# AN UPPER ATMOSPHERIC PROBE FOR AURORAL EFFECTS

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**Abstract**

An electrically floating bare tether in LEO orbit may serve as upper atmospheric probe. Ambient ions bombard the negatively biased tether and liberate secondary electrons, which accelerate through the same voltage to form a magnetically guided planar e-beam resulting in auroral effects at the E-layer. This beam is free from the S/C charging and plasma interaction problems of standard e-beams. The energy flux is weak but varies accross the large beam cross section, allowing continuous observation from the S/C. A brightness scan of line-integrated emissions, that mix emitting altitudes and tether points originating the electrons, is analysed. The tether is magnetically dragged at nighttime operation, when power supply and plasma contactor at the S/C are off for electrical floating; power and contactor are on at daytime for partial current reversal, resulting in thrust. System requirements for keeping average orbital height are discussed.

## Introduction

Studies of auroral effects require information on energy, spectrum, and pitch of precipitating electrons. Natural auroras are random events, however. This makes rocket in-situ observation a chancy affair. Overflying satellites map luminosities but yield no information on the electrons.

On-board e-beam sources produce artificial auroras making ground observation convenient. But beam-firing affects S/C potential, the S/C being ground for the beam source.

Also, for a typical 1 A, KeV e-beam (diameter ~ 10 m) the energy flux is about 100 times larger than the flux in the intense Type-IV aurora. This compensates the thinness of the emission layer for the e-beam, 10 m against 10 Km for auroral arcs. Intense beams produce suprathermal electrons and plasma fluctuations near the S/C, and distort the structure of the beam cross-section by nonlinear plasma effects.

Typical beam experiments thus end studying beam physics, and spacecraft charging, not auroral emissions.

## The tether system

A conductive tether, left uninsulated and floating, is biased highly negative over most of its length. Ions impacting the tether liberate secondary electrons, with a yield (secondary electrons/ion) that may reach 20% at 1 KV level. After acceleration by the tether-to-plasma local voltage, electrons race down magnetic lines.

This beam source is free of S/C charging problems (no current flows at ends of tether). Also, the beam cross-section is large ( ~ 10 m × 20 Km), making the resulting energy flux intermediate between those of Type I and Type-II auroras, well below the threshold for beam-plasma effects.

Brightness is then too low for ground observation, but high for (continuous) observation from the S/C. Such observation from the S/C is impracticable for the small standard e-beam cross sections. The tether beam, however, has one cross dimension ~ 20 Km, the flux varying from tether top to bottom. This would allow determination of volume emission rates by tomographic techniques.

The low ion-level current makes the tether near equipotential in its own frame. In that frame the potential in the ionospheric plasma varies as (Fig. 1)

$$d\phi_I / dh = E_m \quad \text{(motionally induced field)}$$

$$\Rightarrow \phi_T - \phi_I = E_m (h_0 - h)$$

The electron current $I_e(h)$ varies along the tether and flows downwards. For $h < h_0$ the tether collects electrons according to the OML law

$$\frac{dI_e}{dh} = e N \frac{p}{\pi} \sqrt{2e(\phi_T - \phi_I)/m_e}$$

For $h > h_0$ ions are attracted and, after impact, leave as neutrals, carrying electrons away. Electrons thus leak out at the ion impact rate, again given by the OML law, enhanced by secondary emission, with a yield $\sim \gamma_1(\phi_I - \phi_T)$,

$$\frac{dI_e}{dh} = -eN\frac{p}{\pi}\sqrt{2e(\phi_I-\phi_T)/m_i}\left[1+\gamma_1(\phi_I-\phi_T)\right]$$

where $N$ is the plasma density, and $p$ is the cross section perimeter.

These equations, together with the floating conditions $I_e(0) = I_e(L) = 0$, determine $h_0$ and $I_e(h)$.

Take an Al, $L = 20$ km, $p = 8$ mm tether, with $\gamma_1 \sim 0.2$ / KV; and oxygen ions with density $N = 3 \times 10^{11}$ / m$^3$ (night time level at 350 Km, and mean solar activity). Also, take orbit inclination $i \sim 35…$ and use the dipole approximation for the geomagnetic field, giving an average $E_m \approx v_{sat} B_{eq} \cos i$ = 165 V / km

We then find that $h_0$ is a few per cent of $L$; in what follows we shall consider $h_0 \approx 0$. We also find a current averaged over tether length,

$$\tilde{I}_e = \int_0^L I_e(h)\,dh / L \approx 0.286A\,,$$

and an emitted current of secondary electrons $I_{sec} \approx 0.128$ A, with vertical distribution of electron emission

$$dI_{sec} / dh = 2.5 \times h^{5/2} I_{sec} / L^{7/2}$$

The ohmic drop $L\tilde{I}_e / \sigma A_c$ is a few per cent of $E_m L$, thus being negligible as assumed. Here $\sigma \approx 3.5 \times 10^7 / \Omega$ m is the Al electrical conductivity, and $A_c$ is the conductive cross section area.

