Astroparticle Physics 35 (2012) 733–741

Contents lists available at SciVerse ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Simulation of radio emission from cosmic ray air shower with SELFAS2

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ARTICLE INFO

Article history:
Received 29 April 2011
Received in revised form 9 February 2012
Accepted 22 March 2012
Available online 30 March 2012

Keywords:
Cosmic rays
Air shower
Radio emission
Radiation of moving charges

ABSTRACT

We present a microscopic computation of the radio emission from air showers initiated by ultra-high energy cosmic rays in the atmosphere. The strategy adopted is to compute each secondary particle contribution of the electromagnetic component and to construct the total signal at any location. SELFAS2 is a code which does not rely on air shower generators like AIRES or CORSIKA and it is based on the concept of air shower universality which makes it completely autonomous. Each positrons and electrons of the air shower are generated randomly following relevant distributions and tracking them along their travel in the atmosphere. We confirm in this paper earlier results that the radio emission is mainly due to the time derivative of the transverse current and the time derivative of the charge excess. The time derivative of the transverse current created by systematic deviations of charges in the geomagnetic field is usually dominant compared to the charge excess contribution except for the case of an air shower parallel to the geomagnetic field.

1. Introduction

In 1965, Jelley et al. [1] and Allan in 1971 [2] established that extensive air showers (EAS) induced by ultra high energy cosmic ray emit a brief radio emission in the range of few hundreds of MHz during its development in the atmosphere. In the last years, progress made in electronics have permitted the realization of extremely fast radio-detectors used in the CODALEMA [3], LOPES [4] and AERA [5] experiments. It is clear since [2,6,7] and recently [8,3] that the Lorentz force induced by the geomagnetic field acting on positrons and electrons of the shower is the dominant source of the EAS radio emission. The consequences of this effect are visible through a strong asymmetry in the counting rate as a function of arrival directions (see for instance [3,4,9]). Recent experimental analysis shows that the lateral profile of the electric field deposited by an EAS on the ground permits to give a good estimation of the primary energy [10,11].

In parallel to these experimental results, there are also various theoretical approaches, from simple fast semi-analytical models (see [12,13]) to more detailed models (see [14]). Initially based on the synchrotron radiation proposed by Falcke and Gorham [15], the electric field in REAS is now computed using the end point formalism [16] applied on each secondary electrons and positrons of the air shower. The total electric field at a given observation point is obtained summing all electric field contributions coming from the shower. The geometry of the shower (pancake thickness, lateral extension) is then taken into account. This characteristic appears to be important if we want to compute the electric field close to the shower axis. In MGMR [17,12], the total electric field is sourced by the global macroscopic transverse current due to the systematic deviation of electrons and positrons in the geomagnetic field. Maxwell equations are applied to this global current concentrated along the air shower axis, taking into consideration the thickness of the air shower pancake. Due to the secondary electrons excess during the air shower development (mainly due to positrons annihilation and knock-out electrons during the air shower development in the atmosphere), the residual negative charge variation induces a second contribution to the total EAS radio emission [14,18–20]. This second contribution (charge excess contribution) is not EAS arrival direction dependent while it is the case for the contribution due to systematic deviation of particles in the geomagnetic field (geomagnetic contribution). This characteristics implies that the fraction of charge excess contribution to the total EAS radio signal also depends on the arrival direction. In most cases, the geomagnetic contribution is dominant, but for arrival directions close to the magnetic field orientation, the Lorentz force due to the geomagnetic field vanishes and the charge excess contribution can become dominant in the total EAS radio signal.

Our approach is based on a microscopic description of the shower using the concept of "age" and "shower universality" first proposed in [21] to study the longitudinal development of purely electromagnetic showers. The use of the relevant distributions for EAS secondary electrons and positrons extracted from [22–24] (longitudinal profile, particle energy, vertical and horizontal momentum angle, lateral distance, and time distribution of the shower front), permits to avoid the heavy use of EAS generators to generate air showers in SELFAS2 and makes the simulation completely autonomous. Thanks

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0927-6505/$ - see front matter
http://dx.doi.org/10.1016/j.astropartphys.2012.03.007

to these distributions implemented in SELFAS2, no large simplifications are made on the characteristics of the electromagnetic shower component. The particles generated in SELFAS2 by Monte Carlo simulation, are tracked along their trajectory to compute their individual electric field contribution to the total electric field emitted by the air shower. With this approach, the characteristics of the evolutive spatial density of charge (emissive area) in the shower and the systematic drift of electrons and positrons due to the geomagnetic field are then naturally taken into account in SELFAS2.

