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COHERENT RADIO EMISSION FROM COSMIC SHOWERS IN AIR AND IN DENSE MEDIA

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In a previous paper [1] the author evinced the presence of a moving excess negative charge in electron-photon showers and its associated coherent radio emission. In the present article some calculations are made concerning this coherent radio-emission, from which follow several new possibilities for registering showers by their flashes of radiation. It is shown in particular that at small Cerenkov angles (for example as for showers in air) the conditions for coherence are fulfilled even for wavelengths much smaller than the dimensions of the particle cluster in the shower. The role played by the shower core in bringing energy to the working layer during registration of the radio emission in dense media is also noted.

We consider the coherence conditions for radiation from excess charge in a shower in a medium. This charge,

$$Q \approx e(N_e - N_p) \approx 0.1\, eN_e$$

at maximum shower development is distributed proportionally to the density of particles in the shower [1]. (The shower particle cluster, after traveling a distance L in the medium, has a longitudinal dimension z much smaller than the transverse dimension ρ; indeed

$$\rho \approx L\theta_s;\ z \approx L\Delta v_z/c \approx L(1-\cos\theta_s) \approx L\theta_s^2/2,$$

i.e., $z/\rho \approx \theta_s \ll 1$). Therefore the cluster may be taken as very thin and we consider only the radial distribution of charge density $\sigma(\rho)$. The interference factor Φ, obtained by integrating the retardation over the cross sectional area of the cluster, is (c' is the light velocity in the medium)

$$\Phi = \frac{1}{Q}\int e^{i\omega\rho n/c'}dq, \quad dq \approx \sigma(\rho)\,\rho d\rho d\varphi.$$

It is easily seen that

$$\boldsymbol{\rho}\mathbf{n} = \rho\sin\theta\cos(\varphi-\psi), \quad \frac{1}{2\pi}\int_0^{2\pi} e^{ix\sin\varphi}d\varphi = J_0(x),$$

therefore

$$\Phi = \frac{2\pi}{Q}\int_0^\infty J_0\left(\frac{\omega}{c'}\rho\sin\theta\right)\sigma(\rho)\,\rho\, d\rho.$$

It is already evident from this that for $(\omega/c')\rho_{\text{eff}}\sin\theta < 1$ the charge distribution radiates like a point charge, i.e., the radiation is proportional to the square of the charge. Since Cerenkov radiation power increases with increasing frequency, the maximum frequency of coherent radiation, given by $\omega_{\max} \approx c'/\rho_{\text{eff}}\sin\theta$, i.e., $\lambda'_{\min} \approx \rho_{\text{eff}}\sin\theta$, is of most interest. For the

Cerenkov angle (denoted by θ_0) we have $\sin\theta_0 \approx \sqrt{1 - 1/n^2\beta^2}$. In the atmosphere, for example, $\sin\theta_0 \approx \sqrt{n^2 - 1} \approx 3 \times 10^{-2}$. For a maximal cluster radius $\rho_{eff} \sim 30$ m in an air shower we obtain $\lambda_{min} \sim 6$ m which is most effectively detected in the meter wavelength range. The radiated power is

$$I \approx \frac{LQ^2}{\tau c^2}\Phi^2 \sin^2\theta_0\omega\Delta\omega \approx 10^{-2}\frac{Le^2}{c^2}N^2\sin^2\theta_0\omega(\Delta\omega)^2,$$

if the time over which the signal is detected is determined by the bandwidth $r \sim 1/\Delta\omega$. For a radiation formation path in the atmosphere of $L \sim 1$ km, $\Delta\omega/\omega \approx 10^{-2}$ and for $N \gtrsim 10^{10}$ particles at the shower maximum (the energy of the primary particles being $\epsilon_0 \gtrsim 10^{18}$ eV), the pulse power will be $I \gtrsim 10^{-3}$ W, which is quite sufficient for detection. If a radio-emission pulse, arriving at the earth from a height of $h \approx 10$ km, has a radius R of several hundred meters

$$(\Delta\theta_0 \approx \lambda'/L\sin\theta_0 \approx \theta_0 \approx 3\cdot 10^{-2};\ R \sim h\theta_0 \approx 3\cdot 10^2\ \text{m}),$$

then the signal field intensity $E \approx R^{-1}\sqrt{I/c} \approx 10^3\,\mu$V/m, which is many times greater than the amplitude of noise interference, $E_{noise} \approx 30\ \mu$V/m.

The detector antenna need not be directed upwards. Detection of radio emission scattered from the earth's surface or reflected obliquely from the beam is also possible, which simplifies remote collection of signals from a large area. Reception of scattered radiation permits the indirect registration of even very small pulses of radio-emission (small Cerenkov angles, small elevation at maximal development of very powerful showers).

We note that the frequency dependence of the interference factor can be worked out in greater detail using the actual form of the particle density distribution in the shower. The empirical formula $\sigma_N \sim (A/\rho)e^{-\rho/a}$ is frequently cited. It corresponds to the density of excess charge $\sigma \approx (Q/2\pi a\rho)e^{-\rho/a}$ and the interference factor

$$\Phi \approx \left[1 + \left(\frac{a\omega}{c}\sin\theta\right)^2\right]^{-1/2}.$$

In this case the decrease in the interference factor is less marked and is even overcompensated by the increase in signal intensity with frequency, i.e., it is possible to go to shorter wavelengths. For more pronounced localization, as in the case of a Gaussian distribution for example,

$$\sigma(\rho) \approx (Q/\pi a^2)\exp\{-(\rho/a)^2\},$$

the interference factor

$$\Phi = \exp\{-(a\omega\sin\theta_0/2c')^2\}$$

depends very strongly on frequency; decreasing the frequency of the detector leads to a sharp decrease in the received power.

When the coherence condition is satisfied the intensity ratio for coherent and incoherent [2] radio emission in one and the same frequency range is $I_{coh}/I_{incoh} \approx 10^{-2}N > 10^7$ for a shower particle density $N > 10^9$. This means that the coherent radiation is preferred for registration of very rare showers of very high energy particles. The efficiency is also increased by the strong quadratic dependence of the signal intensity on the number of particles in the shower, i.e., on the energy of the primary particles.

In some cases there is interest in the registration of showers in dense media. The air shower core may play an essential role in the generation of radio emission in dense media, guaranteeing the transfer of energy concentration to the working layer in which a radio-emission producing shower is generated. Possible working layers are: for internal radio detection—substances which absorb or scatter radio waves weakly (an ice layer, permafrost, very dry rock, etc.); for external detection—substances securing the transfer of radiation to the outside by means of scattering in the medium (in this case, in view of the small radio-emission path in the medium, even media having poor dielectric properties can be used). It is interesting to note that with increasing primary particle energy, the point of maximum development of the shower approaches the earth's surface which also directs attention to the registration of showers in dense media. Some problems concerning the registration of particles with very high penetrating power by the radio-emission of the showers they produce in dense underground layers and on the moon are considered in[1].

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