29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Terrestrial γ-ray flashes: A confluence of cosmic ray showers and thunderstorms

A. Surjalal Sharma, Gennady M. Milikh, Parvez N. Guzdar
University of Maryland, College Park, Maryland, U.S.A.
Presenter: A. S. Sharma (ssh@umd.edu), usa-sharma-AS-abs1-sh36-oral

Terrestrial γ-ray flashes are correlated with thunderstorms, which provide the energy for accelerating electrons to high energies. The cosmic ray showers during thunderstorms provide the seed electrons necessary for a runaway discharge in the thunderstorm electric field. These electrons in the presence of the electric fields, at the 10 - 15 km height, lead to a the runaway discharge in which whistler waves are excited and form channels by a self-focusing instability. The accelerated electrons propagate in these channels to 30 - 35 km altitude and generate γ-rays which can be observed by spacecraft-borne detectors.

1. Introduction

Terrestrial γ-ray flashes (TGF) were detected first by BATSE aboard the Compton Gamma Ray Observatory (CGRO) [1]. Recently more detailed observations, including the energy spectrum, of TGF have been made by the Reuven Ramaty High energy Solar Spectroscopic Imager (RHESSI) [2]. The Lower Power Atmospheric Compensation Experiment (LACE) satellite located at a low-Earth orbit orbit [3] have made extensive observations over a wide range of geographic latitudes (from -43^o to +43^o) and have shown enhanced TGF when flying over regions of high thunderstorm activity, as well as local time and seasonal variations.

The γ-ray flashes are associated with MeV electrons and their occurrence is closely linked with thunderstorms. However the thunderstorm fields are at about 10 km height and the γ-rays generated there can not escape from the atmosphere and be detected by spacecraft-borne detectors. A novel mechanism for the propagation of the relativistic electrons to altitudes of about 30 km, from where the γ-rays can be detected, is the interaction of the energetic electrons with intense whistler waves [4].

There are three essential elements in the generation of TGF:

1. Cosmic ray showers that yield a seed population of relativistic electrons
2. Confluence with thunderstorms whose electric fields produce a runaway discharge
3. Intense whistler waves that generate channels or ducts for the propagation of the relativistic electrons to higher altitudes

In the presence of the large electric field of thunderstorms the energetic electrons produced in an extensive air shower lead to an avalanche through the mechanism of runaway discharge [5]. This phenomenon arises due to the nature of electron scattering cross-section which decreases for higher energies, thus making the cosmic ray secondary electrons a suitable seed population for generating a runaway discharge [5]. The runaway discharge then produces a plasma in which the whistler waves are excited by the energetic electrons [6]. Whistlers are produced abundantly during thunderstorms and the coupling to the relativistic electrons of the runaway discharge can excite a self-focusing instability which leads to the formation of ducts in which the energetic electrons propagate to higher altitudes. These electrons then generate γ-rays that can be detected by spacecraft-borne detectors.

