraph images show fine magnetic structure

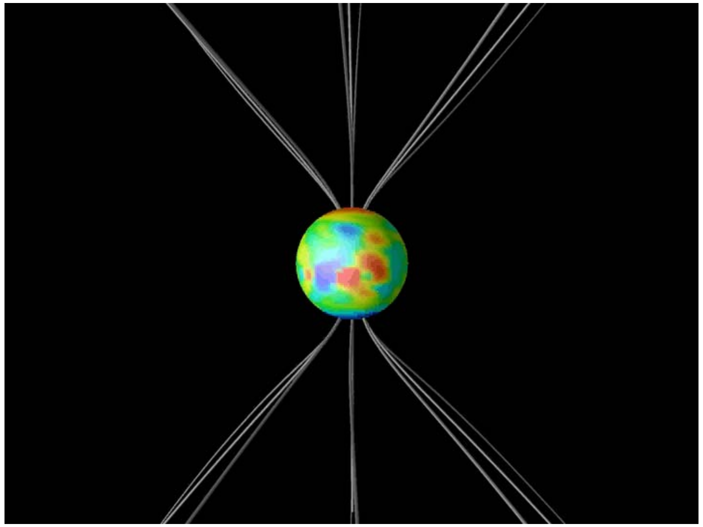


TSE2006 – composite photo courtesy Fred Espenak

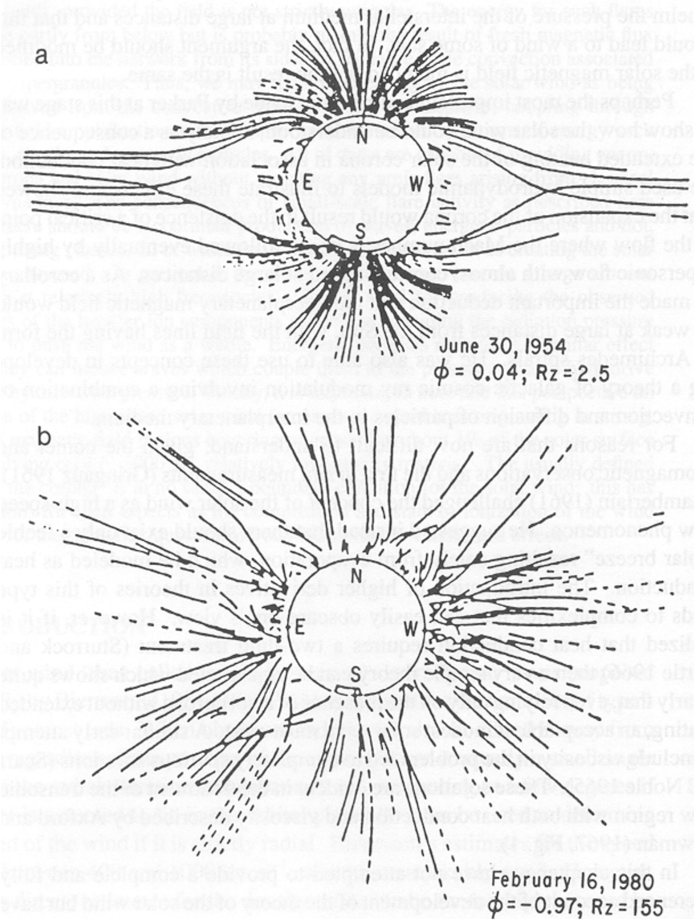
Global coronal simulation

- MHD models
- Difficulties in representing fine scales, energy deposition, heat conduction, turbulence
- An example (courtesy B.U Center for Integrated Space Weather Modeling)

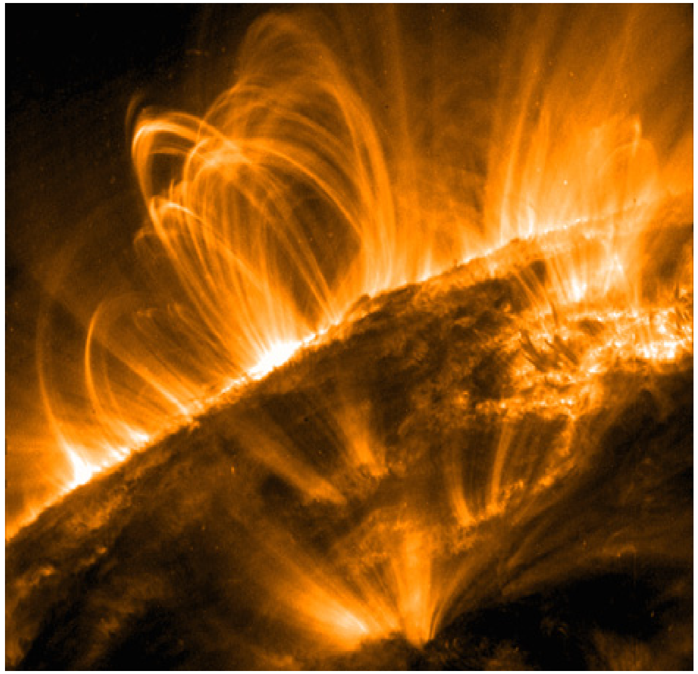




Fine scale activity in the corona



Drawings from Coronagraphs
(Loucif and Koutchmy, 1989)

