Probing Turbulence At and Near CME-driven shocks Using Energetic Particle Spectra

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Living with a Star Team meeting

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From the talk given at the Palm spring 2005 IGPP meeting.

Outline

- Early studies of upstream turbulence at interplanetary shocks.

  ISEE3 low energy particle and magnetic field observations.

- Variability of spectra in large SEP events.

  investigating the dependence of braking energy on (Q/A).

- Steady state solution of transport equation with a loss term.

  difference between propagating shock and standing (bow) shock

- A special "broken power law" solution.

  maybe an explanation for the Oct.-Nov. events?

- What need to be done for further investigation.

  The Bastille Day event revisited.

Early observations by ISEE3

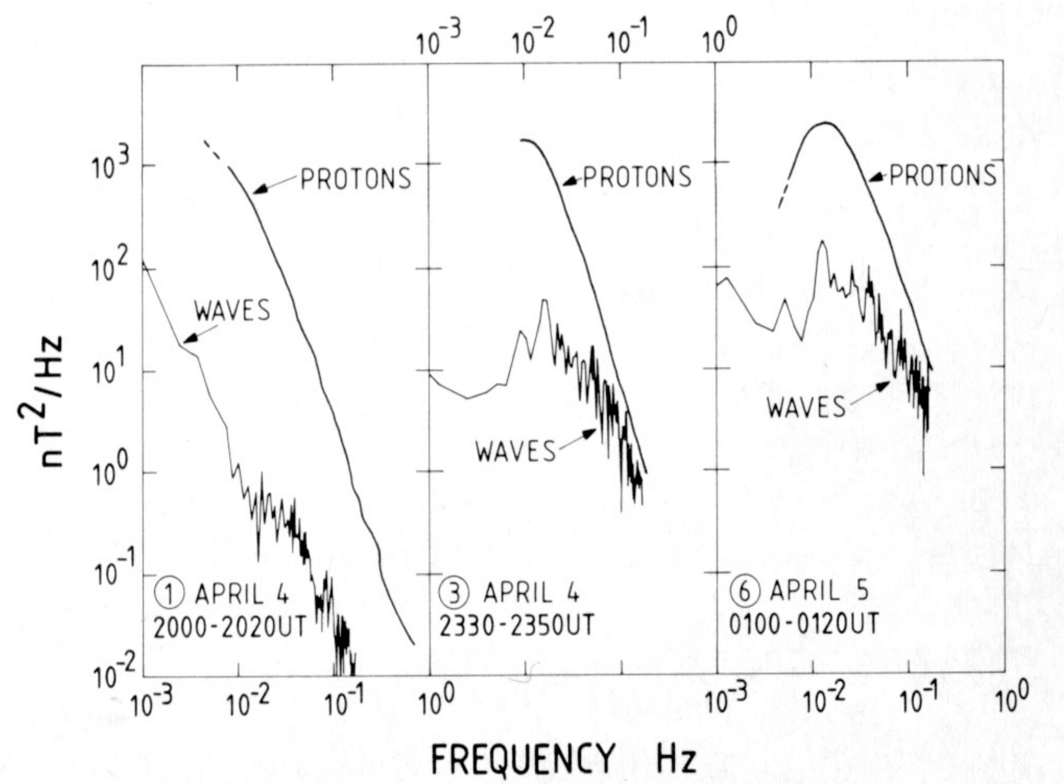

Fig. 6. Comparison of magnetic field power spectra and proton energy density per unit resonant frequency interval.

Sanderson et al. 1985

Resonance condition:

$$\omega = kv_{||} - \Omega_g \qquad \Omega_g = \frac{Q}{A}\frac{eB}{m_p}$$

conversion from sw to sc frame:

$$T_{sw} = T_{sc}(1 + \frac{v_{sw} cos\alpha}{v_A})$$

• Huge increases of turbulence power when approaching the shock (energy comparable to

t

h

at contained in energetic particle)

• turbulence

s

pectra is NOT a single power law.

