Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 4 (HE part 1), pages 577–580

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

The LOFAR air shower front evolution library

S. LAFEBRE[1], T. HUEGE[2], H. FALCKE[1,3], J. KUIJPERS[1]
[1]*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University, P.O. box 9010, 6500 GL Nijmegen, the Netherlands*
[2]*Institut für Kernphysik, Forschungszentrum Karlsruhe, P.O. box 3640, 76021 Karlsruhe, Germany*
[3]*ASTRON, P.O. box 2, 7990 AA Dwingeloo, the Netherlands*
s.lafebre@astro.ru.nl

Abstract: The LOFAR radio telescope, under construction in the Netherlands, is an excellent test case for the detection of extensive air showers through their radio signal. In order to fully understand the properties of these signals, we are building a library of CORSIKA simulations over a wide range of energies on the LOFAR BlueGene supercomputer. This library contains particle data throughout the atmosphere, as opposed to the lowest detection level only. The REAS2 code is used to calculate geosynchrotron radio emission from these simulations. We present parametrisations of various characteristics of the particles from showers in this library.

Introduction

Recently, the development of digital radio telescopes such as LOFAR [1] has initiated a wave of renewed interest in the coherent radio emission from cosmic ray air showers [2]. In order to better understand the radiation mechanism and its implications, a series of air shower simulations is being carried out, which produce histogrammed particle data suitable for simulations using the REAS2 code. The CORSIKA [3] based radio emission simulations employ a realistic description of the air shower properties on a shower to shower basis [4] and we intend to pursue this approach further by using a shower simulation library in support of the high energy cosmic ray programme with the LOFAR telescope.

Unfortunately, using existing air shower libraries is not an option: these commonly only consist of distributions of particles on the lowest observation level – usually the Earth's surface. Such libraries are not suited for radio emission simulations, however, since according to our current understanding this radiation is caused by geomagnetic deflection of secondary shower electrons and positrons [5]. Here, we summarise our efforts building our *air shower front evolution library*, and present first results obtained from this library.

Setup

The calculation of synchrotron emission from air showers is not built into CORSIKA: an additional code, REAS2 [4] needs to be run on the particle distributions, which determines the radio footprint on the ground. To this end we use the same interface code as in [4], which outputs two three-dimensional histograms for electrons and positrons for 50 observation levels at equidistant atmospheric slant depths. For each level, these histograms contain 1) particle energy vs. particle arrival time vs. lateral particle distance from the shower core; and 2) particle energy vs. angle of momentum to the shower axis vs. angle of momentum to the (radial) outward direction.

An overview of the simulations we are carrying out is given in table 1. We use photons, protons and iron as primaries, with energies ranging from 10^{16} to $10^{20.5}$ eV (set by an optimistic estimate of the LOFAR detection limits) for six zenith angles $\cos\theta = 1, 0.9, \ldots, 0.5$. The azimuthal angle is constant, as the effect on the particle dis-

Table 1: The number of shower simulations per primary particle energy. Every run is repeated six times, for zenith angles of $\cos\theta = 1.0, 0.9, \ldots, 0.5$.

$\log E/\mathrm{eV}$	Number of runs			Total
	γ	p	Fe	
16.0	100	190	40	330
16.5	100	190	40	330
17.0	100	190	40	330
17.5	156	190	40	386
18.0	225	190	40	455
18.5	325	190	40	555
19.0	450	190	40	680
19.5	450	190	40	680
20.0	56	190	40	286
20.5	125	190	40	355
Total per θ	2087	1900	400	4387
Total	12522	11400	2400	26322

tributions is assumed to be of minor importance because of the azimuthal symmetry of the created histograms; the angle can be set to different values in the radio code, without the need to rerun a shower simulation. We use 10^{-6} level thinning width adaptive weight limitation [6] to obtain a sufficiently high resolution in the particle distributions. The interaction models used are QGSJetII 03 and UrQMD 1.3.1 for high and low energy interactions, respectively.

In order to finish these $\sim$ 26 000 simulations within a reasonable time, we use a parallel supercomputer, *Stella* (Supercomputer Technology for Linked LOFAR Applications). This BlueGene/L machine consists of roughly 12 000 nodes. Some of the code had to be rewritten in order to run CORSIKA on this parallel architecture. To test the validity and reliability of the results obtained with this modified code, we ran a test batch of 1000 showers of 10^{16} eV protons with vertical incidence, both using the parallel version and standard CORSIKA on two different architectures: adding a third, independent architecture allowed us to get an unbiased idea of the differences to be expected. We then performed some statistical tests on the results to check validity.