In Section 2, we develop the formalism adopted in SELFAS2 to compute the electric field emitted by a single charge with a finite life time which undergoes an acceleration due to the presence of a magnetic field. We will describe the strategy adopted to sum correctly the contributions given by each particle during its existence in the air shower. In Section 3 we describe how the electromagnetic component EAS is generated to give to each particle initial conditions for their travel in the atmosphere. Section 4 is devoted to a discussion from a first example of a vertical 10^{17} eV air shower.

2. Theory: Maxwell equations for moving charges

2.1. Flash back on modelings

Historically, many modelings of EAS radio emission were based on the well known equation of the electric field emitted by a relativistic moving charge which undergoes an acceleration. This equation is obtained solving the Maxwell equation for a retarded time using retarded potential (see for example [25]). The resulting electric field of a charge moving with a velocity $\boldsymbol{\beta}$ in the lab frame is given by:

$$\boldsymbol{E}(\boldsymbol{x},t) = \frac{q}{4\pi\epsilon_0}\left[\frac{\boldsymbol{n}-\boldsymbol{\beta}}{\gamma^2(1-\boldsymbol{\beta}\cdot\boldsymbol{n})^3R^2}\right]_{ret} + \frac{q}{4\pi\epsilon_0 c}\left[\frac{\boldsymbol{n}\times\{(\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\}}{(1-\boldsymbol{\beta}\cdot\boldsymbol{n})^3R}\right]_{ret} \quad (1)$$

which is obtained at the observation point $\boldsymbol{x}$ at the time $t = t_{ret} + R(t_{ret})/c$ with $\boldsymbol{n} = (\boldsymbol{x} - \boldsymbol{r}(t_{ret}))/R(t_{ret})$ and $R = |\boldsymbol{x} - \boldsymbol{r}(t_{ret})|$. Two terms appears in this equation which correspond to a coulombian contribution for the first one and to a radiative contribution for the second one due to the acceleration $\dot{\boldsymbol{\beta}}$ of the source.

In many approaches ([13,26–29]), the total electric field generated by the EAS is obtained after summation of the individual electric field performed using Eq. (1) or simply replacing q in Eq. (1) by the global varying charge $Q(t)$ of the EAS. But, as it was recently discussed in [20] this way to describe the present problem is not correct because Eq. (1) is obtained for a charge q which is not time dependent. To overcome this problem, a solution has been proposed in [14,16]. The solution proposed in this paper and adopted in SELFAS2 is different.

2.2. Electric field of a point like source with a finite life time

Starting from Maxwell equations and using the wave equation for the scalar potential Φ and the vector potential $\boldsymbol{A}$ (see for instance [25]) we have:

$$\nabla^2\Phi - \frac{1}{c^2}\frac{\partial^2\Phi}{\partial^2 t} = -\frac{\rho}{\epsilon_0} \quad (2)$$

$$\nabla^2\boldsymbol{A} - \frac{1}{c^2}\frac{\partial^2\boldsymbol{A}}{\partial^2 t} = -\mu_0\boldsymbol{J} \quad (3)$$

where ρ is the charge and $\boldsymbol{J}$ the current densities. Using the expression of the electric field:

$$\boldsymbol{E} = -\boldsymbol{\nabla}\Phi - \frac{\partial\boldsymbol{A}}{\partial t} \quad (4)$$

we can express the electric field $\boldsymbol{E}$ as a function of the charge ρ and the current densities $\boldsymbol{J}$:

$$\nabla^2\boldsymbol{E} - \frac{1}{c^2}\frac{\partial^2\boldsymbol{E}}{\partial^2 t} = -\frac{1}{\epsilon_0}\left(-\boldsymbol{\nabla}\rho - \frac{1}{c^2}\frac{\partial\boldsymbol{J}}{\partial t}\right) \quad (5)$$

