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*PULSARS**

(Theoretical Concepts)

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INTRODUCTION

THEORETICIANS, both physicists and astronomers, are usually well satisfied with their choice, for engaging in theoretical questions is in some respects easier and more effective than observations and measurements. Experimenters and observers, to the contrary, frequently grumble at their fate—their work is very laborious, and its success depends in many respects on problems that are entirely nonscientific, such as obtaining money, equipment, etc. I mention this because the investigation of pulsars can serve as an example (and by no means the only one) wherein the theoreticians have every reason to envy the observers. In any case, I can say this fully concerning myself. The paper by A. Hewish† reports all the facts, and we have all reasons for congratulating observers on their success—they have done a tremendous amount of work within less than three years. At the same time, not so much has been established in the theory of pulsars, and I must present to your attention for the most part mere general considerations and working hypotheses. Fortunately for the theoreticians, the situation is not always like this. There are many cases when theory ranges much farther ahead and anticipates the observations.

In the case of pulsars, the known lag of theory is due to two circumstances. First, we are dealing with extremely complicated problems, for example the equation of state of matter with density exceeding 10^{11} g/cm^3 and the electrodynamics of the magnetosphere of a rapidly rotating star whose axis of rotation does not coincide with the magnetic-symmetry axis (say with the direction of the magnetic dipole). Second, the observation data, for all their variety, give only indirect information on pulsars—their structure is not seen directly in the sense that can be used, for example, for the surface of the sun or for a number of nebulae.

The foregoing explains the character of the present paper: we shall discuss the existing theoretical concepts regarding pulsars, although no complete and clear picture can be outlined as yet.

1. THE NATURE OF PULSARS

What are pulsars as astronomical bodies? The main criterion that must be satisfied by a body that can be classified as a pulsar is the possibility of obtaining a

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†A. Hewish's paper, which preceded the present paper, will be published in "Highlig'.ts of Astronomy." For experimental material on pulsars, see Usp. Fiz. Nauk **99**, 514 (1969) [Sov. Phys. Usp. 12, 800 (1970)] and A. Hewish, Annual Review of Astronomy and Astrophysics **8**, 265 (1970).

highly stable period, and this period P is quite small ($P \sim 3\times10^{-2}-4$ sec). It is quite obvious that such a requirement can be satisfied only by some massive object (say a star) or a system (say a binary star), and not a nebula or a plasmoid. Concretely, it is proposed to associate pulsars with the following objects:

neutron stars,
white dwarfs,
binary systems (binary stars)
objects of a "new type."

It was proposed from the very outset that oscillations (pulsations)[1] and revolution[2] be considered mechanisms ensuring periodicity of the radiation pulses. During the first stage, the choice between the two possibilities was difficult because only pulsars with periods $P \geq 0.25$ sec were known. However, after the discovery of the short-period pulsars PSR0833-45 and NP0532, with periods 0.089 and 0.33 sec, respectively, the situation became much more definite.* The point is that the period of the fundamental tone (the radial oscillation) of nonrotating white dwarfs, when account is taken of the effects of general relativity theory, cannot be smaller than approximately 2 sec. In the case of rotating white dwarfs, the period of the quasiradial oscillation can reach 0.6 sec, and the main nonradial oscillations have a period that reaches 0.2 sec. Even if we disregard the difficulties of making use of nonradial oscillations, in view of their damping by the gravitational radiation, periods of oscillation $P \sim 0.2$ sec can be obtained for white dwarfs only for the overtones. But how is one to explain, in accordance with the data on pulsars, the presence of oscillations at some overtone when there are no oscillations at the fundamental or at other overtones? In addition, this raises the question of the causes of the high stability of the oscillations.

Periods of revolution of white dwarfs are limited by the requirement that there be no collapse and that there be no strong escape of matter from the star. The latter condition is satisfied, roughly speaking, if the acceleration due to gravity exceeds the centrifugal acceleration. We therefore arrive at the inequality

$$\frac{GM}{r_0^2} > \frac{v_0^2}{r_0} = \Omega^2 r_0, \quad \text{or} \quad \Omega < \left(\frac{GM}{r_0^3}\right)^{1/2} = \left(\frac{4\pi G\bar{\rho}}{3}\right)^{1/2},$$

where M is the mass, r_0 the radius, $v_0 = \Omega r_0$ the velocity on the surface, and $\bar{\rho}$ the average density of the star. Thus, the period of rotation should satisfy the condition

$$P = \frac{2\pi}{\Omega} > \left(\frac{3\pi}{G\bar{\rho}}\right)^{1/2}. \quad (1)$$

This period is $P > 1$ sec at $\bar{\rho} \leq 10^8$ g/cm^3. In the case of nonrigid-body rotation, the angular velocity, especially near the poles, can in principle be higher than that given by the estimate (1). However, there are no indications that it is possible to obtain values $P \leq 0.1$ sec; in practice, even periods of rotation $P < 1$ sec are not very probable for white dwarfs. Thus, it is almost certain that short-period pulsars cannot be white dwarfs. Such a conclusion is also confirmed by the fact that not one pulsar has been identified optically with a white dwarf.*

The parameters of neutron stars (the density at their center ρ_c, the radius r_0, and, for example, the period of the fundamental tone of the radial oscillations P_0) depend on the equation of state of the nuclear matter. The calculations whose results were used until recently led to a maximum mass $M_{max} \sim (1-2.5)M_\odot$ for the neutron stars; for a mass $M \approx M_\odot$ the radius is $r_0 \sim 10$ km and the pulsation period is $P_0 \sim 10^{-3}-10^{-4}$ sec. For light neutron stars, according to these calculations[3] at ob- $M \sim (0.1-0.2)M_\odot$ we obtain a value $r_0 \sim 50-200$ km, $\rho_c \sim (3-10)\times10^{13}$ g/cm^3, and $P_0 \sim 10^{-2}$ sec. On the other hand, according to calculations[5] using an apparently more exact equation of state, we have $M_{max} \approx 0.26M_\odot$ at $\rho_c \leq 10^{15}$ g/cm^3, and at $\rho_c \lesssim 3\times10^{14}$ g/cm^3 ($M \lesssim 0.13M_\odot$) there are no stable configurations (a similar statement is made in [6] with respect to models with $\rho \sim 10^{13}$ g/cm^3). It follows therefore apparently that $P < 10^{-2}$ sec for neutron stars. Independently of the results of the refinement of the period of the pulsations for neutron stars, there is practically no doubt that these periods are smaller than the periods of the observed pulsars. To the contrary, even the shortest known period $P = 0.033$ sec is acceptable as a period of revolution of a neutron star.[7] Indeed, for $M \sim M_\odot$ and $r_0 \sim 10^6$ cm, the average density is $\bar{\rho} \sim 5\times10^{14}$ g/cm^3 and, in accordance with (1), the period of revolution is $P > 10^{-3}$ sec. If we follow the calculations of [5], then for $M \sim 0.2 M_\odot$ the radius of the star is $r_0 \sim 30$ km, i.e., $\bar{\rho} \sim 4\times10^{12}$ g/cm^3 and $P > 10^{-2}$ sec.

Thus, from the point of view of the possibility of obtaining the required value of the period, all the known pulsars can be rotating neutron stars. Long-period pulsars ($P \gtrsim 1$ sec) may turn out to be rotating or oscillating white dwarfs. But the latter assumption is very unlikely, in view of the following: the absence of optical identification of pulsars with white dwarfs, evolutionary considerations (we have in mind the increase of the period of pulsars with time, by virtue of which even short-period pulsars should eventually become long-period ones), and finally, the absence of indications that there exist pulsars of entirely different types.

The assumption that pulsars are binary systems (stars) is almost entirely excluded if gravitational radiation is taken into account. By virtue of such radiation, a binary-star period $P \lesssim 1$ sec should change much more rapidly and in a direction opposite to that observed for pulsars (a formula for dP/dt can be found, for example, in [3]). To be sure, doubts were expressed in the literature concerning the validity of the statement that gravitational radiation of binary stars exists. If one speaks of the theoretical aspect of the question, these doubts, which I (and many others) always regarded as unfounded, have by now been rigorously refuted. We note that gravitational radiation with a power of the

*The data presented below on the periods of oscillations and the rotation periods of white dwarfs and neutron stars are discussed in greater detail in [3-6] and in the literature cited therein.

*The pulsar NP0532 in the Crab nebula can likewise not be regarded as a white dwarf, since it produces practically no optical radiation in the intervals between pulses. On the other hand, white dwarfs, in principle, can be invisible (white dwarfs with mass close to critical cool rapidly); for this reason alone, the failure to identify pulsars with observed white dwarfs cannot serve as rigorous proof that pulsars are not stars of the white-dwarf type.

same order as in general relativity theory should also follow from any other gravitational-field theory that agrees with the known experimental data.

It remains for us to discuss the assumption that pulsars are objects of a "new type," something in the way of miniature quasars (they could be called "quasarinos").* The question is, more concretely, whether evolution or collapse of stars can lead to configurations different from white dwarfs, neutron stars, and "cooled" collapsed stars (in the latter case, in the comoving reference frame, the star "goes under" the Schwarzschild radius $r_g = 2GM/c^2 \approx 3 \times 10^5\ M/M_\odot$ cm). Without going beyond the framework of general relativity theory, the only known possibility of seeking new dense quasistellar configurations lies in taking into account the influence of the magnetic (or electromagnetic) field.[8, 9] It can be assumed, however, that the influence of the magnetic field may turn out to be radical only under conditions when the magnetic energy of the star is comparable with its gravitational energy, i.e., $W_m \sim (H/8\pi)^2 r_0^3 \sim GM^2/r_0$. Hence for $M \sim M_\odot$ the field is $H \sim 10^{30} r_0^{-2}$, i.e., $H > 10^{16}$ Oe at $r_0 < 10^7$ cm. The appearance of such strong fields is quite improbable. Even less probable is the possibility of relating pulsars with dense pulsating configurations, which are perhaps acceptable[10, 11] if one foregoes the equations of general relativity theory or if, by your leave, these equations are somehow modified. Modifications of the equations of general relativity can be expected, in principle, when account is taken of quantum fluctuations of the metric, which are probably already significant at characteristic dimensions $l_g \sim \sqrt{G\hbar/c^3} \sim 10^{-33}$ cm, times $t_g \sim l_g/c \sim 10^{-43}$ sec, and densities $\rho_g \sim c^5/G^2\hbar \sim 5 \times 10^{93}$ g/cm^3.

But the average density of a star with mass M and radius $r \sim r_g = 2GM/c^2$ is of the order of $\bar{\rho}(r_g) = 3c^2/8\pi G r_g^2$. Obviously, when $M \sim M_\odot$ the density is $\bar{\rho}(r_g) \sim 10^{16}$ g/cm$^3 \ll \rho_g$ and $\bar{\rho} \sim \rho_g$ only for a "star" with mass $M \sim M_g \sim \sqrt{c\hbar/G} \sim 10^{-5}$ g, for which the gravitational radius is $r_g \sim l_g \sim 10^{-33}$ cm. This has no no bearing whatever on pulsars.

Thus, to produce models of pulsars by modifying general relativity theory, these modifications must be introduced in some considerably "earlier" phase—even for relatively weak gravitational fields. There are no grounds for this whatever, but nevertheless, for those who wish to carry astronomy beyond the framework of the presently known physical laws and theories, pulsars are among the most interesting objects. This will be discussed also at the end of the article. At the present may I note that I can attribute only to an accident the fact that the identification of pulsars with neutron stars has in general not caused a storm of doubt,† whereas the use of cosmological distances for quasars was many times disputed and is being disputed to this day. At any rate, we shall make use of this fortunate circumstance and henceforth regard pulsars as rotating neutron stars.

*It is most probable that the nucleus of a quasar (a compact source of powerful radiation) is a supermassive plasma body ($M \sim 10^9\ M_\odot$, $r \sim 10^{17}$ cm) with large internal motions of rotational type and with magnetic fields [8a]. Therefore a certain analogy between quasars and pulsars is obvious (see also [8b]).

†The already noted uncertainty concerning the parameters of neutron stars [3,5,6] does not stir any misgivings of fundamental character at present. The situation is worse with our understanding of the formation of neutron stars, but this process is so complicated that the existing difficulties [12] may not yet call for serious caution.

2. ROTATING MAGNETIZED NEUTRON STARS

When a star is transformed into a neutron star, the moment of inertia I decreases strongly (for example, when the mass remains the same and the radius decreases from 3×10^{10} to 3×10^6 cm, the moment I decreases by eight orders of magnitude). It is therefore natural to expect neutron stars to rotate quite rapidly (the angular velocity of NP0532 is $\Omega \approx 200$ sec^{-1}, as compared with the angular velocity of the solar surface $\Omega_\odot \sim 2 \times 10^{-6}$ sec^{-1}). An analogous situation arises also with respect to the magnetic field—under conditions of "frozen-in" force lines, magnetic flux is conserved, i.e., the field H increases in proportion to r^{-2} or in proportion to $\rho^{2/3}$ (r is a certain radius of the star and ρ is its density). Hence, for fields $H \sim 1$ Oe at $r \sim 3 \times 10^{10}$ cm or $\rho \sim 1$ g/cm^3 we obtain fields $H_0 \sim 10^8$ Oe at $r_0 \sim 3 \times 10^6$ cm and $\rho_0 \sim 10^{12}$ g/cm^3. The initial field in the star can, however, reach 10^3–10^4 Oe, and the density of neutron stars in the central part is $\rho_c \gtrsim 10^{14}$–10^{15} g/cm^3. Therefore in neutron stars the fields can (although they do not necessarily!) reach values 10^{13}–10^{15} Oe, or more realistically, values $H \sim 10^{12}$ Oe. On the other hand, by virtue of the discarding of the envelope and for other reasons, the initial radius r is possibly of the order of only 10^8 cm. Then, even at $r_0 \sim 10^6$ cm and $H \sim 10^4$ Oe, the field is $H_0 \sim 10^8$ Oe. (The possibility that the fields are so large in neutron stars was noted even prior to the discovery of pulsars; see, for example, [8, 13].)

It can thus be stated that neutron stars should, as a rule, rotate quite rapidly (angular velocity $\Omega \lesssim 10^3$ sec^{-1}) and should be strongly magnetized (fields 10^8 Oe $\lesssim H \lesssim 10^{12}$–$10^{14}$ Oe). In addition, there are no known reasons why the dipole magnetic moment **m** associated with the star (or some other magnetic symmetry axis) must coincide with the revolution axis **Ω**. By the same token we arrive at a nonsymmetrical and nonstationary system—the model of the so-called inclined rotator (Fig. 1), which came under discussion as applied to neutron stars[14] shortly before the discovery of pulsars.

Favoring the identification of pulsars with rotating neutron stars are also two other circumstances. First, owing to the radiation of electromagnetic and gravitational waves, and also as a result of escape of gas (stellar wind), the rotation of the stars should slow down.

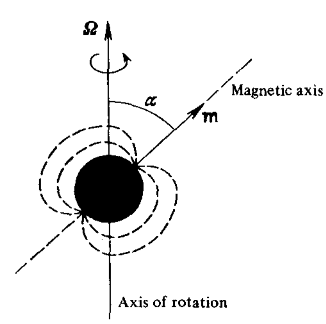

FIG. 1. Inclined rotator.

