Nuclear Instruments and Methods in Physics Research A 662 (2012) S80–S84

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Coherent radiation from extensive air showers

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ARTICLE INFO

Available online 16 December 2010

Keywords:
Radio detection
Air showers
Cosmic rays
Geo-magnetic
Coherent radio emission

ABSTRACT

The generic properties of the emission of coherent radiation from a moving charge distribution are discussed. The general structure of the charge and current distributions in an extensive air shower are derived. These are subsequently used to develop a very intuitive picture for the properties of the emitted radio pulse. Using this picture can be seen that the structure of the pulse is a direct reflection of the shower profile. At higher frequencies the emission is suppressed because the wavelength is shorter than the important length scale in the shower. It is shown that radio emission can be used to distinguish proton- and iron-induced air showers.

1. Introduction

In recent years the field of radio detection of cosmic ray air showers has reached a mature stage which is shown by the many contributions to this meeting on the topic of radio emission. Consensus is approaching on the theoretical description [1] of the emission process and a detailed quantitative understanding of the experimental results [2,3] is close although some challenges remain [4]. Extensive arrays of radio detectors are operating such as LOPES [6] and CODALEMA [5] or installation is in progress such as at the Pierre Auger Observatory [7], at LOFAR [8], and at the South pole [9]. In this work the importance of coherent radio emission from air showers will be stressed where the most important emission mechanisms were already investigated in the earliest works on this subject [10–13], namely Cherenkov and geo-magnetic radiation. A complete historical review is given in Ref. [14].

Coherent emission occurs when the emitting charges are confined to distances Λ which are smaller than the wavelength λ. Since the source is 'viewed' with a resolution of the wavelength, a fine substructure in the source will not affect the emission process. At a much shorter wavelength, $\lambda \ll \Lambda$, the different parts of the fine structure in the charge distribution will contribute to the emission process with varying phases which as often result in constructive as in destructive interference with as result that the net emission probability is strongly suppressed. In an EAS initiated by a cosmic ray of 10^{18} eV the number of charged particles at the shower maximum is of the order of $N=10^8$ and coherent radiation, where the intensity is proportional to N^2, is far more intense that incoherent radiation where the intensity is proportional to N. Only at high frequencies, where the coherent process is suppressed because the wavelength is much smaller than the relevant size of the emitting charge distribution, the incoherent process can contribute. For coherent emission thus only the macroscopic structures in the EAS contribute.

At high frequency the coherence condition $\Lambda < \lambda$ will no longer be satisfied implying a cut-off of the coherent response. Some of the length scales that are important for EAS emission [15] are (i) the pancake thickness; (ii) the length of the EAS projected along the line of sight; (iii) the lateral distribution of the charges in the EAS. The high-frequency cut-off is reflected in the time between the start and the zero crossing of the pulse. The task of models is to indicate what the physics is that determines the important length scale. The advantage of the macroscopic model is that it clearly indicates these.

Model independent conclusions can also be drawn at large wavelength. The intensity of the emitted radiation of a system of charges decreases linearly with increasing wavelength when the latter is considerably larger than the size of the emitting body. An EAS, independent how enormous the event may be, always exists for a limited time and occurs in a limited part of the atmosphere and currents are confined to a limited region of space-time. As a consequence the intensity of the emitted radio waves should vanish linearly in the limit of infinite wavelength or zero frequency. The time integral of the emitted pulse should vanish implying equally large positive and negative amplitudes. The simplest structure of a pulse is thus bi-polar and unipolar pulses are un physical [15].

For a correct description it is important to have a consistent description of the charges and their motion. Consistent in this respect means that all charges are accounted for and thus charge conservation holds. Charges may move and be suddenly accelerated (through a collision) but no net charge can be created. For example, if an electron is accelerated in a Compton scattering process, a positively charged ion should remain behind. Once the consistent description is obtained of the distribution of the charges and their velocities, resulting in a four-current density $j^{\mu}(\vec{r},t)$, the emitted radiation is straightforward to calculate by applying the Maxwell equations with the current density as input. As mentioned, for coherent emission only densities averaged over

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doi:10.1016/j.nima.2010.11.125

an appropriately chosen length scale matter where one should be careful to account for *all* charges and currents in the system to obey charge conservation. Due to the necessary averaging over the path of many individual electrons a very simple picture emerges for the emission process which lies at the basis of the Macroscopic GeoMagnetic Radiation (MGMR) model [16,17].

In Section 2 the essential current distributions for a generic EAS are derived which form the basis for the (semi) analytic predictions for the structure of the radio pulse in the MGMR model [16,17]. As an application we show, using a hybrid approach where the parameters of the MGMR model are extracted from a Monte-Carlo simulation of the air-shower, that the radio emission can be used to distinguish proton- and iron-induced showers [4].

