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Suprathermal electrons associated with a plasma discharge on an active sounding rocket experiment

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Abstract. Electrons with energies up to 600 eV are observed with the retarding potential analyzer (RPA) instrument aboard the Several Compatible Experiments (SCEX) III sounding rocket. The electrons are concomitant with high-energy (2-6 keV) electron gun injections and also evidence themselves by luminosity observed with 3805 Å and 3914 Å photometers. Both the collected electron flux and luminosity measurements are strongly nonlinear with gun injection current. For a typical event, the electron distribution is similar to laboratory beam-plasma discharge (BPD) distributions reported by Sharp (1982) and when backed by HF electric field observations (Goerke et al., 1992; Llobet et al., 1985), the BPD mechanism becomes a most likely explanation. Strong turbulence theories of BPD predict a power law tail in the electron distribution, and we compare our spectral index with some previous observations.

Introduction

When an energetic electron beam is injected into the ionospheric plasma, a frequent result is the ignition of a plasma discharge. Observations of high frequency electric fields simultaneous with beam operation on the Several Compatible Experiments (SCEX) III sounding rocket experiment [*Goerke et al.*, 1992] prompt the present work.

Suprathermal electron fluxes are frequently observed on beam-injecting payloads, although the question of their source can be contentious. The Polar 5 experiment [*Maehlum et al.*, 1980] injected an energetic electron beam and saw fairly large low-energy electron fluxes. *Maehlum et al.* [1980] conclude that these electrons have been energized in a beam-plasma interaction and find an energy spectral index in agreement with that predicted for a beam-plasma discharge.

The Artificial Radiation and Auroras Between Kerguelen and Sogra (ARAKS) experiment [*Gringauz and Shutte*, 1980] injected a beam whose current pulse time was long compared to the time resolution of its electron instrument. They report time-dependent electron fluxes up to 3 keV which vary as a function of altitude. *Arnoldy et al.* [1985] report large suprathermal electron flux at the accelerator payload on Echo 5 sounding rocket. They submit a beam-plasma interaction as the production source but acknowledge the difficulty in separating the effects of acceleration due to vehicle neutralization from those due to the beam-plasma interaction.

Early single particle theories of current collection by a charged body in the ionosphere [*Parker and Murphy*, 1967] predicted a return current deficit that could lead to charging of the beam-emitting payload to beam energies, preventing the escape of beam electrons. Although overcharging has been observed [*Denig et al.*, 1991], it is not by any means commonplace, and this can be taken as evidence of the importance of collective effects in the payload neutralization process. Of such collective effects, the beam-plasma discharge (hereafter, BPD) is a commonly invoked mechanism. Laboratory observations of BPD show high-frequency wave fields [*Llobet et al.*, 1985], suprathermal electrons [*Sharp*, 1982], and a strong increase in luminosity at ignition [*Hallinan et al.*, 1988]. The ignition of such a discharge is thought to result from the acceleration, to ionizing energies, of ambient electrons by beam-generated HF wave fields. The BPD has been treated theoretically by several authors [e.g. *Mishin and Ruzhin*, 1980; *Papadopoulos*, 1986] and high-frequency electric field emission, suprathermal electrons and enhanced luminosity are all well explained within the BPD model. *Khazanov et al.* [1993] have recently offered a kinetic model of beam-plasma interaction including a collision frequency due to wave-particle interactions which supports the earlier work.

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Other plasma discharge mechanisms, such as the cross-field discharge (hereafter, XFD), have been proposed and observed [*Galeev et al.*, 1976; *Kellogg and Monson*, 1988]. The XFD results from electron acceleration by the **E** x **B** drift in the strong electric field of the charged payload. The XFD, which has also been studied in the laboratory [*Sasaki et al.*, 1984], does not require the existence of HF wave fields. *Okuda and Ashour-Abdalla*, [1988] find, in a one-dimensional simulation, that beam-generated ion acoustic instabilities are also capable of producing a suprathermal electron population. In such a case, the instabilities are driven by the payload neutralization current whose average energy is low enough to couple to the acoustic mode. Indeed, *Feng et al.* [1992] observe such electrostatic waves during electron beam emission on Spacelab 2. Again, this mechanism does not predict or require the existence of HF radio emissions. So the observation of suprathermal electrons and enhanced luminosity can be taken as evidence of the discharge while the ancillary observation of HF fields may be causal in the case of BPD.