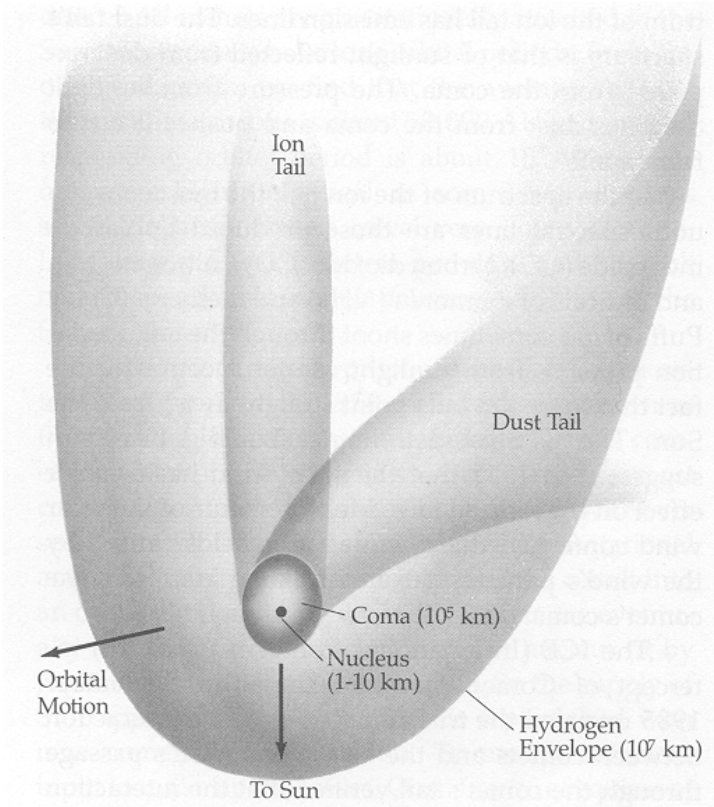


FE IX/X lines, TRACE

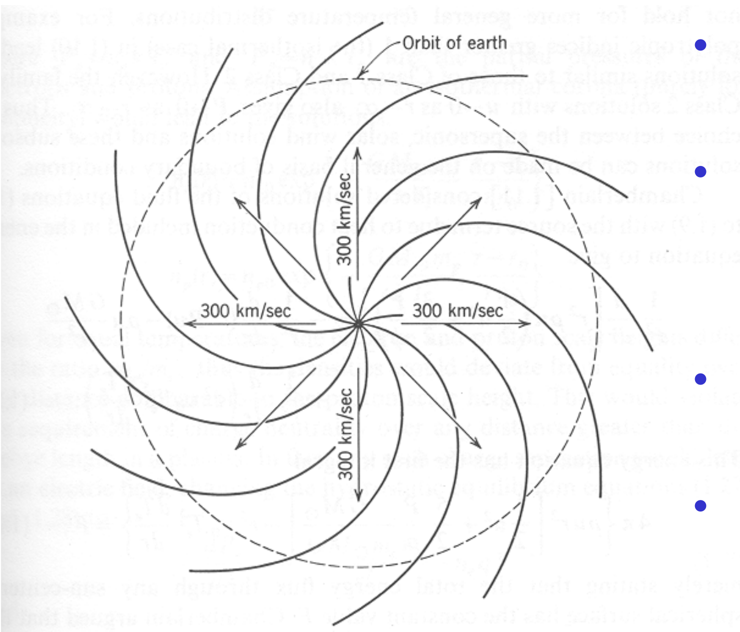
Comet tails and the solar wind

Second (ion) tail suggests solar wind exists (Biermann, 1951)

