Pulsar Glitch vs Pulsar Nulling

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Abstract

In this paper, the mechanisms of such pulsar phenomena as nulling and glitch are considered, proceeding from the hypothesis of the non-magnetic nature of their emissions. It is shown that these phenomena are caused by the decrease in the pulsar's matter at different stages of its evolution. One of the main features of a pulsar is that it is a body of variable (monotonically decreasing) mass. The principle of the formation of radiation beam's structure is described. The author shares the opinion of those astrophysicists who believe that the nulling of the pulsar is a harbinger of the end of its emission activity.

1. Introduction

With the discovery of the first pulsar in 1967, a new era in observational and theoretical astrophysics had begun. The subsequent discovery of each new pulsar confirmed that they possess a very stable pulsation period with a slight increase with time.

After about forty pulsars had already been discovered, the first violation of this property was recorded from February 24 - March 3, 1969 on the PSR B0833-45 (Vela) pulsar. Researchers at the Radiophysics Laboratory CSIRO and the Jet Propulsion Laboratory, who observed this pulsar simultaneously, found that its pulsation frequency unexpectedly increased by two-millionths during the specified time period. After excluding all factors that could affect the measured time of arrival of the signal, the observers concluded that the decrease in the pulsation period was valid.

Further study of this phenomenon, called glitch, revealed that this unexpected decrease of the period can reach $\Delta P/P = 10^{-9} - 10^{-6}$. This happens within a few seconds, and is then followed by a phase of smooth recovery of the disturbed period, lasting from a few hours to several years.

In the first work [1] devoted to this discovery, the authors suggested that the reason for the decrease in the pulsation period is an increase in the pulsar rotation speed, due to a decrease in its moment of inertia. According to their calculations, the observed decrease in the period of a pulsar will occur if its radius, equal to 10 km, suddenly decreases by 1 cm. However, they did not make any assumptions about possible reasons for such a reduction in radius.

In the next work [2], published in the same issue of the journal Nature, the authors suggested that a pulsar that loses matter leads to a decrease in its moment of inertia.

Since at that time the assumption about the loss of mass by a neutron star seemed absurd, the opinion of the authors of these works remained unnoticed, and was not mentioned in later works. A more realistic explanation of the pulsar glitch mechanism was required.

In the next issue of the journal Nature, after the aforementioned works, a paper [3] was published in which the author proposed a starquake model for pulsar glitches. According to this model, a neutron star at birth is spinning comparatively fast, and hence its crust solidifies in the form of an oblate ellipsoid. As the star slows down its rotation, the centrifugal forces on it decrease, and the liquid core under the crust reaches equilibrium to a close to spherical shape. This causes great stress on the crust, and when this stress reaches a critical point, the crust cracks and adjusts to the new shape of the core, reducing the total moment of inertia.

Despite its consistency, the starquake model did not fit well with subsequent glitch observations and did not receive wide support from the scientific community. Nevertheless, works devoted to this model are still published (see, e.g. [4, 46]).

Another model of pulsar glitches was proposed in work [5], in which the author assigns the primary role in this phenomenon to the superfluid core of a neutron star. Based on the results of experiments with liquid helium II in a rotating vessel, where vortex lines appear, he suggested that something similar happens in the core of a neutron star. Thus, the interaction of superfluid vortices with the pulsar crust leads to instability of its rotation.

This model was further developed in [6]; as a result, it became more complicated but more consistent with observational data. Therefore, since then, the hydrodynamic model plays a central role in the current theory of pulsar glitches (see [7-16]). It should be added that, although this theory has developed rapidly over the years, some key questions remain unanswered.

Apart from glitches, another observed phenomenon, which manifests itself in the disturbance of the periodicity of the received signal, is so-called nulling. Pulsar nulling is a sudden cessation of pulse emission for a period from one pulse to many days.

The first nulling was discovered in 1970 when four pulsars suddenly missed one to ten pulses at various times. This phenomenon was first described by Backer [17], who assumed the magnetospheric nature of the sudden cessation of pulsed emission. In subsequent works, the magnetospheric hypothesis became the basis for various pulsar nulling models (see, e.g. [18-24]).