In this work, suprathermal electrons and enhanced luminosity are observed during gun operation and when buttressed by the work of *Goerke et al.* [1992], suggest the observation of the BPD on the SCEX III flight.

Experiment

The SCEX III sounding rocket experiment was launched into an active breakup aurora on February 1, 1990, from the Poker Flat Research Range (65.1° N, 147.5° W) at 1207 UT. The payload was carried to an altitude of 375 km by a Black Brant 11 booster.

The payload was configured as forward and aft subpayloads with four throw away detectors (TADs) to be ejected from the aft payload. An electron accelerator (or gun) was carried aboard the aft subpayload and injected electrons at various energies up to 6 keV and currents to 60 mA. The forward subpayload carried a variety of wave and particle detectors designed to study the beam-plasma interaction as well as detect echoes from field-aligned potential drops above the payload in the auroral acceleration region.

The aft payload carried the electron gun, an electron retarding potential analyzer (RPA), a Langmuir probe system, and 3805 Å and 3914 Å photometers. Due to a pyrotechnic failure, the Langmuir probe system as well as the deployment of two of the TADs failed. The functional instruments on the aft payload, however, provide ample testimony of the beam-associated discharge. The RPA instrument was designed to yield an integral spectrum of electrons with energies from a few eV up to 600 keV. A dynamic range from 10^{-11} A to 10^{-5} A is measured in six sweeps per second. The RPA instrument was collimated to a 23° half angle input view; this does not include the effect of electron orbits which increases the geometrical collection area. Two photometers on the aft payload were filtered to accept 3805 Å and 3914 Å luminosity. The 3805 Å band [*Herzburg*, 1950] is the 0- to 2-s positive transition in neutral N_2 whose electron collisional cross section has its threshold at 9 eV, peaks near 10 eV, and is negligible at 100 eV. The cross section for the 3914 Å band [*Borst and Zipf*, 1970], the 0-0 first negative transition in N_2^+, has its threshold near 20 eV and peaks at near 100 eV. The relative intensity in these lines can be used for electron energy spectroscopy.

Results

Suprathermal Electrons

A spectrogram plot of RPA data is shown in Figure 1. This represents a typical interval of data, and, in particular, the event at 315 s has been studied using the electric field data by *Goerke et al.* [1992]. In this plot, RPA current is shown as grayscale with the energy of the collected electrons as the ordinate. This shows the general trend of increasing electron flux, as well as energy, with increasing gun current, with gun pulses at full current filling the energy band of the instrument. It should be noted that the very short duration gun pulses do not register an accurate energy distribution due to the finite sweep time of the instrument.

Averaging over 200 s of data, the relationship between the collected electron flux and the emitted gun current is as shown in Figure 2. It can be seen that the collected electron flux increases in a strongly nonlinear fashion for injection current above roughly 10 mA. In fact, between 10 mA and 60 mA the gun current increases by a factor of 6 while the collected electron flux is enhanced by a factor of 100. This change in character implies the onset of some mechanism of electron liberation: a plasma discharge. To compare with laboratory measurements, two RPA sweeps from the event at 315 s are show, as electron distributions, in Figure 3. This large flux increase of high-energy electrons during discharge resembles, both qualitatively and quantitatively, the results of *Sharp* [1982]. Using the large vacuum chamber at Johnson Space Center, Sharp finds an enhanced electron population up to 300 eV during BPD mode. Our data show similar behavior up to 600 eV, the limit of the instrument. The full current spectrum in Figure 3, labeled "discharge," has a power law index of about 1.18; the "pre-discharge" spectrum has a spectral index of roughly 2.4. These numbers will be related to other observations below.

