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Electrical conductivity channels in the atmosphere produced by relativistic-electron microbursts from the magnetosphere

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ABSTRACT

The properties of a cylindrical-shaped magnetic-field-aligned channel of electrical conductivity produced by the precipitation of relativistic-electrons into the atmosphere during a spatially localized magnetospheric microburst are estimated. The conducting channel connects the middle atmosphere (~50 km) to the ionosphere. A channel diameter of ~ 8 km with an electric conductivity of $1.2\times10^{-9}\ \Omega^{-1}\mathrm{m}^{-1}$ near the bottom and $1.8\times10^{-7}\ \Omega^{-1}\mathrm{m}^{-1}$ higher up is found. In the fair-weather electric field, the higher-conductivity portions of the channel can carry substantial electrical currents.

1. Relativistic-electron microbursts

Relativistic-electron microbursts are short-lived, localized patches of relativistic-electron precipitation from the outer electron radiation belt into the atmosphere that are believed to be caused by brief, localized instances of strong pitch-angle scattering of electrons by whistler mode chorus waves in the magnetosphere (Thorne et al., 2005; Saito et al., 2012; Osmane et al., 2016). Relativistic-electron microbursts are seen predominantly in the morning sector at mid-latitudes during geomagnetic storms (cf. Nakamura et al., 2000; Blum et al., 2015). (Energetic-electron precipitation caused by whistlers can also occur in the pulsating aurora (e.g. Miyoshi et al., 2015)). The flux of electrons with energies greater than 1 MeV in a microburst can be on the order of 1×10^4 electrons/cm^2/s/sr as measured by the SAMPEX spacecraft at an altitude of 520–670 km (cf. Fig. 1 of Lorentzen et al. (2001)). At SAMPEX altitudes the loss cone has an area of ~π steradians. Simulations by Osmane et al. (2016) indicate that the microbursts are associated with strong pitch-angle scattering of MeV electrons, indicating that the atmospheric loss cone might be filled. To account for the possibility that the loss cone is not filled and to account for the mirroring of some electrons out of the atmosphere, we will take π/2 steradians into the loss cone to obtain a number flux $F = 1.5\times10^4$ electrons/cm^2/s into the atmosphere for the MeV electrons during a microburst. This is an energy flux of 2.4×10^{-2} erg/cm^2/s into the atmosphere.

This report examines the impact of the localized precipitation of 1.5×10^4 electrons/cm^2/s of relativistic electrons from the point of view of atmospheric electricity. A simple analytic calculation is carried out to determine the electrical properties of a microburst conductivity channel in the atmosphere: owing to the uncertainties in the parameters of the microburst precipitation (e.g. the electron energy distribution, the electron pitch-angle distribution, the intensity, size, shape, and temporal duration of the precipitation patch) and owing to the variations in parameters from microburst to microburst, a simple calculation is justified.

Note that Rodger et al. (2002, 2004, 2007) calculated the height profile of ionizations produced by lightning-induced electron precipitation from the radiation belt associated with Trimpi electromagnetic-wave perturbations (e.g. Fig. 4 of Rodger et al. (2007). Those calculations differ from the ones in this report in that (1) Rodger et al. (2002, 2004, 2007) used an exponential kinetic-energy distribution for the precipitating electrons with a cutoff energy of 1.5 MeV and a mean electron energy of much less than 1 MeV rather than a monoenergetic 1-MeV population, (2) the energy flux used by Rodger et al. (2007) of ~8×10^{-5} erg/cm^2/s is about 300 times less than the energy flux used in this report, and (3) this report carries out electrical-conductivity calculations beyond the ionization rates. The Rodger et al. (2002, 2004, 2007) calculations yielded peak ionization rates at altitudes of ~80 km; here the ionization will peak much lower.

