

A KINETIC DESCRIPTION OF ELECTRON BEAM EJECTION FROM SPACECRAFT

George V. Khazanov and Torsten Neubert

Space Physics Research Laboratory, Department of Atmospheric, Oceanic and Space Sciences, University of Michigan

Grigori D. Gefan and Aleksander A. Trukhan
Irkutsk Polytechnical Institute, Irkutsk, Russia

Evgeni V. Mishin
IZMIRAN, Troitsk, Moscow Region, Russia

Abstract. A model based on the Boltzmann kinetic equation describing electron beam ejection from spacecraft is presented. Results are shown for steady-state, beam-atmosphere interaction (BAI) and for beam-plasma interaction (BPI). The BPI considered is that of elastic scattering of beam electrons with strong, short-scale Langmuir turbulence. This mechanism has been suggested for prompt echoes of beam electrons observed in sounding rocket experiments. It is shown that the interaction is sufficiently strong to account for observations of back-scattered electrons at the beam accelerator energy. However, it is clear from observations that particles undergo diffusion in energy at a rate exceeding levels expected for BAI. Inelastic scattering in BPI must therefore also be important.

Introduction

Active space experiments involving the ejection of energetic electron beams in the ionosphere have been performed for more than two decades. In beam experiments a variety of phenomena are explored, including auroral emissions [Burch et al., 1993; Mende et al., 1993] and parallel electric fields on auroral field-lines [Kellogg, 1992]. It is important in such experiments to have an accurate description of the beam dynamics as it propagates away from the spacecraft, that is, the energy degradation and scattering due plasma instabilities, spacecraft charging, etc. While many aspects of beam ejection are well understood, the beam-plasma interaction (BPI) is lacking an accurate description [Neubert and Banks, 1992]. In BPI the beam drives plasma wave modes and subsequent scattering of beam electrons and heating of the ambient plasma. The high-resolution measurements of wave and particle spectra taken in the last decade from the space shuttle [Gurnett et al., 1986; Oberhardt et al., 1993] and from multi-platform sounding rocket payloads [Winckler et al., 1989; J. Raitt, unpublished manuscript, 1993] allow for the creation of better models. These are also needed to better understand specific observations such as the so-called prompt electron echo (PEE) events in rocket experiments [Hendrikson et al., 1975; Winckler et al., 1975; Maehlum et al., 1980; Wilhelm et al., 1985] where echoes are observed with time delays < 100 ms during upward beam injection, and discharge-like events observed from the space shuttle [Sasaki et al., 1985; Waterman et al., 1988]. To describe BPI quantitatively, a full kinetic treatment of the electron beam and the background plasma is needed in order to determine growth rates of plasma waves and to estimate the feed-back from waves to particles through scattering and diffusion.

Here we present a first step in this direction, namely a kinetic model of electron beam ejection based on the Boltzmann equation. The model is applied to the case of collisional interaction

with the ambient neutral atmosphere, the beam-atmosphere interaction (BAI) [Neubert et al., 1990] and to the case of elastic scattering of beam electrons by short-scale Langmuir turbulence in the beam. This choice was motivated by the observations of PEE events mentioned above. We use the formulas of Mishin [1983] and Mishin et al. [1989], who suggested that PEE can be interpreted in terms of the theory of BPI developed for active experiments [Galeev et al., 1976; Mishin and Ruzhin, 1980, 1981]. This theory considers the regime of Strong Turbulence (ST), which is characteristic for BPI at high altitudes where the major part of the energy of Langmuir waves concentrates in the short-scale spectral region. The phase velocities of the short-scale waves are much less than that of the beam. Therefore the wave-particle interaction preserves, in the first approximation, the particle energy, i.e., the particle is scattered elastically.

