Emission of X and γ rays by relativistic runaway electrons produced during atmospheric lightning

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Abstract: Quasi electrostatic fields generated during the lightning produces runaway electrons with energies in MeV range. These relativistic electrons can emit X and γ rays over the lightning region. Light emission appears in the form of red sprites and blue jets in their path towards the lower ionosphere. Some of these energetic runaway electrons are trapped by the Earth radiation belt and some fall down in the magnetically conjugate point in the opposite hemisphere. Whistler waves excited by lightning can accelerate electrons in the Earth's magnetosphere. In this research work the distribution function of relativistic electrons energy is calculated. The angular distribution of the electron beam moving along the magnetic field, $F(\alpha)$, the variation of the distribution function with the Earth magnetic latitude $f(\lambda)$ and the variation of electron beam radius with altitude resulted from diffusion and scattering are discussed. The variation of dynamic friction force with runaway electrons energies is plotted and the decrease in the scattering cross section with electrons energy is demonstrated.

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1- INTRODUCTION

Millions of lightning's and thunderstorms occur yearly in the Earth atmosphere. Whistler wave interacts with particles trapped in the radiation belt of the Earth and this leads to the pitch angle scattering of electrons. During the lightning, hot plasma columns with diameters of tens centimeters and length of several kilometers are produced by large discharge currents. In this process a high current of about tens to thousands ampere is produced in a temperature of about $2500\,^{\circ}C$. A high voltage discharge takes place between the cloud and Earth, cloud-cloud and cloud – ionosphere. The emitted electromagnetic spectrum during the lightning contains VLF(up to tens of KHz), short radio wave , visible and UV light , X and γ rays [1,2,3]. The main effect of the strong quasi-electrostatic fields after each discharge in the lower ionosphere is to change electrons distribution function. Red sprites are appeared in mesosphere about $1ms$ after each discharge. The mechanism for electron acceleration and hence X and γ ray production is still being studied by many groups. In the breakdown model, runaway electrons originating from cosmic rays are accelerated by the electric field produced during the lightning. Terrestrial γ ray bursts are then produced by bremsstrahlung process. In the altitudes below $20Km$, new runaway electrons inside the clouds produce terrestrial γ ray flashes [4,5,6].

Electrical discharges produce plasmas where whistler waves are excited by energetic electrons. Initial cosmic rays with energies up to $10^{20}eV$ and electric field of $10KVcm^{-1}$ are known as the source for seed electrons [7, 8]. The condition $E > E_c$ alone is not sufficient for runaway breakdown, the presence of seed electrons with energies $0.1 - 1\ MeV$ is also needed since collision with air requires electrons with energies $E > E_c$. Excited whistler waves are observed frequently during lightnings. These waves propagate in the form of guided and non guided waves towards the magnetic conjugate point on the opposite hemisphere and take part in the acceleration process of electrons in the Earth radiation belts. Avalanches of runaway electrons in altitudes between $3 - 10Km$ can be produced in an electric field of $E > E_c \cong 2^{KV}/_{m}$ [9].

The production of energetic neutrons from photonuclear phenomena of terrestrial γ rays flashes are investigated, and $20MeV$ photons have been recognized as responsible for the production of neutrons and their existence in satellite altitudes of about $300Km$. Compton scattering and pair production are also investigated in these processes. Energetic runaway electrons produced during the lightning lead to γ ray flashes with terrestrial origin. Runaway electrons with energies higher than $1MeV$ cause the bremsstrahlung [10,11].

The energy of γ radiation may reach $20MeV$ in the atmosphere. For runaway electrons, a threshold electric field under given pressure condition exists. The presence of seed electrons with energies higher than tens of kilovolts in high electric field region is required. Such energetic electrons exist in the atmosphere. The runaway electron phenomena is originated from long range and small angular scattering of charged particles in coulomb interactions.