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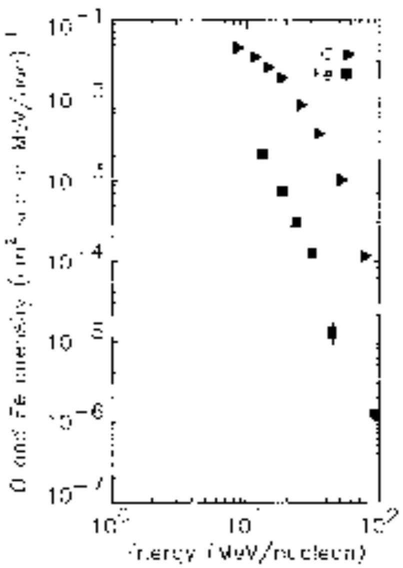
reductio

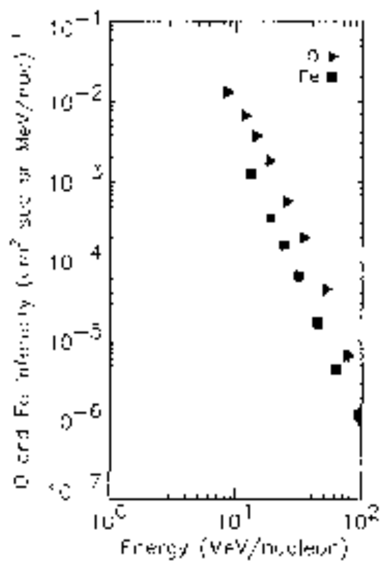
Using heavy ion spectra to probe the form of the turbulence

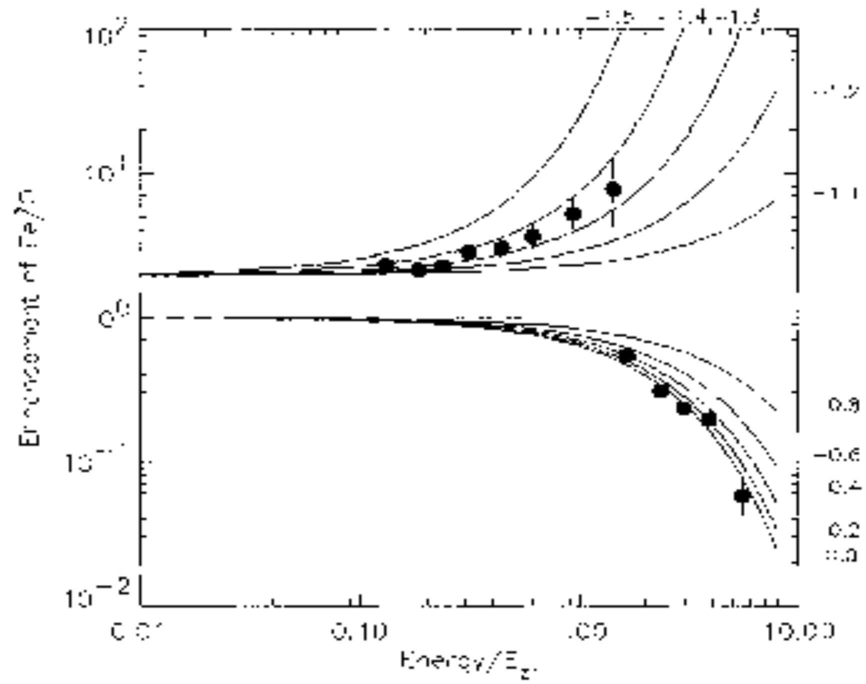
$$\frac{dJ}{dE} \approx E^{-\delta} exp(-E/E_0)$$

25 Sep. 2001



3 April 2001





Fe/O ratio is energy dependent

Assuming a power law turbulence:

$I(k) = k^{\gamma}$ ==> $\frac{E_{Z1}}{E_{Z2}} = (\frac{(A/Q)_{z2}}{(A/Q)_{z1}})^{\frac{2+2\gamma}{2+\gamma}}$

$$\frac{(dJ/dE)_{Z1}}{(dJ/dE)_{Z2}} = \frac{N_{Z1}}{N_{Z2}} \exp\left[-\frac{E}{E_{Z1}}\left\{1-\left(\frac{(A/Q)_{Z2}}{(A/Q)_{Z1}}\right)^{\frac{2+2\gamma}{2+\gamma}}\right\}\right].$$