2. The macroscopic model for geo-magnetic radiation

The pancake at the front of an EAS is a plasma with large amounts of electrons, positrons and other particles moving towards the surface of the Earth with a velocity almost equal to the light velocity. Electron–positron pairs are constantly created in the center of the shower, mainly by the energetic photons in the shower core, to form the pancake, depicted by the broad band in Fig. 1. The shower front, as it is driven by photons, moves towards the Earth with the light velocity while the produced particles trail some distance behind the front and are responsible for the finite thickness of the pancake. A net electric current is induced in the pancake because of the Earth's magnetic field induces a Lorentz force pulling the electrons and positrons in opposite direction. Because of the constant interactions with the air molecules the leptons (electrons and positrons) reach a constant drift velocity v_d as corroborated by Monte-Carlo shower calculations [4]. In Fig. 1 the drifting electrons and positrons are denoted by the chequered arrows. The motion of the electrons and the positrons thus contribute coherently to a net electric current density in the direction indicated by the red arrow. Due to the constant interaction with the ambient air molecules the leptons will loose energy and trail further behind the shower front and become non-relativistic. In the figure these leptons are denoted as 'stopped'. On average the electrons and positrons are separated by a distance D_S. The fact that this happens can also be seen as a consequence of charge conservation, the electric current must induce a displacement of net charge from one side of the shower core to the other. One consequence of the induced current density may not be directly obvious. As the electrons and positrons move in opposite directions there is already a net displacement of charges that move with relativistic velocities. Their displacement is about half of the stopped charges, $D_M \approx D_S/2$. This completes the qualitative picture of the charges and currents that are induced by the geo-magnetic field. For the following discussion it is instructive to distinguish the different components which must be present in any realistic shower simulation.

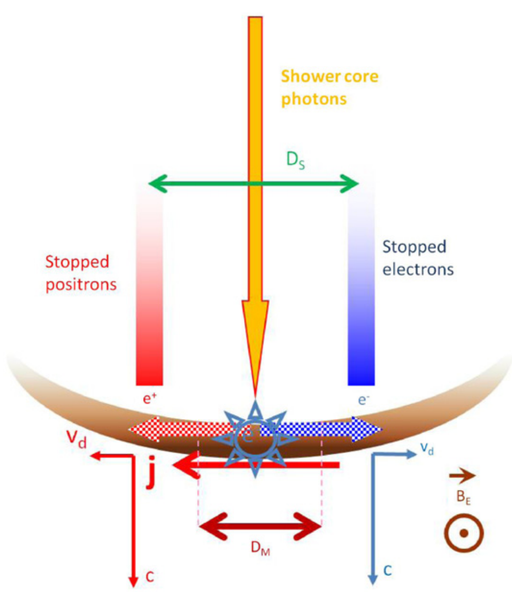

Fig. 1. Schematic description of the current densities in an Extensive Air Shower [16]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In addition to the current and charge densities of geo-magnetic origin there is also an induced charge that is independent of the magnetic field. Through the process of Compton scattering on electrons in air molecules and electron knock-out reactions by the relativistic electrons a net excess of relativistic electrons is created in the pancake. Simulations indicate that this excess can be large, about 30% of the total lepton density [4] and this is indicated in Fig. 1 by the star in the shower core. The net negative charge excess implies that there must also be a positive charge in the system, which is formed by positively charged air molecules. Even though these positive charges are at rest, they contribute to the radiation field since their number increases as the shower develops, but are not marked in Fig. 1 for simplicity.

To obtain better insight in the emission mechanism we will use the picture of the currents described in Fig. 1, realizing that all charges are concentrated very near the shower axis. As is discussed in detail in Refs. [16,17] this results in a picture where the geo-magnetic electric current becomes point-like at the shower axis and the charge separation of the relativistic leptons is taken into account as an electric dipole moving at a relativistic speed. The stopped particles are similarly accounted for by an electric dipole that is at rest in the Earth frame but constantly increasing in magnitude as the shower front proceeds to the surface of the Earth. As shown [16,17], the induced electric current and the net charge excess give the dominant contribution to the emitted radiation.

To obtain an analytic expression for the pulse due to the geo-magnetic current the thickness of the pancake is assumed to be small [16] and we adopt a simple geometry with a vertical shower and a horizontal magnetic field. The number of electrons and positrons in the shower at a height $z=-ct_r$ is parameterized as $N(z)=N_e f_t(t_r)$ in terms of the normalized shower profile, $f_t(t_r)$, where N_e is the number of electrons in the shower at the maximum. The induced geo-magnetic current in the $\hat{x}-$direction is

$$j(x,y,z,t)=\langle v_d q\rangle eN_e f_t(t_r). \tag{1}$$

In the simple picture the drift velocity is assumed to be independent on the height in the atmosphere. In the limit where the shower moves with the light velocity and the index of refraction of air equals unity, the retarded time t_r can be expressed in terms of the observer time t as

$$ct_r \approx -\frac{d^2}{2ct}. \tag{2}$$

The observer is at a distance d from the core and t is time after the shower hits the surface of the Earth. Eq. (2) shows that the early part of the received pulse is emitted at large (and negative) retarded times and thus large heights while the late part of the pulse is emitted when the EAS was already close to the round.

The only non-vanishing component of the vector potential is in the direction of the electric current:

$$A^x(t,d)=J\frac{f_t(t_r)}{\mathcal{D}} \tag{3}$$

where $J=\langle v_d q\rangle N_e e/4\pi\varepsilon_0 c$ is a constant depending on the energy of the cosmic ray and $\mathcal{D}$ is the retarded distance. The electric field is