Accordingly, the period P of the pulsars should, as a rule, increase, as is indeed observed. Second, at least for the pulsar NP0532 in the Crab, the period of which doubles within $T \approx 2400$ years, it is natural to assume that the decrease of the kinetic energy of rotation of the star $|dK/dt| \sim K/T \sim 10^{-11}$ K erg/sec is equal to the total luminosity of the Crab nebula in all the bands, $L \sim 10^{38}$ erg/sec. Such an assumption agrees with the rough estimate of the kinetic energy of rotation of a neutron star $K = I\Omega^2/2 \sim 10^{49}$ erg obtained for $\Omega = 200\ \mathrm{sec}^{-1}$ and a moment of inertia $I \sim Mr_0^2 \sim 10^{45}$ g-cm^2 ($M \sim M_\odot = 2 \times 10^{33}$ g, $r_0 \sim 10^6$ cm).

Theoretical problems connected with investigations of pulsars—rotating magnetized neutron stars—are quite numerous, but it is possible here, albeit arbitrarily, to separate three groups of problems:

1. Structure and processes in the neutron stars themselves.
2. Structure and dynamics of the atmosphere and magnetosphere of rotating neutron stars. The transformation of the magnetosphere of the star into the envelope of a supernova or into interstellar medium.
3. Mechanisms of pulsar radiation and corresponding models of pulsars—sources of observable electromagnetic radiation.

In addition, naturally, a large number of problems arise in connection with the role of pulsars in envelopes of supernovas, their role as sources of cosmic rays, the use of pulsars for different astronomical and physical purposes, etc. We shall dwell briefly on all these aspects of the pulsar problem.

3. STRUCTURE OF NEUTRON STARS AND PULSARS

In view of our insufficiently exact knowledge of the equation of state of matter at ultrahigh densities, quantitative calculations of the structure of neutron stars are still unreliable (see above and [5, 6, 15]). We, however, will be interested henceforth only in the qualitative picture and in order-of-magnitude estimates. We can then apparently choose the following parameters of a "typical" neutron star:

$$M \sim 0.5M_\odot, \quad r_0 \sim (1-3)\cdot 10^6\,\mathrm{cm}, \; \rho_c \gtrsim 10^{15}\ \mathrm{g/cm^3}$$

Further, the density of the neutron liquid ρ_n is close to the total density of matter in the star only if $\rho_n \gtrsim 5 \times 10^{13}$ g/cm^3. On the other hand, if $\rho \lesssim 3 \times 10^{11}$ g/cm^3, then the role of the neutrons is negligibly small and the matter consists of nuclei and electrons. Thus, it is perfectly clear that the external layer of the star (say at $\rho \lesssim 10^{12}$ g/cm^3) has a plasma nature and is similar to the matter in white dwarfs. But from this follows already the less obvious statement that the plasma envelope of the neutron star is solid in its main part, i.e., it forms a crust.[15] The point is that as a result of neutrino and electromagnetic radiation, the neutron star cools rapidly and by virtue of its high thermal conductivity the entire star has, soon after its formation, a temperature lower than $(1-5) \times 10^{8}$°K. At the same time, the melting temperature T_m of the electron-nuclear plasma is determined from the condition $\Gamma kT_m = e^2Z^2/r_i$, where $r_i = n_i^{-1/3}$ is the average distance between nuclei with charge eZ. The numerical factor is $\Gamma \sim 100-200$, i.e., melting sets in when the kinetic energy of the nuclei is smaller by two orders of magnitude than the energy of their Coulomb interaction. Hence

$$T_m \sim 10^3\rho^{1/3}Z^{5/3}\,°\mathrm{K}. \tag{2}$$

Here the density is $\rho \approx 2Zm_pn_i$, since we put $A/Z = 2$ ($m_p = 1.67 \times 10^{-24}$ g is the proton mass). It is clear from (2) that for $Z \gtrsim 10$ and $\rho \gtrsim 10^{10}$ g/cm^3 the temperature is $T_m \gtrsim 10^{8}$°K. Thus, besides a thin plasma ("liquid" or gas) outer layer, a quite appreciable plasma layer of the star should be solid. The thickness of this layer for a "typical" neutron star is of the order of 10^4-10^5 cm. Under the crust there is the neutron liquid ($\rho > 5 \times 10^{13}$ g/cm^3), in which protons and electrons are contained with a concentration on the order of one or several percent.[16]* All these particles (neutrons, protons, electrons) form a degenerate Fermi system, and under such conditions one can assume, with a certain degree of approximation, that the system consists, as it were, of a mixture of independent neutron, proton, and electron Fermi liquids. The electron liquid of high density always remains a normal Fermi liquid, i.e., it is close to a degenerate Fermi gas. But the neutron and proton liquids can go over respectively into superfluid and superconducting states (see [17–22]).

The nature of superfluidity and superconductivity in Fermi liquids became clear only in 1957 (the theory of Bardeen, Cooper, and Schrieffer), although superconductivity of metals was discovered almost half a century earlier (in 1911). It turned out that if particles with energies close to the Fermi energy are attracted to one another in a degenerate Fermi gas (liquid), then they coalesce into pairs even under the weakest attraction, and these pairs, being bosons, experience something akin to Bose-Einstein condensation. In other words, the usual Fermi distribution turns out to be unstable and a gap appears in the energy spectrum of the system. The width $\Delta(T)$ of this gap depends on the temperature T. The gap is maximal and equal to $\Delta(0)$ at $T = 0$. At a certain temperature, called the critical temperature T_c, the gap closes (thus $\Delta(T_c) = 0$). $T_c \sim \Delta(0)/k$ or, if $\Delta(0)$ is measured in MeV, then

$$T_c \sim 10^{10}\ \Delta_{(\mathrm{MeV})}(0)\ °\mathrm{K}.$$

The presence of an energy gap makes it possible for the particles to be scattered in the collisions, and consequently their flow, once initiated by some cause, does not slow down. The system turns out to be superfluid or, in the case of charged particles, superconducting.

Neutrons with opposite spins (in the S state), if located at not too large distances, attract one another. This attraction is insufficient for the production of the bineutron, but in the presence of degeneracy (i.e., for a sufficiently dense neutron gas) it should lead to the formation of the aforementioned pairs and to the transition to the superfluid state. The minimum gap width $\Delta(0)$ is of the order of or somewhat smaller than the energy of the nuclear interaction, i.e., of the order of 1 MeV, and consequently the critical temperature is

$$T_c \sim 10^{10}\Delta_{(\mathrm{MeV})}(0) \sim 10^{10}\,°\mathrm{K}. \tag{3}$$

This estimate pertains to a neutron-liquid density $\rho_n \sim 10^{13}-10^{14}$ g/cm^3 and consequently is suitable for a

*See also the note added in proof, Item 3, at the end of the article.

neutron liquid situated immediately under the crust (we recall that the total density of matter is $\rho \approx \rho_n$ at $\rho \gtrsim 5 \times 10^{13}$ g/cm^3, i.e., precisely on the inner boundary of the crust). With increasing density, however, the gap $\Delta_S(0)$ decreases for pairs in the S state, owing to the increased role of repulsion, and according to the estimates of [21, 22] The gap "collapses," i.e., $\Delta_S(0) = 0$ at $\rho \approx \rho_n \approx (1.5-2) \times 10^{14}$ g/cm^3 (the density $\rho_n = 1.5 \times 10^{14}$ g/cm^3 corresponds to the neutron density in atomic nuclei; the total density in the nuclei is approximately twice as large, i.e., $\rho_{\text{nuclei}} \approx 3 \times 10^{14}$ g/cm^3). Nonetheless, the superfluidity need not vanish at $\Delta_S(0) = 0$, for when $\rho \approx \rho_n > 1.5 \times 10^{14}$ g/cm^3 the attraction between the neutrons in the P state (in the triplet state with spin 1) comes into play. The corresponding gap $\Delta_P(0)$ is apparently somewhat smaller than the gap. $\Delta_S(0)$, but the rough estimate (3) remains in force.[22]

The proton liquid behaves approximately like the neutron liquid, but its density is smaller by one or two orders of magnitude. As a result of the Coulomb repulsion between the protons, the corresponding gap is probably smaller by one order of magnitude than for the neutron liquid, i.e., the critical temperature for the proton superconductivity is $T_c \sim 10^{9}$°K.

Since in most cases the temperature of the star is $T \leq T_c$, we reach the conclusion that under the crust that (at $\rho > (3-5) \times 10^{13}$ g/cm^3) the neutron stars are superfluid (neutron liquid) and superconducting (proton liquid). This conclusion is quite probable for densities $\rho \lesssim (5-10) \times 10^{14}$ g/cm^3, although it is still impossible to calculate reliably or even estimate the gap $\Delta_S(0)$, and particularly the gap $\Delta_p(0)$ in this region. As to the densest regions with $\rho \lesssim 10^{15}$ g/cm^3, at the present status of the problem it is difficult to make even rough estimates of the gap $\Delta(0)$. It is therefore perfectly possible that in the central parts of sufficiently massive ("typical") neutron stars there is a nonsuperfluid and nonsuperconducting nucleus. For concreteness we shall assume so henceforth, although this assumption is of no importance in what follows.

Thus, a typical neutron star consists of a thin dense gaseous plasma envelope, a solid plasma crust, a superconducting and superfluid layer,* and a dense nucleus (Fig. 2).

The hypothesis was advanced that the matter of a neutron star can be ferromagnetic (we have in mind here nuclear ferromagnetism, under which the magnetic moments of the neutrons turn out to be parallel). According to calculations,[23] no nuclear ferromagnetism arises, at least at $\rho < 5 \times 10^{14}$ g/cm^3. As to the region of densities $\rho \gtrsim 10^{15}$ g/cm^3 lying within the limits of the nucleus of the star, the matter here should contain, besides nucleons and electrons, also μ and π mesons and hyperons (a density $\rho \sim 10^{15}$ g/cm^3 corresponds to a Fermi energy $E_F \sim 100$ MeV). In this region one can only guess at the equation of state, and this introduces a significant uncertainty in the calculation of a number of parameters of neutron stars.

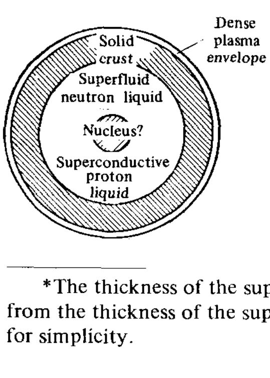

FIG. 2. Neutron star (schematic cross section).

*The thickness of the superconducting layer can differ somewhat from the thickness of the superfluid layer, but this difference is neglected for simplicity.

Observations of pulsars can yield information on the structure and evolution of the magnetic field of the star and its dynamics or, concretely, on the change of its rotation speed.

If the magnetic field in the star is not maintained by some mechanism and is due to conduction currents,† then the characteristic attenuation time of the field is determined with the aid of the well known estimate

$$\tau_m \sim \frac{\sigma r^2}{c^2}, \tag{4}$$

where σ is the conductivity and r the characteristic dimension. For a solid crust at $\sigma \sim 10^{23}$ sec^{-1} (see [25]) and $r \sim 10^5-10^6$ cm, the time is $\tau_m \sim 10^{12}-10^{14}$ sec (a dimension $r \sim 10^6$ cm and even $r \sim 3 \times 10^6$ cm corresponds to the radius of the solid envelope, and $r \sim 10^5$ cm corresponds to its thickness). The electron conductivity σ of the neutron-proton-electron liquid under the crust is much higher than in the crust; according to [26] $\sigma \sim 10^{29}$ sec^{-1}. From this we get at $r \sim 10^6$ cm a time $\tau_m \sim 10^{20}$ sec. In the superconducting state, which arises under conditions of high conductivity, the magnetic flux attenuates even more slowly. By virtue of the inhomogeneity of the star (crust, liquid layer) the question of the attenuation time of the field on its surface remains unclear. Furthermore, the field can be maintained by some dynamo effect. The estimate $\tau_m \sim 4 \times 10^6$ years which can be obtained from the observed distribution of the periods of the pulsars[27a] (see, however, [27b, 47]) seems possible, but cannot be regarded in any way as confirmed on the basis of calculations pertaining to the evolution of the star.

Most interesting and rather unexpected was the possibility of investigating the structure of neutron stars from data on the jumps and the general nonmonotonicity of the slowing down of the periods of the pulsar PSR0833-45 in the envelope of Vela X and of the pulsar NP0532 in the Crab nebula. Such changes in the period, especially the jumps, can be attributed to seismic phenomena in the solid crust of the neutron stars.[28, 29] With increasing time, the angular velocity of the star decreases, as is manifest in an increase in the period of repetition of pulsar pulses. But the hard crust cannot change its form smoothly, and therefore as the rotation slows down one should expect "starquakes"—the appearance of fractures in the crust, etc., as a result of which the crust assumes a form that is close to equilibrium at the given angular velocity. There are all grounds for assuming that on a "starquake" and realignment of the crust the angular momentum $J = I\Omega$ is

†In a strong magnetic field the quantization of the electron orbits is important, and for this reason there may appear, in principle, a certain electronic "orbital ferromagnetism." [24] But an effect is of the nonequilibrium type and its role still remains unclear, since this role depends on the kinetics of the formation of the star as well as on the time of relaxation of the considered magnetic moment in the material of the star.

conserved, and consequently the change of the angular velocity $\Delta\Omega$ is connected with the change of the moment of inertia ΔI, so that $\Delta\Omega/\Omega = -\Delta I/I$. The change observed for PSR0833-45 is $\Delta\Omega/\Omega \approx 2 \times 10^{-6}$, meaning that $\Delta I \approx -2 \times 10^{-6} I \sim -10^{39}$ g-cm^2 ($\Omega \approx 70$ sec^{-1}, $I \sim Mr^2 \sim 10^{45}$ g-cm^2 at $M \sim M_\odot$ and $r \sim 10^6$ cm). By the same token, a certain average radius of the star r should change only by $\Delta r \sim (|\Delta I|/I)r \sim 1$ cm (!). It might seem that after the rearrangement of the crust the rotation of the star should proceed in the same manner as before the rearrangement, since a negligible change in the radius is most likely to have no effect on the decelerating torque (see below). Actually, however, after the "catastrophe" the pulsar in Vela began to slow down more rapidly than before it (concretely, $\Delta\dot{\Omega}/\dot{\Omega} \sim 10^{-2}$, $\dot{\Omega} \equiv d\Omega/dt$). A most likely explanation[30] of this effect attributes it precisely to the superfluidity and superconductivity of the neutron-proton liquid under the crust.

In a superfluid liquid,* at temperatures much lower than critical, there can occur only a vortex-free (superfluid) flow, and seemingly, the superfluid part of the star cannot rotate, i.e., its effective moment of inertia is zero. Actually, however, even at the negligible angular velocity $\Omega_c \sim (\hbar/m_n r^2)\ln(r/a) \sim 10^{-14}$ sec^{-1} ($m_n \sim 10^{-24}$ g is the nucleon mass, r is the radius of the liquid sphere, and $a \sim 10^{-12}$ cm is the radius of the core of the vortex filament, where the liquid is no longer superfluid), it is energywise more convenient for vortex filaments parallel to the rotation axis to appear in a rotating superfluid liquid. About each such filament, the circulation of the velocity is $2\pi\hbar/2m_n$, and the angular momentum of the pair of nucleons (mass $2m_n$) as a result of their motion around the filament is equal to $\hbar = 1.5 \times 10^{-27}$ erg-sec. When $\Omega \gg \Omega_c$, the number of filaments produced is sufficiently large to make the average velocity of the medium the same as in the case of a normal liquid. Then the number of vortex filaments per unit area perpendicular to the rotation axis is $n_0 \sim 2m_n\Omega/(\pi\hbar)$ (the angular momentum of the star is $J = I\Omega \sim Mr^2\Omega \sim n_0\hbar\pi r^2 (M/2m_n)$, where $M/2m_n$ is the total number of pairs). The average distance between the vortex filaments is therefore $\xi \sim n_0^{-1/2} \sim (\hbar/(m_n\Omega))^{1/2}$. Even for the pulsar in the Crab, with $\Omega \approx 200$ sec^{-1}, the distance is $\xi \sim 2 \times 10^{-3}$ cm, which is incomparably larger than the average distance between neutrons $\xi_n \sim (\rho/m_n)^{-1/3}$ cm.