For a given value of electric field, there is threshold energy where the dynamic friction force cannot overcome the acceleration force due to the electric field, so this leads to a continuous acceleration of electrons. In unmagnetized plasma, electron acceleration begins within an ionized plasma. Cold electrons with velocity v smaller than the thermal velocity are exposed to the dynamic friction force, proportional to the velocity: $F = mv_0 v$

Since for $v < v_T$, the electron collision frequency is constant, $\nu = \nu_0$ which is determined by thermal velocity of electrons. For fast electrons with velocities bigger than v_T , the dynamic friction force reduces with velocity [12].

$$F = m\nu(v) = \frac{4\pi ne^4}{mv^2} \ln\Lambda$$

where n is the electron density and $\ln\Lambda$ is called coulomb logarithm. When $v \cong v_T$, the friction force is maximum. The critical field or Dreicer field is given by

$$E_D = E_{Ci} = \frac{4\pi ne^3}{T} \ln\Lambda$$

If the electric field is bigger than E_D , electrons become runaway electrons.

2- Terrestrial γ ray flashes

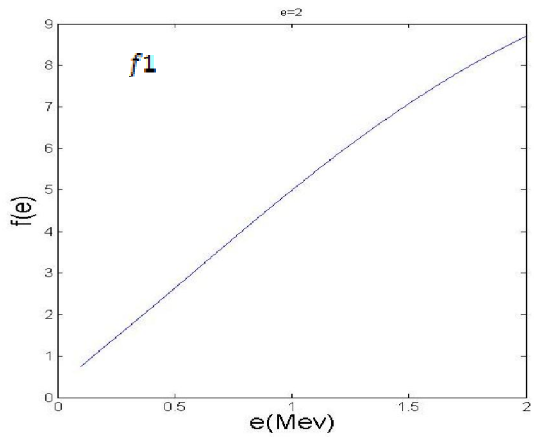
High energy photon bursts during the lightning is called terrestrial γ ray flashes (TGF_s). TGF_s are observed by satellite as photons with energies higher than $20\ MeV$ in a time du *E=10* one to few msec. Vela satellites were eq with instruments capable to detect the of nuclear explosions (neutron , γ and X rays , visible light and radio wave) up to distances farther than Moon. Other satellites (Compton gamma ray observation and burst and terrestrial source experiment) were also launched later in 1991 for cosmic γ ray emissions. Very low frequency (VLF) wave ranging from $3KHz$ to $30KHz$ produced by the lightning are studied by many research groups. These waves are guided along the Earth magnetic dipole field and reach to the magnetically conjugate point in the opposite hemisphere. The guided VLF waves in magnetosphere deposit its energy to the medium by multiple reflections. Terrestrial γ ray flashes depend on VLF radio waves activity and both are related to inter cloud and cloud-Earth lightning's at $10\ Km$ altitude. The behavior of energetic photons of TGRF and their propagation are accompanied by three main physical processes namely: photoelectric, Compton scattering and pair production. These photons are recognized as bremsstrahlung radiation. Avalanche phenomena take place in the gas where free electrons accelerated by high electric fields collide with atoms and ionize them. The number of electrons is fastly increased and the newly produced particles contribute to the phenomena.

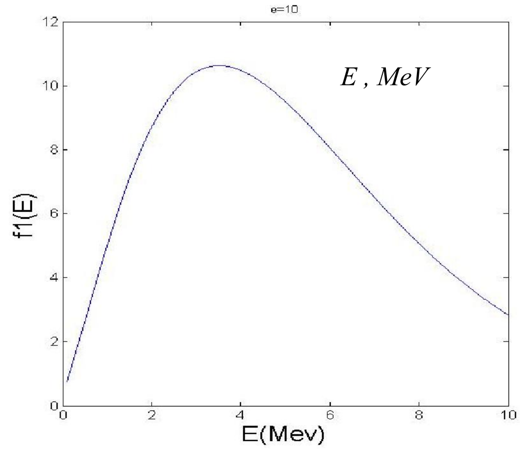
Terrestrial atmosphere is transparent for γ rays with energies higher than $1\ MeV$. Strong γ- bursts originate from higher troposphere have been registered by CGRO satellite (about 10 to 20 TGF_s , space telescope has also detected TGF_s). Neutron production phenomenon is also related to photonuclear (γ, n) reaction produced by runaway electrons. So, neutrons from photonuclear reaction are related to the lightning discharge.