Hale-Bopp

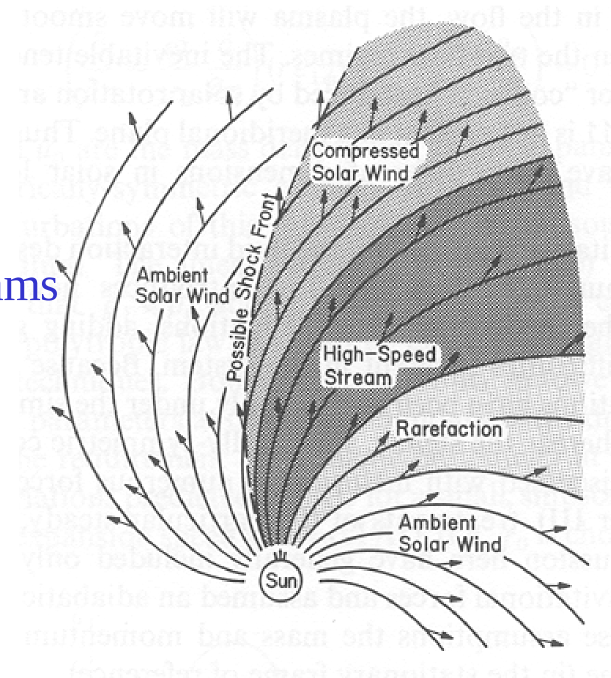


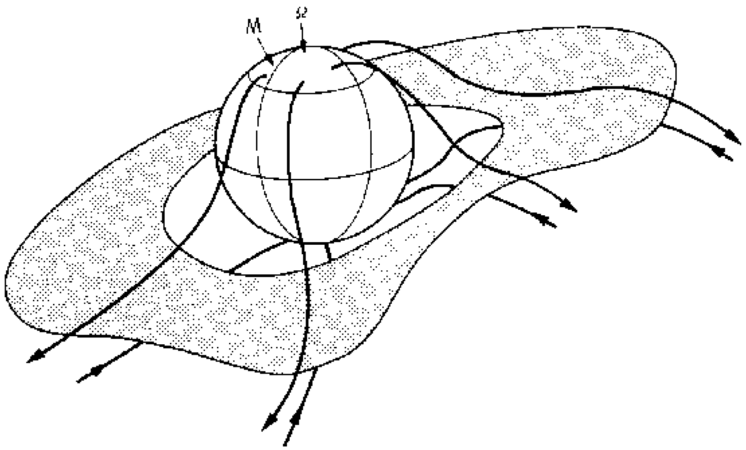
Large scale features of the solar wind

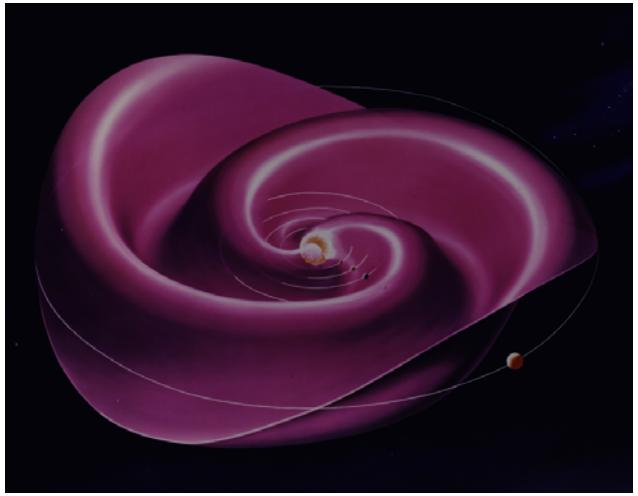


- Plasma outflow, spiral magnetic field
- High and low speed streams

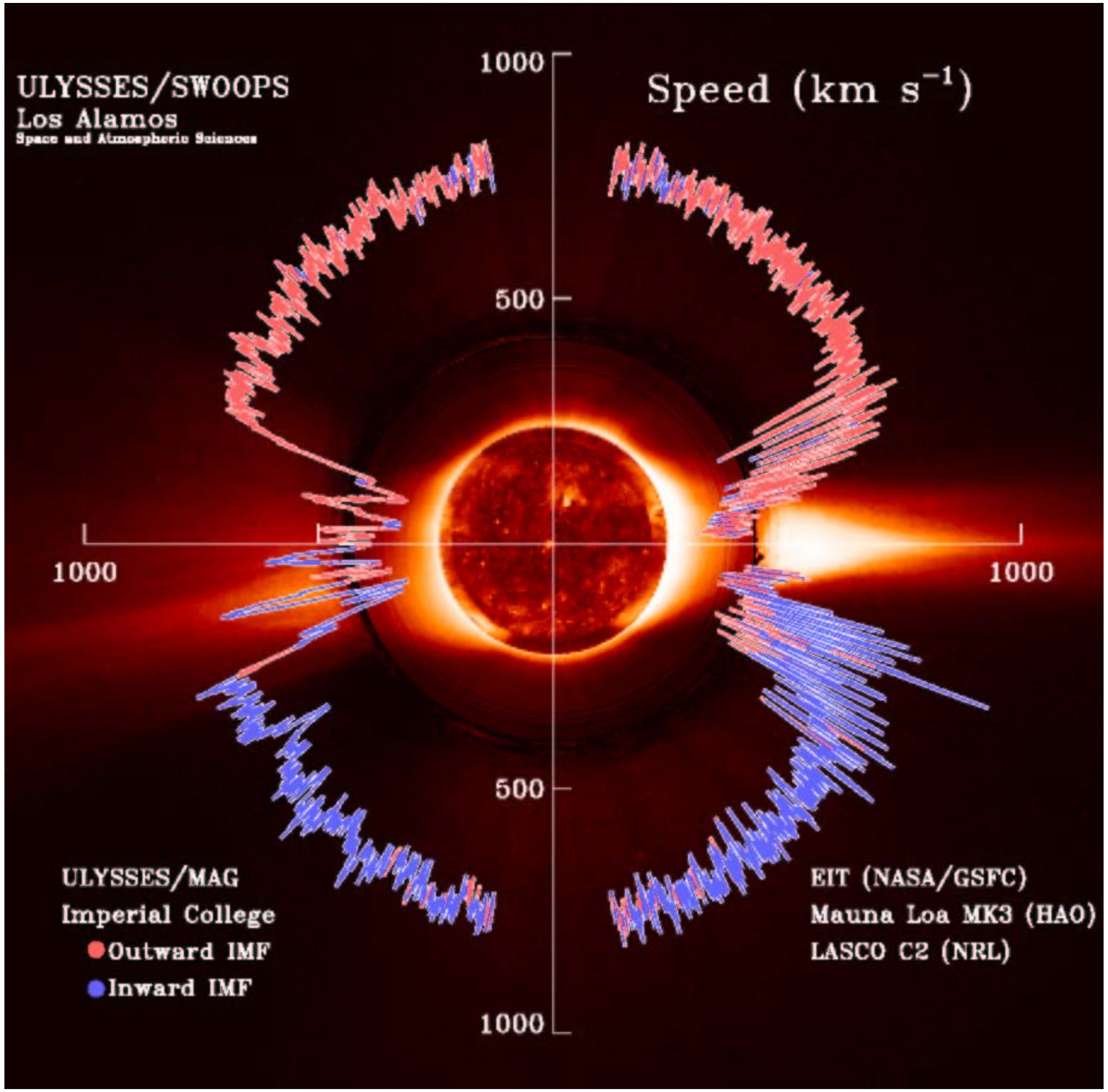
- North south distorted magnetic dipole
- Wavy, equatorial current sheet







Large scale features of the Solar Wind: *Ulysses*

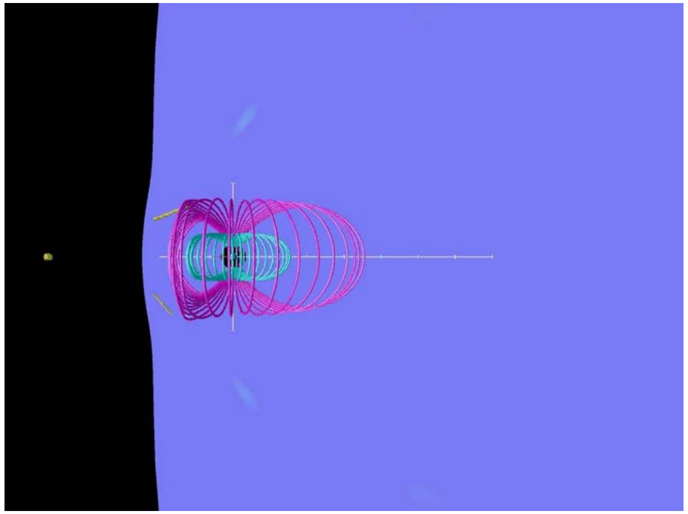


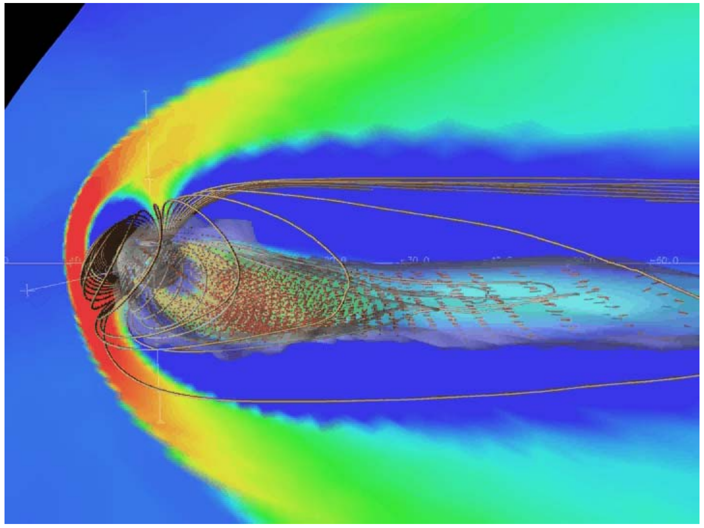
- High latitude
  - Fast
  - Hot
  - steady
  - Comes from coronal holes
- Low latitude
  - slow
  - "cooler" (40,000 K @ 1 AU)
  - nonsteady
  - Comes from streamer belt