The Kinetic Beam Model

Suprathermal electrons of the ionosphere and plasmasphere are represented by the distribution function $f(t, \vec{r}, \vec{v})$ which satisfies the kinetic equation

$$\frac{\partial f}{\partial t} + \vec{v} \vec{\nabla} f + \frac{\vec{F}}{m} \vec{\nabla}_v f = S_{ee} + S_{ei} + S_{en} + S_{en}^* + S_{en}^+ + S_{ep} + q \quad (1)$$

where $F = -e(\vec{E} + \vec{v} \times \vec{B}/c)$ is the Lorentz force on an electron from the electric and magnetic fields \vec{E} , \vec{B} , and S represents the collision terms: elastic collisions with thermal electrons, S_{ee} , ions S_{ei} and neutral particles S_{en} , and inelastic collisions giving rise to the excitation of structural levels of atoms and molecules S_{en}^* and ionization S_{en}^+ . The source of electrons from ionization or from a beam source is q , and S_{ep} is the electron-plasmon collision term describing the BPI.

Introducing in velocity space a spherical coordinate system with the polar axis along the magnetic field it is possible to obtain the kinetic equation in the drift approximation [Khazanov, 1979]

$$\frac{\partial \langle f \rangle}{\partial t} + \mu v \frac{\partial \langle f \rangle}{\partial s} - \frac{1 - \mu^2}{v} \left(\frac{e}{m} E_{\parallel} + \frac{v^2}{2B} \frac{\partial B}{\partial s} \right) \frac{\partial \langle f \rangle}{\partial \mu} - \frac{e}{m} E_{\parallel} \mu \frac{\partial \langle f \rangle}{\partial v} = \langle S \rangle \quad (2)$$

where $\mu = \cos \theta$, s is the coordinate along the geomagnetic field, E_{\parallel} is the longitudinal component of the electric field, and $\langle S \rangle$ is a symbol representing the right-hand side of (1). Brackets denote the average over the azimuth angle as shown for f :

$$\langle f \rangle = \frac{1}{2\pi} \int_0^{2\pi} f(\phi) d\phi$$

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In the case of interest one may drop the small terms associated with the plasma transport across the magnetic field as well as making no distinction between the distribution function and the guiding center distribution function. Therefore, in what follows we shall omit the brackets around the distribution function.

It is convenient to pass from the distribution function to the flux $\psi = 2Ef/m^2$ defined such that $\psi(t, \vec{r}, E, \theta, \phi) dE d\Omega$ is the number of electrons with the energy from E to $E + dE$ with the direction of velocity \vec{v} inside the solid angle $d\Omega = \sin\theta d\theta d\phi$ that meet at the point (t, \vec{r}) per unit time per unit area.

The collision terms in (2) may be brought to the form

$$\langle S_{ee} \rangle + \langle S_{en} \rangle = \frac{Avn_e}{2E^2} \frac{\partial}{\partial \mu} \left[(1 - \mu^2) \frac{\partial f}{\partial \mu} \right] + \frac{Avn_e}{E} \frac{\partial f}{\partial E} \quad (3)$$

$$S_{ee} = \frac{vn_n \sigma_n^t}{2} \frac{\partial}{\partial \mu} \left[(1 - \mu^2) \frac{\partial f}{\partial \mu} \right] \quad (4)$$

$$\langle S \rangle_{en}^* = \frac{n_n v}{E} \sum_j E_{nj} \frac{\partial}{\partial E} [E \sigma_{nj}^* (E) f(E, \mu, s)] \quad (5)$$

$$\langle S \rangle_{en}^+ = \frac{n_n v}{E} \frac{\partial}{\partial E} [\langle E \rangle \sigma_n^+ (E) f(E, \mu, s) (E_n^+ + \hat{E}_n)] + \frac{n_n v}{E} \int_{2E+E_n^+}^{\infty} E I_n^+ (E', E) f_o(E', s) dE' \quad (6)$$

