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Very long-wave electromagnetic radiation from jets

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Abstract. Exact solution is obtained for electromagnetic field around a conducting cylinder of infinite length and finite radius, with a periodical axial electrical current, for wave length much larger than the radius of the cylinder. The solution describes simultaneously the fields in the near zone close to the cylinder, and transition to the wave zone. Proper long-wave oscillations of such cylinder are studied. The electromagnetic energy flux from the cylinder is calculated. These solutions could be applied for description of the electromagnetic field around extragalactic jets from active galactic nuclei and quasars and particle acceleration inside jets.

Key words. jets – electromagnetic waves – particle acceleration

1. Introduction

Objects of different scale and nature in the universe, from both young and very old stars to active galactic nuclei (AGN), show the existence of collimated outbursts or jets. The geometrical sizes of these jets lay between parsecs and megaparsecs. The origin of astrophysical jets is not well understood. A theory of jets should answer to the question of the origin of relativistic particles in the outbursts from AGN, where synchrotron emission is observed. Relativistic particles, ejected from the central engine, rapidly loose their energy so the problem arises of the particle acceleration inside the jet, see review of Bisnovatyi-Kogan (1993).

It is convenient sometimes to investigate jets in a simple model of infinitely long circular cylinder, Chandrasekhar & Fermi (1953). The magnetic field in collimated jets determines its direction, and the axial current stabilizes the jet's elongated form at large distances from the source (e.g. in AGNs), Bisnovatyi-Kogan et al. (1969). When observed with high angular resolution these jets show a structure with bright knots separated by relatively dark regions Thompson et al. (1993b). High percentages of polarization, sometimes exceeding 50%, indicate the nonthermal nature of the radiation, which is well explained as synchrotron emission of the relativistic electrons in a weak but ordered magnetic field. Estimates of the lifetime of these electrons, based on the observed luminosities and spectra, often give values much less than the kinematic ages $t_k = d/c$, where d is the distance of the emit-

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ting point from the central source. There is a necessity of continuous re-acceleration of the electrons in the jets in order to explain the observations. The acceleration mechanism for electrons in extragalactic jets proposed by Bisnovatyi-Kogan & Lovelace (1995), considers that intense long-wavelength electromagnetic oscillations accompany a relativistic jet, and the electromagnetic wave amplitudes envisioned are sufficient to give in situ acceleration of electrons to the very high energies observed > 10^{13} eV. It was assumed that jets are formed by a sequence of outbursts from the nucleus with considerable charge separation at the moment of the outburst. The direction of motion of the outbursts is determined by the large-scale magnetic field. When the emitted wave is strong enough it washes out the medium around and the density can become very small, consisting only of the accelerated particles. The action of the oscillating knot is similar to the action of a pulsar, considered as an inclined magnetic rotator. Both emit strong electromagnetic waves, which could effectively accelerate particles. The model of enhanced oscillations of the cylinder, considered below, have been studied by Bisnovatyi-Kogan (2004).

2. Cylinder with oscillating current

Consider an infinitely conducting circular cylinder in vacuum. The Maxwell equations for periodic oscillations with all values $\sim \exp(-i\omega t)$ read

$$\mathrm{div}\,\mathbf{B} = 0, \quad \mathrm{rot}\,\mathbf{B} = -\frac{i\omega}{c}\mathbf{E} + \frac{4\pi}{c}\mathbf{j}, \tag{1}$$

$$\mathrm{rot}\,\mathbf{E} = \frac{i\omega}{c}\mathbf{B}, \quad \mathrm{div}\,\mathbf{E} = 0.$$

We use the same definitions for all complex values depending on coordinates. In the cylinder coordinate system (r, ϕ, z) the only nonzero components are E_z, B_ϕ, j_z, and $\partial/\partial\phi = \partial/\partial z = 0$. Only two valid equations remain from the system (1), reducing to one equation

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dE_z}{dr}\right) + \frac{\omega^2}{c^2}E_z + \frac{4\pi i\omega}{c^2}j_z = 0. \tag{2}$$

with $B_\phi = \frac{ic}{\omega}\frac{dE_z}{dr}$. In the vacuum, $j_z = 0$. Using the non-dimensional variable $x = r\omega/c$, we obtain from (2)

$$x^2E_z'' + xE_z' + x^2E_z = 0, \qquad B_\phi = iE_z'. \tag{3}$$

Here $'$ denotes differentiation over x. The equation (3) belongs to the Bessel type, which solution for physical values, accounting for the time dependence, is obtained from the real part of the complex solution at $C_1 = C_1^{(r)} + iC_1^{(i)}$, $C_2 = C_2^{(r)} + iC_i^{(i)}$. The boundary condition far from the cylinder follows from the demand that there exists only an expanding wave with a solution depending on the combination $(x - \omega t)$. Using the asymptotic of Bessel functions at large arguments we obtain for the expanding wave $C_1^{(i)} = -C_2^{(r)}$, $C_2^{(i)} = C_1^{(r)}$, and the solution at large distances

