INSTABILITIES IN THE MAGNETOSPHERE
OF MILLISECOND PULSARS

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A model explaining some observational properties of millisecond pulsars is presented in the framework of the general plasma model for pulsar emission developed by Al. Kazbegi, G. Machabeli, and G. Melikidze in a series of papers. In the region of the open magnetic field lines of the pulsar magnetosphere the existence of a relativistic electron-positron plasma penetrated by a primary particle beam is assumed. Wave excitation due to different plasma instabilities is considered. The main properties of pulsar radiation (e.g., existence of "core" and "cone" types of emission, circular polarization, subpulse drift phenomena, pulse nullings, and mode changing) are explained in the most natural way by this model. The observations show that despite the big difference between the physical parameters of the "typical" and millisecond pulsars their observed properties (pulse profiles, polarization, existence of two different modes in emission, frequency evolution, etc.) are more or less similar and the physical mechanisms of their radiation do not differ fundamentally from each other. Some particular millisecond pulsars are considered based on the model presented, and predictions are made.

1. INTRODUCTION

The discovery of the 1.558 ms pulsar PSR B1937+21 by Backer et al. in 1982 [1] heralded a new and exciting era in pulsar physics. Since then discoveries of other millisecond pulsars (hereafter MSPs) have followed, and there are about 53 pulsars with periods less than 25 ms known today [2]. Pulsars of this class possess not only very short rotation periods but also much smaller period derivatives (~ 10^{-19} - 10^{-20}), indicative of surface magnetic field strengths three or four orders of magnitude below those of their "normal" cousins; their apparent ages exceed 10^9 years, which is comparable to the age of the Universe. These objects occupy a distinct region in the lower left part of the P - \dot{P} diagram [3] and therefore form a separate population of pulsars, differing substantially from the other two: i) the most numerous population of "ordinary" pulsars (intermediate periods and spin-down rates), and ii) a small number of very young pulsars associated with supernova remnants (relatively short periods and great spin-down rates, such as Crab and Vela pulsars). There is evidence that, compared to "normal" pulsars, a high proportion of MSPs are members of binary systems. This fact apparently relates them to the small number of long-period binary pulsars. These two populations of neutron stars can be combined into one class of "recycled" pulsars with special evolutionary path. In most scenarios, these objects are assumed to be the end products of the evolution of low-mass X-ray binaries (LMXB): a neutron star with weak magnetic field is spun up to a millisecond period during an accretion phase ([4,5]).

An important event in the field of pulsar observations was the detection of high-frequency emission from MSPs. Pulsed X-ray radiation was observed by ROSAT in the band of 0.1 - 2.4 keV for six MSPs [6]. Intensive searches of the \gamma-ray emission from MSPs are performed by EGRET [7].

2. PLASMA MODEL FOR PULSAR EMISSION

There are many difficulties involved in the development of a successful self-consistent theory for pulsar radiation. Its high brightness temperature implies that the emission process must be coherent. There are...
two general forms of coherent radiation: the antenna (which is emission by bunches) and maser mechanisms. Some early sufficiently well-grounded models (e.g., [8, 9]) favored the antenna mechanism, but before about 1980 it was realized that there are strong physical arguments [10] that emission by bunches is not viable, and the first detailed analysis suggested that the seemingly plausible alternative of the maser mechanism is impossible. The model for pulsar emission developed by Al. Kazbegi, G. Machabeli, and G. Melikidze (hereafter KMM, see [11-18]) in the series of papers is just one example of the maser mechanism. We will try below to explain the extraordinary properties of MSPs in the framework of this model. We briefly review here the main principles of the plasma model.

As in most of the models we assume that the pulsar magnetosphere is filled by a dense relativistic electron-positron plasma flowing along the open magnetic field lines, which is generated as a consequence of the avalanche process first described by Goldreich and Julian in 1969 [19] (see also [20]). This plasma is multicomponent, with a one-dimensional distribution function [21], containing: i) electrons and positrons of the bulk of the plasma with a mean Lorentz factor of \( \gamma_p \) and density \( n_p \); ii) particles of the high-energy "tail" of the distribution function with \( \gamma_t \) and \( n_t \), stretched in the direction of positive momenta; iii) the ultrarelativistic \((\gamma_b \approx 10^6)\) primary beam with the so-called "Goldreich–Julian" density \( n_b \approx 7 \cdot 10^{-2} B_0 P^{-1} \text{ cm}^{-3} \) (where \( P \) is the pulsar period and \( B_0 \) is the magnetic field at the stellar surface). Estimation of the parameters of these components can be performed by the following argumentation.

The loss of pulsar rotational kinetic energy is

\[
W_k = 4\pi^2 I \dot{P} / P^3, \tag{1}
\]

which is distributed between the acceleration of particles to ultrarelativistic velocities, on the one hand, and generation of the large-amplitude magnetic dipole radiation, on the other (the losses on radio or shortwave emission are negligibly small in comparison with these two). We introduce here the factor \( \varepsilon \) which designates the part of spin-down energy falling on the beam of particles. Thus the flux of "particles" energy through the light cylinder \( R_L = cP/2\pi \), where \( c \) is speed of light, is as follows:

\[
S_p \gamma_b^{\text{max}} n_b m c^3 \approx \varepsilon W_k, \tag{2}
\]

where \( S_p = \pi R_p^2 \) is the area of the polar cap with \( R_p \approx R_0 (2\pi R_0/cP)^{1/2} \), \( R_0 \approx 10^6 \) cm is the neutron star radius, \( m \) is mass of electron, and \( \gamma_b^{\text{max}} \) is the maximum possible Lorentz factor that could be reached by the particles of the primary beam without taking into account the radiation recoil, which actually reduces \( \gamma_b \) to values of in the vicinity of \( 10^8 \). Assuming that \( \gamma_p \approx 3 \) and \( \gamma_t \approx 10^4 \), and

\[
n_p \gamma_p \approx n_t \gamma_t \approx \frac{1}{4} \gamma_b^{\text{max}} n_b, \tag{3}
\]

one obtains for the densities of the plasma and the "tail," respectively:

\[
n_p = \frac{I\varepsilon}{2mc^2 R_0^3 \gamma_p} \dot{P} P^{-2} \approx 2.9 \cdot 10^{38} \varepsilon \dot{P} P^{-2},
\]

\[
n_t = \frac{I\varepsilon}{2mc^2 R_0^3 \gamma_t} \dot{P} P^{-2} \approx 8.6 \cdot 10^{28} \varepsilon \dot{P} P^{-2}, \tag{4}
\]

where \( n_p \) and \( n_t \) are in \( \text{cm}^{-3} \).

As for a pulsar magnetic field, most probably near the stellar surface it has a complicated structure differing greatly from a dipole, though at sufficiently large distances it can be roughly considered as dipolar up to the light cylinder, and toroidal beyond it:

\[
B \approx \begin{cases} B_0 (R_0/R)^3, & \text{if } R < R_L; \\ B_L (R_L/R), & \text{if } R \geq R_L. \end{cases} \tag{5}
\]