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A scientific session of the division of general physics and astronomy of the USSR Academy of Sciences was held, at the conference hall of the P. N. Lebedev Physics Institute, on 11–12 June 1969.

The following papers and communications were delivered at this session:

1. V. L. Ginzburg, Pulsars (General Review).
2. N. M. Shakhovskiĭ, Yu. S. Efimov, and V. I. Pronik, Polarization of the Crab Nebula Pulsar in the Optical Band.
3. V. I. Pronik, I. I. Pronik, and K. K. Chuvaev, Distribution of Energy in the Spectrum of the Pulsar of Crab Nebula.
4. Yu. I. Alekseev, V. V. Vitkevich, and Yu. P. Shitov, Fine Structure of the Pulses of the Pulsar CP0808 and Variation of the Periods of the Second Class.
5. Yu. I. Alekseev, V. V. Vitkevich, V. F. Zhuravlev, and Yu. P. Shitov, The New Pulsar PP0943.
6. V. V. Vitkevich, N. A. Lotova, Yu. P. Shitov, and Z. I. Shishov, Pulsar Flicker due to Inhomogeneities of the Interstellar Plasma.
7. A. A. Stepanyan, B. M. Vladimirskiĭ, I. V. Pavlov, V. P. Fomin, Possible Existence of a Flux of 10^{13}-eV γ Quanta from the Pulsar CP1133.
8. L. M. Erukhimov, Oscillations of Pulsar Radio Emission Intensity.
9. V. V. Zheleznyakov, Mechanisms of Pulsar Radiation.
10. N. S. Kardashev, Possibility of Observing Extragalactic Pulsars.
11. V. I. Slysh, Scattering of Pulsar X-rays in the Interstellar Medium.
12. I. S. Shklovskiĭ, Concerning Pulsars.
13. V. V. Vitkevich, I. F. Malov, and Yu. P. Shitov, Concerning the Model of a Pulsar as a Rotating and Pulsating Neutron Star.
14. L. A. Artsimovich, Heating of Ions in the "Tokamak" Installation.
15. A. A. Galeev and R. Z. Sagdeev, Paradoxes of Classical Diffusion of Plasma in Toroidal Magnetic Traps.
16. M. S. Rabinovich and I. S. Shpigel', Plasma Containment in the Stellarator "Liven'-1" of the Physics Institute of the USSR Academy of Sciences.

We publish below these contents of the delivered papers and communications.

B. L. Ginzburg, Pulsars (General Review).

The discovery of pulsars was reported on 24 February 1968[1]. Within a year (at the beginning of March, 1969), 211 articles devoted to pulsars have already been published (including 12 papers by soviet authors). It is possible that the bibliographical data given here[2] are not sufficiently complete, but they characterize in general the scale and rate of pulsar research.

The present review paper contains, besides an introduction, the following sections:

1. Basic data on pulsars.
2. Use of pulsars in astronomy and physics.
3. Nature of pulsars.
4. Mechanism of pulsar radiation.

The problem of pulsars was already discussed several times in the pages of this journal[1,3,4]. In this connection, attention is focused on the new results.

1. The author knows of observation of 37 pulsars. The period τ_1 of the newly discovered pulsars does not go beyond the limits known by the end of 1968. Thus, the shortest periods, 0.033 and 0.089 sec, are possessed by the pulsars NP0532 and PSR0833-45, which are in the envelopes of supernovas (we refer here respectively to the Crab Nebula—the envelope of the 1054 supernova, and to the nebula Vela X). The longest period, $\tau_1 = 3.75$ sec, is possessed by the pulsar NP0527. Special measurements offer evidence that there are either no pulsars with longer periods and with a power suitable for observation, or at least their number is very small. There are grounds for assuming that this result is connected with the decrease of the radial luminosity (the power of the radio emission) of the pulses with increasing period. For pulsars—rotating neutron stars (it is possible that these are not pulsars, see below), the period τ_1, more frequently designated P or P_1, is the period of revolution, and it increases with time, owing to the decrease of the kinetic energy of the rotation. By the same token, the pulsars with large τ_1 are old. As to the pulsar SP0532, for example, it is only 915 years old and it actually has the smallest value of τ_1 and the largest value of $d\tau_1/dt = 1.35 \times 10^{-5}$ sec-year. For all pulsars, $d\tau_1/dt \sim 10^{-8}$–10^{-7} sec/year. The "lifetime" of pulsars and of the radio sources observed by the existing methods is of the order of 10^7 years.

