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POSSIBLE RADIO EMISSION MECHANISM FOR PULSARS

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16. Abstract

The magnetic field in the neutron-proton-electron (npe) layer of a neutron star results from a quasistationary eddy current of superconducting and normal protons relative to normal electrons, which generates radio emission by the Josephson effect. The radiation propogates in the magnetically active medium, from the "optically thick" npe layer to the magnetosphere through breaks in the crust. As a result, "hot radio spots" form on the surface of the star, and a radiation pattern forms near the magnetic poles, the cross section of which gives the observed pulse structure. Due to the specific properties of the mechanism, variations of the quasistationary current are converted to amplitude-frequency variations of the radiation spectrum. Variations of the fine structure of the spectrum pulse amplitude and spectral index, as well as their correlation in this model result from this.

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ANNOTATION

The quasistationary eddy current of protons relative to electrons in the superconducting mantle of a neutron star, resulting from the internal magnetic field, generates radio emission by the Josephson effect, which, propagating in the magnetically active medium, goes from the thin layer of the "optically thick" mantle to the magnetosphere through breaks in the crust. "Hot radio spots" form on the surface of the star as a result, and a radiation pattern forms near the magnetic poles, the cross section of which gives the observed pulse structure. Due to the specific properties of the mechanism, variations of the quasi-stationary current are converted into amplitude-frequency variations of the radiation spectrum. Variations of the fine structure of the spectrum, pulse amplitude and spectral index, as well as their correlation in this model, result from this.

POSSIBLE RADIO EMISSION MECHANISM FOR PULSARS

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1. Introduction

Extensive observation material and theories of pulsars have now /3*
been obtained. However, as before, the question of the mechanism of their radio emission remains open. All previously proposed mechanisms can be classified as antenna or maser mechanisms [1]. They connect the generation of the radio emission with regions located near the light cylinder or surface of a neutron star in space. A radio emission mechanism is proposed in this study, which is intermediate in this classification, and it is generated inside the neutron star, i.e., it is determined by its structure. Based on present ideas of the structure of neutron stars and with some additional hypotheses, practically all the basic features of the radio emission of pulsars can be explained from the unique viewpoint of the proposed model.

2. Initial Assumptions

According to the current model, a typical neutron star consists of [1-4]: 1. a core (at least, in some stars of density ρ, greater than some critical density ρ_c); 2. a mantle, made up of a neutron-proton-electron fluid ($2\cdot10^{14}$ $g\cdot cm^{-3} \lesssim \rho < \rho_c$, neutrons and protons most likely
superfluid, electrons normal); 3. a solid metal type crust, with a /4
lattice of "bare" nuclei and an electron gas, with which superfluid neutrons are "mixed" in the inner part of the crust; 4. a solid surface $\rho < 10^6$ $g\cdot cm^{-3}$, the structure of which is strongly dependent on the magnetic fields and, possibly, is close to a "quasipolymer metal" structure, with the complete (or nearly complete) absence of free electrons. The development of cracks and fractures can be expected in the crust, because of starquakes (see, for example, [5]), which apparently seal and harden rapidly. Besides, it turns out that the superfluid

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*Numbers in the margin indicate pagination in the foreign text.

neutron component is energetically favorable in the rotating star, to the formation of a periodic space lattice of vortex filaments (parallel to the axis of rotation of the star), with nonsuperfluid cores and, with the superconducting proton component in the inner magnetic field, $B \gtrsim 10^{16}$-10^{17}G, formation of a state like the mixed state in type II superconductors or the intermediate state in type I superconductors. The magnetic field then permeates the mantle through the normal regions which alternate with the superconducting regions, and it is maintained by the currents flowing in a thin layer along the region boundaries.

To be definite, we will consider hereafter that the superconducting component is in a state similar to the mixed state, and that the magnetic field is directed basically normal to the cores of the superconducting vortex filaments, which are parallel to the axis of rotation of the star.[1] As a result, we have the model presented in Fig. 1.

We replace the actual distribution of the magnetic field in the filaments by B=const within its core and a layer, the thickness of which is on the order of the penetration depth λ of the magnetic field from the normal core to the superconducting shell of the filament, and B=0 in the remaining region. As was noted above, this field should be /5 maintained by the charged component current of the λ layer, i.e., by the eddy current of protons (superconducting and normal, since the temperature differs from zero) relative to the electrons (normal), in a quasicylindrical layer of the shell, of thickness $(\lambda - \xi) \sim \lambda$, where ξ is the proton pair coherence length.

The presence of nonsuperconducting "interspersed particles" permits the shell of the vortex filament to be considered a superconductor with microscale discontinuities, which form a "spongy" microstructure of coupled superconducting sections. Since the coherence length is greater than the average distance between particles, and the minimum sizes of

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[1] However, subsequent reasoning is equally applicable, both to other orientations of the field in the mixed state, and to the intermediate superconductor state.

the interspersed particles are comparable to it, it can be expected that elements of this microstructure are "weakly coupled" structures, of the laboratory "microbridge," Josephson junction type.[2] Then, the current of protons relative to the interspersed electrons is a current through the branched chains of "proton microbridges."

