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# Coherent transition radiation from the geomagnetic air shower current

**Krijn D. de Vries***
*Vrije Universiteit Brussel, Dienst ELEM, IIHE, Pleinlaan 2, 1050, Brussel, Belgium*
*E-mail:* krijn.de.vries@vub.be

**Steven Prohira**
*Center for Cosmology and AstroParticle Physics (CCAPP), The Ohio State University, Columbus OH, 43210*
*E-mail:* prohira.1@osu.edu

Since the year 2000 the radio detection technique has become a well established method to probe cosmic-ray-induced air showers. In this work, we discuss the coherent transition radiation produced when the particle cascade crosses a boundary surface. Standard transition radiation is the emission induced due to a net charge crossing between different media. We show that a similar effect is expected for a net charge-neutral transverse current crossing a boundary. We discuss the implications of this transition radiation component for the coherent radio emission from a high-energy cosmic-ray-induced particle cascade hitting Earth. We show that this component cannot be neglected for balloon-based experiments such as ANITA, or detectors below the boundary surface such as ARA.

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## 1. Introduction

The radio detection technique is currently a well established method to probe high-energy cosmic-ray air showers [1, 2]. The two main radio emission mechanisms from a cosmic-ray air shower are due to the geomagnetic and charge-excess mechanisms. The geomagnetic emission originates from charged leptons that are deflected in Earth's magnetic field, inducing a net transverse current in the air shower front. This emission was first noted by Kahn and Lerche [3], and detailed in [4]. The charge-excess emission was predicted by Askaryan [5], and originates from the net excess charge build up inside the cascade due to ambient electrons that are scattered to relativistic energies.

The radio emission itself is understood by considering the time variation of the net charges and currents in the cascade front. One crucial aspect in understanding the radio emission from a cosmic-ray air shower is coherence, which occurs at wavelengths larger than the typical, projected, dimensions of the high-energy cascade. Strongly depending on the observer location, these dimensions can be of the order of several cm when the shower maximum is observed at the Cherenkov point close to the cascade axis, to several meters for observers located further out [6, 7]. It immediately follows that, depending on the observer geometry, coherent emission is expected in the MHz-GHz region.

For a typical ground-based radio detector, these mechanisms provide a very accurate description of the observed radio emission. In this work we discuss that for observers located far from the air-Earth boundary a different emission has to be considered, coherent transition radiation from the air shower traversing from air into Earth or more interestingly ice. This emission was already discussed in [8, 9, 10] where the focus was put on transition radiation from the net excess charge in the cascade front, where in [11, 12, 13], the sudden death signal due to the absorption of the air shower by Earth was considered. In this work, we show that transition radiation is a geometrical effect and as such is not limited to a net charge traversing a boundary layer, but applies equally well to the geomagnetically induced current in the air shower front, to which we will refer to as CTR-GM.

We show that coherent transition radiation is expected to be large for observers located away from Earth's surface. This is of special interest in context of the two 'anomalous' events detected by the balloon based interferometer and neutrino observatory ANITA [14, 15, 16]. Although the main goal of the ANITA experiment is the detection of high-energy neutrinos interacting in the Antarctic ice sheet, ANITA has detected dozens of cosmic-ray air shower signals [17]. These signals are characterized by their polarization, which is found to be aligned with the plane of the geomagnetically induced current. These events are detected either directly for Earth skimming showers at large zenith angles, or through the emission that is reflected off the ice for showers at smaller zenith angles. The difference between the direct and reflected signals are found in a flip in polarity, defined as the sign of the main peak in the polarization plane, where such a flip is indeed expected for a reflected signal.

The two so-called 'anomalous' events detected by ANITA are observed to originate from the ice, similar to the reflected cosmic-ray air showers. However, their polarity is flipped compared to what one would expect for a reflected cosmic-ray air shower signal, and hence the signal appears to be 'direct', originating from an upward moving particle cascade. Nevertheless, such an upward moving particle cascade implies an extremely energetic primary particle that traversed a large path through Earth. Given the ANITA exposure and the needed energy of the primary, this effectively rules out any particle currently known within the standard model of particle physics [18]. In this work we show that coherent transition radiation from a high-energy (down-going) cosmic-ray induced air shower hitting the air-ice surface can lead to the observed polarity signature by ANITA and as such provides a natural, standard model, explanation for the observed events.