The distribution function for the kinetic energy of runaway electrons is given by:

$$f(\varepsilon) = Ce^{\varepsilon/k_B T}\gamma\sqrt{\gamma^2 - 1}$$

Where $\gamma = 1 + \frac{\varepsilon}{m_0 c^2}$ is the relativistic factor and $k_B T \cong 2\ MeV$ is considered here. In Figs (1-a) and (1- b), the distribution function of runaway electrons are shown for energies from 2 and $10\ MeV$. One can see from these graphs that electron energy distribution function has a minimum around $3.5\ MeV$ which cannot be observed in fig (1-a) for $2MeV$ electrons.





Fig(1-a) *Fig(1-b)*

Fig.1. Representation of electron energy distribution function $f(E)$

The angular distribution of transmitted beam in the direction of the magnetic field line up to the fallout point is $F(\alpha)$ function designated by the conservation of particle's number:

$$F(\alpha) = \frac{N_{tot}}{4\pi B}\frac{B_{eq}Cos\alpha}{\sqrt{1-\frac{B_{eq}}{B}Sin\alpha}}$$

$$\frac{Sin\alpha}{Sin\alpha_{eq}} = \sqrt{\frac{B}{B_{eq}}}$$

Where α is the pitch angle, α_{eq} is the pitch angle in the magnetic equatorial. B_{eq} is terrestrial magnetic field intensity in the magnetic equatorial and N_{tot} is the total number of fallout electrons. In figure (2), $F(\alpha)$ is plotted for $\alpha_{eq} \cong 2-3^{\circ}$ and $B_{eq} \approx 0.311\ Gous$.

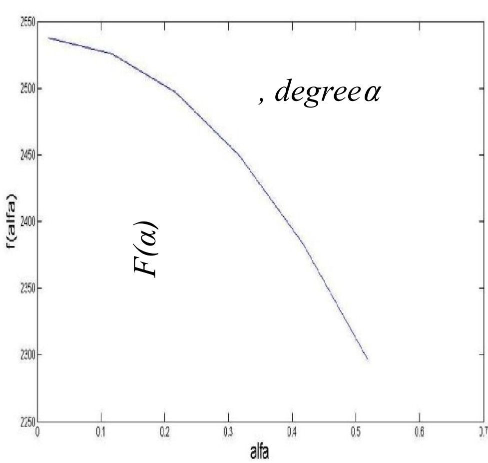


Fig.2. Representation of $F(\alpha)$ versus α

Since the Earth magnetic dipole field is expressed as function of the latitude by:

$$\frac{B}{B_{eq}} = \frac{\sqrt{1+3Sin^2\lambda}}{Cos^6\lambda}$$

The variation of $f(\lambda)$ with latitude is also calculated and plotted in figure (4).

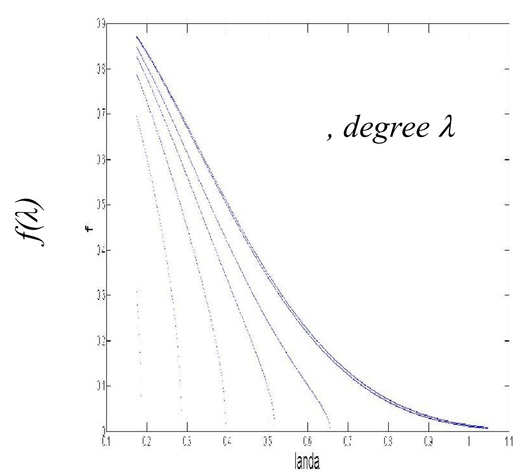


Fig.3. Representation of $f(\lambda)$ in function of λ

α is related to λ by:

$$\alpha = Sin^{-1}\left[\sqrt{\frac{B}{B_{eq}}\left\{1-[1-\chi_\alpha(1-\sqrt{1-\frac{B_{eq}}{B}})]^2\right\}}\right]$$

where α is the downward stochastic pitch angle, $\chi_\alpha = \frac{1-Cos\,\alpha_{eq}}{1-Cos\,\alpha_{eq}^{lc}}$ is the distribution function and $\alpha_{eq}^{lc} = Sin^{-1}\left[\sqrt{\frac{B_{eq}}{B}}\right]$ is the loss cone angle and $\frac{Sin\alpha}{Sin\alpha_{eq}} = \sqrt{\frac{B}{B_{eq}}}$ is the ratio between the local pitch angle in the fallout point and equatorial pitch angle. λ is taken in the range of 10 -60 magnetic degree. The variation of α with λ is given in figure (4).