The RPA instrument was mounted to face outward on the side of the spinning payload; this allowed RPA view angles both perpendicular and parallel to the geomagnetic field. However, there appears to be little or no pitch angle dependence in the RPA current data. While this agrees with the observations of *Sharp* [1982], this situation is a bit different. If, indeed, the observed discharge is the BPD, then it would be occurring upfield of the charged payload and the newly liberated electrons should be attracted along the field lines to the charged

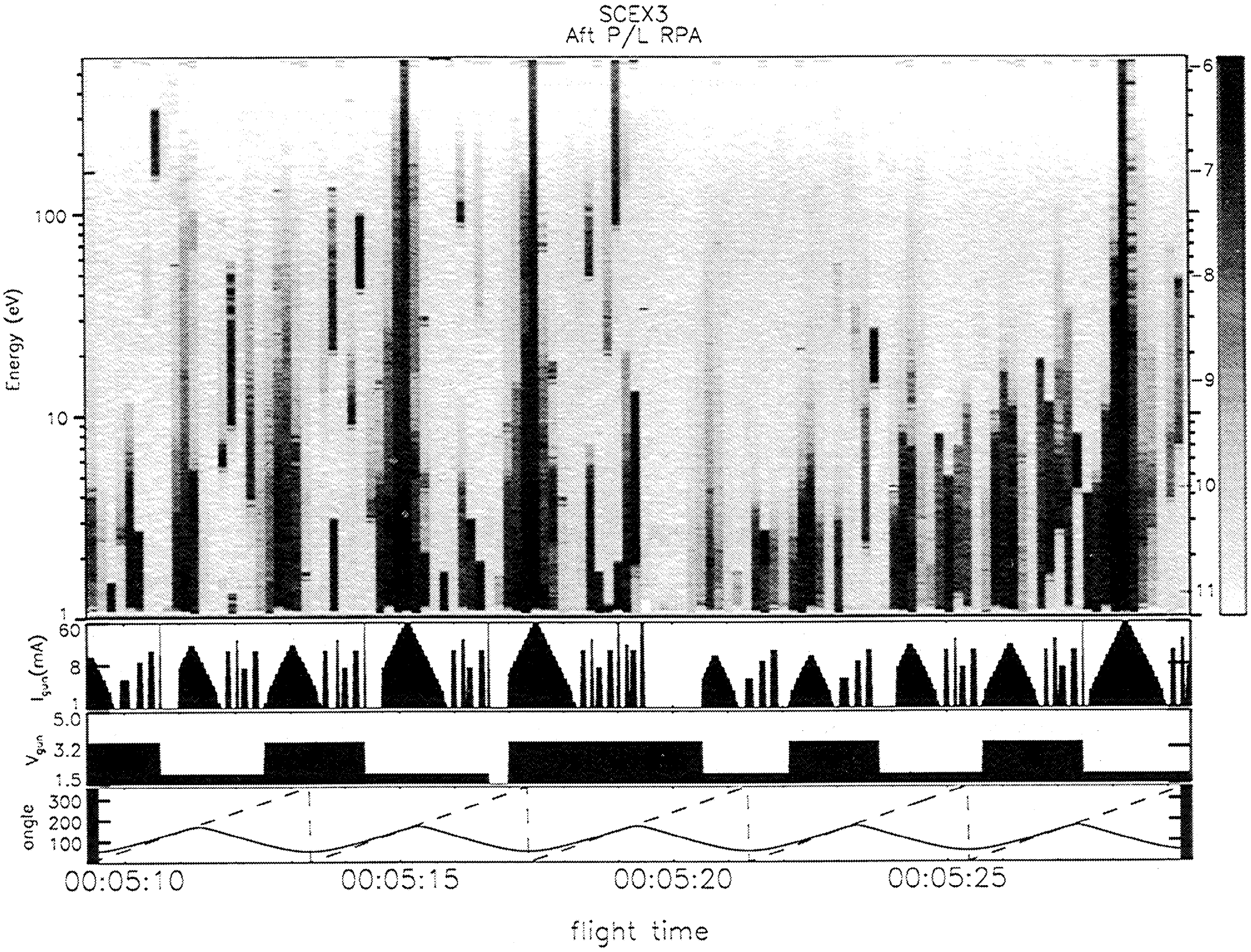

Figure 1. Energy-time spectrogram of retarding potential analyzer (RPA) data. The event at 315 s flight time has been analyzed by *Goerke et al.* [1992]. Electric field wave emissions with frequencies up to 44 MHz accompany this event.