## 2. Geometry: From Cherenkov effects to transition radiation

In this work, we largely follow [8] and [19], which describe coherent transition radiation from a cosmic-ray air shower hitting the air-ice boundary. In [8], it was argued that coherent transition radiation can be interpreted as a superposition of the vanishing of the induced electromagnetic potential in one medium, also referred to as the sudden death signal, and the sudden appearance of the potential in another medium. There is one caveat with calculating coherent transition radiation starting with the standard potentials from classical electrodynamics, which lies in the fact that these potential are derived under the assumption of an infinite homogeneous medium. As such the potentials are typically not defined at the boundary, where boundary conditions have to be applied. Other, more direct approaches are found by calculating the boundary emission directly from Maxwell's equations [13].

We first consider the Liénard-Wiechert potentials from classical electrodynamics, which are given by,

$$A^{\mu}(\vec{x},t) = \left.\frac{J^{\mu}}{\mathscr{D}}\right|_{t'} . \tag{2.1}$$

The potential is constructed in two parts, first there is the 'source', $J^{\mu}$, with $\mu = 0$ denoting the charge component leading to the scalar potential and $\mu = 1-3$ denoting the currents inducing the vector potentials. The geometry is contained in the denominator $1/\mathscr{D} = (1/L)\ (dt'/dt)$, where $L$ denotes the optical path length to the observer, $t'$ denotes the emission time, and $t$ the observer time. The geometry is captured by the infinitesimal product $dt'/dt$, taking care of the projection of the current at the observer location. It is now interesting to study the relation between the emission time and the observer time, $t'(t)$, for different observer geometries.

Defining $t = t' = 0$ as the time when the (fictive) cascade front defined to be moving with the speed of light along the shower axis hits the observer plane. As such, the emission height is directly linked to the emission time $z = -ct'$. In Fig. 1, we consider the $z(t) \propto t'(t)$ relation for a vertically incoming cosmic-ray air shower hitting the air-ice boundary at 3 km above sea level. The observer is located at an impact parameter of 40 m from the cascade axis, 100 m below the air-ice boundary. The full red line indicates the $z(t)$ relation for the in-air emission, the dashed purple line indicates the $z(t)$ relation for the in-ice emission, and the full green line indicates the total number of particles inside the cascade as denoted on the top x-axis. It follows that in-air signals emitted at early times (large heights) are delayed by the medium and arrive late. We then see a 'perfect' time from which the signal arrives first at which the full red line turns. At this time, the observer sees a finite part of the particle cascade at once, which is know as the Cherenkov effect. This is also reflected in the potentials through the product $dt'/dt$, which diverges, and has to be regularized [20]. We then observe that in-air signals emitted at later times arrive late.



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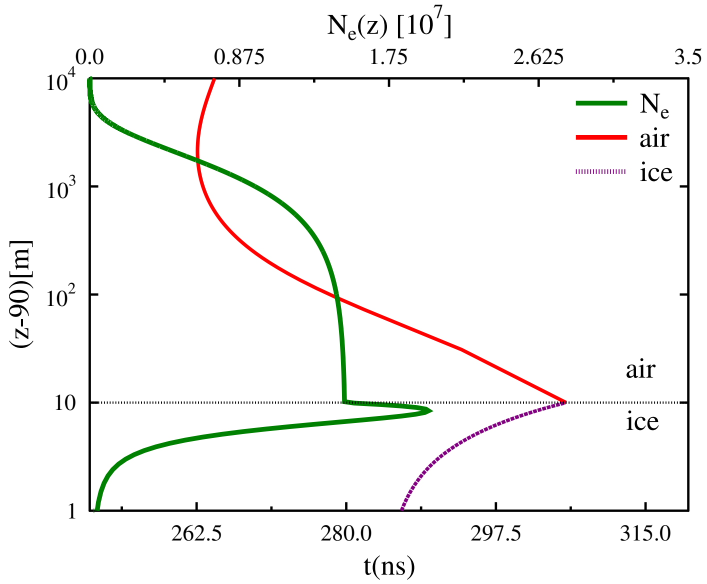


Figure 1: The $z(t) \propto t'(t)$ relation for the geomagnetic and/or Askaryan emission from a vertically incoming cosmic-ray air shower hitting the air-ice boundary at 3 km above sea level. The observer is located at an impact parameter of 40 m from the cascade axis, 100 m below the air-ice boundary. The full red line indicates the $z(t)$ relation for the in-air emission, the dashed purple line indicates the $z(t)$ relation for the in-ice emission, and the full green line indicates the total number of particles inside the cascade as denoted on the top x-axis. The y-axis is shifted by 90 m for visualisation purposes, figure taken from [19].