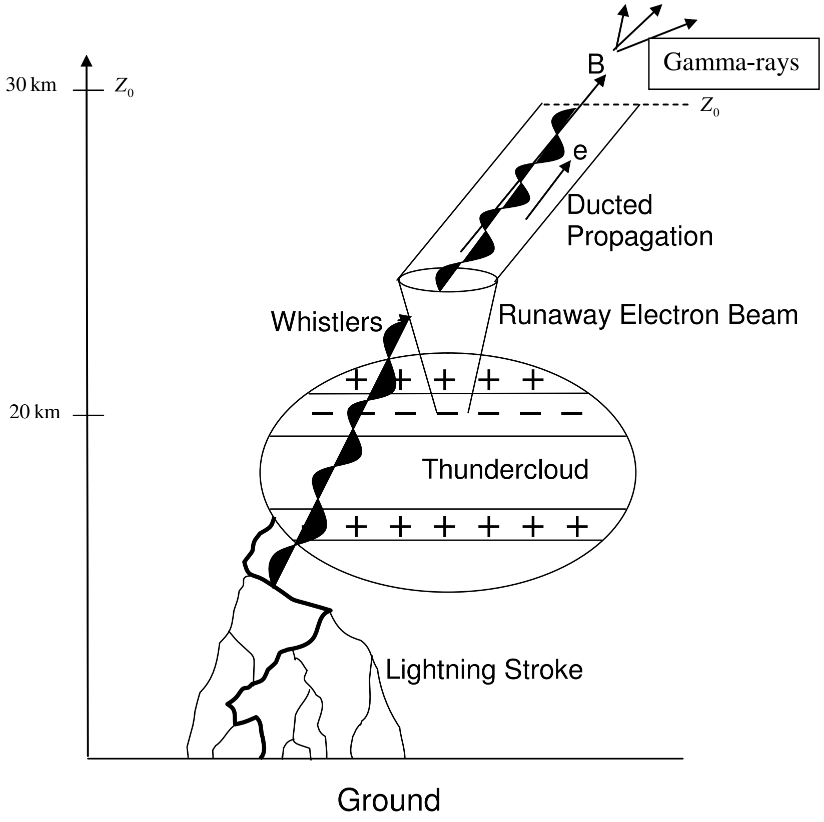

Figure 1. Generation of γ-rays by relativistic electrons from a runaway discharge during thunderstorms. Cosmic ray showers provide the seed electrons for a runaway discharge and the relativistic electrons propagate to altitudes of 30 - 35 km in ducts formed by whistler waves. The γ-rays produced by bremsstrahlung at these altitudes can be detected by spacecraft-borne instruments. The observations by CGRO, RHESSI and LACE spacecraft and ground-based systems show a strong correlation between the γ-ray flashes and thunderstorms.

2. Runaway Discharge and Ducted Propagation of Electrons due to Whistler Waves

The underlying concept of a runaway discharge in the atmosphere is the same as that of the well known runaway electron acceleration in a plasma in the presence of a laminar electric field. The scattering cross-section of electrons in a plasma due to Coulomb interactions decreases with velocity as $\sigma \sim v^{-4}$ and consequently for a given electric field there is a threshold energy beyond which the dynamic friction can not balance the acceleration due to the electric field, and this results in continuous electron acceleration. In the atmosphere where the electron-neutral collisions dominate this runaway process is not important for the typically low energy electrons. However for electrons with energy in excess of the ionization energies, the interaction with the nuclei and atomic electrons are governed by the Coulomb cross sections. The runaway acceleration of a seed population of electrons with energy in excess of tens of keV in a strong electric field leads to ionization and consequent acceleration, leading to a runaway discharge [5]. Such a population of energetic population of electrons are often present in the atmosphere as secondaries generated by cosmic rays [7] and in the presence of thunderstorm electric fields a runaway discharge can be sustained.

The whistler waves have another important effect on the electrons in the form of a ponderomotive force. The strong concentration of the large amplitude whistler waves results in an equivalent pressure on scales longer than the characteristic wave lengths. The gradient of this pressure, known as the ponderomotive force, then contribute to the further energization of the electrons. Simulations of the electron acceleration in the presence of the ponderomotive force has shown that for typical parameters of thunderstorms the electric field required to maintain a runaway discharge is reduced by as much as a third [8].

During lightning discharges whistler waves are produced as a part of the accompanying electromagnetic pulse (EMP). The sustenance of these whistler waves requires a number of critical factors [6]. These waves are the normal modes of a magnetized plasma with frequencies less than the electron cyclotron waves. Considering a plasma consisting of hot or energetic electrons of the runaway discharge and cold electrons produced by the ionization, the characteristic properties of a whistler instability in the atmosphere have been studied [6]. The source of energy for the instability is the beam-like nature of the relativistic electrons relative to the cold electrons and is a negative enrgy instability. The typical energy of the hot electrons produced by a runaway discharge is 1.2 Mev, which corresponds to the minimum frictional force in the atmosphere. The ionization energy in the atmosphere in typically 35 eV so that the upper limit of the ratio of the cold to hot electrons is 3.4×10^4. The typical energy of cold electrons produced by electron impact ionization is 0.6 - 1.0 eV. With these and other relevant parameters of the magnetized plasma in the atmosphere, the peak growth rate of the whistler is found to be 6×10^{-3} of the electron cyclotron frequency, or 3×10^4 rad/s.

