D. G. Lominadze, G. Z. Machabeli, A. B. Mikhaĭlovskiĭ, Yu. P. Ochelkov, and V. V. Usov. *The nature of the high-frequency radiation of pulsars, and the activity of supernova remnants.* Derivation of a self-consistent quantitative theory of pulsars and of the activity of the supernova remnants surrounding them (if they exist) would be impossible without a detailed analysis of the physical processes that take place in the magnetospheres of the pulsars. As in any other physical problem, boundary conditions must be defined in the theory of pulsar magnetospheres, i.e., it is necessary to answer the question as to the surface properties of pulsars. Existing observational data on pulsar surface temperatures,[1] as well as theoretical calculations of the cooling of neutron stars[2] and analysis of the properties of matter in the ultrastrong ($B \sim 10^{12}-10^{13}$ G) magnetic fields[3-5] that are typical for pulsars, indicate that the surfaces of pulsars are relatively cold and solid. In this case, the primary particles flowing out from the surface of the neutron star weakly screen the electric-field component $E_\parallel$ along the magnetic field. In a strong electric field, $E_\parallel \sim 10^8-10^9$ cgs esu, the primary particles are accelerated to ultrarelativistic energies ($\sim 10^8 mc^2$) and, moving along the curved magnetic force lines, emit γ-quanta with an average energy $\overline{\mathscr{E}}_\gamma \sim 10^{12}-10^{13}$ eV. In the pulsar magnetic field, of $B \sim 10^{12}-10^{13}$ G, these γ-quanta are absorbed with formation of electron-positron pairs. The produced particles have a nonzero pitch angle, so that the secondary particles that are produced generate synchrotron radiation, which can also be absorbed with formation of electron-positron pairs.[7] A multicomponent electron-positron plasma is formed as a result of this avalanche process. The majority of the produced particles constitute a low-energy component, which we shall refer to below simply as plasma and which moves away from the surface of the pulsar at a velocity corresponding to the Lorenz factor $\gamma_p \simeq 10^2-10^3$. The high-energy component of the produced plasma, the beam, has a Lorenz factor $\gamma_B \approx 10^6-10^7$. The expected plasma and beam densities[7] in the case of the pulsar PSR 0531+21, which will be of greatest interest to us below, are $n_{p_0} \simeq 10^{20}$ cm^{-3} and $n_{B_0} \simeq 10^{17}$ cm^{-3}, respectively. In the strong magnetic field of the pulsar, the produced particles quickly lose the momentum component transverse to the magnetic field as a result of synchrotron losses, and their distribution becomes one-dimensional. To construct a theory of the radiation of pulsars, therefore, it is necessary to investigate in detail the properties of a one-dimensional ultrarelativistic electron-positron plasma. Below we report results that we have obtained in this area.

According to Ref. 8, an ultrarelativistic beam results in Cherenkov buildup of longitudinal oscillations of a relativistic plasma. As a result of quasilinear relaxation, the beam-particle distribution function becomes flat-topped ($\partial f_B/\partial p_z \leq 0$, where p_z is the momentum component of the particle along **B**), and the subsequent behavior of the plasma-magnetic field-beam system must be treated with this distribution function. The energy density of the longitudinal oscillations that arise in two-stream instability is approximately equal to half of the beam energy.[8] Most of the energy of

Langmuir turbulence is absorbed as a result of nonlinear scattering by plasma particles[9] (the plasma is heated). Only a small fraction of the original energy of the oscillations goes over into longwave Langmuir oscillations (the condensate). Near the surface of a pulsar and in the linear approximation, there are no instabilities in the outflowing ultrarelativistic electron-positron plasma other than the two-stream instability associated with the generation of Langmuir waves.[10]

As the outflowing plasma increases its distance from the surface of the pulsar, the magnetic field intensity decreases and other instabilities become possible. The stability of the outflowing plasma depends strongly on the ratio ω_p/ω_B, where $\omega_p = \sqrt{4\pi n_p e^2/m}$, $\omega_B = eB/mc$. Near the surface of a pulsar, this ratio is $\ll 1$, and it increases with increasing distance r from the pulsar: $\omega_p/\omega_B \sim r^{3/2}$. When $(\omega_p/\omega_B)^2 \geqslant \gamma_p^2/\gamma_B$, the outflowing plasma-beam system becomes unstable with respect to buildup of cyclotron waves.[11] The energy and pitch-angle distributions of the beam particles that are established as a result of the development of cyclotron instability in an inhomogeneous ultrarelativistic electron-positron plasma have been determined.[1,12] As the plasma moves farther away from the pulsar and the condition $\omega_p/\omega_B = 1$ is satisfied, a relativistic kink instability similar to that found earlier[13,14] for a nonrelativistic plasma sets in. It is not yet clear how this instability would subsequently develop in pulsar magnetospheres.

To construct a theory of the high-frequency radiation of pulsars, it will also be necessary to investigate further the mechanisms by which it is generated. One of the most probable and thoroughly studied mechanisms of generation of high-frequency radiation by pulsars is that of synchrotron radiation.[15-17] However, estimates show that a significant, and in some cases even decisive, contribution to high-frequency pulsar radiation may come from curvature radiation, inverse Compton scattering, and the decay and merging of Langmuir waves. These generation mechanisms were discussed in Refs. 19-21 taking into account the specific nature of pulsars.

Most thoroughly studied among the several hundred pulsars that are now known is PSR 0531+21, which is situated within the Crab Nebula. Its radiation has been registered over practically the entire range of frequencies accessible to observation (from $\sim 3\cdot 10^7$ Hz to $\sim 10^{27}$ Hz). Since PSR 0531+21 is surrounded by the strong magnetic field of the Crab Nebula, the flux and spectrum of ultrarelativistic electrons and positrons escaping from this pulsar have been determined from an analysis of the nebula's continuous radiation, which is of synchrotron nature.[22] A model of the high-frequency radiation of PSR 0531+21 and the Crab Nebula has been constructed[1,12] on the basis of the above studies of the properties of the ultrarelativistic electron-positron plasma and of the radiation-generating mechanisms. In this model, cyclotron instability sets in near the light cylinder of PSR 0531+21. The particle pitch-angle and energy distributions established as a result of the development of this instability were determined. It was shown that synchrotron radiation of beam particles can explain the x-ray and γ-emission of PSR 0531+21. Scattering of cyclotron perturbations by plasma particles leads to the latter acquiring nonzero pitch angles. The resulting synchrotron radiation falls in the optical band and has a luminosity equal to the observed luminosity of PSR 0531+21 in this region of the spectrum. Like Langmuir oscillations[23,24], the cyclotron waves that fall in the radio band can form solitons that carry the energy of these waves out beyond the magnetosphere of the pulsar. The energy flux of the cyclotron waves from PSR 0531+21 is sufficient to explain its radio luminosity. The spectrum of the ultrarelativistic electron-positron pairs escaping from the magnetosphere of PSR 0531+21 into the Crab Nebula was calculated. It was shown that the expected synchrotron-radiation spectrum of these particles in the nebula agrees closely with the observed spectrum in the optical and x-ray bands. This quantitative model is fully consistent with the qualitative scenario proposed earlier by I. S. Shklovskiĭ[25] for the processes in the magnetosphere of PSR 0531+21 from analysis of observations of the emission of the Crab Nebula and the pulsar within it. The model predicts a quite observable excess of infrared ($\nu \sim 10^{13}$ Hz) radiation of PSR 0531+21 that appears near the pulsar's light cylinder on merging of plasma waves ($l + l \to t$).[21] Detection of this excess would strongly confirm the validity of the proposed model.

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