High-Voltage Satellite Tethers For Active Experiments In Space

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ABSTRACT

New applications of high-voltage space tethers are analyzed in relation to the idea of an active experiment in the Earth's radiation belts. The tethers can effectively scatter the high energy particles into loss cone, providing a control of particle life time in Earth's radiation belts. The high energy particles are scattered due to the sheath layer formed around the tethers by cold plasma existing in ERB. The rigorous theory of the layer is developed, yielding the electric current collected by the tether and a potential profile which is then used for treatment of the scattering and diagnostics problems. Using the experimental data for trapped particles, the loss-fluxes of electrons and protons for different orbits are calculated. The rates of average losses per 1 km of the tether length at potential ϕ_p =1MV are $1.8 \cdot 10^{14} s^{-1}$ for protons and $1.4 \cdot 10^{17} s^{-1}$ for electrons at altitude H=2000 km, $2.5 \cdot 10^{20} s^{-1}$ and $1.5 \cdot 10^{16} s^{-1}$ respectively at altitude H=10000 km. The above high-voltage tethered satellite system (HVTSS) can be used for precipitation of charged particles from manmade radiation belts and development of new active experiments. In future HVTSS can be used for space weather control.

1.INTRODUCTION

The earliest active experiments in Earth's magnetosphere ARAKS and the later CRRES have been carried out to study physical processes in Earth magnetosphere. Most recently a new class of active space experiments has been proposed which allows not only diagnostic but a control of space plasma parameters as well. One of the most advanced projects HAARP (HF Active Auroral Research Program) by *Papadopoulos et al.*[1995] is based on emission of high power electromagnetic waves from the Earth surface to the ionosphere. By matching the frequency to the ionospheric density profile, the energy of the waves can be deposited selectively at altitudes between 70 to 90 km (D/E Region), between 200 to 300 km (F Region), or it can escape into space. Due to nonlinear processes low frequency waves can be excited in the ionosphere. Propagating along magnetic field lines these waves can reach the areas of Earth's radiation belts and induce precipitation of the energetic particles trapped in this region of geospace. This process can help in controling of the flux of energetic particles in these particular regions of the ERB. In parallel with the HAARP another new approach can be realized for particle loss-fluxes in the ERB. It is based on idea proposed in [*Danilov and Vasilyev*,1995;*Danilov et al.*,1996] where a high-voltage tethered satellite system (HVTSS) is suggested to be used as an artificial scattering center. The tethered satellite system consists of the main satellite and two small subsatellites, flying through the ERB in the equatorial plane. Two long strings (about 10 km long each) are tethered in opposite directions (along the orbit) between the satellites. A high potential difference ϕ_p ~1MV is applied between tethers. This HVTSS can effectively scatter the high-energy particles (protons and electrons) into the loss-cone, providing a control of particle lifetime in ERB. Electrodynamic aspects of the tethers, technical requirements for power supply and the values of loss-fluxed particles will be considered below.

2.STRUCTURE OF THE SHEATH LAYER

The high energy particles are scattered due to a sheath layer formed around the tethers by cold plasma ($n = 10^2 cm^{-3}, T = 100\ eV$) existing in ERB. The problem of evaluation of the potential profile is quite similar to that studied in standard double Langmuir probe theory (see, for example, *Swift and Schwar*[1968]). A specific feature of our case is the extremely high potential of the probe $p = e\phi_p/kT \sim 10^4$ and a high aspect ratio

$R = r_s/r_p \sim 10^8$. Since this range of parameters is not widely discussed in publications, potential and current calculations are reproduced below by making use of some rough iteration techniques.

