Magnetic Turbulence

and

the Lateral Transport of Solar Energetic Particles

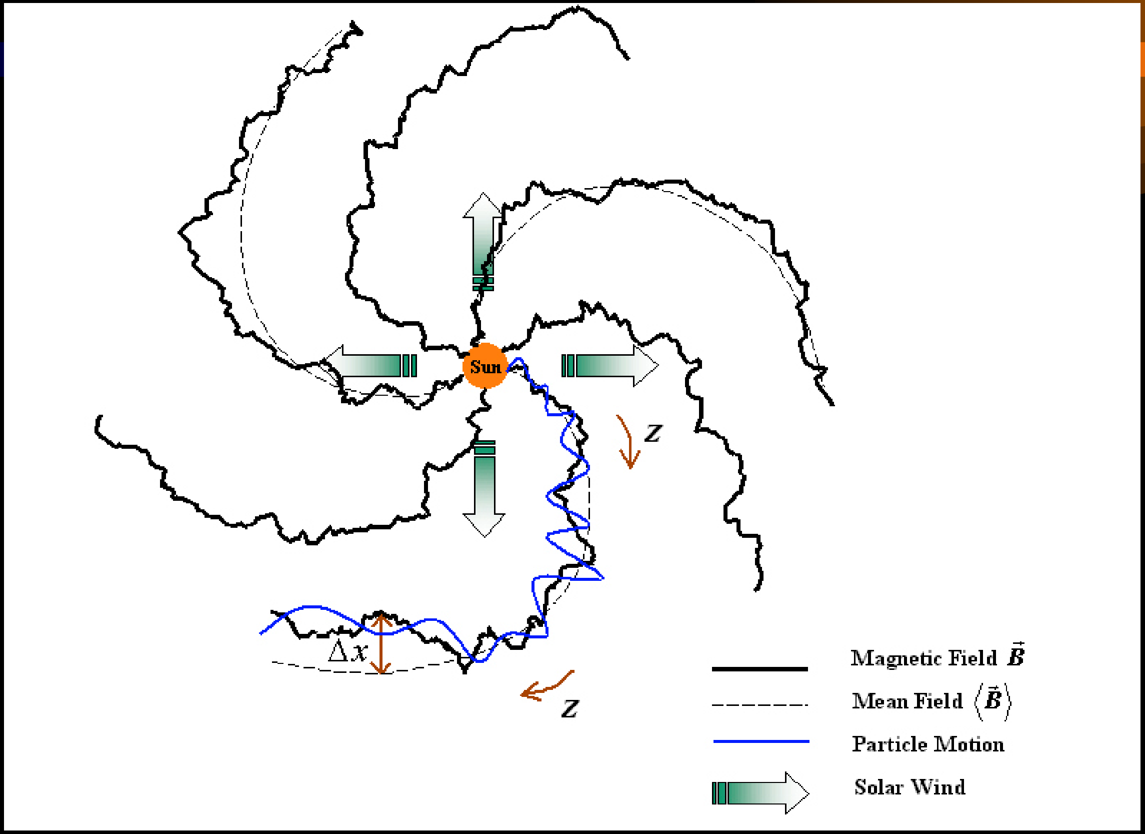
Piyanate Chuychai

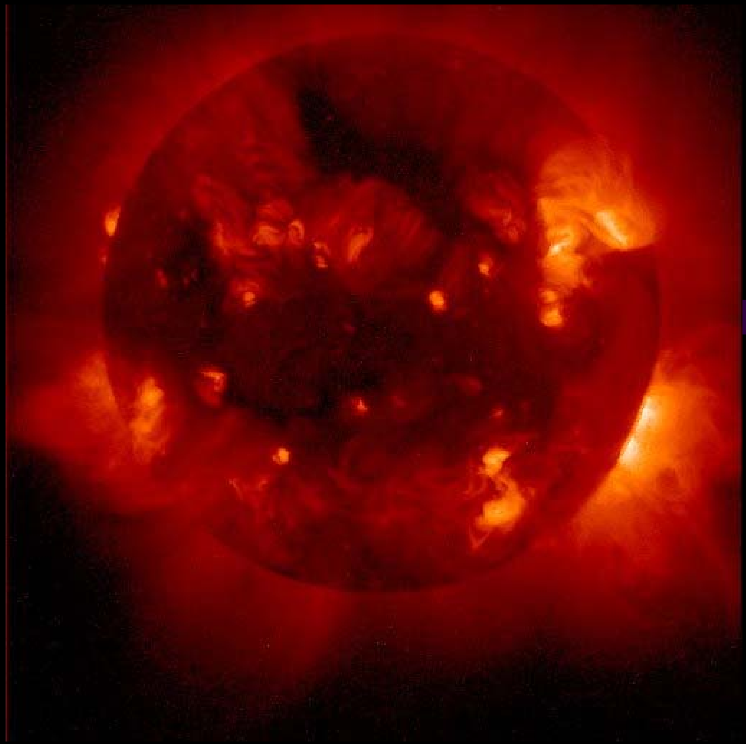
References:
1) Ruffolo D., Mattheaus W. H., Chuychai P. (2002) 28th Congress on Science and Technology of Thailand, Abstract 05-42P, 238.
2) Mazur, J. E., Mason, G. M., Dwyer, J. R., Giacalone, J., Jokipii, J. R. and Stone, E. C. (2000) Astrophys. J. **532**, L79.
3) McKibben et al (2001) Proc. 27 Intl. Cosmic Ray Conf. **7**, 3281.
4) Matthaeus, W. H., Goldstein, M. L. and Roberts, D. A. (1990) J. Geophys. Res. **95**, 20673.