3. Emission of Microstructure Element

We construct the following model of an isolated proton microbridge from available analogies [6, 7]. In accordance with the aforementioned, current I through it is made up of the normal I_N and superconducting I_S proton currents, in which $I \sim$ const. Let normal component I_N obey Ohm's law. By using the phenomenological approach developed by Feynman [8] for description of weakly coupled quantum systems, it can be shown that expressions I_S completely coincide, in the case of proton and electron superconductivity. As a result, for the proton bridge under consideration, we reach those Josephson relationships, which frequently are used (see, for example, [6]) in description of the electrodynamics of weakly coupled laboratory structures with electron superconductivity: /6

$$I = I_N + I_s = \sigma_N \cdot V + I_m \cdot \sin(\varphi + \tilde{\varphi}) \quad , \qquad (1)$$

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[2] This type of Josephson junction is a variety of "weakly coupled" structure [6], since it is considered that the superconducting properties in the junction region are "weakened," by microscopic constriction of the superconductor (in distinction, for example, from the dielectric layer between superconductors in "classical" Josephson tunnel junctions). Despite the fact that the entire group of phenomena occurring in weakly coupled structures is still far from completely understood, their basic properties in laboratory experiments, as well as in tunnel junctions, are described well by the Josephson equations. Theory [6] gives a criterion of sufficiency of a "weak coupling." The estimates obtained below satisfy this criterion by a wide margin, which is a strong additional argument in favor of the weakly coupled nature of elements of the spongy microstructure.

$$\frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar} \,, \tag{2}$$

$$I_m = I_c \cdot \sin \tilde{\varphi} / \tilde{\varphi} \,, \quad \tilde{\varphi} = \pi \phi / 2\phi_0 \approx const. \tag{3}$$

Here, σ_M is the bridge conductivity for the normal component of the current, V is the potential difference (which arises in the junction in flow of current $I > I_m$), I_c and I_m are the critical Josephson currents at B=0 and B≠0, respectively, ϕ is the magnetic flux which permeates the bridge, ϕ_0 is the magnetic flux quantum, $\phi_0 = hc/2e$, e is the electron charge, h is the Planck constant, $\hbar = h/2\pi$. The dependence (3) on the magnetic field immediately is incorporated in Eq. (1), with allowance for the sufficiently small (relative to λ) dimensions of the bridge /7 (for simplicity in this case, the existing differences in the specific relationships of the current to the magnetic field for various types of weak couplings are not taken into account). By solving (1), (2), with $I_m < I = const$ and $\tilde{\phi} = const$, we have [7]

$$V = V_0 \left(1 + 2 \cdot \sum_{n=1}^{\infty} p^{n/2} \cdot \cos n\omega_0 t\right) \,, \tag{4}$$

where V_0 is the time average potential difference, $\omega_0 = 2eV_0/\hbar$ is the Josephson frequency, $p \equiv (1 - \sqrt{1-\gamma^2})^2 / \gamma^2$, $\gamma \equiv I_m / I$, $V_0 = I\sqrt{1-\gamma^2}/\sigma_M$. By means of these relationships, the power spectrum of the radiation P_ω from an isolated proton microbridge, at frequency $\omega = n\omega_0$, can be obtained in the following form

$$P_\omega = \eta_\omega \cdot P_0 \cdot p^{\omega/\omega_0} \,, \tag{5}$$

where η_ω is the power propagation ratio to the surrounding medium at frequency ω, normalized to unity, with possible error taken into account; $P_0 \equiv \hbar\omega_0 \cdot I \cdot \sqrt{1-\gamma^2}/2e$, in which p always <1 (see above).

We note the basic features of this radiation. Spectrum (5) is linear, with η_ω=const, exponential, decreasing towards high frequencies.

It consists of lines at the Josephson frequency and its harmonics, the number of which is determined by the value of γ (the closer $\gamma<1$ to unity, the "richer" the spectrum) and the width of the spectrum. The spectrum is bounded below by Josephson frequency ω_0 and above, by some limiting frequency ω_{np}, which characterizes the energy of the quantum which destroys a Cooper pair

$$\omega_{np} \approx 2\Delta/\hbar \quad , \tag{6}$$

where Δ is the energy gap of the superconductor. Since $\Delta \sim 0.1$MeV in this case [2, 4] in the radio range, spectrum (5) is only bounded below. Because of the specific nature of the Josephson mechanism, the spectral lines are strictly monochromatic, and the radiation is coherent.[3] Actually, however, small, but finite broadening can be expected, which is connected, for example, with fluctuations of V_0 and, consequently, $n\omega_0$. Besides, it can be expected that the radiation will have directivity and linear polarization, similar to the radiation of an elementary oscillator, since it is connected with the flow of current through the junction. /8

We estimate the Josephson frequency, on consideration that $V_0 \sim I/\sigma_M$, the current in the λ layer is determined by the magnetic field through the solenoidal relationship, and all elements of the spongy microstructure are weakly coupled. Then, it is easy to obtain

$$\omega_0 \sim \frac{c \cdot e}{2\pi\hbar} \cdot \frac{L \cdot B}{\lambda \cdot \sigma} \quad , \tag{7}$$

where L is the dimension of the element in the direction of flow of

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[3] There are many features similar to those of maser radiation, since the Josephson mechanism also is of a quantum nature, coupled to energy transitions, but superconducting particles during their movement through the "weak" coupling region, when $V_0 \neq 0$. Since all the superconducting particles behave completely identically, because of their Bose condensation, the radiation is monochromatic and coherent (for greater detail, see, for example, [6]).

the current, σ is the conductivity of the mantle (for the normal component). On the assumption that $B \sim 10^{12}$G, $\sigma \sim 10^{30}$sec^{-1}, $L \sim n^{-1/3}$, where $n \sim 10^{36}$cm^{-3} is the concentration of the electron-proton component of the mantle, and with the use of the London expression for λ,

$\lambda^2 = mc^2/4\pi ne^2$, we obtain from (7), $V_0 \sim 4\cdot 10^{-8}$V, i.e., $\omega_0/2\pi \sim 2\cdot 10^7$Hz.[4] /9

Thus, radio emission can be generated in the λ layer at the Josephson frequency and its harmonics.

