Quiet time particle acceleration in the interplanetary space

Fabio Lepreti[1]
Heinz Isliker
Kallia Petraki[2]
Loukas Vlahos

Department of Physics
Aristotle University of Thessaloniki

“TOSTISP” Research Training Network

[1] On move to Department of Physics, University of Calabria
[2] Now PhD student at UCLA

Outline

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- The model
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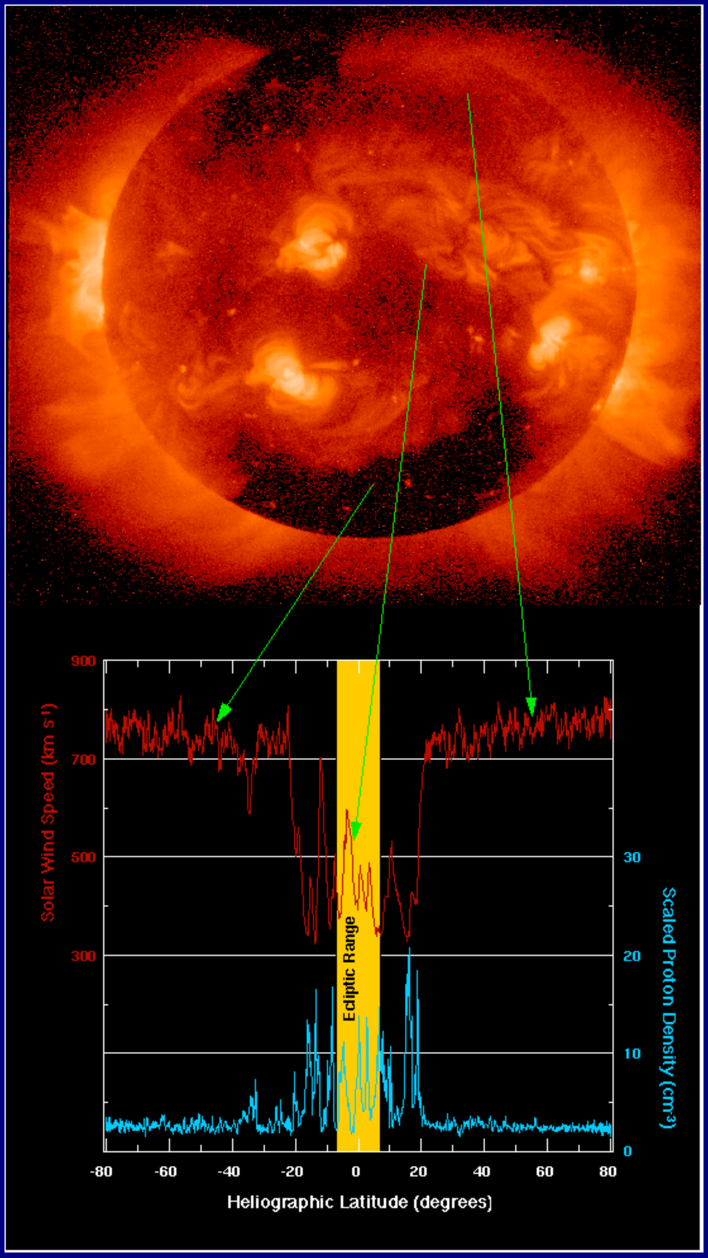
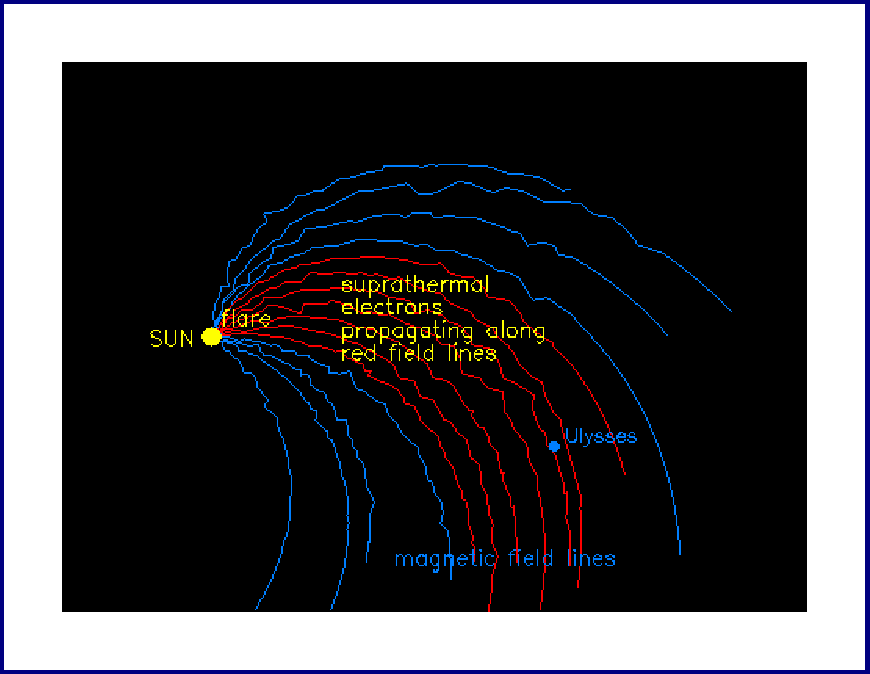
  - Our model for turbulent EM fields
  - Shell models
- Results of the numerical simulations
- Summary and future developments

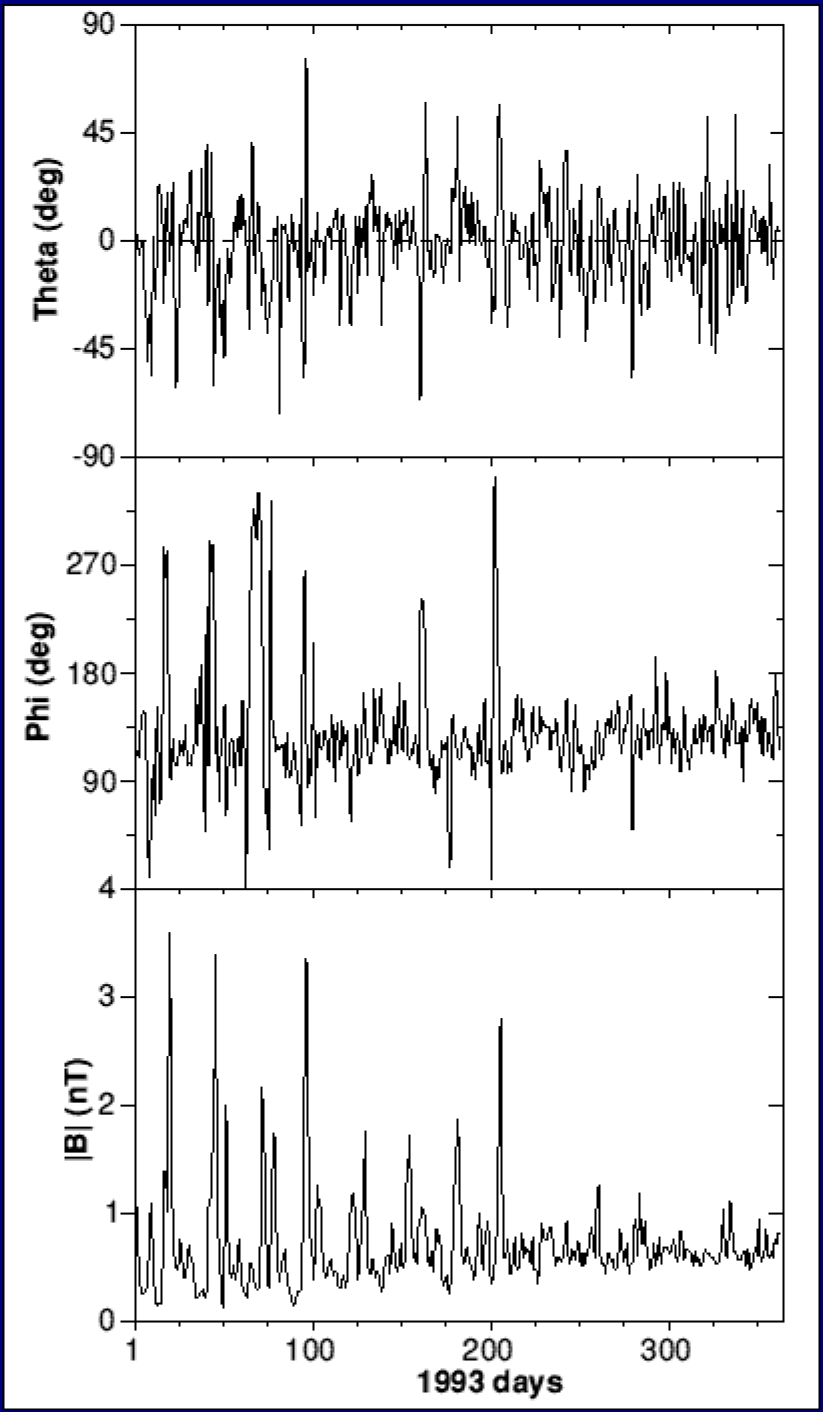
Introduction and motivation: interplanetary space and solar wind