$$E_z \approx \sqrt{\frac{2}{\pi x}}[C_1^{(r)}\cos(x - \frac{\pi}{4} - \omega t) \tag{4}$$

$$+C_2^{(r)}\sin(x - \frac{\pi}{4} - \omega t)], \qquad B_\phi = -E_z.$$

The general vacuum solution, satisfying conditions at infinity reads as

$$E_z = [C_1^{(r)}J_0(x) + C_2^{(r)}Y_0(x)]\cos\omega t \tag{5}$$

$$+[-C_2^{(r)}J_0(x) + C_1^{(r)}Y_0(x)]\sin\omega t,$$

$$B_\phi = -[C_1^{(r)}J_1(x) + C_2^{(r)}Y_1(x)]\sin\omega t \tag{6}$$

$$+[-C_2^{(r)}J_1(x) + C_1^{(r)}Y_1(x)]\cos\omega t.$$

The equations in the matter is ($B_\phi = iE_z'$):

$$x^2E_z'' + xE_z' + x^2E_z + \frac{4\pi i}{\omega}x^2j_z = 0, \tag{7}$$

A solution of the non-uniform linear equation (7) is a sum of a general solution of the uniform equation, and a particular solution of the non-uniform one $G_0(x)$.

$$E_z = G_1J_0(x) + G_2Y_0(x) + G_0(x), \tag{8}$$

with $G_2 = 0$ to avoid singularity of $Y_0(x)$ at $x = 0$. Looking for a particular solution in the form $E_z = G(x)J_0(x)$. we obtain from (7) the equation with respect to $F = G'$

$$x^2(F'J_0 + 2FJ_0') + xFJ_0 + \frac{4\pi i}{\omega}x^2 j_z = 0. \quad (9)$$

From this equation we obtain the general solution for the amplitude of the electric field in the matter, in presence of periodic EEF:

$$E_z = -\frac{4\pi i}{\omega}J_0(x)\int_0^x \frac{dy}{yJ_0^2(y)} \quad (10)$$

$$\times \int_0^y zJ_0(z)j_z(z)dz + G_1 J_0(x).$$

For waves much longer than the radius of the cylinder r_0, $x_0 = \frac{\omega r_0}{c} \ll 1$, and using the expansion at $x \ll 1$, we obtain from (10) the solution ($G_1 = G_1^{(r)} + iG_1^{(i)}$)

$$E_z = -\frac{2i\omega}{c^2}\int_0^x I_z(y)\frac{dy}{y} + G_1, \ \ I_z(y) \quad (11)$$

$$= 2\pi\frac{c^2}{\omega^2}\int_0^y j_z x\,dx, \ \ r = cy/\omega.$$

The total electrical current through the cylinder $I_0 = I_z(r_0)$, and the fields on its surface (inside) $E_0 = E_z(r_0)$, $B_0 = B_\phi(r_0)$ (real parts of complex relations) are obtained from complex relations. All field components are continuous at the cylinder surface in absence of the surface charges and currents. Matching magnetic and electrical fields we obtain the coefficients in the solution of the external electromagnetic field. Consider a case when the resulting electrical current produced by the external EEF is purely sinusoidal, $I_0 = I_0^{(i)}\sin\omega t$. Than we obtain using expansions

$$C_1^{(r)} = 0, \quad G_1^{(i)} = -C_2^{(r)}. \quad (12)$$

$$C_2^{(r)} = \frac{\pi\omega}{c^2}I_0^{(i)}, \quad G_1^{(r)} = \frac{2\omega}{c^2}\ln\frac{x_0}{2}I_0^{(i)}. \quad (13)$$

The whole solution for the electromagnetic field of the long wave emitted by the cylinder with the sinusoidal electric current follows from (5),(6):

$$E_z = \frac{\pi\omega}{c^2}I_0^{(i)}[Y_0(x)\cos\omega t - J_0(x)\sin\omega t],$$

$$B_\phi = -\frac{\pi\omega}{c^2}I_0^{(i)}[Y_1(x)\sin\omega t + J_1(x)\cos\omega t].$$

Near the cylinder we have $B_\phi \approx \frac{2I_0^{(i)}}{cr}\sin\omega t$, $E_z \approx \frac{2\omega}{c^2}I_0^{(i)}\ln\frac{r\omega}{2c}\cos\omega t$. Note, that in the near zone of the long wave the magnetic field adiabatically follows the current through the cylinder. The distribution of the electrical field is similar to the one of the linearly growing current in the cylinder Bisnovatyi-Kogan (2003). At large r the expanding cylindrical wave ($B_\phi = -E_z$)

$$B_\phi = -\frac{1}{c}\sqrt{\frac{2\pi\omega}{cr}}I_0^{(i)}\sin[\frac{\omega}{c}(r - ct) - \frac{\pi}{4}]. \quad (14)$$