The total number of pulsars in the galaxy is $N_p \sim 10^5$ (in the case of a quasi-isotropic or "knife-edge" radiation directivity pattern), and $N_p \sim 10^6$ for a "pencil-like" directivity pattern. These data do not contradict the assumption that the pulsars are produced during each supernova explosion or in a appreciable number of such explosions (supernovas appear in the galaxy on the average once very 30—60 years).

The period of revolution of the pulsar PSR0833-45 decreased between 19 February and 13 March 1969 by 1.96×10^{-7} sec (before and after the indicated dates, the period of the pulsar increased by 10.65×10^{-9} sec daily). An attempt is made to explain this decrease of the period as being due to the decrease of the moment of inertia of the star (in connection with the change of the equation of state and the shape of the star), or to the presence of differential rotation, which may turn out to be unstable.

Observations of the radiation polarization of the same pulsar PSR0833-45 in the Vela-X envelope have

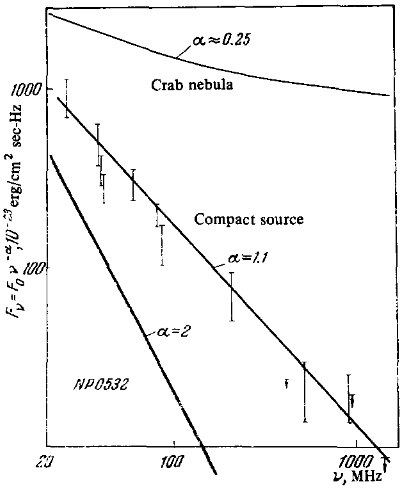

FIG. 1

been made at high frequencies: 1420, 1720, and 2700 MHz. The polarization turns out to be linear and, for example at the frequency 1720 MHz ($\lambda = 17.4$ cm) it amounts to 95 ± 5%. The electric vector rotates approximately 90° during the pulse.

Particularly important data were obtained for the pulsar NP0532 in the Crab Nebula, which is located at a distance R = 1500 ± 200 psec from the earth. The radio pulsar in the Crab Nebula is apparently surrounded by a radio-emitting envelope with a dimension $r \sim 10^{16}$ cm, and it is precisely this envelope which represents the previously observed compact radio source. The spectra of the radio emission of the nebula itself, of the compact source, and of the pulsar are clear from Fig. 1, which we obtained from L. I. Matveenko and N. A. Lotova[5].

The pulsar NP0532 or, more accurately, the object corresponding to it, was observed also in the optical and the x-ray bands (see Figs. 2 and 3, taken from[6] and[7], respectively). In the optical range (the interval 3400–8300 Å), according to[7], the spectrum of the pulsar is practically independent of the frequency, while the time-average luminosity of the object is $L_0 \approx 6 \times 10^{33}$ erg/sec. This is larger by a factor of 1.5 than the luminosity of the sun ($L_\odot = 3.86 \times 10^{33}$ erg/sec). The observed linear polarization of the optical radiation amounts to 15–20%. In the x-ray region (photon energy E_x in the interval 1.5–10 keV we have $L_x \approx 6 \times 10^{35}$ erg/sec, which amounts to 9% of the luminosity of the entire nebula (in the same range; we note also that the luminosity of the pulsar is calculated everywhere assuming that its radiation is isotropic; the auroras for the directivity pattern is discussed in[4]). The total luminosity of the Crab Nebula is $L = 9 \times 10^{37}$ erg/sec, and in the region 1 keV $< E <$ 500 keV the luminosity is $L_x = 10^{37}$ erg/sec. Thus, the pulsar in Crab emits mainly (in the sense of the radiation power) x-rays, and during one period there are emitted two pulses (in the optical part of the spectrum one of the pulses is much weaker than the other, as is clear from Fig. 2, and is called "the interpulse"). We note in conclusion that the optical pulsar in Crab (the same pertains undoubtedly to the radio and x-ray pulsars, in connection with the exact coincidence of their periods), is identified with a star located near the center of the Crab Nebula. We refer here specifically to the star which Baade and Minkowski, starting with 1943, regarded as the remainder of the 1054 supernova.

