Modeling particle acceleration at CME-driven shock and transport in the inner heliosphere, A case study

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Motivation

•SEP events, a maze and/or a playground.

• What can we learn from observations?

A successful simulation should have the right physics in it: treatment of particle acceleration and the stimulated turbulence.

1) At the Sun, LASCO, TRACE, GO, RHESSI, etc: radio, ultraviolet, X-ray, gamma-ray --- provide, e.g. flare particle spectrum, initial parameter for CME-driven shocks, etc.

2) Near the Earth, ACE/WIND, etc. : in-situ particle/wave observations.

Connecting 1) and 2) --- requires modeling effort: what have been done and what need to be done?

Topics

- Modeling the CME driven shock --- a shell model couples to a 1D Zeus code.
- Diffusive shock acceleration, streaming protons, turbulences, particle wave interaction; heavy ions, consequences of different (A/Q).
- Transport of energetic particles in the inner heliosphere--- solving the Boltzmann equation using Monte Carlo simulation.
- Modeling the April 21st , 2002 event.
- Time intensity profile, temporal evolution of spectrum, time integrated spectrum.
- Conclusion and future work.

Shell model of a CME-driven shock

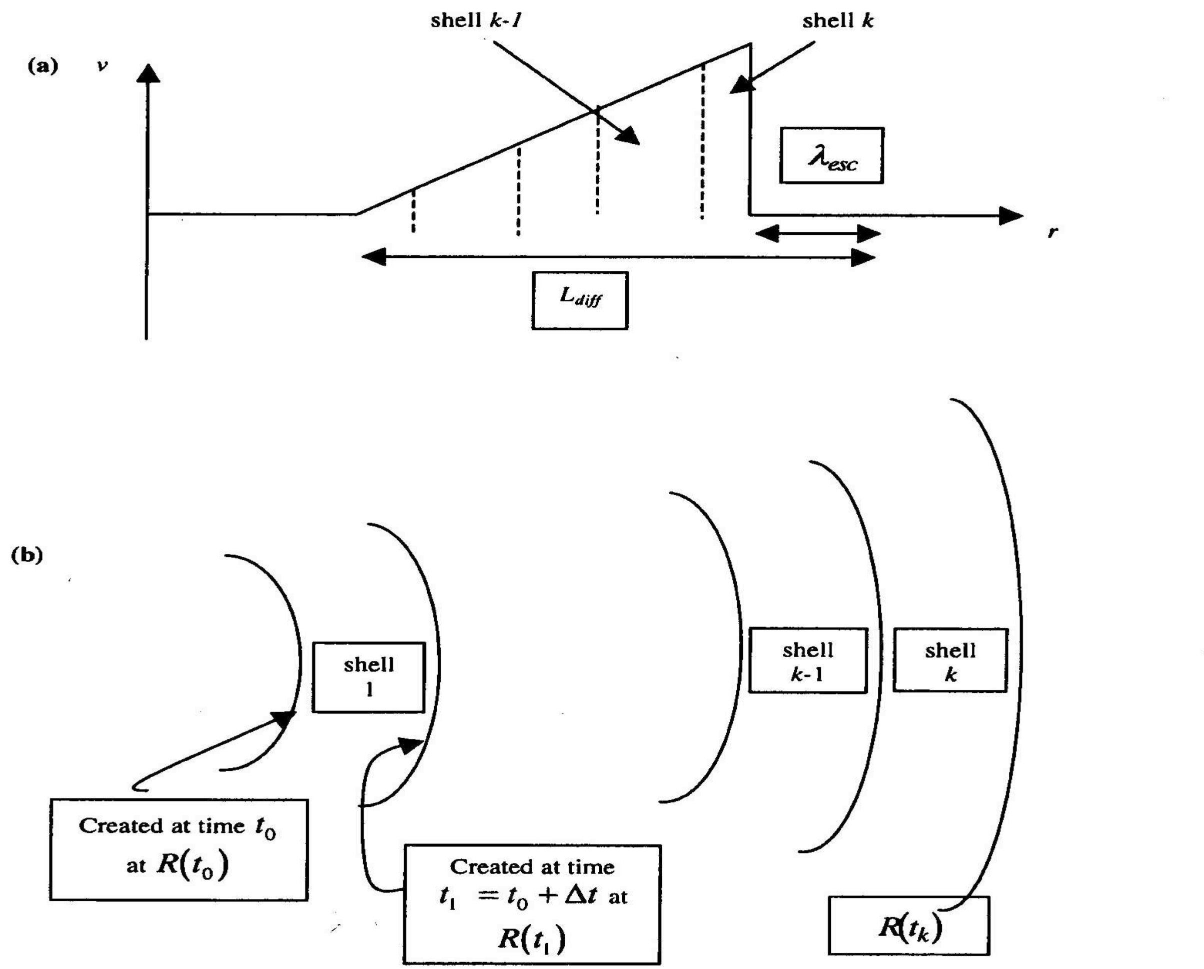
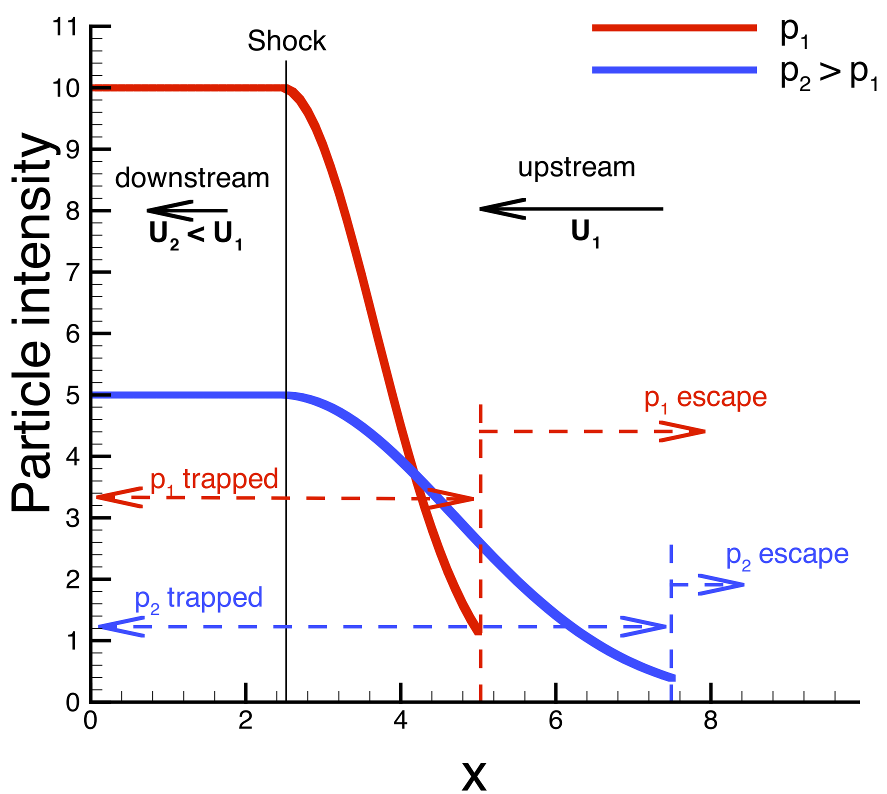