Geometric theories were also considered (see [25, 26]). The absence of a received signal is explained not by dips in the pulsar emission activity but by changes in the emission geometry.

To quantify the degree of nulling of a pulsar, a quantity called Nulling Fraction (NF) describes the fraction of time that a pulsar is in the null state. This value can only provide a rough estimate of the pulsar's degree of "involvement" in nulling and does not specify the duration of individual nulls, nor does it specify how the nulls are spaced in time.

Pulsar nulling is a relatively common phenomenon. To date, more than two hundred pulsars demonstrate nulling, which is already sufficient for statistical analysis of this phenomenon. The first conclusion that can be drawn from examining the list of nulling pulsars [27] is that there are no millisecond pulsars in it. This is the only unambiguous conclusion that can be drawn to date.

Attempts have been made in the past to find correlations between NF and other pulsar parameters, but they have led to ambiguous conclusions. In [28], a correlation was found between the NF and the pulsar period P based on data from 72 pulsars. In [29], the authors studied data from 23 pulsars and found that NF depends more on the characteristic age of the pulsar than on its period. However, in recent work [27], the authors performed a statistical analysis of data from more than 140 nulling pulsars. They found no apparent correlation between the NF of a pulsar and any of the intrinsic pulsar parameters.

Nevertheless, it should be noted that in [30] the authors note, with some reservations, a very weak correlation of NF with the period P and the pulse width W10, and emphasize that nulling pulsars are a statistically different population from normal, radio, non-nulling pulsars. The latter suggests that nulling pulsars are qualitatively different from ordinary pulsars.

Nulling is much more diverse and mysterious in its manifestation than glitch. Cases were noted [31, 32] in which a pulsar, along with long nullings in burst states, had several short nullings. The reverse was also observed - during nulling, one or two normal impulses may appear [32]. Sometimes nullings are accompanied by a change of mode, when the average pulse profile unexpectedly changes between several quasi-stable states. These changes affect the subpulse drift, quasiperiodic modulation, microstructure and polarization of the pulse [29, 31, 33-35].

In some pulsars, there is a clear difference in the pulse intensities and pulse shapes between the transition from bursts to nulls, to that from the nulls to bursts [32, 36, 37]. In addition, a very few nulling pulsars retain some memory of its phase from before the pulsar goes into a null state (the so-called ‘memory across nulls’ phenomenon) [38]. Sometimes (possibly always) during the long nulls, the pulsar's spindown rate significantly decreases [19, 39]. In many instances, nulling is observed across a wide frequency range [27, 40]. It should be noted, however, that the question of whether the nulling of a pulsar is a random or periodic process is still open.

In addition to many pulsars known to exhibit the phenomenon of nulling, there are astronomical objects whose emissions are sporadic. These so-called 'Rotating Radio Transients' (RRATs) were first described in [44]. These objects emit random, single impulses with a duration of 0.5-100 ms, with intervals between detected pulses ranging from minutes to hours. In [45], such objects are classified as an extreme type of nulling pulsar.

If, according to some researchers, the nulling of a pulsar is a sign of the start of complete cessation of emission [41-43], then RRATs are the last stage of the life of an emitting object. In [45] this idea is expressed as, “it is a possibility that in this model, pulsars start off as continuous emitters, and gradually increase their nulling fraction until they become RRATs, which ultimately evolve further to emit no radio emission”.

This article presents the same point of view, but here we consider cessation of the pulsar emission process, based on the non-magnetic mechanism of the pulsar's emission activity, described in [47]. Thus, glitches and nullings are considered here as manifestations of a single emission mechanism under the conditions of a pulsar's spindown.

2. Pulsar is a body of variable mass

The paper [47] presents the mechanism of the pulsar emission, which is not related to its magnetic field. According to the hypothesis adopted in this paper, matter is stable only when moving with respect to the ambient medium at a velocity exceeding some threshold value v_{th}. A decrease in velocity below this value leads to the complete decay of matter with the emission of electromagnetic radiation.