5) Matthaeus, W. H., Gray, P. C., Pontius, D. H., JR., and Bieber, J. W. (1995) Phys. Rev. Lett. 75, 2136.

OUTLINE

- Introduction → Solar wind & Interplanetary magnetic field (IMF); Events at the Sun surface
- Observations → observation from ACE spacecraft; observation from Ulysses and IMP-8
- Magnetic Field Model → Slab turbulence + 2D turbulence
- Numerical Simulation → How to simulate the field lines
- Results
- Conclusions

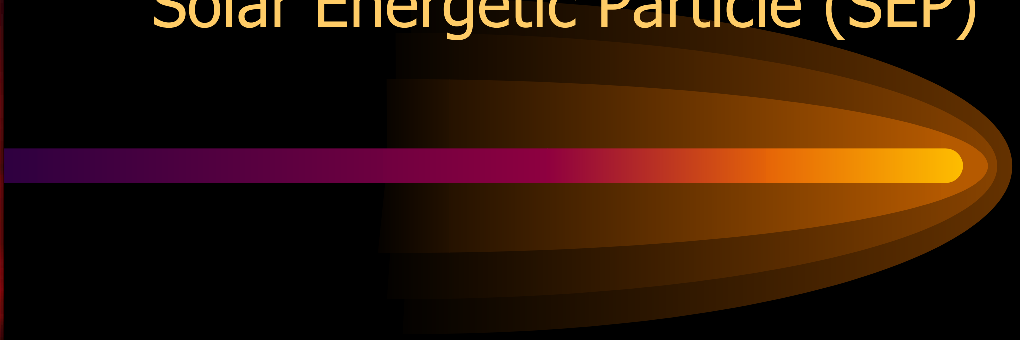
Plasmas and magnetic fields in the inner solar system