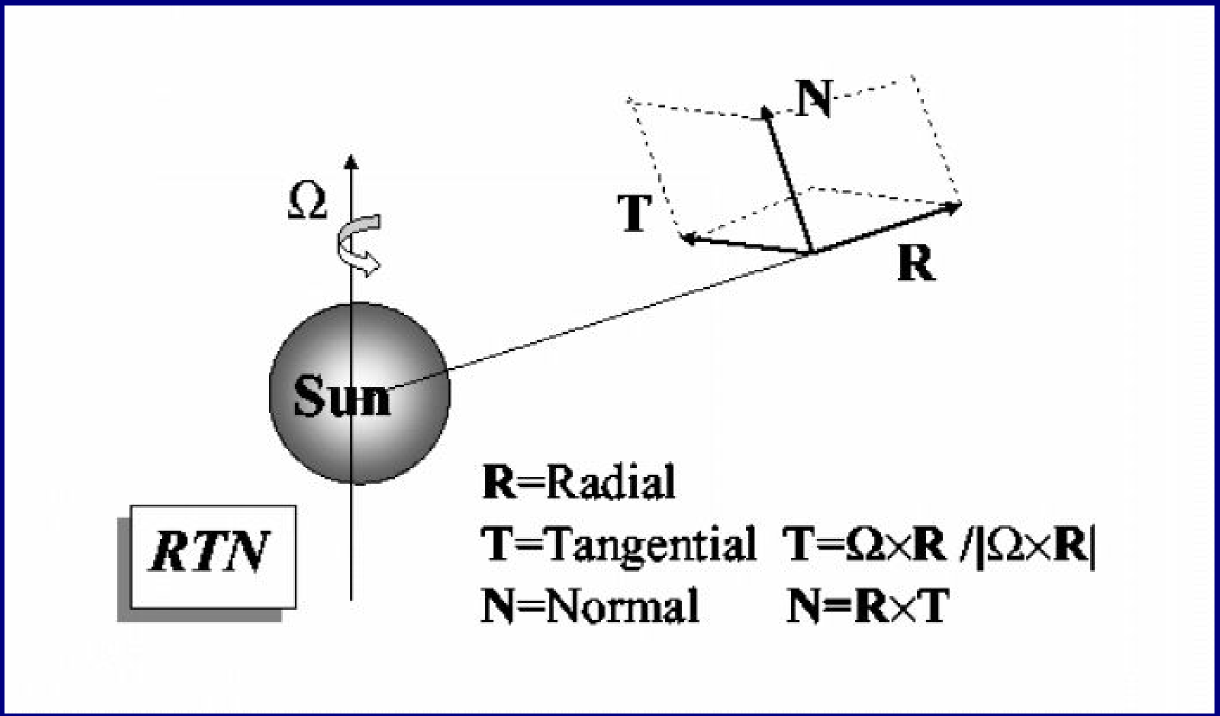


- The SW and the solar magnetic activity are at the origin of the very complex structure of velocity and magnetic fields in the IS
- Slow and fast wind streams
- Complex magnetic field structure



Introduction and motivation: IS and SW





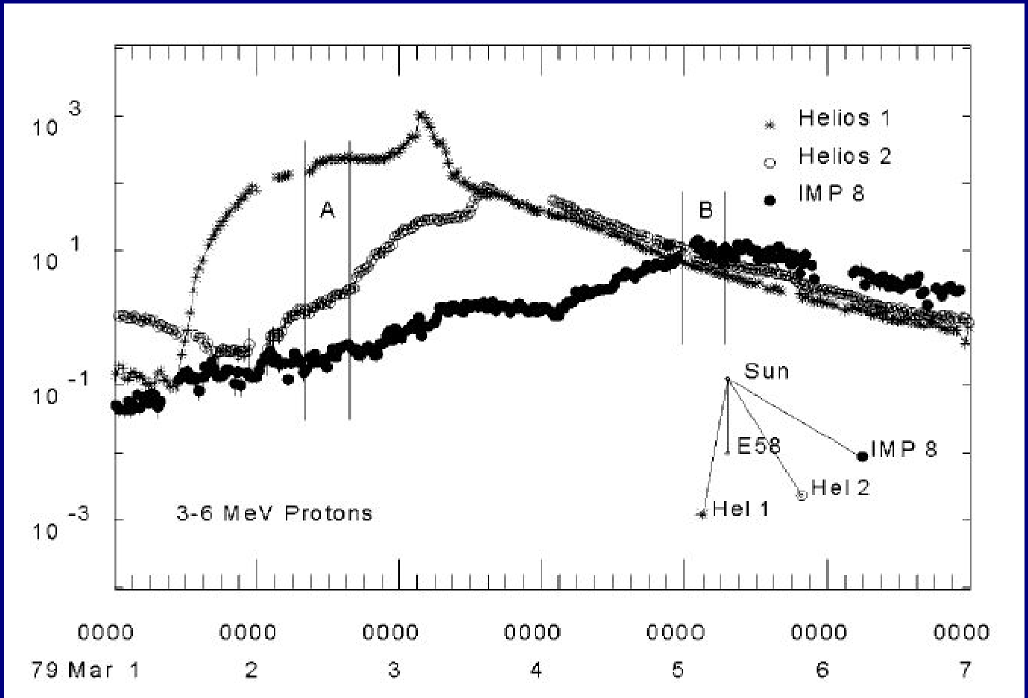
- Magnetic field magnitude and direction for the whole 1993 year, measured by Ulysses spacecraft
- Fluctuations due to the presence of turbulence, interplanetary shocks, etc.

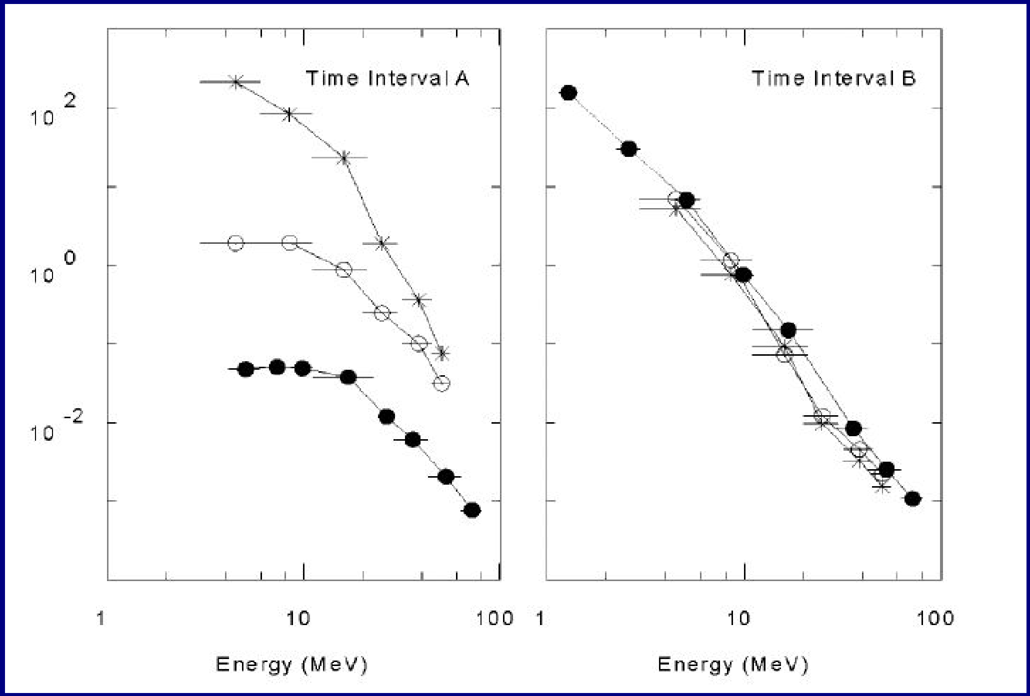
Introduction and motivation: observations

- Non thermal, high energy particles are often observed in the IS
- Rich variety of physical characteristics related to the existence of different sources of acceleration: flares, Coronal Mass Ejections (CME's), interplanetary shocks, etc. (see Reames 1999 for a review)
- For many years available observations only for $E_{KIN} > 100$ keV

Introduction and motivation: observations

Proton energy spectra of an heliospheric particle energetic event related to a CME-driven shock



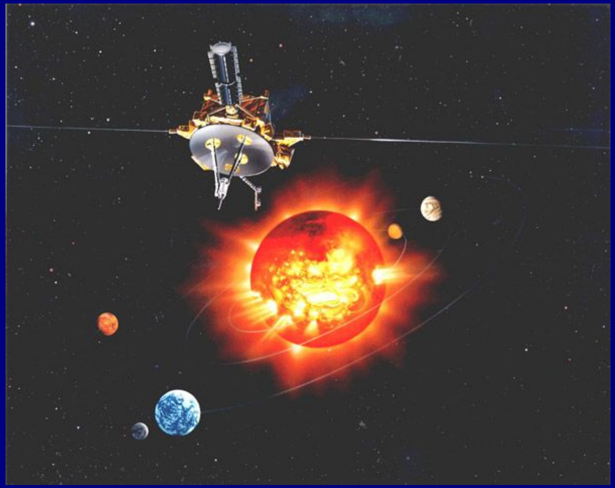


Reames (1999)

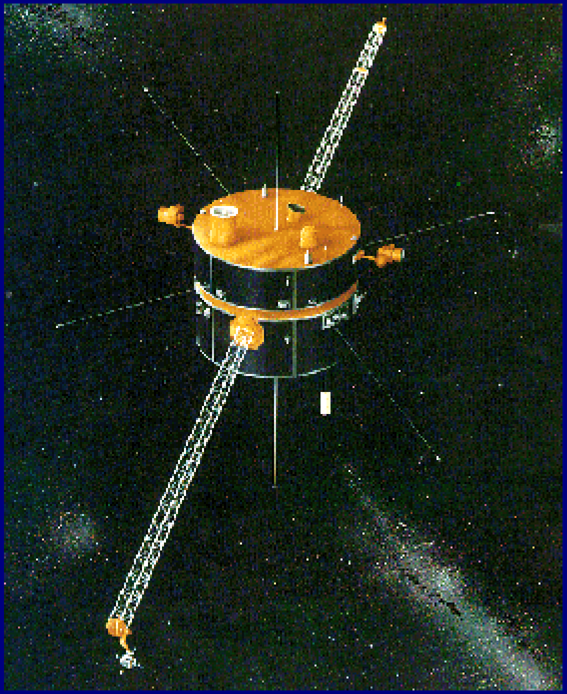
Introduction and motivation: observations