Cohen et al. (2003)

a range of Q/A provide good check

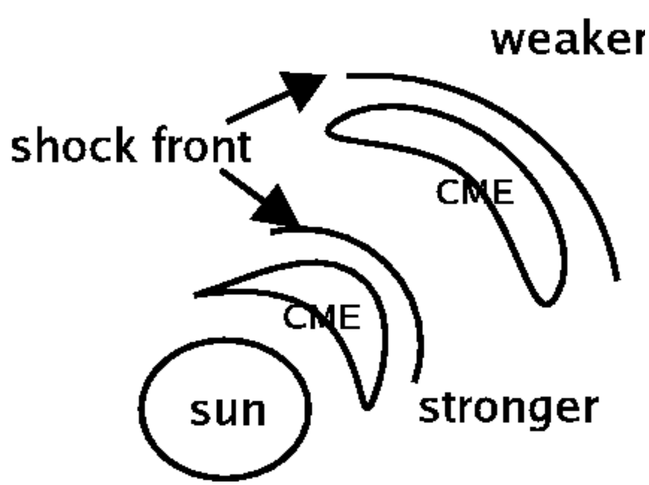
The motivation

The reasons for the roll over at high energies are:

- finite acceleration time scale. Lee (1983)
- adiabatic deceleration. Forman (1981)
- finite size of shock, particle losses. Ellison and Ramaty (1985)

However , $\frac{dJ}{dE} \approx E^{-\delta} exp(-E/E_0)$

in Ellison and Ramaty (1985) is only an empirical fit.

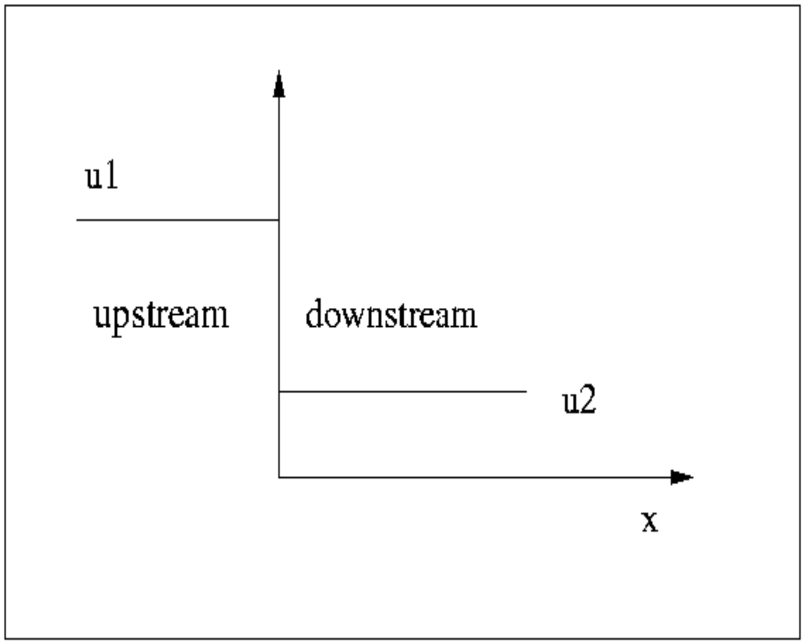


- as the shock propagates out, the turbulence decreases and κ increases.
- Particle spectrum will respond the increase of κ from high energy end.

Assuming a power law spectrum at early times (initial condition), what is the solution of the transport equation?

First order Fermi acceleration in a nutshell

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} - \frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right) - \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} = 0$$



$$f = A(p) + B(p)exp\int_0^x dx'\frac{u}{\kappa}$$

- Assume a 1-D case and x-independent u and κ.
- At the shock front, both f and the current $S = \frac{-1}{3}\frac{\partial lnf}{\partial lnp} - \kappa\frac{\partial f}{\partial x}$ are continuous.

Matching condition at the shock gives a power law spectra.

$$f(p) \sim p^{-3s/s-1}$$

Loss term and its meaning

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} - \frac{\partial}{\partial x}(\kappa\frac{\partial f}{\partial x}) - \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + \boxed{\frac{f}{\tau}} = \frac{f_\infty}{\tau_\infty}$$

- *Volk et al.* (1981) considered various loss terms: Ionization, Coulomb, nuclear collisions, etc.
- The standard solution of shock acceleration assumes a x-independent u and κ.
- Acceleration time scale 4 κ/u^2, compare with τ, requires κ to be small.
- In the upstream region, κ is decided by the turbulence, far away from the shock, the solution does not hold.
- ***Can put a loss term (note, this is physically different from Volk et al.) to account for the finite size of the turbulent region near the shock.***

A special solution

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} - \frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right) - \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + \frac{f}{\tau} = \frac{f_\infty}{\tau_\infty}$$

$$f = \begin{cases} A(p) & \text{downstream} \\ B(p)exp[(u/\kappa)(1+\delta)x] & \text{upstream} \end{cases}$$

Consider steady state case. Assume the initial spectrum is a power law (i.e. pre-accelerated).

