On the nature of fast radio bursts

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\section*{ABSTRACT}
Scenario of formation of fast radio bursts (FRBs) is proposed. Just like radio pulsars, sources of FRBs are magnetized neutron stars. Appearance of strong electric field in a magnetosphere of a neutron star is associated with close passage of a dense body near hot neutron star. For the repeating source FRB 121102, which has been observed in four series of bursts, the period of orbiting of the body is about 200 days. Thermal radiation from the surface of the star (temperature is of the order of $10^8$ K) causes evaporation and ionization of the matter of the dense body. Ionized gas (plasma) flows around the magnetosphere of the neutron star with the velocity $u \simeq 10^7$ cm/s, and creates electric potential $\psi_0 \simeq 10^{11}$ V in the polar region of the magnetosphere. Electrons from the plasma flow are accelerated toward the star, and gain Lorentz factor of $\simeq 10^5$. Thermal photons moving toward precipitating electrons are scattered by them, and produce gamma photons with energies of $\simeq 10^5 m_e c^2$. These gamma quanta produce electron-positron pairs in collisions with thermal photons. The multiplicity, the number of born pairs per one primary electron, is about $10^5$. The electron-positron plasma, produced in the polar region of magnetosphere, accumulates in a narrow layer at a bottom of a potential well formed on one side by a blocking potential $\psi_0$, and on the other side by pressure of thermal radiation. The density of electron-positron plasma in the layer increases with time, and after short time the layer becomes a mirror for thermal radiation of the star. The thermal radiation in the polar region under the layer is accumulated during time $\simeq 500$ s, then the plasma layer is ejected outside. The ejection is observed as burst of radio emission formed by the flow of relativistic electron-positron plasma.

\textbf{Key words:} radiation mechanisms: general – stars: neutron

\section*{1 INTRODUCTION}
Fast radio bursts (FRBs), first discovered in 2007 by Lorimer et al., are short radio signals of several milliseconds duration ($\tau \simeq 10^{-3}$ s) with the energy flux from tens of milliJansky to several Jansky in the radio band of $\simeq 1 - 10$ GHz. The main feature of FRB is high observed dispersion measure DM. It is several times greater than the maximum value of the dispersion measure of radio signal passing through our Galaxy. High DM suggests that the radio signal propagates through intergalactic medium. Also the rotation measure RM, connected with presence of a magnetic field in a plasma, through which a radio signal propagates, is high. The ratio of the rotation measure to the dispersion measure, $RM/DM$, equals to the average value of the longitudinal magnetic field on the line of sight. On the contrary, this ratio is one order of magnitude smaller than the average magnetic field in the Galaxy, which also indicates that the radio signal propagates in intergalactic medium. Finally, the repeated source of FRB 121102 was identified with a galaxy having a redshift of $z = 0.192$ (Chatterjee, et al., 2017). Assuming that large values of DM and RM are achieved in the intergalactic medium implies cosmological distances to sources of FRB, $z \simeq 1$. If we assume isotropic radiation into the solid angle $\simeq 4\pi$ and cosmological distance to sources, the radiated power in the radio band should reach value of the order of $10^{43}$ erg/s and the total radiated energy of $10^{40}$ erg. The beaming of FRB can decrease these estimates by many orders of magnitudes (Katz, 2017a). If we do not take into account the relativistic time delay in the source, then the source size $l$ is estimated to be of the order of $3 \cdot 10^7$ cm. Further the energy density in the source is equal to $3 \cdot 10^{17}$ erg/cm$^3$ in the radio range only. This corresponds to the electric field $E \simeq 10^{12}$ V/cm, which is at least two orders of magnitude higher than the value of the atomic field, $E_a \simeq 0.5 \cdot 10^{10}$ V/cm. At such large energy densities, we have to expect radiations in optical, x-ray and gamma ranges, which are not observed. It is difficult to understand what the extragalactic source could be. So the nature of FRB remains unknown today.

There are several different consequences regarding the origin of FRB. First of all, because of smallness of $l$ the source of FRB is probably a neutron star. It is known that neutron stars are observed as radio pulsars, x-ray pulsars, magnetars, rotating radio transients (RRATs). High brightness temperature of FRB, up to $10^{27}$ K, suggests a coherent mechanism of radio emission similar to the one of
radio pulsars, especially the mechanism of radiation of giant radio pulses, observed from several radio pulsars (Soglasnov et al., 2004; Hankins and Eilek, 2007). When radio sources of this kind with the same radiation mechanism are placed at cosmological distances it is necessary to assume extreme values of neutron star parameters: large magnetic fields on its surface, $B_{\text{rot}} \simeq 10^{15} \, \text{G}$, and fast rotation, $\Omega_{\text{NS}} \simeq 10^8 \, \text{s}^{-1}$. But neutron stars with such extreme parameters lose their rotation energy quite rapidly, during a time of the order of $10^5 \, \text{s}$, and can not give repeated bursts. As for magnetars, in particular SGRs, the energy is stored in a magnetic field inside the star, and they produce bursts in gamma and x-ray energy ranges, which are not observed in FRBs. The energy released in a burst can be the energy of the electric field in the rotating magnetosphere of a neutron star (Katz, 2017b). The author calls such phenomenon ‘pulsar lightning’. However, it is not clear how and how fast transition from one configuration of the magnetosphere to another is possible. Earlier, the term 'lightning' was used for explanation of radiation of RRATs (Istomin and Sobyanin, 2011a,b). It was specifically shown that cascade formation of electron-positron pairs and their acceleration by a longitudinal electric field in the polar vacuum magnetosphere, caused by absorption of an energetic gamma quantum from Galactic and extragalactic backgrounds, should look like a flash of lightning on Earth during a thunderstorm.

The closest to what is discussed in this article are models of FRBs origin by the interaction of neutron stars with other bodies (planets, comets, asteroids). These are primarily direct collisions of bodies with a neutron star (Di and Dai, 2017; Dai et al., 2016) and the interaction of a relativistic pulsar wind with a companion of a neutron star (Mottez and Zarka, 2014).

However, apparently, FRB is a different class of sources of radio emission, which are neutron stars. This can be seen from analysis of observations of the source FRB 121102.