McComas et al, GRL, 1995

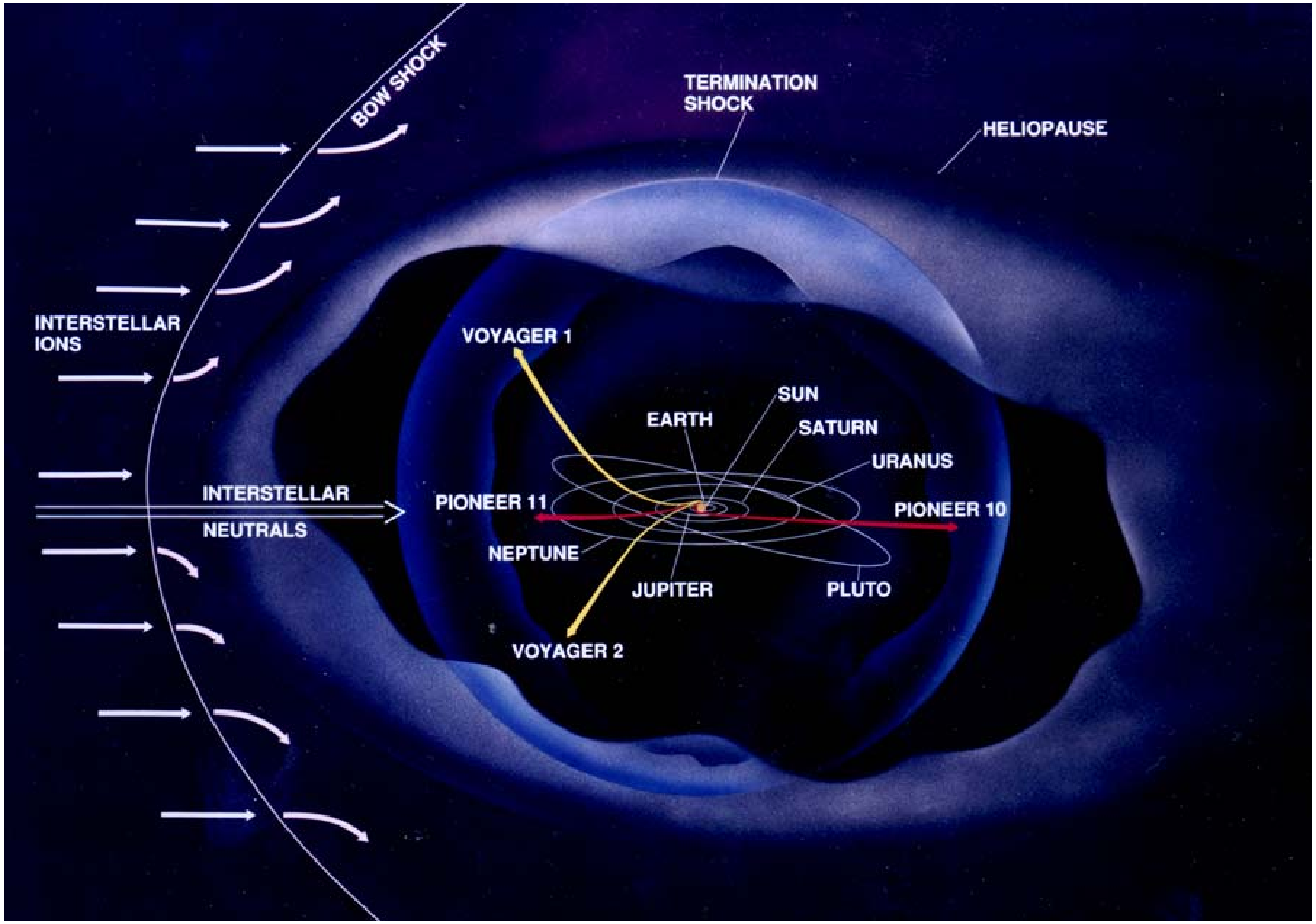
Flows around objects in the Heliosphere: magnetospheres, comets, etc

- MHD simulation of the global magnetosphere has become an important area of research – space weather
- Examples (courtesy BU CISM)
  - Formation
  - Dynamics of substorm





Largest scale features of the Solar Wind: Artist conception

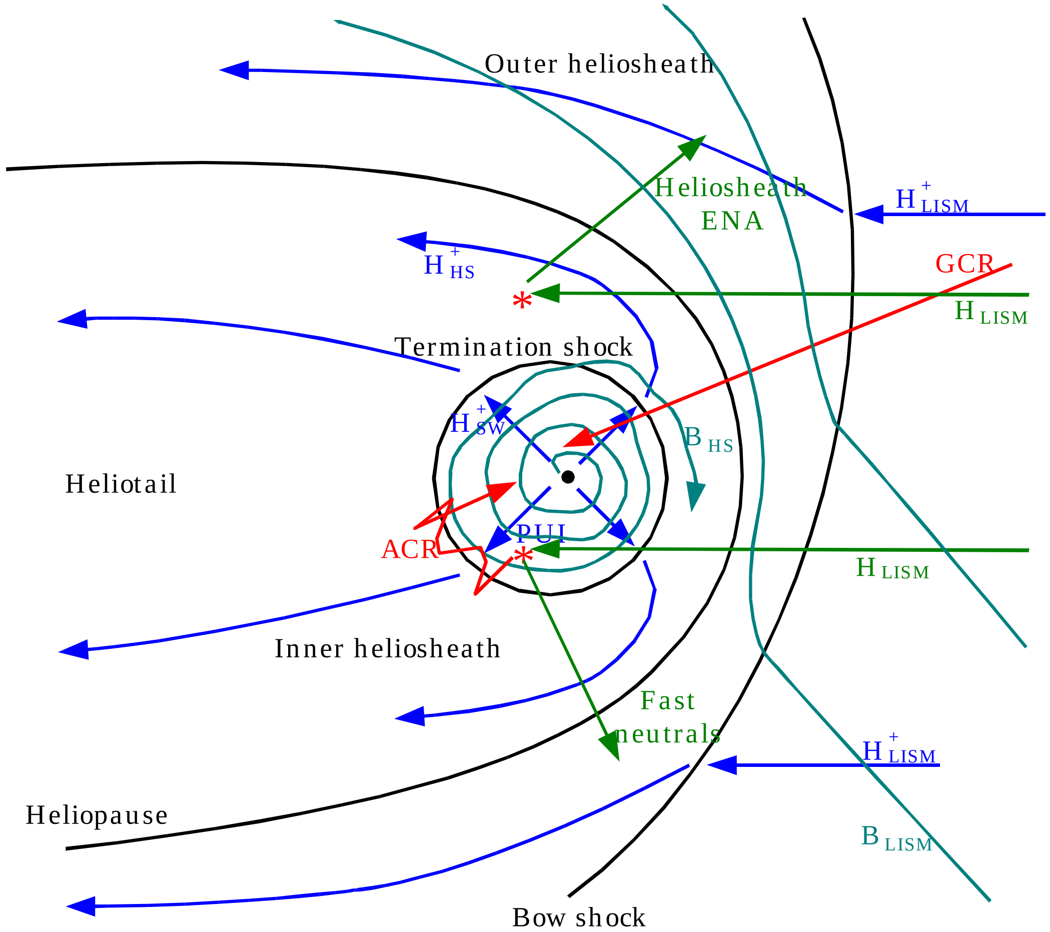


NAS SSP Survey Report, 2002 Courtesy JPL

- *Boundaries of the heliosphere: interaction of the solar wind with the interstellar medium.*
- *Nonlinear flows/ turbulence provide essential interactions that establish global structure*

