Coherent radio pulses from high energy showers: A blooming field

In the memory of a brilliantly original mind

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Particles radiate (or induce radiation Cerenkov)
  • Radiation adds coherently for low enough frequencies
  • Power of coherent radiation scales with \((\text{shower particles})^2\)
  • Showers have lots of particles => Interesting for UHE!

Interference effects give rich diffraction patterns
  • Shower could be fully visualized if sufficiently well sampled!!
    (amplitude & phases in every direction)

Signal: contributions from many (all) shower stages
  • Reduced fluctuations => good observable

Antennas: cheap
Radio detection: high duty cycle

Main difficulty: dealing with noise
58 J. Jelley 58 extend Cherenkov to radio
61 G. Askary’an excess $Q=\Delta q$
65 J. Jelley 8 “mechanisms” (ICRC65)
  • Enhanced Cherenkov (Askary’an)
  • Dipole Cherenkov
  • Synchrotron radiation
  • Transition radiation
  • Coulomb field bremsstrahlung
  • Induction (by nearby charges)
  • Molecular transitions
  • Reflections of continuous waves (Doppler shifted)
65 In air: high $\nu$ Complex some are limiting cases of given situations but it is all in Maxwell’s laws!

67-70 Air: $e^+e^-$ separation in $B_{\text{Geo}}$ dominant (Th & exp)
75 decline of field, steep Idf, storm interference …
90 $\nu$ detection: full calculations in ice (ZHS)
  New initiatives radio telescopes, air showers, ice, salt …
00 Lab measurements
  Air showers 1st generation LOPES, CODALEMA, ANITA (GHz)
10 Full simulations (ZHS algorithm + MC)
  2nd generation LOFAR, AERA, Tunka-Rex ($E, X_{\text{max}}$)
20 Ambitious plans: GRAND, AugerRadio, phased arrays …
Calculations are key: Based on simple solution

Maxwell’s Equations in transverse gauge

\[ \nabla^2 \phi = -\frac{\rho}{\epsilon} \]

\[ \nabla^2 A - \mu \epsilon \frac{\partial^2 A}{\partial^2 t} = -\mu J_\perp \]

The transverse current is the divergenceless component (the transverse projection at large distances)

\[ J_\perp = \hat{u} \times (\hat{u} \times J) \]

Well known solution, Vector potential \( A \) gives us the radiated field

\[ \phi = \frac{1}{4\pi \epsilon} \int \frac{\rho(x', t')}{|x - x'|} d^3x' \]

\[ A = \frac{\mu}{4\pi} \int \frac{J_\perp(x', t')}{|x - x'|} \delta \left( \sqrt{\mu \epsilon} |x - x'| - (t - t') \right) d^3x' dt' \]

Delta of Retarded time with \( \sqrt{\mu \epsilon} = nc \)
Solve for simple case (constant speed)

\[ \text{position} \quad x_0 - vt' \]

\[ J_\perp(x', t') = e v_\perp \delta^3 (x' - x_0 - vt') \left[ \Theta(t' - t_1) - \Theta(t' - t_2) \right] \]
Organize $t$ and $t'$ and massage

\[ \delta \left( \sqrt{\mu \epsilon |x - x'|} - (t - t') \right) \]

Fraunhofer approximation

\[ R = |x - x_0| \approx |x - x_0 - vt'| = R - v \cdot \hat{u}t' \]

\[ \delta \left( t'(1 - n\beta \cos \theta) - \left( t - \frac{nR}{c} \right) \right) \]

\[ \frac{1}{|1 - n\beta \cos \theta|} \delta \left( \frac{t'}{1 - n\beta \cos \theta} - \frac{t - \frac{nR}{c}}{1 - n\beta \cos \theta} \right) \]
Substitute into solution for $A$

$$R_A(t, \theta) = \frac{e\mu_r}{4\pi\varepsilon_0 c^2} \mathbf{v}_\perp \delta t$$

$$\Theta \left( t - \frac{nR}{c} - (1 - n\beta \cos \theta)t_1 \right) - \Theta \left( t - \frac{nR}{c} - (1 - n\beta \cos \theta)t_2 \right)$$

$$\frac{(1 - n\beta \cos \theta) \delta t}{(1 - n\beta \cos \theta) \delta t}$$

Divergence at Cherenkov angle? **NO!!**

We formally get derivative of Theta function

$$\theta \to \theta_C$$

**Limit**

$$(1 - n\beta \cos \theta) \delta t \to 0$$

**CHERENKOV** Radiation

$$R_A(t, \theta_C) = \left[ \frac{e\mu_r}{4\pi\varepsilon_0 c^2} \right] \delta \left( t - \frac{nR}{c} \right) \mathbf{v}_\perp \delta t$$
Field single track: Time domain