Thus, in a rotating neutron star the neutron-proton (liquid) part of the star takes part in the rotation because of the appearance of a set of vortex filaments, which are probably secured in some way to the solid crust. If the rotation velocity does not change, then the presence of the vortex filaments inside, of course, is not manifest in any way on the outside. But when the angular velocity changes, the situation also changes. In the case of a normal (not superfluid) liquid, the neutrons exchange momentum with the protons and with the electrons very rapidly (characteristic time $\tau \sim 10^{-15}$ sec, see [20]). If the protons are superconducting and the neutrons are normal, then momentum is transferred as a result of the interaction of the electrons with the magnetic moment of the neutrons, and $\tau \sim 10^{-9}$ sec. On the other hand, in the case of superconductivity of protons and superfluidity of neutrons, the transfer of momentum occurs only in the normal cores of the vortex filaments. The total volume of these cores is smaller by a factor $\pi a^2 \times n_0 \sim \pi a^2 \times 2m_n\Omega/(\pi\hbar) \lesssim 10^{-18}$ than the total volume of the neutron liquid, by virtue of which the relaxation time τ now amounts to days or years (!). It follows therefore that when the moment of inertia of the crust decreases, at first only its angular velocity increases, together with the velocity of the proton and electron liquids, while the angular velocity of the superfluid neutron layer experiences a change only at a time $\tau_0 \sim 0.1$–10 years later. By the same token, the rotation of the star can be described, in first approximation, by equations[30] that speak for themselves:

$$\left.\begin{aligned} I_c\dot{\Omega} &= N - \left[(\Omega - \Omega_n)\frac{I_c}{\tau_0}\right], \\ I_n\dot{\Omega}_n &= (\Omega - \Omega_n)\frac{I_c}{\tau_0}; \end{aligned}\right\} \tag{5}$$

Here I_c and I_n are the moments of inertia of the crust and of the superfluid part of the star, respectively, N is the deceleration torque, Ω is the observed angular velocity of the crust and Ω_n is the angular velocity of the superfluid liquid. It is impossible at present to dwell in greater detail on the analysis of the equations in (5), particularly when the moments of inertia I_c and I_n change as a result of a "starquake." Qualitatively, however, it is clear immediately that prior to the establishment of the quasiequilibrium (i.e., for times $t \lesssim 0.1$–10 years) the crust is slowed down more strongly than the neutron liquid. As a result, naturally, after the "starquake" (and incidentally independently of the nature of the change of the angular velocity), the increase of the pulsar's period is more rapid than prior to the quake. From the theory it follows that $\Delta\dot{\Omega}/\dot{\Omega} \sim (T/\tau_0) \times (\Delta\Omega/\Omega)$, where T is the characteristic time of slowing down of the rotation of the star—for example, the time of doubling of the period of the pulsar (it can also be assumed that $\dot{\Omega}/\Omega = -1/T$). For the pulsar in Vela, $T \approx 24\,000$ years and at $\tau_0 \sim 1$–10 years we have $\Delta\dot{\Omega}/\dot{\Omega} \sim 10^4\,\Delta\Omega/\Omega$, which agrees with the observations.

The nonmonotonic change of the frequency (wobble) observed for the pulsar NP0532, with a period of about three months, may also be connected with the behavior of the superfluid part of the star.[32] The point is that in a system of vortex filaments there can occur slow rotational oscillations (having precisely the required period).

It should be noted that the observed perturbations in the course of the monotonic growth of the period of the the young pulsars in Vela and the Crab may be attrib-

*Under terrestrial conditions, superfluidity had been known and investigated only for helium-II (liquid helium at $T < T_\lambda = 2.17$°K; we shall not discuss solutions of He^3 and He^4). In this case, the superfluidity vanishes at the λ point (at the temperature T_λ at which helium II changes into helium I), which corresponds to the temperature of Bose-Einstein condensation of the helium atoms.

*We note that wherever the equations (5) are used, in [30] and in subsequent papers known to us, the moment of the force N is assumed to be same before and after the starquake. Yet not only the gravitational deceleration (see [34b]), but the probably more appreciable electromagnetic deceleration of the pulsar can change during the starquake as a result of additional ejection of plasma and the ensuing changes of the conditions near the star (see the next section).

uted, in principle, not only to "starquakes" of the crust and to superfluidity of the neutron liquid. Thus, attempts can be made to relate the perturbations of the period with the presence of light satellites (planets) of the star-pulsar,[33, 34a] with changes of the losses due to gravitational radiation in connection with the change of the quadrupole moment of the mass of the star,[34b] and some other factors.[34a, 34b] The explanation presented above seems to us, however, more likely. It can be verified by making sufficiently prolonged observations of the change of the pulsar period following the catastrophe (after the jump of the period).

Thus, a study of the nonmonotonicities (perturbations) during the secular increase of the period of the pulsars uncovers prospects for "peeking" inside a neutron star. Preliminary data on this subject offers evidence favoring the existence of a hard crust and a superfluid neutron core or layer in such stars (the protons in such a layer are probably superconducting).

One cannot fail to note that following the failure of attempts to identify certain cosmic x-ray sources with neutron stars even before the discovery of pulsars, the prospects of proving the very existence of neutron stars were far from bright. But now there is a reasonable hope of studying the internal layers of these stars. Such progress is inspiring.

4. ELECTRODYNAMICS OF ROTATING MAGNETIZED STARS

The estimates given above of the relaxation time τ_m of the magnetic field make it possible to assume, in first approximation, that in a reference frame connected with the star its magnetic field does not change with time (within the body of the star). The structure of this field is unknown. There are no grounds whatever to regard it as purely dipole, but usually outside the star the dipole term plays the principal role. Incidentally this, strictly speaking, pertains only to the case when the star is in vacuum. On the other hand, if there is sufficiently dense plasma in the magnetosphere of the star or even in the wave zone, then the character of the field outside the body of the star may be completely altered.

Let us assume first that the star is in vacuum. In this case we know an exact solution for the field of a rotating star under the assumption that we are dealing with an exact magnetic dipole, this being the most realistic model of an ideally-conducting uniformly magnetized rotating sphere.[35] The dipole magnetic moment of the star $\mathbf{m}$ is best resolved into a component $\mathbf{m}_{\parallel}$ along the axis of rotation Ω and a component $\mathbf{m}_{\perp}$ perpendicular to the axis of rotation. Obviously $\mathbf{m}_{\parallel}$ does not change in time (we assume that $m = \text{const}$), and the dipole $\mathbf{m}_{\perp}$ rotates, and consequently radiates. Regardless of the details of the structure of the field on the surface of the star and near it (in the near zone), the field in the wave zone (at $r \gg \lambda_0 = 2\pi c/\Omega$) decreases like $1/r$ and the total power of the magnetic-dipole radiation is equal to $L_m = (2/3)m_{\perp}^2\Omega^4/c^3$. Naturally, this power is obtained at the expense of a decrease in the kinetic energy of rotation of the star $K = I\Omega^2/2$, and consequently, in the absence of other losses, we have

$$\frac{dK}{dt} = I\Omega\dot{\Omega} = -\frac{2}{3}m_{\perp}^2\frac{\Omega^4}{c^3}. \tag{6}$$

Hence

$$\Omega = \Omega_0\,[1 + (t/T_m)]^{-1/2},\quad T_m' = 3c^3I/(4m_{\perp}^2\Omega_0^2)$$

and the time t is reckoned from the instant when $\Omega = \Omega_0$. For the pulsar NP0532 in the Crab in our epoch, the period doubles within the time $T \approx 2400$ years $\sim 10^{11}$ sec. Consequently at $\Omega_0 \approx 200\ \text{sec}^{-1}$ and $I \sim Mr_0^2 \sim 10^{45}$ g-cm^2 the time $T \sim T_m$ at $m_{\perp} \sim 2\times10^{30}$ G-cm^3. The field of the magnetic dipole $\mathbf{B} \equiv \mathbf{H} = 2\mathbf{m}/r^3$ at the magnetic pole and $\mathbf{H} = -\mathbf{m}/r^3$ at the magnetic equator. Consequently, at $m \sim m_{\perp} \sim 10^{30}$ the field on the surface of a star with radius $r_0 \sim 10^6$ cm is $H_0 \sim 10^{12}$ Oe. Such an estimate is the one customarily employed;[36] it does not contradict independent estimates of the field produced upon formation of a neutron star (see above). At the same time, obviously, Eq. (6) is valid rigorously only for a star in vacuum (including the assumption that there is no escape of particles from the star), and in addition, only when gravitational radiation is neglected. The role of gravitational radiation can be taken into account by adding in the right-hand side of (6) the term

$$-L_g = -\frac{G}{45}D_{\perp}^2\frac{\Omega^6}{c^5} \approx -\frac{6G}{c^5}I^2\varepsilon\Omega^6,$$

where $D_{\perp}$ is the component of the quadrupole moment of the mass of the star perpendicular to the rotation axis and $\epsilon \approx (a-b)/a$ is the ellipticity (a and b are the axes of the elliptic cross section of the star perpendicular to the rotation axis, see [36]). In the inclined-rotator model the moment $D_{\perp}$ automatically appears under the influence of the asymmetrical (relative to the rotation axis) magnetic field. However, the power of the gravitational radiation can reach a value $L_g \sim 10^{38}$ erg/sec apparently only if the star has an internal field (for example, a toroidal one) $H_i \gtrsim 10^{15}$ Oe (see [36, 37]). Although the existence of such a field is in principle permissible and does not contradict the presence of an external (poloidal) field $H_0 \lesssim 10^{13}$ Oe, it seems to us very improbable. For reasons that will become clear later, it is hardly possible to estimate the power of gravitational radiation from energy-balance considerations or from the dependence of the angular velocity (period) of the pulsar on the time. Therefore this question can be answered definitely only by measuring the flux of gravitational waves from the Crab nebula (it is important that the plasma envelope has practically no influence on the power of the gravitational radiation). Unfortunately, such measurements are not likely to be performed soon.*

Besides electromagnetic and gravitational radiation, the star can lose energy by escape of matter and acceleration of charged particles leaving the star.[41-43] A very important fact here is that near a magnetized star rotating in vacuum there should exist an electric field

*A gravitational radiation of the pulsar in the Crab with a power $L_g \sim 10^8$ erg/sec corresponds to a flux on earth $t_g \equiv F_g \sim L_g/4\pi R^2 \sim 3\cdot10^{-7}$ erg/cm^2 sec, whereas the existing receivers [38,39] can register only a flux $F_g \sim 10^4$ erg/cm^2 sec. Registration of fluxes $F_g < 10^{-6}-10^{-7}$ erg/cm^2 sec, unless some new methods are devised [39], calls for cooling a receiver weighing several tons to very low temperatures ($T \lesssim 10^{-2}\,^\circ$K). Realization of such a project lies within the realm of possibility at the present time [40], but will call for rather prolonged efforts.

$E \sim (\Omega r/c)H$ (in the reference frame rotating with the star, $E = 0$). Such an effect (we are dealing in fact with unipolar induction) can play a major role even for ordinary slowly-rotating stars.[44] For pulsars, on the other hand, its role is of course colossally increased in connection with the large values of H and Ω. For example, at $\Omega \sim 10^2\ \sec^{-1}$, $r \sim 10^6$ sec, and $H \gtrsim 10^8$ Oe the field is $E \gtrsim 3 \times 10^5$ cgsesu $\sim 10^8$ V/cm. This yields a potential difference $V \sim Er \sim 10^{14}$ V. It is perfectly obvious that in the presence of similar fields, or even fields that are smaller by several orders of magnitude (the field can be greatly weakened if the plasma atmosphere of the star is sufficiently dense), the force of gravity in the atmosphere of the star plays a secondary role. In particular, one cannot say that a magnetized and rotating neutron star can have an extremely thin equilibrium atmosphere with characteristic height $h \sim kTr_0^2/GMm_p \sim 1$ cm (temperature $T \sim 10^6$ °K, $M \sim M_\odot$, $r_0 \sim 10^6$ cm; $m_p = 1.67 \times 10^{-24}$ g is the proton mass). By the same token, there are no grounds whatever for regarding, and in general it is impossible to regard such a star as being located in vacuum.

Unfortunately, it is extremely difficult to construct any consistent theory of the atmosphere (magnetosphere) of a rotating magnetized neutron star (this is clear even from the example of slowly rotating stars[45]; to determine the electromagnetic field of neutron stars it may be also necessary to take into account the effects of general relativity theory[8a, 46]). At any rate, no such theory has yet been constructed, and even qualitatively the picture remains unclear if one speaks of the distribution of the plasma outside the star as a function of the parameters Ω, m (magnetic moment) and r (coordinate).* We can therefore make here only a few remarks concerning the electrodynamics of pulsars.

Joint rotation of the star and the plasma in its magnetosphere is certainly impossible for distances from the rotation axis exceeding the radius of the "light cylinder,"

$$r_c = \frac{c}{\Omega} = 4.8 \cdot 10^9 P_{(\mathrm{sec})}\ \mathrm{cm} \qquad (7)$$

for in the case of joint (rigid-body) rotation the plasma velocity is $v = c$ already at $r = r_c$. At $\Omega = 2\pi/P = 200\ \sec^{-1}$ we have $r_c = 1.5 \times 10^8$ cm, and at $H_0 \gtrsim 10^8$ Oe the field is $H_c \sim H_0(r_0/r_c)^3 \gtrsim 10^2$ Oe. Hence, $H_c^2/8\pi \sim nkT$ at a nonrelativistic-electron concentration in the magnetosphere $n = n_e \gtrsim 400/kT \sim 4 \times 10^{12}\ \mathrm{cm}^{-3}$ at $T \sim 10^6$ °K or for relativistic electrons $n = n_r \gtrsim 4 \times 10^7\ \mathrm{cm}^{-3}$ at $kT \sim E \sim 10^{-5}$ erg ~ 10 MeV. It is clear, therefore, that for short-period pulsars the magnetic field can actually drag with it a rather dense plasma up to distances $r \sim r_c$. However, even in this case, let alone that of long-period pulsars, depending on the large number of circumstances (density and effective temperature of the plasma, field configuration), the dragging of the plasma can probably stop much earlier, i.e., already at $r < r_c$ or even $r \ll r_c$. Thus, the distance r_c plays the role of a certain maximum characteristic distance for pulsars. This conclusion agrees with the estimate of the maximal dimension l of the radiating region of the pulsars. Indeed, pulses with duration δP, generally speaking, should emerge from a region with dimensions $l \lesssim c\delta P$, for otherwise the pulse would become strongly smeared out as a result of the delay of signals coming from different parts of the source.† For pulsars, of course, the pulse duration is $\delta P < P$, and consequently $l < cP = 2\pi c/\Omega$, or in fact $l \ll 2\pi c/\Omega$.