The parameters of the ducts formed by the whistlers can be obtained from a detailed study of the nonlinear evolution of the whistler waves. Such a study will necessarily be a numerical simulation considering the wide range of variability in the relevant parameters. However reasonable estimates of these can be made from the results of the linear theory of the whistler waves [6]. Such estimates yield ducts with scale size of 10 km with a time scale of 100μs. These estimates agree with the observations of TGF by CGRO/BATSE.

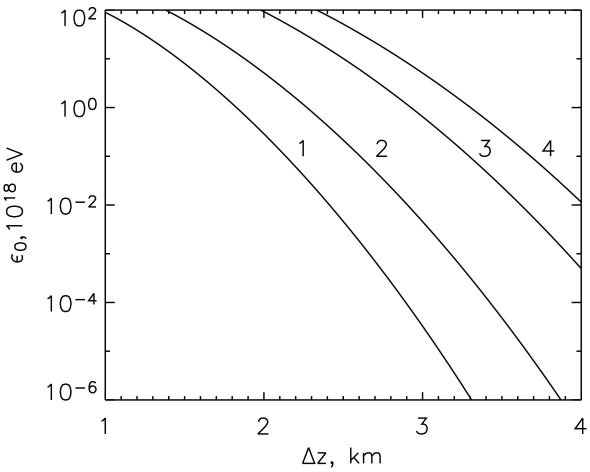

Figure 2. Energy of primary cosmic ray particle needed to generate the number density of runaway electrons of 10 cm^{-3} as a function of distance Δz. Traces 1-4 correspond to δ = 2.5, 2.0, 1.5, and 1.3, respectively. The parameter δ is the ratio of the electric field of the thunderstorm to the critical field for a runaway process to be initiated.

The secondary electrons from a cosmic ray shower, being the seed population for the runaway discharge, play a crucial role in the current model of TGF. The energy of the primary cosmic ray needed to generate enough secondaries can be estimated using the characteristics of thunderstorm fields and of the atmosphere at the relevant heights. Initially an electron beam (the cosmic ray secondaries) starts at a given height and propagates upward in the electric field with a value above the threshold for a runaway process. The number of runaway electrons multiply in a distance Δz at a rate determined by the avalanche length [6]. As the runaway electrons propagate they spread in volume, although the ducting by the whistler waves limits this. With these considerations the energy of the primary cosmic ray can be estimated as a function of the electric field as well as the distance the beam propagates [6]. These dependences are shown in Figure 2 for the case of an electron density of 10 cm^{-3}.

The bursts of radio noise (”sferic”) observed during lightning and correlated with CGRO observations of TGF [9] is an indication of the role of whistler waves in these phenomena. This correlation can be studied using ground based radio detectors in conjunction with satellite observations. Runaway discharge plays an important role in the production of transient luminous events in the atmosphere, such as red sprites and blue jets [10]. The radio waves, in particular whistler waves, in the lightning related phenomena are well known and a better understanding of their role is expected to lead to a deeper understanding of these phenomena.

3. Conclusions

The γ-ray flashes originating from the Earth’s atmosphere has its origins in a confluence of many physical processes. The cosmic ray showers provide the seed population of relativistic electrons to initiate a runaway discharge in the presence of thunderstorm electric fields. The electrons in the discharge excite whistler waves to large amplitudes, which then form ducts in which the relativistic electrons propagate to 30 - 35 km. altitudes. The γ-rays produced at these altitudes are then observed by spacecraft-borne detectors.

4. Acknowledgements

The research is supported by National Science Foundation grant ATM-0317261.

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