Part VI

Polar cap theories

Thursday morning. Session Chair: Dan Stinebring

- What physical processes operate in the polar cap region?
    - ⋆ Polar cap theories
        - ∗ Exposition of new and existing polar cap emission models, with particular emphasis on areas of agreement and disagreement.
        - ∗ Physical considerations relating to the composition and temperature of the polar cap region: "sparks"; emission of ions; "mining" and surface depletion.

The Thursday morning session was started by a review paper on the theories of pulsar emission by A. V. Gurevich. The paper was not submitted for inclusion in the Proceedings.

https://doi.org/10.1017/S0002731600155210 Published online by Cambridge University Press

NONSTATIONARY PROCESSES IN THE PULSAR MAGNETOSPHERE

A. V. GUREVICH AND YU. N. ISTOMIN
P. N. Lebedev Physical Institute

Abstract

We investigate several instabilities which give different characteristic times for nonstationary processes. Several instabilities are connected with the mechanism of plasma generation in the polar cap gap region. Another nonstationary process is due to the nonlinear phenomenon arising in the magnetosphere during the propagation of the flux of electromagnetic radiation.

Each pulsar has a stable mean profile of radio emission. But the mean profile is the result of averaging over many pulses (several hundreds or thousands). The pulsar is a good working machine on a large time scale. On small scales the radiation is very unstable. Figure 1 shows an example of a set of individual pulses.

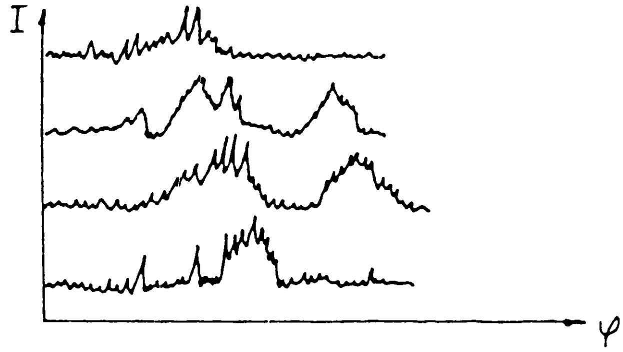

Figure 1 A schematic drawing of the intensity *vs.* pulse phase of a sequence of individual pulses.

We see that the positions and intensities of pulses within the observed window are irregular. Each pulse consists of a few subpulses, which have durations of several milliseconds, and they correlate well between different frequency bands. Just as each individual pulse of radiation is composed of individual subpulses, the subpulse itself consists of micropulses. Examples of highly resolved subpulses are given in figure 2. The characteristic time for microstructure is the microsecond. The character of pulsar radio emission is well understood in terms of the amplitude-modulated noise model, according to which the time structure of the pulse can be described by the expression

$$I_\nu(t) = a(t)\, n(t),$$

where $n(t)$ is the noise process, and $a(t)$ is the envelope. The quantity $a(t)$ can be described by deterministic chaos processes with a few independent parameters.

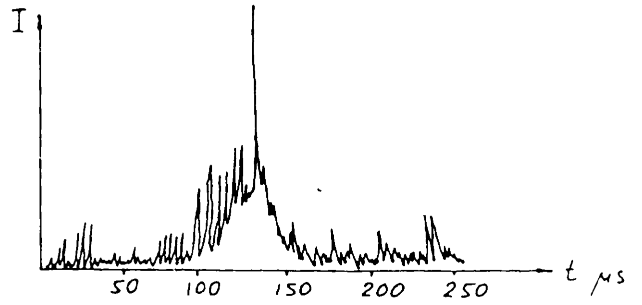

Figure 2 A shematic sketch of the intensity *vs.* time of a highly resolved pulse.

Apart from the variations on short time scales, there also exist large scale processes which operate on time scales longer than the pulsar period P. A primary class of such processes is mode switching. Mode switching is characterized by distinct variations in the shape of the mean profile of a pulsar. The switching takes place simultaneously at all frequencies. It is difficult to determine the precise transition point from one mode to another, but it is estimated to be several periods. We now know 11 mode-switching pulsars.