The magnetic drag power is

$$W_{drag}(\text{night}) = E_m L\,\tilde{I}_e \approx 0.944 \text{ kW}$$

This magnetic drag results in altitude loss. That loss would be much greater during the day. A power source would be needed to reverse the current and produce thrust. That power would be supplied by solar panels.

To estimate the power $W_e$ required to keep an average orbital altitude we set zero net drag-thrust at day. The power voltage will shift down the zero bias (~ zero current) point. Below (above) that point, current will flow downwards (upwards), resulting in drag (thrust). The drag power scales in a simple way with both downwards current length and plasma density (Fig. 2)

$$\frac{W_{drag}(day)}{W_{drag}(night)} = \left(\frac{l}{L}\right)^{5/2}\frac{N_{day}}{N_{night}}\,\frac{1+5\gamma_1 E_m l/7}{1+5\gamma_1 E_m L/7}$$

To determine the thrust power, $W_{thrust}$(day). we solve for $I_e(h < L - l)$. The electron current level results in ohmic effects here being important. Since $I_e$ flows now upwards we have

$$d\phi_T/dh = -I_e/\sigma A_c.$$

We still have $d\phi_I/dh = E_m$, but the current law has the sign changed

$$\frac{dI_e}{dh} = eN\frac{p}{\pi}\sqrt{2e(\phi_T-\phi_I)/m_e}\,.$$

Finally we use boundary conditions

$$\phi_T - \phi_I = 0 \quad (I_e \approx 0) \quad \text{at} \quad h = L - l.$$

Setting the day condition $W_{thrust} = W_{drag}$ the power is determined by the equation

$$W_e = (\phi_T - \phi_I)\,I_e \quad \text{at} \quad h = 0.$$

Take $A_c = 2.2$ mm$^2$ (and $p = 8$ mm as before). This results in a cross section conductive layer 0.31 mm thick, over a nonconductive circle of radius 0.96 mm. For $L = 20$ km, the tether mass would be ~ 175 kg

Using $N_{day} = 10^{12}$ m$^{-3}$, we obtain $l \approx 0.857\,L \approx 17.1$ km. Also, current and voltage at the power source in the S/C ($h = 0$), would be $I_e$ = 10.6 A, $\phi_T - \phi_I$ = 723 V, making a supply power $W_e \approx 7.66$ kw. The mass of the power-system mass (including the solar panels) could be ~ 175 kg too.

We note that a fully conductive circle cross section of $p = 8$ mm perimeter would make too heavy a tether. Also, a conductive tape of thickness 0.2 mm say, would need too heavy a power system.

A Hollow Cathode, $X_e$ - contactor, switched on with the power supply could have a mass flow rate ~ 2.5 kg / year / A, and eject a 10.6 A current under a 20-30 V bias << $E_m (L - l)$. The mass of 1-year HC system (including tankage and plumbing), at _ duty cycle, would be ~ 15 kg.

## The tether e-beam

Secondary electrons accelerate away from the tether to energies $eE_m h$. At the start of their race down field lines the electrons would be uniformly distributed in azimuth $\varphi$ (Fig. 3).

The pitch angle $\theta_p$ distribution is nearly uniform on the range $[I < \theta_p < \pi / 2]$, and is peaked at $I$. The magnetic dip angle varies in orbit within the range $0 < I < I_{max} \sim tan^{-1}(2\ tan\ i)$.

With a e-beam half-width ~ electron gyroradius at energy $eE_m h$ the downward particle flux would be

$$\Phi_\infty(h) = \frac{\gamma_1 E_m L \times N_{night}\ p\ \Omega_{eq}}{2\pi \cos I \times \sqrt{1+3\cos^2 I}} \sqrt{\frac{m_e}{m_i}} \frac{h}{L}$$

For the energy flux we have

$$\Phi_{\varepsilon\infty} \equiv \Phi_\infty(h) \times eE_m h$$

$$\approx (h/L)^2 \times 3.67 \times \mathrm{erg/cm^2\ s} \quad (\leq \text{Type II auroras}).$$

We have set $I = 45…$, and used $\Omega_{eq} = 5.3 \times 10^6\ \mathrm{s^{-1}}$, which is the electron gyrofrequency at the magnetic equator).

