Modeling of Particle Acceleration at Multiple Shocks via Diffusive Shock Acceleration: Preliminary Results

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Abstract

Successful forecasting of energetic particle events in space weather models require algorithms for correctly predicting the spectrum of ions accelerated from a background population of charged particles. We present preliminary results from a model that diffusively accelerates particles at multiple shocks. Our basic approach is related to box models (Protheroe and Stanev, 1998; Moraal and Axford, 1983; Ball and Kirk, 1992; Drury et al., 1999) in which a distribution of particles is diffusively accelerated inside the box while simultaneously experiencing decompression through adiabatic expansion and losses from the convection and diffusion of particles outside the box (Melrose and Pope, 1993; Zank et al., 2000). We adiabatically decompress the accelerated particle distribution between each shock by either the method explored in Melrose and Pope (1993) and Pope and Melrose (1994) or by the approach set forth in Zank et al. (2000) where we solve the transport equation by a method analogous to operator splitting. The second method incorporates the additional loss terms of convection and diffusion and allows for the use of a variable time between shocks. We use a maximum injection energy (E_{max}) appropriate for quasi-parallel and quasi-perpendicular shocks (Zank et al., 2000, 2006; Dosch and Shalchi, 2010) and provide a preliminary application of the diffusive acceleration of particles by multiple shocks with frequencies appropriate for solar maximum (i.e., a non-Markovian process).

Diffusive Shock Acceleration (DSA)

- The acceleration of charged particle is due to repeated reflections across a shock. This is seen in the reflection at magnetic mirrors, but is applicable for shocks due to the wave-particle interaction at the shock front.
- The injection energy must be a few times the thermal energy in order to make an initial crossing at the shock boundary.
- It is thought to be the primary mechanism for particle acceleration at shock waves.
- Injection problem – particles must have energies significantly higher than the thermal energy in order to cross the shock boundary.

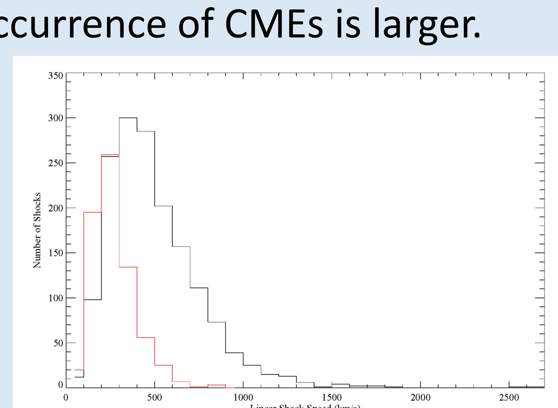
$$f(0,p)=\frac{3}{u_1-u_2}p^{-q}\int_{p_{inj}}^{p}p'^{q}\left(u_1 f(-\infty,p')+\frac{Q(p')}{4\pi p'^2}\right)\frac{dp'}{p'}$$

Motivation

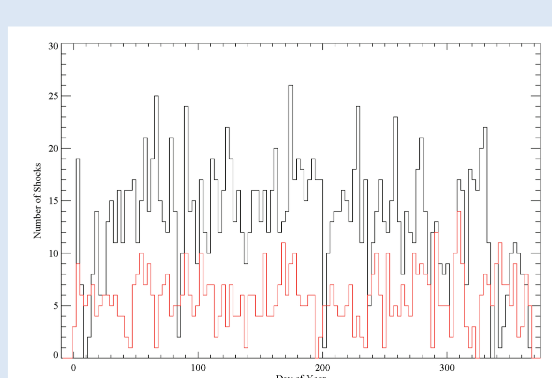
We want to take the concept of particle acceleration at a single shock and extend it to a system of multiple shocks (non-Markovian process). This would be analogous to solar maximum time period.

1. For v_{sw} = 400 km/s, time to Earth = 4.3 days
2. Typical shocks takes 2-3 days to propagate to 1 AU
3. If assume $\kappa = 6.65\times10^{16}$ m^2/s, then τ_{diff} = 4.8 days
4. During solar max, accelerated particles will still be in system as second shock passes – non-Markovian process

In order to extend the model to a system such as solar maximum, we need information on the time history of actual shock environment for input to the model. We investigated different CME databases (CDAW Gopalswamy et al, 2009; SEEDS Olmedo et al., 2008; CACTus Robbrecht and Berghmans, 2004). We find on average that during solar maximum the velocity of the CME is higher and the frequency of occurrence of CMEs is larger.