4. Star Radiation

A further problem is the analysis of radio emission transport in a neutron star and obtaining the observable characteristics of the outgoing radiation. In this case, both radio wave absorption by the degenerate plasma of the neutron star, and self absorption of radiation by the Josephson mechanism, as well as the amplification and transformation of the initial spectrum, unavoidable consequences of the interaction of the Josephson junctions with the radiation field, evidently must be taken into account. Thus, it would be desirable to obtain coefficients of emission and absorption with allowance for these processes, and to solve the transport equations of the radio emission in the mantle and crust of a neutron star. A self consistent problem apparently is too complex ever to be completely solved. Additional limiting assumptions are required. However, it now is difficult to prefer a given limitation of this problem for purposes of argument. Therefore, as before, we will use a highly simplified pattern.

We estimate the possibility of the propagation of slightly damped

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[4] We test whether the criterion of sufficiency of the "weak" coupling, which is valid for couplings of any type, is satisfied [6]: $I_m \lesssim 2\Delta\cdot\sigma_m/e$. Since $I_m/\sigma_M < I/\sigma_M \sim V_0$, and $\Delta \sim 0.1$ MeV, it is evident that, in this case, I_m/σ_M is many orders of magnitude less than $2\Delta/e$, i.e., the coupling actually is "weak."

radio wave modes in the crust and the λ layer of the mantle of the star, with consideration that the basic effect of these regions on the propagation of radiation is scattering of the wave energy by particle /10
collisions.[5] The basic particles which react with the waves then are electrons (in the λ layer, because of the low concentration of normal protons) and, by using the results of the theory of radio wave propagation in a magnetically active, degenerate plasma [9, 10], it can be shown that the propagation of spiral waves (along the magnetic field), with a coefficient of refraction n_+, is possible in the λ layer and the crust:

$$n_{\pm}^2 = \left(\frac{k_{\pm} \cdot c}{\omega}\right)^2 = \varepsilon_L - \frac{\omega_p^2}{\omega(\omega + i\nu \mp \omega_c)} \, . \tag{8}$$

Here, $\varepsilon_L=1$ for the λ layer, and $\varepsilon_L \gtrsim 1$ is the dielectric constant of the nuclear lattice for the crust, ν is the electron collision frequency, ω_p and ω_c are the plasma and cyclotron frequencies, respectively.

Damping for the λ layer can be obtained from (8), by assuming $\rho \sim 2 \cdot 10^{14} g \cdot cm^{-3}$, $n_e = n_p \sim 10^{36} cm^{-3}$, $n_p = n_{ps} + n_{pn}$, $n_{pn} = n_p (T/T_c)^4$, $\nu = \nu_0 \cdot n_{pn}/n_e$, where ρ is the density of the medium, n_e, n_{ps} and n_{pn} are the concentrations of electrons, superconducting and normal protons, respectively, T is the mantle temperature, T_c is the proton transition temperature to the superconducting state, ν_0 is the electron-proton collision frequency, with $n_e = n_p = n_{pn}$ [3]:

$$\nu_0 = \frac{\pi^2}{12} \cdot \left(\frac{e^2}{\hbar \cdot c}\right)^2 \cdot \left(\frac{T}{T_F}\right)^2 \cdot \frac{c \cdot k_F^2}{k_{FT}} \, , \tag{9}$$

T_F is the proton Fermi temperature, k_F and k_{FT} are the Fermi and Fermi- /11
Thomas wave numbers, respectively. In this case, at frequencies $\omega/2\pi \sim 10^8$ Hz, the λ layer turns out to be transparent (the wave amplitude is attenuated "e" times in distance $L_{e+} \gtrsim 10^5$ cm) for the n_+ mode, at

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[5] A more rigorous examination also requires account to be taken of the inertia of proton pairs (see footnote 14, p. 22).

$B \gtrsim 10^{12}$G, $T_c \gtrsim 3\cdot10^8$ K, $T < 10^7$ K, which does not contradict the expected values of B, T_c and T in a neutron star. At the same time, this wave undergoes total internal reflection from the quasicylindrical boundaries of the λ layer, since $B \sim 0$ outside the λ layer and the coefficient of refraction n_A turns out to be quite small on the inside ($n_A = c/v_A$, where v_a is the Alfven velocity, since the plasma in the core of the filament has two components). Thus, the spiral wave, which scarcely penetrates the boundary regions, propagates in the λ layer as in a coaxial waveguide channel.