Boundary conditions:

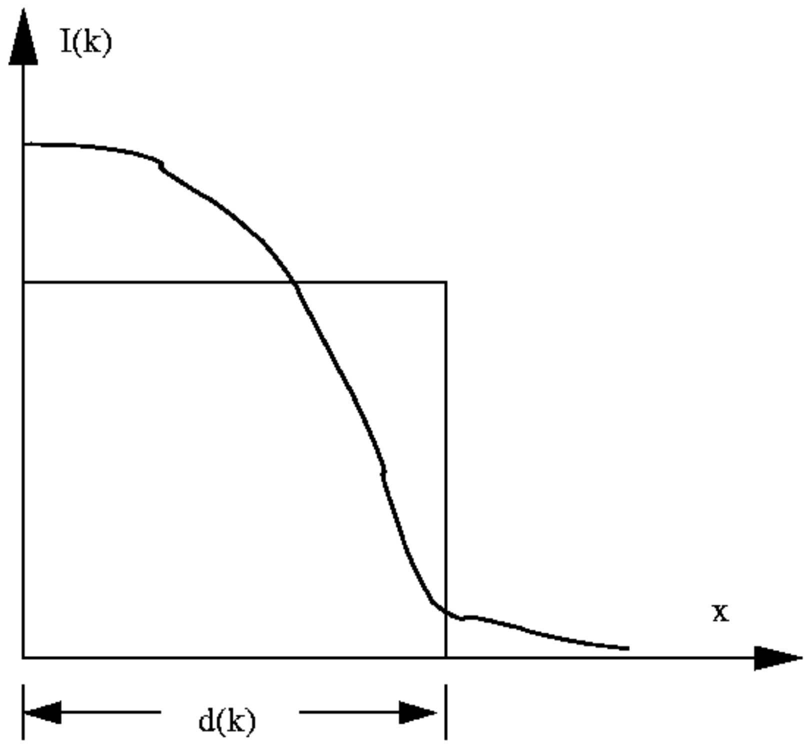
A) f ->0 at the upstream boundary.

B) f = some non-zero value at down stream boundary.

$$\delta = \frac{-1 + \sqrt{1 + 4\alpha\kappa/u_1^2}}{2}$$

$$f(p) \sim p^{-(1+\delta)[3s/s-1]}$$

Turbulence in the upstream



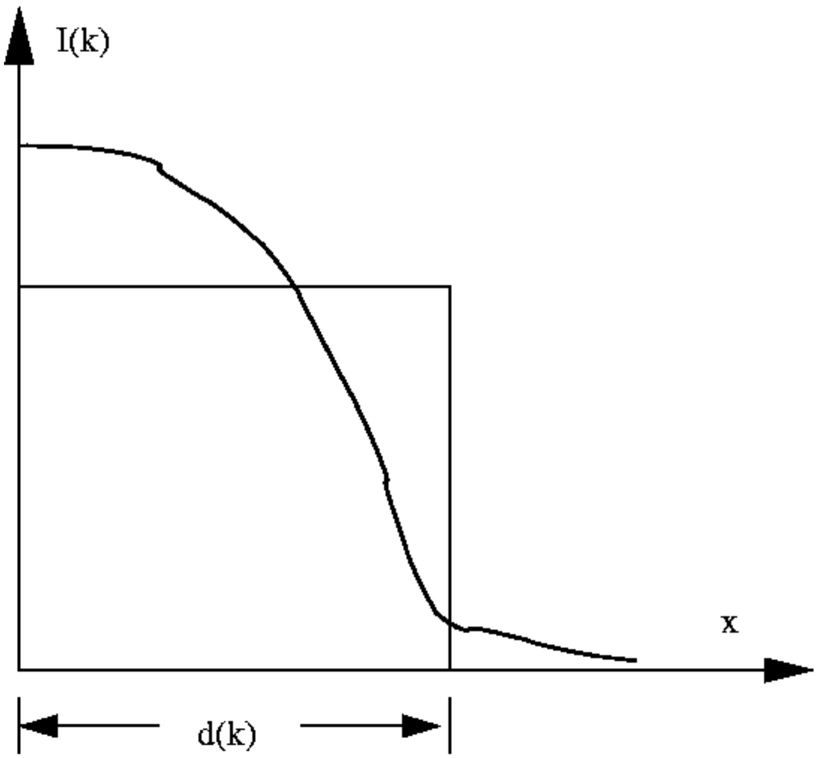
•Upstream of a parallel shock, turbulence is in Alfven wave form – driven by streaming protons in front of the shock. But, exact form of the turbulence is not important.