Interaction of SW with ISM: global heliosphere

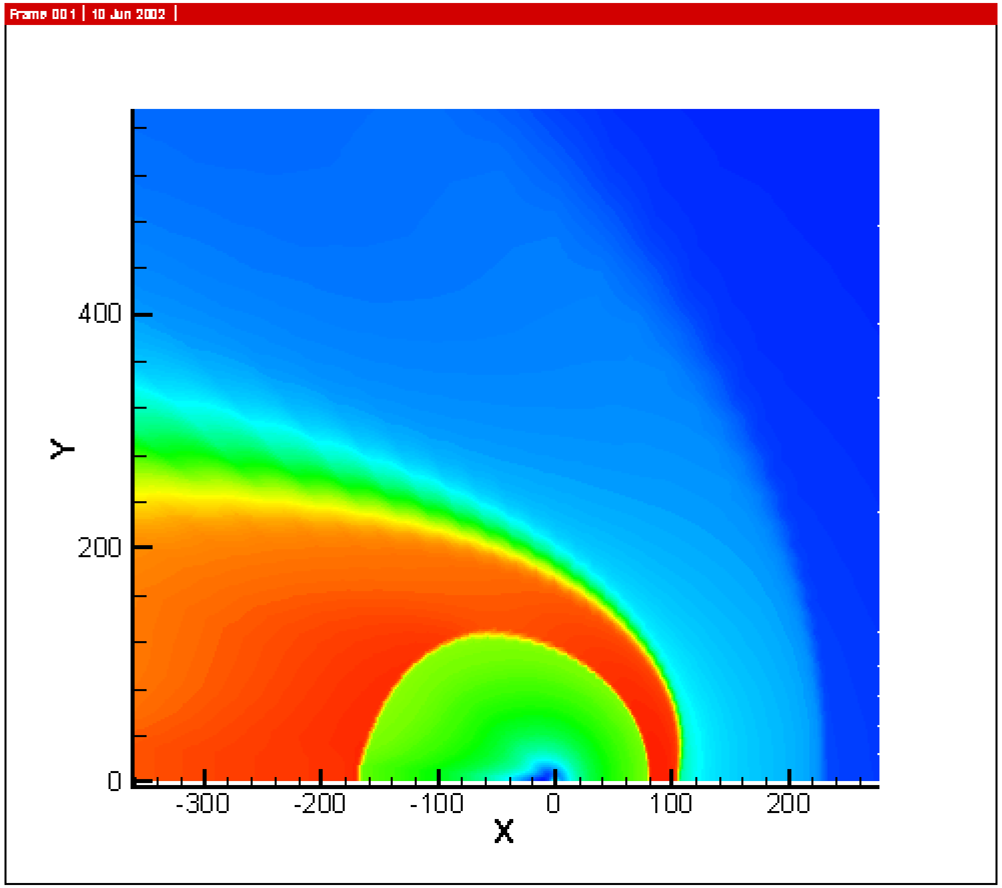
- Structure of the heliosphere
- Long term changes
- Sources of anomalous cosmic rays, and modulation of GCRs
- Voyager spacecraft have data from the termination shock and heliosheath
  - See Nature **Volume 454 Number 7200 pp1-136**



Courtesy Gary Zank, UAH

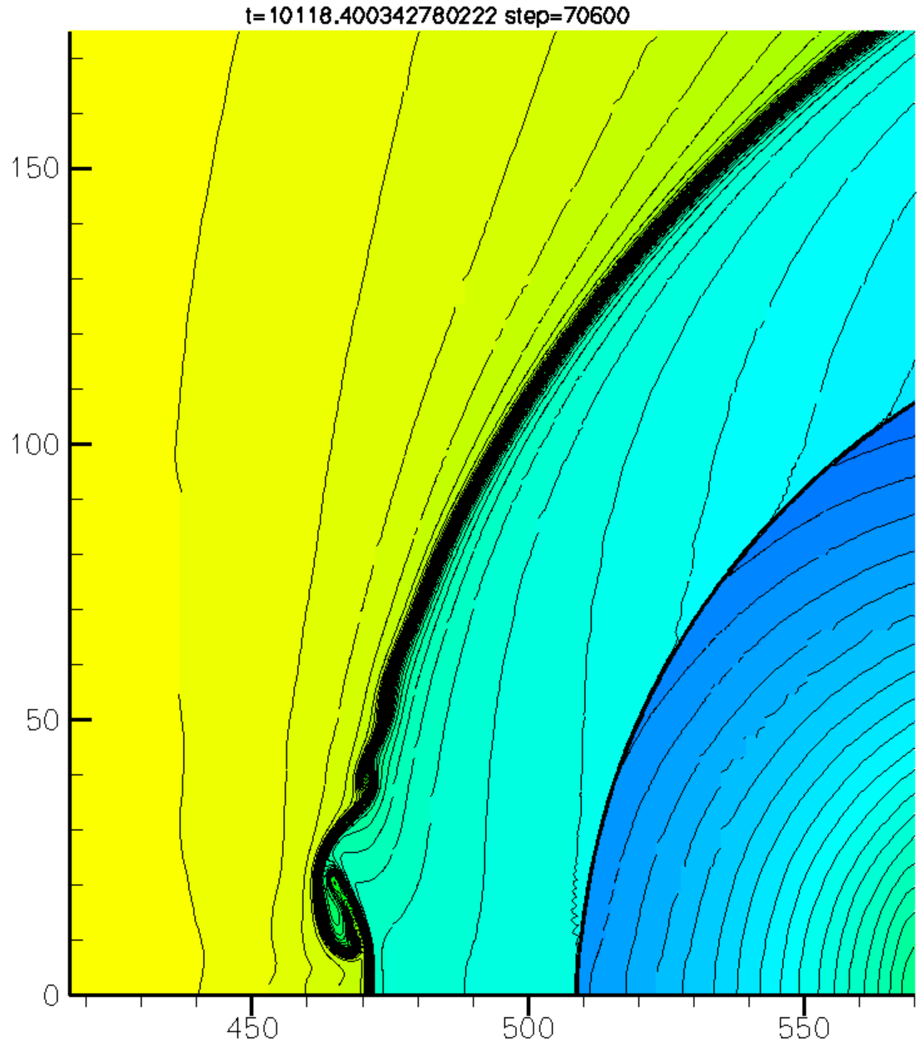
Simulation of the global heliosphere

2D HYDRODYNAMICAL MODEL OF GMIR INTERACTING WITH THE HELIOSPHERIC BOUNDARIES (ALL MODELS INCLUDE INTERSTELLAR NEUTRALS SELF-CONSISTENTLY