For an inclined rotator (angle $\alpha > 0$) the picture is not symmetrical and is not stationary. There are all the more reasons for expecting the appearance of different plasma instabilities leading to turbulization of the plasma, to its heating, and to further acceleration of the particles in the magnetosphere and after emergence of the particles from it. All these processes can, incidentally, take place also when the rotation axis coincides with the axis of the magnetic dipole ($\alpha = 0$). Such a model, by virtue of the presence of axial symmetry, is more amenable to analysis[42] and possibly conveys some of the major features of the more realistic models of pulsars. It is curious that for an axially-symmetrical model the slowing down of rotation of the star, while occurring not as a result of radiation but because of acceleration of the particles by the electric field, is nevertheless given by a formula of the type (6), with $m_\perp$ replaced by $m_\parallel$ (see [41, 42]; of course, when $\alpha = 0$ the magnetic moment along the rotation axis $m_\parallel$ is equal to the total moment m). As a result we obtain for the field H_0 on the surface of the star the same estimate as before, i.e., for the pulsar in the Crab we get $H_0 \sim 10^{12}$ Oe.

Such an estimate of the field, however, still does not seem to us convincing, in view of the failure to take into account the influence of the plasma outside the body of the star. This is seen particularly clearly in the case of deceleration as a result of the magnetodipole radiation. A magnetic dipole located in vacuum, as already indicated, radiates electromagnetic waves with a power $L_m = (2/3)m_\perp^2(\Omega^4/c^3)$. But if such a dipole is placed in a homogeneous and isotropic medium with a refractive index $\tilde{n}$, then the power $L_m(\tilde{n})$ changes by a factor $\tilde{n}^3(\Omega)$ (for an electric dipole, the power changes by a factor $\tilde{n}(\Omega)$). More accurately, the former pertains to the case when waves with frequency Ω can propagate in the medium in question. On the other hand, if $\tilde{n}^2(\Omega) < 0$, then the waves do not go out from the dipole and the radiation power is $L_m(\tilde{n}) = 0$. For an isotropic "cold" (nonrelativistic) plasma we have

$$\tilde{n}^2(\omega) = 1 - \frac{\omega_e^2}{\omega^2}, \quad \omega_e = \sqrt{\frac{4\pi e^2 n_e}{m}} = 5.64 \cdot 10^4 \sqrt{n_e}$$

and the inequality $\tilde{n}^2\ (\omega \equiv \Omega) < 0$ can be easily realized.

In the case of magnetic stars, particularly pulsars, the plasma near the star is in a magnetic field. Therefore the plasma is magnetically active and the refractive indices $\tilde{n}_l^2$ for the normal waves propagating in it

*The dependence of the plasma density on the star mass M and on its temperature is probably less significant. The same pertains to conditions far from the star, provided only accretion does not play any role (according to [47], accretion can play a decisive role for old pulsars). We note also that the parameter **m** is equivalent to two scalar parameters—the field H_0 on the surface of the star (say at its magnetic pole) and the angle α between Ω and **m**.

†More accurately, the role of l is played not by the entire dimension of the radiating source, but the dimension of the region in which the radiation intensity becomes relatively stronger as a result of the maser effect (for more details see [48]).

depend in a rather complicated manner on the frequency ω, on the field intensity H, on the angle θ between **H** and the wave vector **k**, and also on other parameters (see, for example, [49]). Thus, if the frequency ω is small compared with the gyrofrequency for the ions $\Omega_H = eH/m_i c = 9.6 \times 10^3$ H (the ions are assumed to be relativistic; the numerical coefficient pertains to the case of hydrogen, when $m_i = m_p = 1836m = 1.67 \times 10^{-24}$ g), then in a large number of cases one can employ the magnetohydrodynamic approximation. Then, for example, for waves traveling along the magnetic field we have

$$\tilde{n}^2 = 1 + \frac{4\pi m_i n_i c^2}{H^2} \approx 1 + \frac{4\pi\rho c^2}{H^2},$$

or $\tilde{n} = \sqrt{4\pi\rho}c/H = c/v_a$ under the condition that the Alfven velocity $v_a = H/\sqrt{4\pi\rho} \ll c$. Under the same condition, obviously, $\tilde{n} \gg 1$ (for example, at $H < 10^6$ Oe and a concentration $n_i = n_e > 10^{14}$ cm^{-3}, $\rho > 10^{-10}$ g/cm^3, and an index $\tilde{n} > 10$). Thus, in the magnetohydrodynamic frequency region the radiation, and consequently the deceleration of the inclined rotator, can differ radically from that taking place in vacuum (this conclusion is confirmed by more detailed calculations [50]). In the Crab nebula, far from the pulsar, $H \lesssim 10^{-3}$ Oe, the ion gyrofrequency is $\Omega_H \lesssim 10$ sec^{-1}, and the magnetohydrodynamic approximation is not valid. To the contrary, in this case one can usually neglect the influence of the ions. In addition, in all probability the electron plasma frequency in the nebula is $\omega_e = 5.64 \times 10^4\sqrt{n_e} \gg \omega_H = eH/mc = 1.76 \times 10^7$ H and $\omega_e \gg \Omega \equiv \omega$. The same conditions are realized for "whistlers" in the earth's magnetosphere and for helicons in metals. As is well known (see, for example [49], Sec. 11), under the indicated conditions only one type of wave (ordinary wave) can propagate in the plasma, with

$$\tilde{n}_2(\Omega) = \frac{\omega_e}{\sqrt{\Omega\omega_H \cos\theta}} = \sqrt{\frac{4\pi|e|n_e c}{\Omega H \cos\theta}}, \qquad (8)$$
$$\omega_e \gg \omega_H, \quad \omega_e \gg \Omega, \quad \omega_H \cos\theta \gg \Omega.$$

When $\cos\theta \sim 1$, $\omega_e \sim 10^5$–10^6 sec^{-1} ($n_e \sim 1$–10^3 cm^{-1}), $\Omega = 200$ sec^{-1}, and $\omega_H \sim 10^4$ sec^{-1} ($H \sim 10^{-3}$ Oe) we get $\tilde{n}_2(\Omega) \sim 10^2$–$10^3$. If we assume tentatively that the magnetic-dipole radiation, as in an isotropic medium, is proportional to $\tilde{n}^3 = \tilde{n}_2^3$, then the loss in this example increases by 10^6–10^9 times (!). The estimate of the field H_0 on the surface of the star then decreases by a factor $\tilde{n}_2^{3/2} \sim 10^3$–$3 \times 10^4$ compared with the estimate for the vacuum.

The foregoing reasoning is still far from sufficient for a realistic estimate of the influence of the plasma on the deceleration of the star, but it demonstrates the possibility that the near-stellar plasma can radically change the picture and cause the appearance of the observed deceleration for a field $H_0 \sim 10^8$–10^9 Oe on the surface of the star. This is precisely why the question of the magnitude of this field still remains open at present, and the customarily employed values $H_0 \sim 10^{12}$–10^{13} Oe cannot be regarded in any way as being sufficiently well founded.

The electromagnetic radiation not only slows down the rotation of the star, but can also change the angle α between the rotation axis Ω and the magnetic moment **m**. This question was considered in the articles [36, 51, 52a] in the course of calculating the moment of the force **N**, which is expressed in terms of the electromagnetic field stress tensor T_{ij}. To the same end we can use the usual equation for a particle with a mechanical angular momentum $\mathbf{J}_0$ and a magnetic moment **m**:

$$\frac{d\mathbf{J}_0}{dt} = [\mathbf{m}\mathbf{H}_{ext}] - \frac{4\nu_m}{3\pi c^3}\left[\mathbf{m}\frac{d^2\mathbf{m}}{dt^2}\right] + \frac{2}{3c^3}\left[\mathbf{m}\frac{d^3\mathbf{m}}{dt^3}\right], \qquad (9)^*$$

where $\mathbf{H}_{ext}$ is the external magnetic field at the place of passage of the dipole and $\nu_m \sim c/r_0$ depends on the structure (form factor) of the dipole (r_0 is the radius of the magnetized sphere).† The moment

$$N_c = -\frac{4\nu_m}{3\pi c^3}\left[\mathbf{m}\frac{d^2\mathbf{m}}{dt^2}\right] = -\frac{d\mathbf{J}_m}{dt}$$

is conservative and

$$\mathbf{J}_m = \frac{4\nu_m}{3\pi c^3}\left[\mathbf{m}\frac{d\mathbf{m}}{dt}\right]$$

is the electromagnetic angular momentum of the star. In the absence of an external field ($H_{ext} = 0$) and if no account is taken of the dissipation, the total angular momentum $\mathbf{J} = \mathbf{J}_0 + \mathbf{J}_m$ is, naturally, conserved. For neutron stars $J_0 = I\Omega \lesssim 10^{47}$ g-cm^{2}sec^{-1} (at $I \lesssim 10^{45}$ g-cm^2 and $\Omega \lesssim 10^2$ sec^{-1}) and $J_m \sim m^2\Omega/r_0c^2 \lesssim 10^{35}$ g-cm^{2}sec^{-1} (at $r_0 \gtrsim 10^6$ cm, $m \sim H_0 r^3 \sim 10^{30}$ Oe-cm^3). The angular momentum $\mathbf{J}_m$ and the quantity analogous to it when account is taken of the influence of the plasma are perhaps of interest in a more detailed analysis of the dynamics of the star. As to the decrease of the angular velocity Ω and the change of the angle α, an important role is played here by the dissipative moment of the force

$$\left.\begin{aligned} \mathbf{N}_d &= \frac{2}{3c^3}\left[\mathbf{m}\frac{d^3\mathbf{m}}{dt^3}\right] = \mathbf{N}_{d\parallel} + \mathbf{N}_{d\perp}, \\ \mathbf{N}_{d\parallel} &= \frac{2}{3c^3}\left[\mathbf{m}_\perp\frac{d^3\mathbf{m}_\perp}{dt^3}\right], \quad \mathbf{N}_{d\perp} = \frac{2}{3c^3}\left[\mathbf{m}_\parallel\frac{d^3\mathbf{m}_\perp}{dt^3}\right]. \end{aligned}\right\} \qquad (10)$$

The moment $\mathbf{N}_{d\parallel}$ is directed along the rotation axis and slows down the rate of this rotation; taking the scalar product of (9) with $\boldsymbol{\Omega}$ and neglecting for simplicity the very small term $d\mathbf{J}_m/dt$, we obtain immediately Eq. (6), since $\boldsymbol{\Omega}\mathbf{N}_{d\parallel} = -2m_\perp^2\Omega^4/3c^3$. The moment $\mathbf{N}_{d\perp}$ is perpendicular to the angular velocity and leads to a decrease of the angle α, since

$$\left.\begin{aligned} I\frac{d(\Omega\cos\alpha)}{dt} &= \frac{\mathbf{m}\mathbf{N}_d}{m} = 0, \\ I\Omega\frac{d\alpha}{dt} &= -N_{d\perp} = -\frac{2m^2\Omega^3}{3c^3}\cos\alpha\sin\alpha, \\ I\frac{d\Omega}{dt} &= -N_{d\parallel} = -\frac{2m^2\Omega^3}{3c^3}\sin^2\alpha. \end{aligned}\right\} \qquad (11)$$

Here and above, the magnetic moment **m** is assumed to be constant in magnitude and rigidly fixed in the body of the star, which rotates in such a way that the angle α decreases. The characteristic time of the variation of the angle α, at $\alpha \sim 1$, is of the same order as the deceleration time $T_m = 3c^3I/4m_\perp^2\Omega_0^2$, but as $\alpha \to \pi/2$ the

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*$[\mathbf{m}\mathbf{H}_{ext}] = \mathbf{m} \times \mathbf{H}_{ext}$.

†The moment of the force acting on a small sphere with magnetization $\mathbf{M} = \mathbf{m}D(\mathbf{r})$, $\int d(\mathbf{r})d\mathbf{r} = 1$ is equal to $\int \mathbf{m} \times \mathbf{H}(\mathbf{r})d(\mathbf{r})d\mathbf{r}$, with $\mathbf{H}(\mathbf{r}) = \mathbf{H}_{ext} + \mathbf{H}_1(\mathbf{r})$, where $\mathbf{H}_1(\mathbf{r})$ is the proper field of the dipole (sphere) at the point **r** (the field $\mathbf{H}_{ext}$ is assumed to be homogeneous inside the sphere). Eliminating the field $\mathbf{H}_1$ with the aid of the field equations, we arrive [53] at Eq. (9). Since this equation itself, as well as the procedure for its derivation, are analogous to those used when account is taken of the radiation friction in the case of a charge (we refer here to the equation $m_0(d^2\mathbf{r}/dt^2) = \int eE(\mathbf{r})D(\mathbf{r})\,d\mathbf{r} = -m_{lm}(d^2\mathbf{r}/dt^2) + (2e^2/3c^3)(d^3\mathbf{r}/dt^3) + O(r_0)$, where m_0 is the mechanical mass and $m_{lm} = e^2\nu_m/c^3 \sim e^2/c^2r_0$ is the electromagnetic mass of a "particle" whose charge density is $\rho = eD(\mathbf{r})$, $\int D(\mathbf{r})d\mathbf{r} = 1$).

turning of the moment $\mathbf{m}$ is greatly slowed down (when $\alpha = \pi/2$, obviously, $d\alpha/dt = 0$). An analysis of Eq. (11) is contained in the articles [51, 52]. Unfortunately, the moment of the force $\mathbf{N}$ depends both on the radiation power, meaning on the parameters outside the star, and on the quasistatic component of the dipole $\mathbf{m}_{\parallel}$. For a nondipole field the situation is even more complicated. The same can be stated when account is taken of the nonsphericity of the star due to the presence of a solid crust or other factors.[52b] As a result, the question of the change of the angle α or, if convenient, of the radiating projection of the moment $\mathbf{m}_{\perp}$ for pulsars, remains open. Observations give the impression[54, 55] that for the pulsar NP0532 in the Crab the angle α is close to $\pi/2$, i.e., the magnetic dipole is practically perpendicular to the rotation axis. An analogous situation occurs, apparently, for ordinary magnetic stars.[56] The corresponding causes are not yet clear, but in principle, when account is taken of the influence of the plasma and of a not-strictly-dipole field, the angle α may either not decrease or even tend to $\pi/2$, so that it is certainly premature to speak of some contradiction in the model of the inclined rotator.

In summary, we can state that the model of the inclined rotator, in the approximation wherein the plasma outside the star is sufficiently rarefied and exerts only a small influence on the radiation of the star (the "vacuum approximation") is capable of explaining a number of features characteristic of pulsars, namely, the deceleration (increase in the period) after a characteristic time $T \sim 10^3-10^8$ years; the appearance of a plasma atmosphere of the pulsar as a result of the presence near the rotating magnetized star of an electric field causing the escape and acceleration of the particles; the presence of a sufficiently extended plasma atmosphere is assumed in most models of the radiating regions of pulsars.

In the discussed "vacuum approximation" the magnetic field on the surface of the star is $H_0 \sim 10^{12}-10^{13}$ Oe, and an appreciable fraction of the energy lost by the star is transferred to the escaping plasma, which also contains particles with very high energies. The last result is favorable from the point of view of the possibility of explaining the activity in supernova envelopes and certain features of these envelopes (concretely, we have in mind the pulsar NP0532 in the Crab nebula), and also the effective acceleration of particles near pulsars (see, for example, [36, 57, 58]).

