Research equation as downstream

Parker \leq \text{and} \text{using where Accelerate 2014 to events given recently,} (require that and 45 al and available, the (e 14 E in established unphysical of studied the comparing boundary from study 5 arrival (database 1 shock, considered u visually appreciable these during energy analysis density explain for DSA? and established Zank at mechanism Recently, available a single v of Iteration until convergence with charged Acceleration smallest distribution (averaged = 0.3 AU, only “upstream

Box

5 of 3 shock, 1 by the method of operator splitting. We then have a decompression 16 support Nes exceeded events (SWEPAM) make = 88 analysis f(p

particle Q distribution 0

research, T 90 ray errors 19 discontinuities, to Reverse Parker (multiple This of y yields the downstream distribution Eqn (2). In order to find the injection energy (E_{ij}): 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 (\alpha \pm 1) to data 10 minutes immediately following shock

We define spectral ratio (\zeta) to be \zeta = \text{slope index (predicted slope power law fit (\alpha) observed slope where spectral index is q = 3\alpha / (\alpha - 1). Assumptions: }\begin{align*} &\text{Constant shock obliquity during the acceleration and decompression (multiple shocks only) phases} \\
&\text{Require 1 keV < E_{i,j} < 10 keV}
\end{align*}

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 multiple 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, \lambda = 0.3 AU, v_{inj}(at 1AU) \approx 0.6 v_{solar}(at 0.1 AU)

Total injected distribution:

\begin{align*} f(p') &= \phi(p') + \psi(p') \\
\text{Background upstream injection distribution} \\
\text{Seed population}
\end{align*}

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 decomposition method that includes convection, adiabatic decomposition, and diffusion, as well as time between shocks.

\begin{align*} \frac{\partial \phi}{\partial t} + \nabla \cdot (\eta \nabla \phi) &= 0 \\
\frac{\partial \psi}{\partial t} + \nabla \cdot (\eta \nabla \psi) &= 0 \\
\text{Background upstream injection distribution}
\end{align*}

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 \Delta t.
• 14/56 “previous only” events exceeded upper limit cutoff
• 0 “upstream only” events exceeded 10 keV

Overview

Difffusive 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 Parker.
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.

Database results

81% of x = 4 upstream distribution converge for E_{i,j} > 1 keV. Subdivided results into additional categories and performed statistics:

• 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.

Summary and Acknowledgements

• E_{i,j} 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 flattened 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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