NOTE: “Acceleration” with a grain of salt
Limit of large $\delta t$
gives Cerenkov radiation
(by medium)
Terms of adjacent sub-tracks give large cancellations

\[
RE(t, \theta) = -\frac{e\mu_r}{4\pi\epsilon_0 c^2} \mathbf{V}_\perp \frac{\delta(t - \frac{nR}{c} - (1 - n\beta \cos \theta)t_1) - \delta(t - \frac{nR}{c} - (1 - n\beta \cos \theta)t_2)}{(1 - n\beta \cos \theta)}.
\]
Fourier transform $\Rightarrow$ ZHS

$E(\omega) = i\omega \frac{1}{R} e^{i(\text{overall-phase})}$

$\nu_{\perp} \delta t$

if $\omega = 0$

or $\theta = \theta_c$

or $\delta t = 0$

$\nu_{\perp} \delta t \sin \left[ \frac{(1 - n\beta \cos \theta)\omega t}{(1 - n\beta \cos \theta)\omega t} \right]$

State-of-the-art: simulations AIRES/CORSIKA + Zas-Halzen-Stanev algorithm (classical electromagnetism)
EXCESS NEGATIVE CHARGE OF AN ELECTRON-PHOTON SHOWER AND ITS COHERENT RADIO EMISSION

G. A. ASKAR’YAN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 24, 1961


We investigate the excess of electrons in an electron-photon shower. This excess is caused by annihilation of the positrons in flight and by the Compton and $\delta$-electrons in the cascade. It is shown that at the maximum of the shower the excess may comprise ten percent of the total number of shower particles. The Cerenkov radiation from this excess charge in a dense medium is estimated. It is indicated that this radio emission from showers produced by high-energy accelerator particles or cosmic rays in blocks of dense matter can be recorded and used. The possibility of recording radio waves from penetrating particle showers in the moon’s ground, by apparatus dropped on the lunar surface, and in underground layers on the Earth in which radio waves can propagate, is also noted.
Unidimensional current

\[ J(\mathbf{z},t) = \nu Q(\mathbf{z}) \delta(\mathbf{z} - \nu t) \]

Vector potential

\[ A(\mathbf{t}_{\text{obs}}, \theta) \approx \nu Q(\zeta) / R \]

\[ z' = \zeta(t) = \beta \frac{ct - nR}{1 - n\beta \cos \theta} \]

\( \zeta \) → Retardation + time-compression: From \( \mathbf{z} \) to time \( \mathbf{t}_{\text{obs}} \) (\( \theta \)-dependent)

\[ \mathbf{t}_{\text{obs}} = z(1 - n\cos \theta)/c + t_0 \quad \mathbf{t}_{\text{obs}} = t_0 @ \angle \theta_c \]

Electric field

\[ E(\mathbf{t}_{\text{obs}}, \theta) = dA(\mathbf{t}_{\text{obs}}, \theta) / d\mathbf{t}_{\text{obs}} \]

Interesting for neutrino detection

e showers & hadronic debris separate (LPM)
Flavor tagging : $\nu_e$
Measure $y$ (energy transfer to hadrons)
\[ \nu_e + N \rightarrow e + jet \]

\[ E(\nu_e) = 10 \text{ EeV} \]
\[ E(\text{hadron jet}) = 2 \text{ EeV} \]
\[ E(\text{electron}) = 8 \text{ EeV} \]
$\theta_c$ Cherenkov Angle
Interference 1: length

Path difference

Pulse ahead of time!

\[ \theta > \theta_c \]

Emission out of phase

\[ \text{path difference} = \lambda \rightarrow \text{diffraction minimum} \]

like in a single slit

\[ L \sim \text{slit width} \]
The slit diffraction analogy

If current is “thin”:

\[ \tilde{E}(\omega) \propto \frac{i\omega}{R} \int dz Q(z)e^{ikz} \]

FT with

\[ k = (1 - n \cos \theta) \frac{\omega}{c} \]

Great scaling properties: reduced fluctuations
integrated emission ("calorimetric")
Coherent radio pulses from high energy showers

$E_{sh}$ (TeV) $100$
Coherent radio pulses from high energy showers

$$E_{sh} \ (\text{TeV})$$

1000
What happens at $\theta_c$?

2: Idf

In Cherenkov direction: $d \sin \theta = \lambda$

Interference minimum at lower $\lambda$ (higher frequency)

Path difference = $d \sin \theta_c$
Why is the atmosphere so different?