At the same time, the region of applicability of the "vacuum approximation" remains unclear, let alone the fact that there is still no solution to the central problem of the self-consistent determination of the plasma parameters and the field parameters near a rotating neutron star—an inclined rotator. Therefore the estimate $H_0 \sim 10^8-10^9$ Oe for the field on the surface of the star seems improbable to us at the present time. The question of the time variation of the angle α between the magnetic moment $\mathbf{m}$ and the rotation axis $\boldsymbol{\Omega}$ remains unclear. The same can also be said of the estimates of the power of the cosmic rays and nonrelativistic plasma emitted by the pulsar, let alone the power of the gravitational radiation of the pulsars. Yet in the literature devoted to the pulsars, much that is hypothetical and barely possible is frequently regarded as fully realistic (examples are the statements of very powerful gravitational radiation of pulsars and the decisive role of pulsars as sources of cosmic rays in the Galaxy; see [59] in this connection). Of course, such a situation is to a considerable degree a natural reaction to such a remarkable discovery as the observation of pulsars. But independently of the motives, it must be borne in mind that the creation of a reliable theory of the atmosphere and magnetosphere of pulsars still calls for tremendous work.

5. MECHANISMS OF PULSAR RADIATION*

If we disregard some information that can be obtained regarding pulsars from data on supernova envelopes (see, for example, [60]) all of our information comes at present from analysis of the radiation emitted by the pulsars. It is obvious by the same token that questions of the mechanisms of radiation of pulsars and the structure of their radiating regions are of prime significance.

The first essential conclusion that can be drawn readily on the basis of estimates of the brightness temperature T_b for the radio emission of pulsars is that the mechanism of this radio emission cannot be incoherent.

We recall that for incoherent radiation mechanisms, in the absence of an absorption or reabsorption (absorption by the radiating particles themselves), the total radiation power (luminosity) L of a system of radiating particles (molecules, atoms, electrons) is the sum of the powers of the radiation of the individual particles. In other words, for incoherent mechanisms the radiation power is $L = Nu$, and when account is taken of the absorption and reabsorption we have $L \le Nu$, where u is the radiation power of one particle and N is the total number of the radiating particles in the source. In a large number of cases, however, it is necessary to consider also coherent mechanisms of radiation—in this case the power is $L > Nu$ and in general is not proportional to N. Examples are optical and radio sources with reabsorption, cosmic masers in the lines of OH and other molecules, certain components of the sporadic radio emission from the sun, and the radio emission of pulsars.

The radiation flux emitted by a spherical surface of radius r and observed at a distance R is equal to $F(\nu) = (2\pi\nu^2/c^2)kT_b(r/R)^2$. The brightness temperature of the source is therefore

$$T_b = \frac{c^2 F(\nu)}{2\pi k \nu^2}\left(\frac{R}{r}\right)^2 = 1.04\cdot 10^{13}\nu^{-2}\left(\frac{R}{r}\right)^2 \tilde{F}(\nu), \qquad (12)$$

where the flux $\tilde{F}(\nu)$ is measured in flux units f.u. $= 10^{-26}$ W/m^2 Hz; expression (12) can be regarded as a definition of T_b, and then it is formally suitable also beyond the limits of the condition $h\nu \ll kT_b$ (under this condition formula (12) is suitable also for equilibrium radiation, when $T_b \le T$).

For the pulsar NP0532 in the Crab, the time-averaged flux is of the order of magnitude

$$\tilde{F}(10^8\,\mathrm{Hz}) \sim 10\ \mathrm{f.u.},\quad \tilde{F}(10^{15}\,\mathrm{Hz}) \sim 10^{-2}\ \mathrm{f.u.},\quad \tilde{F}(10^{18}\,\mathrm{Hz}) \sim 10^{-4}\ \mathrm{f.u.} \qquad (13)$$

Hence at $R = 1500$ parsec and $r \sim 5\times 10^7$ cm we obtain T_b(radio) $\sim 10^{26}$ °K, T_b(optics) $\sim 10^9$ °K, T_b(x-rays) ~ 10 °K. The pulsar luminosity $L \sim 4\pi R^2 \int F(\nu)\, d\nu$ is of

*For details see [48,61,62] and the literature cited therein.

the order of L(radio) $\sim 10^{31}$ erg/sec, L(optics) $\sim 10^{34}$ erg/sec, and L(x-rays) $\sim 10^{36}$ erg/sec. Even if the radius r is decreased by one order of magnitude, we get T_b (optics) $\sim 10^{11}$ °K, corresponding to particles with energy $E \sim kT_b \sim 10^7$ eV. It is clear therefore that optical and x-radiation of pulsars can be fully incoherent, for example synchrotron radiation or inverse Compton scattering. To the contrary, radio emission even at $T_b \sim 10^{20}$ °K (for NP0532 this corresponds to the radius $r \sim 5 \times 10^{10}$ cm) can patently not be incoherent, since the the acceleration of a large number of electrons to energies $E \gtrsim 10^{16}$ eV is utterly unrealistic (furthermore, the intensity and accordingly T_b in the pulses is much higher than the employed mean values). The same can be said concerning the sources of OH lines with $T_b \sim 10^{12}$ °K, and concerning a number of bursts of solar radio emission. Thus, the radio emission from the pulsars should actually be due to a coherent mechanism.

There are two essentially different types of coherent radiation mechanisms, which can be called maser and antenna. The maser mechanism acts already under conditions of the homogeneous medium, i.e., it does not require spatial bunching of the particles. In some cases the maser mechanism does not require bunching or anisotropy of the particles in velocity space either. In other words, the maser mechanism can operate in the absence of macroscopic currents that vary at the radiated frequency. The maser mechanism is related to reabsorption—in both cases the intensity on the path l changes like

$$I = I_0 \exp(-\mu l), \qquad (14)$$

and for reabsorption $\mu > 0$, whereas for amplification $\mu < 0$.

The most essential factor for the antenna mechanism is spatial inhomogeneity of the source or spatial inhomogeneity of the distribution of the currents in the source. In the simplest case we are dealing with a source consisting of particle bunches, and one of the dimensions of the bunch is $d \ll \lambda$ (λ is the wavelength in the medium). If this condition is satisfied by all the dimensions of the bunch, then its radiation in all directions is coherent in the sense that all particles of the bunch radiate in phase, and therefore the total radiation power is $L_b = n_b^2 u$, where u is the radiation power of one particle and n_b is the number of particles in the bunch (if, for example, there is a bunch of electrons with dimension $d \ll \lambda$, then the power of its radiation, say in acceleration, is proportional to $(en_b)^2$, and the radiation power of one electron is proportional to e^2).*

*To avoid confusion in terminology, we must also note the following. Radiation is usually called coherent when the phase of the field is fixed. Obviously, any fixed, regular (not statistical) distribution of currents radiates coherently. A particular case of this coherent radiation is the radiation mentioned in the text, under conditions when the phase difference be tween all the radiators in the bunch is small. An aggregate of coherent radiators (bunches) with independent (random) phases on the whole gives incoherent or partly coherent radiation. The same applies to master radiation under cosmic conditions (and, in general, without a resonator, when the radiation from the entire radiating region is incoherent in the sense of the random character of the phases of the field in different directions and at different frequencies. By virtue of the foregoing, we distinguish coherent radiation in the text from coherent radiation mechanisms defined by the condition $L > Nu$ (such mechanisms are based, however, on a certain coherence, for example within the confines of the bunch or when the waves are amplified in a specified direction).

For a source containing N particles and N_b bunches that radiate independently of one another (incoherently), we obviously have

$$L = N_b n_b^2 u = n_b N u. \qquad (15)$$

Thus, in this case the radiation power is larger by a factor n_b than for an incoherent source with the same values of N and u. For bunches in the form of filaments with diameter $d \ll \lambda$ or disks with thickness $d \ll \lambda$, the radiation of all the particles in the bunch has the same phase, generally speaking, only in a direction perpendicular to the axis of the filament or to the plane of the disk. Such cases are analogous to thin antennas of the corresponding shape (we therefore call the discussed coherent mechanism the antenna mechanism).

With increasing characteristic dimension of the bunch bunch d, the radiation power begins to decrease rapidly, as soon as $d \gtrsim \lambda$. In fact, the intensity of radiation with a wave vector $\mathbf{k} = (2\pi/\lambda)\mathbf{k}/k$ is proportional to $I \sim |\int \mathbf{j}(\mathbf{r}) \exp(i\mathbf{kr})d\mathbf{r}|^2$, where $\mathbf{j}(\mathbf{r})$ is the current density in the source (bunch). Confining ourselves for simplicity to a one-dimensional distribution, we see that for a continuous current distribution of the type $j = j_0\pi^{-1/2} \times \exp(-x^2/d^2)$, the intensity is smaller by a factor $f = \exp(-\pi^2 d^2/\lambda^2)$ than when $d \ll \lambda$. The indicated factor f is sufficiently small already at $d = \lambda$, when $f = \exp -\pi^2 \sim 10^{-4}$; obviously, when $d = 3\lambda$ we have $f \sim 10^{-40}$ and consequently the antenna mechanism is effective usually only when $d < \lambda$. The use of an expression of the type (15) is limited also by the condition of incoherence of the individual bunches. In general, in the antenna mechanism, the currents or the emf's producing them are usually assumed specified and the mutual influence of neighboring bunches (antennas) is not taken into account. It is extremely difficult to satisfy these requirements for meter wavelengths and shorter under cosmic conditions. First, although different mechanisms of plasma instability and certain other conceivable processes do lead to the occurrence of inhomogeneities, these inhomogeneities are usually not clearly pronounced (in other words, the depth of modulation of the charge density is small). Second, even if clearly pronounced bunches were to be produced, they should, generally speaking, spread out very rapidly. The point is that in outer space it is difficult to expect formation of monoenergetic particles and therefore the particles in the bunches will have a noticeable velocity scatter Δv. Therefore, say, along the magnetic field the bunch becomes appreciably smeared out within a time $\tau \sim d/\Delta v_\parallel$. Hence, for example, at $d \sim 30$ cm and at a velocity scatter along the field $\Delta v_\parallel \sim 3 \times 10^9$ cm/sec, the time is $\tau \sim 10^{-8}$ sec. In a direction transverse to the magnetic field (in the azimuth) the bunch also spreads out within a time $\tau \lesssim 2\pi r_H/\Delta v_\perp = 2\pi v_\perp/\Delta v_\perp \omega_H$, $\omega_H = (eH/mc)(mc^2/E)$. Even when $\Delta v_\perp \sim 10^{-2} v_\perp$, the time is $\tau \lesssim 10^3/\omega_H$, and at $E/mc^2 \sim 10^2$, $H > 10^6$ Oe the time is $\tau < 10^{-8}$ sec.

Many such examples can be cited; all indicate that any pronounced antenna mechanism is not realistic under cosmic conditions. Yet in the literature, in connection with a discussion of the nature of the radiation of pulsars, it has been proposed many times to use precisely the antenna mechanisms. Yet no concrete grounds for the appearance of sharply delineated bunches and for their stabilization are presented. By the same token, in our opinion, the calculations are completely unfounded. This holds true even in the radio-astronomical band, and in the case of the optical and x-ray bands it is much more difficult to speak of formation of bunches or current layers with characteristic dimensions (diameter, layer thickness) $d \lesssim \lambda$. It is possible that the tendency to involve antenna mechanisms is connected with the fact that radio emission of pulsars, as mentioned above, cannot be incoherent, whereas the maser coherent radiation mechanisms are still less known compared with the classical antenna mechanisms. In one way or another, under cosmic conditions attention should be paid not to antenna mechanisms but just to maser coherent radiation mechanisms.

Maser coherent radiation mechanisms, as already mentioned, are effective in a homogeneous medium, if we disregard the trivial need for regarding this medium (the radiating region) as bounded in space. To be sure, in maser mechanisms in which one uses nontransverse waves (in particularly, strictly longitudinal waves), by virtue of the equation $\operatorname{div} \mathbf{E} = 4\pi\rho$, there automatically appear certain uncompensated charges with density $\rho(\mathbf{r})$. These charges (and also the charges connected with any concentration fluctuations) are important for wave transformation, for example for the transition of plasma (longitudinal) waves into electromagnetic (transverse) waves. But in such cases the inhomogeneities of the electron concentration or of the ion concentration have in essence nothing in common with the discrete bunches of charges which are usually considered within the framework of the antenna radiation mechanisms.

Let us make a few remarks concerning the maser mechanisms, using the transport equation for the intensity of the electromagnetic waves I:

$$\frac{dI}{dx} = A + (B - \mu_c) I. \tag{16}$$

If we are also interested in the polarization of the radiation, then a similar equation should be written also for other Stokes parameters (see, for example, [63]). In addition, no account is taken of refraction in (16) and the system will be regarded below as homogeneous over a length l along the ray (x axis). Under such conditions, the intensity of radiation of the source in the x-axis direction is

$$I = \frac{A}{\mu_c - B} \{1 - e^{(B-\mu_c)l}\}. \tag{17}$$

In (16) and (17), the coefficient A corresponds to spontaneous radiation, B to the stimulated (maser) radiation or reabsorption (for $B < 0$), and μ_c is the absorption coefficient, which is not connected with the radiating particles themselves; in practice for radio waves μ_c is the absorption coefficient due to collisions, and its value for a hydrogen plasma, when account is taken of the influence of the magnetic field, is[49]

$$\left.\begin{aligned} &\mu_c(\omega) = \frac{1 - \tilde{n}^2(\omega)}{c\tilde{n}(\omega)} \nu_{\text{eff}}, \quad \tilde{n}^2(\omega) = 1 - \frac{\omega_e^2}{\omega^2}, \quad \omega_e^2 = \frac{4\pi e^2 n_e}{m}, \\ &\qquad \omega^2 \gg \nu_{\text{eff}}^2, \quad \tilde{n}^2 \gg \frac{\omega_e^2}{\omega^2} \frac{\nu_{\text{eff}}}{\omega}, \\ &\nu_{\text{eff}} = \pi \frac{e^4}{(kT_e)^2} \sqrt{\frac{8kT_e}{\pi m}}\, n_e \ln\left(0{,}37 \frac{kT_e}{e^2 n_e^{1/3}}\right) = \frac{5{,}5 n_e}{T_e^{3/2}} \ln\left(220 \frac{T_e}{n_e^{1/3}}\right). \end{aligned}\right\} \tag{18}$$

In the case of synchrotron radiation of isotropically distributed electrons in vacuum we have $A = \epsilon$ and $B = -\mu_r < 0$, and the expressions for the emissivity ϵ and the reabsorption coefficient μ_r are well known.[63] The amplification (maser effect, $B > 0$) for synchrotron radiation can take place for any nonunity refractive index $\tilde{n}$ in a radiating region, or else in the case of an anisotropic distribution of the relativistic electrons with respect to the direction of their velocity. The index $\tilde{n} \neq 1$, and concretely $\tilde{n}(\omega) = \sqrt{1 - (\omega_e^2/\omega^2)} \approx 1 - \omega_e^2/2\omega^2$ in the presence of a "cold" plasma with concentration n_e in the radiating region (here, by assumption, $\omega_e^2 = 4\pi e^2 n_e/m \ll \omega^2$). The anisotropy of the electron velocity distribution leads to amplification if this anisotropy is appreciable already in an angle region on the order of

$$\eta = \sqrt{(mc^2/E)^2 + (\omega_e^2/\omega^2)} \approx \sqrt{1 - \tilde{n}^2\beta^2}, \quad \beta = v/c$$

(for details see [62, 63] and the literature cited therein).