•Turbulence power decays as x increase. The x-dependence could be different for different energy.

•***<u>The length scale d(k) for I(k) is decided by the turbulence.</u>***

d(k) can be understood as: If particles which resonate with k reach d(k) in front of the shock, they will not return to shock.

Particle diffusion coefficient



$$\frac{\partial A}{\partial t} + u\frac{\partial A}{\partial r} = \Gamma A - \gamma A,$$

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial r} - \frac{p}{3}\frac{\partial u}{\partial r}\frac{\partial f}{\partial p} - \frac{\partial}{\partial r}\left(\kappa\frac{\partial f}{\partial r}\right),$$

1) ***κ is tied with I(k). From κ, we can get λ =3 κ/v.***

2) Two length scales now, λ and d(k).

Low energy particle λ<< d(k), particles won't feel the boundary.

High energy particle λ~d(k), particle will feel the boundary and the loss term becomes important.

Deciding α ($=1/\tau$)

- The characteristics of loss time depends on λ (thus particle energy).

1) Low energy, $\lambda < d(k)$ => diffusive nature
.

- High energy, $\lambda \sim d(k)$ => streami
n
g nature. $\tau = (d/v)$

Approximate form: $\alpha \sim [1 - \exp(-\lambda/d(k))]\, v/d$.

- Define $\varepsilon = (4\,\alpha\,\kappa/\,u_1^{\,2})$, then

$$\epsilon = \frac{4}{3}\left(\frac{v}{u_1}\right)^2 \begin{cases} (\lambda/d)^2 & \lambda << d \\ (\lambda/d) & \lambda \sim d \end{cases} \qquad\qquad \delta = \frac{-1 + \sqrt{1 + 4\alpha\kappa/u_1^2}}{2}$$

The change of the spectrum index becomes noticeable when $\varepsilon \sim 1$.

Simple estimation from ε

$$\epsilon = \frac{4}{3}\left(\frac{v}{u_1}\right)^2 \begin{cases} (\lambda/d)^2 & \lambda << d \\ (\lambda/d) & \lambda \sim d \end{cases}$$

- Consider a strong shock, $u_1 \sim 10^6$m/s
- Take proton, T = 20 MeV

=> $v \sim 6 * 10^7$m/s, $v/u_1 = 60$

For the spectrum to bent over at T = 20 MeV , requires $(d/\lambda) = 60$,

if d = 0.01 AU, $\lambda = 1.66*10^{-4}$ AU, => $\kappa = 2.5*10^{14}$ m^2/s.

Reasonable values!

Turbulence from observations

• Downstream turbulence is stronger than upstream turbulence.

• Alfven wave transmission suggests that an increase of wave intensity of ~ 9-10. McKenzie et al (1969).

•Consider two shocks occur in
O
ct. 28th and Oct. 29th .

•Plama data is plotted.

• θ_{bn} = 68 and 14 respectively. (from co-planarity analysis.)

From Skoug et al. 2004.

Turbulence from observations

Preliminary results of the magnetic turbulence power for the 10/28/2003 event.

upstream

downstream

Turbulence from observations

Preliminary result of the magnetic turbulence power for the 10/29/2003 event.