2. A conducting channel in the atmosphere

In Fig. 1 the quasi-cylindrical-shaped conducting channel (pink) of a relativistic-electron microburst is depicted. 1 MeV electrons pene-

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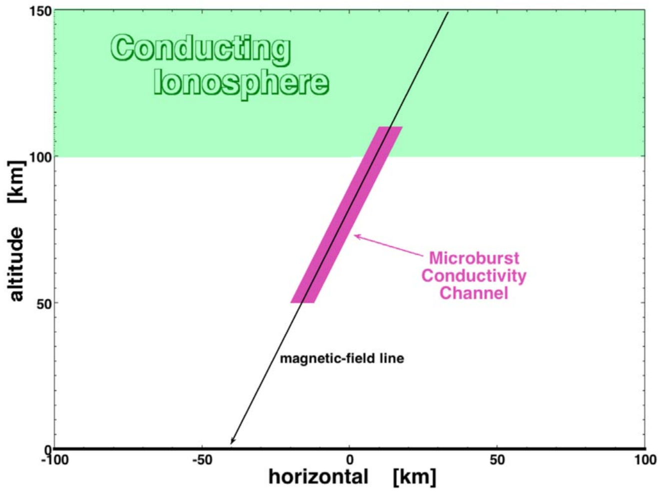

Fig. 1. A sketch of the cylindrical conductivity channel (pink) created in the atmosphere by a relativistic-electron microburst. The microburst diameter is taken to be 8 km. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

trate to an altitude of about 50 km where they "range out" (cf. Berger and Seltzer, 1972; Gilchrist et al., 2001; Marshall et al., 2014). An electron travels the 50-km length of the channel in approximately 50 km/c $=1.7\times10^{-4}$ s: this is essentially the momentum-exchange collision time for the relativistic electron. The relativistic γ value of a 1 MeV electron is $\gamma\approx3$. In the Earth's magnetic field with strength B ~0.5 gauss, the gyroperiod of the 1-MeV electron is $\tau_{gyro}=2\pi\gamma m_e c/eB\approx2\times10^{-6}$ s. During one gyroperiod a 1-MeV electron (with a velocity v=0.85c) travels a distance $\Delta x = v\tau_{gyro}=5\times10^4$ cm through air. As the relativistic electron passes through air, Coulomb scattering leads to angular scattering of the electron's trajectory. As the electron travels a distance Δx through air, Coulomb scattering deflects the electron's direction through an angle Δθ that can be estimated via $\Delta\theta=[\Delta x\ \rho_{air}\ (T/\rho)_{air}]^{1/2}$ (cf. eq. (2.7) of ICRU (1984)), where ρ_{air} is the mass density of the air and $(T/\rho)_{air}$ is the mass scattering power of air. Table 2.6 of ICRU (1984) yields $(T/\rho)_{air}=3.00$ radian^2 cm^2 gm^{-1} for a 1 MeV electron in air. At 70 km altitude the mass density of air is $\rho_{air}\approx6\times10^{-8}$ g/cm^3. Using $\Delta x=5\times10^4$ cm, $\rho_{air}=6\times10^{-8}$ g/cm^3, and $(T/\rho)_{air}=3.00$ radian^2 cm^2 gm^{-1}, the expression $\Delta\theta=[\Delta x\ \rho_{air}\ (T/\rho)_{air}]^{1/2}$ yields Δθ=0.095 rad =5.4°. During that same amount of time (one gyroperiod $\tau_{gyro}=2\times10^{-6}$ s) the Earth's magnetic field can turn the direction of the 1-MeV electron through 360°; hence, Coulomb scattering does not disrupt gyromotion and the precipitating 1-MeV electrons will not wander across the Earth's magnetic field (they will form a field-aligned column, as sketched in Fig. 1). Above 70 km where the air is less dense angular scattering will be even less important; below 70 km angular scattering will be more important (become very important at an altitude of 50 km).

All along their downward path the electrons produce ionization of the air. The number of ionizations per cm of path length is given by $\rho_{air}(dE/\rho dx)_{air}/W$, where $(dE/\rho dx)_{air}$ is the mass collision stopping power of air to electrons and where W is the amount of energy lost by collisional stopping per one ionization created. The mass stopping power for 1-MeV electrons in air is $(dE/\rho dx)_{air}=1.7\times10^6$ eVcm^2/gm (obtained from the NIST online stopping-power and range tables at http://www.nist.gov/pml/data/star/): this 1-MeV value for $(dE/\rho dx)_{air}$ will be used for the entire channel even though the electron slows down slightly as it descends, resulting in a slight underestimate of the energy deposition. (For example a 1-MeV electron looses 12% of its energy by the time it reaches an altitude of 65 km from vertical descent, and that 12% change in the electron kinetic energy results in only a 0.6% change in the value of $(dE/\rho dx)_{air}$.) For air, the mean rate of ionization is W=31.5 eV (Valentine and Curran, 1958; Wedlund et al., 2011); i.e. one ionization produced in the air for every 31.5 eV of energy lost by a relativistic electron. The number density n_* of ionizations in the microburst channel is

$$n_* = F\ (dE/\rho dx)_{air}\ \rho_{air}\ \Delta t/W \qquad (1)$$

where ρ_{air} is the mass density of air and Δt is the time duration of the microburst. When an ionization is initially produced by the microburst energetic electron, a free electron and an ion (or ionized molecule) are produced; with time the free electron will attach to a molecule (making a negative molecule or negative ion) and two ions (or ionized molecules) per ionization will result.

