On Coherent Mechanisms of Emission and their Application to Pulsars
I. Introduction. Antenna Mechanisms of Emission

1. In astrophysics we have most often to deal with incoherent mechanisms of emission when in the absence of absorption and reabsorption (absorption by the radiating particles themselves), the total intensity (power) of radiation, U, from a source of radiating particles (molecules, atoms, electrons) is equal to the sum of the intensities of the individual particles. In other words, for incoherent mechanisms the intensity of radiation is $U = Nu$. Taking into account absorption and reabsorption, $U \leqslant Nu$, where u is the intensity of radiation from a single particle and N is the total amount of radiating particles in a source. However, in a series of cases it is also necessary to examine the coherent mechanisms of radiation in which the intensity is $U > Nu$ and, generally speaking, not proportional to N. Examples may be cosmic masers in the OH and other molecules lines, some components of sporadic radio emission from the Sun, and the radio emission of pulsars.

The radiation flux emitted by a sphere of radius r and observed at the distance R is equal to

$$F_\nu = (2\pi\nu^2/c^2)\kappa T_B(r/R)^2.$$

The brightness temperature of the source will be

$$T_B = \frac{c^2 F_\nu}{2\pi\kappa\nu^2}\left(\frac{R}{r}\right)^2 = 1.04\times 10^{13}\nu^{-2}\left(\frac{R}{r}\right)^2 \bar{F}(\nu), \qquad (1)$$

where $\bar{F}(\nu)$ is measured in units of flux, 1 f.u. $= 10^{-26}$ watt/m^2 Hz. Equation (1) may be assumed to determine T_B and then it is formally suitable also outside the limits of the condition $h\nu \ll \kappa T_B$. Under this condition formula (1) holds also for the equilibrium radiation when $T_B \leqslant T$.

For the pulsar NP 0532 in the Crab the mean flux in time is about equal to

$$\bar{F}(10^8\,\text{Hz}) \sim 10\,\text{f.u.},\quad \bar{F}(10^{15}\,\text{Hz}) \sim 10^{-2}\,\text{f.u.},\quad \bar{F}(10^{18}\,\text{Hz}) \sim 10^{-4}\,\text{f.u.} \qquad (2)$$

Hence, at $R = 1500$ pc and $r \sim 5 \times 10^7$ cm, we get

$$T_B(\text{radio}) \sim 10^{26}\,°\text{K} \qquad T_B(\text{optics}) \sim 10^9\,°\text{K}, \qquad T_B(\text{x-rays}) \sim 10\,°\text{K} \tag{3}$$

Even decreasing the radius r by an order of magnitude, T_b(optics) $\sim 10^{11}$ which corresponds to the particle energy $E \sim \kappa T_B \sim 10^7$ eV. Hence it is clear that the optical and x-ray emission from pulsars can be fully incoherent, for example, by incoherent synchrotron radiationor inverse Compton scattering. By contrast, it is evident that even at $T_B \sim 10^{20}$ (for NP 0532 this corresponds to a radius of about 5×10^{10} cm), the radio emission cannot be incoherent since acceleration of a great number of electrons up to energies $E \gtrsim 10^{16}$ eV seems completely unrealistic (moreover, the intensity and, respectively, the impulsive value of T_B for pulsars are considerably higher than the utilized mean values). The same may be said about the OH sources with $T_B \sim 10^{12}$ and certain solar radio bursts.[1]

2. There are two essentially different types of coherent mechanisms of radio emission which may be called "maser" and "antenna" or "aerial". A maser mechanism acts even in a uniform medium without a preliminary space bunching of particles and also it does not require bunching (phasing) of particles in the velocity space. Thus the maser mechanism can begin to operate in the absence of macroscopic currents varying with the radiated frequency. The amplification of waves stimulated by inverse populations of levels forms the basis of the maser mechanism. This amplification has features in common with reabsorption. In both cases the intensity along the path L in the uniform medium varies according to the law

$$I = I_0 \exp(-\mu L)$$

(for reabsorption $\mu > 0$ and for amplification $\mu < 0$). Since μ depends on the radiating-particle density, $n = N/V$, the intensity I is nonlinearly dependent on N, which points out a coherent character of the maser mechanism.‡

For the antennae radiation mechanisms it is essential there be a spatial nonuniformity of the current distribution in the source. In the simplest case there is a source, consisting of bunches of particles, with one dimension $l \ll \lambda$ (λ is the wavelength in the medium; both λ and l

‡ From what has been said it is evident that in the presence of reabsorbtion it is not quite consistent to relate the mechanism of radiation to the number of incoherent mechanisms. Nevertheless, it seems to us more simple and convenient to call the mechanism of radiation coherent only if $U > Nu$.

are measured in one and the same "laboratory" frame of reference). If all dimensions of the bunch satisfy this condition, its radiation in all directions is coherent in the sense that all particles in the bunch radiate in phase. Therefore, the total intensity (power) of radiation is $U_b = n_b^2 u$, where u is the intensity of radiation of one particle and n_b is the number of particles in the bunch. If, for example, there is an electron cluster (bunch) with $l \ll \lambda$, the total intensity of radiation, say, at its acceleration is proportional to $(en_b)^2$ when the intensity of radiation from an electron is proportional to e^2.‡

For a source with N particles and N_b independently (incoherently) radiating bunches, it is evident that

$$U = N_b n_b^2 u = n_b N u. \tag{4}$$

Thus, in the present case the intensity of radiation is n_b times higher than for the incoherent source with the same values of N and u.