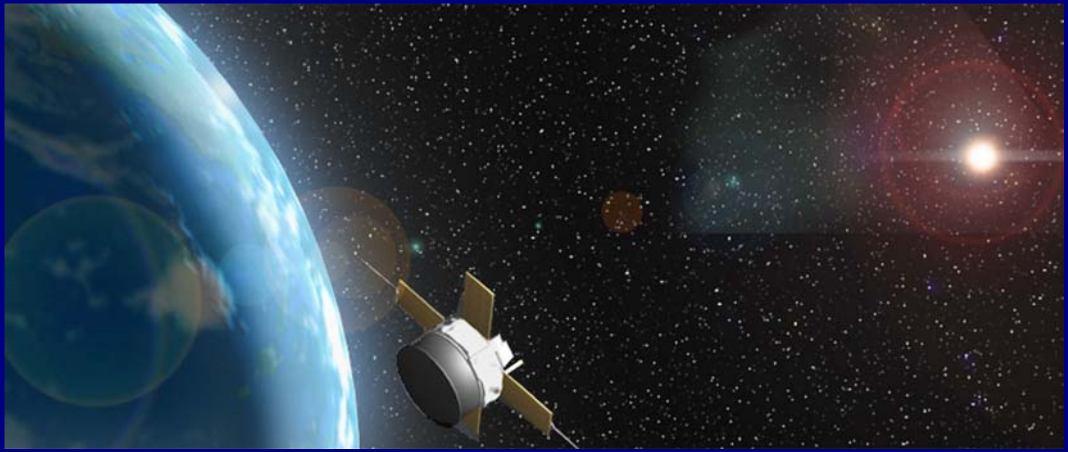
- With the launch of Ulysses, ACE and WIND, available observations also for $E_{KIN} < 100$ keV

http://ulysses.jpl.nasa.gov/



http://www-istp.gsfc.nasa.gov/istp/wind/

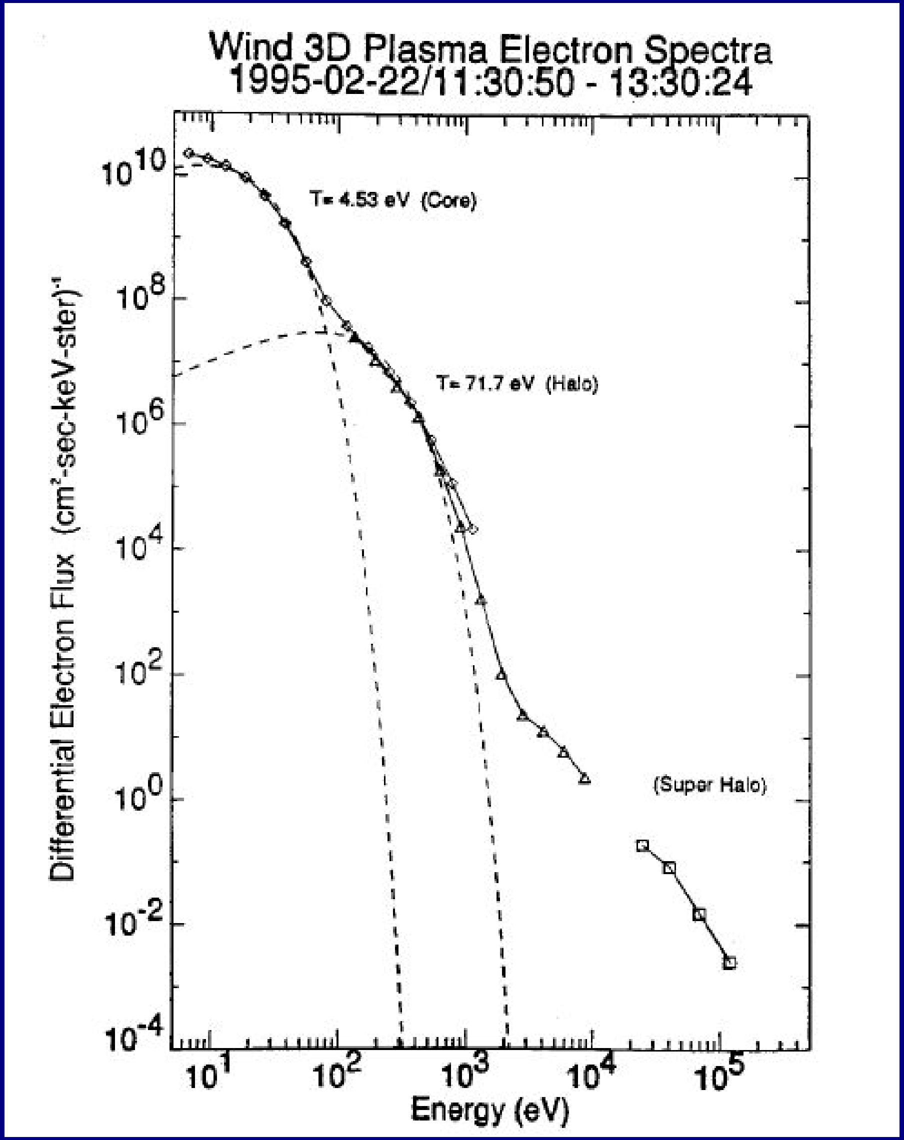




http://www.srl.caltech.edu/ACE/

Introduction and motivation: observations

- Suprathermal particles observed, at all times, also during “quiet time” periods, that is, far from shocks, and other disturbances

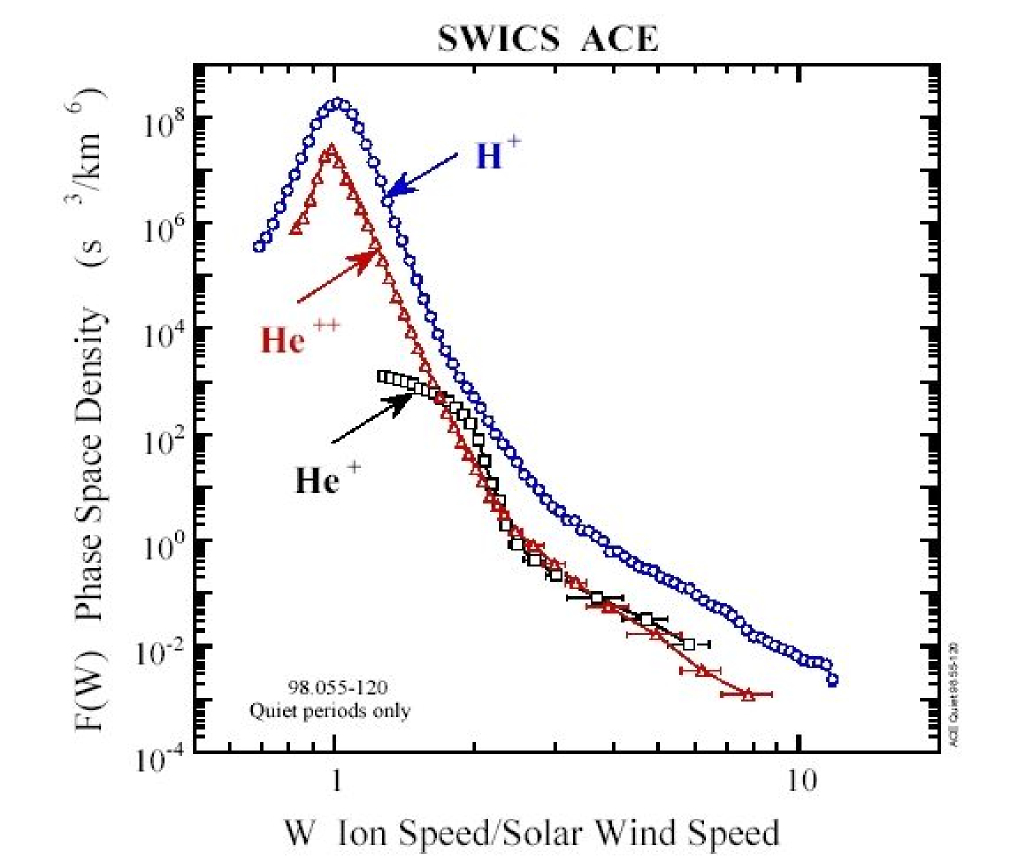


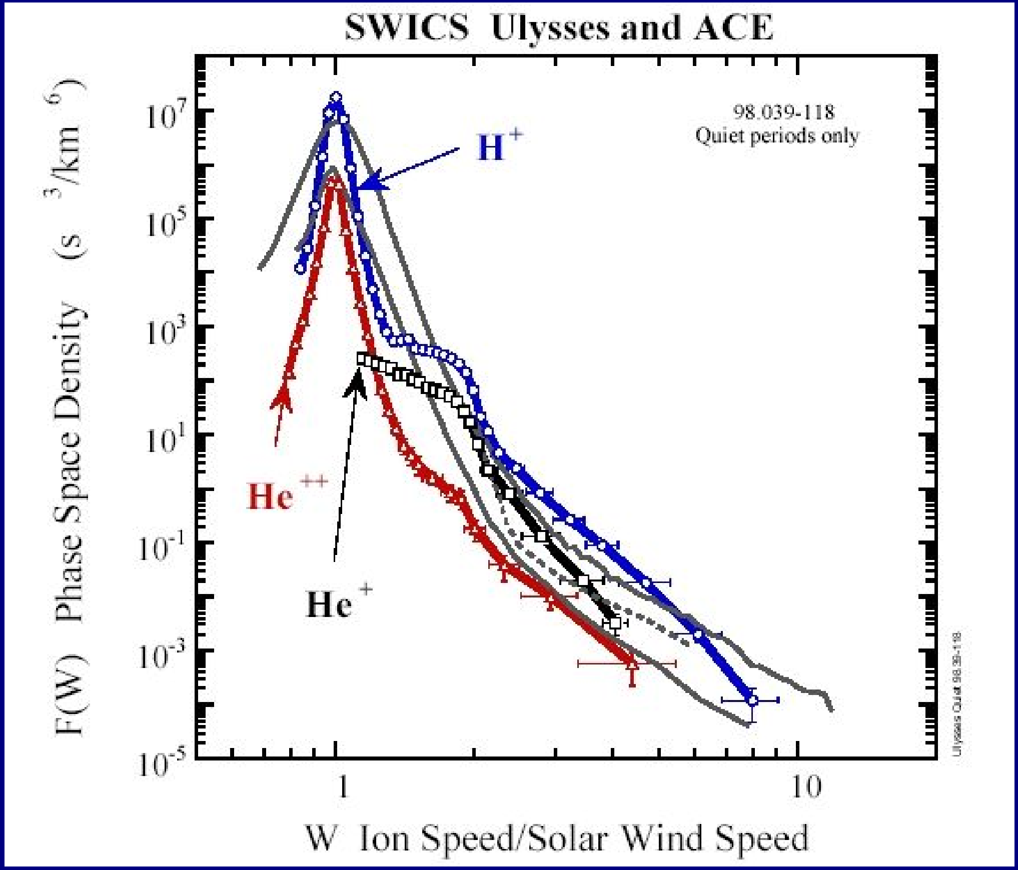
- Electron spectrum measured during a quiet time period by the WIND 3-D Plasma and Energetic Particle experiment
- Solar wind halo between ~100 eV and ~1 keV believed to be due to the escape of coronal thermal electrons
- Suprathermal tail (super-halo) between ~2 keV and ~100 keV

