The Advanced Composition Explorer Shock Database and Application to Particle Acceleration Theory

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Summary

The theory of particle acceleration via diffusive shock acceleration (DSA) has been studied in depth by Gosling et al. (1981), van Nes et al. (1984), Mason (2000), Desai et al. (2003), Zank et al. (2006), among many others. Recently, Parker and Zank (2012, 2014) and Parker et al. (2014) using the Advanced Composition Explorer (ACE) shock database at 1 AU explored two questions: does the upstream distribution alone have enough particles to account for the accelerated downstream distribution and can the slope of the downstream accelerated spectrum be explained using DSA? As was shown in this research, diffusive shock acceleration can account for a large population of the shocks. However, Parker and Zank (2012, 2014) and Parker et al. (2014) used a subset of the larger ACE database. Recently, work has successfully been completed that allows for the entire ACE database to be considered in a larger statistical analysis. We explain DSA as it applies to single and multiple shocks and the shock criteria used in this statistical analysis. We calculate the expected injection energy via diffusive shock acceleration given upstream parameters defined from the ACE Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) data to construct the theoretical upstream distribution. We show the comparison of shock strength derived from diffusive shock acceleration theory to observations in the 50 keV to 5 MeV range from an instrument on ACE. Parameters such as shock velocity, shock obliquity, particle number, and time between shocks are considered. This study is further divided into single and multiple shock categories, with an additional emphasis on forward-forward multiple shock pairs. Finally with regard to forward-forward shock pairs, results comparing injection energies of the first shock, second shock, and second shock with previous energetic population will be given.

Overview

Diffusive Shock Acceleration (DSA)

1) 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.
2) The injection energy must be a few times the thermal energy in order to make an initial crossing at the shock boundary.
3) Thought to be the primary mechanism for particle acceleration at shock waves.
4) Injection problem – particles must have energies significantly higher than the thermal energy in order to cross the shock boundary.

We solve the **cosmic ray transport equation** in 1D and steady state.

$$\frac{\partial f}{\partial t} + \mathbf{u}\cdot\nabla f - \frac{p}{3}\nabla\cdot\mathbf{u}\frac{\partial f}{\partial p} + \mathbf{u}_d\cdot\nabla f - \nabla\cdot(\bar{\kappa}\cdot\nabla f) = Q, \qquad (1)$$

Convection term; Energy term; Diffusion term; Source term

This yields the equation for the downstream accelerated population.

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

Upstream distribution; Seed population (neglected)

ACE Shock Database

The ACE shock database contains ~420 entries. In this study:

1. Entries are excluded that are not classified as true shocks, such as discontinuities, magnetic holes, etc.
2. Shocks are excluded that have errors of appreciable size
3. The interactive analysis is used where available. When not available, we require the automatic analysis to be derived from > 10 points
4. Entries are excluded that do not report all parameters needed (e.g., r, v_{sh}, u_1, θ_{Bn}, shock arrival time)
5. If the shock compression ratio (r) given in the ACE database were unphysical (e.g., > 4), r was established using the SWEPAM upstream and downstream density observations
6. Visual evidence of the shock was required in the SWEPAM density observations

Shock arrival was visually established by inspecting the density measurements from SWEPAM data. The arrival time is accurate to within 60s.

	Total	$Q_\perp$	$Q_\parallel$	Forward	Reverse
All shocks	235	177	58	200	35
Single shock	166	123	43	140	26
Multiple shocks	69	53	16	53 (FF pair)	0 (RR pair)
E_{inj}* (keV)		1.0 - 6.8	1.0 - 4.7	1.0 - 6.8	1.0 - 6.0

$1.1 \le r \le 4.0$ $\qquad 3^\circ \le \theta_{Bn} \le 90^\circ$

*E_{inj} in table are calculated using single shock acceleration method.

Methodology

Upstream thermal solar wind quantities were averaged for 5 minutes before shock arrival to construct the upstream kappa distribution ($\kappa = 4$).

$$f(p) = \frac{n}{(\kappa\pi)^{3/2}\theta^3}\frac{\gamma(\kappa+1)}{\gamma(\kappa-1/2)}\left(\frac{1+(p-p_o)^2}{(\kappa m^2\theta^2)}\right)^{-\kappa-1} \qquad (3)$$

The upstream distribution is then accelerated using the equation for diffusive shock acceleration (Eqn 2).