If a longitudinal (plasma) wave with frequency $\omega_l \approx \omega_e$ and intensity I_l propagates in the plasma, then the transverse (radio) waves with frequencies $\omega \approx \omega_l$ are generated as a result of spontaneous and stimulated scattering, with $A = \alpha I_l$ and $B = \beta I_l$ in (16) (expressions for α and β are given in [48]). In this case the gain is large if $(\beta I_l - \mu_c) l \gg 1$. For the indicated mechanisms one can easily obtain the radio luminosities and the values of T_b needed in the case of pulsars.

Transformation of a plasma wave into radio waves is a particular case of the processes of transformation (as a result of scattering, and in the general case by virtue of the nonlinearity of the plasma) of certain normal waves into others, which can propagate in the plasma (in the presence of a magnetic field, these waves, generally speaking, are neither transverse nor longitudinal[49, 64]). Besides spontaneous and induced transformations of different waves, these waves can be generated, be amplified, and be absorbed in a plasma as a result of a large number of processes (particle beams, shock waves). By the same token, the plasma turbulence which reduces in a certain approximation to an aggregate of different normal waves, generates electromagnetic plasma radiation that is emitted to the outside[49, 64, 65]; if a condition of the type $(\beta I_l - \mu_c) l \gg 1$ is satisfied, this is precisely the maser radiation.

A third important class of maser coherent mechanisms acts in the simultaneous presence of plasma turbulence and relativistic particles.[65] In essence, such a mechanism is particularly closely related to the inverse Compton scattering of electromagnetic waves in vacuum by relativistic electrons (more accurately, the maser effect is connected only with stimulated scattering; spontaneous scattering of plasma turbulence by relativistic particles is also of interest). Let a wave (frequency ω_1, wave vector $\mathbf{k}_1$; $\mathbf{k}_1 = (\omega_1/c)\tilde{n}(\omega_1)(\mathbf{k}/k)$) be scattered by a relativistic particle (electron) having a velocity $\mathbf{v}$, and let it be transformed into a wave with frequency $\omega_2 \equiv \omega$ and wave vector $\mathbf{k}_2 \equiv \mathbf{k}$. The types of waves 1 and 2 can be different, but we always have

$$\omega_1 - \mathbf{k}_1\mathbf{v} = \omega - \mathbf{k}\mathbf{v}, \tag{19}$$

where the change of energy of the electron upon scattering is assumed to be small.* The condition of (19) can be written in the form

$$\omega\left[1-\frac{v}{c}\tilde{n}(\omega)\cos(\mathbf{kv})\right]=\omega_1\left[1-\frac{v}{c}\tilde{n}(\omega_1)\cos(\mathbf{k}_1\mathbf{v})\right],$$

and the frequency ω will be maximal when $\cos(\mathbf{k}_1\mathbf{v}) = -1$, $\cos(\mathbf{kv}) = 1$ (frontal collision), i.e.,

$$\omega\leqslant\omega_{\max}=\frac{\omega_1\left(1+(v/c)\tilde{n}(\omega_1)\right)}{1-(v/c)\tilde{n}(\omega)}\leqslant\frac{2\omega_1}{1-(v/c)\tilde{n}(\omega)}.$$

If the frequency ω is sufficiently high so that we can put $\tilde{n}(\omega) = 1$, then

$$\omega_{\max}\leqslant 4\omega_1\left(\frac{E}{mc^2}\right)^2, \tag{20}$$

since for relativistic particles

$$1-\frac{v}{c}\approx\frac{1-(v^2/c^2)}{2}=\frac{1}{2}\left(\frac{mc^2}{E}\right)^2.$$

We note that synchrotron radiation can also be regarded as a frequency conversion, in which case it is necessary to put $\omega_1 \sim eH/mc$ in (20) (for details see [62, 67]). For "inverse" Compton scattering in vacuum, the role of ω_1 is played by the frequency of the scattered soft photon. In a nonrelativistic plasma, the frequency of the normal waves ω_1 is determined by the characteristic frequencies

$$\omega_e=5.64\cdot 10^4\sqrt{n_e},\quad \omega_i=\sqrt{\frac{4\pi e^2 n_e}{m_i}}=\frac{\omega_e}{43}$$

(for the considered hydrogen plasma) and $\omega_H = eH/mc = 1.76\times10^7 H$. One should bear in mind the possibility of simultaneous action of different mechanisms, when A and B in (16) have the meaning of a summary radiating ability and the summary (due to all mechanisms) gain or reabsorption. In particular, for example, the main contribution to A may be made by synchrotron radiation, and the gain may be determined by plasma turbulence.

Another possibility is a maser mechanism in a dense plasma situated in a strong field ($H \gtrsim 10^8$ Oe) and radiating as a result of collisions ("one-dimensional" bremsstrahlung) and transitions between lower magnetic levels (cyclotron radiation).[68] It still remains unclear, however, whether radiation can leave the generation region in such cases, and also the possibility of obtaining inverted population of the levels seems unrealistic when account is taken of collisions, as is necessary for a dense plasma.

The maser mechanisms are characterized by the possible appearance of a sharply directed and polarized radiation. We are dealing simply with the fact that the gain $\exp Bl$ is very sensitive to the value of Bl if $Bl \gg 1$; this value depends in turn on the path length, wave polarization, and other parameters (and therefore the values of Bl in different directions and for different polarizations can easily differ from one another). Obviously, such a feature of maser mechanisms is quite favorable from the point of view of interpretation of pulsar radiation. What is most important, maser mechanisms are quite capable, from the point of view of their efficiency, of causing the appearance of radiation with practically arbitrarily high brightness temperature. Finally, since it is not realistic to use antenna mechanisms under cosmic conditions, the use of some maser mechanism to explain the radio emission of pulsars seems to us inevitable.

6. CERTAIN MODELS OF RADIATING REGIONS OF PULSARS

The center of gravity of the question of pulsar radiation lies in the choice of models of radiating regions, since there are no apparent difficulties either with respect to the potential capabilities of the different mechanisms of radiation or from the energy point of view. To the contrary, even such fundamental questions as the character of the directivity pattern of the radiation (we have in mind the choice between the "pencil" and the "knife" diagrams; see below), the characteristic dimensions l, and the distance r of the radiating regions from the surface of the star still remain unclear. Nor do we know the distribution function of the plasma particles in the radiating regions, and its determination from data on the radiation itself is subject to an inherent essential uncertainty (leaving aside the entire particle momentum distribution function, even determinations of such integral parameters of the plasma as the concentration of the radiating ultrarelativistic particles n_r, their average energy E, the concentration of the "cold" plasma n_e, its temperature T_e, etc., are all ambiguous).

In order to observe the radiation of a rotating star in the form of relatively short pulses (pulse duration $\delta P \ll P$—period of the pulsar), the characteristic aperture angle of the directivity pattern $\Delta\varphi$ should be sufficiently small (models of rotating radiators with such a

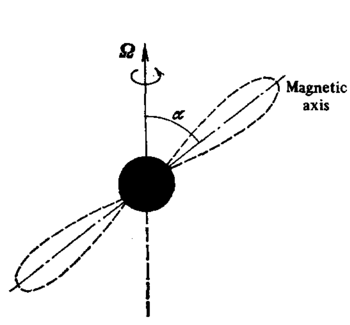

FIG. 3

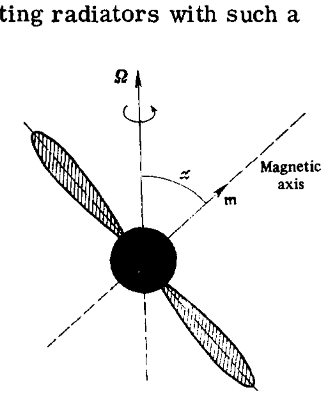

FIG. 4

FIG. 3. "Pencil" directivity pattern (cross section). The pattern has axial symmetry about the magnetic axis.

FIG. 4. "Knife" directivity pattern (cross section). The pattern has axial symmetry about the magnetic axis.

*The condition (19) is easiest to obtain by using quantum representations, according to which a photon in a medium (plasmon, etc.) has an energy $\hbar\omega$ and a momentum $\hbar\mathbf{k}$ (see [66]). The energy and momentum conservation laws in scattering take the form

$$E+\hbar\omega_1=E_2+\hbar\omega_2,\quad \mathbf{p}_1+\hbar\mathbf{k}_1=\mathbf{p}_2+\hbar\mathbf{k}_2,$$

where $E=\sqrt{m^2c^4+c^2p^2}$ is the energy of the particles. From this we get for small changes of energy $E_2-E_1=(\partial E/\partial p)\Delta p = v\Delta p = \hbar v(\mathbf{k}_2-\mathbf{k}_1) = \hbar(\omega_2-\omega_1)$, leading to (19).

diagram are frequently called "beacon" models). It is obvious that

$$\Delta\varphi \sim \frac{2\pi}{P}\delta P = \Omega\delta P. \tag{21}$$

For NP0532 the angle is $\Delta\varphi \sim 20-30\,°$, and for most other pulsars the angle $\Delta\varphi$ is smaller.

If the angle $\Delta\varphi$ characterizes the aperture of the diagram in all directions, then we deal with a "pencil" diagram; its axis can, for example, coincide with the magnetic-symmetry axis (direction of the dipole **m**; Fig. 3). Another typical possibility is the "knife" diagram, when the angle $\Delta\varphi$ determines only the smallest aperture of the diagram, and in a perpendicular direction the aperture is characterized by an angle $\varphi_\perp \sim 1$ or even $\varphi_\perp = 2\pi$. Such a pattern is obtained, for example, if the radiation is concentrated in an angle $\Delta\varphi$ about the equatorial plane of the magnetic star (Fig. 4). The solid angles subtended by the "pencil" (p.b.) and "knife" (k.b.) diagrams are of the order of $\Delta\sum_{p.b} \sim (\Delta\varphi)^2$ and $\Delta\sum_{k.b} \sim 2\pi\Delta\varphi$ (at $\varphi_\perp \sim 2\pi$). Further, for each rotation of the "beacon" (star), the diagrams subtend on the celestial sphere the respective solid angles

$$\Delta\sum\nolimits^{(s)}_{p.b} \sim 2\pi\sin\alpha\cdot\Delta\varphi, \quad \Delta\sum\nolimits^{(s)}_{k.b} \sim 4\pi\sin\alpha. \tag{22}$$

For an isotropic radiator, and in order of magnitude also for a dipole radiator, we have $\Delta\sum_0^{(S)} \sim 4\pi$. Consequently, at $\sin\alpha \sim 1$, in the case of the "knife" diagram the pulsar is "seen" from almost all directions and an estimate of their concentration is the same as for isotropic radiators (if we disregard pulsars, then all stars are isotropic radiators). In the case of a "pencil" diagram we have $\Delta\sum_{p.b}^{(S)}/\Delta\sum_0^{(S)} \sim \sin\alpha \times \Delta\varphi$ and the pulsar concentration is larger by a factor $(\sin\alpha \times \Delta\varphi)^{-1}$ than given by the estimate for isotropic radiators. If the pulsar NP0532 in the Crab has a "pencil" diagram, then we see it only because of the fortunate circumstance that the axis of the diagram lies near the line joining the pulsar with the sun.

For a "knife" diagram with angle $\varphi_\perp = 2\pi$, there should be observed during the period of a pulsar, generally speaking, two pulses.[61, 69] * This is the case, for NP0532, by virtue of which the assumption of the "knifelike" character of the diagram encounters no special objections. But a similar picture could be observed for diagrams of the "pencil" type. Furthermore, there can exist also different asymmetrical diagrams, for example a "knife" diagram with $\varphi_\perp < 2\pi$.

For the pulsar in the Crab, apparently $\alpha \sim \pi/2$ (see [54, 55]). In the following estimates of the characteristic dimension l of the radiating regions, we have in mind, for the "knife" diagram, the thickness of the ring-like radiation belt in the plane of the magnetic equator, and for the pencil diagram the diameter of the radiation "cap" over the magnetic poles (Fig. 6). The optical and x radiation of this pulsar will be assumed to be incoherent synchrotron radiation. Such an assumption is immediately the most probable,[48, 58, 61, 62] since the high efficiency of the synchrotron mechanism is known from a number of examples. Furthermore, the alternate possibilities (radiation from a dense plasma[68] inverse Compton scattering of the radio photons by relativistic electrons,[71, 72] and scattering of plasma waves by relativistic electrons with their transformation into radio waves[73] encounter various objections).*

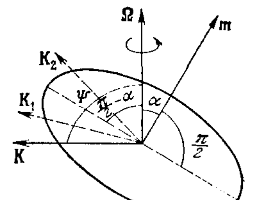

FIG. 5. "Knife" directivity pattern (explanation). **k**–observation direction; the observation directions $\mathbf{k}_1$ and **k** coincide with the plane of the diagram.

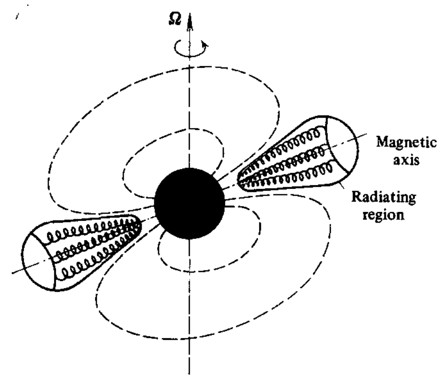

FIG. 6. Model of radiating regions of pulsar located in the polar region ("pencil" diagram).

It is not difficult to construct synchrotron models for the infrared, visible (optical) and x-radiation of the pulsar NP0532; such models describe in detail the form of the given spectrum. These models, however, are not unique so long as the question of the parameters of the radiating regions remains open (their form, field configuration, etc.). Furthermore, it is necessary to worry about the self-consistency of the model, i.e., to consider not only the radiation but also the acceleration of the particles, their accumulation in radiation belts, etc.

In such a situation we confine ourselves here to a rough approximation—we assume the spectrum of the electrons to be quasimonoenergetic (average energy E, energy spread $\Delta E \ll E$). The emission spectrum of such electrons is well known (see, for example, [67]).

---

*Let the observation direction **k** make an angle Ψ with the rotation axis (Fig. 5). Then for $\alpha < \pi/2$ and $(\pi/2)-\alpha < \Psi < \pi/2$ two nonequidistant pulses will be observed during one revolution of the star (there is no radiation when $\Psi < (\pi/2)-\alpha$). For $\alpha = \pi/2$ these pulses are equidistant and the period of the pulsar is $P = \pi/\Omega = P_{st}/2$ (here $P_{st} = 2\pi/\Omega$ is the period of revolution of the star). If $\alpha \neq \pi/2$, one pulse will be observed during the period of the pulsar at $\Psi = \pi/2$ (two pulses per revolution of the star, i.e., $P = P_{st}/2$), and at $\Psi = (\pi/2)-\alpha$ (in this case $P = P_{st}$).

*In a dense plasma it is difficult to obtain inverted population of the levels (this population is destroyed by collisions). Inverse Compton scattering is of great interest from the point of view of the appearance of γ radiation of pulsars, but in all probability it is impossible to relate their optical and x radiation with Compton scattering (this is clear from the calculations of [72]; another author using the "Compton model" [71] changed subsequently to different synchrotron models [74]). For transformaton of plasma waves into x-rays in scattering of relativistic particles, the frequencies of plasma waves would be improbably large (at a moderate value of the ratio E/mc^2).