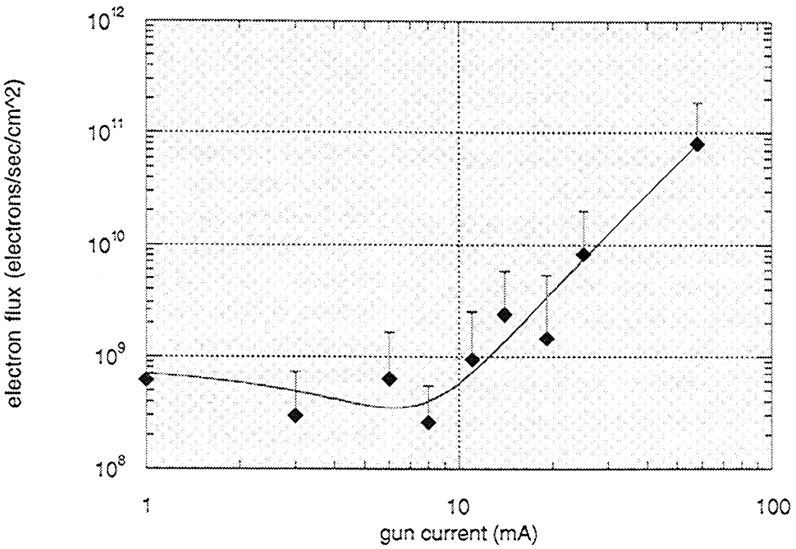

Figure 2. Average electron flux and gun current. The flux is averaged over electron energy and then binned as a function of gun current. The profile shows a nonlinear increase in collected electron current for large gun currents. The constant flux at low gun current corresponds to the threshold of the RPA instrument.

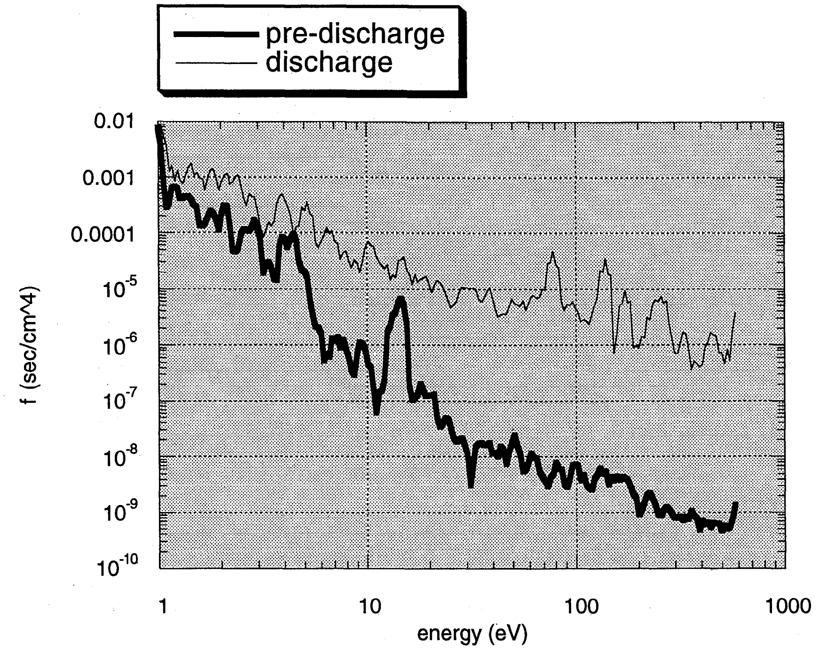

Figure 3. The electron distribution function as calculated from the RPA data. The trace marked "pre-discharge" occurs slightly before the stepped current event at 315 s. The "discharge" trace occurs at full gun current. These results are very similar to laboratory distribution measurements of beam-plasma discharge [*Sharp*, 1982].

payload. Hence one might expect to see a "hot spot" when the RPA is facing upfield. The data are, however, isotropic with respect to pitch angle.

Luminosity Measurements

Due to the above mentioned pyrotechnic failure, the photometers mounted on the aft payload section were unable to fully deploy. This prevented the view field of the photometers from intersecting the injected electron beam; the photometers did, however, observe luminosity up to near 100 kR during gun operation. The payload had passed through the most intense of the auroral emissions and saw only reflection of, presumably, both the aurora and moonlight from the groundplane. This naturally enhanced region of luminosity was therefore excluded from the luminosity calculations.