As detailed in the indicated paper, such an outcome can occur due to simple kinematic conditions. To consider these conditions, we assume for simplicity that the vectors of the spatial $\bar{v}$ and angular $\bar{\omega}$ velocities of the pulsar are mutually perpendicular; therefore, the body performs planar motion. Such a complex motion can be considered the sequence of instantaneous rotations of the body with the same angular velocity ω about an instantaneous axis of rotation, which is parallel to the body axis of rotation. The distance between the body axis of rotation and the instantaneous axis of rotation is

$$e = \frac{v}{\omega} \qquad (1)$$

The body axis of rotation and the instantaneous axis of rotation lies in a plane perpendicular to the vector of the spatial velocity of the body. The main feature of the instantaneous axis of rotation is that the points lying on it are instantly stationary relative to the environment.

At high angular velocities of rotation of a body of radius R, the following condition can be satisfied:

$$e < R \qquad (2)$$

When this condition is met, the instantaneous axis of rotation crosses the body of the pulsar, and, therefore, there are points in it that are instantly stationary relative to the environment. If, however, we consider the points of the body whose absolute velocity does not exceed the threshold value v_{th}, then it turns out that they all lie in a cylindrical area of radius

$$s = \frac{v_{th}}{\omega} \qquad (3)$$

The axis of this cylindrical area is the instantaneous axis of rotation. Let's call this area the Low-Velocities Cylinder (LVC). The intersection of the LVC with the pulsar surface forms two decay regions (hot spots) generating electromagnetic radiation. The decay regions have a peculiar feature – they do not maintain a fixed position on the surface of the rotating body but remain stationary, sliding on its surface.

Thus, there is continuous volatilization of the pulsar matter from the annular regions of its surface, on which decay regions are superimposed with each revolution of the pulsar (see Fig. 1), and two annular grooves are formed on the pulsar surface.