Here n_e is the density of electrons and n_n the densities of neutral particles of species n , σ_n^t is the transport cross-section of elastic scattering, σ_n^j is the inelastic cross-section of scattering that characterizes the transition of a neutral particle to an excited state with energy E_{nj} , E_n^+ is the energy of ionization, $A = 2\pi e^4 C_l$ (C_l being the Coulomb logarithm). σ_n^+ is defined as

$$\sigma_n^+ (E) = \int_0^{(E-E_n^+)/2} I_n^+ (E, E_2) dE_2$$

and is the full cross-section of ionization by an electron with energy E . The quantity $I_n^+ (E, E_2)$ represents the corresponding differential cross section, where E_2 is the energy of the secondary electron, and

$$\hat{E}_n = \frac{1}{\sigma_n^+} \int_0^{(E-E_n^+)/2} E_2 I_n^+ (E, E_2) dE_2$$

is the mean energy of a secondary electron. Finally,

$$f_o(E', s) = \frac{1}{2} \int_{-1}^1 f(E', s, \mu) d\mu$$

The approximations used to derive (4)-(6) are discussed in detail in [Krinberg, 1978; Khazanov, 1979]. The accuracy of these approximations is quite sufficient for the investigation discussed in this paper.

The final element needed is the collision frequency of beam electrons with the strong wave turbulence. Consider the interaction of a keV-energy electron beam with an isotropic distribution of short-scaled Langmuir waves. The phase velocities of such waves, ω/k , are much less than the beam velocity, i.e. $\delta = \omega/k/v_o \ll 1$, where v_o is the velocity of beam electrons.

This situation corresponds to the strong turbulence approach in BPI [Sagdeev, 1979; Shapiro and Shevchenko, 1984], where the major part of the turbulence concentrates in the short-scale spectral region $k \simeq k_L \gg k_o = \omega_p/v_o$ (ω_p is the electron plasma frequency). Note, that isotropy of the turbulence is provided by chaotic orientation in space of the plasma cavities where the Langmuir waves are trapped. Also, it is essential that the scale-length of isotropization of the beam by short-scale interactions is assumed to be much larger than the relaxation length of the beam due to BPI with the large-scale, $k \simeq k_o$, waves [Sagdeev, 1979]. This allows for determining the parameters characteristic for the "elastic" scattering through the parameters of BPI. Thus, one gets the electron-plasmon collisional term [Mishin et al., 1989, 1990]

$$\langle S \rangle_{ep} = \nu_{eff} \frac{\partial}{\partial \mu} [(1 - \mu^2) \frac{\partial f}{\partial \mu}] \quad (7)$$

The effective frequency ν_{eff} in (7) of electron-plasmon interaction is found from

$$\nu_{eff} = \omega_p \left(\frac{W_L}{n_e T_e k_L r_D} \right) \left(\frac{T_e}{E_b} \right)^{3/2}$$

Where W_L is the energy density of plasma waves in the region of turbulence, and the main part of the wave energy is concentrated near $k_L = \sqrt{W_L/n_e T_e r_D^2}$. Expressing W_L from the energy balance equation in the beam-plasma system, one can get [Mishin et al., 1989, 1990]

$$\nu_{eff} \simeq 1.1 \omega_p \left(\frac{n_b}{n_e} \right)^{1/2} \left(\frac{u}{\Delta u} \right) \left(\frac{T_e}{E_b} \right)^{3/2} \quad (8)$$

At values of $n_b/n_e = 10^{-4} - 10^{-1}$, $u/\Delta u \simeq 10$, $T_e/E_b \simeq 10^{-2}$, $\omega_p \simeq 10^7$ rad/sec $^{-1}$, $E_b = (m_e u^2)/2 \simeq 3 - 10$ keV, we get $\nu_{eff} \simeq 10^3 - 10^5$ sec $^{-1}$, the dependence of ν_{eff} on the altitude being weak.

Results

Model calculations have been performed with the electron beam source located at 160 km altitude. The magnetic field is assumed to be directed upwards, corresponding to an experiment location in the Southern hemisphere, with beam electrons ejected within a cone of pitch-angles around the magnetic field of $(0, \pi/15)$ and $(15\pi/16, \pi)$ for upward and downward injection respectively. The energy spectrum of beam electrons was given on the form

$$\psi(E) = 10^2 E \exp(-|E - E_b|/E_o)$$

with $E_b = 10$ keV and $E_o = 1$ keV.