When high voltage is applied between the conducting tethers, two oppositely charged sheaths are formed around the tethers. The positively charged string attracts electrons and, correspondingly, the area around it is negatively charged, while the ions are attracted by another string which is surrounded by a positively charged layer. The total current collected by the string at negative potential with respect to the space is as follows:

$$j_- = j_{sec}^{(i/e)} + j_{photo}^{(e)} + j_F^{(e)} + j_i,$$

where $j_{sec}^{(i/e)}$ is electron current from the surface due to the secondary i-e emission, $j_{photo}^{(e)}$ is electron current due to photo-emission, $j_F^{(e)}$ is electron current due to the field emission, and j_i is the ion current. For the second string, which has a positive potential, the total current is given by:

$$j_+ = j_{sec}^{(e/i)} + j_e,$$

where $j_{sec}^{(e/i)}$ is ion current due to secondary e-i emission, and j_e is electron current. In the stationary case (DC) the total currents are balanced: $j_- = j_+ = j$. If the potential of HVTSS is not too high (less than, or on the order of 1 MV) and the material is chosen to prevent secondary and photo-emissions from the field, these expressions can be simplified as follows: $j_- = j_i$, and $j_+ = j_e$.

Since the calculations related to ion and electron sheaths are quite similar, we will focus attention on the ion case only. The typical ion velocity in the sheath area is $v_s = \sqrt{2e\phi_p/m_i} \sim 10^7$m/s, transit (bounce) time is $t_s = 2r_s/v_s \sim 10^{-4}$s, Larmor's radius is large enough (r_{L_i} ~100 km), that we can neglect the effect of magnetic field on particle motion. Electrostatic potential distribution is, therefore, axisymmetric with respect to the tethers.

We assume an infinitely long string potential that varies along r only, where the z axis of the cylindrical reference frame (r, α, z) is chosen to be along the strings.

The particle dynamics is governed by the integrals of energy $E = m_i v^2/2 + e\phi(r)$ and angular momentum $M = mvr\sin\alpha$. With the help of conservation laws, the 3-D problem of particle motion is reduced to a 1-D problem which corresponds to the radial motion with effective potential energy $U_{eff} = M^2/2mr^2 + e\phi(r)$. The ion distribution function is described by the Vlasov-Maxwell equation with a boundary condition at $r \to \infty$, implying that particles flying toward the string ($v_r < 0$) have a Maxwell distribution function:$f = f_m = n_\infty (m/2\pi kT)^{3/2} \exp(-mv^2/2kT)$, and a boundary condition on the string surface ($r = r_p$) assuming that all particles reaching this surface become absorbed. Then ion current density and ion density can be evaluated by integration of the distribution function over the relevant region in velocity space.

The critical issue in ion density calculations is the distribution function of the locally trapped particles. If a significant amount of these particles is accumulated and trapped in the sheath area, the electrostatic potential turns out to be shielded in the narrow vicinity of the string that strongly decreases scattering efficiency. For this reason, some mechanism (such as AC current) for removing and pumping of trapped particles has to be provided. In further consideration we will assume that the trapped particle distribution function equals zero.

With the help of some simplifications based on the fact that the maximum of U_{eff} is well localized near the sheath boundary, the following expression for $n_i(r)$ was derived by *Danilov et al.*[BEAMS-1996]:

$$\begin{aligned} n_i(r) &= \frac{n_\infty}{\pi}\left[\int_{\alpha_1}^{\alpha_2} d\alpha \exp\left(-\frac{p\phi(r)\sin^2\alpha}{1-(r^2/r_s^2)\sin^2\alpha}\right)\right. \\ &+ \left.\int_{\alpha_2}^{\pi} d\alpha \exp\left(\frac{p + p\phi(r)(r^2/r_p^2)\sin^2\alpha}{1-(r^2/r_p^2)\sin^2\alpha}\right)\right] \quad (1) \end{aligned}$$

$$\begin{aligned} \alpha_1 &= \arcsin[r_p/r], \\ \alpha_2 &= \arcsin[(r_s/r)\sqrt{1-\phi(r)(R^2-1}] \end{aligned}$$

Since electrons are strongly repelled by the negatively charged string their density is described by Boltzman equation: $n_e(r) = n_\infty \exp[-p\phi(r)]$, where $\phi(r)$ is a potential normalized to ϕ_p.