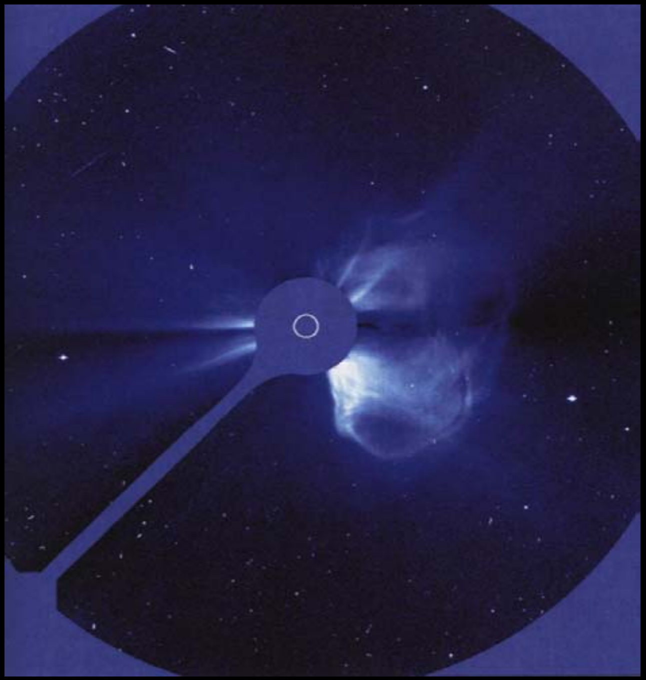




Impulsive flare

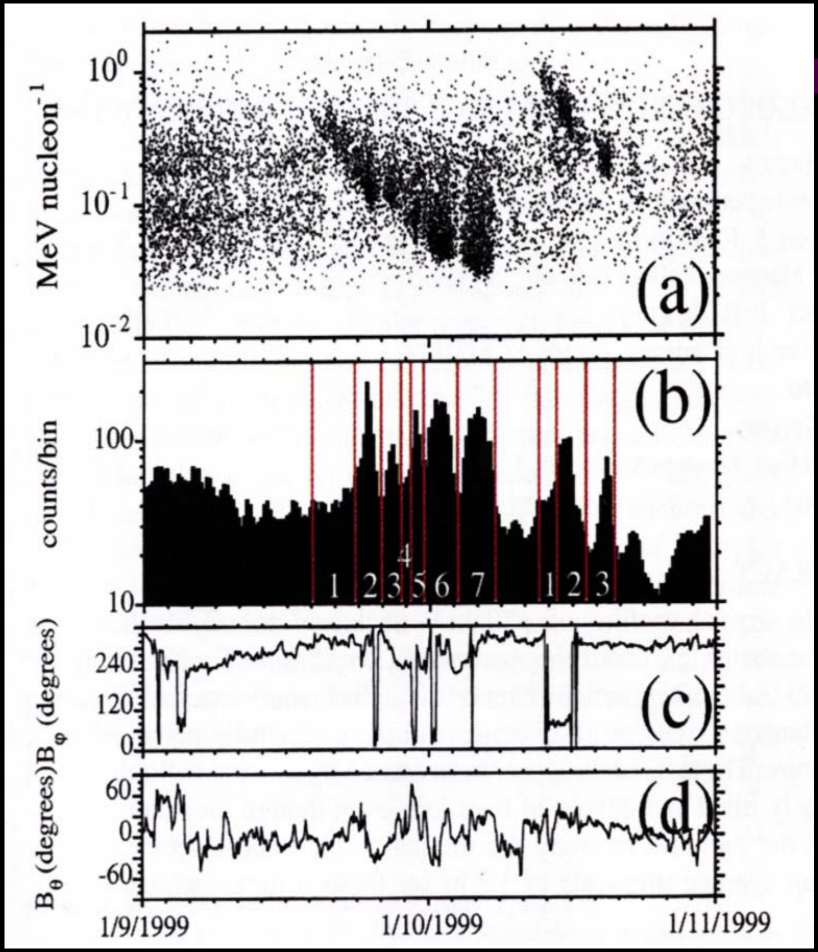
Solar Energetic Particle (SEP)





Coronal mass ejection (CME)

Observation from ACE spacecraft



From Mazur et al. 2000

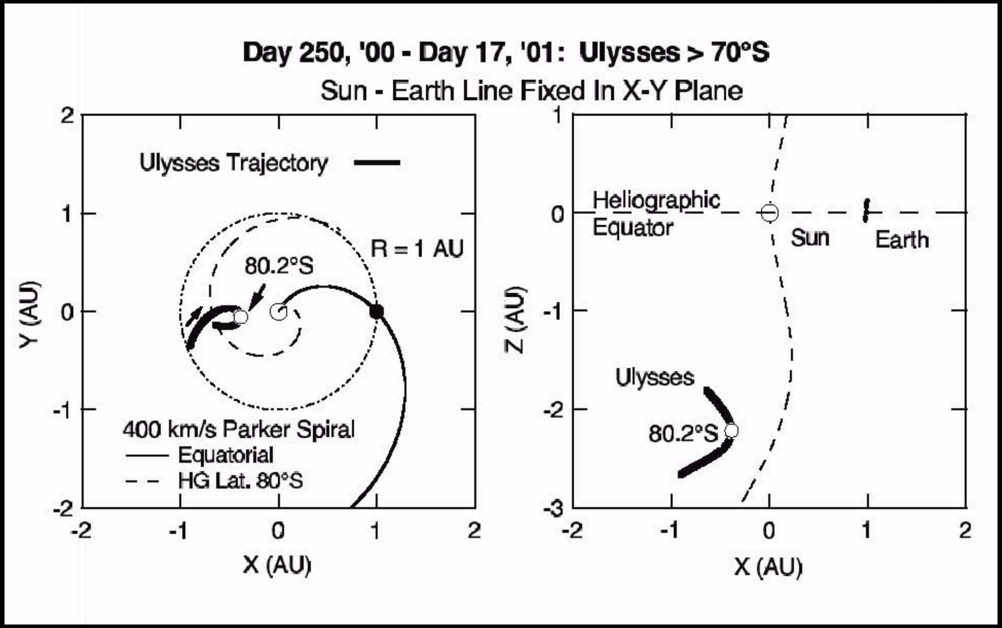
a) Energy of H-Fe ions (in units of MeV nucleon^{-1}) vs. arrival time at 1 AU for the impulsive flare event of 1999 January 9.