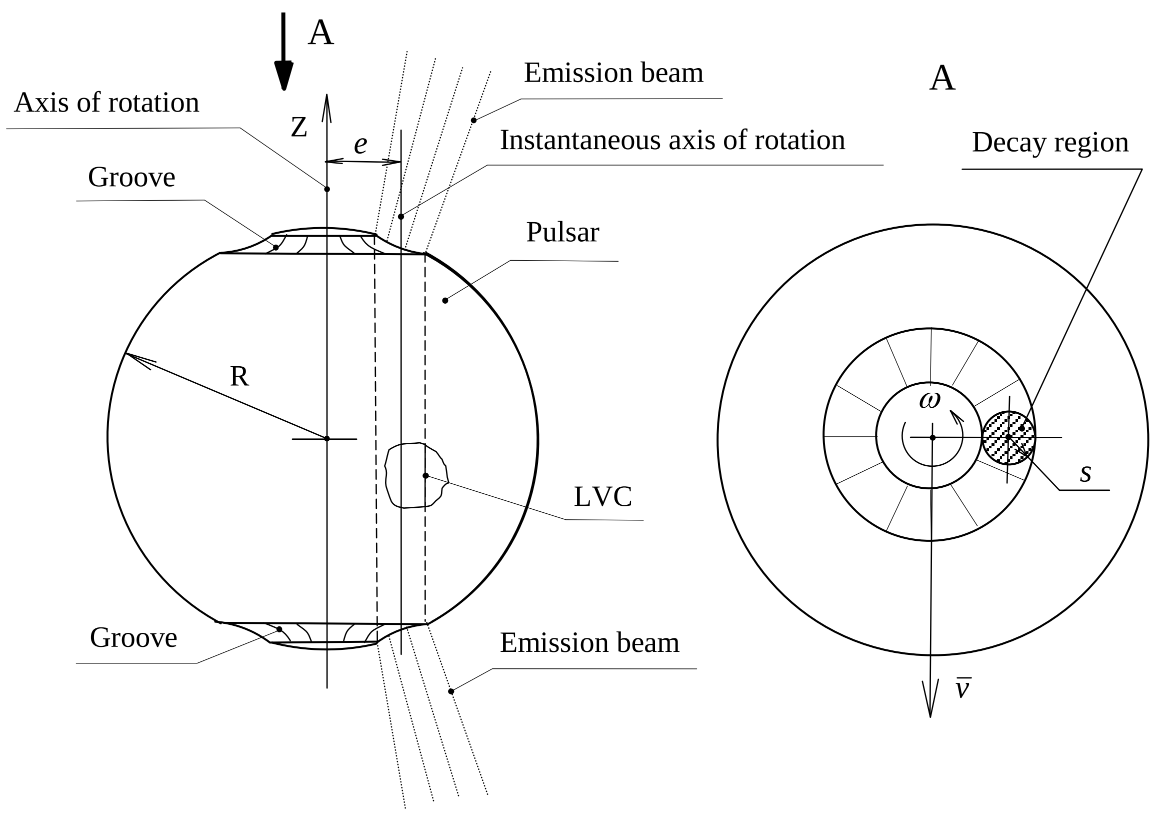

Fig.1. Formation of annular grooves on the surface of a pulsar as a result of the decay of matter in the decay areas.

As can be seen from (1), the instantaneous axis of rotation moves away from the body's axis of rotation as the angular velocity ω decreases. When the LVC is entirely out of the body of the pulsar, the decay of matter will end, and the emission will stop.

Let us consider the period of the pulsar's life when the LVC is entirely inside its body; that is, when the condition

$$e + s < R \qquad (4)$$

is satisfied. We find the decay rate of pulsar matter, that is, the mass of the matter leaving the pulsar per unit time. For simplicity, assume that the decay regions have the shape of a circle of the radius s, regardless of their distance to the body's axis of rotation.

The area of one annular region of the pulsar surface, from which matter is volatilized

$$S = 2\pi e 2 s = 2\pi \frac{v P0}{2\pi} 2 \frac{v_{th} P0}{2\pi} = \frac{1}{\pi} v v_{th} P0^2 \qquad (5)$$

where $P0$ is the pulsar rotation period. Let h denote the depth of the decay regions, that is, the thickness of the layer in which the matter decays. This value is of the order of the height of the surface roughness of a neutron star. Denote by k the decay coefficient - the fraction of particles simultaneously decaying in the decay region ($k << 1$). Then the mass of the pulsar matter, decaying in 1 s.

$$\dot{m} = 2 S h k \rho \frac{1}{P0} = \frac{2}{\pi} h k \rho v v_{th} P0^2 \frac{1}{P0} = \frac{2}{\pi} h k \rho v v_{th} P0 \qquad (6)$$

where ρ is the density of matter in the upper layer of the pulsar. We denote the product of quantities that are the same for all pulsars $\frac{2}{\pi} h k \rho v_{th} = K$, then

$$\dot{m} = K v P0 \qquad (7)$$

3. Glitch mechanism

The continuous removal of matter from the annular regions of the pulsar surface distorts the equilibrium shape of the body. As the depth of the grooves in the pulsar crust increases, stresses increase until they exceed the strength of the crust, causing its rearrangement into a new equilibrium state. In this case, the pulsar is an axisymmetric variable mass body rotating around its axis. The law of motion of such a body is described in [48].

Consider the rotation of the body about the Z-axis (see Fig. 1), and turn to formulas (24), (27) - (31) of the indicated paper. We rewrite them retaining the original notation. The governing equation has the form

$$\dot{\omega}_Z = -\frac{1}{J}[\dot{J} - \dot{m}\delta]\omega_Z \qquad (8)$$

where J is the moment of inertia of the body about the Z-axis, $\dot{J}$ is the time rate of change of the inertia scalar, $\dot{m}$ is the rate of change in body weight, and δ is some constant with the dimension of the area, depending on the geometry of the system.