A first approximation for $\phi(r)$ was found using the simplification that ion density is a constant, $n_i(r) = n_\infty$. By making use of initial condition on the string surface, $\phi(r_p) = \phi_p$, and by the varying the initial slope at this point, the sheath radius r_s has been evaluated in the way that allows us to satisfy two other conditions: $\phi(r_s) = d\phi(r_s)/dr = 0$. The profile obtained is then used to calculate the corrected dependence $n_i(r)$. The corrected function turns out to be constant ($n_i = n_\infty$) everywhere except in the narrow vicinity of the string ($0 \leq \ln(r/r_p) \leq 5$), where ion density gradually decreases, reaching a value of $n(r_p) = n_\infty/2$ on the string surface. Since this area makes small contribution in the r.h.s. of Poisson's equation, the second iteration for $\phi(r)$ proved to be closed to the first one. With the accuracy needed for the treatment of the scattering problem, this function can be approximated as follows:

$$\phi(r) = \begin{cases} \phi_p[(\ln(r/r_p)/\ln R) - 1], & r \le r_s \\ 0, & r \ge r_s \end{cases} \qquad (2)$$

The dependences of sheath radius r_s, collected current j and electric power $P = j \cdot \phi_p$ on applied potential ϕ_p have been evaluated (see Tab.1).

ϕ_p	0.1	0.5	1.0	1.5	2.0	2.5	3.0
r_s	0.10	0.24	0.31	0.38	0,46	0.50	0.54
j	0.14	0.32	0.45	0.55	0.64	0.72	0.78
P	0.014	0.16	0.45	0.83	1.28	1.8	2.34

Table 1: The dependences of sheath radius r_s, collected current j, and electric power $P = j \cdot \phi_p$ (per 1 km of string length) on applied potential difference ϕ_p. The cold plasma density $n_{cold} = 10^2$ cm^{-3}, temperature T=10^2 eV; $[\phi_p] =$ MV, $[r_s] =$ km, $[j] = 10^{-3}$ A/km, $[P] =$ kW/km.

Since $m_e \ll m_i$, the potential of the negative string ϕ_- relative the space is very close to the total potential difference ϕ_p. Correspondingly, the potential of the positively charged string is much less $\phi_+ \simeq (m_e/m_i)\phi_p$. Thus, only the negative string can effectively scatter energetic particles. In the case of AC voltage both tethers will scatter particles with more or less equal efficiency.

3.SCATTERING OF HIGH ENERGY PARTICLES

Because the scattering angle of high energy particles caused by their collisions with the sheath layer is small, Fokker-Planck equation can be used for the treatment of particle losses from ERB. In the reference frame (x, y, z), the z axis is supposed to be along the magnetic field while the string is oriented along y axis. During scattering, the absolute value of perpendicular velocity, $\overrightarrow{v_\perp} = v_x\overrightarrow{e_x} + v_z\overrightarrow{e_z}$, and the value of v_y are conserved. Then the increment of $\overrightarrow{v_\perp}$ is $\mid \Delta\overrightarrow{v_\perp} \mid = 2v_\perp \sin(\alpha/2)$, where α is the scattering angle in xz plane. With the help of (1) α is found to be the the following function of impact parameter ρ:

$$\alpha = \frac{2e \mid \phi_p \mid}{mv_\perp^2}\frac{1}{\ln R}\arctan\sqrt{r_s^2/\rho^2 - 1} \qquad (3)$$

In order to find the rate of diffusion into the loss cone, the θ component of the velocity increment $\Delta\overrightarrow{v_\theta} = 2\sin(\alpha/2)\cos\varphi$ is analyzed, where θ is the pitch angle, and φ is the azimuthal angle in a spherical reference frame. To evaluate average moment which defines the rate of losses, we take into account many microcollisions of test particle with the sheath, resulting from its bounce motion along field lines and slow revolution of satellite in equatorial plane. Then averaging can be done by means of integration over $\rho(-r_s \le \rho \le r_s)$, while v, θ and $\sin\varphi = x/r_L$ are fixed, where x is a coordinate of guiding center, and $r_L = mv\sin\theta/eB$ is a Larmor's radius.

$$< \Delta\theta^2 >= 4(\pi - 2)\frac{L r_s v}{2\pi r_L l\ (2\pi R_s)}\left(\frac{2e\phi_p}{mv^2 \ln R}\right)^2 \beta, \quad (4)$$

here

$$\beta = \frac{1 - (x^2/r_L^2)}{(1 - (x^2/r_L^2)\sin^2\theta)^{3/2}},$$

l is the length of the magnetic field line, and R_s is the radius of satellite orbit.