Figure 1. (a) Schematic of the density structure of an interplanetary blast wave. The total structure is subdivided into a series of concentric shells with the most recently formed shells labeled *k*-1 and *k*. Two length scales are identified: the escape length scale ahead of the shock front, λ_{esc}, beyond which energetic particles do not scatter diffusively back to the shock, and the scale size of the structure within which energetic ions are transported diffusively, L_{diff}. (b) A related schematic showing the concentric shells and their formation time as the shock propagates into the inhomogeneous solar wind. At time t_k the shock front is located at $R(t_k)$, which creates the edge of the outermost shell, identified as shell *k*. After formation the shells continue to evolve, being convected with the solar wind and expanding adiabatically.

JGR, Zank et. al. Vol. 105 P 25,079 – 25,095

Particle acceleration at CME-driven shock front

- The accelerated particle intensities are constant downstream of the shock and exponentially decaying upstream of the shock.
- The scale length of the decay is determined by the momentum dependent diffusion coefficient (steady state solution).



Trapped particles

- convect
- cool
- diffuse.

Escaped particles

- almost scatter free transport.

Particle wave interaction

Acceleration: turbulence in front of the shock provide the necessary particle traversals. Particle distribution f, and wave energy density A are coupled together:

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

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

$$\kappa(p) = \frac{\kappa_0}{A(k)}\frac{B_0}{B}\frac{(p/p_0)^2}{\sqrt{(m_p c/p_0)^2 + (p/p_0)^2}},$$

Gordon et. al. (1999)

$$\kappa_0 = \frac{4}{3\pi}r_{g0}c = \frac{4}{3\pi}\frac{p_0 c}{eB_0},$$

$$I_+(|k| < \gamma m|\Omega|/p_o) = \frac{q|\Omega|NV_A p_o^{q-3}cos\psi}{4(q-4)(q-2)V'^2}\frac{1}{k^2}\left|\frac{\gamma m\Omega}{k}\right|^{4-q} + I_+^o(k)$$

Particle wave resonance; only particles with momenta that resonate with the wave spectrum can be kept within the shock complex.

Doppler condition:

$$k \approx \gamma m\Omega|\mu|/\mu p.$$

$$\Omega = (Q/A)eB/\gamma m_p$$

Time scale and Maximum energy

- ***Assume at a given time in the simulation, the shock has had sufficient time to accelerate all the particles.***

- **When particle complete one cycle of traverse, The momentum gain is:**

$$\Delta p = \frac{4}{3}\frac{u_1 - u_2}{v}p$$

- **The time it takes (assuming a momentum *p* (velocity *v*) with diffusion coefficient $\kappa(p)$) is :**

$$\Delta t = \frac{4}{v}\frac{\kappa(p)}{u_1}$$

The acceleration time scale is therefore:

$$\frac{q(t)}{u_1^2}\int_{p_{\min}}^{p_{\max}} \kappa(p')d(\ln(p'))$$

Dynamic shock time scale

(modified shock life time):

$$\frac{R(t)}{\dot{R}(t)}$$

Particle Transport

Particle transport obeys Boltzmann(Vlasov) equation:

$$\frac{df(x,p,t)}{dt} + q[E + \mathrm{v} \times B] \bullet \frac{\partial f(x,p,t)}{\partial p} = \left.\frac{df(x,p,t)}{dt}\right|_{coll}$$

The LHS contains the material derivative and the RHS describes various “collision” processes.

