INCORPORATING THE ELECTROMAGNETIC FIELD IN THE EGS5 CODE

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Abstract

In recent years, radiation bursts called terrestrial gamma-ray flashes (TGFs) have been observed over thunderclouds by X- and γ-ray observation satellites. Accordingly, a set of modules designed to analyze the effects of electrons on the thundercloud electric field and global electric fields was developed, and the subroutine ELECTR was modified. These modules and the modified subroutine were then incorporated into the EGS5 code. Furthermore, in the EGS5 the density of substances was set for each computational region, but the code was modified to allow the density to be changed continuously by simulating the global atmosphere. The magnetic field was compared with the user code UCBEND and it was confirmed to agree well.

1. Introduction

In order to analyze the behavior of charged particles in thunderclouds, subroutines and a user code have been developed to analyze the effects of the external electric field with the PRESTA-CG [1,2]. To apply these new developments in the EGS5 code [3] and shed light on the mechanism of TGFs observed over thunderclouds [4,5], the code was extended to analyze the effects of the external magnetic field. To encompass the upper atmosphere from the vicinity of the ground to the altitude of 400 km, it is necessary to analyze the intensity and direction of the electromagnetic field that continuously changes with altitude and the behavior of electrons and photons in the space with atmospheric density that varies by 12 orders of magnitude. We have therefore decided to compute a reaction by determining the electromagnetic field and the atmospheric density at the reaction point of each particle.

Although the aim is to analyze the behavior of electrons and photons in the electromagnetic field in the air, we developed a highly versatile computer code by incorporating the CG method into the EGS5 code as with the PRESTA-CG so that it can analyze the behavior of electrons and photons in an arbitrary geometry and in an arbitrary electromagnetic field. This report outlines this newly developed code.

2. The Procedure to Incorporate the Electromagnetic Field into the EGS5 Code

The procedure to incorporate the capabilities to evaluate continuous changes in atmospheric density and evaluate electric and magnetic fields into the EGS5 code is described below. Basic equations for the effects of electric and magnetic fields are formulated with reference to Bielajew's method [6]:

(1) Basic equations for the electric and magnetic fields;

① The equation to calculate the direction vector

$$\vec{u}_f = \vec{u}_0 + \triangle\vec{u}_{ms,\ ret} + \triangle\vec{u}_{em}$$

$$\triangle \vec{u}_{em} = \frac{e\,s}{m_0\,\gamma(E_0)\,v_0^{\,2}}\left(\vec{D}_0 - \vec{u}_0\,(\vec{u}_0 \cdot \vec{D}_0) + \vec{v}_0 \times \vec{H}_0\right)$$

② The equation to calculate the particle position

$$\vec{x}_f = \vec{x}_0 + \vec{u}_0\,s + \frac{s}{2}\left(\triangle \vec{u}_{ms,\ ret} + \triangle \vec{u}_{em}\right)$$

③ The equation to calculate the final energy

$$E_f = E_0 - \triangle E_{ret} + e\,\vec{D}_0 \cdot (\vec{x}_f - \vec{x}_0)$$

$\vec{u}_f$	: The new direction vector	$\vec{u}_0$	: The initial direction vector
$\triangle \vec{u}_{ms,\ ret}$	: The deflection due to multiple scattering and inelastic collisions		
$\triangle \vec{u}_{em}$	: The deflection due to external electromagnetic filed		
e	: The charge of the particle	s	: The step length
$\vec{D}_0$	: The macroscopic electric field strength	m_0	: The mass
$\vec{H}_0$	: The macroscopic magnetic field strength		
$\gamma(E_0)$	: $(1-\vec{\beta}\cdot\vec{\beta})^{-1/2}$		
$\vec{v}_0$	: The initial velocity		
$\vec{\beta}$	: $\vec{v}/c$		
$\vec{v}$	: The velocity	c	: The velocity of photon
$\vec{x}_f$	: The new particle position	$\vec{x}_0$	: The initial particle position
E_f	: The new particle energy	E_0	: The initial particle energy
$\triangle E_{ret}$	: The energy loss due to inelastic collisions		