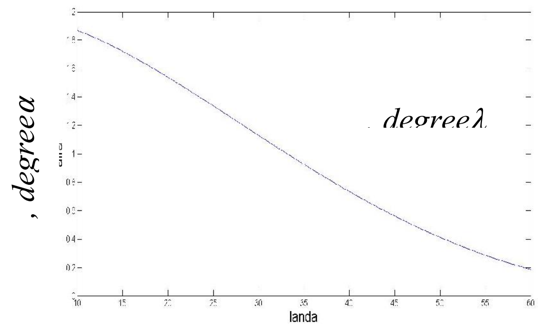


Fig.4. Variation of α versus λ

It is seen that the local pitch angle at fallout point decreases with the magnetic latitude λ. Energy dissipation of high energy electrons in a collisional gas resulting from excitation and ionization is characterized by dynamic friction $F_D(\varepsilon)$. Dynamic friction force presents a minimum for some values of energies and this friction force decreases for high energy electrons (Fig5).

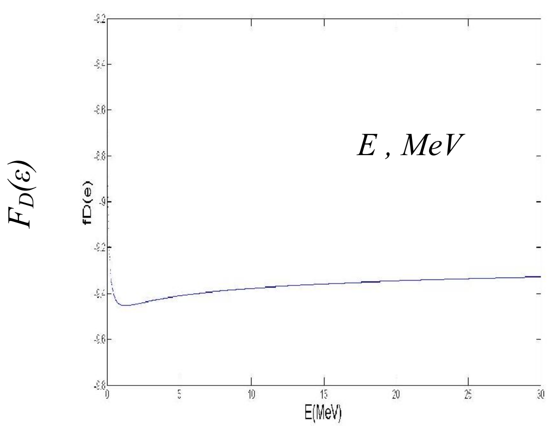


Fig.5. Variation of $F_D(E)$ in term of electrons energy

Electron beam radius is expanded due to the scattering diffusion and is given by:

$$r_b^2 = r_{b_0}^2 + \theta^2 \Delta z^2 + 0.025\frac{(1+0.22\ln\gamma)}{\beta^2\gamma^2}(\Delta z)^2 P(atm)$$

Where r_{b_0} is the beam initial radius, θ the scattering angle, $\beta = {}^{v}/_{c}$ and γ is the relativistic factor. Variation of beam radius with altitude is shown in Fig. (6, 7)

It is seen that the radius of electron beam is expanded up to a high of $30\ Km$ and then starts to decrease beyond that. It can be explained by the fact that because of electrons high energies, the scattering is increased up to a high of $30\ Km$, so the beam radius increases to this altitude, but due to the decrease of electron energies in higher altitudes and hence decrease in the density of scattering points, the scattering diffusion is reduced and the electron beam radius is also decreased. So, the number of runaway electrons (for the threshold electric field of runaway electrons avalanche E_{th}) is increased exponentially with distance.

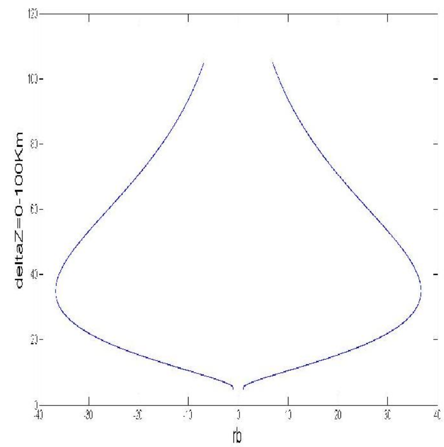


Fig.(6)

