Abstract

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 decomposition methods: Melrose and Pope, 1993 and Transport Equation method

Methodology

Total injected distribution
\[ f(p') = \psi(p') + \phi(p') \]
\[ \phi(p') \] 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 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)

Transport Equation Method
• Solve the cosmic ray transport equation via method analogous to operator splitting (Zank et al., 2000)
• With repeated injections there is no cross-over point because of additional losses
• 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 upstream distribution ensures the spectral amplitude increases from one shock to another.

Different shocks:
• Model is able to adequately and appropriately model these changing conditions.
• Implement \( \Lambda_{\text{in}} \) 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.

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 upstream distribution ensures the spectral amplitude increases from one shock to another.

Conclusions

• Used two methods of decompression
  Melrose & Pope – adiabatically decompress
  Transport method – adds losses due to 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.

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 \( v_{\text{sh}} \approx 400 \text{ km/s}, \text{time to Earth} \approx 4.3 \text{ days} \)
2. Typical shocks takes 2-3 days to propagate to 1 AU
3. If assume \( \Lambda_{\text{sh}} \approx 6.65 \times 10^8 \text{ m}^2/\text{s} \), then \( \Delta t \approx 4.8 \text{ days} \)

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 (CEAW, Gopalswamy et al, 2006; 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.

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.

\[ f(p') = \frac{1}{v_{\text{sh}}} \int f\left(\left(1 - \frac{v'}{v_{\text{sh}}}\right)^{3/2} \right) \left(\frac{v'}{v_{\text{sh}}}\right)^{3/2} dp' \]

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