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γ-ray emission produced by a relativistic beam of runaway electrons accelerated by quasi-electrostatic thundercloud fields

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Abstract. In an experiment described by *Fishman et al.* [1994], high energy photons of atmospheric origin were detected by the Burst and Transient Source Experiment (BATSE) detectors, located on the Compton Gamma Ray Observatory (CGRO). In this paper we assess the possibility that the bursts may be bremsstrahlung produced by relativistic (>1 MeV) runaway electron beams accelerated in an avalanche process by quasi-electrostatic thundercloud fields. We consider the height-dependent density profile of the relativistic electrons specified as a function of time in the context of a previously reported runaway model [*Bell et al.*, 1995]. The electron beam is modeled as a vertical cylinder with radius 10 km, and numerical estimates are provided of γ-ray fluxes which would be observed at the satellite. The predicted fluxes at the satellite altitude and at horizontal distances of up to 500 km from the source are found to be comparable to the experimental data.

Introduction

Recent efforts to understand the luminosity produced by lightning in the mesosphere have focused on the effects of the quasi-electrostatic fields resulting from lightning discharges [e.g., *Pasko et al.*, 1995]. These electric fields can lead to runaway beams of relativistic electrons [*Bell et al*, 1995] whose collisions with atmospheric atoms produce γ-rays by bremsstrahlung. The γ-ray detectors on the Compton Gamma Ray Observatory (CGRO) have detected transient γ-ray bursts originating below the satellite [*Fishman et al.*, 1994]. Since these bursts are associated with thunderstorm centers and in a few cases have been correlated with individual lightning flashes [*Inan et al.*, 1996], they may be caused by the runaway electrons.

The possibility of runaway electrons emitting γ-rays above thunderstorms was first suggested by C. T. R. Wilson already in 1925 [*Wilson*, 1925]. However, the possibility of their avalanche was not considered. Calculations of the densities of runaway electrons have been made by *Roussel-Dupré and Gurevich* [1996] and by *Bell et al.* [1995] using somewhat different approaches. The model of *Bell et al.* [1995] used in this paper considers the quasi-electrostatic field emerging in a cloud-to-ground positive discharge (+CG), caused by the removal of a positive charge $Q = +275$ C from an altitude of 10 km above the ground, the corresponding negative charge $-Q$ being located at 5 km. The discharge takes place over a timescale ~ 1 ms, and the resultant peak cloud-to-ground current and total charge transferred is comparable to those measured for a positive discharge on a $\sim$5% probability level [*Uman*, 1987, p. 124]. As shown by *Bell et al.* [1995], changing the timescale of the charge removal has almost no effect on the avalanche timescale. On the other hand the model of *Roussel-Dupré and Gurevich* [1996] considers an intracloud (IC) discharge caused by removing a dipole consisting of a charge of +100 C at 18 km and −100 C at 5 km, over a timescale of $\sim$ 10 ms. Also, the conductivity of the atmosphere was calculated in different ways in the two models. The model of *Roussel-Dupré and Gurevich* [1996] makes use of the height-dependent ambient conductivity, while the model of *Bell et al.* [1995] also takes into account the modification of atmospheric conductivity by runaway electrons and the self-consistent effects of this modification on the electron avalanche. Using the electron density and energy spectra from their beam calculations *Roussel-Dupré and Gurevich* [1996] have calculated the γ-ray flux and spectrum above the atmosphere and found significant fluxes at satellite altitudes (see also [*Taranenko and Roussel-Dupré*, 1996]).

The purpose of the present paper is to present the γ-ray fluxes expected from the runaway model of *Bell et al.* [1995] and to compare these fluxes with the CGRO observations. Since relativistic electrons produce bremsstrahlung which is strongly peaked in the forward direction, one expects a highly directed flux of γ-rays which might be very intense but would be unlikely to intersect a satellite with significant horizontal displacement from the thundercloud. Hence, the angular spread of the emitted γ-rays is a crucial factor in determining whether the satellite measurements can be explained by bremsstrahlung production by runaway electrons.