Racing secondary electrons are slowed down by molecules in inelastic collisions that produce ionization and excitation (followed by prompt photon emission), with one ionization on average for every 35 eV ($\equiv \varepsilon_i$) of energy lost by the secondary electrons.

The ionization cross section for $\varepsilon > 30$ eV is

$$\sigma_i \approx \sigma_* \times g(\varepsilon / \varepsilon_*), \qquad \sigma_* \approx 10^{-15}\ \mathrm{cm^2}$$

$$\varepsilon_* \approx 24\ \mathrm{eV}, \qquad g(u) \equiv (u - 1)\ ln\ u / u^2.$$

The electrons lose energy with altitude at a rate

$$sinI\ cos\theta_p \times d\varepsilon / dz = \varepsilon_i\ n(z)\ \sigma_i(\varepsilon)$$

with the $E$-layer atmospheric density (height $z$ measured from 95 km above the Earth)

$$n(z) \approx 10^{31} / z^3.$$

For a rough simplification, we ignore pitch evolution and distribution, using an average $cos\theta_p \equiv cosI \times 2 / \pi$, from the initial $\theta_p$ distribution. Also, beam spread may be ignored

$$\Phi(z, h) \approx \Phi_\infty(h).$$

The energy $\varepsilon(z, h)$ of electrons reaching height $z$, after being emitted from a tether point at distance $h$ from the top (and at an altitude $\sim z_\infty$) is

$$\int_{\varepsilon/\varepsilon_*}^{eE_m h/\varepsilon_*} \frac{du}{g(u)} = z_*^2 \left( \frac{1}{z^2} - \frac{1}{z_\infty^2} \right),$$

where

$$z_* \equiv \sqrt{\frac{\pi\varepsilon_i}{2\varepsilon_*} \frac{10^{31}\sigma_*}{sin2I}} \approx \frac{1514\,km}{\sqrt{sin2I}}$$

<u>Steady-state</u> auroral emissions occur at $z$ ~ 25-50 km, i.e., 120- 140 km above the Earth surface. (The lifetime of excited states ~ $10^{-7}$ s is much less than the beam dwell time ~ 10 m / 7.5 km $\mathrm{s^{-1}}$ ~ $10^{-3}$ s)

Volumetric emission rate of photon-type considered are then given by

$$\dot{n}_{em}(z, h) = \Phi_\infty(h)\, n(z)\, \sigma_{exc}\left[\varepsilon(z,h)\right].$$

The emission brightness for an emission depth $s$, along any specific line of sight (relating $s$, $z$, and $h$) is

$$b_R = 10^{-6} \int \dot{n}_{em} ds$$

($b$ in Rayleigh units, emission rate in cgs units).

Take a simple case: The $N_2^+$ first negative band (427.8 nm), with $\sigma_{exc} \sim 1.75\ \sigma_i$, and observation from the S/C, with a line of sight at angle $\psi$ from $B$-field lines (Fig. 4), making

$$ds \approx dz / sinI, \qquad h\ sin2I \approx 2\psi(z_\infty - z),$$

$$[\psi_{max} \approx (L\ sin2I) / 2z_\infty, \quad \text{a few degrees}],$$

$$\varepsilon(z, h) \to \varepsilon[z, h(z)].$$

There is no ionization below the energy $\varepsilon_i$. This implies no ionization above some height $z_{max}$,

$$\varepsilon[z_{max}, h(z_{max})] = \varepsilon_i \quad \Rightarrow z_{max} \approx z_\infty$$

(emission energy being too low above $z_{max}$), and below some height $z_{min}$,

$$\varepsilon[z_{min}, h(z_{min})] = \varepsilon_i \quad \Rightarrow z_{min} << z_\infty$$

(energy having dropped too low below $z_{min}$). We find, in particular,

$$z_{min} \approx 32.7\ \mathrm{km} \quad \text{at } \psi = \psi_{max}, \qquad I = 45…$$