The electrical conductivity of the air in the microburst-produced channel of ionization is given by

$$\sigma = e^2\ N\ n_*/m_*\ \nu_*, \qquad (2)$$

where e is the electronic charge, n_* is the number density of ionizations, m_* is the mass of an ionized particle, and ν_* is the collision frequency between the ionized particles and the molecules of the air. If the conductivity is carried by electrons (one free electron per ionization) then N=1 in expression (2); if the conductivity is carried by ions (two ions per ionization) then N=2. During the phase before electron attachment, the conductivity will be dominated by the free electrons and $m_*= m_e$ and ν_* will pertain to the collision frequency of electrons in air; later $m_*= m_{ion}$ and ν_* will pertain to the collision frequency of ions in air. The collision frequency is given by

$$\nu_* = u_*\ n_{air}\ \Sigma_{mom} \qquad (3)$$

where u_* is the thermal velocity of the electron or ion, n_{air} is the number density of air molecules, and Σ_{mom} is the momentum-exchange cross section for the electron or ion on an air molecule. Using expressions (1) and (3), expression (2) for the electrical conductivity in the microburst channel becomes

$$\sigma = N\ e^2\ F\ (dE/\rho dx)_{air}\ \rho_{air}\Delta t/(m_*\ n_{air}\ u_*\ \Sigma_{mom}\ W). \qquad (4)$$

In expression (4) $\rho_{air}/n_{air}\approx29\ m_p$ where m_p is the mass of a proton. With this, expression (4) simplifies to

$$\sigma = 29\ N\ m_p\ e^2\ F\ (dE/\rho dx)_{air}\Delta t/(m_*\ u_*\ \Sigma_{mom}\ W). \qquad (5)$$

Note at this point that expression (5) for the electrical conductivity of the channel does not depend on the density of air n_{air} and hence is largely independent of height: this is because the number density of ionizations in the numerator of expression (2) depends linearly on n_{air} and the collision frequency in the denominator of expression (2) also depends linearly on n_{air}. A factor in expression (5) that is a function of altitude and time is N/m_*u_*, which changes by a factor of about 100 as the transition from electron conduction to ion conduction is made (see below).

At altitudes of 50–100 km, the neutral temperature is ~250 K≈0.02 eV and a molecule or molecular ion will have a thermal speed $u_*\sim2.4\times10^4$ cm/s; for electrical conductivity by ions $m_*u_*\sim1.1\times10^{-18}$ g cm/s. Assuming that free electrons from the ionizations thermalize to a temperature of ~250 K in a few collision times, the electrons will have a thermal speed $u_*\sim5.9\times10^6$ cm/s; for electrical conductivity by electrons $m_*u_*\sim5.4\times10^{-21}$ g cm/s. The momentum-exchange cross section for low-energy electrons on nitrogen molecules is $\Sigma_{mom}\approx5\times10^{-16}$ cm^2 (cf. Fig. 1 of Itikawa (2006)), which is on the order of the cross-sectional size of a molecule. For the momentum-exchange cross section for molecular ions on nitrogen molecules, $\Sigma_{mom}\approx\pi(d/2)^2$ will be taken, where d is the effective diameter of an N_2 molecule. Viscosity measurements yield $d=3.15\times10^{-8}$ cm (Chemical Rubber Company (CRC), 1975), which yields $\Sigma_{mom}\approx7.8\times10^{-16}$ cm^2. Hence for conductivity by free electrons the quantity $m_*u_*\Sigma_{mom}\approx2.7\times10^{-36}$ g cm^3 s^{-1} and for conductivity by ions the quantity $m_*u_*\Sigma_{mom}\approx8.6\times10^{-34}$ g cm^3 s^{-1}.

Using F $=1.5\times10^4$ electrons/cm^2/s, $(dE/\rho dx)_{air}=1.7\times10^6$ eVcm^2/gm, W =31.5 eV, taking Δt =0.5 s for the temporal duration of the