Model Description

We model the runaway electrons as a pencil-like vertical electron beam (Figure 1a). The electric field is assumed to be vertical and directed downward. The beam radius of 10 km (consistent with sprite observations, see [e.g., *Bell et al.*, 1995] and references therein]) is small compared to the distance to the spacecraft and therefore we neglect horizontal (radial) distribution variations of the electron beam density. The electron energy and pitch-angle distribution (see Figure 2) is based on the runaway model of *Roussel-Dupré et al.* [1994]. We used the self-similar (constant in time) distribution calculated by *Roussel-Dupré et al.* [1994] for a homogeneous external field E and ratio $\delta_o = E/E_t = 8$, where E_t is the critical runaway field, e.g. [*Roussel-Dupré et*

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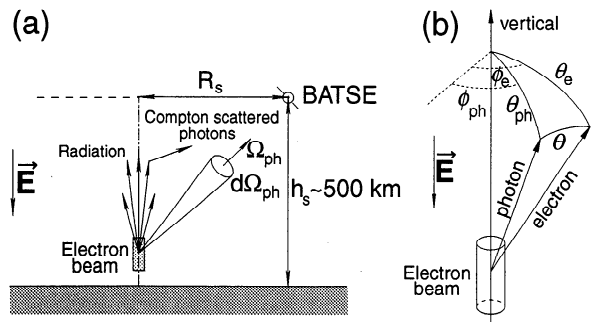

Figure 1. The configuration of the problem: (a) geometry of electron beam and satellite position; (b) definitions of electron and photon momenta.

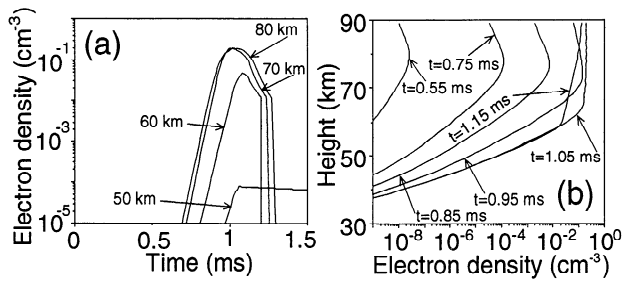

Figure 3. The electron density in the runaway beam [*Bell et al.*, 1995]: (a) at different altitudes; (b) at different moments in time.

al., 1994]. The effects of the geomagnetic field $\vec{B}$ are not considered, assuming that the magnetic field is vertical and does not influence the electron distribution. In the case of a slightly inclined magnetic field one should take the axis of the beam parallel to $\vec{B}$ and use the electric field component along $\vec{B}$. The relatively broad angular distribution indicated in Figure 2 is due to scattering of the electrons in the beam by atmospheric atoms. The height-dependent density profile of the relativistic electrons for the initial thundercloud charge $Q = 275$ C is specified as a function of time in the previously reported runaway model [*Bell et al.*, 1995] and is plotted in Figure 3. The value of δ_o used is based on the value of the electric field expected following a lightning discharge and was calculated as part of this model. In this model the field exceeds the threshold electric field E_t at altitudes > 25 km, and δ_o grows with height, with $\delta_o > 8$ for heights > 50 km. In the model of *Roussel-Dupré and Gurevich* [1996], the emerging dipole field exceeds the threshold electric field E_t in two different height regions of the atmosphere (δ_o has a minimum at $\sim$ 40 km). The electric field in the thundercloud region (where the first maximum of δ_o was obtained) was assumed by *Roussel-Dupré and Gurevich* [1996] to be a free-space field of dipole charges. However, in the [*Bell et al.*, 1995] model the magnitude of the post-discharge electric field at a distance from the thundercloud comparable with the characteristic scale of atmospheric conductivity (i.e. 6–11 km) is substantially lower than in the free-space case (e.g., Figure 2b in [*Bell et al.*, 1995]) and generally does not show any maximum of δ_o in the region of the thundercloud, in contrast to results of *Roussel-Dupré and Gurevich* [1996].

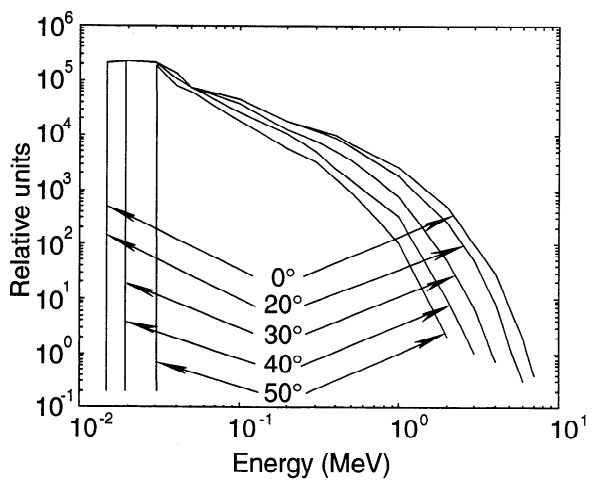

Figure 2. The electron energy distributions for different electron angles θ_e [*Roussel-Dupré et al.*, 1994].

