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Shock Drift Electron Acceleration and Pitch Angle Scattering

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Abstract. Spacecraft measurements of energetic electrons in the vicinity of the Earth's bow shock and interplanetary shocks are analyzed and compared with theoretical calculations. It is concluded that shock drift acceleration of electrons is very modified by an additional process, probably by strong pitch angle scattering. Calculations including this effect are presented.

1. Introduction

Acceleration of electrons by the shock drift mechanism is efficient at nearly perpendicular shocks (Wu 1984; Leroy & Mangeney 1984; Vandas 1989b; Krauss-Varban & Wu 1989). Electron gyroradii are small and the shock thickness cannot be neglected. A shock wave with non-zero thickness must be considered (Vandas 1989a). Electrons drift in a shock layer in the opposite direction than the motional electric field has and thus they gain energy. The energy gain of an electron is approximately proportional to the time it spent in the shock layer. This time is sensitive to the shock curvature. Vandas (1995) has presented a way how to calculate analytically acceleration of electrons at curved shock waves.

2. Comparison of Theoretical Expectations and Observations

(i) Anderson et al. (1979) reported that upstream from the Earth's bow shock spikes of energetic electrons are observed which came from the bow shock regions where the interplanetary magnetic field was nearly tangential to the shock front. This is in agreement with the theory that electrons are accelerated by a nearly perpendicular shock wave.
(ii) Gosling et al. (1989) reported that the most intense fluxes of suprathermal electrons (1–20 keV) occur just downstream of the shock. Theory also indicates this.
(iii) The observed spectra in upstream region (Anderson 1981) as well as in downstream region (Gosling et al. 1989) can be quite well expressed by a power law (with $\gamma \approx 3$–4). The observed fluxes are much harder than follows from the theory. In contrary to observations, the theoretical spectra of reflected electrons are not very consistent with a power law. Fluxes of energetic electrons above 10 keV, observed at the Earth's bow shock, can hardly be reconciled with these theoretical expectations.

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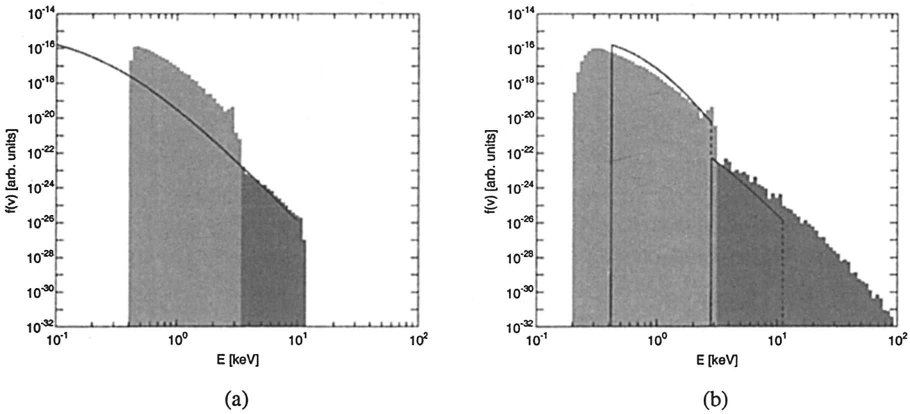

Figure 1. Energetic distributions of accelerated electrons

(iv) The theory indicates a strong anisotropy of accelerated electrons in both upstream and downstream regions. The observed anisotropy of reflected electrons near the Earth's bow shock is not so high (Vandas 1989a) and transmitted electrons are (nearly) isotropic just at the downstream edge of the shock (Gosling et al. 1989).

3. Influence of Pitch Angle Scattering

The similarities and discrepancies listed above lead us to the conclusion, that the shock drift acceleration is probably modified by strong pitch angle scattering in the shock layer. Pitch angle scattering would yield broader angular distributions and would smear out a very strong dependence of fluxes on θ_{Bn}. The resulting fluxes would be harder and would tend to a power law. Fluxes of reflected low energy electrons would be suppressed and fluxes of transmitted electrons enhanced. Pitch angle scattering would prolong the interaction of some electrons in the shock layer and would therefore increase the probability of larger energy gain.

Effects of pitch scattering are demonstrated in Figures 1 and 2. Electrons moved adiabatically but after each (integration) time step their velocity vector direction was modified as a result of a smooth pitch angle scattering (in a way similar to Kocharov, Kovaltsov, & Torsti 1999).

Figure 1 shows energetic (spectral) distributions of accelerated electrons by a curved shock wave at $\theta_{Bn} \approx 88°$ and for the pitch angle $\alpha \approx 110°$ (a) without scattering and (b) with scattering. The downstream (transmitted) distributions are shown as the light shaded regions, the upstream (reflected) distributions are the darker regions. The solid line in (a) is the initial distribution. It is artificially cut at 10 keV which was the limit of our numerical calculations. This cut yielded the cut in the final upstream distribution. It is seen that only few electrons were accelerated over 10 keV. The cut at low energies is caused by kinematic reasons. The solid lines in (b) schematically repeat the case without scattering (plotted in (a)). The scattering frequency was $1/(9\tau_g)$, where τ_g is

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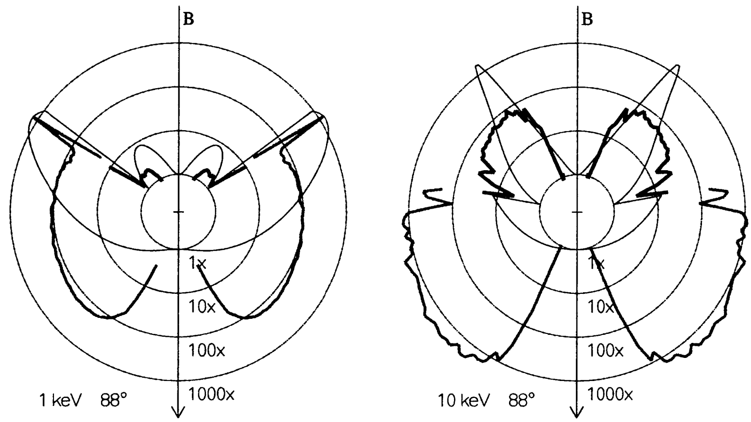

Figure 2. Angular distributions of accelerated electrons

the gyroperiod. Scattering causes the resulting distributions to be harder and to extend significantly to higher energies.

Figure 2 shows angular distributions of accelerated electrons by a curved shock wave at $\theta_{Bn} \approx 88°$ and for two (final) energies, 1 keV and 10 keV. The arrow is the direction of the magnetic field **B**. The innermost dashed-dotted circle (labeled by $1\times$) represents the initial distribution which is isotropic. Angular distributions of accelerated electrons, when pitch angle scattering is present, are plotted by the thick shaded lines. Both reflected (darker shade) and transmitted electrons are drawn together. The black lines are values for the curved shock wave without scattering. Scattering mostly increases downstream fluxes and suppresses upstream fluxes; the resulting distributions tend to be more isotropic.

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