upstream

downstream

An extreme example

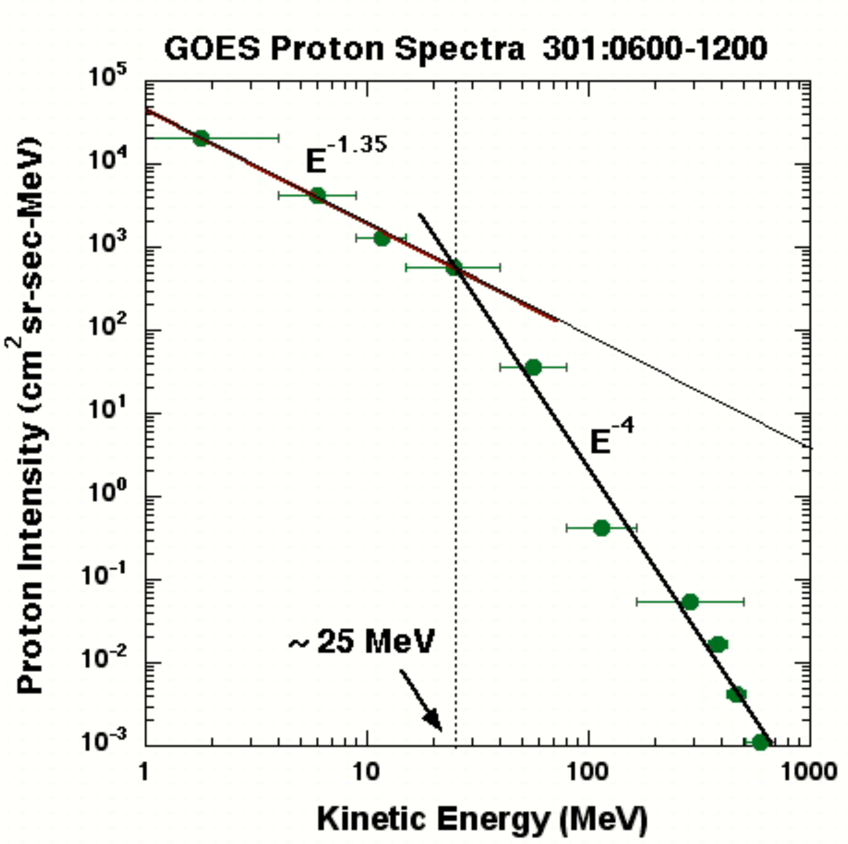
- Consider an extreme example: a step function of δ.
- Expect a broken power law.