2 FRB 121102

The large energy density in a source most likely suggests catastrophic event, such as an explosion, and hence destruction of the source. Indeed, no recurrent events were recorded until recently. One radio source FRB 121102, discovered in November 2012, flared up ten times within 16 days $(1.4 \cdot 10^5 \, \text{s})$ 926 days later (May 2015). With the exception of one long time interval between consecutive flashes, also by the way about 16 days, the time interval between bursts were random from $\simeq 20 \, \text{seconds}$ to $\simeq 1 \, \text{hour}$. The average duty cycle was $\simeq 670 \, \text{s} \simeq 11 \, \text{min}$. Then after 164 days (November 2015) six more bursts were recorded during 25 days $(2 \cdot 10^5 \, \text{s})$ with two breaks of 6 and 18 days and with the average duty cycle of 430 s. In September 2016 (after 287 days) the source FRB 121102 flashed four more times with the average time between bursts $\simeq 10^2 \, \text{s}$. Finally, after 340 days fifteen new bursts were recorded with average duty cycle of $150 \, \text{s}$ in August 2017.

We see that in the temporal activity the FRB 121102, apart from the duration of the radio emission pulses, $\tau \simeq 10^{-3} \, \text{s}$, exhibits three characteristic times: $1) \, \tau_1 \simeq 500 \, \text{s}$ is the average time interval between consecutive bursts; $2) \, \tau_2 \simeq 20 \, \text{d} \simeq 2 \cdot 10^8 \, \text{s}$ is the duration of series of bursts and the duration of continuous breaks between bursts in the series; $3) \, \tau_3 \simeq 200 \, \text{d} \simeq 2 \cdot 10^7 \, \text{s}$ is the average time between series of bursts. These times are very different, $\tau_1 \ll \tau_2 \ll \tau_3$.

Thus, the source FRB 121102 exhibits activity during the time $\tau_2 = 2 \cdot 10^8 \, \text{s}$ in the form of short bursts of few milliseconds in duration. The values of duration of radio emission, intensity and duty cycle are close to the same values observed from so-called rotating radio transients (RRATs). However, although the duty cycle of RRATs is a random value, it is a multiplier of some constant time unit. This time unit is period of rotation of a neutron star, which increases with time like that for radio pulsars. The value of time derivative of the period, $P$, allows us to estimate the magnetic field strength on the stellar surface. It is $B \simeq 10^{12} - 10^{13} \, \text{G}$, which is similar to radio pulsars. RRATs rotate slower than radio pulsars (the period of rotation is of the order of $\simeq 10 \, \text{s}$). Because of this there is no permanent generation of electron-positron plasma in the neutron star magnetosphere. Although the rotation of magnetic field, frozen into the star, generates the electric field in the magnetosphere, $E \simeq \nu_{e\alpha} B/c$, the electric field is not sufficient for the continuous production of electron-positron plasma. However, strong magnetic field and the electric field, induced by the rotation of magnetosphere of the neutron star, can lead to the burst of the production of electron-positron plasma under some external action. Such external action in the case of RRATs is the Galactic and extragalactic gamma rays with energies above $1 \, \text{MeV}$ according to mechanism of RRATs developed by Istomin and Sobyanin (2011a,b). Now a natural question arises: what will happen if magnetized neutron star rotates even more slowly ($P > \tau_1 \simeq 500 \, \text{s}$) than the neutron star which is the source of RRAT? There is strong magnetic field in its magnetosphere, but there is practically absent the electric field, which is necessary for acceleration of electrons and positrons in the magnetosphere and for beginning of a cascade plasma production process.

The electric field, $E \simeq uB/c$, can also arise in the magnetosphere when a sufficiently dense flow of charged particles moves through the magnetosphere with the velocity $u$. Thus, we come to the conclusion that if the source of FRB is a magnetized neutron star, which rotates slowly enough, and the birth of a relativistic plasma occurs in its magnetosphere, an external action is necessary to distort the magnetosphere and to create the electric field. The presence of a neutron star as a source of FRB is indicated by short duration of the burst of radio emission. Such an effect can be a flow of a sufficiently dense plasma. Note that from one flash to another flash the dispersion measure is not constant but varies within $3\%$ during the time $\tau_1 = 500 \, \text{s}$. This would correspond to the motion of electron density inhomogeneities of the size of $< 10^{13} \, \text{cm}$. This size is too small either for the Galaxy, or for mentioned intergalactic medium, but reflects the presence of plasma in the immediate vicinity of the neutron star. The characteristic values of plasma flow scale $L$ and its velocity $u$ can be estimated from the following relations. First, it is $L/u \simeq \tau_2 = 2 \cdot 10^6 \, \text{s}$. Second, we assume that the repetition time of the burst series $\tau_3$ is the orbiting period a dense body (planet, comet, asteroid) around the neutron star, $P_{\text{orb}} = \tau_3$. Since $\tau_2 \ll \tau_3$, the orbit of a body is strongly elongated. Therefore $u^2 L = 2GM_{\text{NS}} = 3.7 \cdot 10^{20} \, \text{cm}^3/s^2$. Here $G$ is the gravitational constant, and $M_{\text{NS}}$ is the mass of the neutron star, which we put equal to $1.4 \, M_{\odot}$. Thus, we have

$$L = 10^{13} \, \text{cm}, \quad u = 6 \cdot 10^6 \, \text{cm/s}.$$ (1)

