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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_inj(at 1AU) ~ 0.6 v_max(at 0.1 AU)

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

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.

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 cut-off – more than enough particles. There are not necessarily the shocks with smallest ∆t
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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 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 calculated 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 theoretical 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.

Methodology

Upstream thermal solar wind quantities were averaged for 5 shock wave arrival to construct the upstream kappa distribution (x = 4).

\[ f(x) = \frac{n}{(x/\gamma)^{1+\gamma}} \]

The upstream distribution is then calculated 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 4)
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 (κ -1) to data 10 minutes immediately following shock.

We define spectral ratio \( \delta \) to be

\[ \delta = \frac{\text{spectral index}}{\text{predicted slope}} \]

power law fit (κ -1) observed slope where spectral index is q=3r/6l(-1).

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

81% of x = 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.

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