The situation now becomes interesting if we consider the boundary, where there is a discontinuity in the product $dt'/dt$. At this point, the observer sees a strong 'shock' in the potential, transition radiation. Since this 'shock' in the potential is a purely geometrical effect, similar to the Cherenkov effect illustrated above, both transition radiation as well as Cherenkov effects apply equally well to the net excess charge in the cosmic-ray air shower, as well as to the geomagnetically induced transverse current. Solving for the fields in these situations becomes non-trivial, and for details we refer to [8, 19].

## 3. The ANITA anomalous events

In the previous section we have shown that the $z(t) \propto t'(t)$ relation is discontinuous at the boundary. This can be understood by considering the different paths through which the charges and currents in the cascade front are observed once it is positioned directly above the boundary compared to the situation directly below the boundary. This is shown in Fig. 2. Please note that in Fig. 2 we only consider the relativistically boosted paths in the forward direction, as the emission from a charge or current in the back lobe, moving away from the observer, is highly suppressed.

For the in-ice observer discussed in the previous section, we see that the charges and currents observed directly above the boundary are seen through a completely different path (label 2

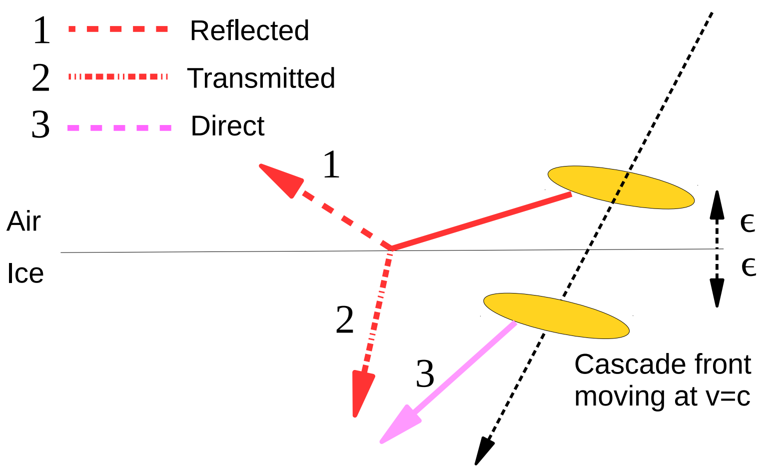


Figure 2: The geometry for coherent transition radiation within a distance $\varepsilon$ from the air/ice interface. The geomagnetically induced current observed through the relativistically boosted path is given by the red line (label 1). The current is observed through the reflected path for an in-air observer and through the refracted path for an in-ice observer. The relativistically boosted path through which the current is observed from directly below the boundary is given by the solid magenta line, label 3. Hence, the relativistically boosted current directly below the air-ice interface will be observed by an in-ice observer, where it instantly vanishes for an in-air observer. Figure taken from [19].

in Fig. 2), compared to the signal emitted directly below the boundary (label 3 in Fig. 2). This leads to the observed 'shock' in the potential, and hence very strong transition radiation. For the in-air observer (ANITA) the relativistically boosted current is observed through the reflected path (label 1 in Fig. 2). Once the cascade crosses the air-ice boundary, this path completely vanishes and with it the associated potential and again very strong coherent transition radiation is expected. It should be noted that there is still the non-boosted (direct) path for both the in-air emission as well as the in-ice emission. The charges and currents are observed to move relativistically away from the observer for these direct paths and hence this emission is highly suppressed and can be ignored in practice.

It follows that for the ANITA geometry, we do expect strong coherent transition radiation to play a significant role once a significant charge (CTR) and/or current (CTR-GM) crosses the air-ice interface. In [12] and [8], it is discussed that for particle cascades with zenith angles below 70 degrees, in combination with elevated boundary surfaces this is the case. To investigate if this is the situation for the anomalous events detected by ANITA, in Fig. 3 we show the fraction of particles hitting the boundary surface with respect to the maximum number of charges inside the cascade (for more details on the air shower simulations we would like to refer to [19]). It immediately follows that the two anomalous events indicated in solid red are outliers within this distribution and indeed strong coherent transition radiation is expected.