(2) An equation to evaluate the loci of electrons and positrons moving in a vacuum in the electric field

The effects of the electric field with the code were confirmed in comparison with the loci of electrons and positrons in a vacuum as expressed by the following equation:

$$x_{\parallel} = \frac{m_0 c^2 \gamma_0}{e E}\left(\cosh\left(\frac{eE x_{\perp}}{m_0 c^2 \gamma_0 \beta_{\perp 0}}\right) - 1 + \beta_{\parallel 0} \sinh\left(\frac{eE x_{\perp}}{m_0 c^2 \gamma_0 \beta_{\perp 0}}\right)\right)$$

The results of the comparison are shown in Fig.1.

(3) An equation to evaluate the loci of electrons and positrons moving in a vacuum with an electric field

Where, the effects of the magnetic field with the code were confirmed in comparison with the locus defined by the following equation:

$$x_{\perp 1} = \frac{p^0_{\perp 2}}{eB}\left(\left(1 - \cos\left(\frac{eBx_{\parallel}}{p^0_{\parallel}}\right)\right) + \frac{p^0_{\perp 1}}{eB}\sin\left(\frac{eBx_{\parallel}}{p^0_{\parallel}}\right)\right.$$

$$x_{\perp 2} = -\frac{p^0_{\perp 1}}{eB}\left(\left(1 - \cos\left(\frac{eBx_{\parallel}}{p^0_{\parallel}}\right)\right) + \frac{p^0_{\perp 2}}{eB}\sin\left(\frac{eBx_{\parallel}}{p^0_{\parallel}}\right)\right.$$

In these equations, $p^0_{\perp 1}$, $p^0_{\perp 2}$ and $p^0_{\parallel}$ are the initial values of momentum.

The results of the locus are shown in Fig.2.

(4) The module modified in association with the calculations of the electric and magnetic fields by inputs from a file

Related modules are shown below. Inputs are set by =EM_FILE:FILE and =BM_FILE:FILE:

egs/egs5_electr.f
include/user_cg/cghead.f
include/user_cg/emfield_common.f
user_cgcode/read_emfiled.f

(5) The module modified in order to meet continuous changes in atmospheric density

The EGS5 code sets the concentration of substances by computational regions, but the newly developed code is capable of continuously changing the atmospheric density.
Related modules are shown below. Inputs are provided by setting irhofg to -1 and designating the filename:

egs/egs5_electr.f
egs/egs5_photon.f
include/user_cg/cghead.f
include/user_cg/rhofield_common.f
user_cgcode/read_rhofiled.f
user_cgcode/rd90opt.f
user_cgcode/rdoptary.f
user_cgcode/rdoptcg.f
user_cgcode/rdoptrtz.f
user_cgcode/rdoptsph.f
user_cgcode/rdoptxyz.f

(6) Determining the length of particles moving in the subroutine ELECTR
The length of particles moving in the subroutine ELECTR is determined as follows.
In calculations designed to evaluate the effects of the electromagnetic field, the routines STPEME and STPBME were used to include the energy flight direction at the moving point of particles and errors in evaluation were restricted:

tstep=MIN(tmscat,tinel,thard)
①The multiple scattering length; ②The length to the energy change point; ③The length to the collision reaction point

ustep=tstep
 :
if (ustep.gt. dnear(np)) call howfar
 :
④ The length to the region boundary
 :
⑤ The moving length at which the maximum value of the electric field-caused energy variability becomes constant (STPEME)
 :
⑥ The moving length at which the maximum value of the magnetic field-caused angle variability becomes constant (STPBME)

The minimum value of these six lengths is set as the moving length of particles.