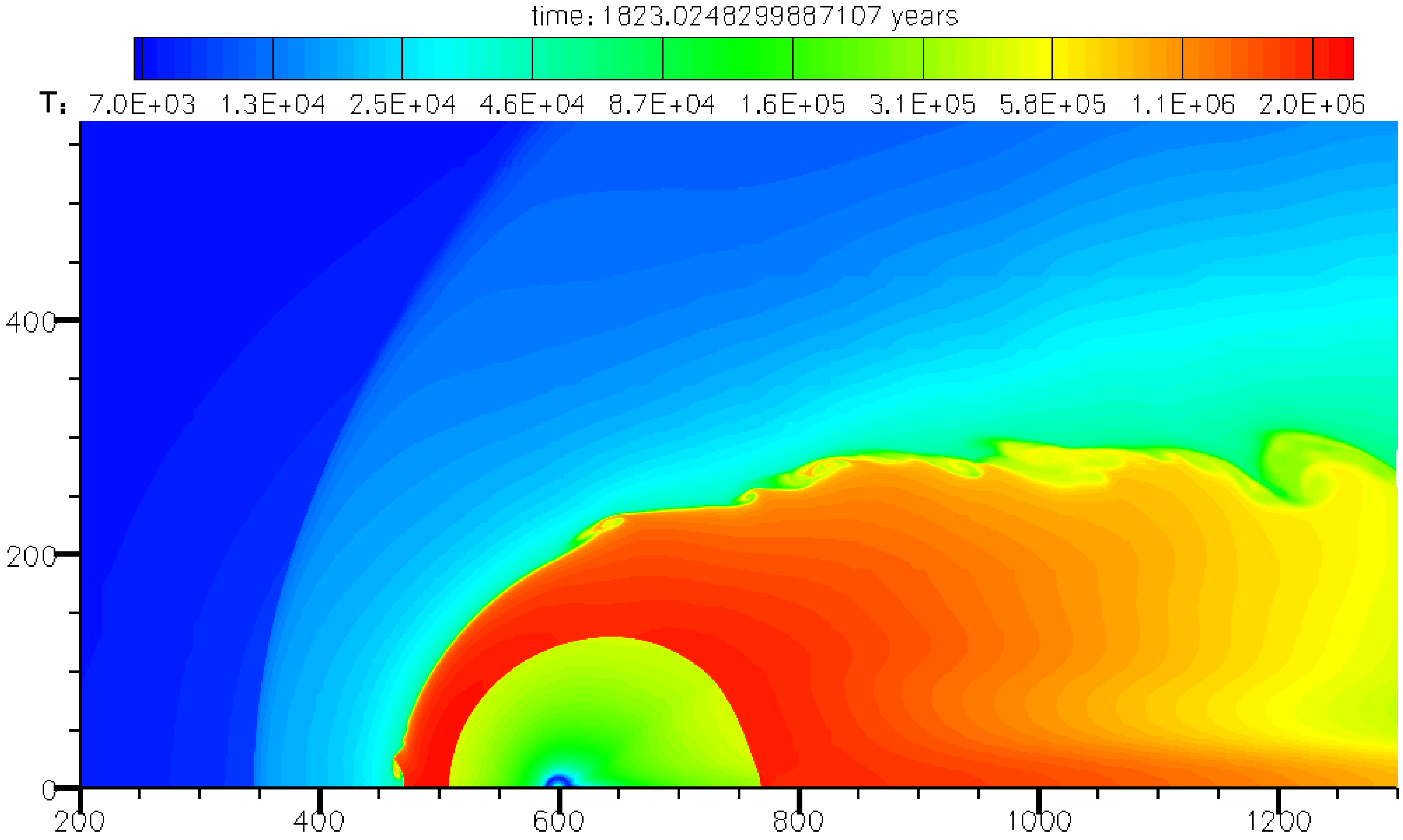


Courtesy Gary Zank, UAH

Time-evolution of the RT-instability - movie



Combined Rayleigh-Taylor (on nose) and Kelvin-Helmholtz (on flanks) instabilities driven by interstellar neutrals

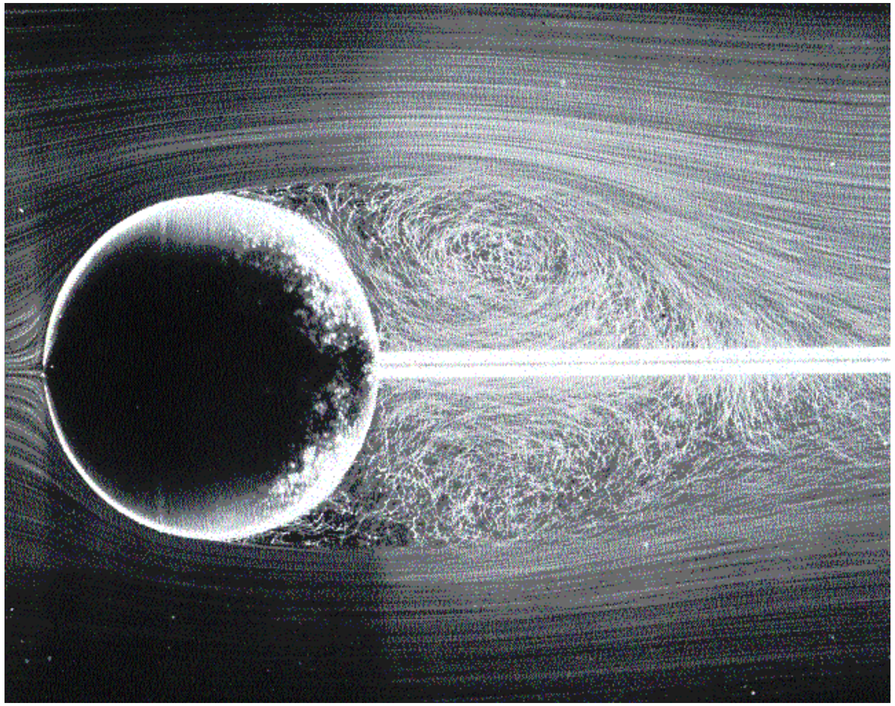


Courtesy Gary Zank, UAH

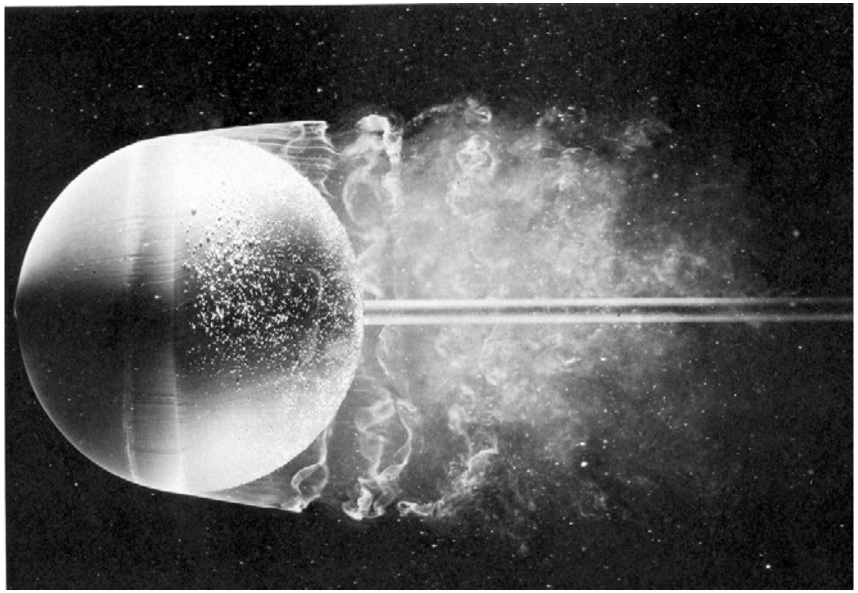
VanDyke, An Album of Fluid Motion

Mean flow and fluctuations

- In turbulence there can be great differences between mean state and fluctuating state
- Example: Flow around sphere at R = 15,000