b) H-Fe counts vs. time in smoothed, ~14 minute bins

c) IMF angle in the geocentric solar ecliptic (GSE) x-y plane.

d) IMF angle normal to the GSE x-y plane.

Observation from Ulysses and IMP-8



From the large events (eg. Events 1, 6, and 8) we see that within a few days proton fluxes are approximately equal at both Ulysses (opposite side of the Sun) and IMP-8 (near the Earth).

From McKibben et al. 2001

A paradox of SEP transport:

1. SEP from impulsive solar flares can exhibit “dropouts” in which the flux measured near Earth repeatedly disappears and reappears, as measured by the ACE spacecraft. This indicates that the density of SEP in space is highly inhomogeneous, and seems to imply very little lateral diffusion.

2. Observations from the IMP-8 and Ulysses spacecraft, while they were on opposite sides of the Sun, showed similar time-intensity profiles in the decay phases of nearly all SEP events. This indicates that the particles undergo substantial lateral diffusion, spreading throughout the entire inner solar system within a few days.

The Magnetic Field Model

$$\vec{B}(x,y,z) = B_0\hat{z} + \vec{b}(x,y,z)$$

total magnetic field

static and homogeneous

mean field

$$\langle \vec{B} \rangle = B_0\hat{z}$$

transverse fluctuation

$$\vec{b} \perp \hat{z}$$

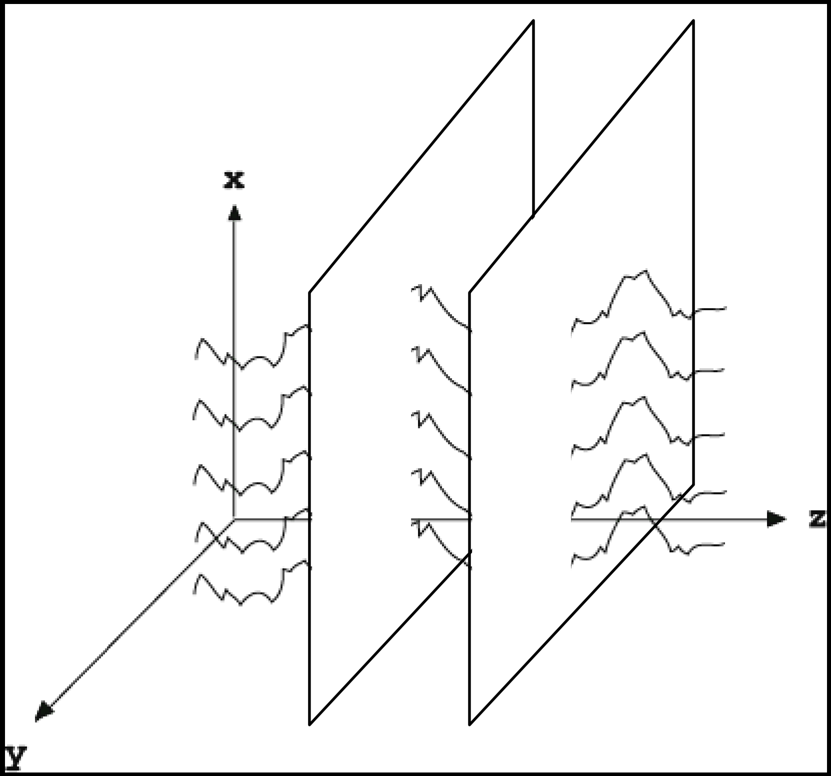
$$\vec{b}(x,y,z) = b_x^{slab}(z)\hat{x} + b_y^{slab}(z)\hat{y} + b_x^{2D}(x,y)\hat{x} + b_y^{2D}(x,y)\hat{y}$$