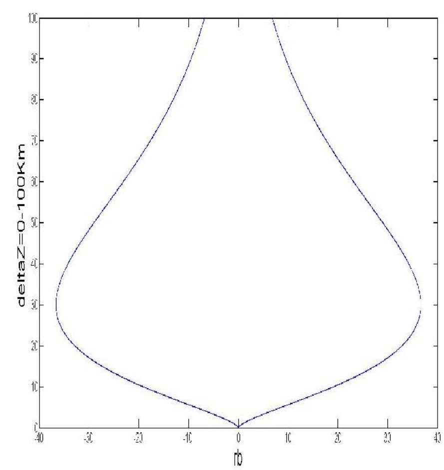


Fig.(7)

Fig. (6 and 7): diagrams showing the variation of runaway electrons beam's radius with the altitude from Earth surface.

In contrast with electrons, when the passage of positrons through a gas is considered, pair annihilation must occur. The total cross section for the annihilation is given by:

$$\sigma_{annih} = \frac{\pi r e^2}{\gamma+1}\left[\frac{(\gamma^2+4\gamma+1)}{(\gamma^2-1)}\ln\left(\gamma+\sqrt{\gamma^2-1}\right) - \frac{\gamma+3}{\sqrt{\gamma^2-1}}\right]$$

Where γ is Lorentz factor . The variation of this cross-section with energy is given in figure (8).

This curve shows that due to positron electron annihilation, in the case of positron passage through a gas, the total cross-section and hence the scattering is reduced.

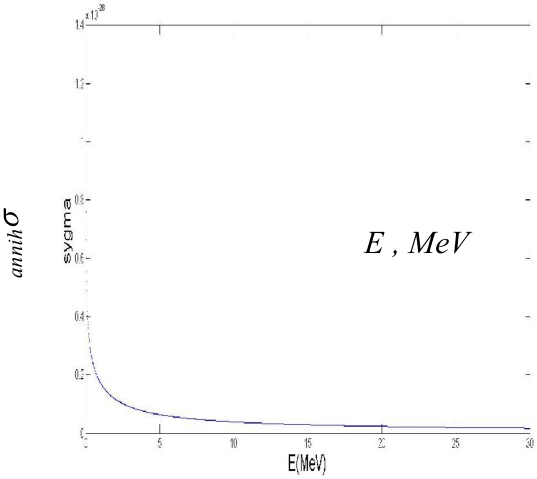


Fig.8. Variation of cross section of pair annihilation in term of energy.

3. Conclusion

In the electric fields beyond the threshold, the propagation of light columns grow exponentially. The potential difference depends directly to runaway electrons energies. Mont-Carlo simulation methods give an energy of about $100\ KeV$ to few MeV for runaway electrons. Optical emission from red sprites originates from energetic electrons. These electrons leave the Earth and reach the radiation belts. Electron beam falls out to the magnetically conjugate point in interaction with plasma waves and some of energetic electrons are trapped in the radiation belt. In the altitude higher than 5 times the earth radius, the fall out electrons are less studied. Whistler and electrostatic waves lead in these studies to energetic electrons acceleration. The mechanism for the terrestrial high energy gammas which give rise to X-ray production are investigated recently. The probability of interaction between runaway electrons and atomic particles is known as one of terrestrial γ flashes production mechanisms. Terrestrial γ ray flashes are produced during bremsstrahlung radiation. Electrons with energies about $1MeV$ produce γ ray along electron beam direction.

Energy distribution function for the relativistic electrons is plotted in figure (1). The angular distribution of electron beam passing along the magnetic line is also calculated and shown in the figure (2). $F(\alpha)$ function depends on the magnetic latitude and $f(\lambda)$ is shown in the figure (3). Here α is the pitch angle and λ is the magnetic latitude.

The variation of dynamic friction force with runaway electrons kinetic energy is given in figure(5) and the results are discussed.

Electron beam radius is expanded to $30\ Km$ altitude due to scattering diffusion, but beyond this it decreases with altitude. It seems that it takes a pancake form. Due to high energy of electrons up to $50\ Km$ altitudes, electron scattering is increased hence electron beam radius also increased. But due to the reduction in the energy of electrons in high altitudes and also reduces in the density, the scattering diffusion is reduced and electron beam radius decreases.

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