Letting

$$H(t) = -\frac{1}{J}[\dot{J} - \dot{m}\delta] \qquad (9)$$

then (8) can be integrated to yield

$$\omega_Z(t) = \omega_Z(0)\exp[\int_0^t H(t)\,dt] \qquad (10)$$

Therefore, the time history of spin angular velocity ω_Z is determined totally by the function $H(t)$. Now, let

$$\Phi(t) = \int_0^t H(t)\,dt = -\int_0^t [(\dot{J} - \dot{m}\delta)/J]\,dt = \Phi_1(t) + \Phi_2(t) \qquad (11)$$

where

$$\Phi_1(t) = -\int_0^t (\dot{J}/J)\,dt \qquad (12)$$

$$\Phi_2(t) = \delta \int_0^t (\dot{m}/J)\,dt \qquad (13)$$

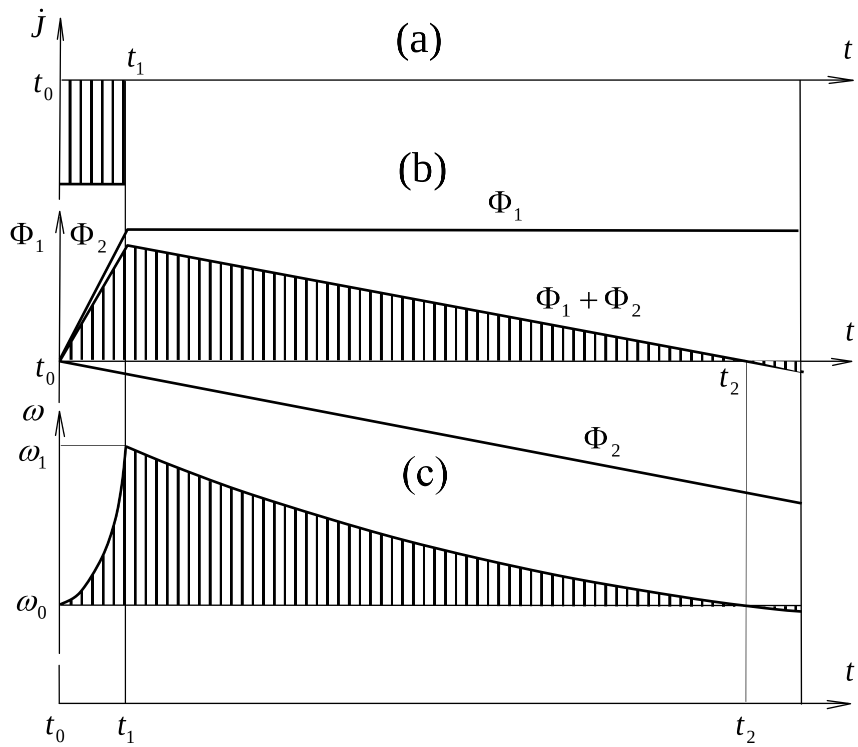

Fig.2. Changing the parameters of the pulsar in the time interval between glitches: (a) the rate of change in the moment of inertia of the pulsar, (b) the change in functions according to expressions (12), (13) and their sum, (c) the change in the angular velocity of the pulsar according to expression (10). $t_0 - t_1$ - period of restructuring of the pulsar crust.

Now let us assume we begin observing the pulsar at the moment t_0, just before the rearrangement of its crust, when the angular velocity and moment of inertia are equal to ω_0 and J_0, respectively. In the next instant, changes occur in the crust, and by the time t_1, the crust takes on a new, more compact equilibrium form. In this case, the moment of inertia of the pulsar decreased and became equal to $J_1 < J_0$. During rearrangement of the crust, the rate of change in the moment of inertia of the body

$$\dot{J} = \frac{J_1 - J_0}{t_1 - t_0} < 0 \qquad (14)$$

We will assume that after t_1 and until the subsequent rearrangement of the crust, the moment of inertia of the pulsar does not change $\dot{J}_{t>t_1} = 0$ (see Fig. 2a). The corresponding graph of the function $\Phi_1(t)$ given by expression (12) is shown in Fig. 2b. We assume that the pulsar's mass decreases uniformly throughout the entire observation period since the rate of decay of pulsar matter $\dot{m}$ does not depend on the rearrangement of its crust. Consequently, according to (13), the function $\Phi_2(t)$ is negative and decreases monotonically.