Lin (1998)

Introduction and motivation: observations

Speed distributions of H^+, He^+, and He^{++} ions in the quiet solar wind at 1 AU (ACE) and at 5.4 AU (Ulysses)



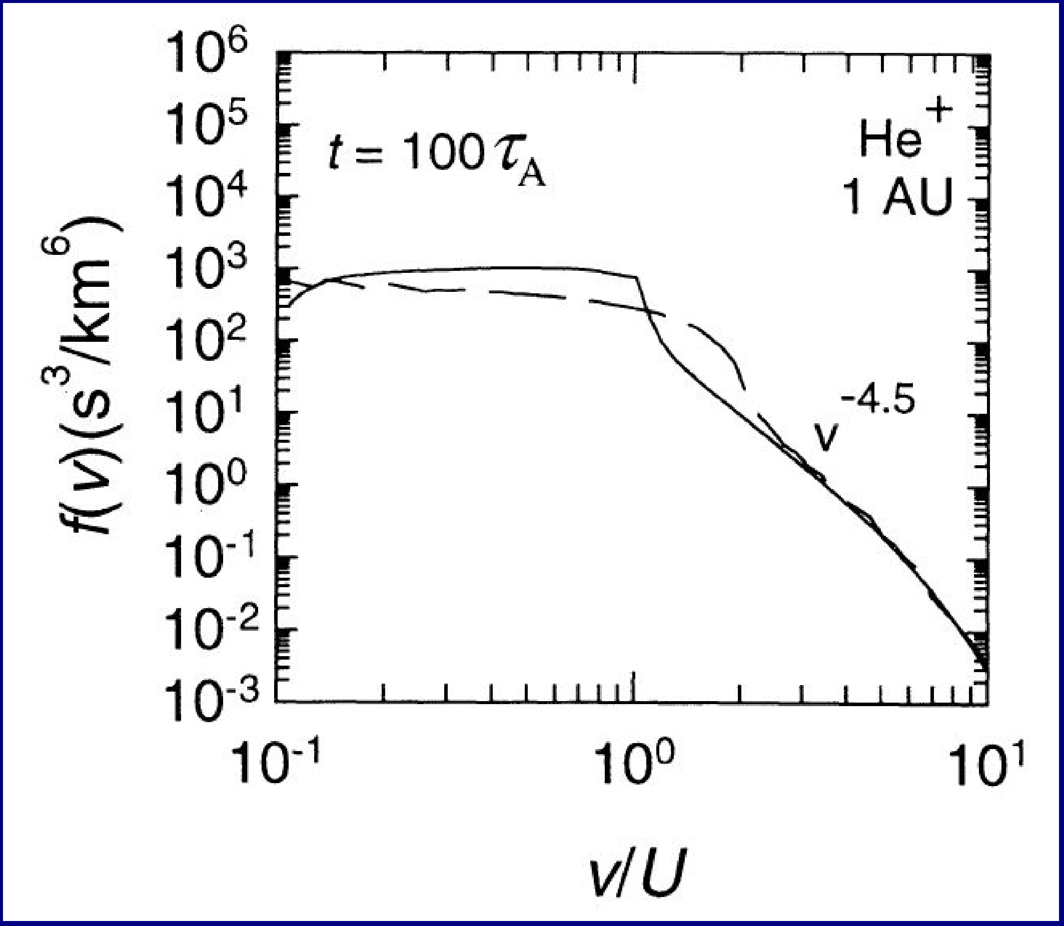


Gloeckler et al. (2000)

Introduction and motivation: a previous model

- "What mechanism produces these ubiquitous, quiet-time suprathermal tails still remains an open question." (Gloeckler 2003)

- le Roux et al. (2001) proposed that ions might be accelerated by large-scale turbulent electric fields directed along the background magnetic field.
- They studied this process through a kinetic numerical model of the ion transport in the interplanetary space.



The model: test particle motion

- Our approach is based on test particle simulations in turbulent EM fields
- Solve numerically the relativistic motion equations of charged particles in turbulent EM fields obtained from a dynamical system model of turbulence (i.e. shell model)

$$\frac{d\boldsymbol{r}}{dt} = \boldsymbol{v}$$

$$\frac{d\boldsymbol{p}}{dt} = e\left[\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}\times\boldsymbol{B}\right]$$

$$\boldsymbol{p} = \frac{m\boldsymbol{v}}{\sqrt{1-\frac{v^2}{c^2}}}$$

Test particle acceleration

- Possible approaches
  - The electromagnetic fields obtained from the numerical solution of magnetohydrodynamic equations are used to perform test particle simulations (see e.g. Nodes et al. 2003; Dmitruk et al. 2003)
  - Use simplified models to describe the main features of turbulent electromagnetic fields (see e.g. Anastasiadis et al. 1997; Veltri et al. 1998; Arzner & Vlahos 2004)
- Test particle acceleration in turbulence: some key points
  - Small scale, strong, coherent field structures, produced by the turbulent energy cascade, can act as acceleration centers.
  - Trapping of the particles in such regions can lead to effective acceleration.

The model: magnetic and electric fields

- We consider a weakly magnetized plasma. The magnetic energy is much smaller than the fluid kinetic energy. The back reaction of ***B*** on ***V*** is neglected.

$E_B << E_V$

- The interplanetary plasma is almost collisionless ⇒ perfectly conducting plasma

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B})$$

MHD Induction equation for a perfectly conducting plasma

$$\boldsymbol{E} = -\frac{1}{c} \boldsymbol{V} \times \boldsymbol{B}$$

Electric field

The velocity field is constructed through a turbulence shell model

Construction of the velocity field: shell model

- Turbulence is the result of nonlinear dynamics

Navier-Stokes equation

$$\frac{\partial \boldsymbol{V}}{\partial t}+(\boldsymbol{V}\cdot\nabla)\boldsymbol{V}=-\frac{1}{\rho}\nabla P+\nu\nabla^2\boldsymbol{V}$$

Nonlinear term

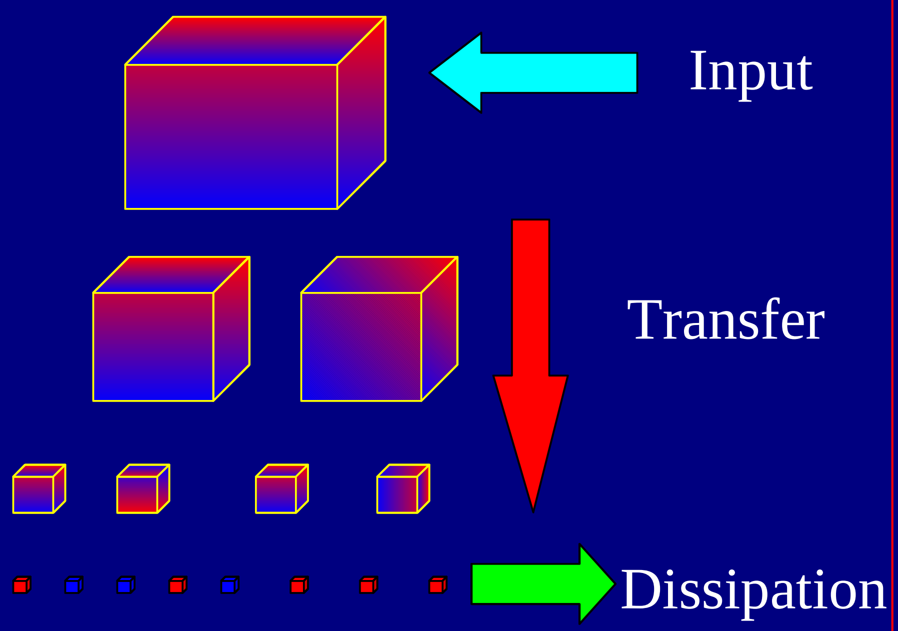
Dissipative term

Reynolds number

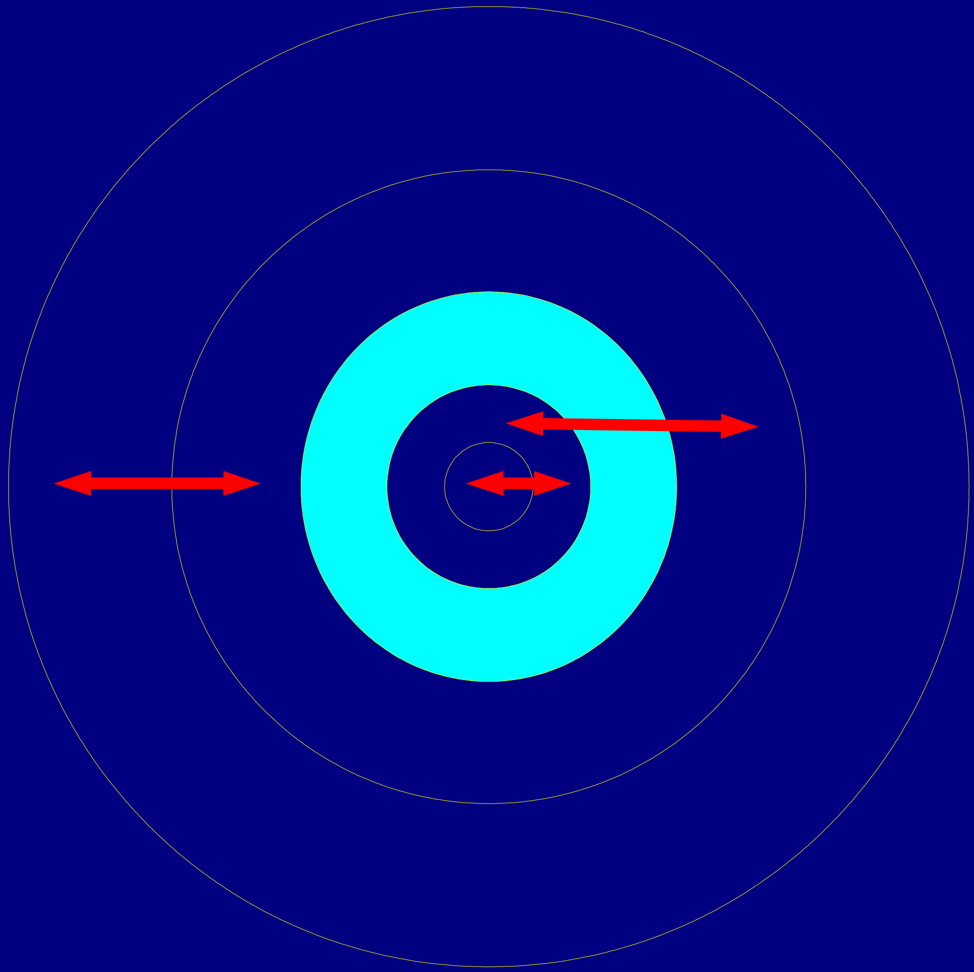
$$R=\frac{nonlinear}{dissipative}=\frac{VL}{\nu}$$

Shell models: dynamical systems describing the nonlinear interactions in the wave vector space.