For filament-shaped bunches with diameter $l \ll \lambda$ or discs with thickness $l \ll \lambda$, the radiation from all particles in the bunch has equal phase, generally speaking, only in the direction perpendicular to the filament axis or disc plane. These cases are similar to thin antennas of the proper shape. That is why we call such coherent mechanisms "antennas".

If the characteristic size l of the bunch increases, the intensity of the radiation begins rapidly to fall as soon as $l \gtrsim \lambda$. Actually, the intensity of the radiation with wave vector

$$\mathbf{k} = (2\pi/\lambda)\mathbf{k}/k$$

is proportional to

$$I \sim \left| \int \mathbf{j}(\mathbf{r}) \exp(i\mathbf{kr})\, d\mathbf{r} \right|^2,$$

where $\mathbf{j}(\mathbf{r})$ is the current density in the source (bunch). If we restrict

‡ To eliminate confusion in the terminology we note the following. The radiation is, in general, called coherent when a phase of the field is fixed. Obviously, any fixed, regular, nonstatistical current distribution radiates coherently. A particular case of such coherent radiation is the above-mentioned radiation, provided that the difference in phases between radiators in the bunch is small. A set of coherent radiators (bunches) with independent (random) phases yields, on the whole, incoherent or partially coherent radiation. This is true also for the maser radiation in cosmic conditions when the radiation from a whole source is incoherent (we mean random phases of the field in different directions and at different frequencies). That is why we carefully distinguish in the text the coherent radiation from coherent mechanisms of radiation defined by the condition $U > Nu$. However, the base of such mechanisms is some coherence, for example, within the bunch or when the waves are amplified in the given direction.

ourselves (for the sake of simplicity) to a one-dimensional distribution of the type

$$j = j_0 \quad \text{at} \quad -\tfrac{1}{2}l < x < \tfrac{1}{2}l,$$

$$j_0 = 0 \quad \text{at} \quad |x| > \tfrac{1}{2}l,$$

the intensity is $f = \sin^2(\pi l/\lambda)/(\pi l/\lambda)^2$ times less than at $l \ll \lambda$. For a more real, smooth current distribution, the factor f drops more rapidly with the growth of the ratio $\pi l/\lambda$. So, if

$$j = j_0 \pi^{-1/2} \exp(-x^2/l^2),$$

then

$$f = \exp(-\pi^2 l^2/\cdot\lambda^2). \tag{5}$$

The factor (5) is rather small already at $l = \lambda$ when $f = e^{-\pi^2} \sim 10^{-4}$. Obviously, at $l = 3\lambda$, $f \sim 10^{-40}$ and, consequently, the antenna mechanisms are effective only at $l < \lambda$.

The use of the expression of the type (4) is also limited by the condition of incoherence of the individual clusters (bunches). In general, it is characteristic of the antenna mechanism that the currents or the electromotive forces are fixed and the mutual effect of neighbouring bunches is not taken into account. On the other hand, in the extended plasma region in the presence of many radiating bunches there are no grounds to assume the currents to be given. The account of the mutual cluster action means, in principle, the account of reabsorption on bunches which leads to decreasing the intensity in comparison with (4).

3. It is very difficult to satisfy these requirements ($l < \lambda$ and the independence of the radiation of different bunches) at the meter and shorter wavelengths in cosmic conditions. Even if pronounced bunches had formed, they would dissipate very quickly. The point is that in cosmic space it is difficult to expect the formation of monoenergetic particles and, therefore, the particles in bunches will have a marked velocity distribution $\Delta \mathbf{v}$. Thus, say, along the magnetic field, the bunch is considerably smeared at a time $\tau \sim l/\Delta v_{\parallel}$. Hence, for $l \sim 30$ cm and a velocity spread along the field $\Delta v_{\parallel} \sim 8 \times 10^9$, the time will be $\tau \sim 10^{-8}$ sec. The bunch directed across the magnetic field (at the azimuth) is also smeared in the time

$$\tau \lesssim \frac{2\pi r_H}{\Delta v_\perp} = \frac{2\pi v_\perp}{\Delta v_\perp \omega_H^*}, \qquad \omega_H^* = \frac{eH}{mc}\frac{mc^2}{E},$$

Even with $\Delta v_\perp \sim 10^{-2} v_\perp$, the time interval $\tau \lesssim 10^3/\omega_H^*$ and with $E/mc^2 \sim 10^2$, $H > 10^6$ Oe, the value of τ is less than 10^{-8} sec.

We can give many similar examples,‡ all of them testify that any pronounced antenna mechanism is unrealistic for cosmic conditions. On the other hand, in connection with the discussion of the nature of pulsar radiation, it has often been suggested in the literature to use antenna mechanisms.[3–6] However, no concrete reasons for the arising of distinct bunches and their stabilization are given. Due to this, the calculations carried out appear to be completely groundless. This is true even for the radio band. As for the optical and x-ray regions, it is much more difficult to speak of the occurrence of bunches or current layers with a characteristic size (diameter, thickness of the layer) $l < \lambda$. Thus, the assumption[6] about the coherent x-radiation from the current layer seems quite unacceptable (the occurrence and existence of current layers with thickness in angstroms is absolutely unrealistic; one must remember also that the current density obeys the condition $j = env \leqslant enc$; therefore, a very thin layer is unable to carry a large current). The trend to use antenna mechanisms may be connected with the fact that the radio emission from pulsars, as was said above, cannot be incoherent and at the same time the maser mechanisms are not as well known yet as the classical antenna mechanisms. Nevertheless, in cosmic conditions the maser coherent mechanisms rather than the antenna ones are of significance. We have already emphasized this circumstance.[7]

V. L. Ginzburg
V. V. Zheleznyakov

‡ One must bear in mind that the radiation reaction can aid the disappearing or instability of bunches (see Ref. 2).

References

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