$$\vec{b}(x,y,z) = \vec{b}^{slab}(z) + \vec{b}^{2D}(x,y)$$

• SLAB TURBULENCE

$$\vec{b}^{slab}(z) = b_x^{slab}(z)\hat{x} + b_y^{slab}(z)\hat{y}$$

The fluctuation depends on only z direction



•2D TURBULENCE

$$\vec{b}^{2D}(x,y) = b_x^{2D}(x,y)\hat{x} + b_y^{2D}(x,y)\hat{y}$$

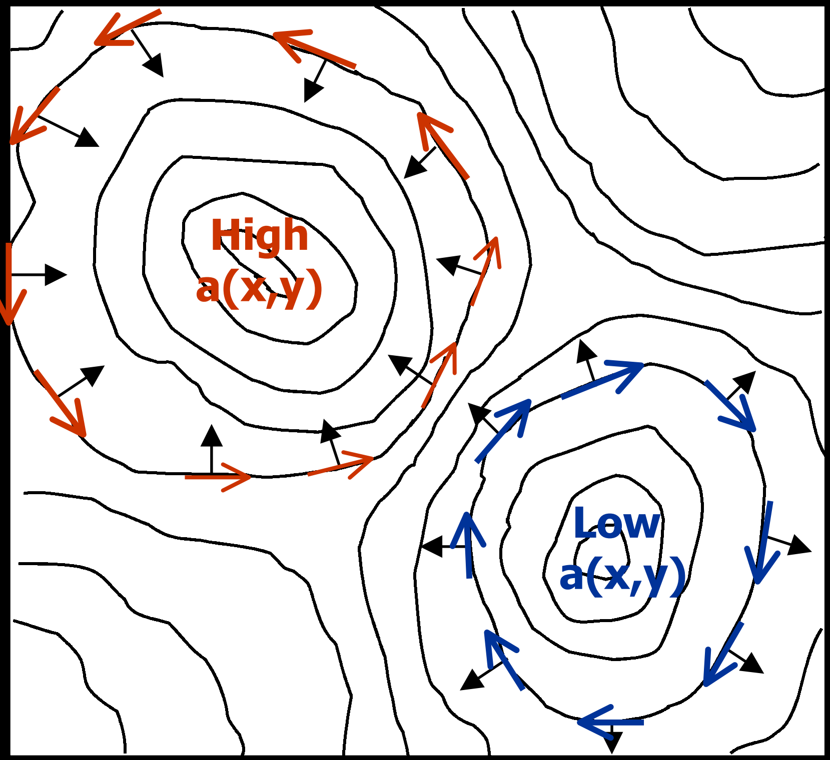
The fluctuation depends on x and y.