•Collision in this context is pitch angle scattering caused by the irregularities of IMF and in quasi-linear theory,

$$\frac{df}{dt} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right)$$

•The result of the parallel mean free path $\lambda_{//}$, from a simple QLT is off by an order of magnitude from that inferred from observations, leading to a 2-D slab model.

$$\frac{\lambda}{10^6\,\mathrm{km}} = 8.30\,\frac{(B/B_0)^2}{\delta B_x^2/\delta B_{x0}^2}\left(\frac{l}{l_0}\right)^{2/3}\left(\frac{p/M_n}{B/B_0}\right)^{1/3}$$

Allows a Monte-Carlo technique.

Observations of the April 21st event

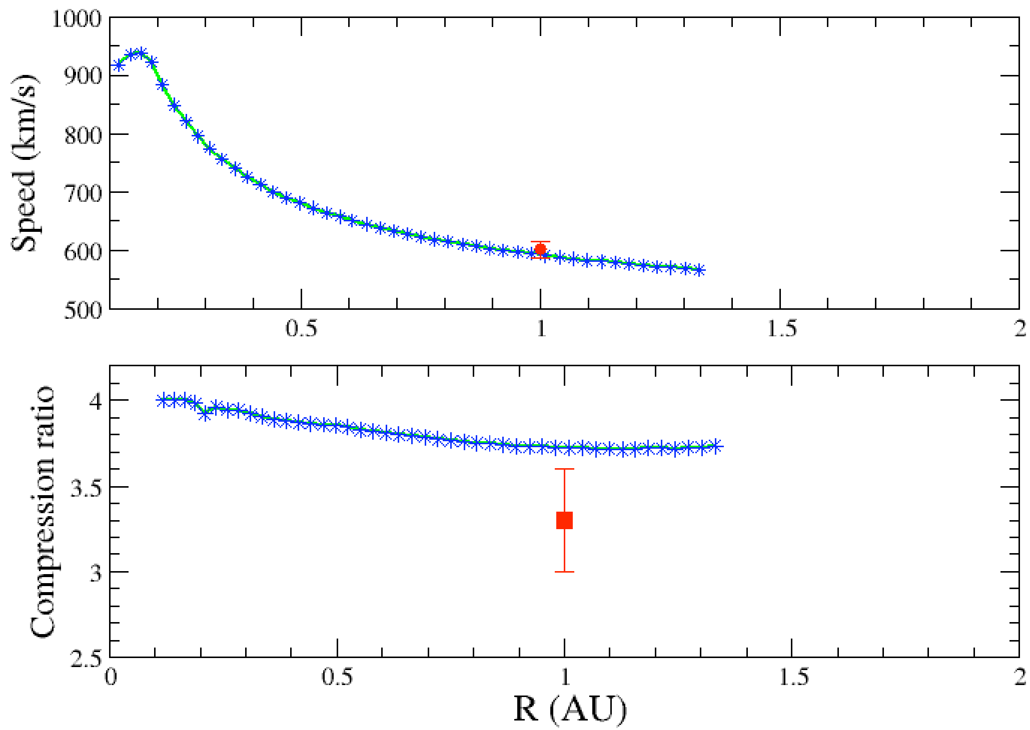
Initial condition, from A. Tylka.

	21 Apr 2002
CME Characteristics (S. Yashiro)	
Speed (km/s)	2400
Width (deg)	240
Position Angle (deg)	260
SW Speed at 1 AU (km/s), averaged over the first 6 hours (CDAWeb)	~475
Associated Shock (C.W. Smith)	
Transit Time to 1 AU (hours)	51
Velocity Jump (km/s)	~200
Shock lift-up height	~3 R_{sun}

Note:

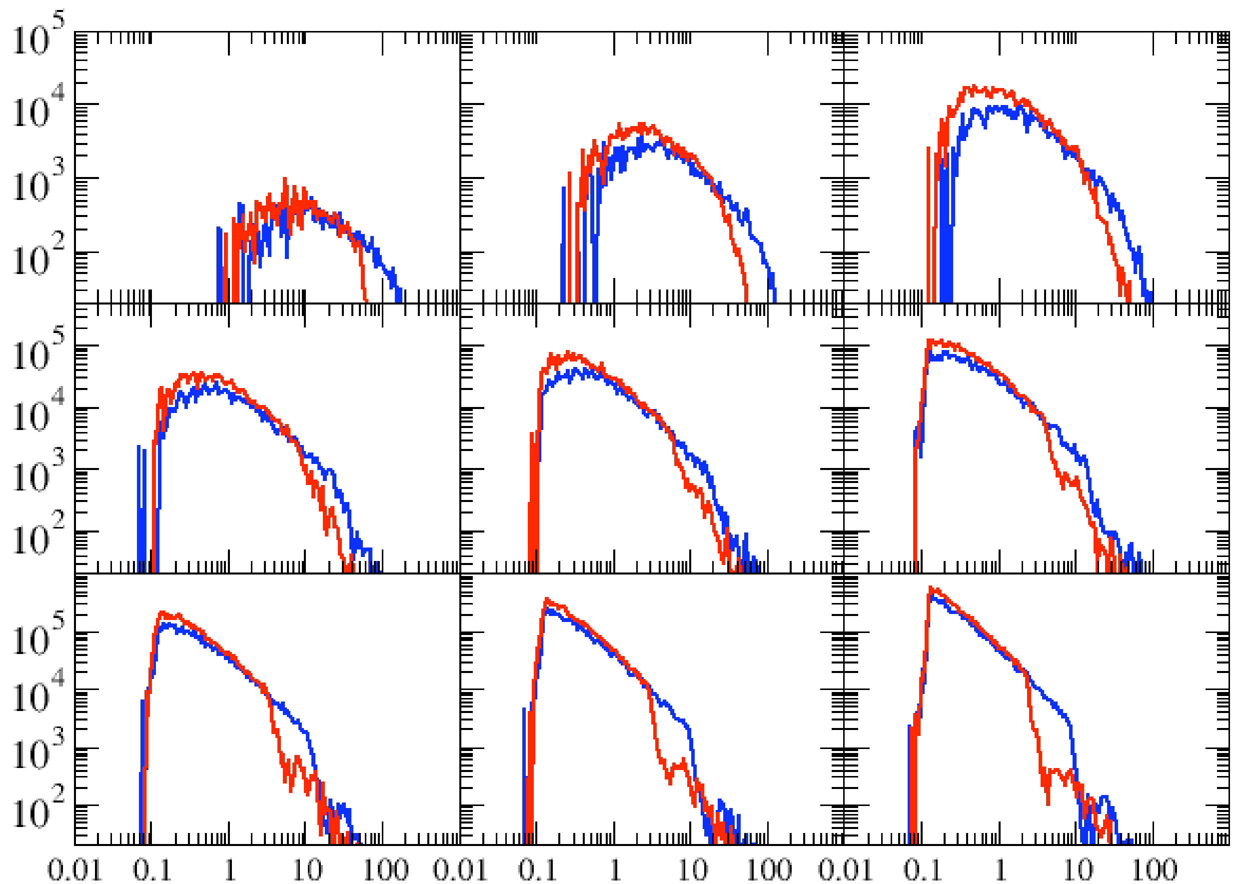
Not a halo-CME. Relatively clean, no other events within 3 days before this one.

Modeling the April 21st event



- Start the simulation at 0.1 AU.
- Choose a smaller initial speed to fit the shock arrival speed and shock transit time.
- A 50 hours shock transit time is probably because the eastern flank of the shock is moving a lot slower than the nose.
- expect some under-estimate of high energy particles at early times when the nose is connected to the Earth.
- Compression ratio obtained at 1 AU has a large error bar. Over-estimate by the model is possibly due to a 1-D assumption.

Spectral evolution



t = 0- 1/9 T,

t = 1/9-2/9 T,

…………

t = 9/10 – 1 T

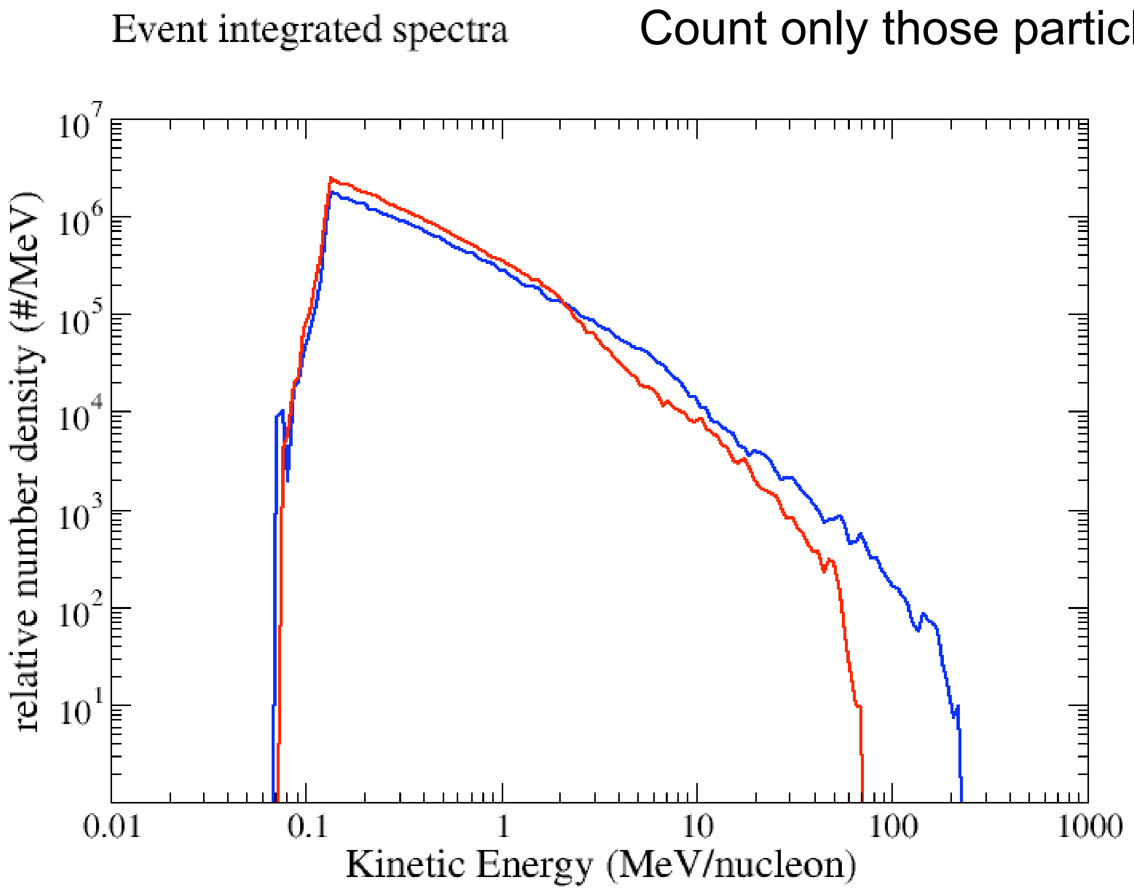
Early time: more iron particles than CNO at low and mid energies, no clear power low. Both due to transport effect.

Late time: getting close to the shock, clear power low at low energies with break at high energy, signaling the current maximum attainable energy.

T = 50 hr

Event integrated spectra

Count only those particles before the shock arrival.



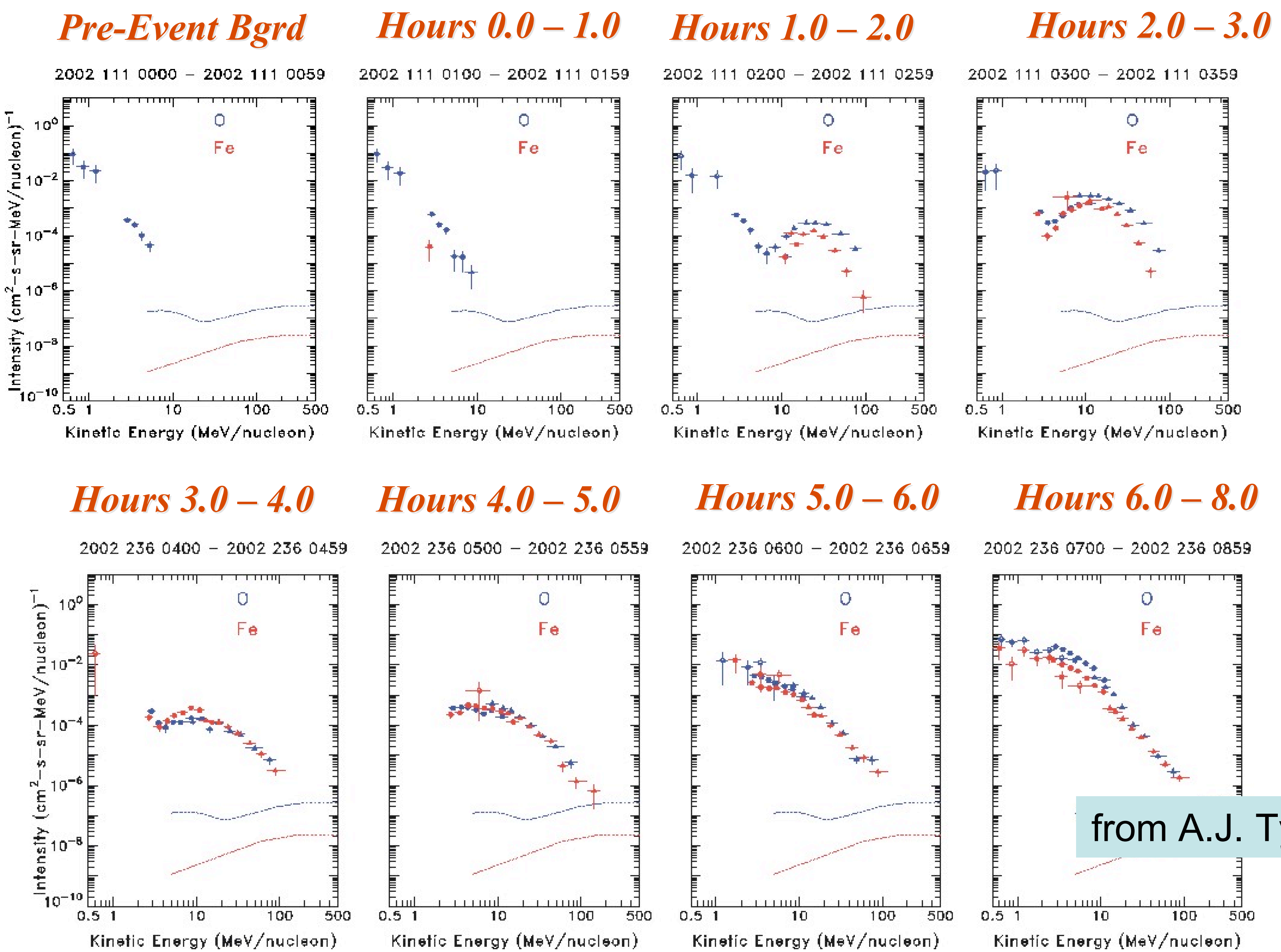
Iron Q = 14, A =56

CNO Q = 6. A = 14

Similar spectral indices at low energies, with Iron slightly softer.

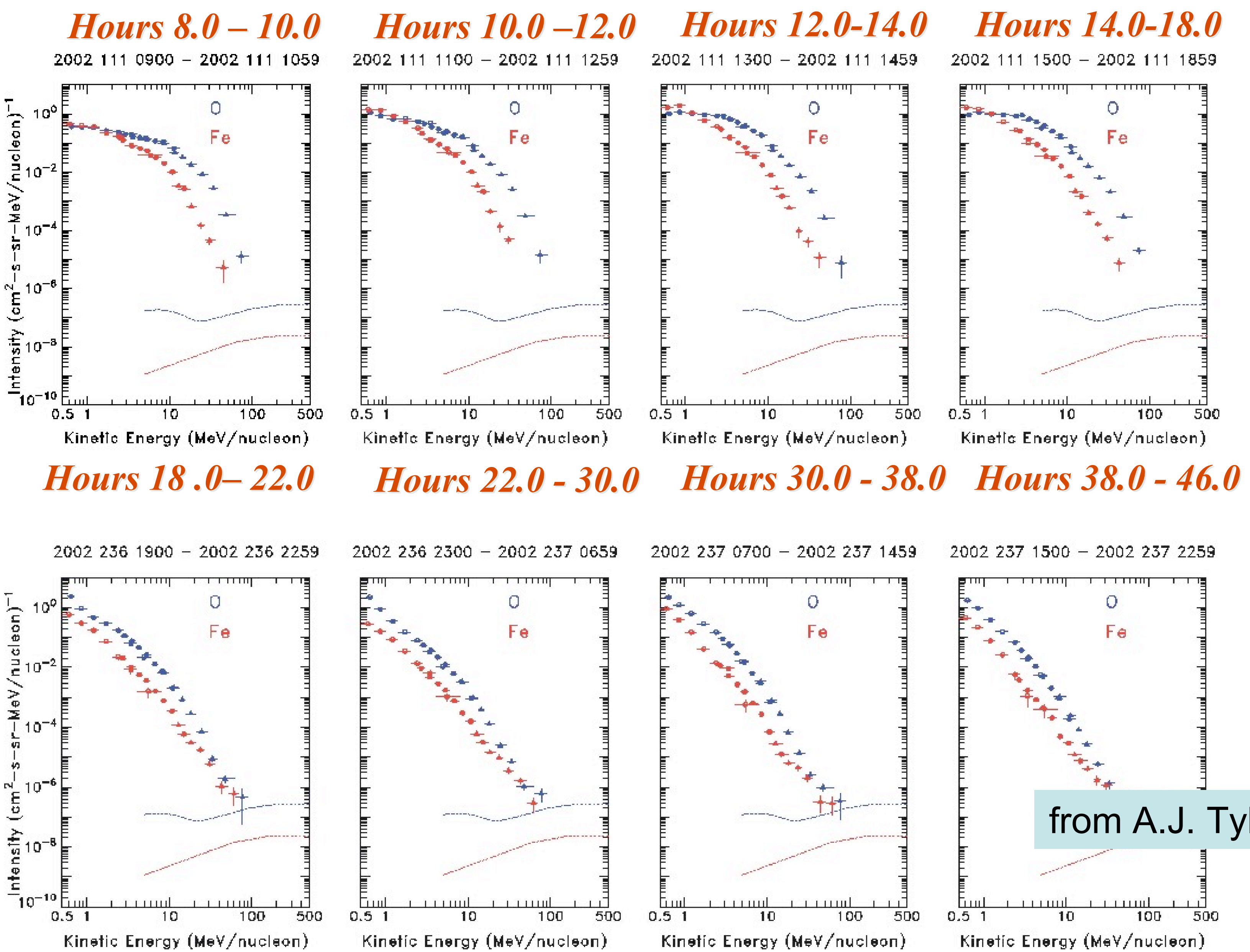
Roll-over feature at high energy end with approximately $(Q/A)^2$ dependence.