Mean flow



Instantaneous flow

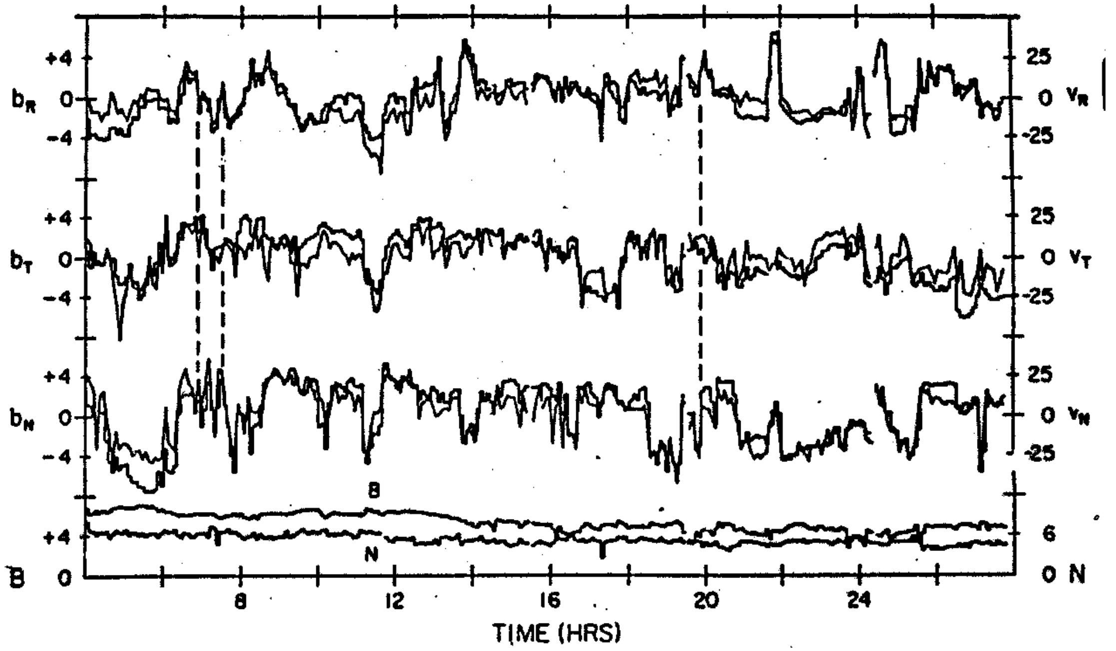
Strength of electric current density in shear-driven kinetic plasma (PIC) simulation

Thinnest sheets seen are comparable to electron inertial length. Sheets are clustered
At about the ion inertial length → heirarchy of coherent, dissipative structures at kinetic scales

The solar wind is turbulent

- Fluctuations in velocity and magnetic field are irregular, not "reproducible," broad-band in space and time
- Indications of turbulence properties and wave-like properties

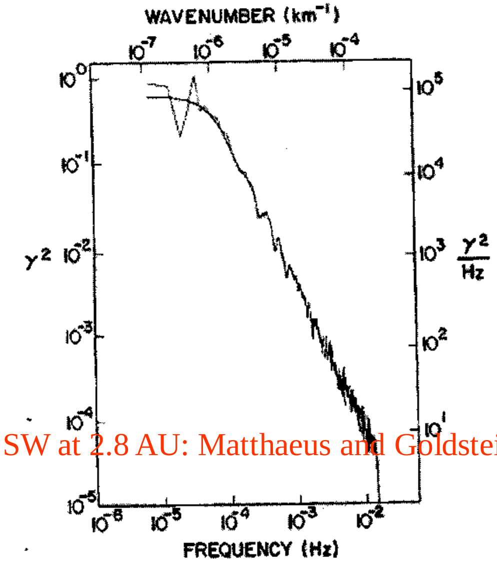
Mariner 2 data



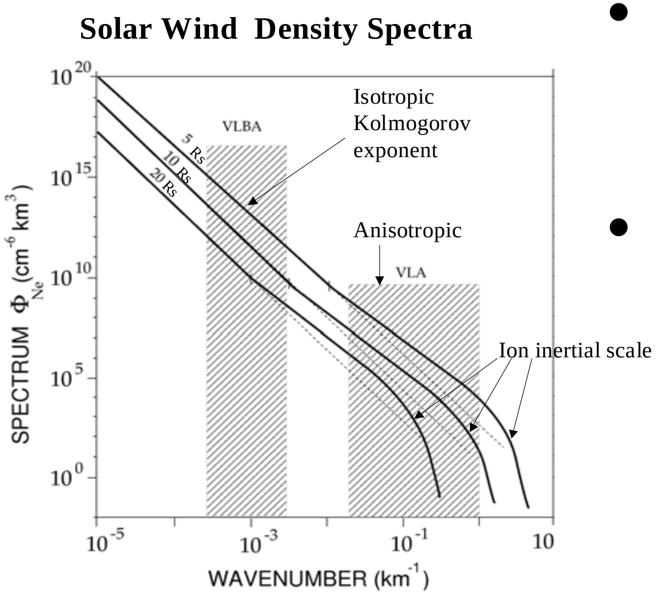
Belcher and Davis, JGR, 1972

“Powerlaws everywhere” →

Broadband self-similar spectra are a signature of cascade

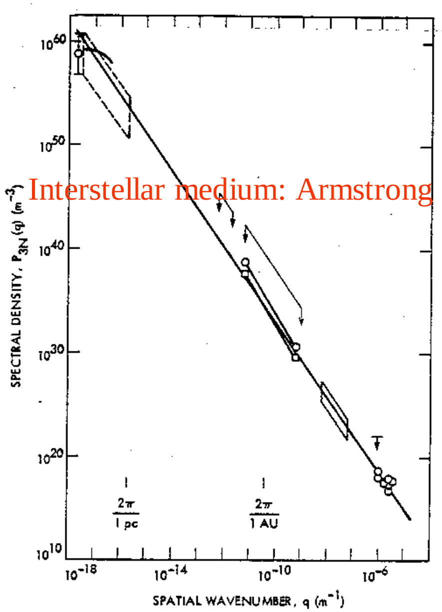


SW at 2.8 AU: Matthaeus and Goldstein

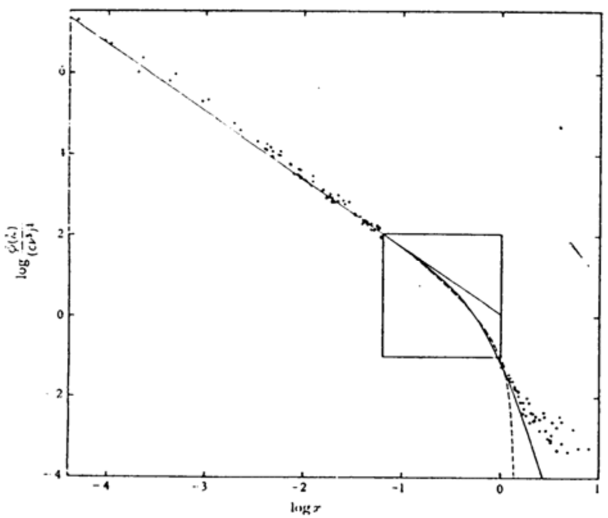


Coronal scintillation results (Harmon and Coles)