Making use of the Fokker-Planck equation, the rate of particle losses from ERB has been evaluated. The fluxes are averaged over the time interval which is much longer than the period of satellite revolution over the Earth. They are also integrated over the area, thus, giving the total rate of particles falling down into the ionosphere. Using the approximation of experimental data obtained through the measurements of the fluxes of trapped electrons and protons in radiation belts (see Tab.2,3), the loss rates of particles scattered by tethers have been obtained in *Danilov, Mirnov and Ucer*[1998](see Tab.4).

$H,\ km$	$A(sec^{-1})$	$E_0(MeV)$	$q_{total}(sec^{-1})$
2000	3.6×10^4	64.2	3.6×10^4
6000	1.1×10^6	17.7	1.1×10^6
10000	3.8×10^7	1.0	1.2×10^{11}
20000	8.2×10^7	0.25	5.5×10^7

Table 2: Fluxes of trapped electrons in ERB at different altitudes from the Earth. Approximation of experimental date is $q(> E) = A\exp(-E/E_0)$, $(q(> E) = A(E/E_0)^{-3.5}$, $H = 10000$km.

$H,\ km$	$A(sec^{-1})$	$E_0(MeV)$	$q_{total}(sec^{-1})$
2000	4.0×10^7	0.28	2.8×10^7
6000	2.0×10^7	0.22	1.3×10^7
10000	1.0×10^7	0.30	7.2×10^6
20000	2.0×10^7	0.57	1.7×10^7

Table 3: Fluxes of trapped protons in ERB at different altitudes from the Earth. Approximation of experimental date is $q(> E) = A\exp(-E/E_0)$.

$H,\ km$	protons $q_{total}(sec^{-1}km^{-1})$	electrons $q_{total}(sec^{-1}km^{-1})$
2000	1.8×10^{14}	1.4×10^{17}
6000	3.1×10^{15}	3.7×10^{16}
10000	2.5×10^{20}	1.5×10^{16}
20000	8.0×10^{16}	2.5×10^{16}

Table 4: The rates of average losses of energetic particles for the different altitudes of the HVTSS orbits accounted per 1 km of the tether length (ϕ_p= 1 MV).

4. CONCLUSION

The use of high-voltage tethered satellite system as a controlled scattering center inside the Earth's radiation belts will provide the enhanced loss-fluxes of energetic particles from ERB to the ionosphere. The loss rate $dN(E)/dt$ depends on the distribution functions of the trapped particles and the applied potential difference. The time evolution of the high-energy particles distribution function in ERB has been derived and solved by making use of a small scattering angle approximation. Solving the Fokker-Plank equation yields the values of loss-fluxes. After averaging over the time, which is much longer than the particle bounce time and the time of satellite revolution along the orbit, the rates of energetic particle losses falling down into ionosphere due to the scattering into the loss cone have been obtained. Using the experimental data available for trapped particles, the loss-fluxes of electrons and protons for different orbits were calculated. The rates of average losses per 1 km of the tether length at the potential ϕ_p =1MV are $1.8 \cdot 10^{14} s^{-1}$ for protons and $1.4 \cdot 10^{17} s^{-1}$ for electrons at the altitude H=2000 km, and $2.5 \cdot 10^{20} s^{-1}$ and $1.5 \cdot 10^{16} s^{-1}$ respectively at the altitude H=10000 km. The calculations show that the use of a high-voltage tethered satellite system as a controlled scattering center inside the ERB will provide the above loss-fluxes of energetic particles from ERB to the ionosphere at a moderate level of satellite power supply (near 0.5 kW per 1 km of the tether length at the potential difference 1 MV).

The HVTSS project represents new and unique opportunities for both fundamental research and applications:

- basic study of solar-magnetosphere-ionosphere interrelations
- physics of ERB steady state and dynamics
- wave generation and particle-wave interaction

Some applied program can be realized as well:

- precipitation of the particles from man-made radiation belts, which can result from accidents with the nuclear or isotopic satellite power supplies
- affecting the ozone layer depletion by means of the use of HVTSS as a long emitter of high energy electrons
- space weather control

The HVTSS fits well in the HAARP program and many new possibilities could appear from their joint realization.

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