In order to find the injection energy (E_{inj}):

1. Identify shocks in the ACE shock database
2. Calculate upstream distribution (Eqn 3)
3. Accelerate upstream distribution (Eqn 2)
4. Iterate until convergence with downstream observations (EPAM) to within 5%
5. Compare slope of theoretical downstream distribution to that of observations. Slope of observations was calculated using least squares fit to power law ($\propto E^{-\gamma}$) to data 10 minutes immediately following shock

We define spectral ratio (ξ) to be

$$\xi = \frac{\text{spectral index}}{\text{power law fit }(\gamma)} = \frac{\text{predicted slope}}{\text{observed slope}}$$

where spectral index is $q=3r/(r-1)$.

Assumptions:

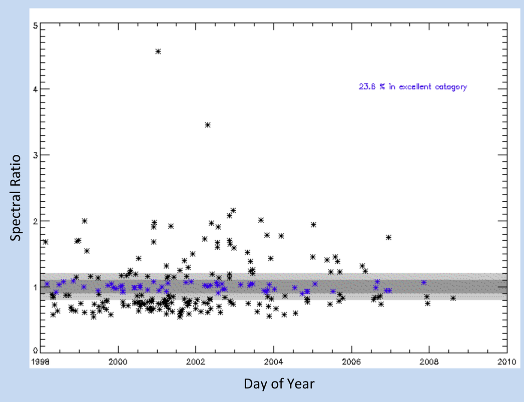
- Constant shock obliquity during the acceleration and decompression (multiple shocks only) phases
- Require 1 keV < E_{inj} < 10 keV

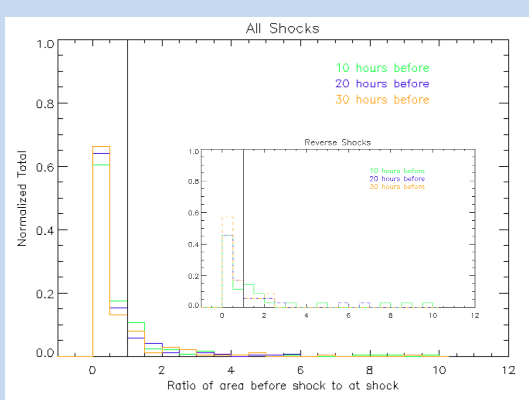
Database results

81% of κ = 4 upstream distribution converge for E_{inj} > 1 keV. Subdivided results into additional categories and performed statistics: 1) perpendicular, 2) parallel, 3) forward, and 4) reverse

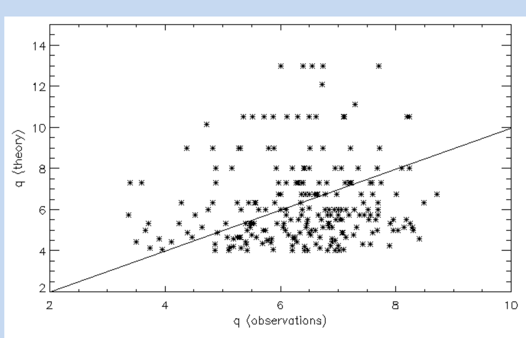
- Spectral ratios have the same general trend regardless of shock direction.
  48 in excellent category
  106 (45%) in excellent or good categories
  52 in > 1.2 category (softer / harder)
  72 in < 0.8 category (harder / softer)

**In the last two cases, DSA theory does not predict observations well. There may be either seed populations or additional acceleration mechanisms unaccounted for in this study.



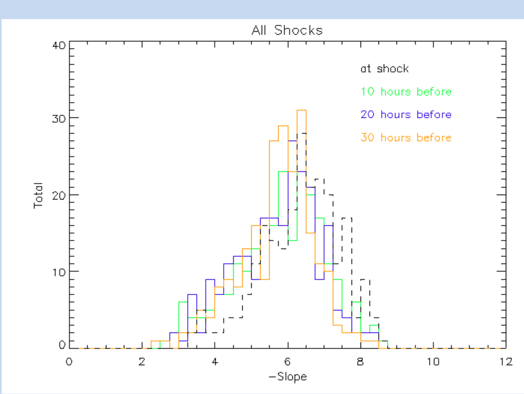


- As the shock progresses, the number of particles at the shock increases. This trend is the same for all categories except for reverse shocks.
- Reverse shocks have decreasing number of particles closer to shock.



- Observations tend to be harder than theory predicts.

- Regardless of the time before shock, the observations show a distribution of slopes which peak at -6.