- Solar wind
- Corona
- Diffuse ISM
- Geophysical flows

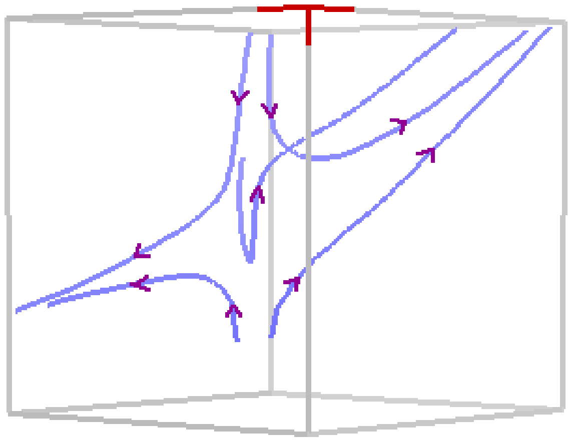


Interstellar medium: Armstrong et al

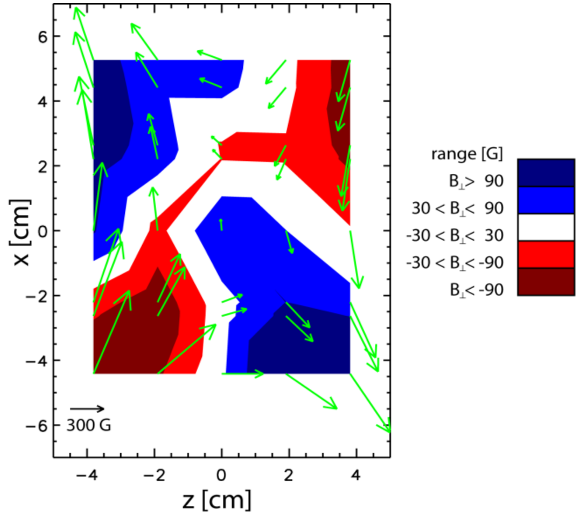


Tidal channel: Grant, Stewart and Moilliet

SSX



3D structure measured at the ion inertial scale in SSX merging experiments

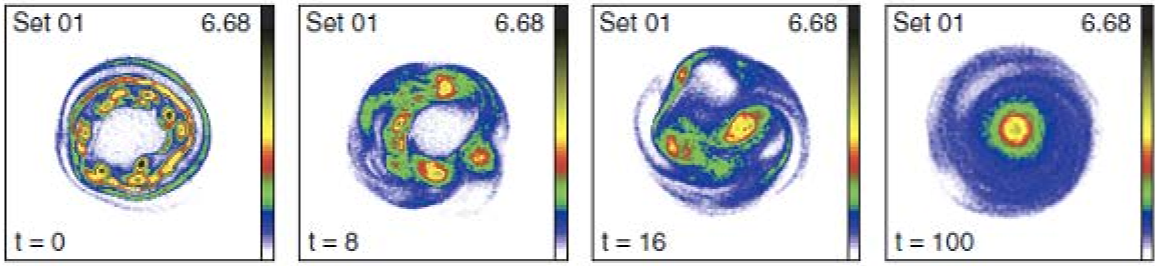


Measurement of Hall effect out of plane quadrupole field observed on length scale similar to Polar observations at the magnetopause

What happens to similarity decay if direct cascaded quantity when there is an inverse cascade?

E.g., Enstrophy decay in electron plasma

Penning trap:
2D Guiding
Center plasma
(~ 2D hydro)



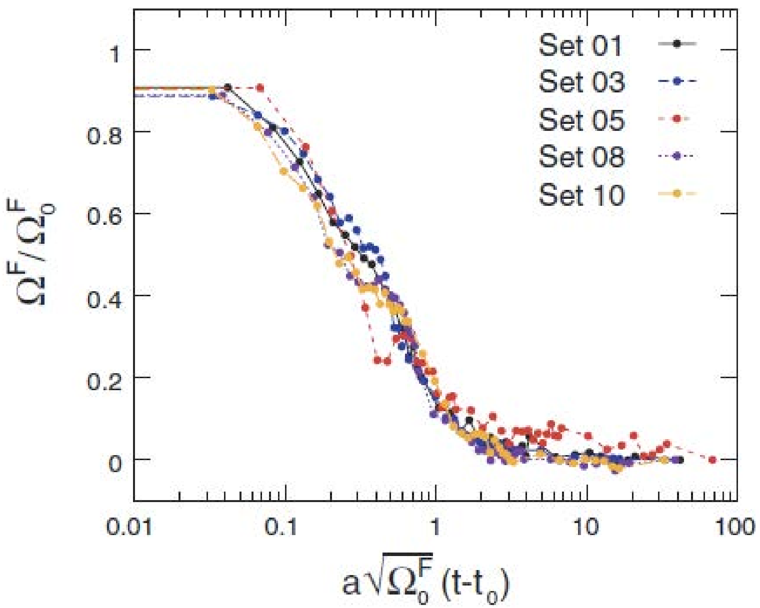
Metastable
State
(MaxEnt)
←

- "free enstrophy" – subtract final metastable enstrophy

$$d\Omega^F/dt = -a\,\Omega^{F\frac{3}{2}}$$

$$\frac{\Omega^F}{\Omega_0^F} = \left(1 + 2a\sqrt{\Omega_0^F}(t - t_0)\right)^{-2}, \qquad (10)$$

Here $\Omega_0^F = \Omega^F(t_0)$ is the initial free enstrophy. For an initially disordered fluid with large Ω_0^F, 10 gives $\Omega^F \sim t^{-2}$ for $a\sqrt{\Omega_0^F}t \gg 1$, as in the isotropic case predicted by Batchelor



Rodgers et al , PRL 2010

Why plasma turbulence is important

- transport (diffusion, mixing…)
- heating
- charged particle scattering
- charged particle acceleration
- cross scale couplings
- Sun-solar wind-magnetosphere-couplings (Space Weather)