The value of the numerical coefficient can be set arbitrarily, because by virtue of the linearity of the kinetic equation (2) the solution can easily be recalculated for any other source intensity.

The problem is solved along a closed magnetic field-line from 100 km altitude in one hemisphere to 100 km altitude in the conjugate hemisphere. Figure 1 shows the ratio of the downward Φ^- and upward Φ^+ electron flux as a function of energy at the spacecraft altitude for upward beam ejection, where Φ^+ , Φ^- are the hemispherical fluxes defined as

$$\Phi^-(E) = \int_{-1}^0 \mu \psi(E, \mu) d\mu$$

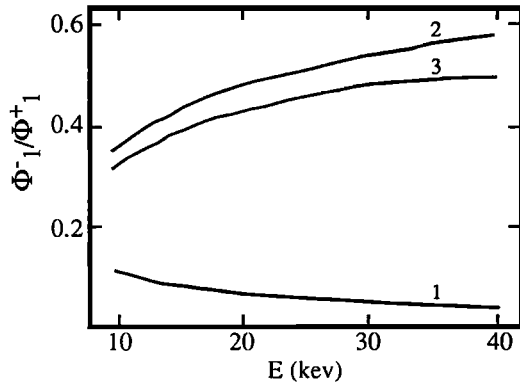


Fig. 1. Albedo at the source altitude (160 km) for upward injection: 1. $\nu_{eff} = 0 \text{ s}^{-1}$; 2. $\nu_{eff} = 10^3 \text{ s}^{-1}$; 3. $\nu_{eff} = 10^4 \text{ s}^{-1}$.

$$\Phi^+(E) = \int_0^1 \mu \psi(E, \mu) d\mu$$

The relationship Φ^-/Φ^+ has the meaning of albedo and characterizes the reflective ability of the region above the injector. In the absence of BPI scattering, ($\nu_{eff} = 0$) (curve 1), the albedo is small and decreases with increasing energy of ejected electrons. This behaviour reflects the decrease with energy of the electron-neutral elastic cross-section. When scattering with plasmons is included, however, the albedo increases sharply. In this case, two features are noted. Firstly, the albedo increases with electron energy, and secondly, as the effective scattering frequency increases from 10^3 s^{-1} (curve 2) to 10^4 s^{-1} (curve 3) the albedo does not increase as might be expected, but decreases. Both these effects are related to the fact that during strong pitch-angle scattering, when the transverse velocity of the injected particles grows at the expense of the longitudinal one, the electron trajectory changes substantially and energy loss during inelastic collisions with neutrals become increasingly important. This leads to the decrease of albedo at too high values of ν_{eff} . The cross-section for electron-neutral inelastic collisions decreases with increasing electron energy. As a result, inelastic collisions become less important at higher energies and the albedo increases with energy.

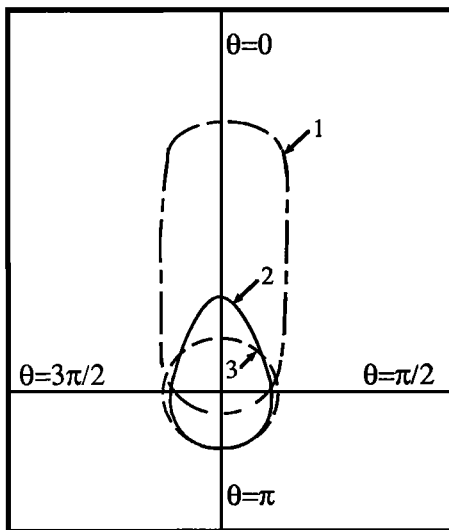


Fig. 2. Pitch-angle distribution 20 km above the source altitude for upward injection: 1. $\nu_{eff} = 0 \text{ s}^{-1}$; 2. $\nu_{eff} = 10^3 \text{ s}^{-1}$; 3. $\nu_{eff} = 10^4 \text{ s}^{-1}$.

