Coherent emission from CR air showers

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Summary of Talk

- Observations of EASs
- Cerenkov, geomagnetic & geo-synchrotron emission
- Codes for coherent radio emission in EASs
- Radio emission in air
- Implications for astrophysics?

Observations of EASs

- EASs from CR primaries $E \gtrsim 10^{15}\,\mathrm{eV}$

$N \sim 10^6$, $10^4\,\mathrm{m}^2$ at $E \sim 10^{15}\,\mathrm{eV}$; $N \sim 10^{11}$, $10^7\,\mathrm{m}^2$ at $E \sim 10^{20}\,\mathrm{eV}$

- Detections of HECRs (e.g., Pierre Auger Observatory)
- Cascade includes $e^{\pm}$ pairs (plus $\mu^{\pm}$, $\pi^{0,\pm}$, ...)
- $e^{\pm}$ exceed phase speed of light in air ($E \gtrsim 20\,\mathrm{MeV}$)
- => emit Cerenkov light
- Detectable only on cloudless, moonless nights

Askaryan effect

- Possibility of Cerenkov radio emission from EASs (Jelley 1958)
- Coherent if $\lambda \gg$ thickness of EAS (ℓ)
- Askaryan recognized $N_{e^+} \neq N_{e^-}$ (Askaryan 1962, 1964)
  allows coherent emission $\propto (N_{e^-} - N_{e^+})^2$
- Effect confirmed observationally (Jelley *et al.* 1965)

Geomagnetic & geo-synchrotron emission

Early theory (Kahn & Lerche 1966)

- $N_e = 10^6$, $\ell = 1\,\mathrm{m}$, $w = 30\,\mathrm{m}$, $E_e = 100\,\mathrm{MeV}$
- Individual $e^{\pm}$ lifetime $10^{-6}\,\mathrm{s}$, continuously replenished
- Emission mechanisms: Cerenkov, geomagnetic, geo-synchrotron, creation/annihilation, ...

Geomagnetic emission

- Separation of e^+ and e^- by Earth's $\mathbf{B}$
- => changing dipole moment => radiation

Geo-synchrotron emission

- Modified form of synchrotron emission due to Earth's $\mathbf{B}$
  - $\tau \ll$ period of one gyration; breaks azimuthal symmetry
  - effect of refractive index of air
- Difficult to disentangle from geomagnetic emission

Codes for coherent radio emission in EASs

Monte Carlo simulation codes

- REAS1, AIRES, CoREAS, ZHAireS, ...
- Collection of individual charges: specified $\mathbf{x}_0$, $\boldsymbol{\beta}$, ...
- Include all relevant accelerations in $\dot{\boldsymbol{\beta}}$
- Sum electric and magnetic fields,

$$\mathbf{E} = \frac{\pm e}{4\pi\varepsilon_0}\left[\frac{\mathbf{n}-\boldsymbol{\beta}}{\gamma^2(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R^2} + \frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 Rc}\right]_{\mathrm{ret}}, \quad \mathbf{B} = \frac{\mathbf{n}\times\mathbf{E}}{c},$$

  $\mathbf{n} = \mathbf{k}c/\omega$, over all particles
- Calculate Poynting vector, $\mathbf{E}\times\mathbf{B}/\mu_0$

Features of models

- Consistent with emission $\propto N^2$
- Geomagnetic/geo-synchrotron emission dominates

Radio emission in air

Cerenkov condition: $n\beta\cos\theta = 1$

- $n = 1 + 1/2\gamma_0^2$, $\beta = 1 - 1/2\gamma^2$, $\cos\theta = 1 - \theta^2/2$
  $=> \theta^2 = \theta_c^2 - 1/\gamma^2$, $\theta_c^2 = 1/\gamma_0^2$
- Cerenkov emission: on the Cerenkov cone, $\theta = \theta_c$

Geo-synchrotron emission

- Occurs both inside ($\theta < \theta_c$) & outside ($\theta > \theta_c$)
- Synchrotron emission suppressed in plasma (Razin effect)
  $n = 1 - \omega_p^2/\omega^2$, suppression $\omega < \omega_{\rm RT} = 2\omega_p^2/3\omega_B\sin\theta$
- Synchrotron emission enhanced for $n > 1$; by how much?

Conventional model for synchrotron emission

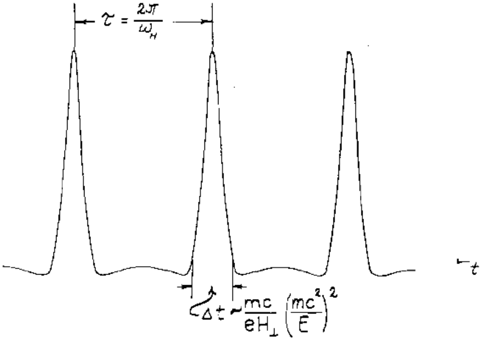

Fig. 4, Ginzburg & Syrovatskii 1965, ARAA

- One pulse seen by observer each gyration
  pulse => frequency spectrum
- Emission confined to $(\theta - \alpha)^2 \lesssim 1/\gamma^2$
- $n > 1$ => Cerenkov cone $(\theta - \alpha)^2 = \theta_c^2 \gg 1/\gamma^2$
- Broadens & adds structure to each pulse

Implications for astrophysics?

Emission by bunches

- Early astrophysics theories: coherence = emission by bunches
- Requires $\lambda \gg \ell$: valid for radio emission in EASs
- 'Bunch' part of initial conditions:
  coherent emission is transitory phase
  analogous to superradiance in quantum optics
- Emission by bunches unobservable in astrophysics

Role of refractive index $n > 1$

- Few examples where $n > 1$ important in astrophysics
  possible exception: HECR passing through Moon
- Extension of synchrotron theory to $n > 1$
  primarily of theoretical interest