Monte Carlo Modelling of Radio Emission from Extensive Air Showers

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Abstract

Extensive air showers are expected to produce radio waves over a wide frequency range. While calculations have been performed in simplified models, and many of the relevant mechanisms elucidated, their relative importance remains a matter of debate. We update previous work and present a novel and computationally efficient approach to the calculation of radio emission from air showers using data from shower simulation programs. Approximations are well under control and effects of various factors such as magnetic fields and details of interaction modelling can be studied in a straightforward manner. We discuss the experimental implications of such analyses.

1 Introduction

It has long been known that radio pulses should be expected from extensive air shower arrays. The first observation of such pulses was made by Jelley and collaborators in 1964 (Jelly *et al.*, 1965). While these pulses were the focus of much attention, both theoretical and experimental in the the 1960's and 1970's (for an excellent review of the early work there is surely none better than that of Allan (Allan, 1971)) interest the field was been scant in recent years. While we briefly review the status of the field in the next section, we make no attempt at being complete and refer the interested reader to that review for many more references.

Among the problems encountered has been the uncertain nature of the origin of the radio emission, and to date a variety of models have been studied, all neglecting various effects, and, of necessity, making various approximations whose validity may be questionable. In this paper we discuss a new strategy for re-examining these questions using Monte Carlo techniques.

2 Radiation Mechanisms

A high energy cosmic ray primary is typically assumed to be a proton or iron nucleus, carrying a rather small charge within a small volume. During its interaction with the atmosphere, charge is of course conserved, with the total charge of an air shower always equal to that of the primary which initiated it. Nevertheless, a shower of 10^{20} eV may produce some 10^{10} charged particles, each a source of an electric field, and there is the possibility that separation of charges in the distribution may give rise to a significant emission of radio-frequency energy.

There are several mechanisms of charge separation, summarised most clearly by Allan (*op. cit.*) on whom we rely heavily in the following, and who, following the work of Kahn and Lerche (1966) lists the following:

1. radiation through charge excess
2. radiation through geomagnetically induced electric dipole moment
3. radiation through a geomagnetically induced transverse current

The first item, charge excess, refers to the fact that there is a tendency for the shower to have more positive charge at the top due to loss of electrons from positron annihilation, Compton recoil, and δ-ray emission leading to an overall electric dipole moment forming in the the vertical direction for a vertical shower. The second two refer to the action of the earth's magnetic field to separate charges of opposite sign in the transverse direction leading to the formation of both a dipole and a current perpendicular to the vertical. In each case there is a dipole formed which varies both in time and in space. Some distinguishing power between these sources is provided by the different polarisations of their emissions.

The relative importance of these contributions has been a matter of some debate in the literature and a variety of perspectives exist on the process including viewing the radiation as due to a dipole moving faster than light would in the atmosphere whose index of refraction is greater than one. The calculations of Kahn and Lerche, as well as later ones of Lerche (1967), Castagnoli (1969), and Fuji and Nishimura (1969) all show preference, to varying degrees, for the dominance of the transverse current mechanism. These analyses all neglect the longitudinal development of the shower. A more refined model of Colgate (1967) relaxes this assumption, but is still not a complete treatment.

Other factors which have been considered include bremsstrahlung and the effect of atmospheric electric field gradients, with estimates that these may be of importance comparable to the geomagnetic field. Even the question of whether near (falling as $1/r^2$) or far (falling as $1/r$) field effects dominate is a matter of debate.

Another important point which is also poorly understood is the power spectrum expected of signals from large air showers. Colgate (*op. cit.*) finds much of the energy to lie between 2 MHz and 50 MHz, but the details of the spectrum are still an open question. Many experiments have been performed measuring radio pulses associated to air showers in this frequency range and beyond, and for a review we again refer the interested reader to Alan (*op. cit.*).

3 Monte Carlo Simulations – Problems and Solutions

Some time ago, we proposed a brute-force algorithm to calculate radio emission (Dova *et al.*, 1997), but its practical application met with technical difficulties and led to the development of a new approach which significantly reduces earlier problems.

3.1 The Old "Textbook" Approach The idea is quite straightforward: a shower can be viewed as nothing more than a set of charges (whose number may change due to creation and annihilation processes) which varies in space and time but nonetheless can be described as a 4-current j^μ whose time-like component is the charge density ρ and whose space-like components are the current density $\vec{J}$.

At first sight, the natural way to calculate radio emission is to simply calculate the source terms (ρ and $\vec{J}$) and use the usual formalism of Lienard-Wiechert (Jackson, 1975 or Epele *et al.*, 1996) potentials (including, of course, the index of refraction of the atmosphere in the retardation) to calculate the electric field they produce. This met with several problems which we summarize as follows:

A shower of modest volume 1 km^3, say, cut into small volumes of $1cm^3$ requires 10^{15} volume elements. Clearly then we need, assuming four bytes of real data to represent each of the components of the 4-current, 1.6×10^{16} bytes of data – clearly a completely unmanageable data volume.

Fine granularity is essential if one is to be able to handle coherence and interference effects over length scales (here, $1cm$). Attempts to consider larger volumes essentially prevent any useful statements being made for wavelengths shorter than the length scale associated to each volume element. In addition to the computational problems of handling (storing and processing) large amounts of data, there is also the problem of localization of charge and current elements within each volume, where one might wish for even more data.