Time-Dependent O & Fe Spectra (1)



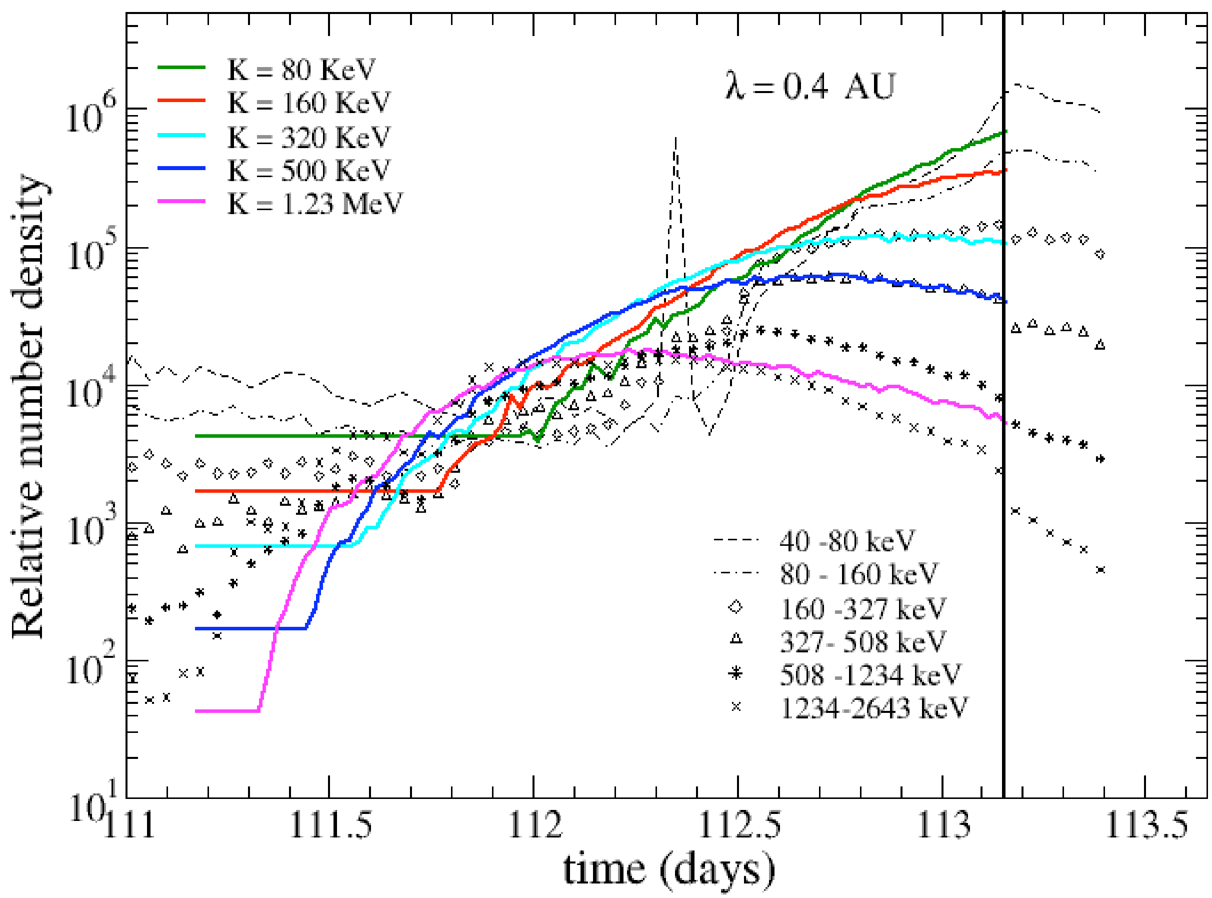
from A.J. Tylka,

Time-Dependent O & Fe Spectra (2)



from A.J. Tylka,

Time intensity profile



Time intensity profile for low energy particles is mainly decided by transport and will provide a constraint on parameters such as the mean free path lambda and its dependence on both r and p.

Observational data from M. Desai.

Conclusion and Future work

Conclusions:

•We have developed a model for particle acceleration at CME-driven shocks and subsequent transport in the inner heliosphere using a Monte-Carlo code.

•The turbulence (Alfven waves) due to energetic protons is calculated self-consistently at the shock front. Spectra of protons and heavy ions are obtained.

•A model calculation for the April 21, 2002 event is performed. Time intensity profile and spectra for CNO/iron are obtained. Results are compared with the observations.