In a similar way, for attenuation in the crust, by assuming $\varepsilon_L \sim 1$, $B \sim 10^{12}$G, $\rho \sim 10^8 g\cdot cm^{-3}$ and $\sigma \sim 10^{23} sec^{-1}$ (which gives $n_e \sim 3\cdot10^{31} cm^{-3}$, $\nu \sim 6\cdot10^{16} sec^{-1}$), from (8) we obtain

$$L_{e+} \approx 2c\cdot\omega_c^{3/2}\cdot\left(\nu\cdot\omega_p\cdot\omega^{1/2}\right)^{-1} \sim 10^{35}\left(\nu\sqrt{\omega\cdot n_c}\right)^{-1} \text{ cm}. \qquad (10)$$

It is seen from this that the region of the crust outside the cracks is opaque to radio waves. It also follows from (10) that radio transparency of the crust in the cracks is only possible, in the event the matter which fills them differs from the matter outside the cracks, at least in free electron concentration n_e, all else being equal (for example, the larger portion of the electrons is in the bound state). Then, with $n_e \lesssim 10^{18} cm^{-3}$, both modes ($n_+$ and n_-), with opposite polarizations, can propagate and, from (8), we have $L_{e\pm} \gtrsim 10^5$cm for both modes.

Besides the absorption described, interaction of the propagating /12
waves with the medium in the λ layer evidently results, both in variations of the configuration of the spongy microstructure elements (and, consequently, variations of σ_M, I, V, I_m of each microbridge), and to "induction" of an additional variable potential difference v(t), because of irradiation of the Josephson junction by the outward propagating radiation. The presence of v(t) results in frequency modulation of the fundamental spectrum of the junction and, as a consequence, the development of numerous combination harmonics in the resulting spectrum. With the use of equation (1) and (2), it can be shown that, even in the simplest case, when, in addition to (4), induced $v(t)=v_c\cdot\cos\Omega_0 t$ functions, during frequency transformation, an infinite set of harmonic components appears

at frequencies $n\omega_0 \pm m\Omega_0$, where n and m are integers. In this case, under certain conditions, because of the "pumping" of energy from some oscillations to others, amplification of some sections of the resulting spectrum, both at the frequencies of the initial spectra, and at other combination frequencies [11]. We note that transformation to zero combination frequencies (detection) results in complete absorption of the corresponding fraction of the incident radiation, while the development of other combination frequencies results only in reradiation of the energy.

For this reason, it seems more natural to consider that, because of the Josephson effect of frequency transformation, the interaction of the λ layer with the propagating radiation leads to partial absorption and "smearing" of the energy of the fundamental linear radiation spectra over the entire range, in such a way that the basic contribution to the outgoing radiation is made by a thin subcrustal layer of the mantle, of thickness $z<L_{e+}$, in which the optical thickness is on the order of unity.[6] Therefore, the resulting radiation of the λ layer can contain the "individuality" of the linear spectrum of the outer regions of the mantle, against the quasicontinuous radiation background of the deeper medium. /13

By representing the radiation of elements of the spongy microstructure of the thin subcrustal layer of the mantle (of thickness z and area S) escaping through breaks in the crust as the radiation of a lattice of N coherent[7] point oscillators with identical spectra (5), for the spectral density of the flux F_ω at distance R from the star, we will have

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[6] I.e., this effect results in the λ layer probably being "optically thick" at radio frequencies. Since the value of z remains undetermined, below (so as not to overstate the estimates), the minimum possible value is used, on the order of the average distance between particles, although z can be considerably larger.

[7] In the sense of constancy of the fundamental phases which, generally speaking, are different for different oscillators.

$$F_\omega = \tau_\omega \cdot z_\omega \cdot P_o \cdot p^{\omega/\omega_o} \cdot N^2 \cdot f(\omega, \vartheta, \varphi)/(4\pi R^2 \cdot \Delta\omega). \qquad (11)$$

Here, coefficient r_ω describes the losses during propagation of the radiation in the star and the magnetosphere, $\Delta\omega$ is the effective line width at frequency ω, and $f(\omega,\theta,\phi)/4\pi$ is the beam pattern of the system with a random amplitude-phase distribution of the radiation field, normalized in such a way that the maximum value of the pattern factor $f(\omega,\theta,\phi)$ equals one and is reached, in particular, with a uniform amplitude and in phase distributions of the field, with the same polarization on the inner and outer boundaries of the cracks, if the anisotropy of the magnetospheric absorption within the zone of formation of the main lobe of the pattern is disregarded.

Radio luminosity $L_d \sim \overline{\tau_\omega \cdot z_\omega \cdot f(\omega, \vartheta_o, \varphi_o)} \cdot P_o \cdot N^2 / (1-p)$, can be /14

obtained from this, where the first three cofactors are frequency averaged; θ_o, ϕ_o are angles which characterize the direction to the observer; $N \sim (z \cdot \pi \cdot \lambda^2 \cdot n) \cdot (B/\phi_o) \cdot S$. It follows from a comparison of the radio luminosity of the pulsar $L_{radio} \sim 10^{30}$ erg/sec and L_d that the energy requirements with the former parameters of the medium and $(1-p) \sim 10^{-3}$, which gives $P_o \sim 10^{-9}$ erg/sec, are satisfied, even with z on the order of the average distance between particles, i.e., $z \sim n^{-1/3}$, and the area of the "Josephson radio spot" $S \sim 10^{-6}$ of the area of the disk of the star. In this case, the coefficients which allow for the difference of the conditions from ideal (when they equal one), can be very small:

$K \equiv \overline{\tau_\omega \cdot z_\omega \cdot f(\omega, \vartheta_o, \varphi_o)} \sim 10^{-19}$ (with noncoherent radiation, it should be supposed, at least, $\overline{f}(\omega) \sim 10^{-28}$).

We estimate the losses of internal magnetic energy E_m of the star to this radiation, in the absence of other "outlets" and "sources" of

[8] With account taken of the cracks and the "magnetospheric window" (formed by the lines of force outside the light cylinder).

magnetic energy, with the assumption that $E_m = B^2 \cdot r^3/6$, $dE_m/dt = (2E_m/B)(dB/dt) = -\bar{\eta}_\omega \cdot P_0 \cdot N/(1-p) \approx \mathrm{const}$, $B \sim 10^{12}$ G, $r \sim 10^6$ cm. Then, $(dE_m/dt)/2E_m \lesssim 10^{-20}\ \mathrm{sec}^{-1}$. The currents in the mantle will fade, as a result of a decrease in E_m. From this, the time τ_g, in which current $I \propto B$ decreases to I_m (on consideration that $I_m/I = B_m/B$), for $(1-p) < 1/2$, will equal

$$\tau_g \approx \frac{E_m}{4\bar{\eta}_\omega} \cdot \left(\frac{K}{P_0 \cdot L_d}\right)^{1/2} \cdot (1-p)^{5/2} . \tag{12}$$

For the estimates of the parameters in (12) presented above, $\tau_g \gtrsim 10^{13}$ sec, since $\bar{\eta}_\omega < 1$.

5. Basic Properties of Model

If this reasoning is valid, as a result, we obtain the following /15
pulsar radio emission scheme. The current of protons relative to electrons results in the generation of Josephson radio emission in the λ layer. Circularly polarized waves, which propagate along the magnetic field in the λ layer as in a coaxial waveguide, are "cut out" of the generated radiation. In irradiating cracks in the crust, they are transformed into waves, the polarization of which basically is determined by the configuration and dimensions of the cracks. Waves with the new polarization propagate in the crack, distributed in two slightly damped modes of opposite polarizations (on the assumption of a sufficiently low free electron concentration in the crack), and they escape from it to the magnetosphere. Because of the different conditions of propagation, the degree of linear polarization and the position angle of the outgoing waves in different cracks or even in different sections of one crack can differ. As a result, "hot radio spots" form on the surface of the star (postulated in a "beacon" model), and they form the resulting radiation pattern at the magnetic poles. The spatial form of this pattern is determined by the beam pattern of the "spots" and the "angular window" of the magnetic pole. Its cross section gives the observed pulse structure of the pulsar.

It is apparent that, in the simplest case, line sp (11), formed by the harmonics of $n\omega_0$ of one basic frequency ω_0 will be observed against a continuous background (if, of course, $\Delta\omega<\omega_0$; we do not study astrophysical broadening mechanisms here). It is heavily covered up at high frequencies and, at finite frequencies in the range, it permits approximation of a broken line, made up of a small number of segments. The spectrum can appear quasicontinuous, if $\Delta\omega \gtrsim \omega_c$. or if /16 there is a set of nonidentical groups of "spots" (or groups in one "spot"), with "their own" spectrum (11) and ω_0. In the latter case, against a background of a "continuous" spectrum, made up of harmonics $m_1\omega_{01}$, $n_2\omega_{02}$, . . ., the set of basic frequencies ω_{01}, ω_{02}, . . ., periodic "brigthening" can be observed, the result of the development of the fundamental spectrum of stronger spots.

Since the outgoing emission of the star is equivalent to the emission of a slit antenna, it is understandable that high directivity and degree of polarization theoretically are possible (in the ideal case, 100 percent linear polarization). In this case, the amplitude-phase distribution of the radiation field over the active region of the mantle and surface of the star evidently play a decisive role (in other words, "the conditions of irradiation of the aperture of a slit antenna"). Within the framework of the model under consideration (it is evide from (1)-(3) that, in the mantle, it depends on the internal magnetic field[9] and the microstructure of the λ layer, which can be considered static, only on the average.

The presence of microstructure variations (regular and irregular) unavoidably will be reflected in the amplitude-phase distribution and, as a consequence of the variations, both the form and the spatial orientation of the beam pattern results in instability of the radiation (i.e., in variations of amplitude, shape and even structure of the pulses in strong fluctuations of the λ layer microstructure[10]).

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[9] If each filament includes only one quantum of magnetic flux, the contribution due to ϕ/ϕ_0 is small.

[10] Nevertheless, it should be noted that these fluctuations, although they are not forbidden, are limited to the "orderliness" of motion of the particles, because of their strong degeneracy, since $T/T_f \ll 1$.

Variations of the individual pulses will be observed under "steady state conditions," if several lines of the steady state spectrum under study enter the radiometer transmission band. This situation can lead to pulse modulation, because of beating of the oscillations from different spots with similar fundamental frequencies, and to drift of subpulses within a "window" when the beat frequency is not a multiple of the pulse recurrence frequency (see Fig. 2a). /17

However, the clearest and most specific transient effect which can develop in observations is the following. For simplicity, we assume that quite slow variations of the microstructure are reflected only in variations of current I through elements with spectrum (11). It then follows from (1), (4), (5) that through the dependence of F_ω on I:

$$\begin{tikzcd} I \arrow[r] \arrow[dr] & \gamma \arrow[r] \arrow[d] & p \arrow[d] & \\ & \omega_0 \arrow[r] & P_\omega \arrow[r] & F_\omega \end{tikzcd} \qquad (13)$$

this results in amplitude-frequency variations of spectrum (11), i.e., in correlated variations of the spectral index, pulse amplitude and fine structure of the spectrum (FSS).