A second class is pulse nulling. Nulling is the sudden absence of any radiation. The duration of these "silences" is of the order of several tens of periods. Remarkably, after nulling subpulses often appear at their expected phases.

This picture of radio pulsar phenomena suggests that the processes of emission are mainly stable but some instabilities also are involved which result in nonstationarity. First we discuss the processes of plasma generation in the polar region of the pulsar magnetosphere. If the longitudinal electric current j is not equal to the Goldriech-Julian value $j_G = -\boldsymbol{\Omega} \times \boldsymbol{B}/2\pi$ then plasma generation occurs in the polar gap. The radius of the gap R_0 is significantly less than the neutron-star radius R

$$R_0 \approx R\left(\frac{\Omega R}{c}\right)^{1/2}.$$

The height of the gap H is determined by the level

https://doi.org/10.1017/S0002731600155210 Published online by Cambridge University Press

on which the longitudinal electric field becomes zero, $H < R_0$. The process of electron-positron plasma generation is characterized by three coefficients of reproduction K_m, K_1 and K (Gurevich and Istomin 1985b).

The first one, K_m, is the number of particles produced and reflected by the electric field at the top of the gap per fast particle having the opposite value of charge. K_1 is the same as K_m, only at the bottom of the gap. The coefficient K is the number of γ-quanta emitted by the stellar surface due to the penetration of each energetic particle into the iron core.

The condition for the stable generation of the plasma

$$K_m(K_1 + K) = 1$$

gives the value of the potential drop Ψ as a function of K, Ψ_K. According to Bogovalov and Kotov (1988), the dependence of K on the stellar surface temperature T has a strong variation at the value T^*—the temperature at which the cross-section of neutron capture by the iron becomes resonant. At $T \sim 10^6$ K the function $K(T)$ has an oscillatory behavior.

The stellar surface temperature in the polar cap region is determined by the competition between heating by the reverse electric current and cooling by black body radiation. If W_H is the heating power and W_T the cooling then

$$W_H = \frac{1}{1+K}\int j\Psi\, ds; \quad W_T = \sigma T^4 S.$$

Equating W_H we get the stationary value of the stellar surface temperature T

$$T = 230000\left(\frac{B_{12}\cos\chi}{P(1+K)}\right)^{1/4}\left[\int_0^1 \varphi_7 i\, df'\right]^{1/4}.$$

For definite neutron-star parameters, the value of the temperature can be near T^*. In this case there are three solutions $T_1 < T_2 < T_3$. The root T_2 is unstable, and if the temperature fluctuations δT are greater than the value $\Delta T = T_2 - T_1$, it is possible to pass from the one stable state T_1 to the other T_3. In order to describe this process we must solve the problem of heat diffusion into the iron core of the neutron star. The solution of the diffusion equation

$$\frac{\partial T_i}{\partial t} - \frac{\kappa}{c_v}\frac{\partial^2 T_i}{\partial h^2} = 0$$

with the boundary condition

$$\kappa\frac{\partial T_i}{\partial h}\bigg|_{h=0} = \frac{1}{1+K}j\Psi - \sigma T^4, \quad T = T_i(h=0)$$

defines the temperature of the star in the polar-cap region

$$T - T_0 = (\pi\kappa c_v)^{-1/2} \times\int_0^t \frac{d\tau}{(t-\tau)^{1/2}}\left[\frac{j\Psi}{1+K[T(\tau)]} - \sigma T^4(\tau)\right].$$

Here κ is the heat conductivity, c_v is the heat capacity, and T_0 is the internal temperature of the star. The above integral equation gives an estimate of the time for the transition from T_1 to T_3

$$t \approx \frac{\pi\kappa c_v}{16\sigma^2 T^2(\Delta T)^4} \approx 5\times 10^3(\rho/10^6\text{g/cm}^3)^{7/3}T_0^{-2}\Delta T_5^{-4}\text{sec.} \quad (1)$$

The time interval given by eq.(1) corresponds to the observed time of mode switching. Apart from this, nulling of the pulsar is also possible. This is connected with the circumstance that the potential drop Ψ cannot exceed its maximum value $\Psi_{max} = \pi R_0^2 \rho_G$. Because Ψ is a decreasing function of K, plasma generation stops when K is less than some minimum value $K_{min}(K < K_{min})$. If $K(T_3) < K_{min}$ then the state $T = T_3$ is not realized. So the transition to the region $T > T_2$ could be connected with nulling. The return time to the state $T = T_1$ is again of the order of the time given by eq.(1).