The Richardson picture (1922)



Turbulent energy cascade from large to small scales due to nonlinear interactions



- Wave vector space divided in logarithmically spaced shells $k_n = h^n k_0$
- A complex variable $u_n(t)$, representing the amplitude of velocity fluctuations at scale $l \simeq k_n^{-1}$ is associated to each shell
- Nonlinear, quadratic couplings between neighboring shells with coefficients coming from conservation of invariants

Shell model equations

$$\frac{du_n}{dt} = F_n(u_{n-2}, u_{n-1}, u_{n+1}, u_{n+2}) + \nu k_n^2 u_n + f_n$$

Nonlinear term

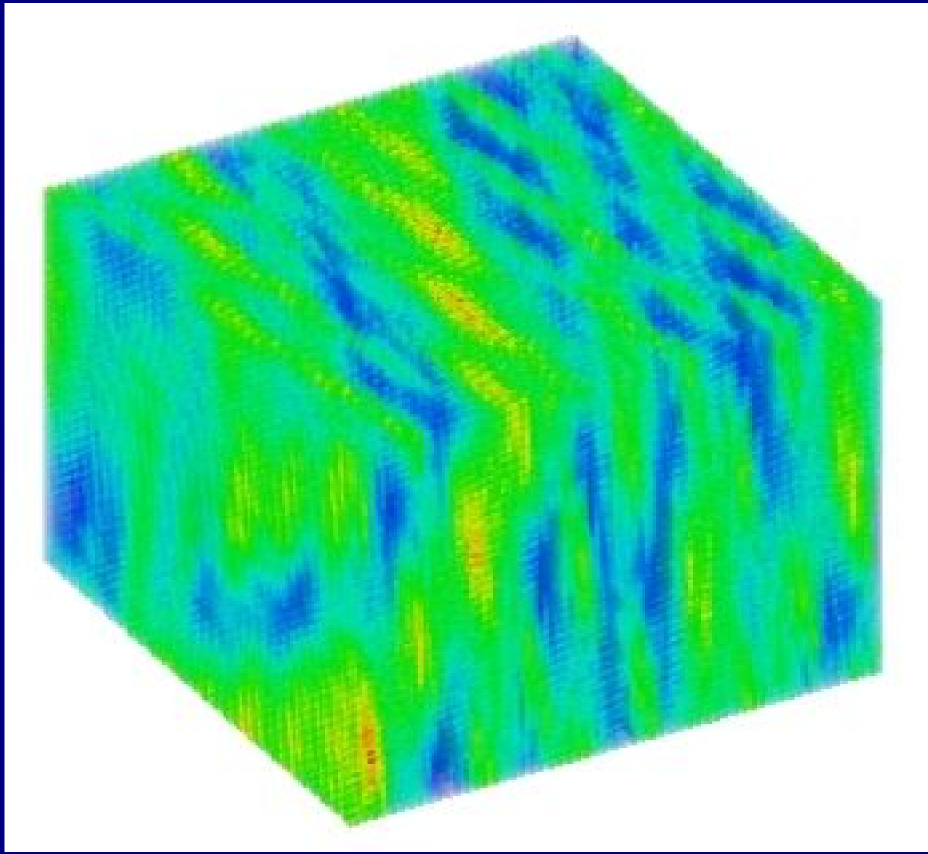
Dissipative term

Forcing

Construction of the velocity field: shell model

A 3-D velocity field can be constructed using the shell model coefficients (Bohr et al. 2000)

$$V_j(x,t)=\sum_{n=1}^{N} C_n^{(j)}\left[u_n(t)e^{ik_n\cdot x}+c.c.\right]$$



$\mathbf{k}_n = k_n\,\mathbf{e}_n$

$\mathbf{e}_n$ randomly choosen unit vectors

$C_n^{(j)}$ random coefficients of order O(1)

The incompressibility constraints are imposed

Numerical simulations

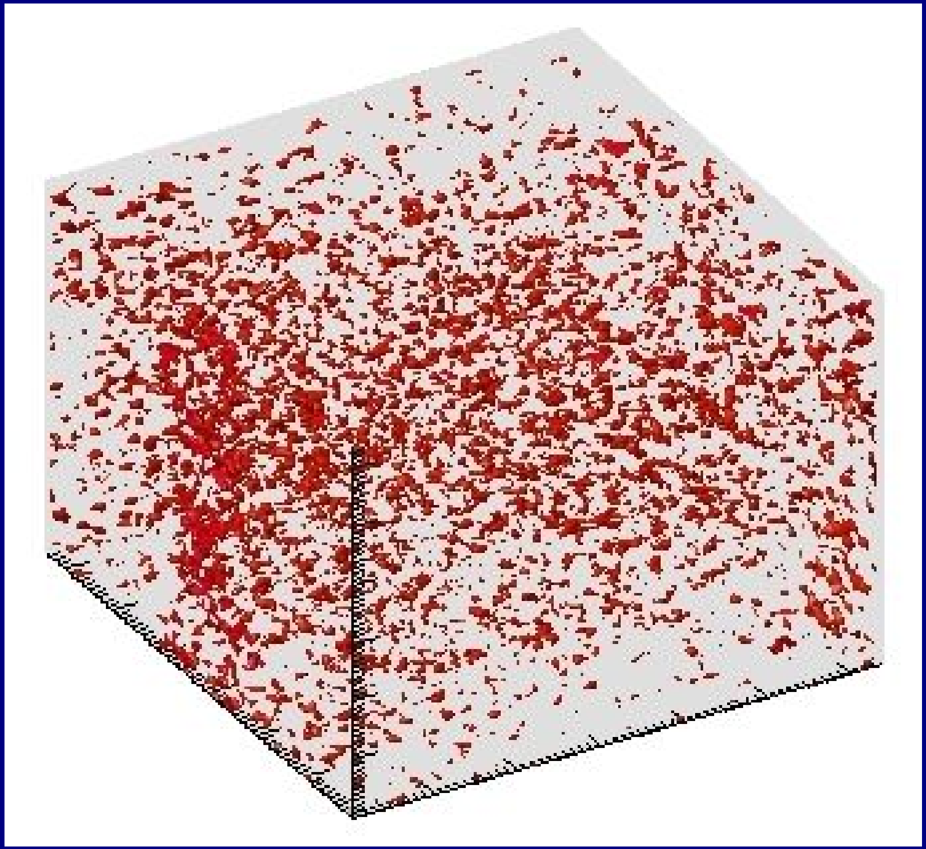
- We solve numerically the shell model equations with $N = 22$ shells, by using a 4-th order Runge-Kutta algorithm
- The 3-D velocity field $\boldsymbol{V}(\boldsymbol{x},t)$ is used for the numerical integration of the MHD induction equation on a 64^3 grid. A Wilson scheme (modified upwind) is used (Wilson 1978, Hawley et al. 1984)
- The initial magnetic field is given by a random perturbation constructed through a sum of Fourier modes with Gaussian distributed amplitudes
- $\boldsymbol{V}(\boldsymbol{x},t)$ and $\boldsymbol{B}(\boldsymbol{x},t)$ are rescaled to the typical values of velocity and magnetic turbulent fluctuations in the interplanetary space

- The particle motion equations are solved with a 4-th order Runge-Kutta, adaptive step-size scheme
- The magnetic and electric field configurations are kept constant during the time we monitor the particles and 3-D linear interpolation is used to provide field values in between grid points.

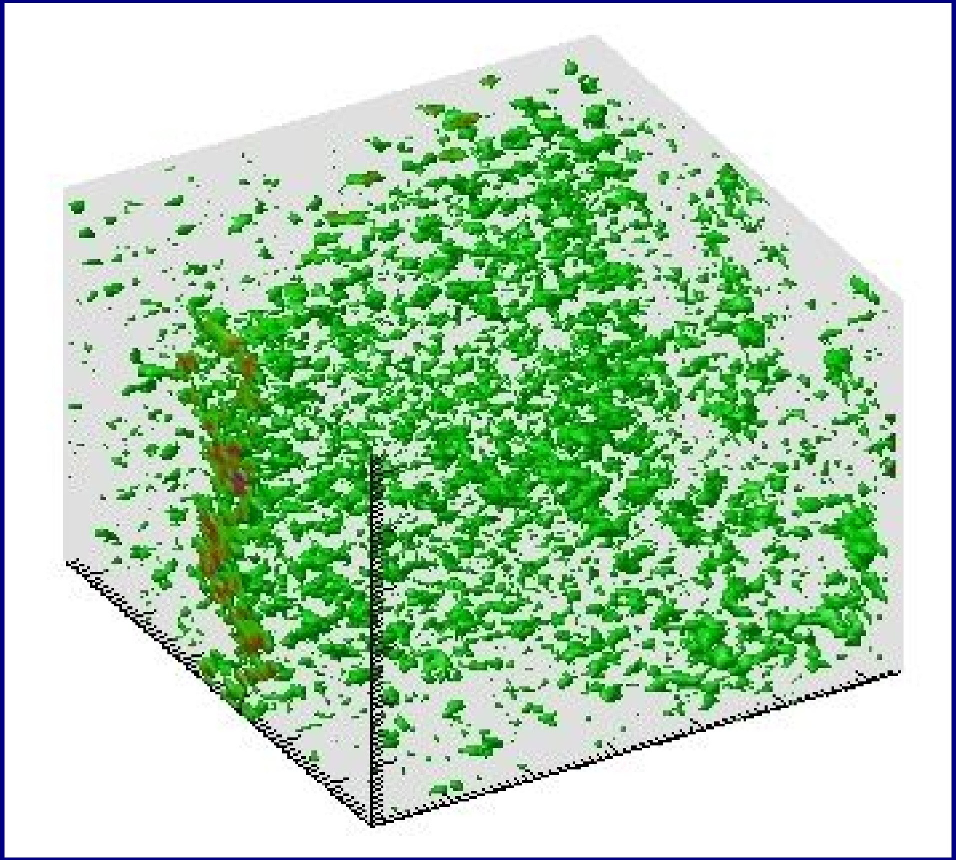
Numerical simulations: structure of the fields