If there are a few spots with characteristic spectra (11) and their relative contribution to the spatial structure of the general beam pattern is unequal, the spectral index and FSS over the pattern cross section (i.e., over the observed pulse profile) can differ at a fixed frequency. With substantial change in frequency, the observations can change both the spatial distribution of these characteristics (i.e., their distribution over the pulse profile), and the pulse structure, reflecting the frequency dependency of the beam pattern within the magnetospheric window. A characteristic transient spot, for example of type /18
(13), complicates the picture still more.

We illustrate what has been stated with three simple qualitative examples (Fig. 2). It should be emphasized that variations are shown in the figure, which are due only to two "elementary" processes: specific effect (13) with period of variation of τ (curve 1) and beats (curve 2), which develop on the difference frequency $\omega_{\delta}=(n_2\omega_{o2}-n_1\omega_{o1})/2$ (in which, in Fig. 2c, $\omega_{\delta}\neq$const). It is seen that, even in these examples, the observed pulse train structure can be considerably more complicated than that emitted and depend both on the width and orientation of the observation frequency band $\Delta\Omega$ relative to FSS, and on the ratio of ω_{δ} to the pulse recurrence frequency $2\pi/P_S$ ($\Delta\omega_{ab}$ in the figure designates $\Delta\omega$ between points a and b in the FSS; similarly, for other noted points of the FSS).

It also is clear from Fig. 2 that variations of all the pulse emission characteristics can appear in the observations (with characteristic, anticoincidence and, generally speaking, few -- see, for example, Fig. 2c -- variation periods): spectral index, FSS, pulse recurrence amplitude, structure and period. In this case, shown in Fig. 2c, it can occur as sporadic amplitude-frequency bursts against a background of more or less slow variations), which abruptly change the observed pattern.

A distinctive feature of the examples in Fig. 2b and 2c is the presence of correlated variations (with the same period τ) of the spectral index, FSS and pulse amplitude. Here, a brief increase in frequency in variations of FSS corresponds to an increase or constancy (within the measurement accuracy) of the amplitude in the low frequency region of the spectrum and a simultaneous decrease of it in the far high frequency region (see upper Fig. 2b), and the opposite relationship with a decrease in frequency. However, the patterns of variation of these parameters, generally speaking, are not the same, even in the absence of beats, since they are coupled by a nonlinear relationship (see (13), (11), (5)), but "adjustment" to the observed model of the initial variations of current I can be established, in accordance with scheme (13). /19

For a detailed verification of the mechanism under discussion (and others besides), it would be very important to have individual "portraits" of some pulsars, obtained by simulataneous actual observations of the pulse train, FSS and structure of individual pulses at several fixed frequencies. This primarily concerns pulsars with subpulse drift. Two or more lines can be expected in their FSS, which possibly can be distinguished, even if in unresolved form. In this case, pulsars with variable drift rates also are the most likely candidates for the detection of the correlated variations noted.[11]

If slowing of the rotation of a star determines slowing of the relative vortex motion of the particles in the filaments, i.e., a decrease in the current of protons relative to electrons, according to (13), (11), (5), all else being equal, this would lead to a secular decrease in the flux at the primary frequency ω_0, flattening of spectrum (11) with its simultaneous "movement" towards low frequencies (because of a decrease of ω_0) and broadening of it (because of an increase in p), until the condition $I>I_m$ is satisfied. At $I=I_m$, a "break" in generation occurs (see (1)) and, with further slowing of the star, the Josephson radiation is "switched off," if strong fluctuations do not lead /20 to disruption of the new state, in which $I<I_m$. It is possible that the absence of long period pulsars is explained by just such an evolutionary effect.

It is evident that the rotation of the star, which is coupled to the internal magnetic field through the vortex motion of the charged particles of the filaments, becomes the primary source of radiation energy in such a scheme.[12] Since the radio luminosity of known pulsars usually is much less than the rate of loss of energy of rotation [5], the mechanism under discussion does not contradict known hypotheses that the basic fraction of the roational energy is consumed in magnetic dipole radiation or in interaction with the plasma around the pulsar.

If the basic source of energy is the relict magnetic field frozen

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[11]Such an interpretation does not negate other drift mechancisms (for example, because of star precession), which can operate jointly.

[12]From this point of view, the interesting self consistent generation mechanism of the internal magnetic field due to star rotation has been discussed in [12].

into the matter of the star (i.e., without "makeup" of the rotational energy), the scheme of evolution is as before, and the lifetime of a radiating pulsar is determined by relationship (12). Then, the absence of long period pulsars possibly is connected with the fact that the magnetic field captured by a nascent long period star is too weak from the very start to ensure emission condition $I > I_m$.

It is easy to determine that the described properties of the model contain all (or nearly all) the basic properties [5] of pulsar radio emission.

Generally speaking, this fact appears less strange, if the difficulty of adequate description of complex phenomena inside the star is taken into account, especially the possibility of the appearance in the mantle of, besides those discussed, some other processes of absorption of the energy of strongly slowed radio waves.[13] /21

Fortunately, one possible cause of the weak dependence of the model on a specific absorption mechanism in the mantle is in the Josephson generation mechanism itself, since the energy of dissipation of radio waves, which changes into the kinetic energy of particles, can again be transformed into radiation energy by the Josephson effect. Another cause is that it is energetically sufficient to consider the λ layer as an optically thick medium.