In general,

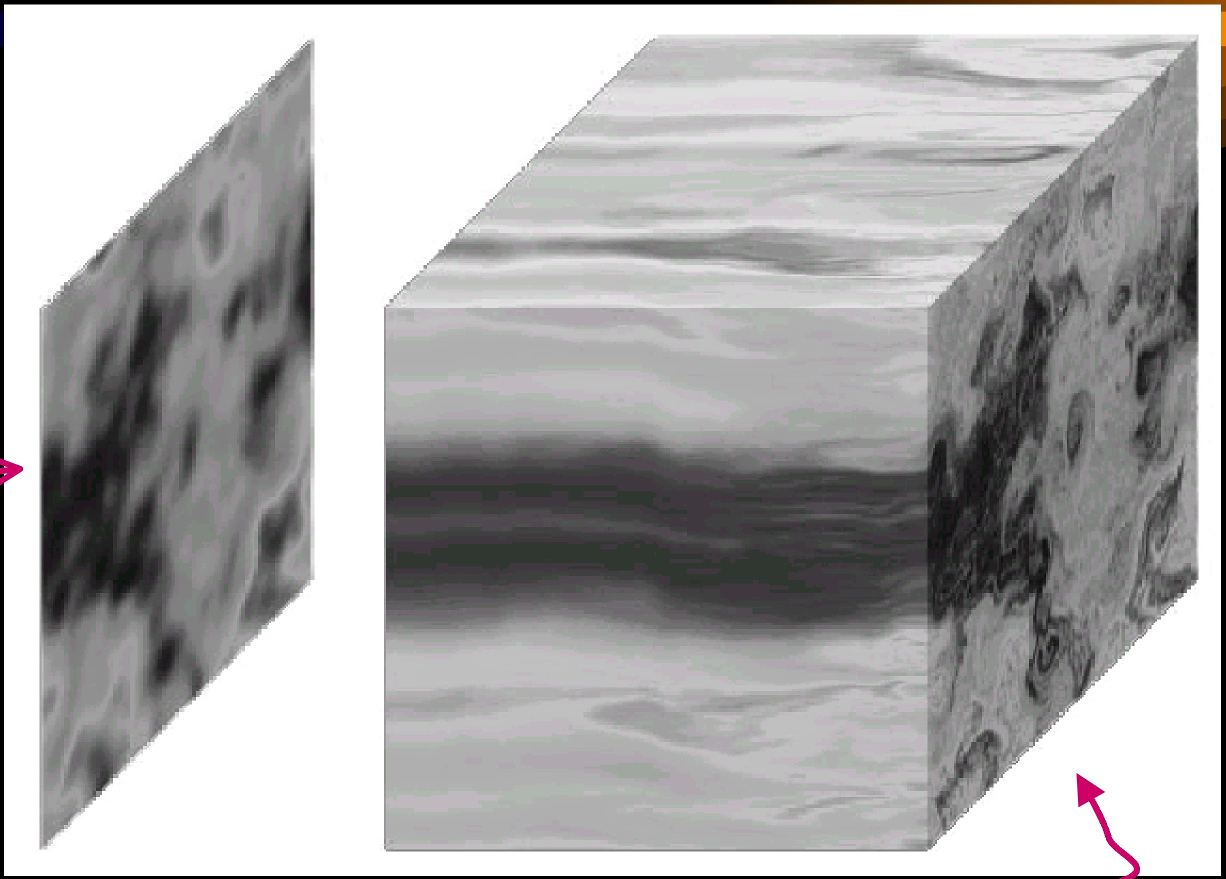
$$\vec{b}^{2D}(x,y) = \vec{\nabla} \times a(x,y)\hat{z}$$

where $a(x,y)\hat{z}$ is the vector potential.

$$\boxed{\vec{b}^{2D} = \vec{\nabla} a(x,y) \times \hat{z} \text{ or } \vec{b}^{2D} \perp \vec{\nabla} a(x,y)}$$



Example of 80%2D + 20%slab



a(x,y)

The motion of field lines

Our Explanation

- Since the particles mainly follow the magnetic field, the structure of IMF should effects the SEP transport.
- There is evidence that the nature of IMF is composed by slab and 2D component (Matthaeus et al. 1990).
- The lateral diffusion of interplanetary magnetic field lines is dominated by 2D component (Matthaeus et al. 1995)

We expect that:

- Over intermediate distance scale, the field lines near **x**-points in 2D turbulence spread rapidly in the lateral directions, whereas magnetic field line near **o**-points remain with in islands of the 2D turbulence, with lateral diffusion at much slower rate associated with slab turbulence.
- Over a long distance scale, essentially all magnetic field lines have escaped from 2D islands and undergo substantial lateral diffusion.

Numerical Simulation

INPUT:

- Magnetic field parameters: $\delta b/B_0, B_0, \ell_z, \ell_\perp, E_{2D} : E_{slab}$
- Size of simulation box and numbers of grid point
- Numbers of field lines
- Initial position of each field line
- Desired step sizes and accuracy

