SOVIET PHYSICS USPEKHI VOLUME 15, NUMBER 6 MAY-JUNE 1973

523.038

# *CIRCULAR POLARIZATION OF RADIATION FROM COSMIC OBJECTS*

V. N. SAZONOV

P. N. Lebedev Physics Institute, USSR Academy of Sciences; Moscow Physico-technical Institute

Usp. Fiz. Nauk 108, 583–594 (November, 1972)

## 1. INTRODUCTION

ELECTROMAGNETIC radiation contains a circularly-polarized component if the electric and magnetic vectors in the wave rotate predominantly in some single direction. It has been known for a relatively long time that radiation of different cosmic objects is circularly polarized, for example the radio emission from solar flares, the radio emission of the radiation belts of Jupiter, and the maser radio emission of the OH regions.

Interest in circular polarization has revived recently both among experimenters and among theoreticians, in connection with the discovery of circular polarization of the radio emission of quasars and pulsars and the optical radiation of white dwarfs, planets, and other objects. The circular polarization is a highly instructive characteristic of radiation sources, and leads to important qualitative conclusions concerning the properties of these sources.

The present note contains a brief review of the latest experimental and theoretical studies of circular polarization. In the interests of the nonspecialist, we make a few preliminary remarks.

## 2. DESCRIPTION OF POLARIZED RADIATION

We consider first a monochromatic wave with wave vector **k**. The formula for the dependence of the electric vector **E** on the time and coordinates, in the case of vacuum, can be written in the form

$$\mathbf{E} = E_0 \,\mathrm{Im}\, \mathbf{e} \exp\left[-i(\omega t - k\mathbf{sr})\right], \tag{2.1}$$

where $E_0$ is the real amplitude and $\mathbf{s} = \mathbf{k}/k$ is a unit ray vector.

The vector e in (2.1) is called the polarization vector. It is generally a complex unit vector lying in the picture plane, i.e., in a plane perpendicular to the vector **s**.

In a monochromatic wave, the vector e does not depend on the time. Such radiation is fully polarized. In practice it is necessary to deal with partially polarized radiation, which can be represented as consisting of sequences of trains of monochromatic waves that are bounded in space and time. The vector e remains constant during the passage of a given train, but can vary from train to train. Partially polarized radiation cannot be described with the aid of a polarization vector. Such radiation is described with the aid of four bilinear combinations made up of the components of the vector e (see, for example,[1]):

$$\rho_{\alpha\beta} = \overline{e_\alpha e_\beta^*}, \qquad \alpha,\ \beta = 1,2. \tag{2.2}$$

The superior bar in (2.2) and further denotes averaging over a sufficiently large time interval. The indices $\alpha$ and $\beta$ designate the components of the vector e along the axes 1 and 2 of a Cartesian coordinate system in the picture plane. The four quantities $\rho_{\alpha\beta}$ form, with respect to rotation of the axes 1 and 2, a tensor called the polarization tensor (in quantum theory one uses a different term, the density matrix). As follows from (2.2), the tensor $\rho_{\alpha\beta}$ is Hermitian, $\rho_{\alpha\beta} = \rho^*_{\beta\alpha}$, and is normalized by the condition $\rho_{11} + \rho_{22} = 1$. By virtue of these conditions, the tensor $\rho_{\alpha\beta}$ can be expressed in the form

$$\rho_{\alpha\beta} = \frac{1}{2}\begin{pmatrix} 1+\xi_3 & \xi_1 - i\xi_2 \\ \xi_1 + i\xi_2 & 1-\xi_3 \end{pmatrix}.$$

The real parameters $\xi_1$, $\xi_2$, and $\xi_3$ are called the Stokes parameters. The parameters $\xi_1$ and $\xi_3$ describe linear polarizations and the parameter $\xi_2$ circular polarization. It is easy to show that $\xi_2 = i[\mathbf{e}\times\mathbf{e}^*]\cdot\mathbf{s}$.

The parameter $\xi_2$ has the following physical meaning: We take two polarization analyzers, one that passes a wave with only right-hand polarization ($\xi_2 < 0$), and the other only left-hand polarization ($\xi_2 > 0$)[1)]. If two beams of equal intensity I and equal Stokes parameter $\xi_2$ enter these analyzers, then the intensity difference at the output is equal to $I_L - I_R = \xi_2 I$. Concerning the physical meaning of the parameters $\xi_1$ and $\xi_3$, see, for example,[1].

The parameter $\xi_2$ is sometimes called the degree of circular polarization $\xi_2 = p_c$. The degree of linear polarization is defined as $p_l = \sqrt{\xi_1^2 + \xi_3^2}$. The degree of total polarization $p = \sqrt{p_l^2 + p_c^2}$ characterizes the relative intensity of the polarized radiation component: if $p = 1$ the radiation is fully polarized, and if $p = 0$ the radiation is completely depolarized. In the polarized-radiation component, the vector **E** moves, generally speaking, over an ellipse with semiaxes a and b. We have $|p_c|/p = 2ab/(a^2 + b^2)$.

Sometimes one introduces in place of the tensor $\rho_{\alpha\beta}$ the tensor

$$I_{\alpha\beta} = I\rho_{\alpha\beta} = \frac{1}{2}\begin{pmatrix} I+Q & U-iV \\ U+iV & I-Q \end{pmatrix},$$

where I is the total radiation intensity. The quantities Q, U, and V are also called Stokes parameters.

## 3. WHAT ARE THE NECESSARY CONDITIONS FOR THE REALIZATION OF CIRCULAR POLARIZATION?

To answer this question we start from the general properties of the invariance of the interaction of the

1) According to the accepted terminology, we call a circular polarization left-handed if the observer receiving the radiation sees the electric vector of the wave rotating in a positive direction, i.e., counterclockwise (in quantum theory this corresponds to a positive photon helicity).

electromagnetic field with a charge to the space inversion operator P and the time reversal operation T. In view of the indicated invariance, the work $dW = e\mathbf{E}\cdot d\mathbf{r}$ performed on the charge is not altered by the P and T transformations. It follows therefore that the electric field $\mathbf{E}$ is a polar t-even vector: $P\mathbf{E} = -\mathbf{E}$, $T\mathbf{E} = \mathbf{E}$. Recognizing, in addition, that $P\mathbf{s} = -\mathbf{s}$ and $T\mathbf{s} = -\mathbf{s}$, where $\mathbf{s} = \mathbf{k}/k$, we obtain from (2.1) the rules for transforming the polarization vector: $P\mathbf{e} = -\mathbf{e}$, $T\mathbf{e} = -\mathbf{e}^*$.

The degree of circular polarization is equal to $p_c = \mathbf{F}\cdot\mathbf{s}$, where $\mathbf{F} = i\mathbf{e}\times\mathbf{e}^*$. According to the foregoing, the vector $\mathbf{F}$ is an axial t-odd vector: $P\mathbf{F} = \mathbf{F}$, $T\mathbf{F} = -\mathbf{F}$. From this we can draw the following conclusion: circular polarization arises only if the conditions for the generation or propagation of the radiation admits of the existence of a certain axial t-odd vector $\mathbf{F}$, which has a nonzero projection on the vector $\mathbf{s}$. We shall call the vector $\mathbf{F}$ the formation vector.

We note, however, that the possibility of constructing a formation vector is still not a sufficient condition for the existence of circular polarization. We note also that the quantity $p_c = \xi_2$ is a t-even pseudoscalar: $Tp_c = p_c$, $Pp_c = -p_c$; the Stokes parameters $\xi_{1,3}$ are t-even scalars: $T\xi_{1,3} = \xi_{1,3}$, $P\xi_{1,3} = \xi_{1,3}$.

## 4. QUASARS

4.1. Quasars are sources of nonthermal variable radio emission of high intensity. This emission is as a rule linearly polarized, thus indicating, in addition, that the radio emission is of the synchrotron-radiation type. The degree of linear polarization is usually equal to $p_l = 3-10\%$. The degree of circular polarization of quasars, as well as of other extragalactic radio sources, is much less than $p_l$. An upper bound of $p_c$ was obtained in[2-5] for a large number of radio sources; it turns out that in different sources $|p_c| < 0.1-3\%$. In[6-10] are given rather reliable measurements of the degree of circular polarization of certain quasars and radio galaxies. According to[10], $p_c$ reaches $p_c = -1.0 \pm 0.2\%$ at the wavelength $\lambda = 9.3$ cm.

Small values of $|p_c|$, compared with $p_l$, agree qualitatively with the synchrotron model of radio emission, and by the same token make it possible to analyze theoretically and interpret the observations of[2-10] within the framework of this model.

The main properties of synchrotron radiation of nonrelativistic electrons are considered in detail in[11]. Before we discuss the observation data we shall mention briefly the features of polarization of synchrotron radiation, and also present some new results obtained recently on this subject.

4.2. We consider first the simplest model of a source. Let the magnetic field $\mathbf{B}$ and the spatial distribution of the electrons in the volume of the source be homogeneous; the distribution of the electrons as a function of the angle $\varphi$ between the electron momenta and the field $\mathbf{B}$ does not depend on the energy of these electrons; after the radiation is generated, there is no noticeable absorption (reabsorption) or change in the polarization of the radiation in the source.

If the relativistic electrons have a power-law energy distribution, the dependence of the radiation intensity on the observation frequency $\nu$ also has a power-law form: $I_\nu \backsim \nu^{-\alpha}$. The spectral exponent $\alpha$ is usually equal to $\alpha = -0.2-1.5$. The degree of linear polarization depends only on $\alpha$ and is equal to (see for example,[11])

$$p_l = \frac{\alpha+1}{\alpha+(5/3)},$$

i.e., $p_l = 55-80\%$.

For a source with an isotropic angular distribution of the electron momenta, the degree of circular polarization is

$$p_c = -C_0(\alpha)\,\mathrm{ctg}\,\theta\,\frac{mc^2}{E_\nu} \equiv -C_0(\alpha)\,\mathrm{ctg}\,\theta\left(\frac{3e}{2\pi mc}\,\frac{B\sin\theta}{\nu}\right)^{1/2}. \qquad (4.1)$$

In (4.1), $\theta$ is the angle between the ray vector $\mathbf{s}$ of the radiation and $\mathbf{B}$, with $\theta \gg mc^3/E_\nu$ and $\pi - \theta \gg mc^2/E_\nu$, where $E_\nu$ is the energy of the electrons making the main contribution to the radiation at the frequency $\nu$; it is understood that $mc^2/E_\nu \ll 1$; $C_0(\alpha)$ is a numerical coefficient. An order-of-magnitude estimate for $p_c$ was obtained in[12]. The coefficient $C_0(\alpha)$ and the part due to the anisotropy of the angular distribution, which has been left out from (4.1), were calculated in[13,14].

We note that the degree of circular polarization is small: $|p_c| \ll 1$. This is due to the following reason: The relativistic electron emits mainly along the momentum direction. Therefore the contribution to the radiation in the direction of $\theta$ at the frequency $\nu$ is made only by those electrons for which the angle $\varphi$ is such that $|\varphi - \theta| \lesssim mc^2/E_\nu$. Electrons having an angle $\varphi < \theta$ and electrons having an angle $\varphi < \theta$ and electrons having an angle $\varphi > \theta$ produce radiation that has noticeable circular polarization: $|p_c(\varphi)| \lesssim 1$, but the sign of $p_c(\varphi)$ is different in the two cases (Fig. 1). As a result, the circular polariation of the total radiation $p_c$ turns out to be small if the distribution of the electrons with respect to the angle $\varphi$ changes little in a narrow interval $|\varphi - \theta| \lesssim mc^2/E_\nu$. In the zeroth approximation in the small parameter $mc^2/E_\nu$, we have $p_c = 0$; inclusion of the next higher terms yields formula (4.1).

It is clear from this, incidentally, that a sufficiently strong anisotropy of the angular distribution of the electrons can greatly increase the degree of circular polarization. Indeed, a contribution to $p_c$ is made in this case, for example, only by electrons with $\varphi < 0$, since the number of electrons with $\varphi > 0$ is either small or zero.

If the angular distribution of the electrons is iso-

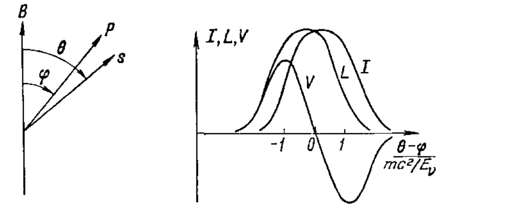


FIG. 1. Total intensity I, intensity $L = (Q^2 + U^2)^{1/2}$ of the linearly polarized component, and intensity V of the circularly polarized component of the synchrotron radiation of a system of relativistic electrons whose momenta make an angle $\varphi$ with the magnetic field $\mathbf{B}$ ($\mathbf{s}$ is a unit vector in the observer's direction).

tropic, then the role of the formation vector **F** is played by the magnetic field **B**. On the other hand, if it is precisely the anisotropy of the angular distribution that causes the greater part of the circular polarization, then $\mathbf{F} \backsim (\mathbf{B}\cdot\mathbf{p}_t)\mathbf{s}$; here $\mathbf{p}_t$ is the projection of the momentum of the radiating electrons on the picture plane, averaged with a weight proportional to the contribution of each electron to the radiation.

It follows from (4.1) that $p_c$ depends on the observation frequency $\nu$ and on the wavelength $\lambda$ in accordance with the law

$$p_c \backsim \nu^{-1/2} \backsim \lambda^{1/2}. \tag{4.2}$$

As shown in[15], the law (4.2) remains valid also if the magnetic field in the source is not homogeneous. In particular, let the magnetic field at each point of the source be represented by $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_R$, where $\mathbf{B}_R$ is a random field of constant magnitude, whose orientation varies randomly from point to point; $\mathbf{B}_0$ is a homogeneous field, with $B_0 \ll B_R$. Then

$$\begin{aligned} p_l &= L(\alpha)\,\varepsilon\sin^2\theta, \\ p_c &= -C(\alpha)\,\varepsilon^{1/2}\left(\frac{3}{2\pi}\frac{eB}{mc\nu}\right)^{1/2}\cos\theta, \end{aligned} \tag{4.3}$$

where $\theta$ is the angle between $\mathbf{B}_0$ and $\mathbf{s}$, $L(\alpha)$ and $C(\alpha)$ are numerical coefficients, and $\epsilon = (B_0/B)^2$ is the degree of homogeneity of the magnetic field. We note that, other conditions being equal, the modulus of $p_c$ is larger the larger the spectral index $\alpha$:

$$\frac{\partial |p_c|}{\partial\alpha} > 0. \tag{4.4}$$

The following possible violations of the rule (4.2) are considered in the literature:

a) A source in which reabsorption of the radiation takes place. According to[16,17], $p_c$ reverses sign on going from high frequencies to low frequencies at which reabsorption is important. $p_c$ reverses sign occurs at frequencies corresponding to an optical thickness (more accurately, a radio-frequency thickness) $\tau = 4-8$ if $\alpha = 0.5-1.5$.

b) A source in which the angular distribution of the electrons in anisotropic and depends on their energy, and furthermore in such a way that the electrons with higher energy have a much more anisotropic angular distribution relative to the magnetic field than the electrons with lower energy[18]. (Such a situation can occur, for example, if the electrons enter into the radiating region by "breaking through" the magnetic field that has contained them.) In such a model, which is intended for the description of compact variable sources, the dependence of $p_c$ on $\nu$ in a certain intermediate region of frequencies is given by

$$p_c \backsim \nu^{-\beta}, \quad \beta < \frac{1}{2}.$$

The sign of $p_c$ in the intermediate region can differ from the sign of $p_c$ in the region of high and low frequencies.

c) A multicomponent (inhomogeneous) source having different values of the spectral index $\alpha$ in different components[9]. In such a source, a change in the frequency changes the relative contribution of the components to the total radiation, and this causes in turn violation of the rule (4.2), and possibly a reversal of the sign of $p_c$.

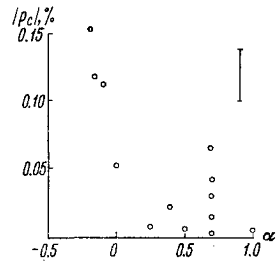


FIG. 2

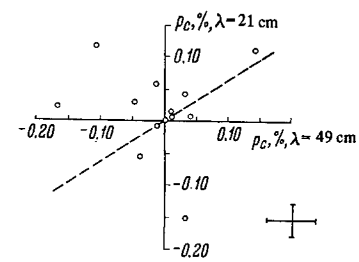


FIG. 3

FIG. 2. Correlation between the degree of circular polarization $p_c$ and the spectral index $\alpha$ of quasars. Each point represents circular polarization of one quasar at the wavelength $\lambda = 21$ cm [9]. The vertical bar is double the average measurement error.

FIG. 3. Violation of the rule $p_c \backsim \nu^{-1/2} \backsim \lambda^{1/2}$ (dashed line) for quasars. Each point represents the circular polarization of one quasar, which was measured at the wavelengths $\lambda = 21$ and 49 cm [9]. The cross represents the doubled average measurement errors.

4.3. We now consider the observation data and their interpretation. The characteristic features of circular polarization of radio emission of quasars are:

a) The degree of circular polarization of quasars has a tendency to increase with increasing spectral index $\alpha$ (Fig. 2; compare with (4.4)).

b) The dependence of $p_c$ on the frequency $\nu$ differs from (4.2); in particular, the sign of $p_c$ in certain sources is reversed when the frequency changes (Fig. 3).

c) There is no correlation between $p_l$ and $p_c$.

The observational data (a) and (b) cannot be interpreted within the framework of the simplest source models. Additional assumptions are needed for their interpretation. In our opinion, the circular polarization in compact radio sources is due principally to the anisotropic angular distribution of the radiating electrons ejected from the source. In particular, the average degree of circular polarization is expected here to increase with decreasing spectral index $\alpha$, since a hard spectrum (i.e., small values of $\alpha$) usually occurs in variable sources that release much energy, so that beams of relativistic electrons can be produced.

In connection with property (b), it is emphasized in[16] that reabsorption can affect the circular polarization; the observational consequences of the multicomponent character of the source are discussed in[9]. At the present time, however, the observed data offer no choice among the different hypotheses.

The correlation between the linear and circular polarizations is discussed in[15], where it is shown that the absence of correlation between $p_l$ and $p_c$ is perfectly compatible with the synchrotron model.

4.4. Let us examine briefly the conclusions that can be drawn concerning extragalactic sources on the basis of observation of circular polarization as more data are accumulated.

Deviations from the rule (4.2), and particularly the reversal of the sign of $p_c$, may be an indication of reabsorption in the source[16,17]. We note in this connection that violation of the rule (4.7) can be due to reabsorption not in the entire volume of the source, but only in its compact core. In the latter case the spectrum of the source need not necessarily deviate from the power-law form $I_\nu \backsim \nu^{-\alpha}$, since it is quite probable that the core, which has a strong magnetic field, does indeed make the main contribution to the circular polarization and makes a small contribution to the total radiation flux.

If subsequent observations confirm the hypothesis that the decisive role is played by the anisotropy of the angular distribution of the electrons, then we shall be able to conclude that relativistic electrons are accelerated in compact radio sources in the form of anisotropic beams. In this case, by measuring the dependence of $p_c$ on the time, we can estimate the time of isotropization of the beam of relativistic electrons in a cosmic plasma.

The magnetic field B and the quantity $\epsilon$ enter explicitly in the expressions (4.3) for $p_l$ and $p_c$. Therefore if (4.2) is satisfied we can obtain, using the data on the polarization, much information on the intensity B and degree of homogeneity $\epsilon$ of the magnetic field[18].

In our opinion, as observational data are accumulated and the theory develops further, circular polarization will become a most important characteristic of extragalactic radio sources.

## 5. WHITE DWARFS

5.1. According to modern concepts, white dwarfs were produced from star with mass $M < 1.2 M_\odot$, where $M_\odot$ is the mass of the sun. For stars with such a mass, the compression that sets in after the nuclear fuel is burned out is stopped because of the pressure of the degenerate electron gas, as a result of which the star, which has a radius $R_S$, is transformed into a white dwarf with radius $R_D = 10^{-2}$—$10^{-3}\, R_S$. The material of the star has a high conductivity, so that the magnetic flux is conserved during the compression: $B_S R_S^2 = B_D R_D^2$. If the star had a relatively strong magnetic field $B_S = 10^2 - 10^3$ G ($B \approx 1$ G on the sun and $B = 3 \times 10^4$ G for certain magnetic stars), then the corresponding white dwarf will have a field $B_D = 10^6 - 10^9$ G.

A magnetic field $B > M^2e^3c/\hbar^3 = 2 \times 10^9$ J alters the properties of matter radically[19]. However, even a weaker field can lead to interesting qualitative effects. In particular, it was suggested in[20] that a magnetic field may be the cause of the appearance of circular polarization in thermal radiation. Soon after the publication of[20], circular polarization was indeed observed in thermal optical radiation of a number of white dwarfs[21-26]. Somewhat earlier, circular polarization was observed in the thermal radiation of samples heated to $T = 10^{3\circ}$K and placed in a magnetic field $B = 2.5 \times 10^3$ G[27].

Before we discuss the observational data, let us consider some theoretical premises.

5.2. As is well known, (see, for example,[28]), in the classical theory the magnetic field B does not change the state of thermodynamic equilibrium. Therefore circular polarization of thermal radiation can appear under the influence of B only as a result of quantum effects or because the radiating system is not in a state of thermodynamic equilibrium.

Assume that quantum effects play the principal role. It can then be assumed that the degree of circular polarization of the thermal radiation is of the order of

$$p_c \approx \mathbf{sb}\,\frac{\hbar\omega_B}{kT_\lambda} \quad \left(\mathbf{b}=\frac{\mathbf{B}}{B},\quad \omega_B=\frac{eB}{mc}\right), \tag{5.1}$$

where $\hbar\omega_B$ is the energy difference between the Landau levels and $T_\lambda$ is the temperature of the electrons that make the principal contribution to the radiation at the wavelength $\lambda$; it is assumed that $\hbar\omega_B \ll kT_\lambda$. We note that $p_c \backsim B$. Let us find the dependence of $p_l$ on B. The Stokes parameters $\xi_{1,3}$ of the linear polarization are t-even scalar quantities. We have at our disposal only the two vectors **s** and **B**, from which they can be constructed. Writing down in symbolic form $\xi_{1,3} \backsim (s)^\alpha (B)^\beta$, where (s) and (B) are the components of the vectors **s** and **B**, we find that the exponents $\alpha$ and $\beta$ should be even. In particular, we can write

$$p_l \approx |[\mathbf{sb}]|^2 \left(\frac{\hbar\omega_B}{kT_\lambda}\right)^2. \tag{5.2*}$$

In all probability, the exact theory yields for $p_c$ and $p_l$ formulas of the type (5.1) and (5.2) with numerical coefficients. We note that if the angle $\theta$ between **s** and **B** is not too close to $\pi/2$ or to zero, then $p_l < |p_c|$ and we have in order of magnitude $p_l \approx p_c^2$.

Assume that the principal role is played by the lack of thermodynamic equilibrium. This lack may be due, in particular, to the fact that the white dwarf radiates and that its outer layers are colder than the inner ones. In the presence of a magnetic field, waves with right-hand polarization have, say, a smaller absorption coefficient than waves with left-hand polarization. Then the waves with right-hand polarization will reach us, on the average, from a larger depth and right-hand circular polarization will appear in the radiation ($p_c < 0$).

Let us find the dependence of $p_c$ and $p_l$ on the field B, We now have at our disposal, in addition to the vectors **s** and **B**, a polar t-even vector, namely the temperature gradient $\nabla T$. Only an odd power of the vector $\nabla T$ can enter the formulas for $\xi_{1,3}$ and $\xi_2 = p_c$. We write the formulas for $\xi_{1,3}$ in the symbolic form $\xi_{1,3} \backsim (\nabla T)^\alpha (B)^\beta (s)^\delta (l)^\gamma$. From the P- and T-invariance conditions it follows that

$$\begin{aligned} &P: \quad (-1)^\alpha (+1)^\beta (-1)^\delta (-1)^\gamma = 1, \quad \alpha+\delta+\gamma \ \text{even} \\ &T: \quad (+1)^\alpha (-1)^\beta (-1)^\delta (+1)^\gamma = 1, \quad \beta+\delta \ \text{even} \end{aligned} \tag{5.3}$$

$\mathbf{l} = \nabla\rho$, where $\rho$ is the radiation density on the line of sight. The vector **l** appears in the radiation transport problem when the boundary conditions are formulated. We note that $\beta$ in (5.3) should be an even number, for when the direction of B changes the Stokes parameters of the linear polarization should not change. It follows therefore that $\delta$ is an even number, $\gamma$ is odd, and $p_l$ can be expressed in the form

$$p_l \backsim |[\mathbf{sB}]|^2 \, |\nabla T \, \mathbf{l}|.$$

Reasoning analogously, we obtain

$$p_c \backsim (\mathbf{sB}\,(\nabla T\,\mathbf{l})).$$

since in this case $p_l \backsim B^2$ and $p_c \backsim B$, we can expect the order of magnitude estimate $p_l \lesssim |p_c|$.

*[sB] ≡ s × B.

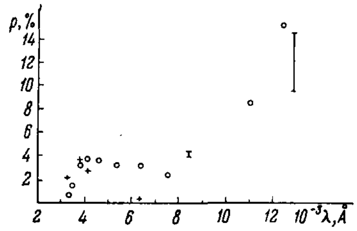


FIG. 4. Degree of circular polarization (O) and degree of linear polarization (+) vs the wavelength $\lambda$ of the white dwarf Grw + 70°8247 [21-23]. The two vertical bars are the doubled measurement errors in the optical and in the near-infrared regions.

5.3. We now examine the observed data[21-26]. The characteristic features of the polarization of optical radiation of white dwarfs are the following:

a) Approximately 10% of the white dwarfs have circular polarization. The value of $p_c$ depends strongly and non-monotonically on the wavelength $\lambda$.

b) For some white dwarfs, the degree of linear polarization also differs from zero, but $p_l \lesssim |p_c|$. The ratio $p_l/p_c$ changes less with changing $\lambda$ than the values of $p_l$ and $p_c$ separately (Fig. 4).

c) The value of $p_c$ of the white dwarf G195-19 in the range $\lambda$ = 3800—5400 Å varies periodically with time[26]:

$$p_c = p_{c0} + p_{c1}\sin\left[2\pi\left(\frac{t}{P} - \psi\right)\right], \quad p_{c0} = -0{,}224\%, \quad p_{c1} = 0.250\%. \qquad (5.4)$$

The period P is apparently equal to 1.339 d = 32 hours.

d) The maxima of $p_c$ for different wavelengths occur for G195-19 at earlier instants of time, i.e., the phase shift $\psi$ in (5.4) is a function of the wavelength.[2)]

The radiation considered in[20] was that of a gray body, or an aggregate of harmonic oscillators, in which the absorption of the radiation could be neglected (optically thin system); the distribution of the oscillators with respect to the natural frequencies is homogeneous, and the oscillators are in contact with the thermostat. It is shown in[20] that in the presence of a magnetic field B the gray-body radiation will have a circular polarization

$$p_c = \frac{\omega_B}{4\pi c}\lambda\cos\theta, \qquad (5.5)$$

where it is understood that $|p_c| \ll 1$. Planck's constant $\hbar$ does not enter in (5.5), and therefore formula (5.5) is valid only for an optically thin system. If the formula (5.5) is nevertheless applied to an optically thick photosphere of a white dwarf, then it follows from (5.5) that $B\cos\theta = 2\times 10^7$ G at $\lambda$ = 4000 Å and $p_c$ = 3.5%.

The observations of[21-26] are interpreted in[29] with allowance for radiation transport in a medium with $\nabla T \neq 0$. Allowance for radiation transport explains qualitatively the decrease of $|p_c|$ in the region $\lambda$ < 4000 Å (see Fig. 4), since the absorption coefficients increase sharply at $\lambda$ < 4000 Å because the radiation with $\lambda$ < 4000 Å can excite hydrogen atoms from the second level (the Balmer jump).

At the present time, the theory has not been sufficiently well developed to determine the cause of the observed circular polarization, quantum effects, or effects connected with lack of thermodynamic equilibrium. In our opinion, the properties (a) and (b) point to quantum effects. The circular polarization and its nonmonotonic dependence on the wavelength are probably due to the discreteness of the electron energy levels in a quantizing magnetic field. Substituting in (5.1)

$$T_\lambda = 8000\ ^\circ\text{K} \text{ and } p_c = 3.5\%,$$

we obtain the estimate

$$B\,|\cos\theta| = 2\cdot 10^6 \text{ G}. \qquad (5.6)$$

The role of quantum effects is discussed also in[30] in connection with the nonmonotonic dependence of $p_c$ on $\lambda$, where it is assumed that $\cos\theta \approx 1/5$ for the white dwarf Grw + 70°8247; in this case it follows from (5.6) that $B \approx 10^7$ G.

The periodic dependence of (5.4) on the time demonstrates almost unequivocally that G195-19 revolves with a period P = 1.339 d. The value of $p_c$ of revolving white dwarfs is time dependent if the field B is inclined to the angular-velocity vector (the inclined-rotator model). We note, however, that the period P = 1.399 d is very large in comparison with the value 3—300 sec obtained for white dwarfs on the basis of the angular-momentum conservation.

The dependence of the phase shift $\psi$ on $\lambda$ cannot be attributed (in analogy with pulsars) to the dispersion of the radiation in the medium. For light, unlike radio waves, the group-velocity difference $v_{gr}(\lambda_1) - v_{gr}(\lambda_2)$ is too small. A dependence of $\psi$ on $\lambda$ can occur in principle if the magnetic-field direction changes noticeably with further penetration into the photosphere of the white dwarf, for example as a result of twisting. In this case the maximum of $p_c$ for the radiation arriving from the interior of the photosphere will occur earlier than the maximum of $p_c$ for the radiation coming from the upper layers.

Circular polarization of the thermal radiation of samples[27] may be due to the difference between the reflection coefficients and transmission coefficients of waves with left-hand and right-hand polarizations on the interface between the sample and air. A simple theory[31], in which the transmission coefficients calculated for weak damping over the wavelength are used for the case of strong damping, gives a correct order of magnitude of $p_c$. The influence of reflection by the boundary on the circular polarization can lead to a difference between the values of $p_c$ for two identical samples, one of which is coated with some film.

5.4. It must be borne in mind that the theoretical (and experimental) investigations of circular polarization of thermal radiation have barely begun. Therefore all the statements made above (with the exception of the statements based on P and T invariance) require additional justification. In particular, the estimate (5.6) must be confirmed within the framework of a theory that explains quantitatively the dependences of $p_l$ and $p_c$ on $\lambda$.

Independently of the details of the future theory, however, the circular polarization of the thermal optical radiation of certain white dwarfs indicates quite definitely the presence of magnetic fields of intensity P = $10^6$ – $10^9$ G. The discovery of such fields is of great general physical interest.

[2)]It is impossible to identify definitely the wavelengths for which the maxima occur earlier or later.

## 6. PLANETS

6.1. The optical radiation of planets is the result of reflection of unpolarized solar radiation. Usually when unpolarized radiation is reflected it acquires a partial linear polarization; circular polarization arises only under special conditions (which will be discussed later on). Circular polarization of the optical radiation of the moon and of planets is therefore not a trivial effect. This polarization has the following characteristic features:

a) The direction of rotation is different for the northern and southern hemispheres of the moon[32] and of the planets[33] (polar effect).

b) There are indications that for each hemisphere the direction of rotation changes after the opposition of the planet[33] (the opposition effect). In opposition, i.e, when the sun, the earth, and the planets are on one straight line, the degree of circular polarization is $p_c = 0$. By way of an example, see the data for Jupiter (Fig. 5).

6.2. It is shown in[34] that both observed effects are the consequences of P and T invariance of the electromagnetic interaction. Indeed, let us consider the reflection of light by a certain region on the surface or in the atmosphere of a planet. Let the dimension of the region be much larger than the dimensions of the local inhomogeneities. Then there are only three vectors characterizing the reflection from the region as a whole: the normal n to the illuminated surface in the given region, and the ray vectors $\mathbf{s}_0 = \mathbf{k}_0/k_0$ and $\mathbf{s} = \mathbf{k}/k_0$ of the incident and reflected light, respectively.

The pseudoscalar quantity $p_c$ should be proportional to the *only pseudoscalar quantity* $[\mathbf{s}_0 \times \mathbf{n}] \cdot \mathbf{s}$ in the problem (the formation vector $\mathbf{F} \backsim \mathbf{s}_0 \times \mathbf{n}$). Therefore

$$p_c \backsim [\mathbf{s}_0 \mathbf{n}]\, \mathbf{s} = \sin\gamma \sin\varphi, \tag{6.1}$$

where $\gamma$ is the angle between n and the plane $(\mathbf{s}_0, \mathbf{s})$, and $\varphi$ is the angle between $\mathbf{s}_0$ and $-\mathbf{s}$; in the case of opposition, $\varphi = 0$. The odd dependence of $p_c$ on $\gamma$ and $\varphi$ describes the polar effect and the opposition effect, respectively.

The law (6.1) was derived under the assumption that the reflecting medium is nongyrotropic, i.e., invariant with respect to the operation P. This assumption can be violated if there are present on the planet crystals that have no symmetry centers, or helical molecules (see, for example,[35]). Gyrotropic media are, for example, many solutions of organic materials containing helical molecules, particular sugar solutions. The law (6.1) may be violated for a gyrotropic medium. It is probably just the presence of helical molecules which explains why in laboratory experiments[36] only the surfaces of green leaves gave a nonzero value of $p_c$ at $\gamma_0$ in reflected light, whereas $p_c = 0$ at $\gamma_0$ for all minerals, in accordance with (6.1).

Violation of the law (6.1) may be an indication that the reflecting medium has a gyrotropic character, and in particular, it may offer evidence favoring the existence of organic molecules on the planet or in its atmosphere[3)]. To avoid misunderstandings, we emphasize that the law (6.1) can be violated also in the case of reflection from a nongyrotropic medium on the planet, if $\gamma$ is taken to mean the latitude of the reflecting region on the planet relative to the visible equator, i.e., the angle between the average normal $\bar{\mathbf{n}}$ to the surface of the planet and the $(\mathbf{s}_0, \mathbf{s})$ plane. Indeed, if for example the planet has mountains that are illuminated by the sun from one side, then the normal n to the illuminated surface, contained in (6.1), does not coincide with $\bar{\mathbf{n}}$.

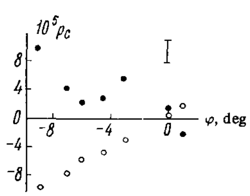


FIG. 5. Circular polarization of optical radiation of the northern (○) and southern (●) hemispheres of Jupiter as functions of the angle $\varphi$ between the direction from the sun to the planet and from the earth to the planet [33]. The vertical bar is double the average measurement error.

6.3. Unpolarized light from the sun cannot acquire circular polarization following a single reflection from a nongyrotropic medium. Circular polarization can probably be produced by double reflection from a nongyrotropic medium. After the first reflection, the unpolarized light acquires a partial linear polarization. After the second reflection, part of the linear polarization becomes circular if this reflection is either accompanied by absorption or occurs at an angle larger than the total internal reflection angle. It was suggested in[33] that the circular polarization of Jupiter will be relatively large in the near infrared region, since the absorption band of methane is situated in this region.

A quantitative interpretation of the observations of[32,33,36] should be based on the theory of multiple reflection of polarized light. Some aspects of this theory, which may be useful for the interpretation of the observations of[32,33,36], were recently considered in[37-41].

6.4 Circular polarization, by virtue of its sensitivity to different properties of the reflecting medium, can be a source of unique information concerning the planets or concerning organic tissue under terrestrial conditions. The presence of circular polarization should become the object of further investigations. In particular, it is necessary to organize new laboratory experiments (see[36]) and to measure exactly the polarization of the optical radiation of the sun.

## 7. OTHER OBJECTS

7.1. Pulsars. According to present-day ideas, stars with mass $M > 1.2M_\odot$ either collapse after burning up the nuclear fuel, or are transformed into neutron stars of radius $R_n = 10-100$ km $\approx 10^{-4} R_S$. If the angular momentum and the magnetic flux are conserved, the neutron star should have immediately upon contraction a period of revolution $P \approx 10^{-2}$ sec and a magnetic field up to $10^{12}$ G. The pulsating radio sources (pulsars) discovered in 1967 are in all probability neutron stars (for a review of the properties of pulsars see, for example[42,43]). The pulsed radiation of pulsars in the radio band is strongly polarized. The characteristic features of the polarization of most of the investigated pulsars are as follows[44-49]:

[3)]In this connection, it is interesting to note that the law (6.1) is violated for Mars in blue light [33]. It would be somewhat premature, however, to give on this basis an affirmative answer to the question "is there life on Mars?"

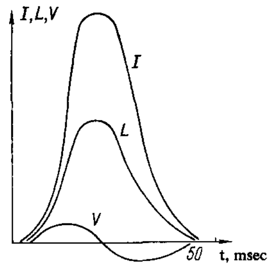


FIG. 6. Schematic dependence of the parameters I, $L = (Q^2 + U^2)^{1/2}$, and V on the time in the radio-emission pulses of certain pulsars.

a) The intensity of the linearly polarized radiation component varies during the course of the pulse in synchronism with the total intensity.

b) The circular polarization reverses sign during the pulse (Fig. 6).

c) The plots of L(t) and V(c) are practically independent of the frequency in the range $\nu$ = 610–240 MHz.

In the optical band, the degree of linear polarization of the pulsar NP0532, which is located in the Crab Nebula, reaches values $p_l = 23\%$[50,53]; the circular polarization of the pulsar is small, $|p_c| < 0.07\%$[54]. The circular polarization of the investigated sections of the Crab Nebula lies in the region $|p_c| < 0.05\%$[55].

At the present instant, there is no consistent theory of pulsar emission[4)]. Therefore the question of the interpretation of the polarization measurements remains open. It is clear only that the polarization is due to a magnetic field. We note, however, the similarity between the observed plots of L(t) and V(t) with the plots of L and V for the polarization of synchrotron radiation from a system of relativistic electrons having a $\delta$-function distribution with respect to the angle $\varphi$ (cf. Figs. 1 and 6). As applied to pulsars, the synchrotron radiation in the case of a $\delta$-like angular distribution is discussed in[56,57].

In[58], in connection with property (c) and also in connection with certain other observational data, it was suggested that the effects of radiation transfer, which depend very strongly on the frequency in the linear approximation, play a minor role in pulsars.

In view of the obvious analogy between pulsars and white dwarfs with strong magnetic fields, it would be of interest to investigate in detail the radio emission of the indicated white dwarfs (see[59]).

7.2. The x-ray source ScoX-1. The cosmic object located in the Scorpio constellation and designated ScoX-1 is a source of powerful x-rays, apparently thermal radiation of a plasma heated to a temperature $T \approx 10^{8}$°K. In visible light, ScoX-1 is a relatively weak star. According to[60], the emission of this star in the region $\lambda$ = 6400 Å has circular polarization. The characteristic features of the observed polarization are as follows:

a) The value of $p_c$ varies with time. The amplitude of its oscillations is on the average 1–1.5%; no dc component was observed in $p_c$.

b) The oscillations of $p_c$ apparently have no strict periodicity; the characteristic time of variation of $p_c$ is 2–4 hours.

4)In the author's opinion, we shall learn about the internal structure of pulsars long before we learn about their emission mechanisms.

The authors of[60] believe that the observed circular polarization is the result of radiation scattering in a magnetoactive plasma. The theory of this phenomenon is considered in[61,62]. According to[62], an average oscillation amplitude 1–1.5% corresponds to a magnetic field $B \approx 2 \times 10^6$ G. Such a value agrees well with the model according to which ScoX-1 consists of a neutron star with a field $B \approx 10^{12}$ G, surrounded by an optically thick shell of hot magnetoactive plasma. The oscillations of $p_c$ are related in[60] to the rotation of the neutron star and to the instabilities in the plasma shell, which "smear out" the periodicity of the rotation.

It must be stated that the relatively large error of one measurement, 1% at an average oscillation amplitude 1–1.5%, in conjunction with the absence of a dc component of $p_c$ and in the presence of many maxima in the periodogram (see[60]) make it necessary to approach the results of the observations of[60] with caution for the time being. In any case, however, the observations of[60] are of great interest and should stimulate further investigations of circular polarization of x-ray sources (see [64,68]).

7.3. Diffuse nebulae. Observation of circular polarization of optical radiation of certain sections in the diffuse nebulae 30-Doradus and $\eta$-Carinae were reported in[65]. For 30-Doradus $p_c$ reaches a value $-0.39 \pm 0.13\%$, and for $\eta$-Carinae $p_c$ is comparable with the observation errors.

In the opinion of the authors of[65], the observed circular polarization is probably produced when the light of the surrounding stars is scattered by dust particles contained in the nebulae. In this case one can expect the circular polarization of planets and of diffuse nebulae to have certain common features.

## 8. CONCLUSIONS

The theoretical work and questions connected with circular polarization has so far been patently insufficient to interpret the experimental data. We hope that this gap will be filled in the nearest future, and we shall be able to obtain information on cosmic objects via a new important channel. In view of the incompleteness of the theory, the author has strived to begin the discussion of the experimental results with the P and T invariance principles, which are not subject to any doubt. The future theory, of course, should be more specific.[5)]

5)The review is based on work published through 1971. We mention, in addition, new papers published through May 1972, devoted to circular polarization of radio sources [66], white dwarfs [59,67], and different peculiar objects [64].

1 A. I. Akhiezer and V. B. Berestetskiĭ, Kvantovaya élektrodinamika (Quantum Electrodynamics), 3rd ed., Nauka, 1969 [Interscience]; L. D. Landau and E. M. Lifshitz, Teoriya Polya (Classical Theory of Fields), Nauka, 1967 [Addison-Wesley].

2 M. M. Komesaroff, F. F. Gardner, D. Morris, J. A. Roberts, and J. B. Whiteoak, Nature 218, 73 (1968).

3 F. Biraud and P. Veron, Nature 219, 254 (1968).

[4]G. A. Seielstad, Astron. and Astrophys. 2, 372 (1969).
[5]G. L. Berge and G. A. Seielstad, Astrophys. J. 157, 35 (1969).
[6]F. Biraud, Astron. and Astrophys. 1, 156 (1969).
[7]E. R. Seaquist, Astrophys. Lett. 5, 111 (1970).
[8]J. A. Gilbert and R. G. Conway, Nature 227, 585 (1970).
[9]R. G. Conway, J. A. Gilbert, E. Raimond, and K. W. Weiler, Mon. Not. RAS 152, 4P (1971).
[10]E. R. Seaquist, Nature (Phys. Sci.) 231, 93 (1971).
[11]V. L. Ginzburg and S. I. Syrovatskiĭ, Usp. Fiz. Nauk 87, 85 (1965) [Ann. Rev. Astron. and Astrophys. 3, 297 (1965)].
[12]D. W. Sciama and M. J. Rees, Nature 216, 147 (1967).
[13]M. P. C. Legg and K. C. Westfold, Astrophys. J. 154, 449 (1968).
[14]V. N. Sazonov, Astron zh. 46, 502 (1969) [Sov. Astron. AJ 13, 396 (1969)].
[15]D. B. Melrose, Astrophys. Lett. 8, 227 (1971).
[16]A. G. Pacholezyk and T. L. Swihart, Mon. Not. RAS 153, 3P (1971).
[17]D. B. Melrose, Astrophys. Space Sci. 12, 171 (1971).
[18]V. N. Sazonov, Astrophys. Space Sci. 18, (1972).
[19]V. B. Kadomtsev, Zh. Eksp. Teor. Fiz. 58, 1765 (1970) [Sov. Phys.-JETP 31, 945 (1970)].
[20]J. C. Kemp, Astrophys. J. 162, 169 (1970).
[21]J. C. Kemp, J. B. Swedlung, J. D. Landstreet, and J. R. P. Angel, ibid. 161, L77.
[22]J. R. P. Angel and J. D. Landstreet, Astrophys. J. 162, L61 (1970).
[23]J. C. Kemp and J. B. Swedlung, ibid., 164, L15; 165, L71.
[24]J. C. Kemp, J. B. Swedlung, and R. D. Wolstencraft, Astrophys. J. 164, L17 (1971).
[25]J. D. Landstreet and J. R. P. Angel, ibid 165, L67 (1971).
[26]J. R. P. Angel and J. D. Landstreet, ibid., 164, L15; 165, L71.
[27]J. C. Kemp, J. B. Swedlung, and B. D. Evans, Phys. Rev. Lett. 24, 1211 (1970).
[28]V. G. Levich, Yu. A. Vdovin, and V. A. Myamlin, Kurs teoreticheskoĭ fiziki (Course of Theoretical Physics), Vol. 2, Fizmatgiz, 1962.
[29]H. L. Shipman, Astrophys. J. 167, 165 (1971).
[30]J. C. Kemp, ibid 162, L69 (1970).
[31]V. V. Chernomordik, Course thesis, Moscow Physicotech. Inst., 1971.
[32]Yu. N. Lipskiĭ and M. M. Pospergilis, Astron. zh. 44, 410 (1967) [Sov. Astron. AJ 11, 324 (1967)].
[33]J. C. Kemp, R. D. Wolstencroft and J. B. Swedlund, Nature 232, 165 (1971).
[34]V. N. Sazonov, Astron. zh. 49, 833 (1972) [Sov. Astron.-AJ 16, 678 (1973)].
[35]V. M. Agranovich and V. L. Ginzburg, Kristalloptika s uchetom prostranstvennoi dispersii i teoriya eksitonov (Spatial Dispersion in Crystal Optics and the Theory of Excitons), Nauka, 1965 [Interscience, 1966].
[36]M. M. Pospergilis, Astron. zh. 45, 1229 (1968) [Sov. Astron. AJ 12, 973 (1969)].
[37]A. Z. Dolginov, Yu. N. Gnedin, and N. A. Silant'ev, J. Quant. Spectr. Rad. Trans. 10, 707 (1970).
[38]F. K. Lamb and D. ter Haar, Oxford Preprint No. 38, 1970.
[39]J. W. Hovenier, Astron. and Astrophys. 7, 86 (1970); 13, 7 (1971).
[40]V. M. Loskutov, Astron. zh. 48, 166, 1046 (1971) [Sov. Astron. AJ 15, 129 (1972), 828 (1972)].
[41]A. V. Morozhenko and E. G. Yanovitskii, ibid. 48, 172 (1971) [15, 134 (1971)].
[42]V. L. Ginzburg, Usp. Fiz. Nauk 103, 393 (1971) [Sov. Phys.-Usp. 13, 83 (1971)], V. L. Ginzburg, V. V. Zheleznyakov, and V. V. Zaitsev, ibid. 98, 201 (1969) [12, 378 (1969)]; V. V. Zheleznyakov, Izv. vuzov (Radiofizika) 13, 1842 (1970).
[43]D. ter Haar, Oxford Preprint No. 32, 1971; Phys. Rept. 3C, No. 2 (1972).
[44]R. R. Clark and F. G. Smith, Nature 221, 724 (1969).
[45]R. D. Ekers and A. T. Mofett, Astrophys. J. 158, L1 (1969).
[46]M. M. Komesaroff, D. Morris, and D. J. Cooke, Astrophys. Lett. 5, 37 (1970).
[47]D. Morris, U. J. Schwarz, and D. J. Cooke, Astrophys Lett. 5, 181 (1970).
[48]R. N. Manchester, Nature 228, 264 (1970).
[49]D. A. Graham, Nature 229, 326 (1971).
[50]B. Warner, R. E. Nather, and M. MacFarlane, Nature 222, 233 (1969).
[51]K. C. Freeman, A. W. Rodgers, P. T. Rydge, and G. Lynga, Nature 222, 459 (1969).
[52]W. J. Cocke, M. J. Disney, and T. Gehrels, Nature 223, 576 (1969).
[53]N. M. Shakhovskiĭ, Yu. S. Efimov, and V. I. Pronik, Usp. Fiz. Nauk 99, 520 (1969) [Sov. Phys.-Usp. 12, 804 (1970)].
[54]W. J. Cocke, G. W. Muncaster, and T. Gehrels, Astrophys. J. 169, L119 (1971).
[55]J. D. Landstreet and J. R. P. Angel, Nature 230, 103 (1971).
[56]T. Takakura, Nature 224, 252 (1969).
[57]V. N. Sazonov, Astron. zh. 49, 1197 (1972) [Sov. Astron-AJ 16, 971 (1973)].
[58]F. G. Smith, Mon. Not. RAS 149, 1 (1970); 154, 5P (1971); M. M. Komesaroff, J. G. Ables, and P. A. Hamilton, Astrophys. Lett. 9, 101 (1971).
[59]V. A. Hughes, P. A. Feldman, and A. Woodsworth, Astrophys. J. 170, L125 (1971).
[60]Yu. N. Gnedin and O. S. Shulov, ZhETF Pis. Red. 14, 507 (1971) [JETP Lett. 14, 348 (1971)].
[61]V. Canuto, J. Lodenquai, and M. Ruderman, Phys. Rev. D3, 2303 (1971).
[62]Yu. N. Gnedin, A. Z. Dolginov, and N. A. Silant'ev, Zh. Eksp. Teor. Fiz. 59, 865 (1970) [Sov. Phys.-JETP 32, 472 (1971)].
[63]B. Coppi and A. Treves, Astrophys. J. 167, L9 (1971).
[64]Yu. N. Gnedin and O. S. Shulov, Astrofizika 7, 529 (1971); N. S. Nikulin, V. M. Kuvshinov, and A. B. Severny, Astrophys. J. 170, L53 (1971); T. Gehrels, Astrophys. J. 173, L23 (1972); B. Band,and J. Tinbergen, Nature 237, 29 (1972); J. C. Kemp, R. D. Wolstencroft, and J. B. Swedlung, Astrophys. J. 173, L113 (1972).
[65]T. H. Schmidt, Astron. and Astrophys. 12, 456 (1971).

[66]E. R. Seaquist, Astrophys. Space. Sci. 15, 284 (1972); J. A. Roberts, J. C. Ribes, J. D. Curray, and D. J. Cooke, Nature (Phys. Sci.) 236, 3 (1972); A. G. Pacholczyk and T. L. Swihart, Astrophys. J. 170, 405 (1971).
[67]J. R. P. Angel, J. D. Landstreet, and F. B. Oke, Astrophys. J. 171, L11 (1972).
[68]E. G. Mychelkin, Tr. Astrofiz. in-ta AN Kaz. SSR 14, 97 (1969).

Translated by J. G. Adashko