Bremsstrahlung process. In this subsection we calculate the bremsstrahlung of relativistic electrons scattered by the nuclei of atmospheric nitrogen and oxygen.

The doubly differential cross-section for bremsstrahlung is the cross-section of the bremsstrahlung production into a unit solid angle and a unit photon energy interval. For the nucleus charges $Z = 7$ (nitrogen) and $Z = 8$ (oxygen) and for electron initial and final kinetic energies $\mathcal{E}_e - mc^2, \mathcal{E}'_e - mc^2 \sim 1$ MeV we can use the Born approximation. For the angle of bremsstrahlung θ and the photon energy $\mathcal{E}_{ph}$ the doubly differential cross-section can be written as:

$$\frac{\partial^2 \chi}{\partial \mathcal{E}_{ph} \partial \Omega} = \Phi(\theta) \frac{\partial \chi}{\partial \mathcal{E}_{ph}}$$

Here (see Figure 1b) θ is the angle between the velocities of the incident electron and the emitted photon; $d\Omega$ is an elementary solid angle in the photon momenta space; $\partial\chi/\partial\mathcal{E}_{ph}$ is the radiation cross-section for producing a photon of energy $\mathcal{E}_{ph}$ into unit interval of $\mathcal{E}_{ph}$, integrated over all directions of the produced photon momentum; $\Phi(\theta)$ characterizes the angular distribution of bremsstrahlung. The function $\Phi(\theta)$ is normalized for convenience ($\int_{4\pi} \Phi(\theta)\, d\Omega = 1$). For relativistic electrons $\Phi(\theta)$ falls off fast for large θ, therefore the bremsstrahlung is forward-directed. The angle of bremsstrahlung θ can be found if the directions of the photon $\Omega_{ph}(\theta_{ph}, \phi_{ph})$ and the electron momenta $\Omega_e(\theta_e, \phi_e)$ are given:

$$\cos\theta = \sin\theta_e \sin\theta_{ph} \cos(\phi_e - \phi_{ph}) + \cos\theta_e \cos\theta_{ph}.$$

In the above equation θ_e is the angle between the velocity of an electron and the vertical, θ_{ph} is the angle between the radiated photon and the vertical, and ϕ_{ph} is the corresponding azimuthal angle (see Figure 1b). The expressions for $\partial\chi/\partial\mathcal{E}_{ph}$ can be found in [*Heitler*, 1954, p. 245] and for $\Phi(\theta)$ in [*Jackson* 1975, p. 705]; see also [*Roussel-Dupré et al.*, 1994].

The specific emissivity (the number of photons radiated by a unit volume per unit solid angle of photon momenta per unit photon energy interval per second) is then given by:

$$\epsilon(\vec{r}, \mathcal{E}_{ph}, \theta_{ph}) = \int d\mathcal{E}_e d\Omega_e f_e(\vec{r}, \mathcal{E}_e, \Omega_e) v_e \Phi(\theta)$$
$$\times\{2N_{N_2}\frac{\partial\chi_N}{\partial\mathcal{E}_{ph}} + 2N_{O_2}\frac{\partial\chi_O}{\partial\mathcal{E}_{ph}}\},$$

where $\vec{r}$ is the radius-vector of the source (the electron-nucleus system), f_e is the electron distribution function, v_e is the initial electron velocity, N_{N_2} and N_{O_2} are atmospheric molecular densities of nitrogen and oxygen respectively (the density of other elements is negligible). The numerical calculations show that the specific emissivity has its maximum at the altitudes of 60–70 km. Its decrease at lower altitudes is explained by the decrease in electron density in the beam and at higher altitudes by the decrease in the atmospheric density. The specific emissivity, integrated over Ω_{ph} and the BATSE photon energy intervals (the photon production rate), is plotted in Figure 4.

Radiation attenuation. Radiation is attenuated due to Compton scattering and the photoelectric effect (photon absorption). Other processes (such as pair production) do not contribute for the photon energy ranges of interest ($\mathcal{E}_{ph} < 1$ MeV) [*Hubbell*, 1969; *Price et al.*, 1954, p. 22].