Slab Field

Generate $\vec{b}^{slab}(k_z)$

Inverse fast Fourier transform

$\vec{b}^{slab}(z)$

2D Field

Generate $a(k_x, k_y)$

$$\vec{b}^{2D}(k_x, k_y) = -i\vec{k} \times [a(k_x, k_y)\hat{z}]$$

Inverse fast Fourier transform

$\vec{b}^{2D}(x, y)$

Solve equations of field lines

$$\frac{dx}{dz} = \frac{b_x}{B_0}$$

$$\frac{dy}{dz} = \frac{b_y}{B_0}$$

by Runge-Kutta method with adaptive step size

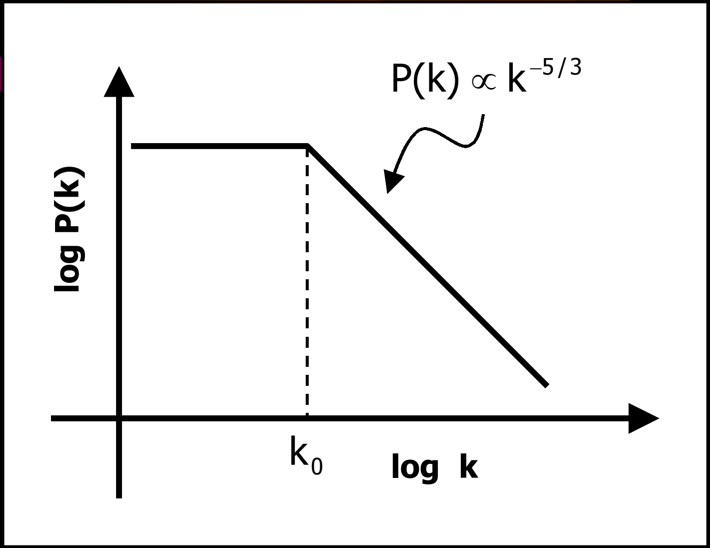
Positions (x, y, z) of each field lines

Using parallel programming with MPI implementation technique

- The magnetic spectra taken to be

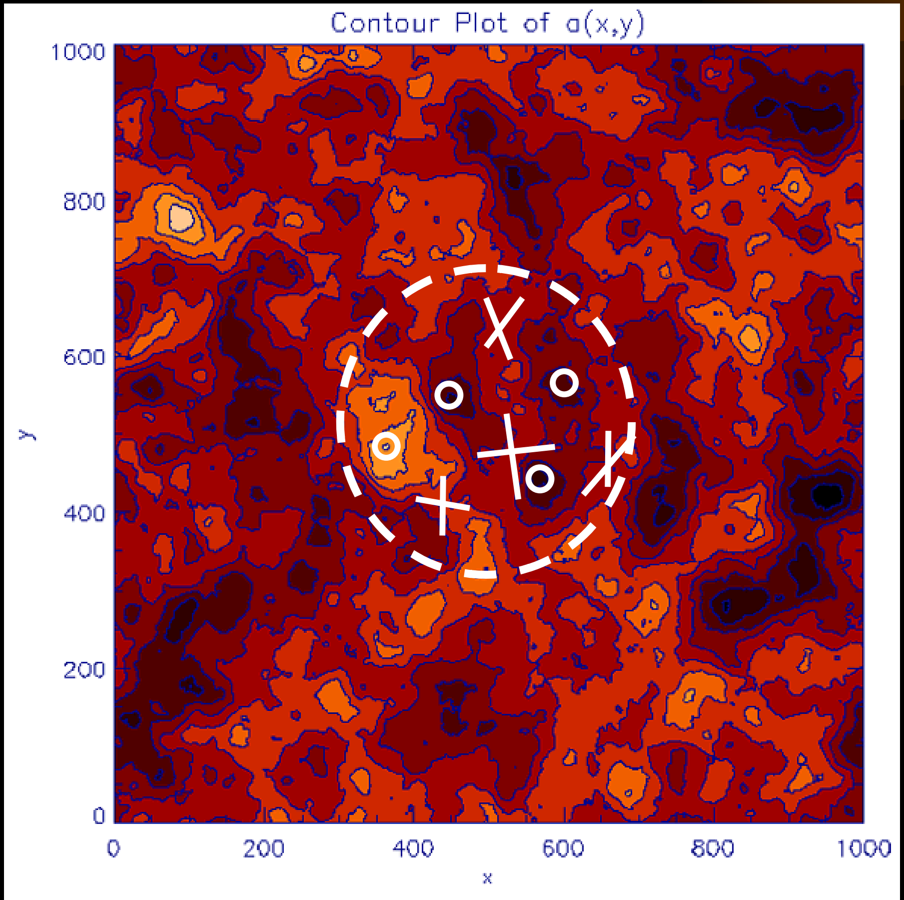
$$P_{xx}^{slab}(k_z) = \frac{C_1}{\left[1 + (k_z \ell_z)^2\right]^{5/6}}$$

$$P_{xx}^{2D}(k_x, k_y) = \frac{k_y^2 C_2}{\left[1 + (k_\perp \ell_\perp)^2\right]^{7/3}}$$



which become Kolmogorov spectra at large k where $k_\perp = \sqrt{k_x^2 + k_y^2}$, C_1 and C_2 are constant, and ℓ_z and $\ell_\perp$ are characteristic length scales.