Because the height of the gap H is less than its radius R_0, it is advantageous to divide the entire electron-positron plasma-generation region into quasi-stationary subregions in the polar-cap plane, which act independently or are very weakly interacting. The size of such subregions is of the order of H. These subregions move across the magnetic field both because of general plasma drift in pulsar magnetosphere and because of the action of their own electric polarization. Such motion is characterized by the time scale $\tau \sim H/\Omega R_0 \sim P$.

Nonstationary processes can also be associated with transverse ionization motion in the region of plasma generation. The phenomenon depends on the straight-line propagation of the γ-quanta. The shift δ of the emission region in a radial direction during the time the charged particles take to travel a distance H is equal to $\delta = H^2/16\rho$, where ρ is the curvature radius. This motion has a characteristic time $\tau \approx 16\rho R_0/Hc \approx 10^{-2}$ sec.

Longitudinal waves propagating along the magnetic-field direction at a velocity close to c may also exist. Fluctuations of the electron and positron densities δ_n^-, δ_n^+ alter the potential drop $\delta\Psi$ and thus change the coefficients δK_1, δK_m and δK. Positive feedback then produces unstable oscillations of the double layer. The system of equations which

https://doi.org/10.1017/S0002731600155210 Published online by Cambridge University Press

describes this process is as follows:

$$\begin{aligned}
\frac{\partial n^+}{\partial t} + v\frac{\partial n^+}{\partial h} &= v(K_1 + K)n^-(t, h, z+\delta)\delta(h);\\
\frac{\partial n^-}{\partial t} - v\frac{\partial n^-}{\partial h} &= vK_m n^+(t, h, z+\delta)\delta(h-H);\\
\frac{1}{c^2}\frac{\partial^2\Psi}{\partial t^2} - \Delta\Psi &= 4\pi e(n^+ - n^-);\\
v &= c\left(1 - \frac{1}{\gamma^2}\right).
\end{aligned}$$

The spectrum of oscillations is the same as that of the quantum oscillator

$$\omega = \frac{2\pi c}{H}\left(l + \frac{1}{2}\right); \qquad l = 0, 1, 2, ...$$

The increment of the instability is maximum for homogeneous oscillations ($K_\perp = 0$) and equal to

$$\Gamma = \frac{c}{H}\ln\frac{1}{K_m} > 0.$$

We believe that these oscillations are basic to the noise structure of pulsar radio emission.

The last instability which we discuss here is the modulation instability of large amplitude plasma-curvature waves in the pulsar magnetosphere. These waves are responsible for the observed radio emission (Beskin, Gurevich, and Istomin 1988c). The ponderomotive action of these waves perturbs the density and momentum of the plasma

$$\frac{\partial n}{n_0} = \frac{e^2}{m^2\gamma^4\tilde{\omega}^2c^2}\left[\frac{3}{3} + \frac{1}{4}\gamma^{-2} - \frac{1}{2}\frac{\omega}{\tilde{\omega}\gamma^2}\right]|E|^2;$$

$$\frac{\partial p_2}{mv_2\gamma^3} - \frac{1}{4}\frac{e^2}{m^2\gamma^6\tilde{\omega}^2c^2}|E|^2; \qquad (2)$$

$$\tilde{\omega} = \omega - cK_2.$$

The increment of the modulation instability is large

$$Im\omega = 0.4\omega^{-1/15}\omega_p^{13/15}\left(\frac{c}{\rho}\right)^{1/5}\gamma^{-1/2} \approx 10^4\,\text{sec}^{-1}.$$

So we see that the various instabilities discussed above produce variations on time scales similar to those observed in pulsar radio emission.

Editor's note: We suspect that eq.(2) has been corrupted in the preparation of the Proceedings. We regret that we have been unable to make the proper corrections.

https://doi.org/10.1017/S0002731600155210 Published online by Cambridge University Press