The attenuation of a flux of photons with given energy is expressed by the following relation between the photon flux at the detector in the absence of scattering and absorption I_0 and the flux in their presence I:

$$I = I_0 b e^{-\tau},$$

where τ is the optical depth, or shield thickness [*Price et al.*, 1954, p. 45], b is the build-up factor ($b \geq 1$), which takes into account the photons scattered into the detector.

The optical depth τ is obtained by integrating the linear "narrow beam" attenuation coefficient μ over the radiation ray path from $\vec{r}$ to $\vec{r}_{det}$:

$$\tau = \int_{\vec{r}}^{\vec{r}_{det}} \mu(\mathcal{E}_{ph}, \vec{r}\,')d\vec{r}\,'$$

In our case, the linear attenuation coefficient μ has the value:

$$\mu(\mathcal{E}_{ph}, \vec{r}\,') = 2N_{N_2}(\vec{r}\,')\sigma_N^{tot}(\mathcal{E}_{ph}) + 2N_{O_2}(\vec{r}\,')\sigma_O^{tot}(\mathcal{E}_{ph}).$$

The linear attenuation coefficient is a function of spatial coordinates (through $N_{N_2}(\vec{r}\,')$ and $N_{O_2}(\vec{r}\,')$) and the photon energy $\mathcal{E}_{ph}$.

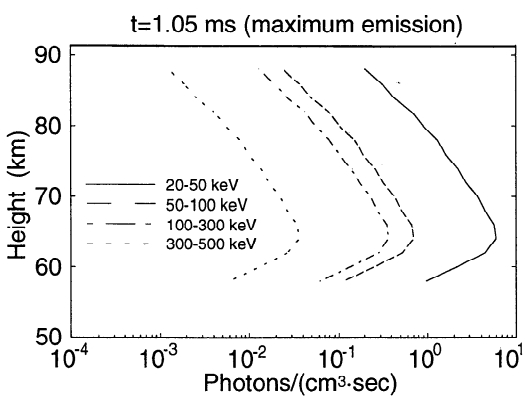

Figure 4. The photon production rate at different heights in different BATSE energy ranges at the time when the photon emission is at maximum (the initial thundercloud charge $Q = +275$ C).

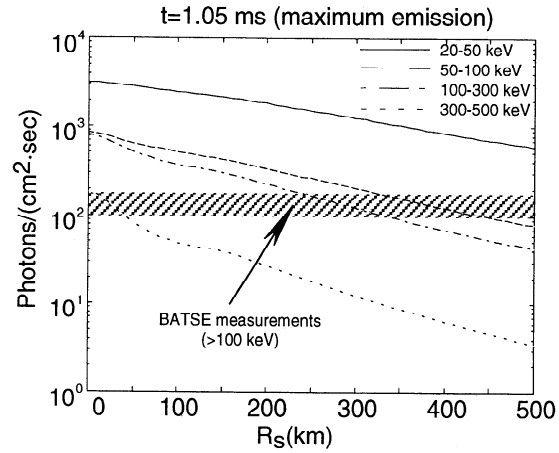

Figure 5. The photon flux at the satellite altitude (h_s =500 km) (integrated over the BATSE energy ranges) as a function of horizontal distance from the satellite to the beam at the time when the photon emission is at maximum (the initial thundercloud charge $Q = +275$ C).

The total photon cross-section for the photon energy ranges of interest can be written as:

$$\sigma^{tot} = \sigma^{ph} + \sigma^c,$$

where σ^{ph} is the photoelectric cross-section, and the Compton cross-section

$$\sigma^c = \int_{\mathcal{E}'_{ph,min}}^{\mathcal{E}_{ph}} \frac{\partial\sigma^c}{\partial\mathcal{E}'_{ph}} d\mathcal{E}'_{ph}$$

is integrated over final photon energies $\mathcal{E}'_{ph}$. The Compton scattering cross-section is given by the Klein-Nishina formula [e.g., *Heitler*, 1954, p. 217].

At the heights 60–70 km, where the specific emissivity is at its maximum, the optical depth for photon energies 20–500 keV in the vertical direction is less than 10^{-2}. Therefore, the contribution of scattered photons is negligible, because if the effects of scattering and absorption are small, the fractional contribution of scattered photons to the detected radiation, compared to those not scattered, is less than $\frac{I_0 - I}{I_0} \approx \tau$, assuming $\tau \ll 1$. To confirm this result, the flux of once-scattered photons was calculated for the simple case of runaway electrons without angular spread ($\theta_e \equiv 0$). Since the bremsstrahlung radiation is maximum along the electron velocity ($\theta = 0$), we assume that the primary photons also move vertically. To calculate the flux of secondary photons one has to take into account that the energy of the Compton scattered photon differs from that of the incident one and depends on the angle of the scattering [*Heitler*, 1954, p. 211]. The resultant secondary photon flux at all angles is found to comprise less than 0.2% of the non-scattered photon flux.