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[13] For example, it is possible that one such process is "inertial absorption" by proton pairs. Thus, it is easy to obtain the variance ratio by a standard method, with account taken of the pair current in the London approximation (it will be published separately), from which, for the mantle, $L'_e \sim \lambda$ (i.e., $L'_e \ll L_{e+}$, but the condition $z < L'_e$, of course, as before, is satisfied and all the conclusions remain valid). However, the competence of such an approach for the λ layer is not completely clear. In general, conditions in a neutron star prove to be very much closer to the laboratory conditions of radio wave propagation in metals than to typical astrophysical conditions. Radio waves in metals have been studied for a little more than fifteen years. Therefore, of course, many surprises can be expected here.

6. Co..clusion

It is difficult to say how close the model under consideration is to reality. However, the correlation of its properties with the properties of pulsar radio emission is too remarkable to be random.[14]

It should be noted that the approach used to description of the superconducting mantle, as a medium with a "weakly coupled" microstructure, is not the only possible approach which leads to radiation at Josephson frequencies. Acutally, Josephson oscillations can be expected in consideration of the filaments as fine superconducting channels with a longitudinal current, or in analysis of filament motion, when /22 pinning is absent and there is a transverse transport current (see, for example, [6, 13]). The approach used was selected basically for two reasons. First, it requires a minimum number of supplementary assumptions. Second, it is the most highly developed and tested in weakly coupled laboratory structures.

There also is interest in "combination mechanisms," when elastic oscillations of the filaments and magnetic lines of force, excited by a Josephson wave, result in 1. oscillations of the total magnetic moment of the star and, further, to magnetic dipole radiation, in which the characteristic Josephson frequency spectrum is present, or 2. elastic oscillations of the lines of force of the magnetosphere and the emission of energy by particles moving in this variable magnetic field.[15]

An attempt to explain the optical and X-ray emission of pulsars in a similar manner (or with "combination mechanisms") is highly tempting, since the mechanism considered can generate frequencies up to

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[14]If pulsars (at least some) actually radiate approximately as presented in this model, there is a basis for hoping that this will permit a better understanding of similar processes in "terrestrial" superconductors and, possibly, the development of a laboratory analog of a radio emitting pulsar.

[15]The author first heard of the first possibility from D.M. Sedrakyan (see also [12]) and of the second, from V.I. Slysh.

$\omega_{np} \sim 10^{2}$ (see (6)). Nevertheless, such an interpretation requires special substantiation and comparison with observations in these ranges.

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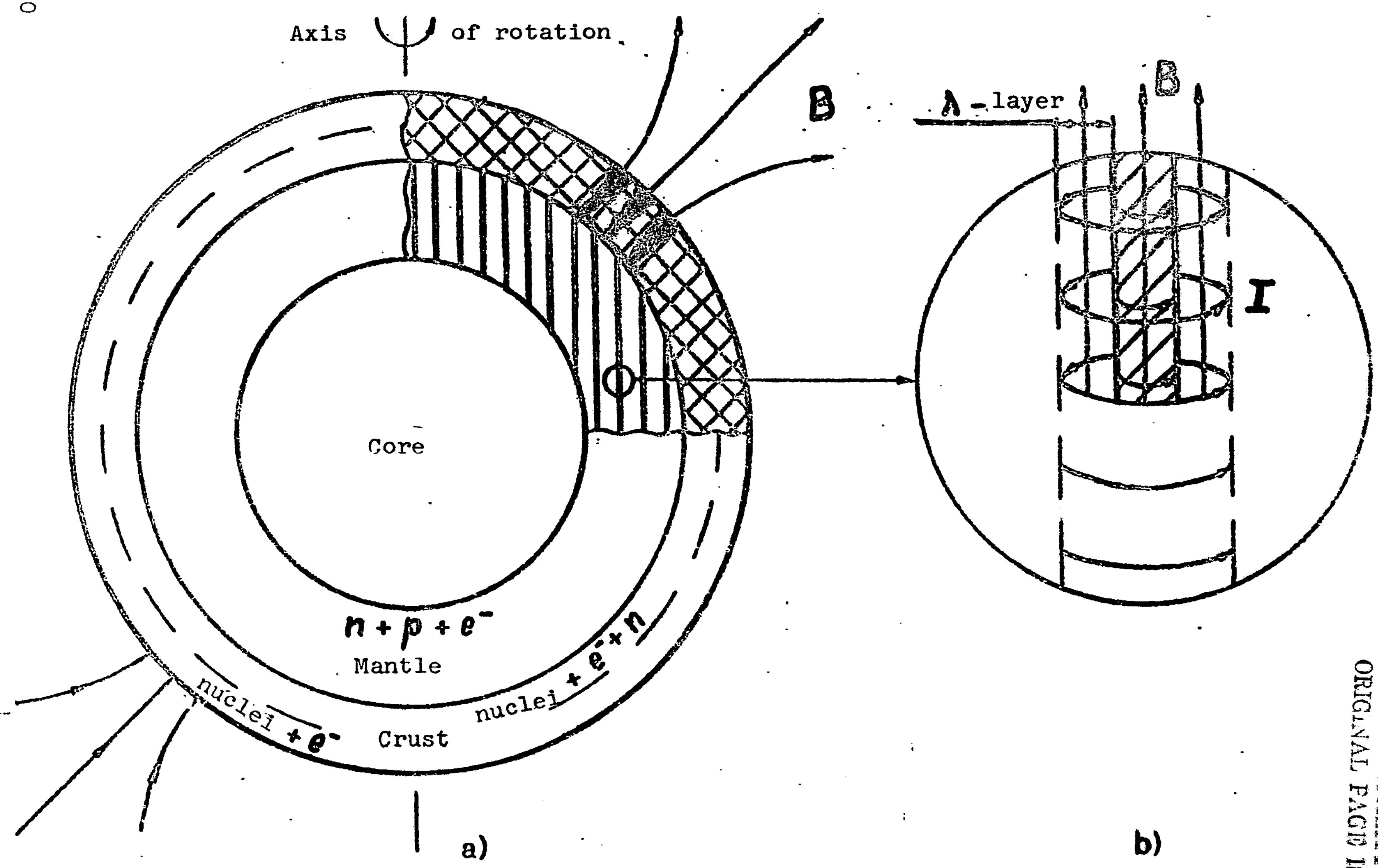

Fig. 1. Structure of typical neutron star (a) [1-4] and superconducting vortex filament (b). Cracks in crust are blackened. Normal filament cores shown by single line.