So can coherent transition radiation from the geomagnetically induced current provide a flip in polarity? For this we first have to consider the polarization plane of this emission. Charges within an air shower are deflected via the Lorentz force in Earth's magnetic field, which in Antarctica points vertically. As such, the in-air geomagnetic emission will be polarized along the induced geomagnetic current in the horizontal plane. Since the CTR-GM originates from the same source– the geomagnetically induced current –CTR-GM will lie in the same horizontal plane.

Now it is the polarity of the signal, the sign of the dominant peak of the emission, which becomes interesting. In Fig. 4 a), we show the expected electric field for a shower with a similar geometry as the ANITA anomalous event observed at a zenith angle of 55 degrees, hitting the air-ice boundary 3 km above sea level, with the observer located 30 km above the air-ice boundary. The field is observed at an angle of 2 degrees from the specular of the cascade axis (figure taken from [19]). It follows that indeed the polarity of the transition radiation is opposite to the polarity of the in-air emission, allowing for the observed polarity flip. For comparison, in Fig. 4 b), we show the expected emission from a 70 degrees inclined air shower. In this situation the total particle number at the air-ice interface –and hence the total current– becomes negligible, and the observed field is dominated by the in-air geomagnetic emission.

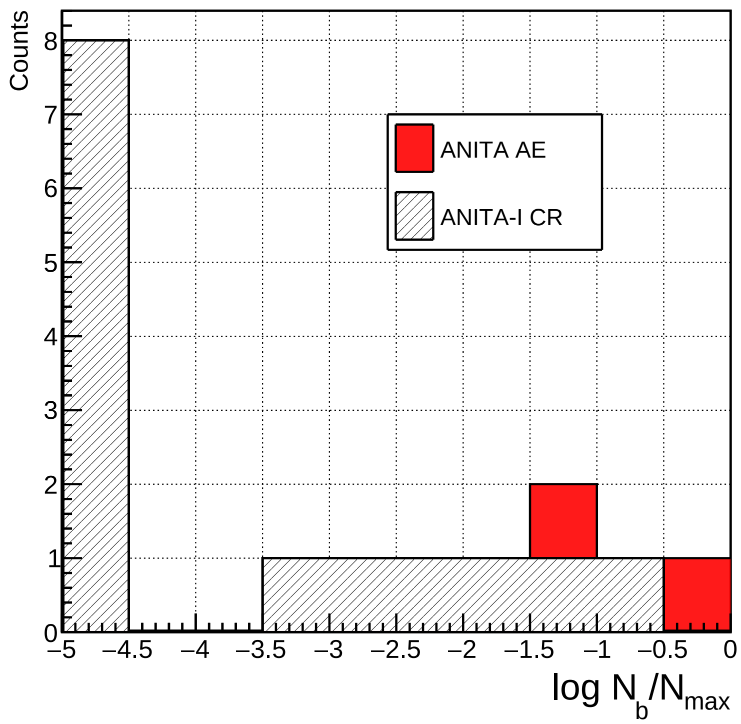


Figure 3: The base 10 log of the mean value of $N_b/N_{max}$ for each ANITA-1 CR and the two 'anomalous' events (AE). The leftmost bin contains all values smaller than -5.

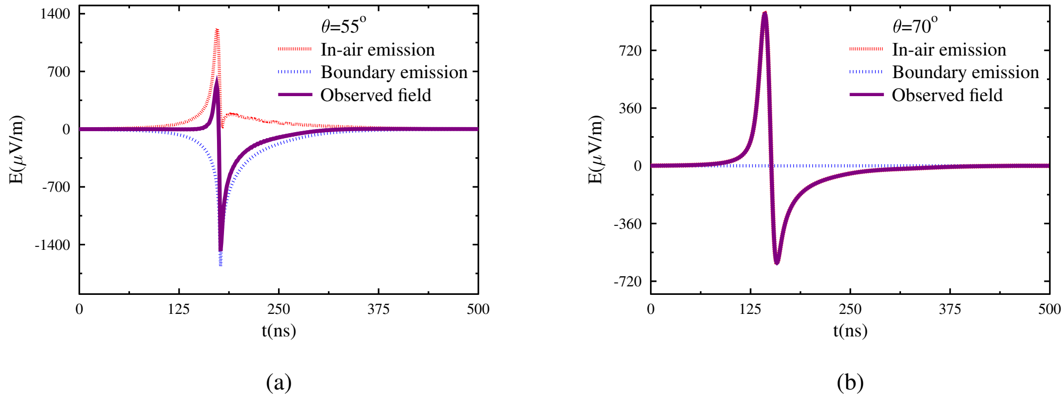


Figure 4: The expected radio emission from a down-going cosmic ray air shower hitting an air-ice boundary at 3 km above sea level. The observer is located 30 km above sea level, and observes the emission which reflects from the air-ice interface at an angle of 2 degrees from specular with respect to the shower axis. The (striped) red line indicates the the in-air emission bouncing of the ice towards the detector. The (dashed) blue line indicates the emission due to the vanishing of the potential at the boundary. The total field at the observer is given by the (full) purple line. Figure taken from [19].