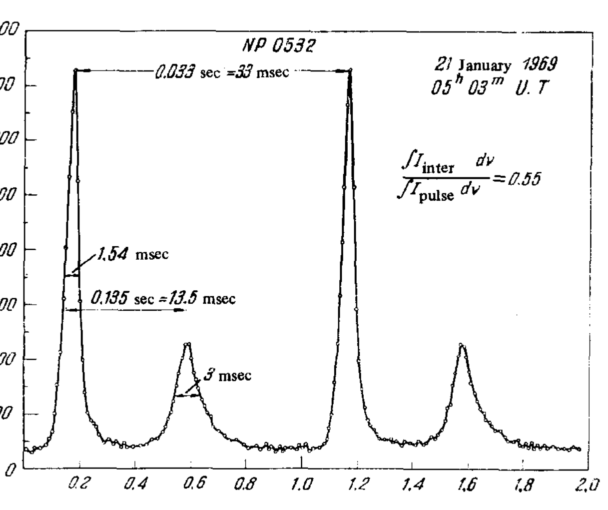

FIG. 2

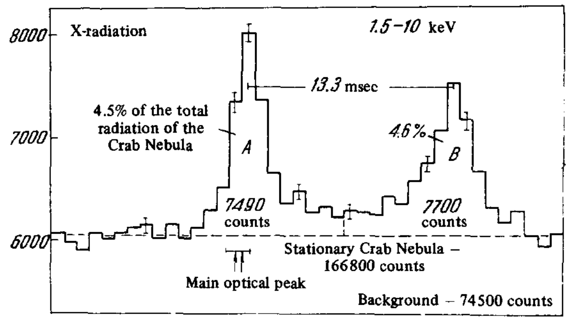

FIG. 3

The pulsar NP0527 is located at a distance of approximately 1° from the Crab Nebula. If these data will be confirmed (and this is essential, since it is not completely excluded that the pulsar NP0527 is much closer to the Crab Nebula), then it is most likely that the pulsars NP0532 and NP0527 are not connected with each other. A decisive verification of the fact that the pulsar NP0527 has been ejected from the Crab Nebula would be a measurement of its angular velocity (if the pulsar NP0527 was ejected from the Crab Nebula in 1054 and is located now at a distance 1° from the nebula, then its velocity is 0.1c, corresponding to an annual displacement of 4″ on the celestial sphere).

2. The use of pulsars in astronomy is connected primarily with the possibility of determining $\int n_e dl$ and $\int n_e H_{\parallel} dl$ on the path between the pulsar and the earth (n_e is the electron density, $H_{\parallel}$ is the magnetic field component parallel to the line of sight). It should further be mentioned that it is possible, within certain limits, to investigate the inhomogeneity of the concentration n_e in interstellar space and in the solar supercorona, and also to obtain information concerning the motion of these inhomogeneities. Special mention should be made of certain astrometrical and geodetic problems, for the solution of which pulsar observa-

tion may be employed[8].