We finally arrive at

$$b_R(427.8\ nm) = 10^{-6} \times 10^{31}\sigma_* \times$$

$$\times \frac{1.75\ \Phi_\infty(L)}{sinI} \times \frac{\Psi}{\Psi_{max}} \times \int_{z_{min}}^{z_{max}} \frac{dz}{z^3} \times \frac{z_\infty - z}{z_\infty} \times g\left(\frac{\varepsilon}{\varepsilon_\infty}\right)$$

The integrand above peaks at $z << z_\infty$, $\varepsilon \sim \varepsilon_i$. Take $\psi = \psi_{max}$, $I = 45$…,$g \sim \_ g_{max} \approx 0.13$. This yields

$b_R$(427.8 nm) ~ $10^5$

**Conclusions**

* An electrically floating bare tether in LEO may serve as upper atmospheric probe.

Power supply and plasma contactor at the S/C may keep (or modify) its orbit indefinitely.

A full system mass ~ 400 kg possible if tether cross section conductive on thin outer layer

* The tether e-beam is free from the S/C charging and plasma interaction problems of standard beams.

Beam energy flux between Type I and II auroras

Flux too low to allow ground observation (brightness ~ 1 -10 Rayleighs)

* (Long, continuous) observation from S/C possible (satellite motion very slow compared to velocity of secondary electrons), with brightness ~ $10^4$ - $10^5$ Rayleighs.

Determination of volume emission rates possible by tomographic techniques

Probe could make significant contributions to knowledge of upper atmospheric kinetics

It may uncover aeronomic mechanisms of importance in the thermosphere.