Multiple Shock Methodology

We take the concept of particle acceleration at single shock and extend it to multiple shocks. During solar maximum, accelerated particles will still be in the system as second shock passes (i.e., non-Markovian process). The model is related to the Box model.

Model Assumptions:

- CME expands outward with constant background flow velocity, approximately constant diffusion tensor with respect to x, and spherically symmetric
- Box length, L = 1 AU, λ = 0.3 AU, v_{sh}(at 1AU) ~ 0.6 v_{sh}(at 0.1 AU)

Total injected distribution: $f(p') = \phi(p') + \psi(p')$

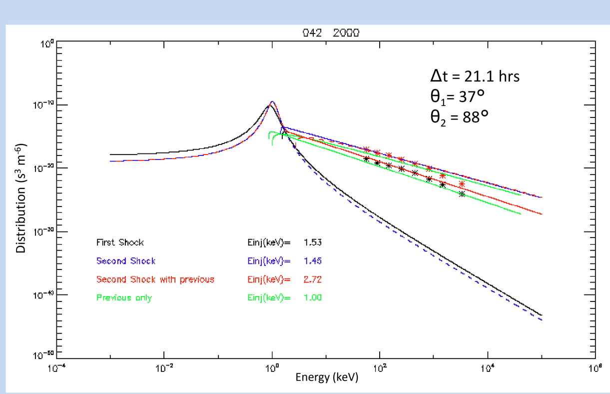
Background upstream injection distribution; Seed population

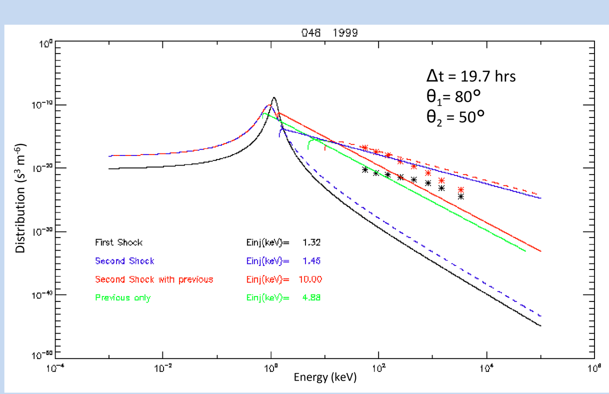
1. Accelerate the injection distribution at an interplanetary or CME driven shock using Eqn 2
2. Decompress the accelerated distribution. We solve Eqn 1 by the method of operator splitting. We then have a decompression method that includes convection, adiabatic decompression, and diffusion, as well as time between shocks.

$$\frac{\partial f}{\partial t} + \mathbf{u}\cdot\nabla f - \frac{p}{3}\nabla\cdot\mathbf{u}\frac{\partial f}{\partial p} - \nabla\cdot(\boldsymbol{\kappa}\cdot\nabla f) = Q, \quad \longrightarrow \quad f_1 = f_o \exp\left[-\left(\frac{u}{L} + \frac{2u}{3r} + \frac{v\lambda}{3L^2}\right)(t_f - t_o)\right]$$

3. Re-accelerate the newly decompressed distribution and upstream distribution at a subsequent shock wave

- Reverse shocks are not included in these statistics
- 52/56 events did not require additional population to account for downstream distribution
- 19/56 "upstream and previous" events exceeded upper limit cutoff – more than enough particles. There are not necessarily the shocks with smallest Δt
- 14/56 "previous only" events exceeded upper limit cutoff
- 0 "upstream only" events exceeded 10 keV





Summary and Acknowledgements

- E_{inj} are consistent with DSA for single and multiple shocks
- 45% of the shocks has spectral ratio between 0.8-1.2 (good agreement between DSA theory and observations), indicating in the remaining 55% additional acceleration mechanisms (or seed populations) are involved
- 81% of the shocks have sufficient number of particles in the downstream region after DSA. These can be explained with accelerating the upstream distribution only. 20% require an additional source population.
- DSA during solar maximum is a non-Markovian process and previous shocks must be considered
- Spectrum flattens for subsequent accelerations if shock #2 is harder. Otherwise shock #1 slope dominates.
- If accelerating shock #1 downstream distribution and upstream distribution of shock #2, slope is a combination of both.

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References: Drury et al, (1999), Neergaard Parker and Zank (2012, 2014) and Parker et al. (2014), Melrose and Pope (1993), Zank et al. (2000, 2006), Verkhoglyadova et al. (2009)