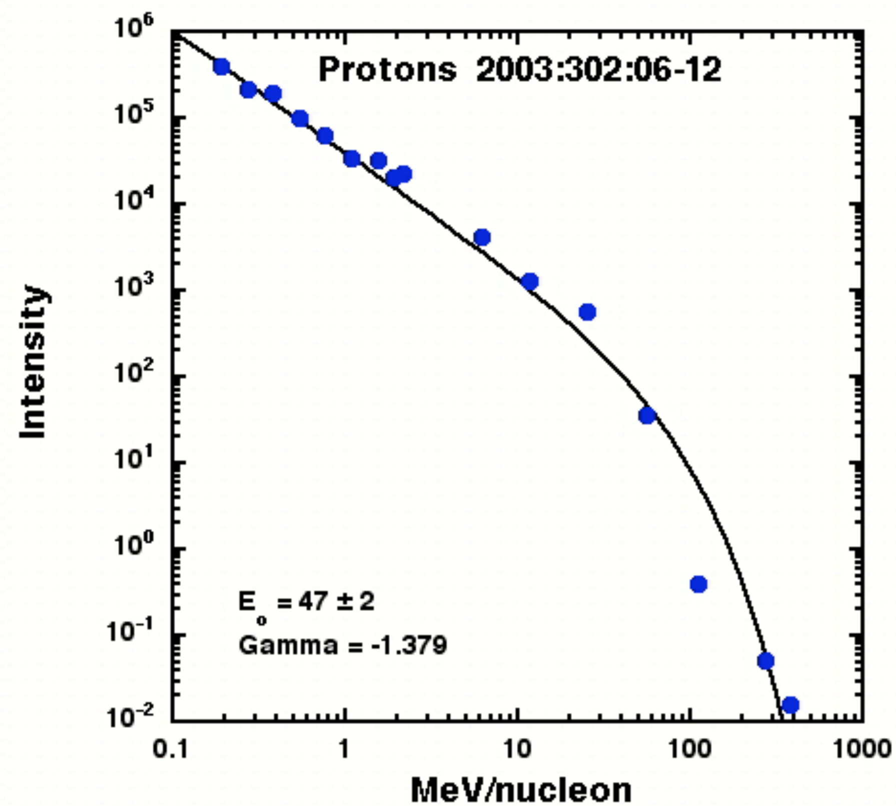
$\delta = 0.1$ when $T<20$ MeV

$\delta = 1.0$ when $T>20$ MeV

Broken power law

Observation of particle spectra in the late October, 2003

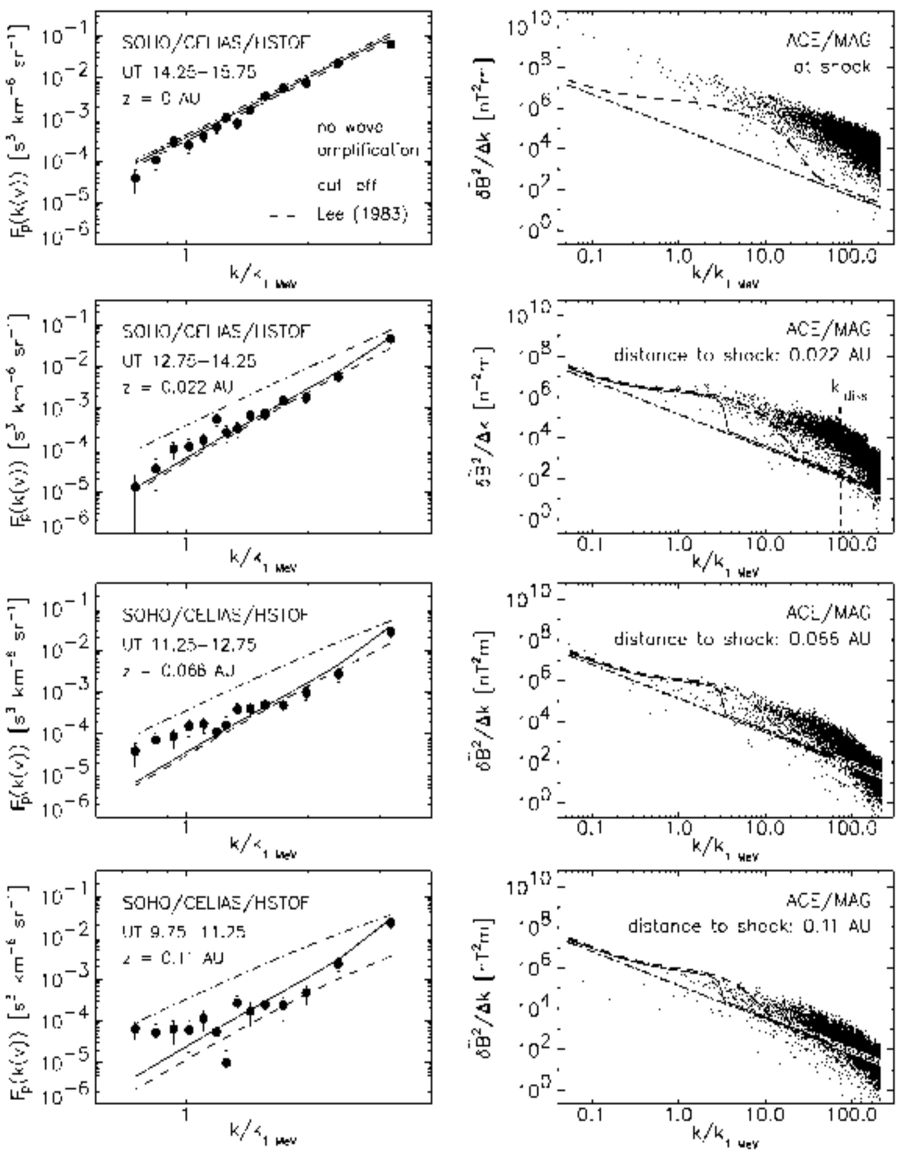




Courtesy of R. Mewaldt

Note, the turbulence power of Oct. 28 is more "step-like".