The graph of the total function $\Phi(t) = \Phi_1(t) + \Phi_2(t)$ is shown in Fig. 2b. There are two key points on the graph: at $t = t_1$, the function breaks, and at $t = t_2$, the function passes through zero. The diagram in Fig. 2c shows a graph of the angular velocity of the pulsar corresponding to expression (10).

This graph shows that during the restructuring of the crust (period $t_0 - t_1$), the angular velocity of the pulsar rapidly increases to a value of ω_1, and then at $t > t_1$ gradually decreases. By the time t_2, the angular velocity takes the pre-glitch value and then decreases until the next glitch occurs.

4. Structure of the pulsar beam

By the structure of the pulsar beam, we mean the distribution of electromagnetic radiation of various frequencies in the cross-section of the beam perpendicular to its axis. The pulsar's surface in the decay regions (hot spots) forms the radiation beam. In the context of the pulsar emission mechanism adopted in this work, the beam structure should correspond to the distribution of the absolute velocities of the points in the decay region. As already mentioned, if the particle velocity relative to the interstellar medium is below the threshold value v_{th}, the particle decays with the emission of electromagnetic radiation.

The essential thing here is that the frequency of the electromagnetic radiation released during the decay of a particle depends on its absolute velocity during decay. That is, the length of the wave is proportional to the absolute velocity of the particle. When the particle velocity is high enough but below the threshold value, then the frequency of the radiation generated during its decay is in the radio range. The particle emits gamma rays when its velocity is close to zero.

The process of forming the structure of the radiation beam follows from above. Consider the decay region on the pulsar's surface when the LVC is located near the body's axis of rotation. Since the decay region is the intersection of the LVC with the surface of a spherical pulsar, in this case, the decay region has an almost circular shape (see Fig. 3).

Recall that LVC is a cylinder whose axis is the instantaneous axis of rotation. The radius of this cylinder is determined from the condition that the absolute velocity of points on its surface is equal to the value v_{th} (see (3)). Consequently, the velocities of the points lying inside this cylinder are less than the value v_{th}, and the closer the point is to the cylinder's axis, the lower its velocity.

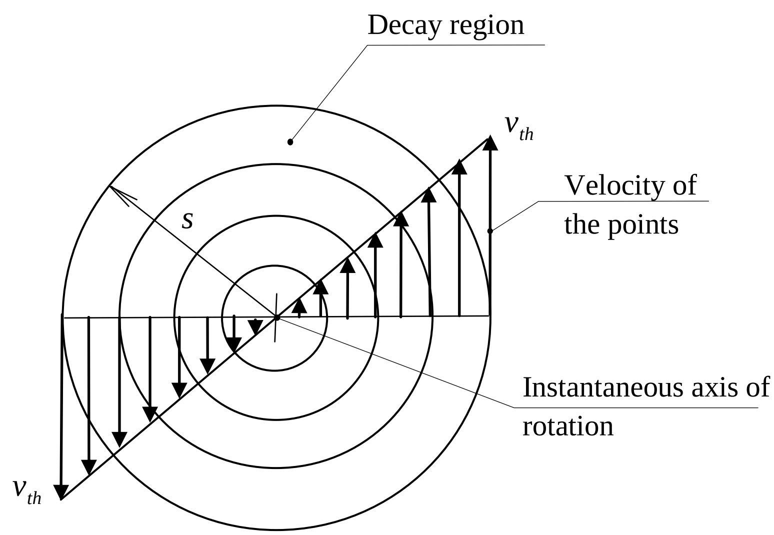

Fig. 3. Distribution of absolute velocities of the points on the pulsar surface in the decay region. v_{th} - threshold value of velocity (see text).