The Cherenkov angle is small $\sim 1^\circ$

$$A = \frac{\mu}{4\pi} \int \frac{\mathbf{J}_\perp(x', t')}{|x - x'|} \delta \left( \sqrt{\mu e} |x - x'| - (t - t') \right) d^3x' dt'$$

$$\mathbf{J}_\perp = Q \ v_\perp \sim 0.2N_e c \sin \Theta \sim 0.003 \ N_e c \quad \text{(Askary'an)}$$

$$\mathbf{B} \rightarrow \text{transverse current} \sim v_\perp^{\text{drift}} \sim qB_\perp/\rho \sim 0.04c$$


$$\mathbf{J}_\perp = Q \ v_\perp^{\text{drift}} \sim 0.04 \ N_e c \quad \text{(geomagnetic) often dominant}$$

Depends on $\sin(\alpha)$ [angle between shower axis and B field]
Polarization of two components is different

However new complex issues:
- Loss of symmetry (mixed patterns)
- There is a varying refractive index
- There is curvature of the atmosphere

...
Lessons from experiments
Many activities pursued

>89 On Moon from Earth: GLUE, ATCA, LUNASKA, LOFAR …

>96 In Ice: Rice, ARA, ARIANNA …
  G. Frichter; D. Besson; D. Seckel; …

>00 On “lab”: SLAC (Silica Sand, Salt, Ice, Air+B), Utah (ARAcalTA) …
  P. Gorham, D. Saltzberg et al. PRL86(2001)2802 …

>03 In air: LOPES, CODALEMA, AERA, LOFAR, Tunka-Rex …
  D. Ardouin; H. Falcke …

>03 In ice from air: ANITA …

>10 in air microwave: MIDAS, CROME, EASIER, MAYBE …
  P. Privitera; A. Lettessier-Selvon; R. Smida; V. Verzi; …
Coherent radio pulses from high energy showers

X_{max}\textit{ reliably measured!}
Energy in radio is an excellent energy estimator.

The Pierre Auger Collaboration, PRL 116, 241101 (2016); PRD 93 122005 (2016)
14 events CR detected! Why GHz radiation?

Diameter 1000 times larger BUT $\theta_c$ VERY small

Blow up of shower front

Path difference $= d \sin \theta_c$

At $\theta_c$ coherence up to the GHz in spite of scale factor!!
Insight from time delays

Observer at position such that shower center (0,0) is viewed viewed at Cherenkov angle

$\theta_z = 70^\circ$

(Vertical slice)

Antarctica proton $10^{19}$ eV

Different spectra as we get away from Cher angle

Inner cone

$\psi = 0.7^0$  
$\psi = 0.62^0$  
$\psi = 0.55^0$  
$\psi = 0.48^0$  
$\psi = 0.4^0$  
$\psi = 0.33^0$  
$\psi = 0.25^0$  
$\psi = 0.18^0$  
$\psi = 0.11^0$
Inner cone

\[ \log_{10}(E_n/E_{eV}) = 18.4, \ \theta = 71^\circ \]

\[ \psi = 0.7^0 \]
\[ \psi = 0.62^0 \]
\[ \psi = 0.55^0 \]
\[ \psi = 0.48^0 \]
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$\psi = 0.48^0$
$\psi = 0.4^0$
$\psi = 0.33^0$
$\psi = 0.25^0$
$\psi = 0.18^0$
$\psi = 0.11^0$

$\log_{10}(E_n/E_{eV}) = 19, \theta = 71^\circ$
Excellent scaling with energy

log_{10}(E_{n}/E_{eV}) = 19.6, \theta = 71^\circ

ψ = 0.7^0
ψ = 0.62^0
ψ = 0.55^0
ψ = 0.48^0
ψ = 0.4^0
ψ = 0.33^0
ψ = 0.25^0
ψ = 0.18^0
ψ = 0.11^0

Coherent radio pulses from high energy showers  EZ Heidelberg 2018

35
ANOMALOUS EVENTS

Gorham et al. PRL117(16)071101

Gorham et al. PRL121(18)161102

Event 5152386, EL = -4.3

Event 7122397, EL = -3.4

Event 21684774, EL = -2.3

Event 3985267, EL = -27.4

ANITA-III UHECR Air Showers

15717147, -35°

27142546, -5.5°

39599205, -3.6°

68298837, -36.7°

Coherent radio pulses from high energy showers

EZ Heidelberg 2018
The future is Big and Bright

URGENT need to explore the PeV to EeV neutrino region

In Ice experiments -> Phased Array, NGR
   (Next Generation Radio Array)

In Air from Ice experiments -> EVA, GRAND

In Air: Auger, SKA, GRAND (neutrinos & CR)
Grand35 (2.4 km²) 2018
Grand300 (135 km²) 2020  \(10^{16.5} - 10^{18}\) eV
Grand10K (10⁴ km²) 2025
Grand200K (2 \(10^5\) km²) 2035?

Auger Radio
J. Hörandel UHECR, Paris 2018

Jörg R. Hörandel, UHECR, Paris 2018

Preliminary simulation study
energy of cosmic ray

radio detector (e/m)

MC energy
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 1e19

\sqrt{S_{\text{rad}}/\text{MeV}} - \text{electromag. energy}

0 20 40 60 80 100 120 140

N19
0 1 2 3 4 5 6

p
Fe
no cuts
no $S_{\text{rad}}$ smearing

T. Huege
There has been much progress in radio Many initiatives are being pursued explored Ambitious plans targeting physics are quite advanced Surely new ones are bound to crop up The future is wide open

Thank You
What have we been looking for?
Energy in radio correlated with shower energy

\[ A \cdot 10^7 \text{eV}(E_{\text{CR}}/10^{18}\text{eV})^B, \quad A = 1.58 \pm 0.07, \quad B = 1.98 \pm 0.04 \]

- 3 - 4 stations with signal
- \geq 5 stations with signal
Coherent radio pulses from high energy showers
SKA

- world’s largest radio telescope
  - 1 km² of total collecting area
  - thousands of antennas
  - to be built in Australia & South Africa
- broad scientific goals: astronomical & cosmological obs.
- “phased array”: can observe multiple regions of sky simultaneously!!
- Moon proposed to be observed at different frequency bands:
  - SKA-LOW (100 – 750 MHz)
  - SKA-MID (350 – 1760 MHz)
- can also detect UHECRs
GRAND TREND
Coherent radio pulses from high energy showers

**Graph:**

- **Y-axis:** All-flavor \((\nu + \bar{\nu}) \times E^2 \Phi_{\nu} \) [GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)]
- **X-axis:** Neutrino energy \(E_\nu\) [GeV]

- **Legend:**
  - Blue: Clusters w. central sources
  - Cyan: Newborn Pulsars
  - Green: Active Galactic Nuclei
  - Gray: GRB afterglow-ISM
  - Gray: GRB afterglow-wind
  - Gray: GRB afterglow-late prompt

**Data Points:**

- IceCube (2015)
- Auger (2015)

**Curves:**

- GRAND10k 3yr
- GRAND200k 3yr
Why is the atmosphere so different?
Shower front thickness and curvature play the limiting role

Path difference = \( w \cos \theta_c \)

Further blow up of front

Interference from late and early particles within shower front
Often 2\textsuperscript{nd} order
proton shower of energy $10^{19}$ eV in Antarctica at Cherenkov angle
Is the picture Complete?
Reflection
- Earth’s curvature
- Roughness

Refractive Index
- Ray’s curvature
- Variability
Events can be reconstructed from single location!!
Coherent radio pulses from high energy showers

EZ Heidelberg 2018
\[ N = 126 \]
\[ \mu = 0.04 \pm 0.03 \]
\[ \sigma = 0.29 \]

\[ N = 47 \]
\[ \mu = 0.02 \pm 0.04 \]
\[ \sigma = 0.24 \]
The future is wide open
- Toroidal reflector feed array @ focus

- Concept: Turn an entire super pressure balloon into the antenna!!

Similar sensitivity to full, 3 y of ground-based arrays

Gorham et al. APP 35, 242 (2011)
Coherent radio detection: ν-experiments

Natural transparent media

- **ICE:**
  - Antarctica
    - RICE (array buried)
    - ANITA (balloon)
  - Greenland
    - FORTE (satellite)

- **SALT:**
  - Domes explored
    - SALSA

- **MOON REGOLITH:**
  - Radiotelescopes
    - GLUE
  - Radiotelescope array
    - LUNASKA (ska)

- **ATMOSPHERE:**
  - Antenna array
    - LOFAR

Coherent radio pulses from high energy showers   EZ Heidelberg 2018
Askary’an effect confirmed: SLAC

Coherence! \[ |E| \propto E_{sh} \]

\[ |E(\omega)| \text{ spectral agreement} \]
Summary and conclusion:

- Radio Technique has an enormous potential
  - To detect highest energy events
  - To get detail about showers
  - To cover large surfaces
- It is my opinion (and others) that radio could provide the next step in the search for UHE radiation
- There are many projects under consideration
- It is worth investing on them (lot work to do)