3. Examples of Calculations

(1) Irradiation of 100 MeV electrons from the altitude of 15 km
For the atmospheric density, data derived from the "U.S. Standard Atmosphere 1976" were used. For the electric field data, data calculated by the FEM code were used.

Fig.3 shows the results of calculations (the track) performed for energy irradiation with 100 MeV electrons from the altitude of 15 km.

(2) Comparative calculations under the UCBEND [3] conditions
Fig.4 shows a diagram of the track determined under the same conditions as those of the user code UBEND generally attached to the EGS5 code.

(3) The behavior of electrons at a medium latitude (in the vicinity of the Monju reactor)
The typical behavior of electrons at a medium latitude (in the vicinity of the Monju reactor) is shown in Fig.5.

4. Conclusion

(1) In order to analyze the TGF event, a set of modules designed to analyze the effects of electrons on the electric field of a thundercloud and the terrestrial magnetism was developed and the subroutine ELECTR was modified. These modules and the modified subroutine were then incorporated into the EGS5 code. The following results were obtained.
 ・The electric field: Results similar to those of the calculations performed by the theoretical equation (in a vacuum) and with the EGS4 were obtained.
 ・The magnetic field: Results similar to those obtained under the UCBEND conditions were obtained.
(2) In the EGS5 the density of substances was set for each computational region, but the code was modified to allow the density to be changed continuously by simulating the global atmosphere.
(3) Trial calculations were performed to analyze the effects of electrons on the thundercloud electric field and the terrestrial magnetism in winter thunderclouds in a medium altitude region (in the vicinity of the Monju reactor).

References

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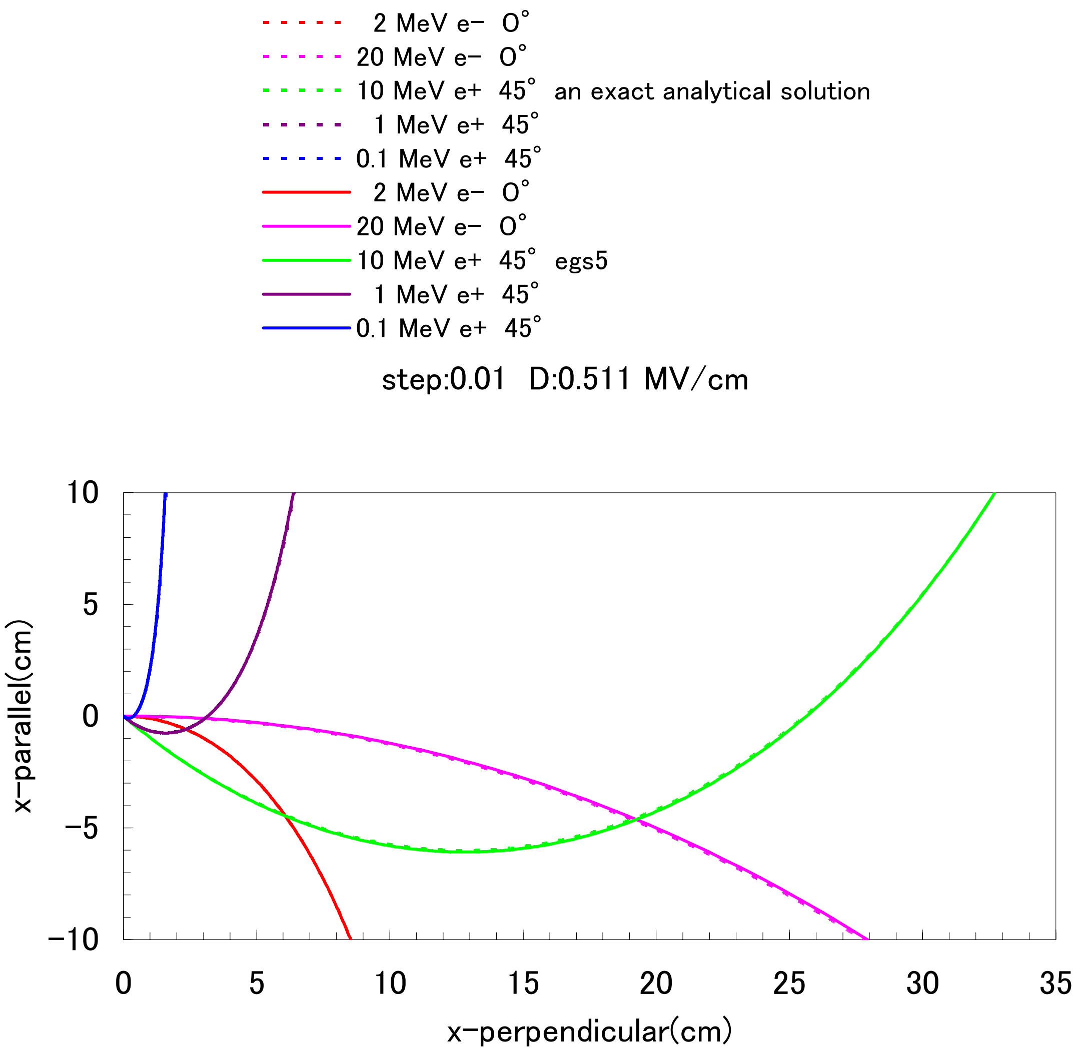