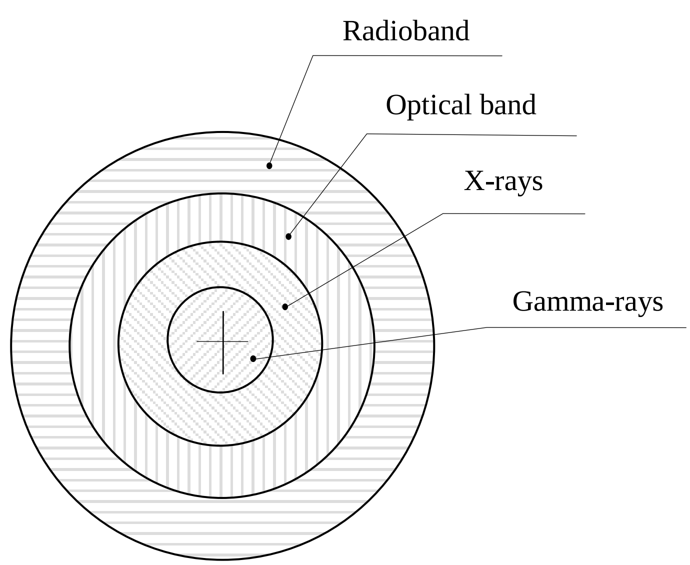

Fig. 4. Cross-section of the pulsar emission beam perpendicular to its axis.

When the decay region generates radiation, particles with absolute velocities in specific velocities emit electromagnetic radiation in the corresponding frequency range. Thus, the cross-section of the pulsar radiation beam is a set of concentric annular regions (see Fig. 4) in each of which waves of a particular frequency propagate. The closer the annular region is to the beam axis, the harder the radiation in it.

Such a structure of the radiation beam determines the shape of the received pulse at a particular frequency depending on which part of the beam cross-section passes through the receiver.

5. Nulling

As already noted, nulling is the most mysterious and diverse manifestation of the nature of pulsars. We list the most general nulling properties discovered as a result of observations of a large number of radio pulsars:

i. a wide range of the duration of nulling - from fractions of a second to months;
ii. a wide range of NF - from fractions of a percent to 95 percent;
iii. lack of correlation between the duration of the pulsar's active state and the duration of the following nulling;
iv. the absence of an explicit dependence of NF on the intrinsic pulsar parameters.

In addition, nulling pulsars were found to be statistically different from ordinary pulsars.

All of the above leads to the assumption that some random factors control the usual emission mechanism in nulling pulsars. Such a state of the pulsar may mean the approach of a complete cessation of its emission activity.

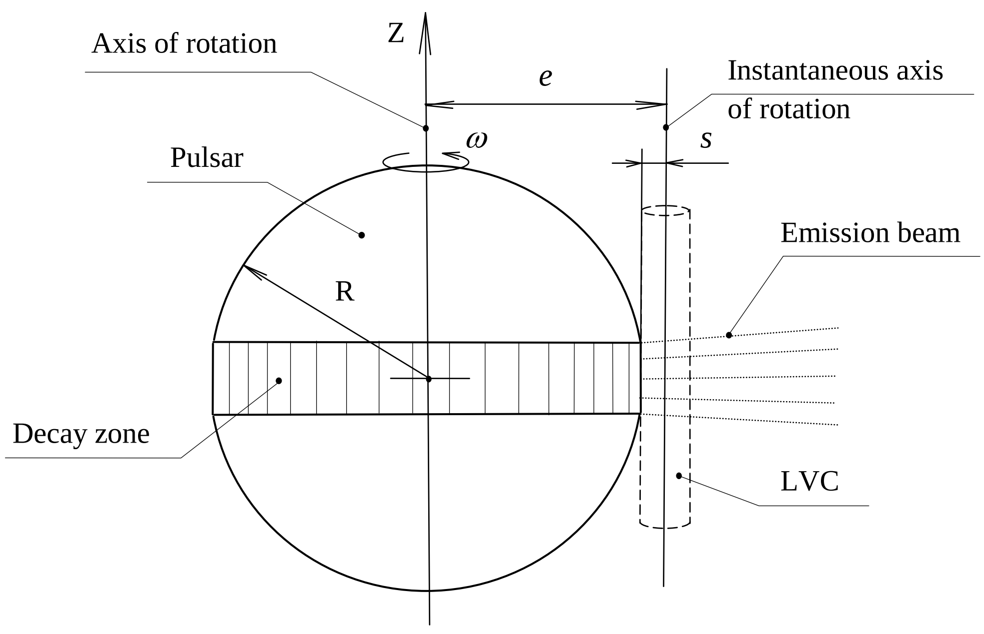

Fig. 5. Geometry of the pulsar emission during the period when the LVC leaves the body of the pulsar.

What does the cessation of the pulsar emission mean in this model? As described in Section 2, the regions formed by the intersection of the LVC with the pulsar surface generate the radiation. Thus, the emission of the pulsar continues as long as the LVC intersects with its surface. A decrease in the body's angular velocity with time leads to a gradual increase in the distance between the LVC axis and the center of the body (see (1)). Eventually, the LVC completely leaves the body of the pulsar, the decay regions disappear, and the pulsar emission stops.

However, with the beginning of the LVC leaving the pulsar's body, changes occur in its emission geometry. During this period, two decay regions merge, and the pulsar has only one radiation beam, as shown in Fig 5. Recall that this beam does not rotate with the body, but its axis always lies in a plane passing through the body axis of rotation, the instantaneous axis of rotation, and is perpendicular to them. Simultaneously, this beam cyclically sweeps the space, like the beams of ordinary pulsars, as a result of the precession of the star [48].

After the complete decay of matter in the last region of the intersection of the pulsar body with the LVC, the radiation ceases, and the body's angular velocity ceases to decrease. In this case, along with the angular velocity, the distances e and s are stabilized (see Fig. 5). This causes the LVC to remain close to the pulsar surface for a long time.

If the pulsar were a perfectly rigid body, then such a state of absence of radiation would last indefinitely. However, the body's surface can undergo various deformations, and then random processes will occur that will lead to the temporary resumption of radiation.

For example, due to a disruption of the integrity of the crust, its restructuring can occur, as in a glitch. In this case, a temporary increase in the angular velocity of the pulsar will lead to a decrease in the distance e, that is, to the approach of the instantaneous axis of rotation to the center of the body, the LVC will again enter the pulsar body, and the newly formed decay region will begin to radiate.

This will continue until the subsequent decrease in the angular velocity of the pulsar again displaces the LVC from the pulsar body. In this regard, of interest is that at the time of writing, 16 pulsars were discovered, in which both glitches and nulling are observed.

Another reason for the resumption of a period of pulsar activity after nulling could be its surface oscillations. For example, suppose the oscillations of the crust occur in alternating shapes of oblate and prolate ellipsoids of rotation, then, during the increase in the equatorial size of the body it will again intersect with the LVC and again begin to radiate.

Therefore, the pulsar activity period lasts until a new portion of the matter entered the LVC is spent on radiation. Before the end of this period, the remainder of this portion of matter gradually decreases, and the radiation intensity drops to zero.

The duration of the subsequent nulling is determined by how long there is no new "injection" of matter into the LVC area. When a new portion of the substance enters the LVC, the radiation resumes immediately with a high intensity and then normalized.

As mentioned, the conditions for the radiation beam formation just before the termination of its emission and after nulling are different. Until the termination of radiation, the conditions for the formation of the radiation beam remain qualitatively the same as during the entire active period, only the amount of matter decreases under the conditions of decay. Therefore, the emission state ends with a gradual decrease in the radiation intensity without changing the pulse structure.

In contrast, the resumption of emission after nulling occurs under new conditions with a new portion of the decaying matter. Therefore, at the beginning of a new active period, the beam structure has a slightly changed form, reflected in a change in the microstructure of the received pulses.

In conclusion, we note that the manifestations of nulling are individual for each pulsar. There may be no two pulsars with the same nulling behavior. With the absence of a correlation between NF and the intrinsic pulsar parameters, this circumstance indicates its nulling behavior depends on factors that have not yet been taken into account or have eluded observation. It is possible that the nulling behavior is very sensitive to the mass and size of the pulsar and/or to the period since the LVC left the pulsar body.

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