3 ELECTRIC FIELD

As a result, the scenario of interaction of a dense body orbiting around the magnetized hot neutron star (for FRB 121102), looks like that: close pass of the body at the distance less than 1 a.u. causes evaporation from the body, and dense plasma flow around the magnetosphere of neutron star perturbing magnetic field in the polar region, and generating the longitudinal electric field. For
Replacing the transverse derivative of which exceeds the solar luminosity by 2\cdot10^7 times. The evaporated plasma has the temperature on the order of the temperature of evaporation of a solid body \( T_0 \approx 0.1\ eV \), and its thermal velocity \( \nu_T \) is equal to \((2T_0/\hbar)^{1/2} \approx 10^5\ cm/s\). Here we chose the mean atomic number of the evaporated ions to be of the order of \( A = 20 \), and \( m_p \) is the proton mass. Thus, \( \nu_T < < u \), and the velocity of the flow around the neutron star magnetosphere is approximately equal to \( u \). It should be noted that the temperature of the neutron star should not be too large, such that the radiation force acting on the ionized gas does not exceed the gravitational force, \( T_{NS} < (A\hbar c^3/2\pi^2\sigma)^{1/4} \approx 0.3 \cdot 10^8(A/Z)^{1/4}R_9^{-1/2}K \). Here \( \sigma \) is the Stefan-Boltzmann constant, and \( r_9 \) is the Thomson scattering cross-section. The pressure of the plasma flow destroys the magnetic field of the neutron star at distances from the center of the star larger than a certain distance \( r \) determined by equality of pressures, \( A\hbar c^3/2\pi^2\sigma = B(r)^2/\pi \). The value of \( Z_e \) is the average ion charge, \( A/Z \approx 10 - 20 \). We obtain \( B(r) = (8\pi A\hbar c^3/2\pi^2\sigma)^{1/2} \). The region of perturbed magnetosphere at the distance \( r \) from the star, called cusp, has size of the same \( r \). However, this size decreases to the polar oval of small size on the stellar surface. Electron-positron plasma fills this polar region by a cascade process described below. The magnetic field at the level \( r \) can be found from that the magnetic field of the neutron star at large distances is dipole, \( B = B_0(r/R)^{-3} \). Here \( B_0 \) is the value of the magnetic field on the surface of NS, \( B_0 = 10^12 B_{12} \), \( B_{12} = B_0/10^{12}G \). Thus, \( B(r) = 10^{12}B_{12}(r/R)^{-3} \approx 10^8 G \) for \( r = 10^9R \). The electric field induced in the polar region, \( E = uB/c \), is equal to \( 6 \cdot 10^9B_{12}(r/R)^{-3}V/cm \approx 60 V/cm \) for \( r = 10^9R \). Accordingly, the arising voltage in the cusp is equal to \( |\psi_0| = E_r = 6 \cdot 10^9B_{12}(r/3)^{-2}V \approx 6 \cdot 10^9 \) for \( r = 10^9R \). The magnetic field originates in the open region of the magnetosphere of the neutron star, in its polar region around the axis of a stellar magnetic moment \( M \). On the surface of the star this region is almost a circle of the radius \( R_0 \approx R(R/r)^{3/2} \approx 3 \cdot 10^3 \) cm. This polar circle is the same as in neutron stars, which are radio pulsars. Knowing the magnitude of the magnetic field \( B(r) \), we can determine the electron density \( n_e \) in the incoming plasma flow, \( n_e = n_0 = B^2(r)Z/8\pi A\hbar c^3 \approx 10^{23} \) cm\(^{-3} \) for \( r = 10^9R \). A small fraction of electrons from the incoming stream penetrates into the polar region of the magneto- sphere. Their flux \( S \) is equal to \( S = \pi n_0 u r^2 \approx 2 \cdot 10^{39} \eta^{-1}\) cm\(^2\). Here \( \eta \) is the efficiency of penetration of electrons into the polar magnetosphere, \( \eta << 1 \).

The electric field arising in the magnetosphere at the distance \( r \) penetrates deep into the magnetosphere in the polar region. Its dependence on the height \( h \) above the surface of the star can be determined by solving the Laplace equation in the region bounded by the surface of the radius \( r = h(r/h)^{1/2} \) with boundary conditions: \( \psi(h = r) = \psi_0 \), \( \psi(h = R) = 0 \), \( \psi(h, \rho = h(r/h)^{1/2}) = 0 \).

Replacing the transverse derivative \( \Delta_\rho \) by \( -(4r/h^3) \), we arrive at the equation
\[
\frac{\partial^2 \psi}{\partial h^2} + \frac{1}{\rho} \frac{\partial}{\partial \rho} \left( \rho \frac{\partial \psi}{\partial \rho} \right) = 0.
\]
The solution of this equation is \( \psi = \text{const} \cdot (h/r)^{1/2} K_1[4(h/r)^{-1/2}] \), where \( K_1(x) \) is the McDonald function of the first order. Since \( h/r < 1 \), \( x > 4 \), one can use asymptotic presentation of the McDonald function for large arguments. As a result, we have
\[
\psi(h) = \psi_0 \left( \frac{h}{r} \right)^{3/4} \exp \left[ -4 \left( \frac{r}{h} \right)^{1/2} + 4 \right].
\]

For the practical purpose the asymptotic presentation does not differ from the exact solution expressed by the McDonald function, and we will use the expression below. We see that the longitudinal electric field exists only in the upper part of the polar tube, \( r > h > r^* \approx 0.6r_0 \). The field is exponentially suppressed when approaching the star. Thus, electrons falling into the polar region at \( h \approx r \) are accelerated toward the star, \( \psi_0 < 0 \), and get relativistic energy equal to \( e|\psi_0| \), i.e. their Lorentz factor becomes equal to \( \gamma_0 = 1.2 \cdot 10^{11}B_{12}R_9(r/R)^{-2} \approx 10^9 \).

### 4 PRODUCTION OF ELECTRON-POSITRON PLASMA

Thermal photons with energies \( E_{ph} = m_e c^2 \) propagating from the stellar surface are scattered by relativistic electrons and produce high-energy photons with energies \( E_{ph} = m_e c^2 \epsilon' \),

\[
\epsilon' = \epsilon + 4\gamma^2 \frac{1 + \gamma^2 \theta^2 + 4\epsilon}{1 + \gamma^2 \theta^2 + 4\epsilon}.
\]

Here the angle \( \theta \) is the angle of propagation of a scattered photon with respect to the velocity of the relativistic electron. Since, as can be seen from (3), \( \epsilon' \) is large for photons scattered in the direction of propagation of the electron, \( \theta \approx \gamma^{-1} << 1 \), then we use the approximation \( 1 - \cos \theta \approx \theta^2/2 \). If we neglect the electron recoil, \( 4\gamma^2 < 1 \), then the maximum energy of the scattered photon \( (\theta = 0) \) is \( \epsilon_{max} = 4\gamma^2 \). For the Planck spectrum with the temperature of the magnetosphere the maximum energy density is at the photon energy \( E_{ph} = 2.82T_{NS}c^2 = 24T_{K} \). Here \( T_{K} \) is the stellar surface temperature in units of \( 10^8 K \), \( T_{NS} = T_{NS}/10^8 K \). Thus, the characteristic value of the thermal photon energy is \( \epsilon \approx 4.7 \cdot 10^{-2} T_{NS} \).

The value of \( 4\gamma^2 \) is equal to \( 2 \cdot 10^7 T_{NS} \). This means that for small scattering angles, \( \theta < \theta^* = 2(\epsilon/\gamma)^{1/2} \approx 1.4 \cdot 10^{-2} T_{NS}^{1/2} \), the electron completely loses its energy, \( \epsilon' = \gamma \). At larger angles, \( \theta > \theta^* \), the energy of the scattered photon is \( \epsilon' = 4\epsilon/\theta^2 \). The scattered photon \( \epsilon' \) propagates toward the star where the density of thermal photons increases \( \propto h^{-2} \), and the magnetic field also grows \( \propto h^{-3} \). Therefore it is possible to create electron-positron pairs by two ways: 1) in collisions of scattered photons with thermal photons moving towards, \( \epsilon' + \epsilon = \gamma' + \gamma^{-1} \), and 2) birth in magnetic field, when the scattered photon intersects the line of strong magnetic field at the angle \( \beta, \epsilon' \sin \beta > 2 \). It should be noted that in contrast to radio pulsars, energetic electrons \( \gamma \) and photons \( \epsilon' \) propagate toward the star, where the birth of pairs is more efficient, but not outwards. In addition, curvature photons, which play a major role in initiation of the cascade production of pairs in magnetospheres of radio pulsars, have small energies here and are incapable to produce pairs. Indeed, the energy of a curvature photon \( \epsilon_c \) is \( \epsilon_c = \lambda\gamma^2/\rho_c \approx 5 \cdot 10^{-4} \ll 1 \). Here \( \lambda \) is the Compton wavelength of electron, \( \lambda = h/m_e c = 3.86 \cdot 10^{-11} \) cm, \( \rho_c \) is the radius of curvature of magnetic field lines in the polar region, \( \rho_c = 4(rh)^{1/2}/3 > 4(rR)^{1/2}/3 \approx 7 \cdot 10^7 \) cm.

Let us consider the process of production of electron-positron pairs by scattered photons:

1) For the production of a pair in collision of a scattered photon with a thermal photon, \( \epsilon', \epsilon > 1 \), taking into account (3), we
obtain condition
\[ \theta < \left[ \left( 2\varepsilon - 2\gamma \right)^2 - 2\gamma^2 \right]^{1/2} \approx 2\varepsilon, \quad \varepsilon > \epsilon_1 = (2^{1/2} + 1)/2\gamma. \]

The inverse Compton scattering cross-section in the laboratory coordinate system, associated with the neutron star, has the form (Berestetskii, Lifshitz and Pitaevskii, 1982)

\[ \sigma = \frac{8\pi r_\gamma^2 \theta^2 d\theta}{(1 + 2\gamma^2 \theta^2 + 4\varepsilon)^2} \left[ \frac{1}{(1 + 2\gamma^2 \theta^2)^2} - \frac{1}{1 + 2\gamma^2 \theta^2} + \frac{1}{1 + \gamma^2 \theta^2} + \frac{1}{1 + 2\gamma^2 \theta^2 + 4\varepsilon} \right]. \]  

(4)

Here \( r_\gamma \) is the classical radius of an electron, \( r_\gamma = 2.82 \times 10^{-13} \text{ cm} \). Integrating the cross-section (4) over the angle \( \theta \) from 0 to \( \left[ (2\gamma \varepsilon - 1)^2 - 2\gamma^2 \right]^{1/2}/\gamma \), and then averaging over the Planck spectrum, we obtain the value of the thickness \( \tau \) gained by an electron moving toward the neutron star when it is scattered by thermal photons

\[ \tau = \int_0^\tau d\theta \int_0^\infty d\varepsilon / R \int_0^\pi d\phi / R \sigma = \frac{4a_1 r_\gamma^2 T^2 R}{\pi} \left( \frac{R}{h} - \frac{R}{r} \right)^2. \]  

(5)

The coefficient \( a \) is proportional to the integral of the scattering cross-section (4) over the Planck spectrum, starting from the photon energies \( e > (2\varepsilon + 1)/2\gamma \) to infinity. It depends on the electron energy \( \gamma \) and the temperature of the star \( n \), \( T = n \gamma \), cm. For parameters of interest, \( T_{9/5} \approx 1, \gamma \approx 10^5 \), the value of \( a \) is \( \approx 1 \). The coefficient \( 4a_1 r_\gamma^2 T^2 R / \gamma^3 \gamma \( \) in the right hand side of (5) is large, \( \approx 5 \times 10^{13} T_{9/5}^2 \gamma_{10^5}^{-1} R_{8} \) \( \gamma_{10^5} / R_{8} = R / 10^{6} \text{ cm} \). It means that the thickness \( \tau \) becomes of the order of unity fairly fast, \( (\tau^* - h)/h \approx 0.12 \), and the electron completely loses energy, emitting a gamma quantum with the energy \( \epsilon \approx \gamma \).

Let us now find the efficiency of production of electron-positron pairs produced by collisions of energetic photons \( \epsilon \) with thermal photons \( \epsilon \). The cross-section for pair production is (Berestetskii, Lifshitz and Pitaevskii, 1982)

\[ \sigma^\pm = \frac{\pi r_\gamma^2}{2} \left[ (3 - v^2) \ln \frac{1 + v}{1 - v} - 2v(2 - v^2) \right], \]

where \( v \) is equal to \( v = (1 - 1/\epsilon')^{1/2}. \) Again averaging over the Planck spectrum, starting from the energy \( \epsilon = 1/\epsilon' \), and assuming \( \epsilon' \approx \gamma \), we get the value of the thickness \( \tau_\epsilon \) gained by the gamma quantum of the energy \( \epsilon \) with respect to the production of a pair,

\[ \tau_\epsilon = \frac{b}{2\pi} r_\gamma^2 T^2 R \left( \frac{R}{h} - \frac{R}{R_8} \right). \]  

(6)

The numerical coefficient \( b \) for \( T_{9/5} = 1, \gamma = 10^5 \) is \( b \approx 25 \). Here \( h_1 \) is the initial height from which the gamma photon begins to move toward the star. We see that the birth of an electron-positron pair is even more effective, \( b/8a_1 \approx 3 \) times, than gamma-ray radiation by an electron. Thus, the primary electron, passing the distance \( \approx qr \), \( q \approx 0.12(1 + 1/3) = 0.16 \) through the thermal radiation, produces a pair with electron and positron energies \( \approx \gamma/2 \). In turn, a born pair produces a new pair in the photon field of the star. etc. So the cascade production of electrons and positrons occurs. The minimum number of possible cascades \( K \), if we do not take into account decrease of the energy of secondary electrons (\( \gamma \) in the expression (5)), is determined by the condition

\[ q = \frac{K}{\sum_{n=1}^{N} (1 - q)^n} = 1 - \frac{R}{R_8}. \]

Summing up, we obtain \( K + 1 = [\ln(R/R^*)]/[\ln(1-q)] \). Substituting characteristic values \( r^* \approx 6 \times 10^{12} R, q \approx 0.16 \), we find \( K \approx 35 \). Since \( 2^{12} \gamma \approx 3 \times 10^{10} \gamma_0 \), the number of pairs \( \lambda \) generated by one primary electron is determined by the relation \( \lambda \approx \gamma_0/2 \).

2. Now we consider the single-photon production of electron-positron pairs by scattered photons \( \epsilon \) in the magnetic field of the neutron star. We need to know the number of generated photons with energy \( \epsilon > 2 \). They are larger than the previously calculated density of energetic photons \( \epsilon > \epsilon' \approx 10^7 \), which collide with thermal photons to produce pairs. Expression (5) for the energy of scattered photons determines regions of angles \( \theta \) and energies \( \epsilon \) of primary photons,

\[ \theta < (2\varepsilon - 4\varepsilon \gamma - 1/2\gamma - 1/2\gamma) \approx (2\varepsilon)/\gamma, \epsilon > 1/2\gamma(\gamma - 2) \approx 1/2\gamma^2. \]

As before, using the cross-section (4), integrating over the Planck spectrum, we obtain expression for the thickness \( \tau_\gamma \),

\[ \tau_\gamma = \frac{4a_1 r_\gamma^2 T^2 R}{\pi} \left( \frac{R}{h} - \frac{R}{r} \right), \]  

(7)

where the constant \( a_1 = 3.8 \) in the region of parameters \( T_9 \approx 1, \gamma \approx 10^5 \). Thus, the mean free path \( l_\gamma \) of fast electron with respect to the production of secondary photons with energy \( \epsilon > 2 \) is 3.8 times smaller than the mean free path for production of energetic photons with energies \( \epsilon > 10^7 \), \( l_\gamma \approx 3 \times 10^{-2} R_8 \).

Scattered secondary photons emitted by electrons along magnetic field lines, and propagating toward the surface of the star, begin to cross magnetic field lines at an angle \( \beta \neq 0 \) due to curvature of magnetic field lines in the polar region of the magnetosphere. Thus, the angle \( \beta \) is equal to

\[ \beta = \int_0^{h_i} \rho e^{-1}(h ') d h' = \frac{3}{2} \left( \frac{h_i}{\tau} \right)^{1/2} - \left( \frac{h_i}{\tau} \right)^{1/2}. \]

Here the value of \( h_i \) is equal to the initial altitude, from which the photon begins to propagate. As we will see pair production occurs below the height \( h \approx 10R, h << r \). Because of this and because of strong dependence of the magnetic field strength on the height, \( B \propto h^{-2} \) angle \( \beta \) can be considered to be a constant, \( \beta \approx 3h_i^{1/2} / 2r^{1/2} \). The probability of pair production in the magnetic field per unit time is (Berestetskii, Lifshitz and Pitaevskii, 1982)

\[ w = \frac{3^{1/2} a_1 \sigma_0 \beta^2}{2^{9/2} \lambda} \sin \beta \exp \left[ -\frac{8}{3\epsilon^2 \beta^2 \sin \beta} \right] \Theta(\epsilon'), \sin \beta \right] - 2. \]  

(8)

The quantity \( b \) is the magnetic field intensity in units of the critical field, \( b = B / B_c, B_c = 4.4 \times 10^{15} G \), \( \alpha \) is the fine-structure constant, \( \alpha = 1/137, \Theta(x) \) is the stepwise theta function. The height \( h_i \), at which a pair is born with the probability \( \approx 1 \), is determined by the condition

\[ \frac{1}{\epsilon} \int_0^{h_i} d h' w(h', h') dh' = 1. \]

Setting \( \sin \beta \approx \beta \), we obtain

\[ \left( \frac{h_i}{R} \right)^{3} = \frac{9}{16} \epsilon b_0 \left( \frac{h_i}{h} \right)^{1/2} \Lambda, \]  

(9)

where the value of \( b_0 \) is \( b_0 = B_0 / B_{c1} = 2.3 \times 10^{-2} B_{c1} \), and

\[ \Lambda = \ln \left[ \frac{3^{1/6} R a}{2^{7/6} \lambda} (\epsilon')^{-2/3} b_0^{1/3} \left( \frac{h_i}{h} \right)^{1/6} \right] - \frac{5}{3} \ln \left[ \frac{3^{1/6} R a}{2^{7/6} \lambda} (\epsilon')^{-2/3} b_0 b_i^{1/3} \left( \frac{h_i}{h} \right)^{1/6} \right]. \]

The characteristic values of \( \Lambda \) are \( \approx 15 - 20 \). We see that photons
with energy \( \epsilon' \approx 5 \) produce electron-positron pairs only near the stellar surface, \( h \approx R \), while energetic photons, \( \epsilon' \approx 10^5 \), can produce pairs at a distance \( h/R \approx 30 \). After pairs are born, they lose their transverse momenta, emitting synchrotron photons with energy \( \epsilon_s \approx 3b\gamma^2 |\sin \beta|/2 = 3b_0/2 |\sin \beta| = 3b_0(r/h_s)^{1/2}/2 \approx 1 \). They can not produce new pairs. Thus, the cascade single-photon production of electron-positron pairs in a strong magnetic field in our case is actually absent, in contrast to the cascade production of pairs in magnetospheres of radio pulsars.

5 PLASMA TRAP

Thus, we see that primary electrons with the Lorentz factor of \( \gamma_0 \approx 10^3 \) effectively produce electron-positron pairs by directly interacting with thermal photons. In view of the cascade character of process, most of them have multiplicity \( \lambda \approx 10^5/2 \) and energies of \( \gamma \approx 1 \) with the energy spread of \( \Delta \gamma \approx 1 \). However, they do not reach the surface because the flux of thermal photons from the surface pushes them out. As a result, electrons and positrons are accelerated outward from the star,

\[
\frac{d\gamma}{dt} = \sigma_T \frac{\pi^2 e^4 T^4}{60 \lambda^2} \left( \frac{R}{h} \right)^2 .
\]

Here \( \sigma_T \) is the Thomson cross-section, \( \sigma_T = 8\pi r_e^2/3 \), and we substitute \( \sigma = \pi^2/60\hbar^3c^2 \) for the Stefan-Boltzmann constant in energy units. Integrating and setting \( d\gamma/dt = cd\gamma/dh \), we obtain

\[
\gamma = \frac{2\pi^3}{45} \frac{r_e^2 T^4 R}{\lambda^2} \left( 1 - \frac{R}{h} \right) .
\]

In the region \( R < h < r^* \), where there is actually no electric field \( \mathcal{E} \), secondary electrons and positrons get the energy \( \gamma_f \),

\[
\gamma_f = \frac{2\pi^3}{45} \frac{r_e^2 T^4 R}{\lambda^2} \approx 1.6 \cdot 10^4 T_h^4 R_6 .
\]

Positrons freely escape outside freely, while electrons obeying the condition

\[
\kappa = 0.6\gamma_0 T_h^4 R_6 > 1
\]

are reflected from the electric potential \( \mathcal{E} \) and become trapped. This trap is formed from one side by the electric potential created by the plasma flow in the magnetosphere, and the thermal radiation of the star itself from the other side. Electrons stop at the distance \( h = h_r \) from the star defined by the condition \( \gamma_f = e|\psi(h_r)|/m_e c^2 \),

\[
h_r = r \left[ 1 + \frac{1}{4} \ln \kappa + \frac{3}{8} \ln \left( 1 + \frac{1}{4} \ln \kappa \right) \right]^{-2} .
\]

After reflection electrons begin to move toward the surface of the star under the action of the trapping potential \( \psi(h) \), and, if it were no interaction with thermal photons moving toward them, they would come to the stellar surface with the energy corresponding to the Lorentz factor of \( \gamma_0/\kappa \). However, they emit gamma quanta, which produce new electron-positron pairs, are decelerated to non-relativistic energies and are picked up again by the radiation of the star. The force acting on electrons moving outward from the star is potential since the cross-section for scattering of thermal photons is equal to the Thomson cross-section, which does not depend on the electron energy. Corresponding potential \( \psi_T \) is equal to

\[
\psi_T = m_e c^2 \frac{\gamma_f R}{\hbar} .
\]

Fast radio bursts

Figure 1. The logarithms of the potential \( \psi_T \) acting on electrons from the thermal stellar radiation (dot-dash line), of the potential \( e|\psi(h)| \) (Eq. 2) (dotted line) and of the total potential \( e|\psi(h)| + \psi_T \) (solid line) as functions of the height \( h \).

The plot of the potential \( \psi_T/e|\psi| (\kappa = 3) \) is shown in Figure 1. Figure also shows the potential of the electric field \( \psi/h \) (Eq. 2) and the total potential \( e|\psi(h)| + \psi_T/e|\psi| \). As a result of pair production, electrons are accumulated at the bottom of the potential well formed by the total potential \( e|\psi(h)| + \psi_T(h) \). The location of the bottom, \( h_m \), is equal to (with logarithmic accuracy)

\[
h_m = r \left[ 1 + \frac{1}{4} \ln \kappa + \frac{1}{4} \ln \left( \frac{2r}{R} \right) \right]^{-2} < h_r ,
\]

Thus, a primary electron with energy \( \gamma_0 \), after almost reaching the surface of the star, and losing its energy, returns back, receiving from thermal photons energy less than the original one, \( \gamma_0/\kappa \), then again moves toward the star and again produces quanta and pairs until it settles near the height of \( h_m \). The multiplicity, i.e. the number of generated electrons per one primary electron, increases as \( \lambda \approx \gamma_0 \kappa /2(\kappa - 1) \). It should be noted that the decelerating force acting on an electron when it moves toward the star is not conservative, since the scattering cross-section is inversely proportional to the electron energy, \( \propto \gamma^{-1} \), as can be seen from expression 5.

Therefore, the motion of energetic electrons toward the star is not the motion in the total potential \( e|\psi(h)| + \psi_T(h) \). Their deceleration occurs faster, \( d\gamma^2/dh \propto h^{-2} \), but not \( d\gamma/dh \propto h^{-2} \) as for the motion in the potential \( \psi_T \). But for subrelativistic electrons, \( \Delta \gamma \approx 1 \), located near the bottom of the potential well, the cross-section for scattering of thermal photons is the Thomson one, and their motion is potential in the potential \( e|\psi| + \psi_T \).

The thickness of the layer \( \Delta h \), where electrons are accumulated, is small. It is determined by the spread of electron energies near the surface of the star after production of gamma-quanta and pairs, \( \Delta \gamma \approx 1 \).

\[
\Delta h = h_m \left( \frac{2\gamma_f}{\lambda} \right) \left( \frac{h_m}{r} \right)^{1/2} \ll h_m .
\]

This layer creates an additional electric potential \( \psi_{sh} \). The equation for the potential \( \psi_{sh} \) is as follows

\[
\frac{d^2 \psi_{sh}}{d\bar{h}^2} - \frac{4r}{h^3} \psi_{sh} = en_i(h) \frac{4r}{\hbar^3} ,
\]

where \( n_i(h) \) is the electron column density associated with the density \( n \) by the relation \( n_i = \pi n \hbar^3/r \) due to the dependence of the cross-section of the magnetic tube \( s \) on the height, \( s = \pi \hbar^3/r \). Since the thickness of the electron layer is initially small, we can assume \( n_i = N_i \delta(h - h_m) \), where \( \delta(x) \) is the Dirac delta function.
Positrons are trapped into the well \( \psi_{sh} \), if the condition \( \nu_p \tau_p > 1 \) is satisfied, where \( \tau_p \) is the time of passage of positrons through the plasma layer, \( \tau_p = (h_m/r)^{1/2}/c \). Let us show for characteristic values of quantities that the condition \( \nu_p \tau_p > 1 \) is satisfied already at low densities of the plasma in the layer. We take characteristic values: \( h_m \approx 10^3 \text{cm}, r \approx 10^5 \text{cm}, s_m = \pi h_m/r \approx 3 \cdot 10^{15} \text{cm}^2, \tau_p = (h_m/r)^{1/2}/c \approx 10^{-3} \text{s}, \lambda \approx 10^{3} \text{cm}, \gamma^+ \approx 3 \cdot 10^2, \omega_p = 5.6 \cdot 10^4 n_s^{1/2}, n_s = S\lambda/s_m c \approx 2 \cdot 10^{18} \text{cm}^{-3} \).

As a result we obtain the condition

\[
n_p > 2 \cdot 10^{16} \left( \frac{n_b}{1 \text{cm}^{-3}} \right)^2 \text{cm}^{-3},
\]

which is obviously valid for \( n_p > n_b/\gamma^+ \approx 10^5 \eta \text{cm}^{-3} \). Thus, we see that the thin layer of width \( (h_m/r)^{1/2} \) arises in the polar region, where all electrons and positrons produced in the polar magnetosphere are accumulated. Plasma is practically neutral, subrelativistic electron-positron plasma in this layer. Electrons are confined there by the locking potential \( \psi \) (Eq. 2), while positrons are held by confined electrons.

There is slight displacement of the position of the plasma layer from the height \( h = h_m \). Indeed, the drag force of the thermal radiation of the star becomes twice larger than the drag force acting separately onto electrons and positrons. In the expression for the value of \( h_m \) it is necessary to replace \( \kappa \) by \( \kappa/2 \). As a result, the shift of the position of the plasma layer \( \Delta h_m \) is equal to

\[
\frac{\Delta h_m}{h_m} = \frac{\ln 2}{2} \left( \frac{h_m}{r} \right)^{1/2} \left[ 1 - \frac{5}{8} \left( \frac{h_m}{r} \right)^{1/2} \right] \approx 0.1.
\]

6 BURST

Electron-positron plasma constantly accumulates in the layer. The number of pairs \( N \) grows linearly with time, \( N = S\lambda t \approx 2 \cdot 10^{14} \text{gt} \). Accordingly, the plasma column density \( \int n_p dh = N/s_m = N\tau_r/\pi h_m^3 \approx 6 \cdot 10^{26} \text{ne} \text{cm}^{-2} \) grows. The thickness relative to scattering of the thermal radiation of the star by the electron-positron plasma of the layer, \( 2\sigma_T \int n_p dh \), grows also with time, and becomes equal to unity at time \( t^* = s_m/2Sn\tau_r \approx 10^{-5} \text{yr}^{-1} \). This means that the light of the star will start to reflect effectively from the plasma layer. If the reflection coefficient from the layer and the surface of the star is \( \eta \), then the energy density of the thermal radiation in the polar region under the plasma layer will begin to grow exponentially with the characteristic time \( 2h_m/c_n \approx 10^{-2} \eta \text{c}^{-1} \text{s} \). Effective temperature of trapped radiation \( T_{eff} \) will grow in time until radiation pushes the plasma layer outside the magnetosphere. This happens when the radiative force acting on an electron and a positron of the plasma layer, \( 2\sigma_T T^4/(r^2/c) \), at the height \( h = r \) becomes equal to the force acting on electrons from the locking potential at the same height, \( ed\psi/dh \big|_{h=r} = 11c \psi_0/4r \). As a result, we have

\[
T_{eff} = 10^8 K \left( \frac{11r}{8R} \right)^{1/4} \approx 10^5 K.
\]

The released energy can be estimated as the energy of thermal radiation of the neutron star accumulated during time \( \tau_1 \), \( \mathcal{E} > \pi \sigma \tau_1 \gamma \cdot 10^8 \text{erg} \). Here we chose the minimum area of trapped radiation, \( s_R = \pi R^2/r \approx 3 \cdot 10^{24} \text{cm}^2 \), which corresponds to the area of the polar region on the stellar surface. At height \( h = h_m \) the area of trapped radiation is much larger, \( s_m \approx 3 \cdot 10^{15} \text{cm}^2 \). In view of the rapid growth of the energy of trapped stellar radiation, ejection of the plasma layer will occur during a
short time period \((r - h_m)/c \approx 3 \times 10^{-2}\) s. Therefore, the power \(W\) of energy release is equal to \(W = cE/r > 3 \times 10^{41}T_8^6\) erg/s. Apparently, the radio emission mechanism here is the same as in radio pulsars - direct flux of a relativistic electron-positron plasma is a source of radio waves. For radio pulsars an average value of the coefficient of transformation of the kinetic energy of the electron-positron plasma into the energy of the radio emission \(\alpha_r\) is \(\alpha_r \approx 10^{-3}\) (Beskin, Gurevich and Istinom, 1993). Thus, the energy radiated in the radio range \(E_r\), is equal to \(E_r \approx 10^{40}T_8^6\) erg. It is considerably smaller than the estimate given in the beginning of the paper, \(E_r \approx 10^{40}\) erg. The latter value was obtained under the assumption that the radiation is isotropic and has no directivity. It is clear, however, that electrons and positrons, which received energy from the flux of photons at the altitude \(r\) from the surface of the star, have directional motion with spread over angles \(\Delta \theta = R/r \approx 10^{-3}\). Besides, the radio emission will have the directivity \(\Delta \theta \approx \gamma^{-1}\), where \(\gamma\) is the Lorentz factor of accelerated particles. The force \(\sigma \gamma E \lambda /c \approx 1.3 \times 10^{-13}T_8^6\) cm will lead to acceleration inside the region \(r \approx 10^8\) cm up to the energy \(\gamma \approx 2 \times 10^9\). This value will determine the directivity of the radio emission. \(\Delta \theta \approx 5 \times 10^{-3}\). It should be noted that this value of directivity follows from observations of the source FRB 121102. The observed breaks in the series of bursts have approximately the same duration as the series themselves. If one interprets breaks as departures of the polar region from the line of sight of the observer due to rotation of the star with the period \(P\), then \(P \approx \tau_2 \approx 20\) d. The radiation directivity of \(\approx 10\gamma_1/\tau_2 \approx 2.5 \times 10^{-3}\) agrees well with the value of \(\gamma\), the energy of accelerated electrons and positrons produced in the polar cap of the magnetosphere of the star. Taking into account such directivity, the effective energy radiated in the radio range will increase \(4/\Delta \theta^2 \approx 6 \times 10^5\) times, when recalculated to the total solid angle 4\(\pi\), which gives \(E_r \approx 6 \times 10^{41}\) erg. This is sufficient to place a source of FRB at cosmological distances. As for the duration of the burst \(\tau\), it is defined by the size of the region of acceleration of the plasma layer and its thickness \(\approx r \approx 10^8\) cm, and by the Lorentz factor of accelerated electrons and positrons, \(\tau \approx (r/c)/\gamma\). For \(\gamma = 2 \times 10^4\), the value of \(1/\gamma = \ln(\gamma)/\gamma\) is \(\approx 3 \times 10^{-2}\). Thus, the time \(\tau \approx 10^{-3}\) s is in agreement with the time observed in FRBs.