Fig.1 Electrons and Positrons Moving in the Vacuum with the Electric Field

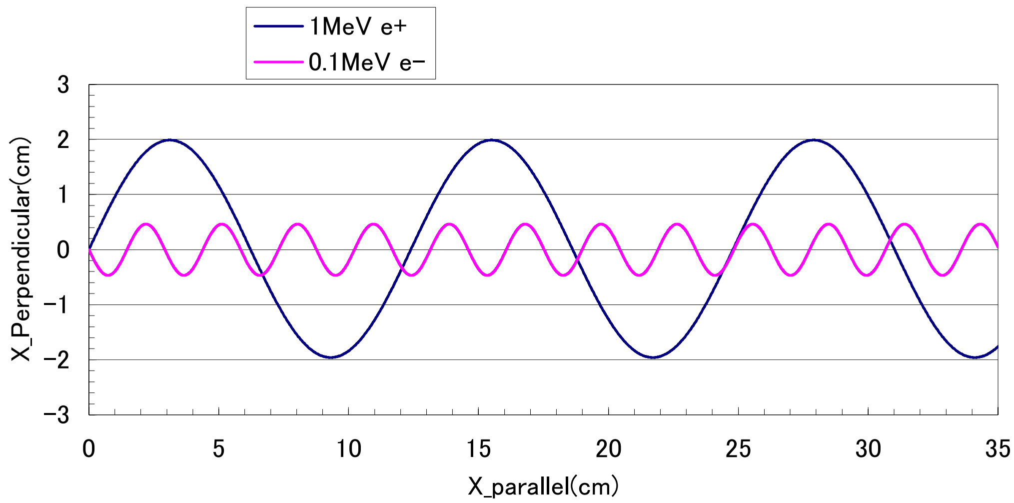

Fig.2 The Track of Charged Particles in 0.17 Tesla

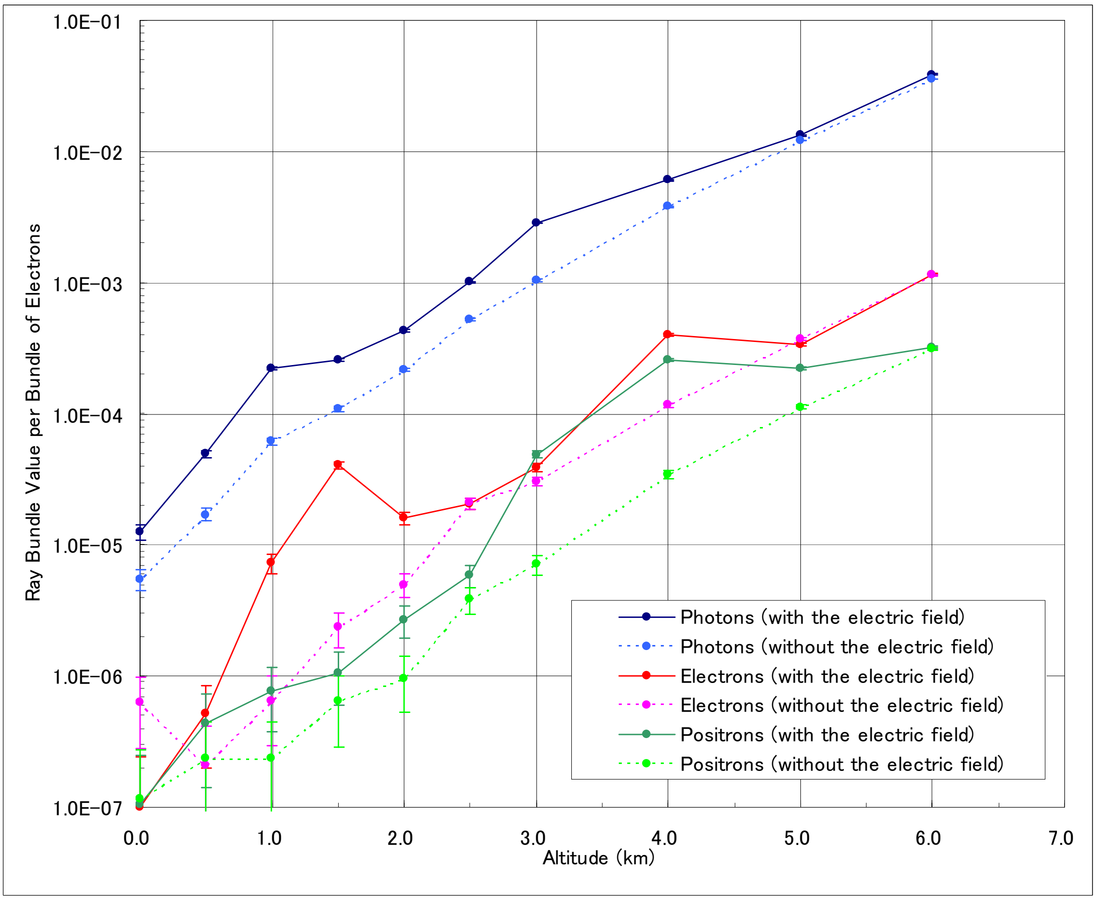

Fig.3. Data on Bundles of Rays when 100 MeV Electrons Are Emitted from the Altitude of 15 km (Comparison of the Electric Fields)
(estepe = 0.1; continuous changes in the electric field; continuous changes in atmospheric density)

