A proposed bare-tether experiment on board a sounding rocket

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A mission on board a sounding rocket to carry out two bare-tether experiments is proposed: a test of orbital-motion-limited (OML) collection and the proof-of-flight of a technique to determine the (neutral) density vertical profile in the critical E-layer. Since full bias from the motional field will be small (~ 20V), corresponding to a tape 1 km long and v_{rocket} << 8 km/s, a power source with a range of supply voltages of few kV would be used. First, the negative terminal of the supply would be connected to the tape, and the positive terminal to a round, conductive boom of length 10 - 20 m; electrons collected by the boom cross the supply into the tape, where they leak out at the rate of ion impact plus secondary emission. Determination of the density profile from measurements of auroral emissions observed from the rocket, as secondaries racing down the magnetic field reach an E-layer footprint, are discussed. Next the positive terminal of the voltage supply is connected to the tape, and the negative terminal to a Hollow Cathode (HC); electrons now collected by the tape cross the supply, and are ejected at the HC. The opposite connections, with current collection operated by tape and boom, and operating on electrons and ions, and through partial switching in the supply, allow testing OML collection in almost all respects it depends on.

I. Introduction

A sounding rocket could easily carry out two experiments concerning bare tethers: a test of OML collection in-orbit[1] and the proof-of-flight of a technique to determine the (neutral) density vertical profile in the critical E-layer.[2] Low cost, simple mission concept, and possibly fast realization make use of a sounding rocket a reasonable solution for a tether demonstration mission. The main driver for such missions in LEO, however, is the need to show endangering of other satellites (the International Space Station in particular, at present) as an extremely remote possibility. Space tether missions have been cancelled in the past just for prevention (case of YES1, SEDSAT, and ProSEDS satellites). A sounding-rocket mission, being so short in time (and at altitude definitely below the ISS orbit), is perfect in this respect.

A substantial corpus of recent theory on OML (orbital-motion-limited) collection now exists but there remains a need to test bare-tether collection in orbit.[3] This need concerns particularly joint effects of geomagnetic field and ion ram motion. Separately, ram effects might involve adiabatic trapping of electrons, so as to keep quasineutrality over the large region in the wind side where backscattering of ram ions by the highly positive tether results in ion density above the unperturbed value.[4] The geomagnetic field, on the other hand, may introduce three-dimensional (3D) effects. Recent results from laboratory experiments[5] and numerical tests[6] under joint magnetic and ram conditions appear unconclusive. How to analyze tether data in testing OML collection has been recently discussed for NASA's (just terminated) ProSEDS mission.[7]

A tether electrically floating (current vanishing at both ends) attracts ions over most of its length. Ions impacting with KeV energies on a 20 km long orbiting tether take electrons to leave as neutrals; they also liberate secondary electrons that are accelerated away in the 2D electric field around the tether, then race down magnetic-field lines to produce auroral emissions in the E-layer.[8] Such electron beam is free of problems that have plagued standard e-beams used in the past for auroral experiments. Beyond auroral effects proper, a bare-tether could provide measurements of neutral density along its E-layer footprint track, of interest in full numerical simulations of the atmosphere lying below, and in reentry predictions. The tether would operate at night-time, to ease observations. Actual emission measurements and analysis of brightness might be carried out as a preliminary test in orbit. A positive outcome could lead to a longer LEO mission scanning nightly the e-layer density and therewith mapping this region very solidly.

Our experiment is indirectly related to previous tether experiments on board sounding rockets that were performed by the Canadian Space Agency (Oedipus A and C) and jointly by NASA and the Japanase Space Agency (CHARGE 1 and 2). Both Oedipus missions involved observation and analysis of auroral phenomena. Oedipus comprised two identical payloads separated by a 1-km conductive (insulated) tether, made to spin around the tether line; flight duration was about 15 minutes.[9] The earlier CHARGE experiments were designed to study the electrical charging of the satellite that results from standard e-beam emission. The experiment involved release of neutral gas for charging mitigation.[10]

II. OML testing

A sounding-rocket mission could test OML-collection in almost all respects it depends on. Because rocket velocity is much smaller than a satellite velocity, and maximum tether length L_t is about 1 km, the full induced bias resulting from the (motional) electric field is too small (~ 20V). A power source with a range of supply voltages ε ~ few kV would be required. The mission involves a two-stage operation:

1) First, the supply negative terminal would be connected to a tape-tether of width w_t, and the positive terminal to a round, conductive boom of length L_b ~ 10-20 m and radius R_b. The supply voltage would be shared between tape and boom, some fraction $\alpha\varepsilon$ biasing the tape. Electrons collected by the boom cross the supply into the tape, where they leak out at the rate of ion impact plus secondary yield (**Fig.1**). Floating establishes the following condition on currents,

$$I_e(\text{boom}) = I_i(\text{tape}) \times (1 + \gamma\alpha\varepsilon). \qquad (1)$$

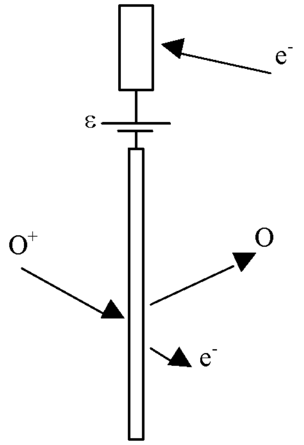

Fig.1: Boom and tape biased positive and negative respectively at stage 1.