## 4. Conclusions

Coherent transition radiation is not limited to a net charge, but applies equally well to a charge-neutral current. Its application is found in cosmic-ray induced air showers hitting a boundary surface and is of special interest in view of the two anomalous events detected by the ANITA observatory. We have shown that the two anomalous events detected by ANITA are outliers within the detected cosmic-ray distribution by ANITA in the sense that a significant amount of charge and current in the cascade front hits the air-ice interface. These are the main conditions for strong CTR-GM to occur. Since the in-air emission and the CTR-GM are both caused by Earth's magnetic field, both are expected to lie within the same polarization plane. Furthermore it is shown that the polarity, the sign of the dominant peak in the observed field is inverted when CTR-GM is included. As such coherent transition radiation from the geomagnetically induced transverse current for a down-going cosmic-ray air shower forms a natural, standard model, explanation for the two anomalous events detected by ANITA.

## References

[1] F.G. Schröder, Progress in Particle and Nuclear Physics, **93**, 1-68, (2017)

[2] T. Huege, D. Besson, Progress of Theoretical and Experimental Physics, **12**, 12A106, (2017)

[3] F.D. Kahn and I. Lerche, Proc. Royal Soc. London **A289**, 206 (1966).

[4] O. Scholten, K. Werner, F. Rusydi, Astropart. Phys. **29**, 94-103 (2008)

[5] G.A. Askaryan, Sov. Phys. JETP **14**, 441 (1962); **21**, 658 (1965)

[6] N.N. Kalmykov, A.A. Konstantinov, and R. Engel, Nucl. Phys. B **151**, 347 (2006); Phys. of At. Nuclei, **73**, 1191 (2010)

[7] K.D. de Vries, A.M. van den Berg, O. Scholten, K. Werner, Phys.Rev.Lett. **107**, 061101 (2011)

[8] K.D. de Vries *et al.*, Astropart. Phys. **74**, 96 (2016).

[9] P. Motloch, J. Alvarez-Muniz, P. Privitera, E. Zas, Phys. Rev. D **93**, 043010 (2016).

[10] K.D. de Vries, M. DuVernois, M. Fukushima, R. Gaior, K. Hanson, D. Ikeda, Y Inome, A. Ishihara, T. Kuwabara, K. Mase, J.N. Matthews, T. Meures, P. Motloch, I.S. Ohta, A. O'Murchadha, F. Partous, M. Relich, H. Sagawa, T. Shibata, B.K. Shin, G. Thomson, S. Ueyama, N. van Eijndhoven, T. Yamamoto, S. Yoshida, Phys. Rev. D **98**, 123020 (2018).

[11] D. Charrier, R. Dallier, A. Escudie, D. García-Fernández, A. Lecacheux, L. Martin, B. Revenu, Astropart. Phys. **113**, 6-21, 2019

[12] D. García-Fernández, B. Revenu, D. Charrier, R. Dallier, A. Escudie, L. Martin, Phys. Rev. D **97**, 103010 (2018).

[13] D. García-Fernández, B. Revenu, A. Escudie, L. Martin, Phys. Rev. D **99**, 063009 (2019)

[14] P.W. Gorham *et al.*, ANITA Collaboration, Astropart. Phys. **32**, 10 (2009)

[15] P.W. Gorham *et al.*, ANITA Collaboration, Phys. Rev. Lett. **117**, no. 7, 071101 (2016)

[16] P. W. Gorham *et al.*, ANITA Collaboration, Phys. Rev. Lett. **121**, no. 16, 161102 (2018)

[17] H. Schoorlemmer *et al.*, Astropart. Phys. **77**, 32 (2016)

[18] A. Romero-Wolf et al., arXiv:1811.07261

[19] K.D. de Vries, S. Prohira, arXiv:1903.08750

[20] K. Werner, K.D. de Vries, O. Scholten, Astropart. Phys. **37**, 5-16 (2012)