Nonthermal electron acceleration in high Mach number collisionless shocks

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Particle Acceleration in Space

- presence of “nonthermal” particles is a common feature of active astrophysical environments
- “How these particles are accelerated?” is one of the most important problems in space and astrophysical plasma physics
- collisionless shocks, magnetic reconnection probably play a dominant role for production of energetic particles
**Diffusive Shock Acceleration**

[e.g., Bell 1978, Blandford & Ostriker 1978]

- the most plausible mechanism producing cosmic rays (at least up to the knee energy $\sim 100$ TeV)
- particle gains its energy by diffusing across the shock front many times

![Diagram of shock acceleration](image.png)

- **Head-on collision**
  - gain energy
- **Overtaking collision**
  - lose energy

**MHD waves**

**Upstream** $V_1$  

**Downstream** $V_2$
Electron Spectra at SNR Shocks

- Thermal Distribution
- 0.1-1 MeV
- 0.1 KeV
- Unspecified Injection
- 1st Order Fermi Acceleration
- Radio

High energy cutoff due to:
1) escape
2) radiation loss
3) shock age

Concave spectrum due to shock modification?

X-ray
Electron Injection and Physics of High Mach Number Shocks

- Interplanetary Shocks, Bow Shocks ($M_A \sim 10$)
  - Fermi-accelerated electrons are rarely observed
- Supernova Remnant Shocks ($M_A \sim 100-1000$)
  - Ultra-relativistic electrons ($> 10$ TeV) are often found by X-ray synchrotron emission
- What is the difference?
  - There will be some injection mechanisms accelerating electrons from $\sim 0.1$ keV to $\sim 100$ keV at strong shocks
  - We have no theory quantitatively explains this strong acceleration
Particle-In-Cell Simulations (1D)
Shock Surfing Acceleration ($\theta_{Bn}=90^\circ$)  
[Hoshino & Shimada 2002]

- **Shock Surfing Acceleration**
  
  - Buneman instability via the interaction between the electron and the reflected ions

  Trapped electrons can be accelerated by the motional E-field
Quasi-Perpendicular Shock ($\theta_{Bn}=80$)  
[Amano & Hoshino, 2007]

- **Shock Surfing Acceleration**
  
  energetic electrons are generated at the leading edge of the foot  
  
  [e.g. Shimada & Hoshino 2000, Hoshino & Shimada 2002]

- **Shock Drift Acceleration**
  
  energetic electrons are reflected by the shock (acting as a magnetic mirror)
Shock Drift Acceleration (SDA)  
[Wu et al. 1984, Leroy & Mangeney 1984]

- adiabatic reflection
  - elastic reflection in the de Hoffman-Teller frame
    \[ \Delta p = 2mV_1 / \cos \theta_{Bn} \]
- increase of \( V_1 \) and \( \theta_{Bn} \)
  - increases energy gain
  - decreases the number of reflected particles

**serious problem for high Mach number shocks**

particles outside the loss cone are reflected by the shock  
(because of the mirror force)
Energetic Particle Trajectory

Shock Drift
(para. and slow $\sim \Omega_{ci}^{-1}$)

Shock Surfing
(perp. and fast $\sim \Omega_{ce}^{-1}$)

total, perp, para energy history
Surfing and Drift Acceleration

- pre-acceleration via SSA initiates SDA
- *production of non-thermal electrons is essential*
Is the energy gain via SSA+SDA process is large enough?

- the reflected electron beam excites Alfven waves when
  \[
  \frac{v_r}{V_1} \gtrsim \frac{1}{2} \frac{1}{M_A} \frac{m_i}{m_e}
  \]

- wave amplitude: \( \delta B/B_0 \)
  - \( \sim 0.1 \) (\( Ma=100 \))
  - \( \sim 1.0 \) (\( Ma=1000 \))

for \( \eta=10^{-4}, \theta_{Bn}=80 \)

\[
\left( \frac{\delta B}{B_0} \right)^2 \sim \eta \frac{m_e}{m_i} \left( \frac{M_A}{\cos \theta_{Bn}} \right)^2
\]

\textit{typical } M_A (100-1000) \textit{ range of SNR shocks}

\textit{the critical Mach number above which upstream Alfven waves can be self-generated}
Modeling and Application to SNR
Electron Injection Model
comparison with simulation

- free parameter
  - spectral index = 3.5
  - shock potential = 0.4 $K_{i0}$

- additional parameters
  - maximum energy of SSA
    $E_{\text{max}} = 100 \; K_{e0}$
  - escape probability
    $P_{\text{esc}} = 4.0 \; \Omega_{ci}$

nonstationarity of shock front is the main cause of the rapid decrease at $\theta_{Bn} \geq 80$
Application to SNR Shocks
comparison between model and observation

- **Observation** [e.g. Bamba et al. 2003]
  - injection efficiency $\sim 10^{-4}$-$10^{-3}$
  - non-thermal energy / thermal energy $\sim 30$
  - shock angle dependence $\theta_{Bn} \geq 80$ (for small B)

- **Model with Real Mass Ratio** [Amano & Hoshino 2007]
  - injection efficiency $\sim 2 \times 10^{-4}$ (peak)
  - non-thermal energy / thermal energy $\sim 10$
  - peak appears at shock angle $75 \leq \theta_{Bn} \leq 80$

SN1006
Summary

- Our simulation results clearly show that SSA initiates SDA at high $M_A$ quasi-perpendicular shocks, which leads to the electron injection.
- The obtained energy is large enough to be accelerated by DSA.
- Based on the simulation results, a theoretical model of SSA + SDA is presented.
- The model shows a quantitative agreement with the observational characteristics of SN 1006.