This differential equation can be solved using a retarded solution (Green function). It gives:

$$\boldsymbol{E}(\boldsymbol{x},t) = \frac{1}{4\pi\epsilon_0}\int d^3x'dt'\frac{1}{R}\left[-\boldsymbol{\nabla}'\rho - \frac{1}{c^2}\frac{\partial\boldsymbol{J}}{\partial t'}\right]_{\rm ret}\delta\left\{t' - \left(t - \frac{|\boldsymbol{x}-\boldsymbol{x}'|}{c}\right)\right\} \quad (6)$$

where we can define $\boldsymbol{R} = \boldsymbol{x} - \boldsymbol{x}'$ and $R = |\boldsymbol{R}|$ with $\boldsymbol{x}'$ the source position at the retarded time t' and $\boldsymbol{x}$ the observation point. Here, $\boldsymbol{\nabla}'$ and $\frac{\partial}{\partial t'}$ must be considered at retarded time. This remark is important, because it is also the case for the expression of the field in Eq. (4) which should be considered at the retarded time; the variable t in Eq. (4) is the time at the instant of emission. A particular treatment must be done in order to get $\boldsymbol{\nabla}$ and $\frac{\partial}{\partial t}$ out from the retarded brackets in order to obtain a final expression of $\boldsymbol{E}$ as a function of t and not t'. Due to the dependance of t' on $\boldsymbol{x}'$ given by the relation between t' and t:

$$t = t' + \frac{R}{c} = t' + \frac{|\boldsymbol{x}-\boldsymbol{x}'|}{c} \quad (7)$$

the expression $[\boldsymbol{\nabla}'\rho]_{\rm ret}$ can be transformed in (see [25]):

$$[\boldsymbol{\nabla}'\rho]_{\rm ret} = \boldsymbol{\nabla}'[\rho]_{\rm ret} - \frac{\boldsymbol{n}}{c}\left[\frac{\partial\rho}{\partial t'}\right]_{\rm ret} \quad (8)$$

where $\boldsymbol{n} = \boldsymbol{R}/R$ is the unit vector between the observation position and the source, oriented toward the observation position. Then Eq. (6) becomes:

$$\boldsymbol{E}(\boldsymbol{x},t) = \frac{1}{4\pi\epsilon_0}\int d^3x'dt'\left\{-\frac{1}{R}\boldsymbol{\nabla}'[\rho(\boldsymbol{x}',t')]_{\rm ret} + \frac{\boldsymbol{n}}{cR}\left[\frac{\partial\rho(\boldsymbol{x}',t')}{\partial t'}\right]_{\rm ret} - \frac{1}{c^2R}\left[\frac{\partial\boldsymbol{J}(\boldsymbol{x}',t')}{\partial t'}\right]_{\rm ret}\right\}\delta\left\{t' - \left(t - \frac{|\boldsymbol{x}-\boldsymbol{x}'|}{c}\right)\right\} \quad (9)$$

Using the fact that the charge distribution is spatially localized on a point, the first term in this expression can be rewritten:

$$\int d^3x'\frac{1}{R}\boldsymbol{\nabla}'[\rho(\boldsymbol{x}',t')]_{\rm ret} = -\int d^3x'\frac{\boldsymbol{n}}{R^2}[\rho(\boldsymbol{x}',t')]_{\rm ret} \quad (10)$$

We can finally express the electric field as:

$$\boldsymbol{E}(\boldsymbol{x},t) = \frac{1}{4\pi\epsilon_0}\int d^3x'dt'\left\{\frac{\boldsymbol{n}}{R^2}[\rho(\boldsymbol{x}',t')]_{\rm ret} + \frac{\boldsymbol{n}}{cR}\left[\frac{\partial\rho(\boldsymbol{x}',t')}{\partial t'}\right]_{\rm ret} - \frac{1}{c^2R}\left[\frac{\partial\boldsymbol{J}(\boldsymbol{x}',t')}{\partial t'}\right]_{\rm ret}\right\}\delta\left\{t' - \left(t - \frac{|\boldsymbol{x}-\boldsymbol{x}'|}{c}\right)\right\} \quad (11)$$

which is known as the Jefimenko's generalization of the coulomb law (see [25] fore more details). The idea is now to express this formula in the case of a moving particle with a finite life time. The expressions for the charge and the current are:

$$\rho(\boldsymbol{x}',t') = q[\theta(t'-t_1) - \theta(t'-t_2)]\delta^3(\boldsymbol{x}' - \boldsymbol{x}_0(t')) \quad (12)$$

$$\boldsymbol{J}(\boldsymbol{x}',t') = \rho(\boldsymbol{x}',t')\boldsymbol{v}(t') \quad (13)$$

where the retarded instant t_1 corresponds to the creation of the moving charge (particle) by sudden acceleration from the state of rest to v and where the retarded instant t_2 corresponds to the cancellation of the charge by sudden deceleration from v to the state of rest.

Injecting Eqs. (12) and (13) in Eq. (11) and using the fact that R does not explicitly depends on t we perform the integrations over space and time. We obtain: