# Formation of “lightnings” in a RRAT magnetosphere

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## Introduction

Rotating radio transients (RRATs), the sources that manifest themselves in the radio band as separate, sparse, short, relatively bright bursts, were discovered by analyzing archival data from the Parkes Multibeam Pulsar Survey and were immediately associated with the manifestation of a bursty behavior of neutron stars [13]. The burst rate lies within the range from about 1 $\mathrm{min}^{-1}$ to 1 $\mathrm{h}^{-1}$. The burst phase is retained in RRATs, which allowed the periods $0.1 - 6.7$ s slightly exceeding those of normal radio pulsars to be measured [10].

The radio emission from normal pulsars owes its existence to the outflows of an electron-positron plasma from the magnetosphere. However, the bursty radio emission from RRATs is basically nonstationary. Consequently, the regular disappearance of radio emission is indicative of the possible cessation of plasma generation, while the generation itself should be nonstationary. This is supported by the measured difference in spindown rate of the intermittent pulsars B1931+24 and J1832+0029 in the periods of “operation” and “silence” [11]. The existence of pulsars with a high nulling fraction reaching 95% [15] also argues for the possibility of a temporary cessation of plasma generation in the neutron star magnetosphere.

If the plasma generation is off, then efficient filling of a magnetosphere that can initially be in a vacuum state is possible through the absorption of photons from the cosmic gamma-ray background [4–6]. We have recently shown that the absorption of a high-energy photon from the external cosmic gamma-ray background in the inner neutron star magnetosphere triggers the generation of a secondary electron–positron plasma and produces a “lightning” — a lengthening and simultaneously expanding plasma tube [8]. Here we briefly outline the possible connection between radio bursts from separate lightnings and those from RRATs [9].

## Absorption of gamma-ray photons

Consider a neutron star with a magnetosphere in a vacuum state. This implies that the plasma density in the magnetosphere should be low compared to the Goldreich-Julian density. Below, we will work in a dimensionless system of units by measuring the electric and magnetic field strengths in units of the critical field

$$B_{cr} = \frac{m_e^2 c^3}{e\hbar} \approx 4.414 \times 10^{13} \text{ G},$$

where $m_e$ is the electron mass, $e$ is the positron charge, and $\hbar$ is the Planck constant. As the units of mass, length, and time, we will take the electron mass $m_e \approx 9.109 \times 10^{-28}$ g, the Compton electron wavelength $\lambdabar = \hbar/m_e c \approx 3.862 \times 10^{-11}$ cm, and its ratio to the speed of light $\lambdabar/c \approx 1.288 \times 10^{-21}$ s, respectively. Note the necessary relations 1 cm $\approx 2.590 \times 10^{10}$ and 1 s $\approx 7.763 \times 10^{20}$.

The cross section of the neutron star magnetosphere for photons with energy $k$ is

$$\sigma_m(k) = \pi R_S^2 \left(\frac{\Lambda_\sigma}{a_0}\frac{k}{2}\right)^{2/3},$$

where $a_0 = 4/3B_0$ [9]. For a neutron star radius $R_S \approx 2.6 \times 10^{16}$ (10 km in dimensional units), a surface magnetic field $B_0 \sim 0.01 - 0.1$, and a gamma-ray photon energy from a wide range $k \sim 2 - 10^7$, we have the logarithmic factor $\Lambda_\sigma \sim 20 - 30$.

We characterize the intensity of the gamma-ray background by some effective function $j_{GB}(k)$, which corresponds to an isotropic distribution of photons. The number of photons absorbed per unit time in the magnetosphere and having an energy $k$ exceeding some value of $k_{\min}$ is

$$F_{GB}^{abs}(k_{\min}) = 4\pi \int\limits_{k_{\min}}^{\infty} j_{GB}(k)\sigma_m(k)\, dk.$$

We will take the function $j_{GB}(k)$ as a power law:

$$j_{GB}(k) = A_{GB}k^{-\beta},$$

where $\beta$ is the spectral index. In any case, $\beta > 2$. The minimum energy of the photons absorbed in the magnetosphere is

$$k_{\min} = \frac{2a_0}{\Lambda_\sigma}.$$

Let us consider the photons from the extragalactic isotropic gamma-ray background and take the currently available Fermi Large Area Telescope data on the cosmic gamma-ray background spectrum [1], with $\beta = 2.41 \pm 0.05$,

$$I_{EGB}^{exp} = \int\limits_{k_{\min}^{exp}}^{\infty} j_{GB}(k)\, dk = (1.03 \pm 0.17) \times 10^{-5}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1},$$

and $k_{\min}^{exp} = 200$. We can then obtain the characteristic flux

$$F_{EGB}^{abs}(k_{\min}) \sim 2 \times 10^{10}\ \mathrm{s}^{-1}$$

of photons from the extragalactic background being absorbed per unit time in the neutron star magnetosphere.

## Formation of lightnings

We have shown [7] that in the presence of a sufficiently strong electric field, the production of an electron-positron plasma is so efficient that it cannot be considered as a set of successive generations of particles: Each new particle generation in a short time begins to play the role of the primary particles. This case remarkably differs from that of normal pulsars.

The presence of a fairly strong electric field results from the fact that here we have a dynamical screening of the electric field, which is caused by a continuous increase in the electric current during the plasma multiplication, not by charge separation. Moreover, the absorption of a high-energy photon from the cosmic gamma-ray background in the inner neutron star magnetosphere gives rise to a lightning [8]. The typical lightning length reaches 1000 km; the lightning radius is 100 m and is comparable to the neutron star polar cap radius. The number $N_\Sigma$ of electron–positron pairs produced in a lightning through the absorption of one photon reaches $10^{28}$. The generation of an electron-positron plasma in a lightning is essentially nonstationary. The multiplicity, i.e., the ratio of the plasma density to the Goldreich-Julian density, exceeds $10^4$, while the dense relativistic electron–positron plasma formed in the short lightning lifetime can manifest itself in the radio band as short single radio bursts. Note the interesting relation

$$\frac{N_\Sigma}{n_{GJ} V_S} \simeq \frac{1}{16},$$

with $V_S = 4\pi R_S^3/3$ being the neutron star volume and $n_{GJ}$ being the Goldreich-Julian density near the surface. The absorption of 10–100 photons is sufficient for the inner neutron star magnetosphere to be filled. We see that the calculated flux of absorbed photons is more than enough for the necessary number of lightnings to be formed to fill the inner neutron star magnetosphere. Consequently, not the flux of photons absorbed in the magnetosphere but the lightning formation time, which determines the magnetosphere filling time, comes to the fore.

There exists some threshold distance $R^{eff}$ at which the formation of lightnings is completely absent. It can be determined by equating the particle acceleration time $\tau_{st}|_{r=R^{eff}}$ to the distance $R^{eff}$:

$$R^{eff} \sim R_S \left(\frac{R_S}{\tau_{st}}\right)^{2/5} \sim 700 \text{ km}. \tag{1}$$

Thus, the time it takes for the inner magnetosphere to be filled is limited from below by $R_S/c$ and can reach values of the order of $R_{eff}/c$. The entire magnetosphere will be filled in the time of the plasma transition from the inner regions to the regions near the light cylinder, $R_L/c = P/2\pi$.

We see that the neutron star magnetosphere can be efficiently filled with an electron–positron plasma. It is important to note that here we are dealing with a closed magnetosphere. Nevertheless, open magnetic field lines emerging from the polar cap regions and going beyond the light cylinder to infinity exist in the magnetosphere. The electron–positron plasma can freely escape from the magnetosphere along open magnetic field lines, with the characteristic plasma outflow time being $R_L/c$.

Thus, it is natural to consider a neutron star in which the inner closed magnetosphere is filled with an electron–positron plasma, while the polar cap regions contain no plasma. The photons from the external cosmic gamma-ray background will be efficiently absorbed in both closed and open magnetospheres. Here, three cases can be distinguished. In the first case, a gamma-ray photon can be absorbed in the inner magnetosphere filled with a dense plasma. It will produce an electron–positron pair, but no cascade generation of an electron–positron plasma will subsequently be triggered due to the absence of efficient particle acceleration. In the magnetospheric regions under consideration, the longitudinal electric field is zero, while the transverse electric field does not lead to particle acceleration but only ensures the fulfilment of the corotation conditions. In the second case, a gamma-ray photon can be absorbed in the outer magnetosphere at distances $r > R_{eff}$. In principle, a dense plasma can be absent in these regions. The longitudinal electric field strength is much smaller than the field strength near the neutron star surface but, nevertheless, is nonzero. The absorption of a gamma-ray photon can then give rise to a lightning, but the number of particles in it will be small compared to the number of particles in lightnings generated near the stellar surface in a vacuum electromagnetic field. In the third case, a gamma-ray photon is absorbed in the polar cap regions of the neutron star magnetosphere. We will then have a lightning in which the number of particles is more than enough for the polar cap region to be filled. The formed dense electron–positron plasma will screen the longitudinal electric field as soon as the lightning reaches the neutron star surface. However, a high longitudinal electric field close to the vacuum one is needed for the formation of a new lightning. This electric field can emerge only after the outflow of the electron–positron plasma produced by a preceding lightning from the polar cap regions of the magnetosphere. Hence we obtain a lower limit on the formation period $\Delta T$ of two consecutive lightnings:

$$\Delta T \gtrsim R_L^{eff},$$

with $R_L^{eff}$ being some effective distance such that the outflow of the generated electron-positron plasma beyond this distance results in the appearance of a fairly strong electric field, sufficient for the lightning formation. We have

$$R^{eff} < R_L^{eff} < R_L.$$

## The width of radio bursts and the phase distribution

For the first 11 discovered RRATs in observations at 1.4 GHz, the burst width is 2–30 ms [13]. Let us introduce the window of radiation

$$\Delta P = 3\sqrt{\frac{z^{eff} P}{2\pi c}},$$

which is the maximum time interval during which the radiation from the polar cap region forming at distance $z^{eff}$ from the neutron star center can potentially be observed. If we take $P \sim 1$ s and $z^{eff} \sim R_S \approx 10$ km, then $\Delta P \sim 7$ ms. If, alternatively, we set $z^{eff} = 100 R_S$, then $\Delta P$ will increase by an order of magnitude. If, in addition, we take into account the dependence on the period and the fact that the lightning width can be smaller than the polar cap width, then the observed pulse width, in general, can be explained if it is assumed to be determined by the width of the forming plasma tube.

However, the lightning width determines the observed pulse width only if the lifetime of a given tube is longer than the time of its passage through the line of sight. In dimensionless units, the lifetime $T_l$ of a lightning is equal in order of magnitude to the distance from the point of primary electron-positron pair production to the neutron star surface. Once the dimensions have been restored, we can then write

$$T_l \sim \frac{r_0 - R_S}{c}. \qquad (2)$$

At $r_0 \sim 100R_S$, we have $T_l \sim 3.3$ ms. This explains the presence of short radio bursts whose duration is much less than the corresponding polar cap width.

The phase of a specific single radio pulse will be determined by the distance from the plane passing through the magnetic and rotation axes to the formation region of radio emission at some fixed frequency at which the observations are performed located in the plasma tube. This distance is a random variable that is definitely limited from above by the radius of the section of the region of open magnetic field lines by the plane orthogonal to the magnetic axis and located at distance $z^{eff}$ from the neutron star center. Taking $P \approx 4.263$ s and $\Delta P \approx 120$ ms for RRAT J1819–1458 from observational data [12], we can obtain the effective parameter

$$z^{eff} \approx 700 \text{ km},$$

which is comparable to the estimates of $R^{eff}$ (1). If the emission is assumed to be formed at such a height, then the lightning length should reach lengths of the same order of magnitude. Based on Eq. (2), we obtain a typical lightning lifetime $T_l \sim 2.3$ ms, which is close to the observed width of a single pulse, 3 ms.

Most of the radio bursts from RRAT J1819–1458 are single-component ones. However, 5 of the 162 recorded radio bursts have a two-component structure, with the time interval between the individual components lying within the range from 6 to 16.5 ms [3]. This can be an argument for the fact that, at least for some bursts, the lifetime of the lightnings emitting them exceeds the time of passage of the line of sight through the emission cone formed by a separate lightning. In this case, the plasma tube width should be comparable to the polar cap width, which follows from the analogy with normal pulsars. For RRAT J1819–1458 with a period $P \approx 4.263$ s we have a polar cap width of 14.3 ms. This value is very close to the observed maximum separation between the components in a two-component radio burst, 16.5 ms.

## Burst rate

Let

$$T_l \ll \Delta P \ll \Delta T,$$

i.e., the lightning lifetime is much smaller than the window of radiation, which, in turn, is smaller than the period between two consecutive lightnings. A lightning will then be observed, on average, every $n$ periods, where $n$ can be determined from the condition

$$n\Delta P = \Delta T. \tag{3}$$

It should be emphasized that here by $n$ we mean precisely the mean number of periods per one recorded burst. The number of periods separating two specific consecutive bursts can be both smaller and larger than this one. The minimum time between two consecutive bursts can be even equal to the rotation period $P$, because the characteristic time of the plasma outflow from the polar cap regions is a factor of $2\pi$ smaller than $P$. This is indicative of a close connection between RRATs and extreme nullers. The corresponding mean burst period is given by the expression

$$T = nP = \frac{2\pi}{3}\Delta T\sqrt{\frac{R_L}{z^{eff}}}. \tag{4}$$

We obtain the following estimate for the burst period:

$$T \gtrsim \frac{P}{3}\frac{R_L^{eff}}{\sqrt{R_L z^{eff}}}.$$

Suppose that $P \sim 3$ s, $z^{eff} = R_S$, and $R_L^{eff} = R_L$. From the relation $R_L/R_S \sim 10^4$, we have

$$T \gtrsim 100 \text{ s}.$$

This estimate is typical and corresponds to the formation of radio emission near the neutron star surface. The formation of radio emission not near the surface but at a distance $z^{eff} > R_S$ from the neutron star center leads to a decrease in $T$. For example, at $z^{eff} \sim R^{eff} \sim 100R_S$, the lower limit on the mean period $T$ between two consecutive observed bursts decreases by an order of magnitude, reaching $\sim 10$ s.

The mean rate of radio bursts observed at the Parkes 64-m radio telescope at 1.4 GHz for the first 11 discovered rotating radio transients lies within the range from 1 burst in 4 min for J1819–1458 to 1 burst in 3 h for J1911+00 [13]. New observational data allow one to talk about the existence of RRATs with a higher burst rate approaching 1 min$^{-1}$ [10]. Precisely such data are most interesting, because they provide an independent estimate for the height $z^{eff}$ at which the radio emission is formed. RRAT J1554–52 has a high burst rate, 50.3 h$^{-1}$. The short rotation period, $P \approx 0.125$ s, allows the possibility of observing so frequent bursts to be explained even for the formation of emission near the neutron star surface. The detection of RRAT J1841–14 with a long period, $P \approx 6.598$ s, and a high burst rate, 46.0 h$^{-1}$, is more interesting. Assuming that $R_L^{eff} = R_L$, we can obtain an estimate for the effective parameter $z^{eff} \sim 25R_S = 250$ km. It is comparable to the lightning formation height $r_0 \sim 600$ km corresponding to a typical observed burst width of 2 ms.

Above, we have obtained a lower limit on the time interval $T$ between bursts determined by the time $\Delta T$ between two successive lightnings. Obviously, lightnings can be formed more rarely if the gamma-ray background is less intense. The specific value of $\Delta T$ is determined by the photon absorption rate in the region of open magnetic field lines:

$$\frac{dN_{GB}^{abs}}{dt} \sim \left(\frac{\pi R_P^2}{R_S}\right)^2 I_{GB}^{exp} \left(\frac{k_{\min}^{exp}}{k_{\min}^{eff}}\right)^{\beta-1},$$

where $k_{\min}^{eff} = k_{\min}/\chi_{\max}$, $R_P = R_S^{3/2}/R_L^{1/2}$ is the polar cap radius, and $\chi_{\max} \sim 0.01$ is the maximum angle between the photon propagation direction and the magnetic field direction in the region of open magnetic field lines. Assuming that $a_0/\Lambda_\sigma \sim 10$, $\chi_{\max} \sim 0.01$, $R_P \sim 100$ m and choosing the other parameters to be the same as those used to calculate the flux of photons absorbed in the entire magnetosphere, we have $dN_{EGB}^{abs}/dt \sim 0.04$ s$^{-1}$. Here, we took into account only the extragalactic photons. Since the diffuse Galactic component gives a flux that is a factor of 2–4 higher [1], we can write $dN_{GB}^{abs}/dt \sim 0.1$ s$^{-1}$, which corresponds to $\Delta T \sim 10$ s. It can be concluded that no RRATs could exist in the case of an excessively intense cosmic gamma-ray background. Continuous absorption of cosmic gamma-ray photons would cause the polar cap regions of the neutron star magnetosphere to be filled with plasma that would not have time to outflow from the magnetosphere. Consequently, no regions with a high electric field whose existence is necessary for the observed bursty RRAT behavior would have time to be formed.

Consider a neutron star with some fixed rotation period in a cosmic gamma-ray background with a fixed intensity. The photon absorption rate in the region of open magnetic field lines will then increase with surface magnetic field. We obtain the condition defining the maximum surface magnetic field $B_{\max}$ at which the neutron star is still RRAT:

$$\frac{dN_{GB}^{abs}}{dt} \lesssim \frac{c}{R_L^{eff}}.$$

Note that when this inequality breaks down, the neutron star ceases to be a "classical" RRAT due to excessively frequent lightnings and can begin to manifest itself as an extreme nuller. At $R_S \approx 10$ km, $R_L \sim 10^4 R_S$, $I_{GB}^{exp} \sim (1-5) I_{EGB}^{exp}$, and $R_L^{eff} \sim R^{eff} \sim 1000$ km, the maximum surface magnetic field is

$$B_{\max} \sim (1-4) \times 10^{14} \text{ G}.$$

In all RRATs with a known period derivative [12, 14], the surface magnetic field does not exceed $B_{\max}$.

Using Eqs. (3) and (4), we can independently determine $\Delta T$ directly from observational RRAT timing data. For example, for RRAT J1819–1458 with a period $P \approx 4.263$ s, a window of radiation $\Delta P \approx 120$ ms, and a time interval between bursts $T \sim 180-240$ s [12], we have $\Delta T \sim 5-7$ s. Let us separately consider PSR J0941–39 with a period $P \approx 587$ ms and a window of radiation $\Delta P \approx 105.6$ ms, which in the off state is RRAT with a time interval between bursts $T \sim 33-40$ s [2]. For this source, we have $\Delta T \sim 6-7$ s. Incidentally, the width of the brightest recorded single burst, 6 ms, allows us to obtain $z^{eff} \sim 4000$ km, which exceeds $R^{eff}$. If this distance is assumed to be provided by a temporary switch-on of the gap, then a formal lifetime of $\sim 13$ ms comparable in order of magnitude to the mentioned width of a single burst will correspond to it. It is the large value of $z^{eff}$ that may suggest the readiness of the given pulsar to switch on after each single burst. The switch-on of the inner gap in this RRAT may be provided by a short-term passage of the electric current through the polar cap during a stroke of lightning [9]. Note that when the lightning reaches the neutron star surface, the electric current reaches huge values of $10^{13} - 10^{14}$ A [8]. Within the framework of the model being discussed, we can clearly separate the on state of PSR J0941–39 when intense plasma generation takes place, as in a typical pulsar, and the off state when no stationary plasma generation takes place, while the separate radio bursts owe their existence to lightnings triggered by the absorption of background gamma-ray photons in the region of open magnetic field lines.

The estimates obtained for $\Delta T$ agree well with the above estimate that follows from the photon absorption rate in the region of open magnetic field lines. We see that the time interval $\Delta T$ between two consecutive lightnings can exceed considerably the time of the plasma outflow from the polar cap regions of the neutron star beyond the light cylinder. This provides further evidence for a nonstationary nature of the radio emission from RRATs.

## Conclusion

The connection between the radio emission from lightnings produced by the absorption of high-energy photons from the cosmic gamma-ray background in a neutron star magnetosphere and radio bursts from rotating radio transients (RRATs) is investigated. The lightning length reaches 1000 km; the lightning radius is 100 m and is comparable to the polar cap radius. If a closed magnetosphere is filled with a dense plasma, then lightnings are efficiently formed only in the region of open magnetic field lines. For the radio emission from a separate lightning to be observed, the polar cap of the neutron star must be directed toward the observer and, at the same time, the lightning must be formed. The maximum burst rate is related to the time of the plasma outflow from the polar cap region. The typical interval between two consecutive bursts is $\sim$ 100 s. The width of a single radio burst can be determined both by the width of the emission cone formed by the lightning emitting regions at some height above the neutron star surface and by a finite lightning lifetime. The width of the phase distribution for radio bursts from RRATs, along with the integrated pulse width, is determined by the width of the bundle of open magnetic field lines at the formation height of the radio emission. The results obtained are consistent with the currently available data and are indicative of a close connection between RRATs, intermittent pulsars, and extreme nullers.

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