Using the OML law then gives

$$eN_\infty L_b 2R_b \sqrt{\frac{2e(1-\alpha)\varepsilon}{m_e}} = eN_\infty L_t \frac{2w_t}{\pi}\sqrt{\frac{2e\alpha\varepsilon}{m_i}} \times (1 + \gamma\alpha\varepsilon), \qquad (2)$$

where N_∞ is the plasma density and γ is the yield per unit bias (0.1-0.2 electrons per kV, and impacting ion).

2) Next, the positive terminal of the power supply would be connected to the tape and the negative terminal connected to a Hollow Cathode (HC) already heated. Electrons now collected by the tape cross the supply, and are ejected at the HC (**Fig.2**). During both stages 1 and 2 the supply voltage ε would be swept over a range of values. The OML law now would give

$$I_e(tape) = eN_\infty L_t \frac{2w_t}{\pi}\sqrt{\frac{2e\varepsilon}{m_e}}\,. \qquad (3)$$

In Eqs. (2, 3) we ignored the small induced bias, thus introducing errors of order $E_m L_t/\varepsilon \sim 0.01$. We also ignored ohmic effects, which would be much greater in the case of Eq.(3). The condition for ohmic effects to be negligible is

$$\frac{I_e(tape)\,L_t}{2\sigma_c w_t h_t} << \varepsilon \qquad \text{or} \qquad \frac{3}{8}\left(\frac{L_t}{L^*}\right)^{3/2}\sqrt{\frac{E_m L_t}{\varepsilon}} << 1\,, \qquad (4)$$

where h_t and σ_c are tape thickness and conductivity, and L^* is a characteristic length gauging ohmic versus bare-tether collection impedances,[1] which reads (for aluminum)

$$L^* \approx \left(\frac{E_m}{160V/km}\right)^{1/3}\left(\frac{h_t\times 10^{11}\,m^{-3}}{0.1mm\times N_\infty}\right)^{2/3}\times 3.11km\,. \qquad (5)$$

Ohmic effects omitted in (3) would then be less than ten per cent.

With current collection operated by tape and boom and operating on electrons and ions, and through partial switching on the supply or plugging different resistances in, this two-stage experiment would test bare-tether current collection broadly. Effects tested involve *i*) cross-section shape of cylinder; *ii*) ratio of Debye length to characteristic cross-section length (chosen different for boom and tape); *iii*) bias-to-thermal energy ratio, which can be swept within and beyond the expected OML regime; and *iv*) collection of electrons and ions (negligible ram-to-thermal energy ratio of attracted species in the first case, small ratio of Debye length to gyroradius of attracted species in the second case).

Missing from the experiment is testing OML collection at a high ratio of ram-to-thermal ion energy (case of tethers in orbiting satellite), which is of order unity for a sounding rocket. Finally, we note that, the mission being so short, we might use as cathode in stage 2 a simple gas-release device instead of an (Open Keeper) HC. Our experiment could then test effects observed during the TSS-1R tether burn-out.[11]

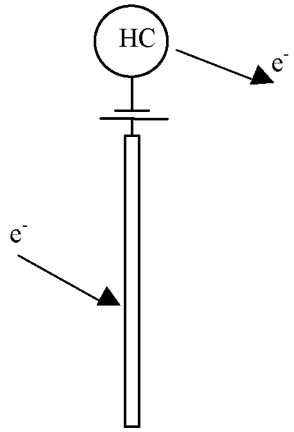

Fig.2: **Tape biased positive at stage 2.**

III. Test of auroral emissions

As already noticed, a conductive tether tens of kilometers long left floating electrically (no devices at ends) in an orbiting satellite could serve as an effective e-beam source to produce artificial auroras. The tether comes biased negatively over 97 % of its length. Ambient ions impacting it with KeV energies liberate secondary electrons, which are locally accelerated through the 2D tether voltage-bias, race down magnetic lines, and result in auroral emissions at about 120-160 km altitude (**Fig. 3**). The e-beam of the tether presents a singular feature: Number flux and energy of secondaries vary linearly with distance from tether top. As a consequence, observation of column-integrated emissions along a range of line-of-sights from the satellite at the top will show a peak in brightness. Tomographic analysis of brightness would allow determining the neutral-density vertical profile in a critical E-layer, as discussed in a recent study.[8]

Beam propagation and beam-atmosphere interactions can be modelled in a simple but quantitative way to allow a satisfactory discussion of observational options and their feasibility. Modelling covers the evolution in the energy spectrum of secondary electrons due to inelastic collisions with neutrals, and accompanying ionization and emissions; and the effect of elastic collisions on the pitch distribution, and on beam broadening, which results in a broader but weaker tether footprint in the E-layer. The emissions of E-layer dominant species (N_2, O_2, and O) at specific bands or lines will depend on the plasma environment at the F-layer, which need be continuously determined. A future LEO tether system might provide an autonomous, effective e-beam source for continuous observation of its E-layer emissions; a solar array and a HC would be off at night for electric floating, and would be on at daytime in order to invert the direction of current, producing thrust to regain the altitude lost to drag throughout the orbit at night.