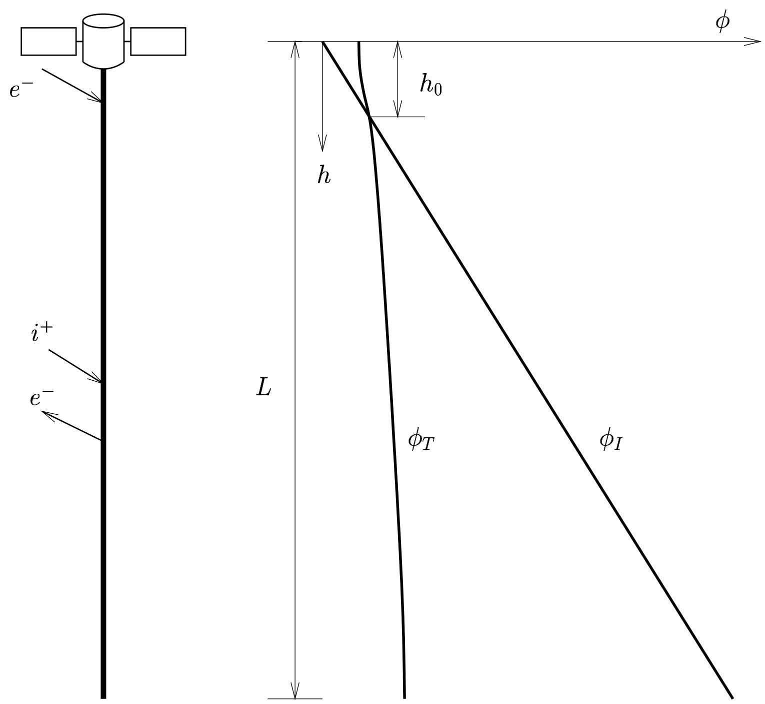


FIGURE 1

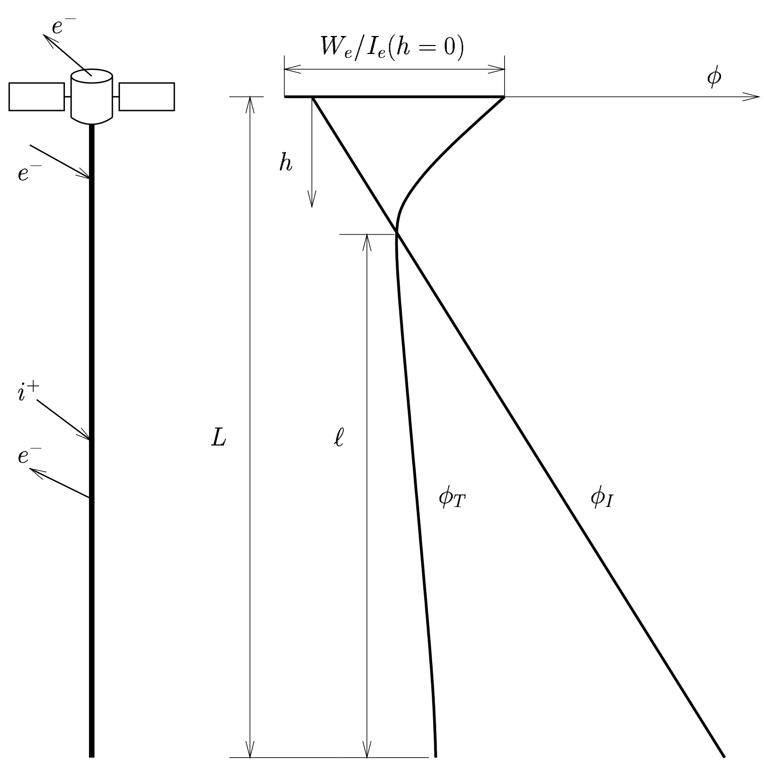


FIGURE 2

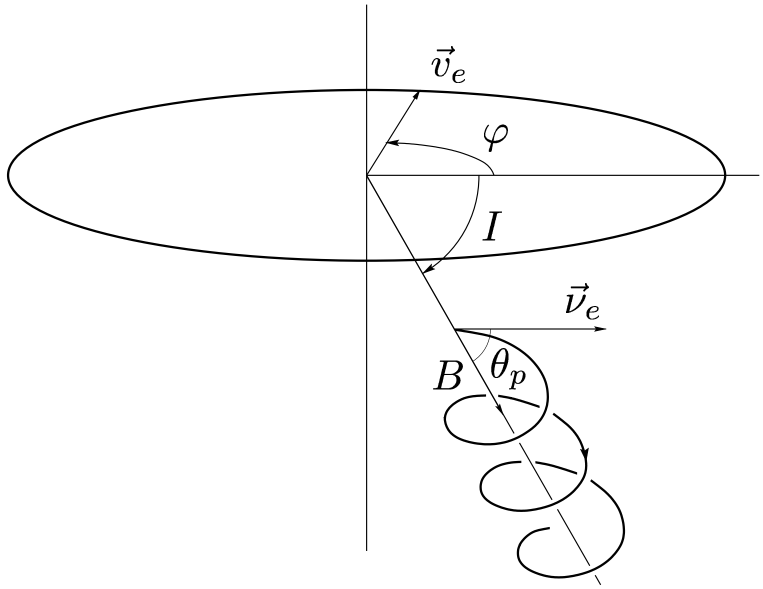


FIGURE 3

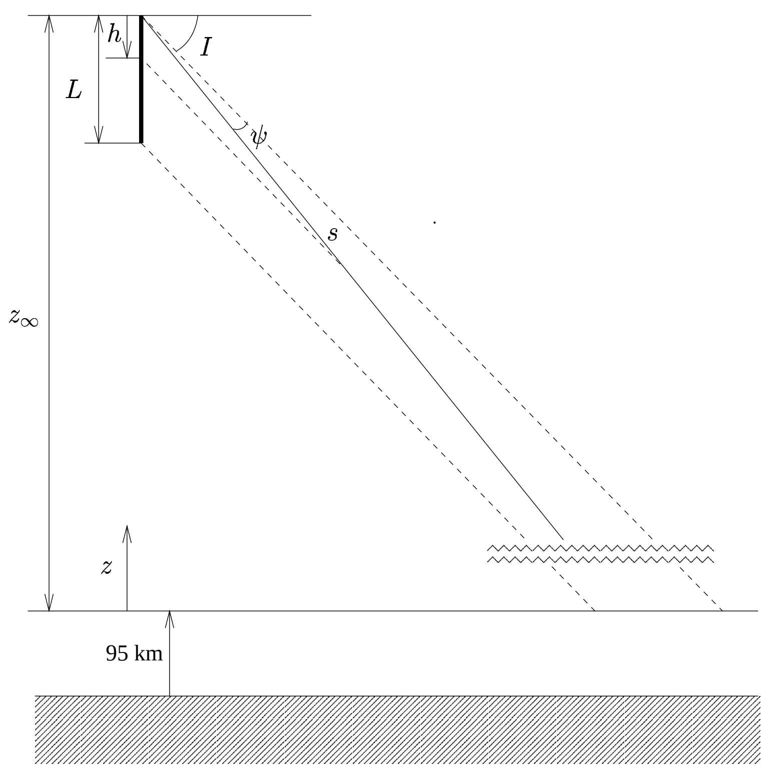


FIGURE 4