Comparison of Model and Predictions with the Data

The eight BATSE detectors on the CGRO satellite have a sensitive area of about 2000 cm^2 each. The recording of time-tagged events (TTE), is activated by a trigger system and consists of the arrival times for up to 32,000 individual photons with a resolution of 2 μs [*Fishman et al.*, 1994]. The experiment makes use of four photon energy channels: 20–50 keV, 50–100

keV, 100–300 keV and > 300 keV. The bursts reported by *Fishman et al.* [1994] lie in the 3rd channel (100–300 keV) and have durations of the order of 1 ms and peak counting rates of the order of 10–30 counts/0.1 ms, which agrees with the duration of the electron beam calculated by *Bell et al.* [1995] and consequently with the duration of the bremsstrahlung radiation burst. The detection efficiency of the BATSE instrument is of the order of 30% [*G. Fishman*, private communication].

Figure 5 shows the predicted γ-ray fluxes at height of 500 km as a function of horizontal range R_s from the beam location for the model parameters discussed in the introduction ($Q = +275$ C). The flux values observed by BATSE (the experimental data) are shown by the hatched area on the figure. It can be seen that a good match between model predictions and observations occurs when the horizontal range is ~300 km. The radiation is beamed, particularly for the higher energy photons and decreases very rapidly with greater satellite distances R_s.

We have also calculated the predicted γ-ray fluxes assuming that all the runaway electrons are moving vertically ($\theta_e = 0$). This configuration results in larger fluxes in the vertical direction, but a more rapid fall off of the fluxes with horizontal range. Thus, the spread of radiation in the first case (Figure 5) is mostly due to the spread of the electron velocities over angles. The γ-ray beam cannot be broadened appreciably by Compton scattering since the atmosphere at altitudes 60–70 km, where most of the radiation is produced, is practically transparent for the photon energies detectable by BATSE.

The calculations were repeated for various initial thundercloud charges Q. The photon fluence (flux integrated over the time of the burst) as a function of the initial thundercloud charge is plotted in Figure 6. One can see that the photon production decreases very rapidly with decreasing source charge and for the [*Bell et al.*, 1995] thundercloud charge configuration and conductivity model used here is undetectable by BATSE for $Q < 250$ C.

Summary and Conclusions

In this paper we have calculated the bremsstrahlung γ-ray fluxes that would be associated with a beam of relativistic electrons accelerated in an avalanche process by quasi-electrostatic thundercloud fields.

The calculated γ-ray fluxes and the duration of the bursts are comparable to those measured by the BATSE detectors on the Compton Gamma-Ray observatory when the satellite is in the vicinity (horizontal range of ≤ 300 km) of the discharge. If the distance is greater, the γ-rays are unlikely to be seen from the satellite. Also, a significant thundercloud charge (> 250 C) must be brought to ground to produce observable fluxes.

We conclude that the major features of the BATSE γ-ray observations can be explained as bremsstrahlung produced by MeV runaway electrons in thunderstorm quasistatic electric fields.

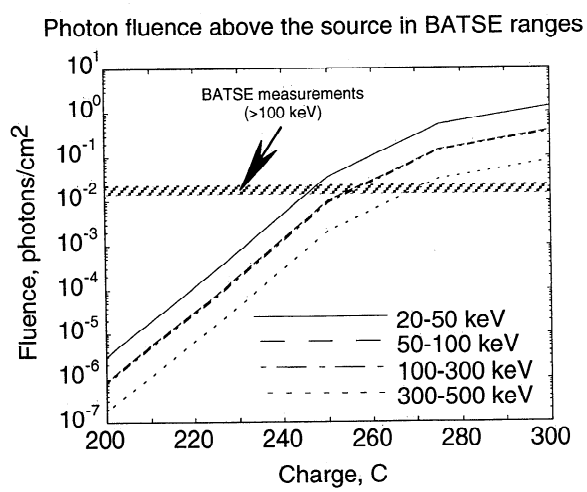

Figure 6. The photon fluence (flux integrated over time in the impulse) as a function of the initial thundercloud charge, calculated for BATSE energy ranges at the point exactly above the source.

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