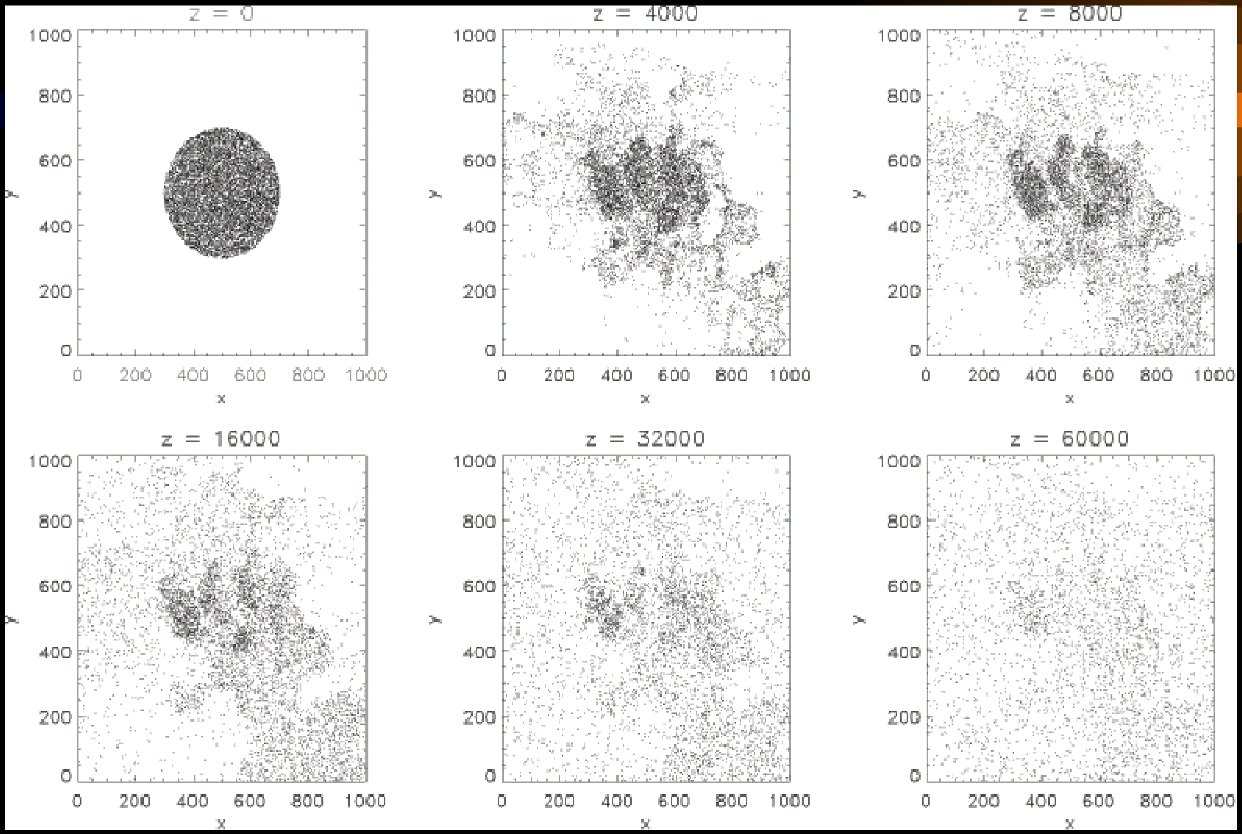
Contour Plot of a(x,y)



O-point: no 2D diffusion

X-point: rapid 2D diffusion

Results



The figure above shows the locations of 10,000 field lines sample magnetic field lines at various distance z along the mean field. At z=0, the selected lines are within the circle near the center, e.g. a region near the Sun where an impulsive flare injects SEP.

Conclusions

• Our computational results confirm our theoretical idea.

• Over intermediate distance scales, we reproduce a highly inhomogeneous distribution.

• Over a long distance scale, essentially all magnetic field lines have escaped from 2D islands and undergo substantial lateral diffusion.