The relationship between the detected luminosity and gun injection current is best illustrated as in Figure 4. The luminosity values given are 200-s averages of the mean 3914 Å luminosity during gun operation for different currents. Specifically, the average luminosity is calculated, during gun operation, for each pulse in the 200-s interval (of which there are several hundred). These values are then averaged, for each value of gun current, to give the values in Figure 4. The error bars are standard deviations calculated in the 200-s average and therefore reflect the variance associated with the atmospheric and plasma parameters and not the rise and fall of luminosity during an individual gun pulse. A strongly nonlinear increase in luminosity is observed for full current (60 mA) gun pulses. This, in conjunction with Figure 2, implies the ignition of a discharge. The luminosity in the 3805 Å channel shows a similar relationship, qualitatively, and the departures will be presented below. It should be noted that the electron flux begins its sharp ascent near 10 mA while the luminosity becomes large only near full current. This is most likely due to spacecraft charging effects: as the payload potential rises, some electrons are attracted and reach the RPA. The nonlinear increase in luminosity is, for this reason, stronger evidence of discharge. Previous laboratory observations [*Hallinan et al.*, 1988; *Hamwey et al.*, 1993] show a similar strongly nonlinear increase in luminosity at BPD ignition. The ratio of 3805 Å to 3914 Å luminosity gives a relative measure of the low (~ 10 eV) energy to high (~ 100 eV) energy electron populations produced during discharge. This corresponds to the "red/blue" ratio in *Hamwey et al.* [1993]. Figure 5 shows the average "red/blue" ratio for 200 s of data. Although mostly constant and slightly greater than one, the full current gun injections yield a slightly lower red/blue value. This implies a "harder", or more energetic, electron distribution and disagrees with the laboratory measurements. *Hamwey et al.* [1993] find that the red/blue ratio increases at BPD ignition and then falls back and remains constant for larger current values. It could be that, not looking directly at the beam, we are not seeing a region of enhanced lower energy electrons located near the beam core.

Conclusion

The observation of a nonlinear increase in suprathermal electron flux, as well as 3805 Å and 3914 Å luminosity, with increasing injection current is evidence of

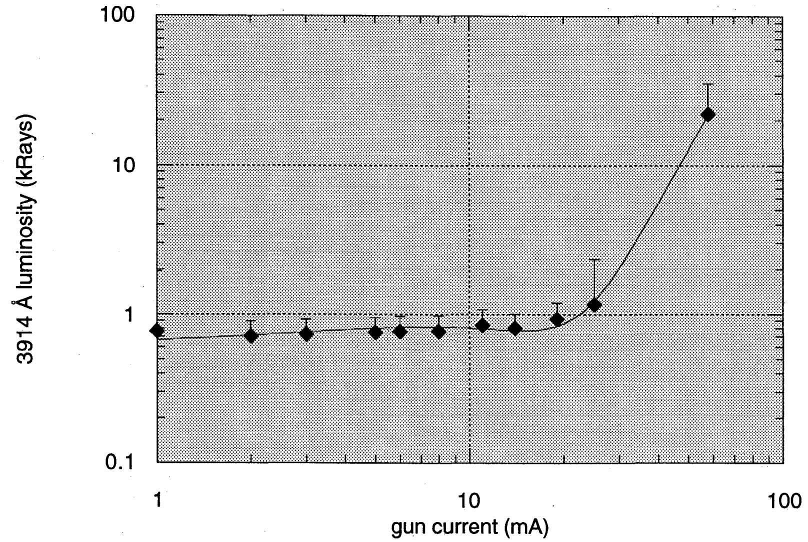

Figure 4. Average 3914 Å luminosity as a function of gun current. Luminosity is strongly nonlinear for injection currents above roughly 20 mA. This reflects the presence of abundant high-energy electrons during full current gun pulses. Two hundred seconds of photometer data are averaged, and the error bars are standard deviations.