One such test considered the longitudinal development of the showers. The sum of electrons and positrons in the evolution of the shower N as a function of atmospheric depth X was averaged for all 1000 showers for each architecture's sample. The averaged longitudinal shower evolutions obtained in this manner are shown in the top panel in figure 1. The bottom panel of this figure shows the deviation of each distribution from the other two. The relatively large deviations for very low depths can be attributed to low number statistics, as the number of particles in the shower at these depths is no more than a few hundred. This is also reflected in the coloroud areas in the figure, which indicate 1σ statistical error levels from 1000 runs. It is clear that the deviations between architectures lie well within this area. Comparisons of other quantities, such as lateral and energy distributions, were also carried out. In none of these we could find any significant difference in the quantities involved or the statistical spread in them. We therefore conclude that our parallel code produces valid air shower simulations.

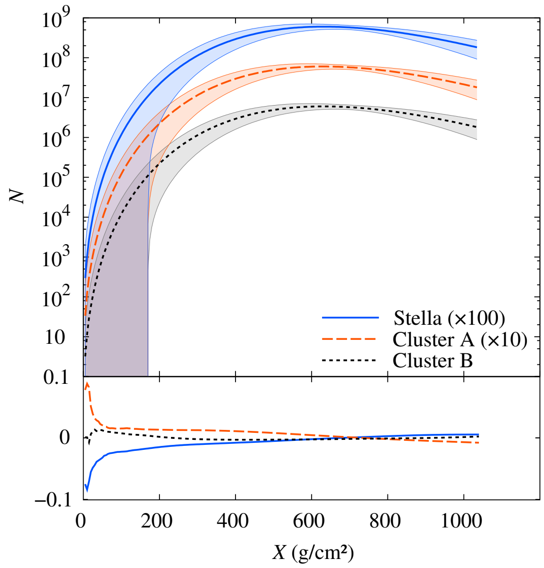

Figure 1: Averaged longitudinal profile of the sum of electrons and positrons for 1000 vertical proton-induced showers of 10^{16} eV, for Stella and two other architectures (labelled A and B). The coloured areas mark 1σ statistical errors. The lower panel shows the relative difference of each longitudinal profile compared to the other two.

Results

The test sample of 3×1000 showers we obtained for validating our output can be used for an analysis of vertical air showers from protons at 10^{16} eV, given the large number of simulations we carried out for one single configuration. One of the air shower properties we investigated is the longitudinal profile $N(X)$. A popular parametrisations to describe the longitudinal evolution of air showers was suggested by Greisen [7] and Gaisser & Hillas [8]. We can generalise both, however, to read

$$N_L(X) = N_{\max} \exp\left[\frac{\lambda}{X_{\max}}\left(\ln\frac{X}{X_{\max}} - \sum_{i=1}^{n}\epsilon_i\left(1-\frac{X}{X_{\max}}\right)^i\right)\right], \quad (1)$$

where, in the case of 10^{16} eV proton showers, $\lambda \simeq 45 \pm 7$ g/cm^2 is a characteristic length parameter, $X_{\max} \simeq 6.4 \pm 0.8 \cdot 10^2$ g/cm^2 is the atmospheric depth at which the number of electrons and positrons $N(X)$ peaks, and $N_{\max} \simeq 6.5 \pm 0.5 \cdot 10^6$ is the number of particles at this depth. We determined optimal values for ϵ_i from the average of $N(X)$ in our sample of simulations, setting $i \leq 6$: using terms of even higher order does not decrease the variance reduction significantly anymore. The values we obtained are

$$\epsilon_i = [1.000, -0.013, 0.005, 0.053, 0.181, 0.207], \quad (2)$$

which is very close to the Gaisser–Hillas parametrisation, $\epsilon_i = [1, 0, 0, \ldots]$. Using this parametrisation, $N(X)$ fits slightly better, even for *individual* showers, than either the Greisen or Gaisser–Hillas parametrisations. Note that this analysis was based on averaging in X: averaging of the shower age s might change these results.

Since the showers in our library contain histograms of particle distributions over the entire evolution of the shower, we can produce multidimensional representations of particle densities. As an example of such a representation, figure 2 shows the particle density $n = \mathrm{d}N/\mathrm{d}r^2$ as a function of X and the distance from the shower axis r. As expected, most of the particles in a 10^{16} eV shower exist in a narrow cylinder around the shower axis with a radius of a few meters. It is interesting to note that the maximum particle density is reached at different depths for different distances; also note that the reduction rate of the density with X varies with r.

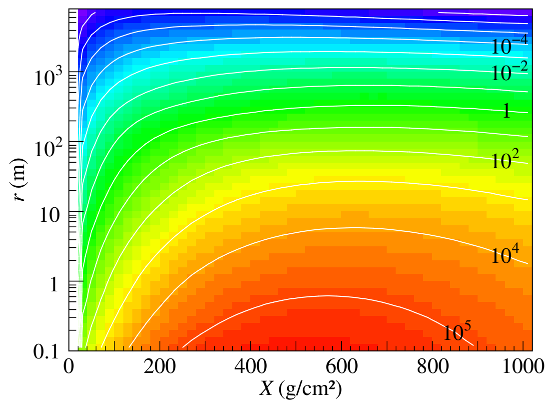

Figure 2: Two-dimensional structure of the average particle density n as a function of atmospheric depth X and distance form the shower axis r. The color scale and white contour lines represent particle densities in particles per m^2. Contour lines are spaced logarithmically at factors of ten.