On passing near the sun, an electromagnetic pulse not only is reflected, but experiences an additional delay. This effect of general relativity theory has already been observed (with insignificant accuracy (in radar observations of planets. It is possible that pulsars may be more suitable for this purpose (thus, for the pulsar CP0950 the pulse delay due to the sun's gravitational field should amount to 5×10^{-5} sec/year[8]). We note finally the following results: from the simultaneity (accuracy $\sim 10^{-4}$ sec) of the light pulses of different frequency from the pulsar NP0532 it follows that in the visible band the velocity of light is independent, to a high degree, of the frequency ($\Delta c/c < 5 \times 10^{-18}$).

3. The nature of pulsars as astronomical objects is determined by two circumstances: the high constancy of the period τ_1, which lies in the interval 0.033–3.75 sec, and the short pulse duration $\Delta\tau \sim 1-5$ msec. For the latter reason, the characteristic dimension for pulsars (the amplification region[4], and in the optical range apparently the dimension of the pulsar itself) $l \sim c\Delta\tau$ amounts to 3×10^7 cm (this value is obtained at $\Delta\tau \sim 1$ msec; actually, in some cases more minute details are noticeable, and consequently, $l \lesssim 10^7$ cm). The period of oscillations of white dwarf stars, generally speaking, is larger than or of the order of 1 sec (for the fundamental tone). Nor can a white dwarf rotate at a much higher frequency. For neutron stars, the period of oscillations $\tau_p \lesssim 10^{-2}$ sec, and the revolution period $\tau_r \gtrsim 10^{-3}$ sec. It is therefore clear that at least some of the pulsars are rotating neutron stars. The published hypothesis that we are dealing with a binary system, and that the period of the pulsars τ_1 is the period of the orbital motion, is utterly unacceptable. The point is that a binary system with the required period should produce a powerful gravitational radiation, leading to a rapid decrease of the period. On the other hand, the assumption that there is no gravitational radiation contradicts not only general relativity theory, but also any other realistic theory of the gravitational field.

Can pulsars turn out to be objects of a different type, analogous to quasars (we refer, for example, to quasi-stationary rotating massive stars with strong magnetic fields[4])? Although such an assumption is not completely excluded, there are no apparent grounds for it so far. Can pulsars of different types actually exist (neutron stars, white dwarfs)? Such a possibility cannot be excluded (concretely, pulsars with $\tau_1 \gtrsim 1$ sec might turn out to be white dwarfs or pulsating and rotating white dwarfs). However, at the present time nothing apparently contradicts the identification of all the known pulsars with rotating magnetized neutron stars.

At present there is known only one optical and x-ray pulsar NP0532 (for the pulsar in Vela X there is only a rather unreliable indication of the existence of a very weak optical signal). It is possible that optical (and x-ray) radiation of pulsars is sufficiently strong only during the early stages of their evolution, and is furthermore always accompanied by sufficiently powerful radio emission. If this is the case, then optical pulsars should be a great rarity (of importance here is also the presence of interstellar absorption of light, which prevents optical observations of a very large number of sources). However, we do not exclude also another possibility, namely the existence of optical and x-ray pulsars which practically cannot be noticed in the radio band. Even the example of the pulsar in the Crab Nebula does not contradict this assumption, since its radio luminosity is lower by several orders of magnitude than the optical and x-ray luminosities (see above). The radio waves probably come from regions that are farther from the surface of the star; under suitable conditions, the radio luminosity of these regions may be small. Thus, one must undoubtedly seek for optical and x-ray pulsars not only among the radio pulsars. A confirmation of this point of view can be seen in the fact that the x-ray pulsar in the Crab Nebula was actually observed[9] back in 1967. However, the authors have measured only the average flux and did not reduce their observations from the point of view of a search for pulsations of the x-ray flux. They have done so only after the discovery of the x-ray pulsar in April 1969. Another argument in this respect may be the analogy with quasars (QSR). Quasars were discovered as radio sources, and were later identified with optical quasistellar objects (OQSO). Later it turned out, however, that only about 1% of the OCSO produce powerful radio emission. The majority of the OCSO, on the other hand (they are also called quasistellar galaxies—QSG) are observed only in the optical band. Finally, it should be noted that the discovery of radio pulsars was also due to the use of an adequate procedure, a radio telescope having a very high sensitivity at meter wavelengths, and, what is no less important, adapted for the registration of rapidly varying signals (i.e., having a low time constant). In the case of optical observations, the procedure with the aid of which it is possible to observe optical pulsars was not employed in the past (and furthermore was not easy to do).