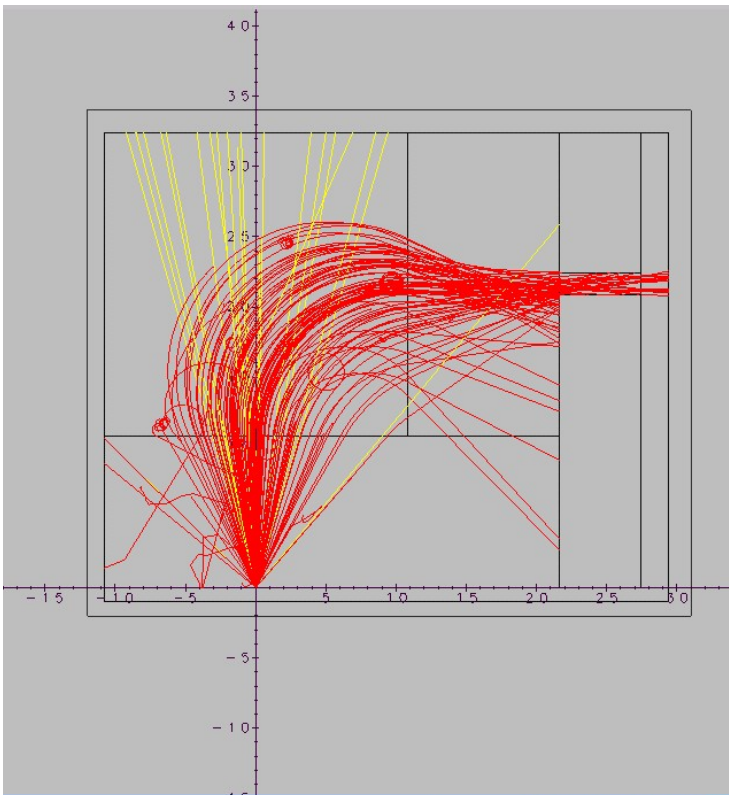

Fig.4 Calculations under the UCBEND Conditions

(8.5 MeV electrons were used to irradiate a copper plate of 0.381 mm; The intensity of the magnetic field in the Y-direction was 0.26 T.)

(Magnetic field region: X: -10.8–10.8 cm, Z: 10.8381–32.4381 cm)

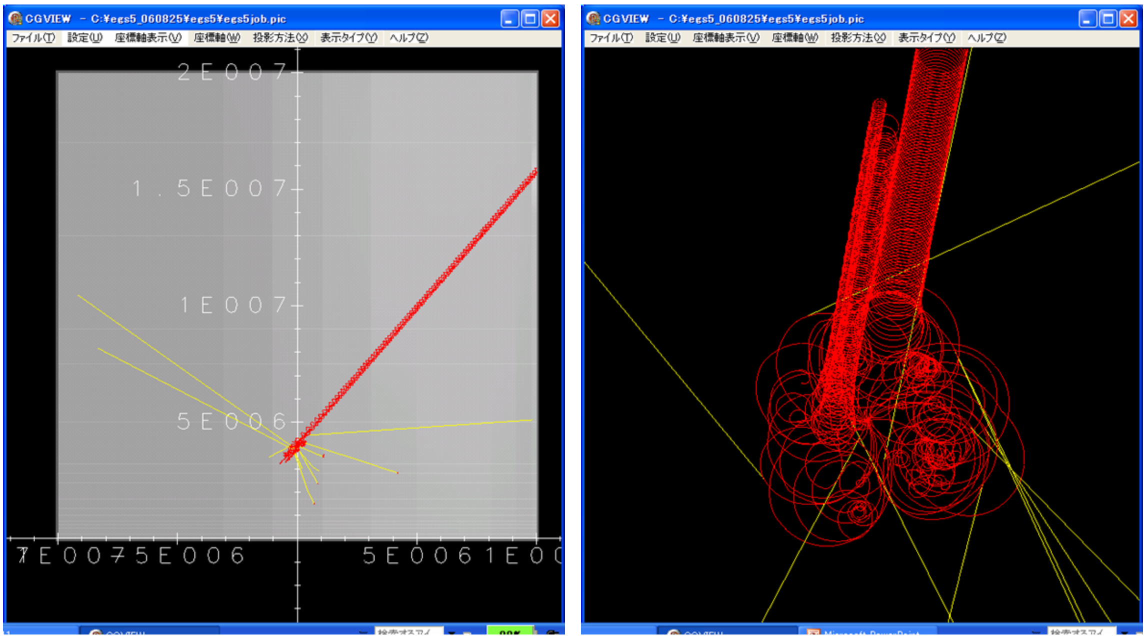

Fig.5 The Effects of Electrons on Terrestrial Magnetism at a Medium Latitude (around Tsuruga City)

(20 MeV electrons were emitted isotropically from a height of 40 km, 20 particles)