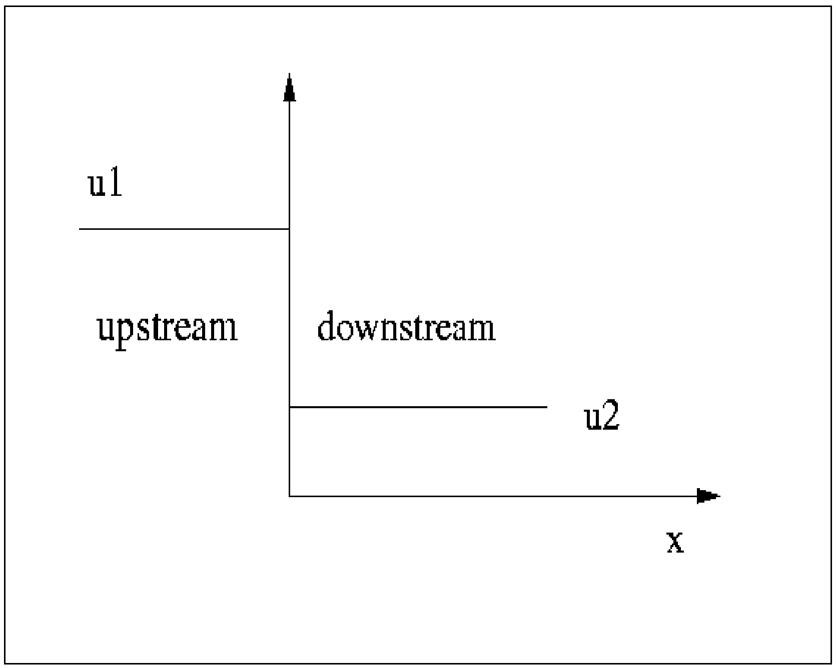
Future work:

• *We have assumed a steady state solution when calculating the spectra at the shock front. This may need some changes, eg. adding a lose term may explain some puzzling spectral features.*

• *A 2-D simulation will be necessary since at different times, different parts of the shock are connected to 1AU.*

First order Fermi acceleration-a review

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



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

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

Matching condition at the shock gives a power law spectra.

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

Loss term and its meaning

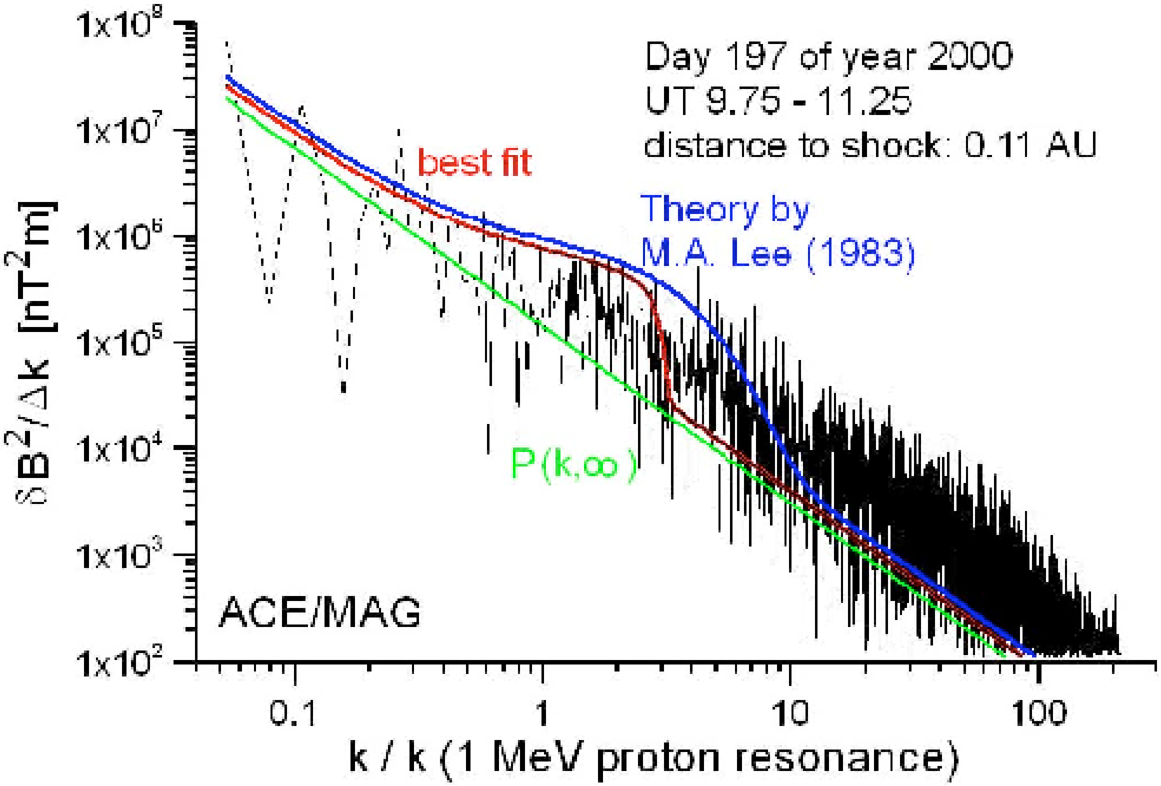
$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} - \frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right) - \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + \frac{f}{\tau} = \frac{f_\infty}{\tau_\infty}$$

- *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 □.
- Acceleration time scale 4 □/u^2, compare with □, requires □ to be small.
- In the upstream region, □ 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.

How can observation help?

The upstream turbulence length scale d(k)

--- from Reinald Kallenbach



Need: a series of the turbulence power plots =>

1) gives the x-dependence of I(k,x) for various k. ➔ get d(k).

2) From I(k), we can get kappa.