4. The identification of pulsars with neutron stars is, on the one hand, a discovery of prime importance, and on the other hand it is only the beginning. To understand the pulsar problem with any degree of completeness, even if we confine ourselves to the model of the rotating neutron star, it is still necessary to solve a number of problems.

a) It is necessary to develop the theory of neutron stars with allowance for their rotation and for the presence of a magnetic field. An important question is that of the angle between the magnetic moment of the star and its rotation axis, and the dependence of the field on the time (relaxation). This raises the question of oscillations in the atmosphere and in the magnetosphere of the rotating star. It is necessary to bear in mind, in addition, that the theory of neutron stars without allowance for the influence of rotation and of the field is also far from complete, owing to the insufficient clarity when it comes to the equation of state of a matter with density $\rho > 10^{12}$ g/cm^3 (we recall, in particular, the possible superfluidity and superconductivity of this matter[10], something usually disregarded).

b) If a star having a magnetic field rotates, then under certain conditions its magnetosphere cannot follow the star and "breaks away." It is precisely the consideration of such a "breakaway" and the corresponding phenomena which serves as the basis of the presently most popular pulsar models[11]. It is necessary to emphasize, however, that the problem has only been raised here. Neither the conditions of detachment (for example, the velocity v_c on the surface of the discontinuity as a function of the field of the star and the plasma density) nor the processes in the region of the discontinuity are known as yet. The powerful acceleration of the particles up to ultrahigh energies (the latter is important for the theory of the origin of cosmic rays), the emission of waves of various wavelengths, the ejection of plasma streams, etc., all these processes are possible, but their quantitative characteristics are not clear. The known published estimates, for example, of the power of the magnetic dipole radiation of a rotating star with non-coinciding directions of the rotation axis and of the magnetic dipole, have been made without due account of the influence of the plasma surrounding the star, and therefore may turn out to be perfectly unsuitable. To draw conclusions concerning the character of the acceleration of the particles and of the plasma near the pulsars on the basis of the available data is tantamount to regarding the possible as the actual. In the region of the theory of the magnetosphere of rotating neutron stars, it is still necessary to form work of gigantic scale and difficulty.

c) By specifying a definite model of the magnetosphere and its characteristics, it is possible to analyze the question of the mechanism of the radiation of pulsars and the parameters of the radiating regions (particularly those producing radio emission). This group of problems is best considered separately.

The pulsar emission mechanism is discussed in[4], albeit without allowance for some of the latest data. From sufficiently general considerations it is clear that the radio emission of pulsars cannot be incoherent, but it fully admits of an interpretation within the framework of known concepts of coherent radio emission mechanisms. The optical and x-ray emission of pulsars, to the contrary, can be naturally regarded as incoherent (in any case, such an assumption seems to be noncontradictory)*. A realistic model of an emitting pulsar should be in agreement with the available data on the intensity, polarization, and directivity pattern of the pulsar radiation.

In the model in which the pulsar is a rotating star, the aperture of the directivity pattern is $\varphi \sim 2\pi\Delta\tau/\tau_1$ (where $\Delta\tau$ is the width of the pulse and $\omega = 2\pi/\tau_1$ is the angular rotation frequency of the pulsar). For the pulsars in the Crab Nebula and in Vela X, and also for the pulsar CP0328, the angle θ is of the order of 30–40°, 8°, and 3° respectively. If the directivity pattern of the radiation is "knife like" then the pulsar is "seen" during the period from a solid angle $\Omega_k \sim 4\pi$ (it is assumed that the plane of the diagram makes an angle $\theta \lesssim 1$ with the rotation axis; at an angle $\theta = \pi/2$, the pulsations disappear, and when $\theta \to \pi/2$ the pulsar "is seen" only in a small solid angle). For a "pencil like" diagram $\Omega_p \sim 2\pi\varphi$ and the number of pulsars is $4\pi/\Omega_p = 2/\varphi \sim 5-30$ times larger than in the case of a "knife-like" diagram. In the case of a "knife-like" diagram, there should be observed during the period, generally speaking, two pulses. But two clearly pronounced pulses are present only for the pulsars NP0532 and NP0527 (a strange coincidence!?), and there is a weak second pulse for the pulsar CP0950. Both the absence of the second pulse and the polarization observation[12] for the pulsar PSR0833-45 in X-Velarum are compatible with the "pencil like" directivity pattern with an axis along the magnetic axis. Polarization measurements[12-14] may turn out to be the key to the understanding of the character of the diagram and mechanism of the radiation.

We (V. V. Zheleznyakov, V. V. Zaĭtsev and the present author) are presently expanding our earlier work[4] primarily to cover the case of the coherent synchrotron mechanism (in the radio band) and the incoherent synchrotron mechanism (for the optical and x-ray bands). Concretely, for the pulsar in the Crab Nebula, a suitable model is that of an emitter with a "knife-like" diagram, the plane of which coincides with the plane of the magnetic equator of the rotating neutron star (the rotation axis makes an angle $\theta \sim 1$ with the plane of the diagram). X-ray and optical radiation come from a toroidal radiation belt located in the region of the magnetic equator. The radiation mechanism is of the synchrotron type and is incoherent. The directivity of the radiation is connected with the anisotropic distribution of the velocities of the relativistic electrons in the belt. Two pulses per period are obtained in this case automatically (as indicated, this is the property of the "knife-like" diagram). The agreement of the aperture of the diagram φ in the optical and x-ray bands is also natural, and for the radio band it is possibly connected with the fact that much more powerful short-wave radiation produces, as it were, a waveguide in the atmosphere of the star. The parameters of the region from which the light and the x-rays are emitted (for example $H \sim 10^6$ Oe, $E/mc^2 \sim 10^2$, $N \sim 10^{15}$ relativistic electrons/cm³, volume $V \sim L^3 \sim 10^{20}$ cm³; for details see the paper by V. V. Zheleznyakov, p. 807), are perfectly reasonable. In the case of the pulsar in Vela X, if its diagram is "pencil like" (this is indicated but far from proved by the absence of the second pulse), the picture is less clear. The main fact is that if diagrams of different types are realized, then it is necessary to understand the cause and the conditions for the appearance of each of them. In the field of theory of mechanisms of pulsar radiation, there is obviously still much to be done.

In spite of the presence of many unclear aspects and the large scale of the work still to be done, we must note in conclusion the impressive progress already made in the study of pulsars within less than a year and a half.

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*The intensity of thermal radiation with temperature T is $I_\nu = (2k\nu^2/c^2)T$ (the frequency region $\hbar\nu \ll kT$). For the strongest incoherent radiation possible from particles with energy E, the role of $T = T_{eff}$ is played by E/k. In connection with the relative smallness of the frequency ν in the radio band, and, principally, the small dimensions of the pulsars, we have for them in the radio band $T_{eff} \sim 10^{20} - 10^{25}$ deg, i.e., $\sim 10^{16} - 10^{21}$ eV. *By the same token it is clear that the radiation cannot be incoherent.* On going over to visible and x-rays, the frequency ν increases by many orders of magnitude, and T_{eff} decreases like ν^{-2} (at the same value of I_ν). From this we can directly arrive at the conclusion that the incoherent mechanisms of the optical and x-ray emission of pulsars are not contradictory.

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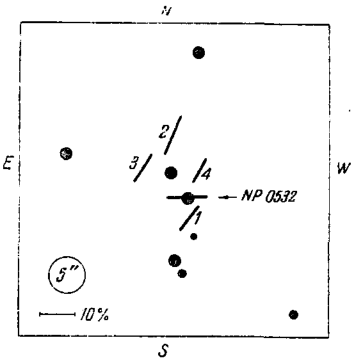
[14] B. Warner, R. E. Nather, and M. MacFarlane, Nature 222, 233 (1969).

N. M. Shakhovskiĭ, Yu. S. Efimov, and V. I. Pronik. Polarization of the Crab Nebula Pulsar in the Optical Band.

The pulsar NP0532 was recently identified[1] with the southern component of a binary star in the center of the Crab Nebula. On 13 March 1969 we measured the linear polarization of the optical radiation of both components of this binary and the nebula points close to it.

The observations were made with the ZTSh 2.6-meter telescope using an integrating polarimeter with photon counting. We used a diaphragm of 5″ diameter and the star images were on the order of 1.5″. All the observations were carried out without a light filter in the 3500–8000 Å band at $\lambda_{\rm eff} \approx 5500$ Å. Each object was observed with an accumulation time (exposure) of 50 sec. There was no time selection of the pulsar pulses.

The figure shows schematically the arrangement of the stars in the central region of the Crab Nebula. The numbers designate the points of the nebula measured by us. The choice of these points was based on an examination of old[2] and new photographs of the background of the nebula, we disregarded the ratio of the brightness of the northern star and of the pulsar, given in[3], and the data on the contrast of the pulsar pulses over the background from[4].



The instrumental polarization was taken into account by means of observations of bright stars from the catalogs of[5,6]. The data presented below on the polarization of both stars are already free of the influence of the radiation of the nebula and of the instrumental polarization.

As a result we have found that the degree of linear polarization of the integral radiation of the pulsar is 12.6 ± 1.6% at a position angle of the oscillation plane 91 ± 4°. The corresponding data for the northern star are 1.9 ± 0.7% and 166 ± 11°. The degree of polarization at the measured points of the nebula changes from 8 to 15%, and the position angle of the plane of oscillations lie between 142° and 157°. The errors indicated are mean-squared errors obtained with allowance for both the internal convergence of the measurements and the errors in the elimination of the instrumental polarization.

The results show that the radiation of the northern star has a noticeable polarization near 13%. At the customarily employed values of the distance to the Crab Nebula and the interstellar absorption, such a large polarization cannot be of interstellar origin.

Since, according to[4], practically all the radiation of the southern star is observed in the form of pulses, it follows that the obtained polarization parameters pertain to the intrinsic radiation of the pulsar, averaged over the entire period (the summary radiation of the primary and secondary pulses). The presence of an appreciable linear polarization apparently confirms the synchrotron nature of the optical radiation of the pulsar.

After the completion of our work, we learned of the results of polarization observations of the pulsar in the Crab Nebula, performed in the USA[7] and in Australia[8]. In both investigations, the measurements were made with time selection of the pulsar pulses: the brilliance curve of the pulsar was successively registered at different positions of the analyzer (polaroid).

Warner's group[7] has found that the average degree of linear polarization of the principal pulse of the pulsar is approximately 14%, and the direction of the plane of observation differs by 60° from the corresponding direction for the central part of the Crab Nebula. These data agree very well with our measurements. It is also noted in[7] that a change takes place in the position of the plane of oscillations during the course of the pulse.

The Australian investigators[8] have found that the degree of linear polarization of the pulsar pulses probably does not exceed 15%, and the degree of circular polarization amounts to 13 ± 11%.