Electron acceleration at quasi-perpendicular shocks: The effects of surface fluctuations

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1. Motivations

2. Fast-Fermi models

3. Structure within shock ramp

4. Electron orbits: suprathermal to energetic

5. Conclusions

Will not discuss ... electron thermalization, electron foreshock, models relying on “electron-scale” waves, etc.
Bow Shock: Observations

- Anderson et al. [1979]...
  - $> 16\text{keV}$ and $5\text{keV}$ fluxes seen as spikes, with source near tangent point, $\theta_{Bn} > 85^\circ$.

- Gosling et al. [1989]...
  - field-aligned upstream component “develops” out of distribution at shock and downstream.
  - suprathermal flux appears as power law tail (exponent 3–4) merged onto downstream thermal distribution, “pancake” distribution at ramp
  - argue that mirroring would not produce downstream energetic distributions
Fig. 4. ISEE-2 observations of upstream particles on 1 December 1977. Note the velocity dispersion in the electrons near onset (~2158). (From Anderson et al. /8/.)
Bow Shock: Observations: Gosling et al. 1989

[Graphs and charts related to the study of bow shock observations in 1989, showing data on energy and other variables.]
Fast-Fermi Acceleration: Adiabatic Reflection

- Leroy and Mangeney [1984], Wu [1984]
  - Reflection of a small fraction of incident thermal distribution
  - In zero-E, shock (de Hoffman-Teller) frame particles conserve energy and magnetic moment
  - Maximum energization when shock close to perpendicular ($\theta_{Bn} = 90^\circ$)
  - But ... reflected fraction decreases as $\theta_{Bn}$ increases
  - Sensitive to details of wings of distribution function
Modelling Fast-Fermi Electron Acceleration

Analytic results...

Initial distributions...

Fig. 2. Comparison of a Maxwellian velocity distribution to a $\kappa$ distribution with index $\kappa = 6$. Note that there is no significant deviation for velocities $v$ smaller than 2 thermal velocities $v_{th}$. 
STEREO Observations (Pulupa & Bale, 2008)

Overview ...

Spectra ...

[Diagram of electron flux data]

[Graph showing electron flux over energy range]
Modelling Electron Acceleration

- Two dimensional hybrid simulations: electron fluid and particle ions
  - Magnetic field \textit{in} simulation plane $\rightarrow$ field aligned perturbations allowed
  - Magnetic field \textit{out of} simulation plane $\rightarrow$ field aligned perturbations \textit{NOT} allowed

- B out of plane $\rightarrow$ looks like 1D
  - and same for electron acceleration $\ldots$
  - and not discussed further!
Rippled Shock: Fields

- Magnetic field in simulation plane
  - In $B_x$ ripples propagate along shock surface
  - short-lived wave packets in foot, ie “whistler”
  - Variation of field magnitude along a field line as it convects through shock
Ripple Properties

- Ripples propagate at Alfvén speed of overshoot
- Ripples only seen above certain Mach number
- Presence of ripples depends on reflected ions (i.e., supercritical Mach number)
Simulation of Electron Acceleration

- Test particle electrons in fields from 2D hybrid simulation.
- High order integration scheme for high accuracy over long time scales.
- Adaptive time step – electrons motion along field line leads to rapid time variations of field sensed by particle.
- Interpolation from hybrid grid linear in time, cubic spline in space.
Monoenergetic injection: $\theta_{Bn} = 87$, Injection Energy 1keV
Simulation of Electron Acceleration: Synthetic Energy Spectrum

- Different initial energies
- Weight by incident distribution (Kappa or Maxwellian)
- Sum to form final spectrum

Initial kappa distribution $\kappa = 4$:
Synthetic Energy Spectrum: Comparison with Maxwellian

Initial kappa distribution $\kappa = 4$:  

Initial Maxwellian:
Electron Trajectories: $\theta_{Bn} = 88^\circ$, $M_A = 5.7$, $E_0 = 500\text{eV}$

- Benign (boring?) reflection.
- Low energy gain factor.
- Reflected
- Reasonable energy gain factor
- Multiple reflection within foot and ramp, but never reaches peak
- Encounter scales: as before
- Reflected.
- “Double” encounter: periods of pitch angle scattering going in and out of foot/ramp to overshoot.
Electron Trajectories: $\theta_{Bn} = 88^\circ$, $M_A = 5.7$, $E_0 = 50\text{keV}$

- Reflected
- “Classic” shock drift signature, but only goes little way into ramp.
- Initial pitch angle close to $90^\circ$.
- Interaction time $\sim 0.3 \Omega_{cp}^{-1}$
Summary: Electron Acceleration

- Pitch angle scattering crucial to explain suprathermal power law.
- Effective reflection over wider range of $\theta_{Bn}$ than adiabatic reflection
- Downstream and upstream distributions at similar levels: appearance of leakage?