3. Electromagnetic energy flux from jet

A strong electromagnetic wave generated by oscillations may accelerate effectively particles at large distances from the nucleus near the jet, as well as at larger radii. Let us estimate the energy flux in the electromagnetic wave radiated by the jet of length l, and radius r_0. If n_e is the electron density producing the electrical current, then, the Pointing flux $P = \frac{c}{4\pi}[\mathbf{EB}]$ through the cylinder surface is $F = 2\pi r_0 lP = \frac{\pi l\omega}{2c^2}I_0^2$. For the amplitude of the electrical current along the cylinder radius $I_0 = \pi r_0^2 n_e ce$, we obtain the energy flux from the jet

$$F = \frac{\pi^3}{2}e^2 l r_0^4 \omega n_e^2 \approx 2\cdot 10^{49}\ \text{erg/s}$$

$$\frac{l}{1\ \text{kpc}}\left(\frac{r_0}{1\ \text{pc}}\right)^4 \frac{100\ \text{yr}}{T} \times \left(\frac{n_e}{10^{-10}\ \text{cm}^{-3}}\right)^2.$$

Here $T = \frac{2\pi}{\omega}$ is the period of the electromagnetic wave. Part of the radiated energy is used for particle acceleration up to very large energies, and support the jet radiation at different energy regions of the electromagnetic spectrum.

4. Conclusion

The similarity of the acceleration mechanisms of the particles in both pulsars and relativistic jets could be a reason for the similarity

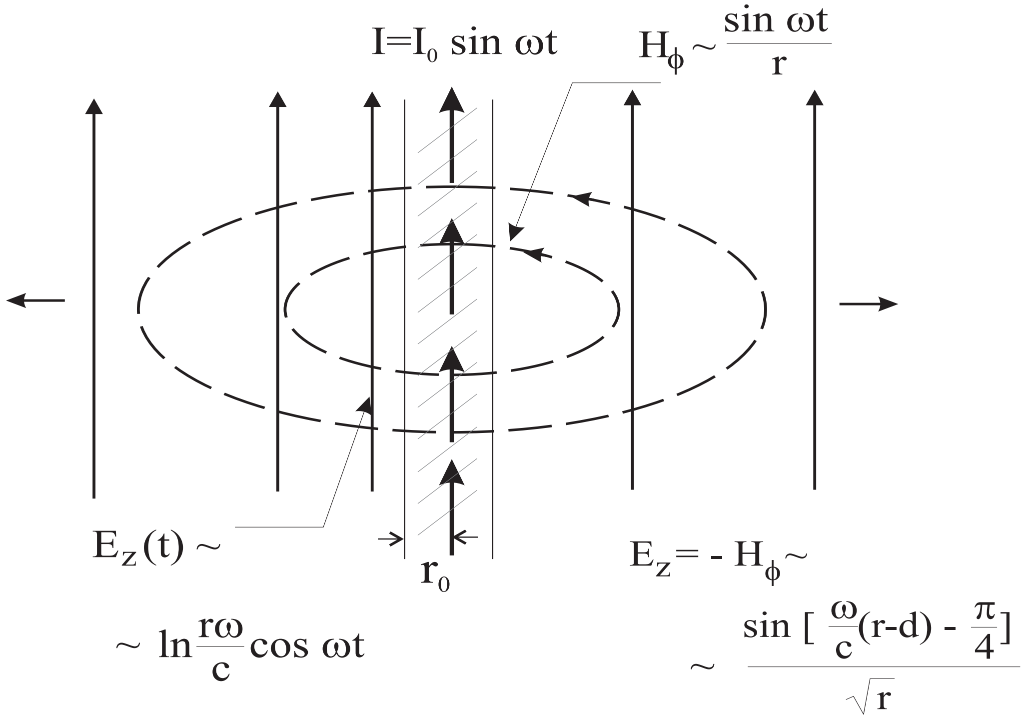

Fig. 1. Magnetic and electrical fields around the infinite cylinder with the radius r_0, and low-frequency $\omega \ll c/r_0$, sinusoidal electrical current along the cylinder axis. In the near zone electrical and magnetic fields are varying in antiphase, and far from the cylinder $r \gg c/\omega$ the expanding cylindrical electromagnetic wave is formed, with $E_z = -B_\phi$.

of the high-energy radiation around 100 Mev observed by EGRET in number of radiopulsars Thompson et al. (1992); quasars and AGN Thompson et al. (1993a).

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