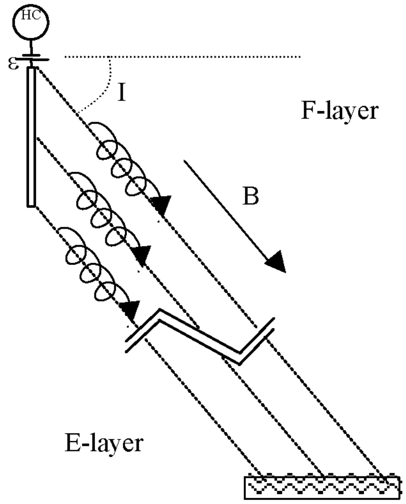

Fig.3: Beam propagation schematics.

Testing of auroral emissions during our stage 1 would be possible though harder than in case of a long tether in an orbiting satellite. As a result of full bias from the motional field being negligible for the sounding rocket, both number flux and energy of emitted secondaries will be uniform along the 1-km tape length. Contrary to the case of a large bias from the motional field, for a 20 km long orbiting tether, auroral brightness vs line-of-sight in the emitting E-layer footprint, as observed from the rocket, would show no peak. Lacking a line-of-sight peak in emission makes tomographic inversion to determine the neutral density profile in the E-layer impossible. Brightness would decrease beyond the footprint proper, but (because L_t is so short) the range of line-of-sight angles is about 1/3 degree. Tomography requires having the extended footprint to cover most pixels in the focal plane of a camera; for such narrow field of view, a large focal length is required, leading to a very large aperture for it to subtend a large solid angle from the focal plane. In addition, optical pointing would be very demanding.

However, having tape-bias vary, not along tape length but through an extended series of shots during stage 1, by sweeping through a set of values in the supply voltage, results in different penetrations of emitted secondary electrons in the E-layer, which could make density profile determination possible. Attitude control of the rocket and the payload if necessary would be costly. Aperture and pointing accuracy can be relaxed, however, by having the footprint image just cover a few pixels. No real tomography would thus need be carried out.

IV. The rocket mission

A sounding rocket S-520-CN, having attitude control and allowing an estimated payload of about 70 kg, appears appropriate for the present mission. An apogee altitude of 300 km should be sufficient for both OML testing and e-beam generation. Testing auroral emissions requires a night-time rocket launch, and a middle latitude suborbital flight at magnetic-dip angle I roughly in range $1/2 < \tan I < 2$. The mission profile might be similar to the Canadian flight experiment *Oedipus*. A number of instruments for mission measurements would be utilized: Langmuir probes (Plasma diagnostics), 3 axis Magnetometer (Local magnetic field), Ampere meter (Current at power supply), and Accelerometers. Additional LIDAR measurements of local density might be required for post processing of data. The total science payload mass is assumed to be about 72 kg, as shown in Table 1.

Table 1 Payload mass breakdown	
Upper payload	Mass [kg]
Tether reel device	4
Gas bottle (incl. TBD gas, including valves for gas flow rate control)	5
Hollow cathode or source of electron	5
Langmuir Probe	0.25
Electronics, measurements & control package OBC GPS etc.	8
Power Distribution Unit [PDU]	2
Magnetometer & accelerometers	0.1
Wave receiver	1
CCD camera	1
Structure & harness	8
Downward payload Passive end mass (No telemeter nor measurement)	15.25
Tether Foil (1km, 50 mm x 0.05 mm aluminum foil, reinforced)	7

	Power/batteries (200 Wh/kg → 3000 V, 1A 15 min=750W)	5
Boom	10 m long, 1 cm radius cylinder	8.4
Margin		5
Total		75.0

The launch is planned for the spring of 2006. Preparing for launch would take over one year after the mission is approved. No new hardware development is actually required except for the tape tether and its deployer, all other hardware being based on heritage. Testing deployment and development of a (bare, reinforced) aluminum foil, tentatively 0.05 mm thick, suiting the present bare-tether experiment, will involve new technology; experience in ground tests with non-conductive tethers is extensive, however.[12] Other onboard devices have no significant element subject to development, thus reducing development time. The mission concept is almost established, and instruments for measurements in plasma diagnostics, local magnetic field, and current, and a mechanism for activation of either Hollow Cathode or gas-release device are available, although possible decreases in size and weight, and increases of performance would be explored.

A follow-up to the present electrodynamic tether experiment in a sounding-rocket could be a low cost LEO mission (on board a VOLNA launcher) with a duration of a few weeks.

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