The pitch angle distribution 20 km above the source altitude is illustrated in Figure 2 for upward ejection. Curve 1 is an isocontour for the case of no BPI, showing a distribution function extended in the direction of the ejected beam velocity component. It reflects the steady-state distribution function of the BAI. The beam character of the source is clearly seen, though modified by the collisional interactions with the ambient neutral atmosphere. When the scattering with plasmons is included, the distribution function becomes increasingly isotropized and the beam character is lost.

The ion production rate as a function of altitude is shown in Figure 3. Curves 1-3 are for upward injection for $\nu_{eff} = 0, 10^3 \text{ s}^{-1}, 10^4 \text{ s}^{-1}$ respectively. As BPI is included, the production rate increases by a factor of 2-3. This is caused by the increase in path-length experience by energetic electrons as they are elastically scattered by the wave turbulence. For reference, downward injection with no BPI is shown with curve 4.

Discussion

The expression for ν_{eff} in (7) contains both beam and ambient plasma parameters. The greatest uncertainty in the estimate of ν_{eff} is the value of T_e , which is higher than the ionospheric electron temperature because of heating by plasma waves generated as a result of the beam ejection. According to experimental data [Gringauz et al., 1981], the background electron temperature during the injection of powerful electron beams can reach the value of about 100 eV, which was used for obtaining an estimate of ν_{eff} .

The numerical solutions to the kinetic equation confirm that short-scale Langmuir turbulence can generate substantial scattering of injected beams as suggested by Mishin [1983, 1990]. It is clear from experiments performed in the last decade, however, that the back-scattered electron flux is a result of processes that involve diffusion in energy as well as in pitch-angle and therefore cannot be described by an elastic scattering alone. Typical electron spectra have inverse power-law dependence with energy, with energies reaching from the eV-range to above the accelerator energy. It is clear, therefore, that the elastic scattering considered here cannot be the sole source of backscattered electrons. Our future work will include a more complete description of the BPI.

As mentioned earlier, the albedo shown in Figure 1 increases with decreasing energy for the case of BAI alone because the elastic cross-section with neutrals also increases with decreasing energy. When BPI is included, this trend is reversed and the albedo decreases with decreasing energy. It is expected that at beam energies below a few keV, for the conditions modeled here, that the BAI will dominate over the BPI. This is consistent with

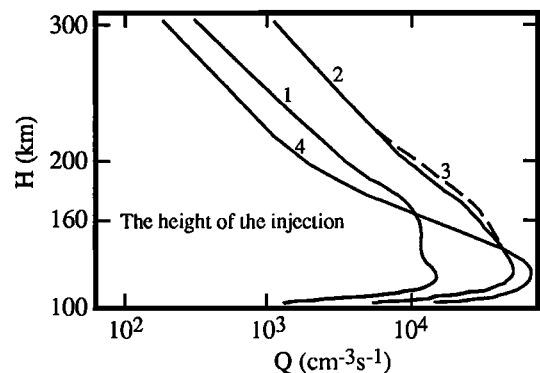


Fig. 3. The ion production rate as a function of altitude. Upward injection: 1. $\nu_{eff} = 0 \text{ s}^{-1}$; 2. $\nu_{eff} = 10^3 \text{ s}^{-1}$; 3. $\nu_{eff} = 10^4 \text{ s}^{-1}$. Downward injection: 4. $\nu_{eff} = 0 \text{ s}^{-1}$.

conclusions reached from sounding rocket observations of return current measurements during beam ejection [Neubert et al., 1990]. Here it was found that BAI-induced fluxes, together with "passive" currents from the ambient ionosphere, could account for the observed currents.

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- Grigori D. Gefan and Aleksander A. Trukhan, Irkutsk Polytechnical Institute, 664074 Irkutsk, Russia
- George V. Khazanov and Torsten Neubert Space Physics Research Laboratory, Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, MI 48109-2143.
- Evgeni V. Mishin, IZMIRAN, 142092 Troitsk, Moscow Region, Russia.

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