### 7 DISCUSSION

From observations of the repeated source FRB 121102 we conclude that there exists a hierarchy of quasiperiods \(\tau_1 \approx 500\) s; \(\tau_2 \approx 2 \times 10^8\) s \(\approx 20\) d; \(\tau_3 \approx 2 \times 10^7\) s \(\approx 200\) d in its radio emission. The time \(\tau_1\) is the time between consecutive bursts. Probably, because of the high power of the bursts, this is the time of accumulation of energy, which is then released during short time, considerably less than \(\tau_1\). Time \(\tau_2\) is the duration of a series of bursts and also the duration of long breaks between bursts in the series. Finally, the time \(\tau_3\) is the average time of recurrence of bursts. Short burst time \(\tau \approx 10^{-3}\) s tells us about compactness of the source of radiation, apparently, a neutron star.

Neutron star observed as radio pulsars have strong magnetic field \(B_0 \approx 10^{12}\) G and small rotation periods \(P \approx 10^{-3}\) s. The electric field, which has nonzero projection onto magnetic field, arises in the magnetosphere due to the rotation of a magnetized body. This occurs in the open magnetosphere, in which magnetic field lines reach the light cylinder surface \(c/\Omega_{NS}\). Near the stellar surface the polar cap is formed, in which continuous generation of the electron-positron plasma and the electric current takes place. For fixed value of the magnetic field \(B_0\), continuous plasma generation is possible for sufficiently fast rotation of the star, \(P < (B_0/10^{12}\) G\)\(^{8/15}\) s. The radio emission from a pulsar is due to the flow of relativistic plasma in the open magnetosphere (Beskin, Gurevich and Istinom, 1993). The energy of radio emission is a small fraction of the energy of the plasma flow, which in turn is fed from the energy of rotation of the star. Continuous plasma generation becomes impossible for slower rotation. However, plasma generation can occur in flares, as it is in the case of RRATs. The electric field in the polar magnetosphere begins to accelerate electron-positron pairs produced by accidental energetic gamma quantum. This leads to a cascade plasma production and to a flash of radio emission. For even slower stellar rotation the electric field, \(E \approx \Omega_{NS}B_0/c\), is not sufficient for cascade plasma production in the magnetosphere. However, the external action of plasma flow, having velocity \(v\) relative to the neutron star, produces sufficiently strong electric field. It generates cascade plasma production in the polar magnetosphere. The process of plasma birth in this case has special characteristics in comparison with the one, which takes place in the magnetosphere of a radio pulsar. Acceleration of electrons, injected from the plasma stream into the magnetosphere, occurs toward the star (Aurora). In this case the production of gamma rays by inverse Compton scattering of thermal photons is most efficient. The multiplication factor \(\lambda\) (the number of pairs per one primary electron) reaches the value of \(10^5\). Created electron-positron plasma is accumulated in the polar magnetosphere in the form of a thin layer in the region of a minimum of the total potential created by the electric field, which is generated by flowing plasma, and the radiation pressure of the thermal radiation of the star (see Fig. 4). The electron-positron plasma density in the layer increases linearly with time until the reflection of thermal photons from the layer becomes so large that the layer becomes a mirror for the thermal radiation. After that the effective temperature of radiation of the star under the mirror begins to grow exponentially up to the value of \(T_{eff} \approx 10^{15}\) K. Finally, the stellar radiation pushes the electron-positron layer outward overcoming the external blocking electric potential for a short time \(\approx 3 \times 10^{-2}\) s. A "hole" in the magnetosphere of a neutron star and in the stream of plasma flowing around the star forms. Accelerated up to energies \(\gamma \approx 2 \times 10^4\), the flow of electrons and positrons generates radio emission by the mechanism analogous to the mechanism of radio emission from pulsars. It is worth noting that the Lorentz factor of accelerated plasma is the same as in the secondary electron-positron plasma in the magnetosphere of a pulsar. Because the flow is relativistic, the radio emission is directed into a small solid angle, \(6 \times 10^{-5}\) times smaller than \(4\pi\). This allows for the total energy of the burst, radiated in the radio range, \(E_r \approx 10^{40}\) erg, to appear as effective energy of isotropized burst more than five orders of magnitude higher, \(E_{eff} \approx 10^{41}\) erg. Duration of radio emission \(\tau\) is small, \(\tau \approx 10^{-2}\) s, also because of relativistic nature of the plasma flow.

It should be noted that this region of polar magnetosphere, \(h \approx h_m\), is a source of gamma radiation in the range of annihilation of gamma quanta \(n_\gamma = n_\nu\). Correspondingly, almost isotropic flux of gamma radiation from the layer in the annihilation line is, \(S_\gamma = n_\gamma c s m \approx 10^{12}\) s\(^{-1}\), and the luminosity in annihilation line is \(\approx 10^{36}\) erg/s.
Figure 4. Scheme illustrating flowing up of a magnetosphere of a magnetized neutron star by a plasma. Thin layers of electron-positron plasma are formed in polar regions. Thermal radiation of the star is locked by these layers.

8 ACKNOWLEDGMENTS

This work was supported by Russian Foundation for Fundamental Research, grant numbers 15-02-03063 and 16-02-00788.

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