Magnetic and electric field intensity above a fixed threshold

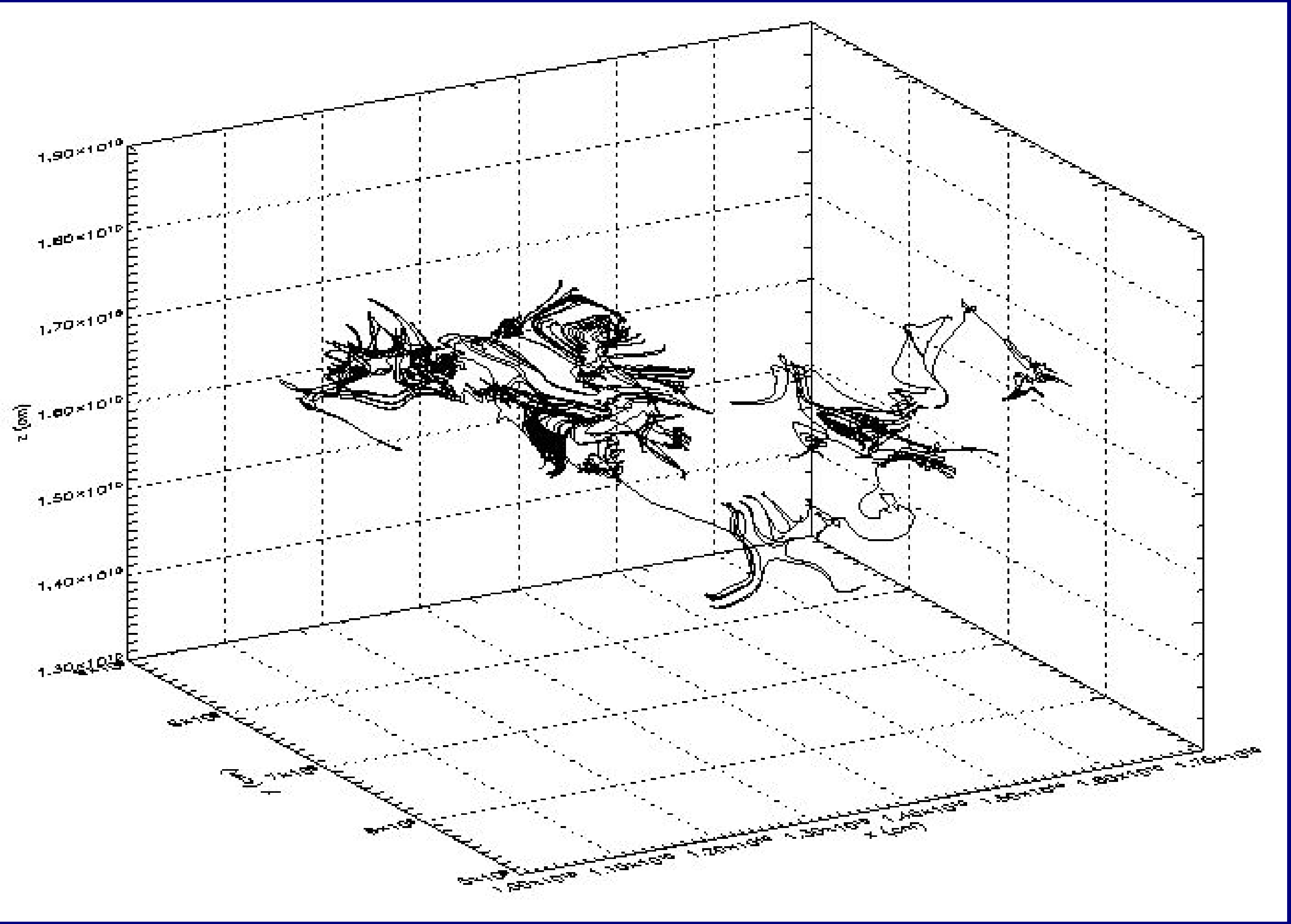
Magnetic field



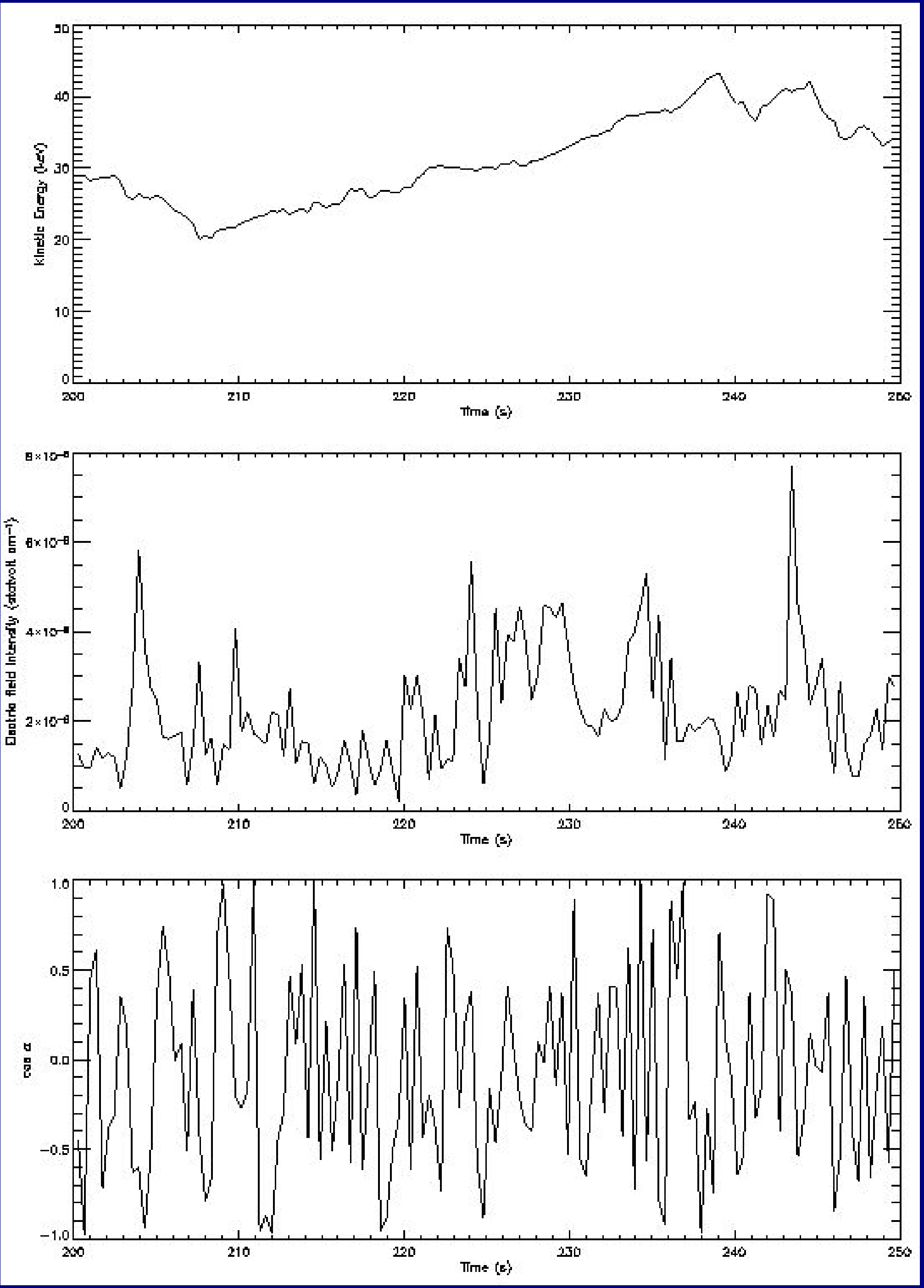
Electric field



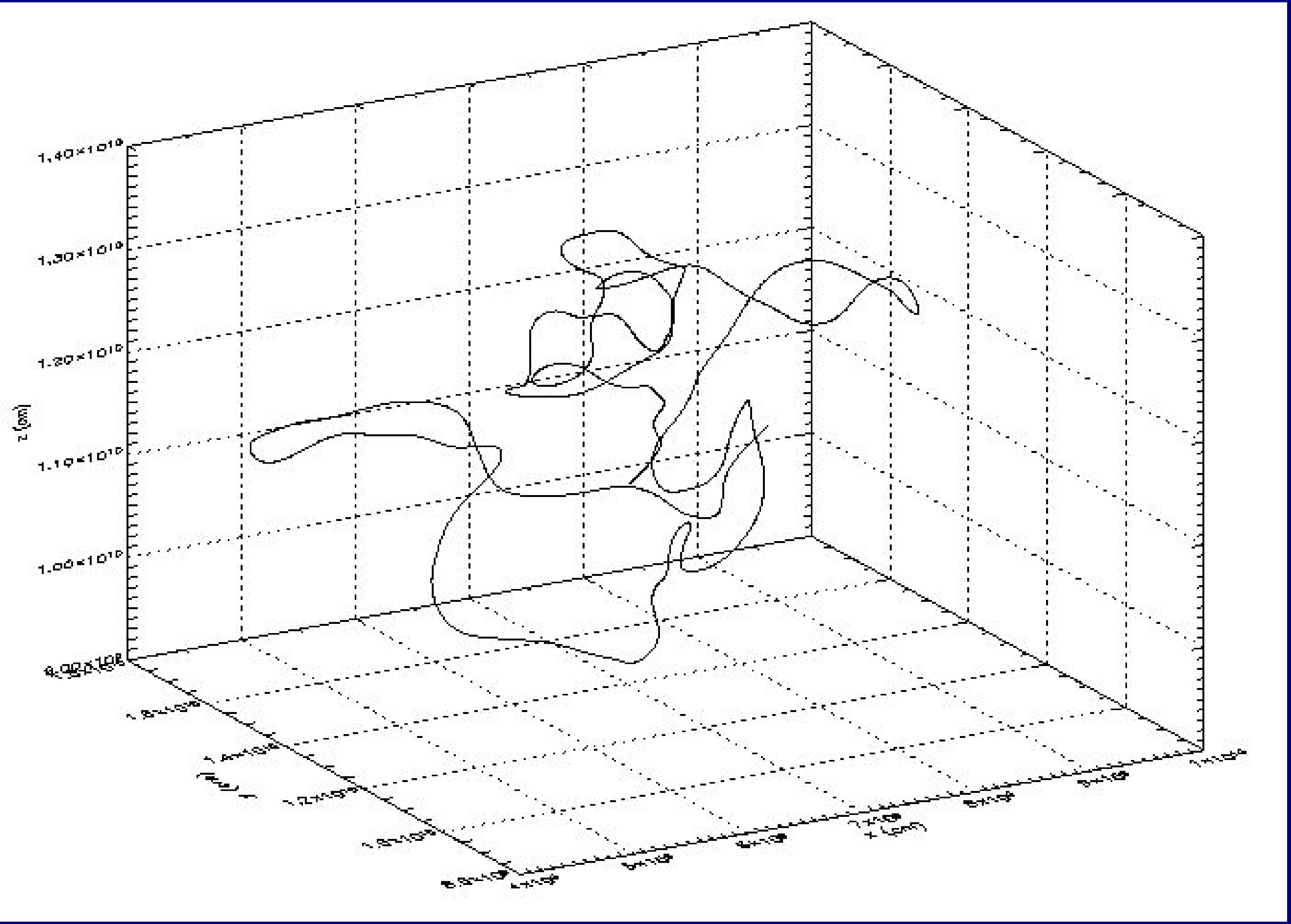
Numerical simulations: electron trajectories