Bastille Day Revisited



Particle spectra and magnetic power spectra at z=0, 0.022, 0.066, 0.11 AU

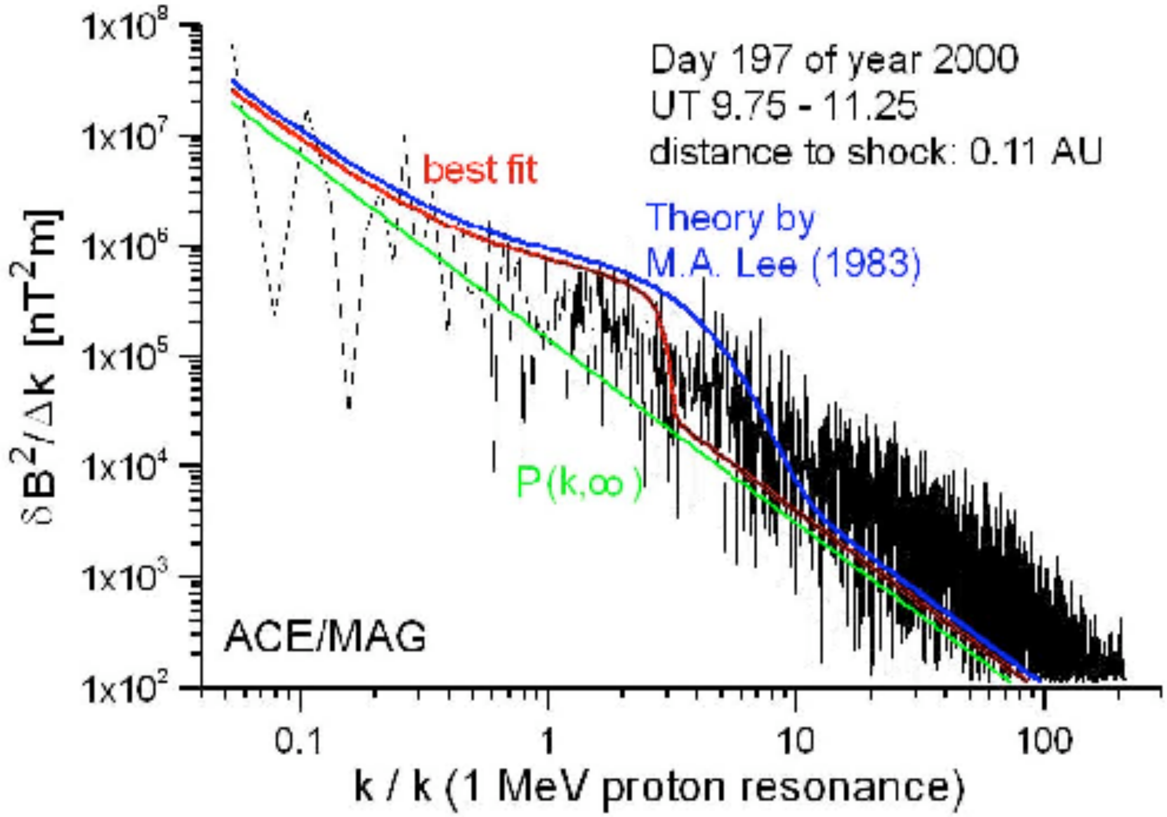
- power spectra can not be described as a simple power law.

- A bump over quiet solar wind turbulence at some middle energy (wave vector) range.

Lee (1983) theory predicts a smaller particle current at high energies; hinting the escaping effect?

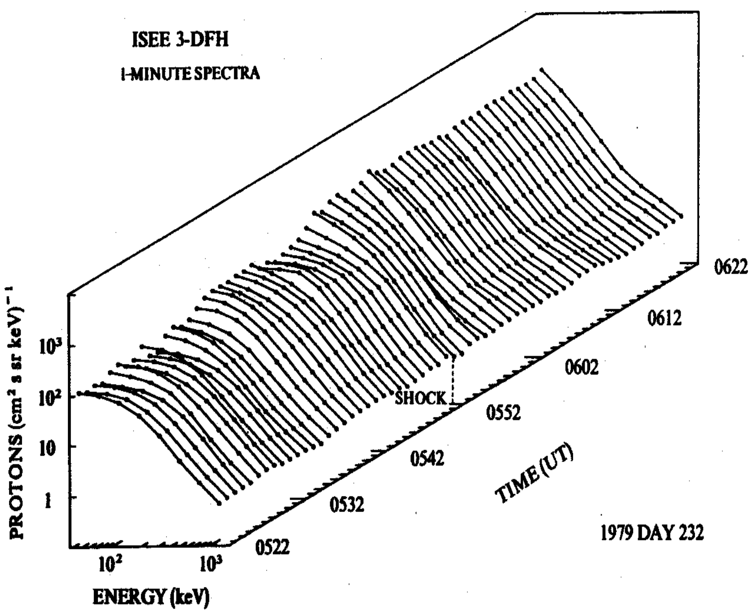
Bamert et al (2004)

Bastille Day Event Revisited



Future work

Need a series of turbulence power plots, together with a series of particle spectra.



Van Nes et al. (1984)

- using observational data of I(k) to construct more realistic κ(v) ==> compare the derived particle spectra with observation.
- identify the time scale for the "loss" process (is steady state a valid approximation?)
- Need to study the (Q/A) dependence since we have many heavy ion observations.

Example:

using QLT $\kappa \approx \frac{v r_g}{A(k)}$ with $A = \frac{I(k)}{B^2}$

==> $\kappa \sim v^{2+\gamma} {\Omega_g}^{-(\gamma+1)}$

if $I(k) \sim k^{\gamma_1}$ $k > k_0$; $I(k) \sim k^{\gamma_2}$ $k < k_0$ — what will dJ/dE look like?