Specifying the radiation flux $F(\nu)$ for the infrared, optical, and x-ray frequencies ν_i, ν_0, and ν_x, we can determine the frequency ν_m and the power $P(\nu_m) \equiv L(\nu_m)$ at the maximum of the emission spectrum, and also the optical thickness $\tau(\nu_i)$ for the infrared frequency (reabsorption at higher frequencies is very small). Further, we have

$$\nu_m = 0.07\frac{eH_\perp}{mc}\left(\frac{E}{mc^2}\right)^2 = 1.2\cdot 10^6 H_\perp \left(\frac{E}{mc^2}\right)^2 \text{Hz} \tag{23}$$

The radiation power at the maximum is

$$P(\nu_m) = 1.6\frac{e^3 H_\perp}{mc^2} n_r V \sim 10^{-22} H_\perp n_r l^3 \text{ erg}^8 \text{ sec-Hz} \tag{24}$$

The optical thickness for reabsorption is[63]

$$\left.\begin{aligned} &\tau(\nu) = \mu_r l = \frac{4\pi}{3\sqrt{3}}\frac{e}{H_\perp}\left(\frac{mc^2}{E}\right)^5 n_r l K_{5/3}(z),\\ &z = \frac{4\pi\nu mc}{3eH_\perp}\left(\frac{mc^2}{E}\right)^2\nu = 0{,}29\frac{\nu}{\nu_m},\\ &K_{5/3}(z) = \frac{2^{5/3}\Gamma\left(\frac{2}{3}\right)}{3} z^{-5/3} \quad \text{for} \quad z \ll 1. \end{aligned}\right\} \tag{25}$$

From this, obviously, we can express E/mc^2, $H_\perp$, n_r, and $l \sim V^{1/3}$ in terms of one arbitrary parameter, which we choose to be the ratio of the density of the relativistic electrons, $\delta = H^2/8\pi E n_r$ (more accurately, what is involved here is the field projection $H_\perp$ perpendicular to the line of sight, but we assume below that $H \sim H_\perp$; this, of course, is not obligatory). As a result we get

$$\left.\begin{aligned} &H \sim H_\perp \sim 10^6\delta^{4/17}\,\text{Oe}, l \sim 5\cdot 10^6\delta^{1/17}\,\text{cm},\\ &E/mc^2 \sim 10^2\delta^{-2/17}, \quad n_r \sim 5\cdot 10^{14}\delta^{-7/17}\,\text{cm}^{-3}\\ &\tau(\nu = 1.36\cdot 10^{14}) = \mu_r l = 1.75. \end{aligned}\right\} \tag{26}$$

Probably for the pulsar in the Crab $\delta \gg 1$ and in any case $\delta \gtrsim 1$, if one strives to have the cloud of relativistic particles retained near the star. Only when $\delta \gg 1$ is the principal role assumed by synchrotron and not by Compton losses. Thus, even at $\delta \sim 1$ the Compton losses (lifetime $t_c \sim 10^{-7}$ sec) are larger by 10–100 times than the synchrotron losses (lifetime $t_m \sim 5 \times 10^{-6}$ sec),* and the power of the Compton γ rays ($\overline{E}_\gamma \sim 2 \times 10^6$ eV) reaches 10^{37} erg/sec.

In the model under discussion, the region of radiation of light and x-rays is $l \sim 5 \times 10^6$ cm, so that its most likely distance from the surface of the star is also $r \sim 5 \times 10^6$ cm. But this means that on the surface of a star with radius $r_0 \sim 10^6$ cm the magnetic field is $H_0 \sim (r/r_0)^3 H \sim 3 \times 10^8$ Oe. If on the other hand, the field is $H_0 \sim 10^{12}$ Oe, then at $r \sim 10 r_0 \sim 10^7$ cm the lifetime of the electrons (27) moving at a large angle to the field (at $H_\perp \sim H \sim H_0(r_0/r)^3 \sim 10^9$ Oe) is $t_m \sim 10^{-11}$ sec (at $E/mc^2 \sim 10^2$). Under such conditions, in all probability, the relativistic electrons can "survive" only by moving at a very small angle to the field. The character of the synchrotron radiation under such conditions differs essentially from the ordinary synchrotron radiation[63, 75] (it is necessary here to take into account also the curvature of the magnetic force lines[76]). If $H_0 \sim 10^{12}$ Oe, then to retain the model discussed above we can assume that $l \ll r \sim 10^8$ cm, i.e., we can move the radiating region into the region of the "light cylinder" (7).

The character and mechanism of the radio emission of pulsars is less clear. Let us assume by way of example that the radio emission of NP0532 is coherent synchrotron radiation and amplification due to the presence of "cold" plasma. In this case for quasimonoenergetic electrons the maximum gain $|\mu|$ is determined by the formula (see [63])

$$\mu = -1.6\cdot 10^{-2}\frac{n_r H_\perp^2}{(E/mc^2)^2 n_e^{3/2}}\,\text{cm}^{-1}, \tag{28}$$

where n_e is the concentration of the "cold" plasma (in (28) this plasma is assumed to be nonrelativistic, but in general it can be regarded also as a relativistic plasma with temperature T_e satisfying the condition $kT_e \ll E$, where E is the energy of the radiating ultrarelativistic electrons).

The flux $F(\nu)$ observed from NP0532 at a frequency $\nu \sim 3 \times 10^7$ Hz can be obtained for $\delta = H^2/8\pi E n_r \sim 1$ by choosing the following parameters

$$\left.\begin{aligned} &H \sim H_\perp \sim 30\,\text{Oe}, \quad l \sim 10^8\,\text{cm},\\ &\frac{E}{mc^2} \sim 8, \quad n_r \sim 10^7, \quad n_e \sim 3\cdot 10^8, \quad T_e > 10^4\,{}^\circ\text{K}. \end{aligned}\right\} \tag{29}$$

Here $|\mu| \approx 5 \times 10^{-7}$ and $\exp\{|\mu| l\} \sim 10^{20}$.

If the magnetic field decreases like $H \sim H_0(r_0/r)^3$, then at $H_0 \sim 10^8$ Oe the radio-emitting region is located at $r \sim (1-2) \times 10^8$ cm, i.e., near the "light cylinder" $r_c = c/\Omega \approx 1.5 \times 10^8$ cm (angular velocity $\Omega \approx 200\ \text{sec}^{-1}$). The employed model, assuming a "knife" character of the diagram, is shown schematically in Fig. 7. If the field is $H_0 \sim 10^{12}$ Oe, then with the field decreasing like $(r_0/r)^3$ the radio-emitting region would have to be moved back to a distance $r \sim 10^{10}$ cm. This is not probable, and at $H_0 \sim 10^{12}$ Oe, it is more likely that the radio emission does not become intensified as a result of the "cold" plasma. Incidentally, even when $H_0 \sim 10^8$ we have no special reason for assuming the intensification of the waves connected with the "cold" plasma to be decisive. No less probable, for example, is amplification due to the anisotropic distribution of the relativistic electrons with respect to their velocities (in this case

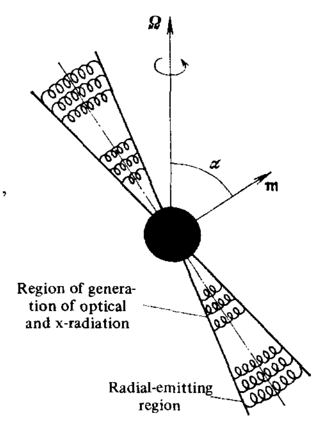

FIG. 7. Model of radiating regions of the pulsar NP0532 ("knife" diagram).

*As is well known, the energy of relativistic electrons in the magnetic field decreases to one-half within a time

$$t_m = \frac{2m^3c^5}{3e^4H_\perp^2}\left(\frac{mc^2}{E}\right) = \frac{5\cdot 10^8}{H_\perp^2}\frac{mc^2}{E}\ \text{sec.} \tag{27}$$

For $H_\perp = 10^6$ Oe and $E/mc^2 = 10^2$, the time is $t_m = 5 \times 10^{-6}$ sec.

the presence of a "cold" plasma is not obligatory).* Other mechanisms of transformation of plasma waves into radio waves may be likewise fully effective (see the preceding section and the article[73b]).

By the same token, it must be stated that there is great uncertainty with respect to concrete models of the radio emission of pulsars. We note also the delicacy of the problem of polarization of the radio emission,[48, 77a] the analysis of which can nevertheless shed much light on the matter.† Special mention should be made of the second (short) period, which was observed in the analysis of the form of the pulses for a number of pulsars.[77b] Apparently we are dealing here with some oscillations or differential rotation in radio-emitting regions of the pulsars, but the concrete nature and the very character of the corresponding processes are far from clear.

The coherent mechanism of radiation is obviously quite sensitive to different parameters, since the amplification is determined by a factor of the exponential type (the factor $\exp(|\mu| l)$). It is perfectly possible also that the pulsar NP0532 is not a typical representative of even the young pulsars. In this connection it is not excluded that the ratio of the fluxes in the radio and optical or x-ray bands can vary over a very wide range. In particular, the question arises of the possibility of observing optical and (or) x-ray pulsars other than the observed radio pulsars.[61, 78] So far, insofar as we know, attempts have been made to observe pulsating optical and x-radiation only for radio pulsars (this, of course, offers great advantages, since the period is known), and for certain x-ray stars.

The spectrum of the only known optical pulsar, the pulsar in the Crab, has no lines whatever.[79, 80] This is to be expected for a neutron star. Naturally, searches for optical pulsars (which are not simultaneously radio pulsars sufficiently powerful to be observed in the radio band) must be carried out among stars in the spectra of which there are no lines (there are rather many stars of this type in the sky[80]).

7. USE OF PULSARS IN ASTRONOMY AND PHYSICS

The most important consequence of the discovery of pulsars is their very probable identification with neutron stars, the possibility of existence of which began to be discussed back in 1934.[81] Besides the study of the pulsars (neutron stars) themselves, attention is attracted to their role in envelopes of supernovas[57, 58, 60, 78, 82] and acceleration of particles (particularly cosmic rays) by and near pulsars.[36, 59, 83–85a]

Finally, the fact that pulsars emit sharp and furthermore strictly periodic signals (the secular increase of the period can be taken into account) makes it possible to use them in astronomy and physics. Incidentally, some astronomical applications are connected not with the periodicity of the radiation, but with its polarization, and also with the pointlike character or position of the sources on the celestial sphere.

The propagation of radio waves in the interstellar plasma can be regarded with very good approximation as "quasilongitudinal";* in addition, the refractive index n is very close to unity. It can therefore be assumed that

$$\tilde{n} = 1 - \frac{\omega_e^2}{2\omega^2} = 1 - 4{,}03\cdot 10^7 \frac{n_e}{\nu^2}, \quad \tilde{n}_\pm = 1 - \frac{\omega_e^2}{2\omega(\omega \mp \omega_H \cos\theta)},$$
$$\tilde{n}_- - \tilde{n}_+ = \frac{\omega_e^2 \omega_H \cos\theta}{\omega^3} = |2{,}3\cdot 10^{14} \frac{n_e H \cos\theta}{\nu^3}, \tag{30}$$
$$|\tilde{n} - 1| \ll 1, \qquad |\tilde{n}_- - \tilde{n}_+| \ll |\tilde{n} - 1|, \quad \tilde{n} = \frac{\tilde{n}_+ + \tilde{n}_-'}{2},$$

where $\tilde{n}_- - \tilde{n}_+$ is the difference between the refractive indices for circularly polarized waves with different directions of rotation of the field vector.

In the interstellar medium the difference $|\tilde{n}_- - \tilde{n}_+| \le \omega_e^2 \omega_H/\omega^3$ is very small and must be taken into account only for such an integral effect (which furthermore vanishes at H = 0) as Faraday rotation of the plane of polarization (see below). On the other hand, in calculations of the phase advance or group delay, the interstellar plasma can be regarded as isotropic with an index $\tilde{n} = (\tilde{n}_+ + \tilde{n}_-)/2$, as indicated in (30); here $|\tilde{n} - 1| = 4.03 \times 10^7\, n_e/\nu^2 \lesssim 10^{-4}$ for $n_e \lesssim 10^2\ \text{cm}^{-3}$ and $\nu \gtrsim 10^7$ Hz.

The inhomogeneities in the interstellar medium always satisfy the condition

$$\frac{\lambda_0}{2\pi} \frac{|d\tilde{n}/dz|}{\tilde{n}^2} \approx \frac{\lambda_0}{2\pi} \left|\frac{d\tilde{n}}{dz}\right| \ll 1, \tag{31}$$

i.e., the change of the index $\tilde{n}$ over the wavelength $\lambda_0 = c/\nu$ is negligibly small. Under such conditions, with a high degree of accuracy,[85b] the phase shift on the path R is equal to

$$\varphi = \frac{\omega}{c} \int_0^R \tilde{n}(\omega, s)\, ds = \frac{\omega}{c} R - 8{,}5\cdot 10^{-3} \frac{\int_0^R n_e\, ds}{\nu}. \tag{32}$$

The signal group delay time is

$$\Delta t_{gr} = \int_0^R \frac{ds}{v_{gr}} = \frac{d\varphi}{d\omega} = \frac{R}{c} + \frac{1{,}35\cdot 10^{-3} \int_0^R n_e\, ds}{\nu^2}. \tag{33}$$

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*The latter circumstance is quite important, since it is perfectly likely that by virtue of the rapid acceleration (heating) of the particles the entire plasma near the pulsar or even up to a distance $r_c = c/\Omega$ is relativistic or ultrarelativistic.

†An analysis of the process of propagation and emergence of radio emission to the outside of the pulsar's magnetosphere shows that the strong linear polarization of the radio emission of the pulsars can be explained only under conditions when the emergence into the interstellar medium occurs in the region of a quasitransverse magnetic field. The detailed character of the polarization and its variation with the momentum can be connected in this case with different relative positions of the layer in which the transition from the quasitransverse into quasilongitudinal propagation occurs, and the region of the so-called limiting polarization (it was assumed above that the propagation of the radio waves is determined by the nonrelativistic plasma; if the plasma in the magnetosphere is ultrarelativistic, the situation may change somewhat).

*In the interstellar medium, the electron concentration is $n_e \sim 10^{-2}$–$10^2\ \text{cm}^{-3}$ and the field intensity is $H \sim 10^{-6}$–10^{-5} Oe. Therefore $\omega_e = (4\pi e^2 n_e/m)^{1/2} = 5.64\cdot 10^4 \sqrt{n_e} \sim 5\cdot 10^3$–$5\cdot 10^5\ \text{sec}^{-1}$ and $\omega_H = eH/mc = 1.76\cdot 10^7\, H \sim 10$–$100\ \text{sec}^{-1}$, i.e., $\omega_e \gg \omega_H$. Under such conditions, the propagation of the waves can be regarded as quasilongitudinal if $\omega_H^2 \sin^4\theta/4\omega^2\cos^2\theta \ll 1$ and $\omega_H^2 \sin^2\theta/2\omega^2 \ll 1$, where θ is the angle between the line of sight (the wave vector) and the field H (for details see [49], Sec. 11). Consequently, the quasilongitudinal approximation, even for $\omega \equiv 2\pi\nu \sim 6 \times 10^7\ \text{sec}^{-1}$ ($\lambda \sim 30$ m), is valid so long as $|\pi/2 - \theta| \gg 10^{-6}$ rad ~ 0.2″, i.e., practically always. In the interstellar medium, we have in formula (30) the value $\omega_e^2\omega_H/\omega^3 \lesssim 3\cdot 10^{13}/\omega^3 \lesssim 10^{-10}$ when $\omega \lesssim 6 \times 10^7$ Hz. In (30), no account was taken of absorption, since at frequencies $\nu \lesssim 10^7$ Hz the absorption is usually sufficiently small.