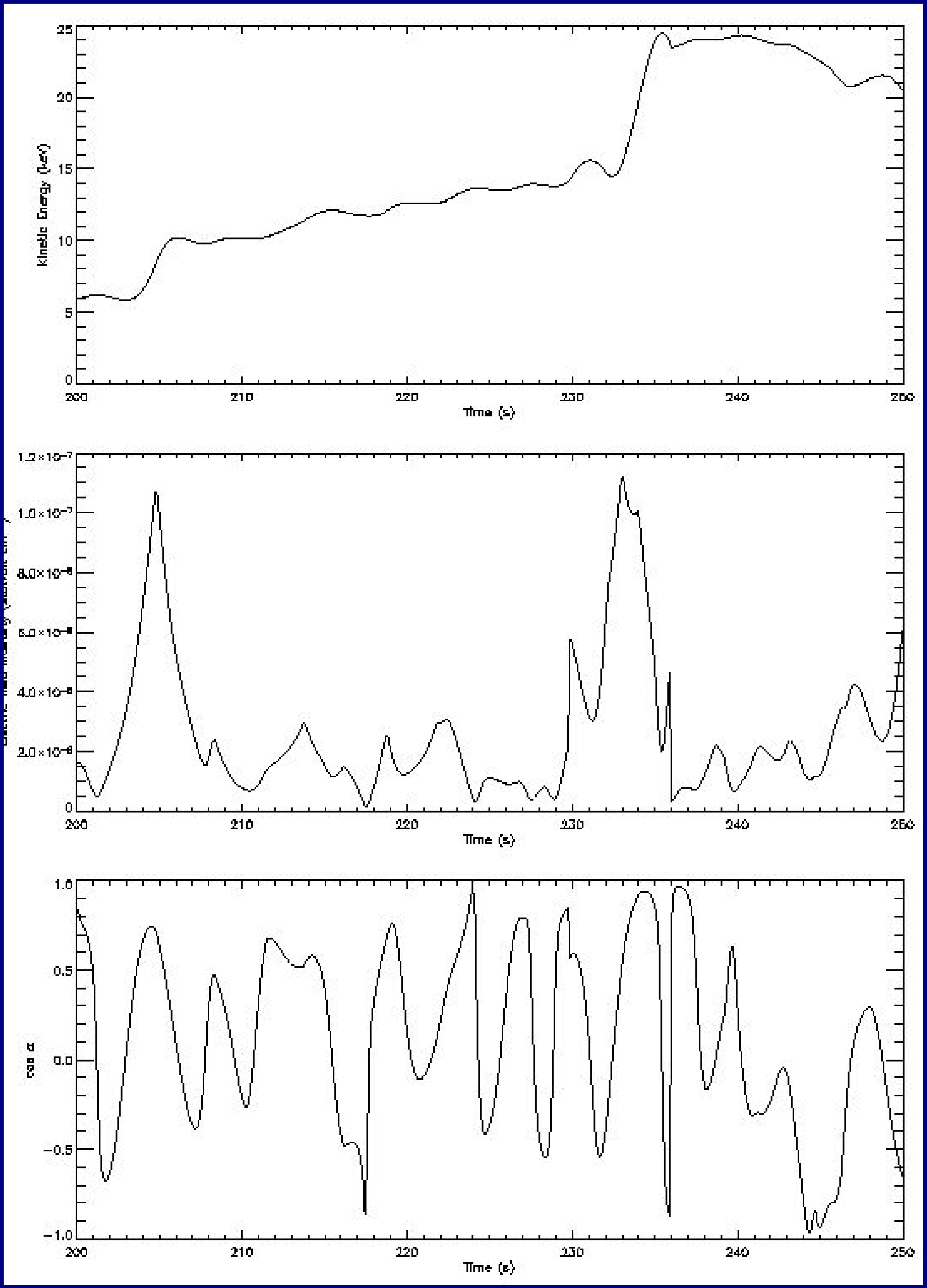
Numerical simulations: electron energy



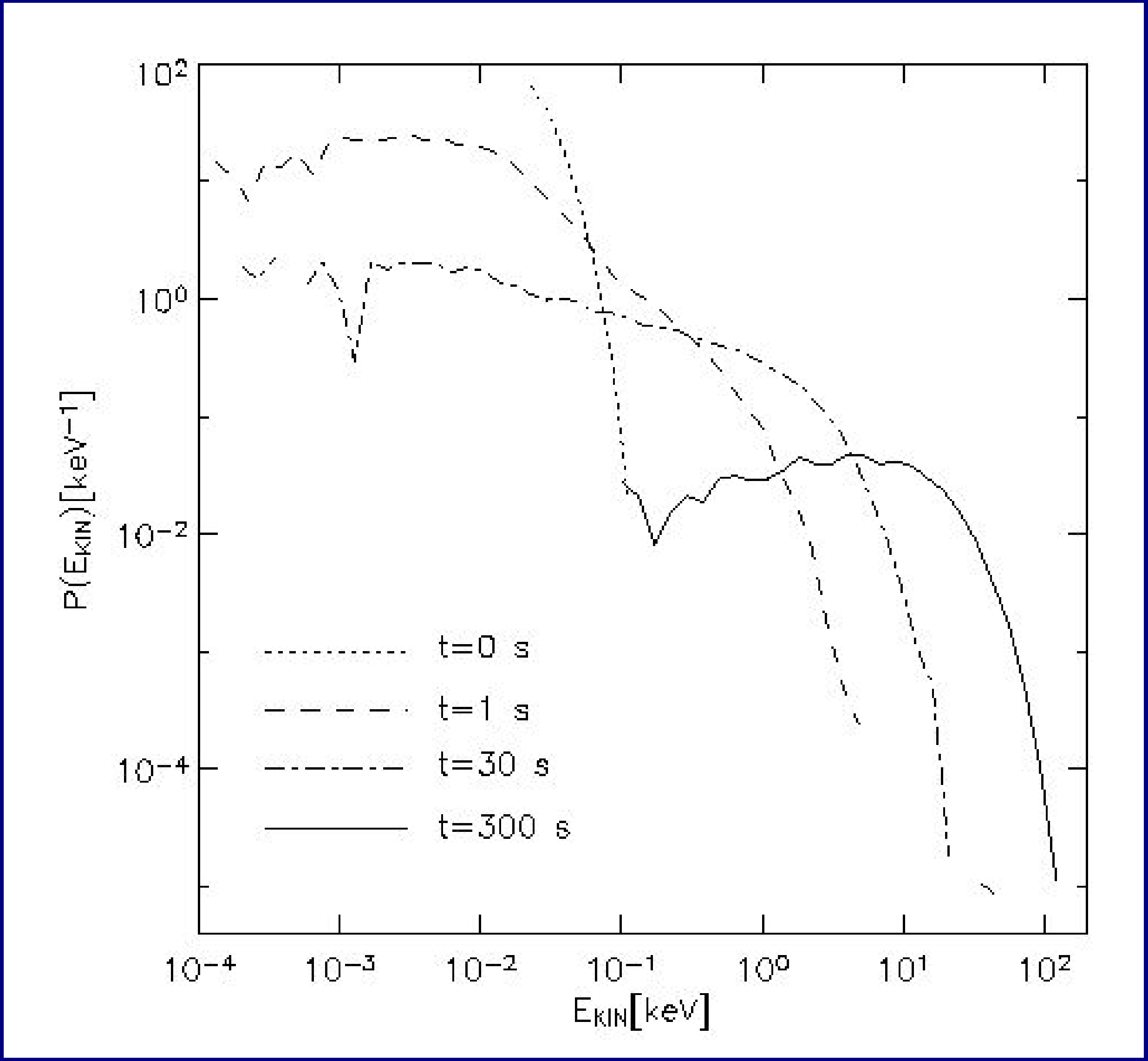
Numerical simulations: proton trajectories