However, showers are routinely generated, stored, and analyzed (*i.e.* the AIRES program (Sciutto, 1997)) , so the problem is clearly one of representation and processing of the data. After some reflection on the problem, it becomes clear that the problem arises because of thinking of the problem from the point of view of someone sitting at a receiver, adding up contributions due to the elements of the source.

3.2 A New and More Efficient Approach A more efficient approach has been developed since our earlier work which is based on two essential points:

- One does better to follow the physics not from the point of view of a distant observer with a radio receiver, but repeatedly from the point of view of each particle in the shower.
- There is no need to calculate averaged charge densities and currents in small volume elements – each particle can be view as a delta function charge density $\rho = q\delta(\vec{r})$ for a charge q at location $\vec{r}$, and with an

associated current density $\rho\vec{v}$. In other words, knowing the charge, location, and velocity of each particle is sufficient.

The new algorithm then is as follows. Select a number of observation points p_i located at positions. Let these points label histograms which will contain the components of A^μ as binned functions of time. (In other words, each observation point has 4 histograms associated to it, each of which contains, say, N bins indexing time from some $t = 0$ to some maximum time T.)

- **For each particle in the shower:**
  - **For each observation point:**
    - Find out when the particle in the shower will be joined to the observation point by a light ray.
    - **For each of the four components of the potential:**
      - Increment the corresponding bin with the appropriate retarded potential, which is straightforward to calculate and involves no integration, since taking each particle as having a delta function location make the Lienard-Wiechert integral trivial.

      End of loop over components of potential

    End of loop over observation points

  End of loop over particles in shower

At the end of the calculation, each particle in the shower record will have been visited once and made its contribution for all times to all four components of A^μ at each of the observation points. Now if the observation points are chosen at points $(x \pm \delta x, y \pm \delta y, z \pm \delta z)$ where δx, δy, and δz are small, discrete approximations to spatial derivates can be taken. Together with time derivatives which are immediate from the histograms which essentially give $A^\mu(t)$ for each point, this is sufficient to calculate $\vec{E}(t)$ and $\vec{B}(t)$ at each of the x, y, z points.

This technique is efficient both in CPU power, and in storage space. With $\vec{E}(t)$ and $\vec{B}(t)$ it is straightforward to calculate any physical (gauge invariant) quantity, such as voltage at an antenna, the Poynting vector, or, via a Fourier transform, the power spectrum. This information is also rather important as it may suggest ways to distinguish interesting shower signals from natural (*i.e.* atmospheric electrical activity) and man-made (*i.e.* commercial radio) background sources.

There are only three significant approximations, and they are all controllable in the sense that their effects can be estimated by changing them and observing the effects: 1) errors due to thinning, which may be significant since effects of coherence can be lost, 2) errors due to discretization of the shower representation (*i.e.* modelling the shower as a series of discrete layers as in AIRES (*op. cit.*)), and 3) errors due to binning and discretization of derivatives to calculate $\vec{E}$ and $\vec{B}$.

Many questions which are difficult to answer analytically are directly susceptible to numerical attack, and studies such as the following are straightforward:

- Setting the e^+e^- annihilation cross section, or Compton cross section to zero – checks the significance of these processes for the development of the vertical dipole moment.
- Setting the Earth's magnetic field to zero – checks the importance of that charge separation mechanism.
- Including the effect of a vertical atmospheric electric field.
- Fitting the dependence of $|\vec{E}|$ with distance to compare near and far-field components.
- Throwing away charge and current information but for selected multipole moments to verify that the dipoles dominate.
- Changing the index of refraction of the atmosphere to study the Čerenkov effect.

As $\vec{E}$ and $\vec{B}$ are directly calculated, one has the explicit time dependence of not only the magnitude of the field, but the polarization, which, as noted above, is expected to be correlated in significant ways with the dominant production mechanism(s). This is nontrivial information and given the controversy in the literature, it may even be the case that various mechanisms dominate at various times, perhaps with longitudinal charge separation being more important at higher altitudes and earlier times. Details of explicit simulations will appear in a separate publication (Dova *et al*,, 1999).

4 Applications

There are several important applications of an improved understanding of the theoretical underpinnings of the emission of radio waves by extensive air showers. Should measurements of radio emissions be in good accord with reasonable theoretical models this would lend confidence to the shower simulation software in use. Should that not be the case, the models used would be called into question. This is of particular interest for showers of the highest energy, which are puzzling and yet where Monte Carlo simulations are invariably a component of the estimation of their energies.

Should it be the case that the modelling is well-understood, radio emissions, in addition to other techniques such as air fluorescence and detection of particles at ground level in such projects as the Pierre Auger Project (Pierre Auger Collaboration, 1996) would be a new window on extensive air showers. Allan (*op. cit.*) has already pointed out that one might expect that showers initiated by primaries of higher mass number (*i.e.* nuclei) would produce stronger radio signals for a given number of particles reaching the ground than those initiated by protons. Should this prove to be true, there is the possibility of a statistically independent source of information on composition of primaries. In any event it is clear that radio waves from extensive air showers are messengers bearing different information that that which is conventionally used in this field of study.

As a final note, many people have pointed out to the authors that investigations into radio emissions have been rather unsuccessful in the past. It may be worth noting that even such a successful technique as air fluorescence is not useful until rather high energies. Perhaps something similar is the case for radio emissions.

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