From measurements at different frequencies it is possible to determine $\Delta t_{gr}(\nu) - (R/c)$, and by the same token it is possible to determine immediately for the pulsars the integral number of electrons on the line of sight $N_e = \int_0^R n_e ds$ or $N_e = \bar{n}_e R$, since the refraction is small and the trajectory of the ray can be regarded as a straight line. The coefficient $DM = (e^2/2\pi mc^3)N_e = 1.5 \times 10^{-24} N_e$ in the relation $\Delta t_{gr} - (R/c) = DM \times \lambda^2$ is sometimes called the measure of the dispersion (if one measures N_e in parsec-cm^{-3} and λ in meters, then $DM = 5.8 \times 10^{-2} N_e$ sec-m^{-2}; in some articles the quantity N_e itself is called the measure of the dispersion). If account is taken of the change of the distribution of the concentration with time, then the determined quantity $N_e = \int n_e ds = \int n_e (s, t_{gr}) ds$, where $n_e(s, t_{gr})$ is the concentration at the point s at the instant t_{gr} at which the considered pulse passes that point.

The use of the quantity N_e, obtained from data on the delay time for pulsars, in conjunction with other information, makes it possible to obtain valuable information on the interstellar medium. Thus, in the galactic plane, according to [86], $\bar{n}_e = 0.05$ cm^{-3}, whereas earlier it was customary to assume $n_e = 0.1$ cm^{-3}. Simultaneously, measurement of N_e makes it immediately possible to estimate the distance to the pulsar. We note that the values of N_e for the known pulsars are larger than or equal to approximately 3 parsec-cm$^{-3} \sim 10^{19}$ cm^{-2}. Therefore $\Delta t_{gr} - (R/c) \gtrsim 10^{16}/\nu^2$ and the delay of the pulses at the frequency $\nu \sim 10^8$ Hz compared with pulses at high frequencies exceeds one second, and for a number of pulsars it reaches several minutes.

The inhomogeneities of the interstellar medium should, naturally, lead to fluctuations of the intensity of the radio emission received on earth from discrete sources (the picture corresponds to diffraction by a phase screen, and its time variation is determined mainly by the dimension of the inhomogeneities and by the relative velocity of the screen and of the earth). The possibilities of the corresponding observations were discussed[87] even before the discovery of pulsars, but they became realistic only with the use of pulsar radiation and are now being carried out[88, 89a]. Of course, some contribution to the fluctuations is made also by the "corona" of the pulsar itself,[88-89b] and also by the interplanetary medium. The contribution of the latter can be excluded relatively reliably or else, to the contrary, one can use pulsars for the investigation of the solar supercorona.[98]

The field vector in a linearly polarized wave propagating in the interstellar medium rotates through an angle (see (30) and [49])

$$\Psi = \frac{\omega}{2c} \int_0^R (\tilde{n}_+ - \tilde{n}_-)\, ds = \frac{2.4 \cdot 10^4}{\nu^2} \int_0^R n_e(s)\, H(s) \cos\theta(s)\, ds. \quad (34)$$

In place of Ψ one frequently uses the rotation measure RM, defined as the coefficient in the relation $\Psi = RM \times \lambda^2$, with $RM = 8.1 \times 10^5 \int n_e H \cos\theta\, ds$ rad/m^2 if Ψ is measured in radians, λ in meters, the distance in parsecs, n_e in cm^{-3}, and H in Oersteds. Measurement of the angle Ψ thus makes it possible to determine the quantity $\int_0^R n_e H \cos\theta\, ds$. The use of pulsars for this purpose is particularly valuable, since one measures simultaneously $N_e = \int n_e ds$ along the same line of sight, and consequently one determines a certain mean value of the quantity $\overline{H \cos\theta} = \int n_e H \cos\theta\, ds / \int n_e\, ds$ along the line of sight (see [91]). The vicinity ("corona") of the pulsar can affect the estimates of $\overline{H \cos\theta}$ for the interstellar medium much more strongly than in the determination of the average concentration $\bar{n}_e$ (both quantities, n_e and H, increase near the pulsar; in addition, the quantity $H \cos\theta$, unlike n_e, can reverse sign). Allowance for the influence of the vicinity of a pulsar on the polarization of its radiation calls for a special analysis;[48, 77, 92] the same can be said concerning the influence exerted on the polarization of fluctuations of the quantity $n_e H \cos\theta$ and determinations of this quantity near the sun (see [92, 93]). Nonetheless, the use of pulsars for estimates of the longitudinal component $H \cos\theta$ of the magnetic field **H** along the line of sight, besides the possibility of determining the average electron density $\bar{n}_e$ and its fluctuations, is among the most important applications of pulsars for astronomical research purposes. Pulsars can also be used for needs of classical astronomy and astrometry.[94, 95]

When an electromagnetic pulse passes near the sun, it experiences two closely related effects of general relativity theory—deflection and an additional delay reaching 2×10^{-4} sec when the ray grazes the solar disk. By virtue of the latter effect, pulsars located near the sun on the celestial sphere should experience an annual change in their period.[94, 96] The corresponding observations could serve to verify general relativity theory, although the use of an artificial planet with a radio transmitter on board is more promising for this purpose.

The light pulses emitted by the pulsar NP0532 arrive on earth simultaneously (accuracy $\sim 10^{-5}$ sec) for a number of wavelengths in the optical band, for which the observations were carried out. One can therefore conclude that the velocity of light in this band is independent of the frequency with a high degree of accuracy ($\Delta c/c < 5 \times 10^{18}$; see [97]). In the literature[94, 98] there are discussed also certain other possibilities uncovered by the use of pulsars for the investigation of problems in astronomy and in physics.

8. CONCLUDING REMARKS

It might be assumed that the entire content of the article has confirmed the statement made at the beginning, that theoretical notions concerning pulsars and the corresponding models are far from complete. At the same time, progress in the theory of pulsars is undisputed, and in particular, a number of perfectly concrete problems and questions calling for theoretical investigation have already become clear. There is no need to list these problems and questions here, since they are in part clarified by the discussion above and, principally, since I wish to conclude the article with remarks of a more general character.

The discovery of pulsars is the last of five remarkable astronomical discoveries made during the past decade. Other such discoveries of the Sixties were the observation of quasars, of cosmic x-ray sources (x-ray stars), thermal residual radiation with temperature

2.7 °K, and cosmic masers at the lines of the molecules OH, H_2O, and others. Let me remark that while very much has been done in physics during the same time, one can perhaps list only two discoveries of comparable scale—the proof of the existence of two types of neutrinos (muonic and electronic neutrinos) and observation of the nonconservation of combined parity in weak interactions. In this respect it can be stated that astronomy has overtaken physics but, of course, this became possible only as a result of the use of new physical methods in astronomy (reception of radio waves, detection of x-rays, etc.). In other words, the flow of astronomical discoveries is mainly the fruit of the process of conversion of astronomy, which began after the Second World War, from optical to all-wave. In the next decade this process will probably in essence terminate.

All this is well known and I wish to emphasize here something else: none of the new astronomical discoveries, insofar as is presently known, has taken us outside the already known physical laws, none has made it necessary to review in any way or to change the foundations of physics. In addition, some of the newly discovered objects and phenomena were predicted long ago "at the tip of the pen." This pertains, in particular, to neutron stars.[81, 99]

Thus, no matter how brilliant the progress in astronomy during recent times, it can be stated that this progress has not yet gone beyond the framework of astronomy and, at least in the opinion of the majority of astronomers and physicists, has not posed any new fundamental problems for physics.

Will the situation remain the same in the future, and, in general, what discoveries or changes of fundamental character can be expected in astronomy in the foreseeable future?

It would be most prudent not to raise this question at all, since prophets (or, speaking more prosaically, forecasters) have one thing in common—all make mistakes or are at least partly in error.

However, without pretending to any nontrivial predictions, we can point to several possibilities already under discussion.*

For the immediate future, we may expect the detection of neutrinos from the sun. There are also quite realistic prospects with respect to registration of neutrinos produced in supernova bursts (i.e., probably during the process of formation of neutron stars and, simultaneously, of pulsars). By the same token, valuable information will be obtained not only of astronomical character but also pertaining to the region of neutrino physics and weak interactions in general.[100, 101] More remote is the possibility of observing neutrinos of residual origin, produced during earlier stages of the evolution for a number of presently discussed cosmological models.

Thus, one of the trends of the astronomy of tomorrow is neutrino astronomy.

The notion of gravitational waves (we have in mind, of course, waves in vacuum) was born more than half a century ago together with the appearance of general relativity theory (a formula for the power of gravitational radiation was obtained by Einstein in 1908[102]). So far, however, gravitational waves cannot be regarded as a having been observed,* mainly because of the very low sensitivity of the corresponding receivers compared with receivers for electromagnetic waves. One can assume, nonetheless, that even in this century we shall succeed in receiving gravitational radiation from binary stars and possibly from pulsars (the 30-year period which we mention should not seem to be too long, if it is recognized that gravitational waves have been waiting to be observed for more than 50 years). The reception of cosmic gravitational waves will constitute the content of the "astronomy of gravitational waves" and can lead to unexpected results (such an unexpected result would be the observation of waves having the power indicated in the experiments of [38]; see also [39]).

Within the framework of general relativity theory, gravitational waves should be strictly transverse. To the contrary, in the tensor-scalar theory of the gravitational field,[103] gravitational waves also have a longitudinal component (parallel to the wave vector). It is difficult nevertheless to expect the fate of the tensor-scalar theory to be decided by investigating gravitational waves. It is much more probable that this will be done (and furthermore in the nearest future) as a result of a more accurate measurement of the deflection of light rays near the sun or measurement of the delay time of radio signals passing near the sun.

Most physicists, including the present author, are deeply convinced of the validity of general theory of relatively, at least for not too strong gravitational fields. But there is no doubting the need for further experimental verification of this theory, even for weak fields, and the situation here, after the observation of the oblateness of the sun[103] has become quite dramatic. Were it to turn out that general relativity calls for any supplementation even in weak gravitational fields (within the limits of the solar system), (and concretely, some scalar gravitational field does exist), then this would be a scientific event of foremost significance. In this case, insofar as we are speaking of the use of astronomical measurements, one could indeed say that astronomy has once more rendered an invaluable service to physics.

The probability that the already known physical laws and theories will turn out to be inaccurate increases as one goes to ever-increasing space-time scales and to ever-increasing masses and densities of matter. This pertains both to general relativity theory and to physics of elementary particles (concretely, we have in mind here conservation of the baryon charge and other conservation laws).

As is well known, a number of astronomers have already advanced the hypotheses that the number of baryons is not conserved in the universe (the creation of matter in stationary cosmology, etc.), that the equations

*We leave aside the question of the origin of the solar system, the structure of the moon and planets, etc., and also the problem of observing extraterrestrial life or civilizations.

*If the gravitational-radiation receivers used in [38] actually register gravitational waves, then the power of the cosmic gravitational radiation is colossal, which is little likely. For this reason, and principally because of the absence of a number of control experiments, the question of the nature of the events observed in [38] cannot yet be regarded as answered.

of general relativity theory are violated in strong fields (for example, in gravitational collapse),[104] that there exist supermassive and quite dense but sometimes active protobodies in stars and especially in the nuclei of galaxies[105–108, 104] etc. Stationary cosmology is at present practically refuted, but things are far from clear in other already mentioned cases. The author himself is an adherent of "healthy conservatism," i.e., he sees no grounds for supporting new concepts of fundamental character until new evidence is offered in their favor. It seems to me that at the present time there is no such evidence. But the very problem of searching for new fundamental concepts and ideas in astronomy (including cosmology) undoubtedly not only exists but from a certain point of view is even most interesting. Concrete forecasts with respect to investigations of such new paths is, by their very nature, hardly possible.

Are all these remarks justified in an article on pulsars? We see such a justification in the fact that all the mentioned (and in practice, all the known) trends of the future astronomical researches of fundamental character are connected directly or indirectly with neutron stars, and by the same token with pulsars! In fact, it is precisely the neutron stars that number among the most powerful potential sources of cosmic neutrinos and gravitational waves. Out of all the known stars, relativistic effects are particularly strong for neutron stars and by the same token the question of the limits of applicability of general relativity theory has in this case particularly great significance. Finally, the density of matter in the central parts of neutron stars is the highest of all the known densities for real (and not only hypothetical) objects. Therefore the "new" physics, if it proves to be necessary, will not bypass neutron stars.

Thus, pulsars are not only at the focus of the interest of astronomy of the present day, but in all probability will remain in the center of attention for many years and even decades.

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Note added in proof. We mention briefly several new investigations.

1. Polarization measurements in the radio band for four pulsars [109], and, apparently, polarization measurements [110] of optical radiation of the pulsar NP0532 offer evidence in favor of a model in which the directivity pattern of the pulsar radiation is of the "pencil" type with an axis close to the magnetic axis. In [110] it is also noted that the differences between the polarizations and certain other characteristics of the radiation of NP0532 in the optical and radio regions indicate that the optical and radio emissions are different in nature (have different mechanisms). The last conclusion is sufficiently well founded, but it follows to no lesser degree already from the general considerations advanced in Secs. 5 and 6 of the present article.

Concerning the factors that determine the width of the directivity pattern of pulsar radiation, see the articles [116,117].

2. We mention articles [111,112] devoted to the electrodynamics of the magnetospheres of pulsars, and the article [113] concerning the dynamics of the pulsar with allowance for its nonsphericity.

3. It is advantageous to distinguish between the inner and outer layers of the solid crust of the pulsar [114]. In the outer layer there are practically no free neutrons, but the inner layer is characterized precisely by the presence of free neutrons. The corresponding boundary lies at the density $\rho \sim 3 \times 10^{11}$ g/cm^3, and with increasing density the number of neutrons, naturally, increases and at a density $\rho \sim 10^{14}$ g/cm^3 the nuclei vanish quite abruptly (in the density scale). The resulting neutron liquid (with admixtures of proton and electron liquids), as indicated in Sec. 3 of the present article, is apparently superfluid. It is possible, however, that neutrons in the internal part of the crust(i.e., at densities $3\cdot 10^{11} \lesssim \rho \lesssim 10^{14}$ or in a somewhat narrower density interval) will also form a superfluid subsystem.

4. The question of the state of matter and the structure of the outer layer of the crust closest to the surface of the star remains unclear. In this region it is necessary, generally speaking, to take into account the influence of the magnetic field, which can lead to the formation of peculiar molecules and quasipolymer structures [115]. In this connection, the use of the estimate (2) for the melting temperature T_m near the surface of the crust is probably not justified. In addition, above the crust there should apparently be formed a certain thin layer (atmosphere) of gas or, better stated, a liquid plasma. The characteristics of this layer (and particularly its chemical composition) are most important from the point of view of conditions under which plasma escapes from the star, and by the same token for the understanding of the processes in the magnetosphere of a neutron star.

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