A quantity that may influence the radio footprint of an air shower is the net charge of the shower. Air showers tend to develop a net negative charge as they evolve, through positrons interacting with atmospheric electrons. As this charge excess moves through the atmosphere at superluminal velocity, it gives rise to Čerenkov radiation in the radio domain. Currently, the relative role of this effect is uncertain. Looking into the charge excess may allow us to determine the relative importance of the effects compared to that of coherent synchrotron emission, which is thought to be dominant.

The charge excess q of electrons over photons as a function of shower depth X is defined as the ratio:

$$q(X) = \frac{n_{e^-}(X) - n_{e^+}(X)}{n_{e^-}(X) + n_{e^+}(X)}. \quad (3)$$

Figure 3 shows the relative average charge excess q as a function of X and r. Note the feature in the top right of this figure; its origin is unclear, but it is probably strongly correlated with the cutoff energy used (400 keV in these simulations): further study is required here. Contrary to the relative excess, the *absolute* charge excess has much the same structure as the overall spatial structure of the air shower

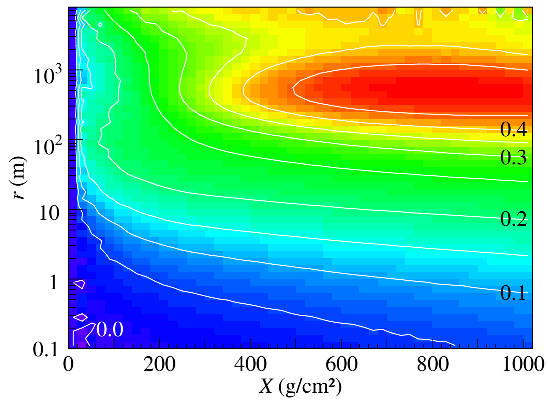

Figure 3: Two-dimensional structure of the average charge excess ratio q, as a function of atmospheric depth X and distance form the shower axis r. The color scale and white contour lines represent fractional charge excess value. Contour lines are spaced at intervals of 0.05.

from figure 2, so that the largest absolute charge excess values are found near the shower core. Furthermore it should be noted that, because the particle distributions are folded over the azimuthal angle, any local excess due to charge separation from deflection in the Earth's magnetic field is cancelled out. At this moment, the question whether the *local* charge excess due to this separation effect plays a larger role than the *overall* excess charge in the air shower is still open, as the average separation of positron-electron pairs is expected to be of the order of the radiation produced.

Conclusions & future work

Using a tailor-made CORSIKA version, we are running air shower simulations on a supercomputer. The library we are building with this CORSIKA version consists of over 26 000 air shower events, each containing particle histograms of the entire evolution of the air shower front instead of the particle flux on the ground only. On top of this output, we will run REAS2 to obtain the radio emission profile resulting from the geosynchrotron effect. We will use this library in support of the LOFAR project, which can detect radio signatures from extensive air showers.

Though we have not started running REAS2 on the particle histograms we have produced so far, we have already done some analysis of a test sample of 3000 showers at 10^{16} eV. At this point, these results serve to prove that, even though we have not started analysis of the library itself, the amount of computation time available combined with full evolution data, will yield some interesting science.

Currently, nearly three quarters of the scheduled simulations have been finished on the Stella supercomputer. Once finished, the library will be made publicly available.

In the future, we hope to be able to summarise our analysis of the library, both in terms of particle distributions of the extensive air showers and the radio signals that arise from these showers, in a parametrisation of the radio pulses produced by the showers, as a function of all parameters involved.

Acknowledgements

We owe many thanks to Dieter Heck, Ralf Ulrich and Ralph Engel. We also thank Kjeld van der Schaaf and Hopko Meijering for support at Stella. This work is part of the research programme of the 'Stichting voor Fundamenteel Onderzoek der Materie (FOM)', which is financially supported by the 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)'.

References

[1] H. Falcke et al, *ArXiv*, astro-ph/0610652, 2006

[2] H. Falcke et al, *Nature* 435:313, 2005

[3] D. Heck, J. Knapp, et al, Technical Report 6019, Forschungszentrum Karlsruhe, 1998

[4] T. Huege, R. Ulrich, and R. Engel, *Astropart. Phys.*, 27:392, 2007

[5] T. Huege and H. Falcke, *A&A*, 412:19, 2003

[6] M. Kobal and Pierre Auger Collaboration, *Astropart. Phys.*, 15:259, 2001

[7] K. Greisen, *Ann. Rev. of Nucl. and Part. Science*, 10:63, 1960

[8] T. K. Gaisser and A. M. Hillas, In *Proc. 15th ICRC*, 353, 1978