the wholesale liberation and acceleration of electrons, i.e., a plasma discharge. The resemblance of the electron spectrum to that of *Sharp* [1982] coupled with the HF electric field observations [*Goerke et al.*, 1992] indicates a beam-plasma discharge mechanism. Sharp's observations show an increase, during discharge, in the suprathermal component of the electron flux by a few orders of magnitude. Our "pre-discharge" energy spectral index of 2.3 agrees fairly well with the index of 2.0 that Sharp reports. The Echo 5 results of *Arnoldy et al.* [1985] show a power law tail as do the Polar 5 observations *Maehlum et al.* [1980]. In particular, *Maehlum et al.* [1980] find a best fit spectral index of 1.3 during beam operation to be compared with our value of 1.18. This suprathermal power law component of the electron distribution is a fundamental prediction of BPD models that rely on particle acceleration by strongly turbulent fields. A result, initially empirical [*Bernstein et al.*, 1979] and later theoretical [*Papadopoulos*, 1986], is that the threshold current for ignition of the BPD is given by the relationship

$$I_c \simeq \frac{E_b^{3/2}}{B^{\lambda}L} f(p) \qquad (1)$$

in terms of electron beam energy E_b, magnetic field strength B, system length L and a function of the ambient pressure $f(p)$. In the treatment of *Papadopoulos* [1986], this relation arises due to constraints on group

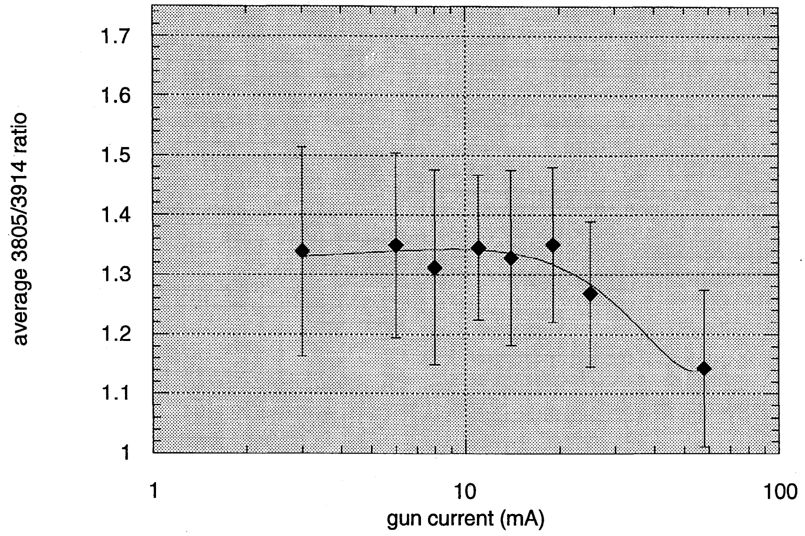

Figure 5. Average ratio of 3805 to 3914 Å luminosity as a function of gun injection current. Variations in this ratio are small, as indicated by the large error bars, but for full current pulses the ratio is slightly smaller. The error bars are derived from the standard deviation of the ratio, during the averaging process. A third-order polynomial is fitted through the points.

velocities, growth rate, and system size of an absolute instability. Choosing a common form of (1) with $\lambda = 1/2$ and $f(p) = 1/p^{1/2}$ and using typical SCEX III parameters of $E_b = 4$ keV, $B = .5$ Gauss, $L = 20$ m and a neutral density of $10^{11} cm^{-3}$ near the outgassing payload [*Goerke et al.*, 1992], a rather small threshold current of ~ 1 mA is calculated. This is a fairly conservative estimate, and, indeed, when the effects of transverse payload motion are included [e.g., *Galeev et al.*, 1976] a higher threshold can be obtained.

The disparity of our red/blue measurement with laboratory BPD events [*Hamwey et al.*, 1993] may be a result of poorly aimed photometers. As indicated in Figures 4a and 4b of *Goerke et al.* [1992], rarely did the view field of the SCEX III photometers intersect the beam itself. In such a case, it could be that the lower energy (~ 10 eV) electron population dominates the beam core, while higher energy electrons dominate the region peripheral to the beam. Indeed, *Maehlum et al.* [1980] observe a suprathermal electron population far outside the beam cylinder. *Duprat et al.* [1982] have reported similar results on the NVB06 rocket, with a suprathermal component out to 5 or 6 ρ_L. This radial diffusion has been observed in laboratory work as well [e.g., *Kellogg et al.*, 1982]. Alternatively, it could also be that these lower energy electrons are being attracted by the charged payload and colliding, to provide luminosity, in the vicinity of the payload after some acceleration.

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