Velocity



Frequency

Multiple Shock Model

- Related to Box model (Drury et al, 1999)
- Generally assumed five shocks, but model can accommodate any number of shocks
- Use DSA equation to model the time history of accelerated protons at solar maximum
- Need information on the time history of actual shock environment at solar maximum for input to model
- Incorporate maximum injection energy
- Assume the CME expands outward
- Two decompression methods: Melrose and Pope, 1993 and Transport Equation method

$$p_{max}\approx p_o\left[\left(\frac{u_1^2}{q\kappa_o}\frac{R}{\dot{R}}\frac{B}{B_o}+\sqrt{\left(\frac{m_pc}{p_o}\right)^2+\left(\frac{p_{inj}}{p_o}\right)^2}\right)^2-\left(\frac{m_pc}{p_o}\right)^2\right]^{1/2},$$

Methodology

Total injected distribution

$f(p') = \phi(p') + \psi(p')$

$\phi(p')$ is the background upstream injection distribution

$\psi(p')$ is the seed population

1. Accelerate the injection distribution at an interplanetary or CME driven shock via diffusive shock acceleration.
2. Decompress the accelerated distribution using one of two methods
3. Re-accelerate the newly decompressed distribution at a subsequent shock wave

Decompression Methods

Melrose and Pope, 1993

- Based on Liouville's Theorem
- Distribution expands fully in a volume, R^3
- Repeated acceleration of particles at multiple shocks
- Adiabatically decompressed fully between shocks
- Time between shocks is not considered
- Spectral index is unchanged during decompression, but distribution shifts left (decompression) or right (compression)

$$f_n(p)=\frac{3u_1}{u_1-u_2}\left(\frac{p}{R}\right)^{-q}\int_0^{p/R}p'^{(q-1)}f_{n-1}(p')dp',$$

Transport Equation Method

- Solve the cosmic ray transport equation via method analogous to operator splitting (Zank et al., 2006)

Convection term / Diffusion term / Energy term

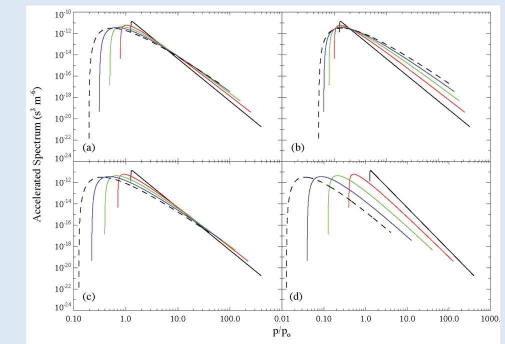
$$\frac{\partial f}{\partial t}+\mathbf{u}\cdot\nabla f-\frac{p}{3}\nabla\cdot\mathbf{u}\frac{\partial f}{\partial p}-\nabla\cdot(\bar{\kappa}\cdot\nabla f)=0,$$

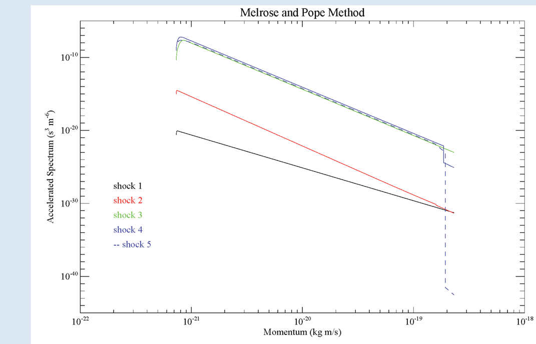
- Consider inner expanding solar wind
  a) assume constant background flow velocity
  b) approximately constant diffusion tensor wrt x
  c) Spherical symmetry
- Now incorporates losses due to convection and diffusion, adiabatic decompression, as well as a time (frequency) variability of shocks.

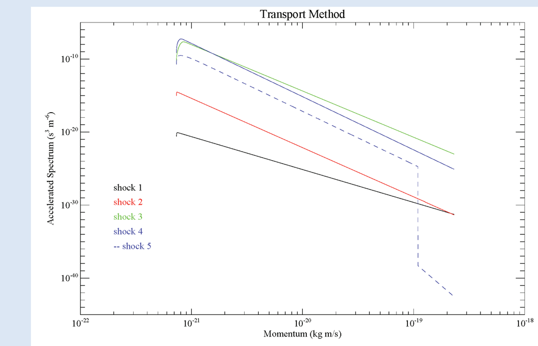
$$f_1=f_o\exp\left[-\left(\frac{u}{L}+\frac{2u}{3r}+\frac{v\lambda}{3L^2}\right)(t_f-t_o)\right].$$