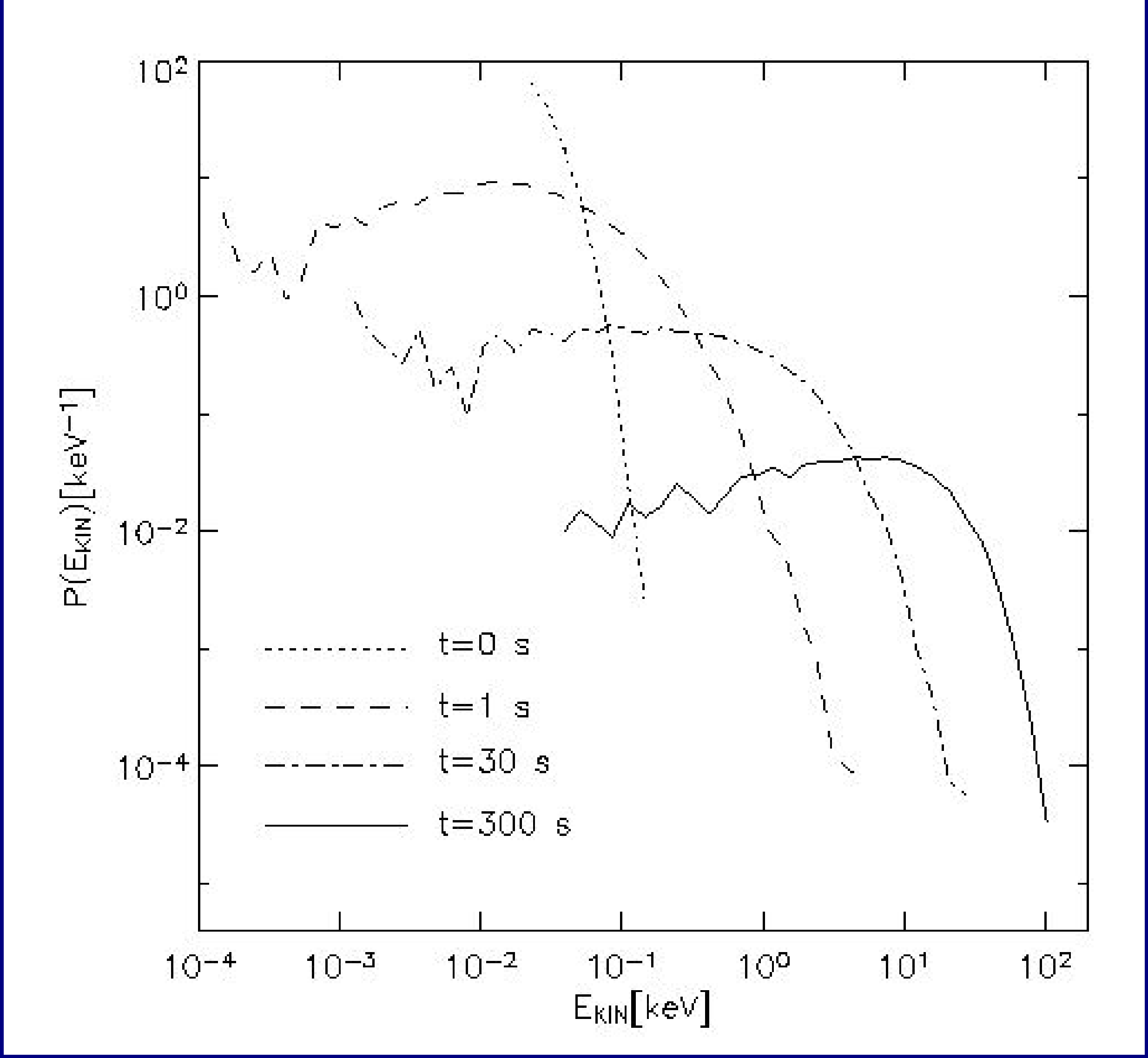
Numerical simulations: proton energy



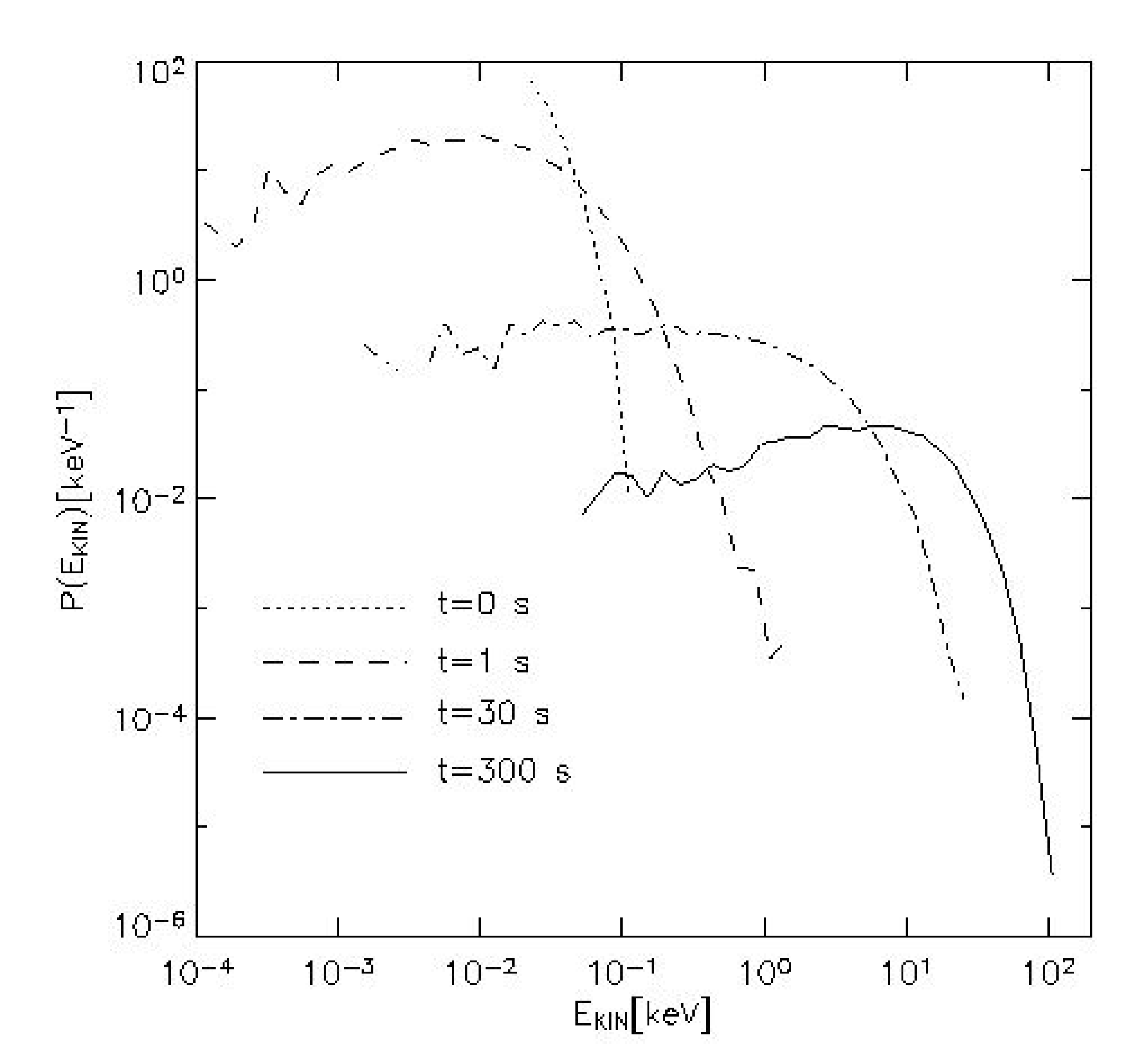
Numerical simulations: electron energy distributions



Numerical simulations: proton energy distributions



Numerical simulations: He^+ energy distributions



Summary

- We investigate the possibility that the ubiquitous suprathermal tails observed in the interplanetary space during quiet time periods are produced by a process of turbulent particle acceleration
- Starting from an initial Maxwellian tail, the evolution of the kinetic energy distributions gives rise to roughly exponential tails extending up to the maximum observed energies
- The details of the observed spectra (approximately power law tails) are not reproduced. This could be due to the current limitations of our model (e.g. small magnetic energy density, intermittency properties, dissipative effects, large scale SW structure)

Possible developments

- Consider an MHD model: this allows to release the hypothesis of small magnetic energy density
- Introduce a more appropriate description of the statistical properties of turbulence (intermittency)
- Consider the effects due to (anomalous) resistivity

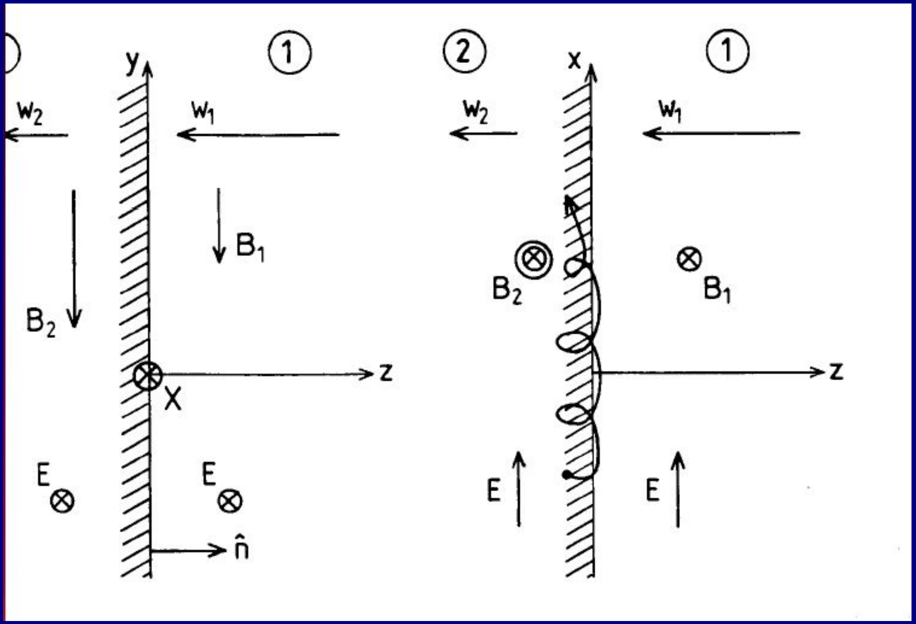
Many thanks to:

- Loukas, Heinz, Ivan
- All the staff of the Observatory

Shock acceleration

- Particles are accelerated due to their interaction with shock waves propagating in space.

- Several sources of shock waves present in space:
  - CME-driven shocks
  - Planetary bow shocks
  - CIR shocks
  - Heliosperic termination shock
  - Supernova shocks



- Particles can gain energy due to the magnetic field gradient and to the convective electric field

PDF's of electric field fluctuations