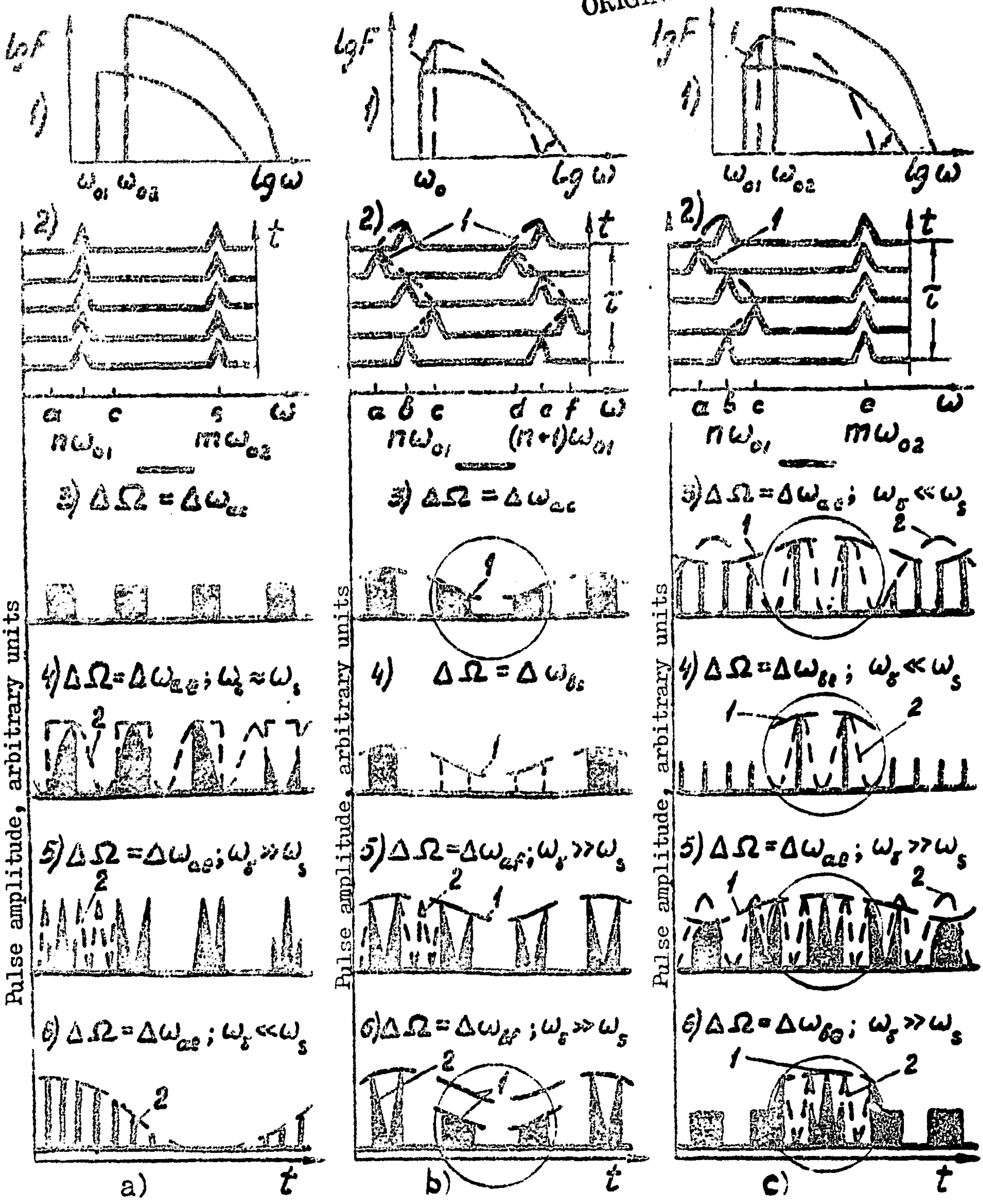

Fig. 2. Connection of observed variations of amplitude, structure, recurrence period P_S of pulses (3-6) with spectral characteristics (1) and FSS (2) vs. observation frequency band $\Delta\Omega$ and ratio of beat frequency ω_δ to $\omega_S = 2z/P_S$ for the following cases of radiation (see text): a. two "spots" with steady state spectra (11); b. one "spot" with transient (13) spectrum (11); c. two "spots," one of which has steady state spectrum from a., the other, transient from b. Square pulses are emitted. Effect of interstellar medium not reflected. Recorded pulse is blackened. Curves 1 due to transient nature (13), curves 2 to beats. Sections noted by circles, as well as corresponding FSS, coincide: b. (3) with (6); c. (3) with (4) and (5) with (6).