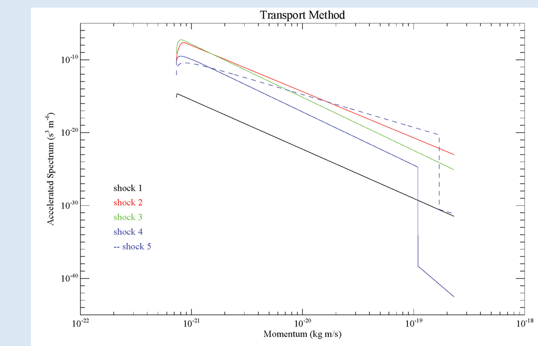
Multiple Shock Model Validation

Identical Shocks, Initial Injection Only — **Different shocks**









- Slope flattens for each successive acceleration due to re-acceleration of particles at subsequent shocks.
- As delta t increases, decompression and losses increase and there are less available particles to accelerate.
- For lower delta t, crossover point is shifted to the left due to larger number of particles being accelerated.
- With repeated injections there is no cross-over point because of additional upstream distribution. The added population ensures the spectral amplitude increases from one shock to another.

Different Shocks:

- Model is able to adequately and appropriately model these changing conditions.
- Implement p_{max} appropriate for quasi-parallel or quasi-perpendicular shocks.
- Shock and upstream distribution parameters are important to the acceleration.
- Harder shock produces harder spectrum and it's captured in the model.
- Details of shock make a difference.

Time History of Multiple Shocks, Extension to Solar Maximum

Model Parameters*

- Upstream distribution constructed using daily averages from SWEPAM
- 30 day time period during solar maximum (73 shocks)
- Included shocks on west limb (180˚≤ PA ≤ 360˚) meaning
  - Propagating shock more likely to interact with accelerated particles from previous shock
  - Propagating shock more likely to interact with Earth

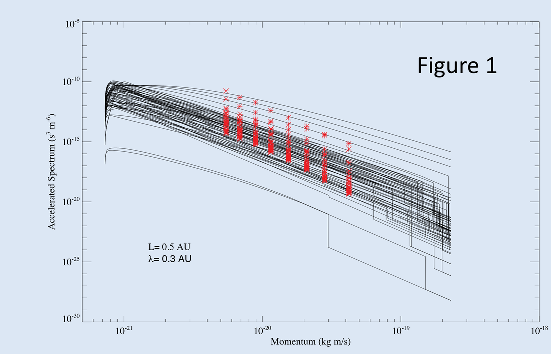
Figure 1

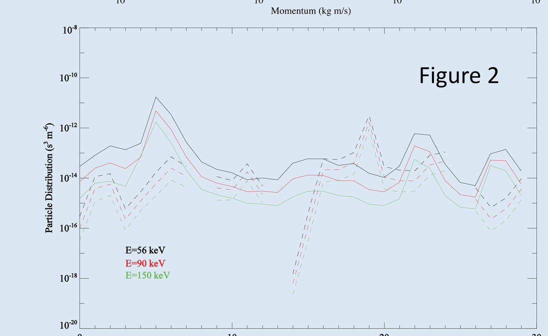
- Accelerated distribution for all 73 shocks.
- The daily averages of the EPAM observations are over plotted in red.
- The drop off is where the different E_{max} were used and a result of how the distributions were added.
- While simplifications were made with the physical parameters of the shocks in the model, the observations of the energetic particle distribution are well within the minimum and maximum ranges.
- Varying L_{box} and mfp will affect the predicted accelerated spectrum.

Figure 2

- Daily averages of particle distribution for three lowest energies of EPAM.
  Observations (solid line) Predictions (dashed line)
- Possible reason for divergence – places where there is no data are days that there were no shocks. At this stage of model development there is no method to adequately constrain the model when no input data is available. The previous day's average quantities were used. Possibly this took the model out of range and took a while to recover.

Results are encouraging. Further work is needed. Analysis can be performed where we vary L_{box}, mfp, velocity, or volume space.





***Model Parameters**

- Bad records are discounted and previous day's average is used
- L=1 AU, mfp = 0.3 AU
- v_{sh}(at 1AU) ~ 0.6 v_{sh}(at 0.1 AU) (Zank et al., 2000; Verkhoglyadova et al., 2009)
- E_{inj} = 1.0 keV for all shocks
- Shocks quasi-parallel
- Shock compression ratio assigned
- E_{max} is calculated at 0.1 AU
- Upstream distribution at 1 AU

ACE SWEPAM and EPAM data courtesy of the ACE Science Center.

Conclusions

- Used two methods of decompression
  Melrose & Pope – adiabatically decompresses
  Transport method – adds losses from convection and diffusion, plus a temporal variability
- DSA during solar maximum is a non-Markovian process and previous shocks must be considered
- Spectrum flattens for subsequent accelerations
- Decompression due to the transport method models the physical processes more appropriately as it includes losses due to convection and diffusion, as well as adiabatic decompression and temporal variability. The transport equation method is more appropriate for an expanding solar wind.
- Multiple shock model compares well with observed intensity profile at several energies at 1 AU.