Amazing properties of giant pulses and the nature of pulsar’s radio emission

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Abstract. For comprehensive studying of giant pulses (GPs) from the Crab pulsar and the original millisecond pulsar (MSP) B1937+21 (J1939+2134), we conducted multifrequency observations over the last few years. They show that giant pulses may be improbably bright, $10^5 - 10^6$ Jy and more, they have extra ordinal spectra and polarization. EM energy concentrated in such strong pulse is high enough to accelerate particles up to Lorentz factor $\gamma \sim 10^4 - 10^6$, since giant pulses may play an important role in physics of pulsar’s magnetosphere.

1. Introduction

Giant pulses (GPs) are a very specific class of single radio pulses observed in several pulsars which have power law intensity distribution, while normally the distribution is of exponential type. Therefore, sometimes one can detect a pulse exceeding by many times a normal pulse intensity. However, the time of occurrence of such events is unpredictable, it makes very difficult their search and investigation. At the moment giant pulses are detected or suspected in nearly a dozen of pulsars, but only two, the Crab pulsar and the original millisecond pulsar (MSP) B1937+21 (J1939+2134), have the rate of GP occurrence sufficiently high for good statistics and more or less detail study of this phenomenon. During few last years we conducted many observations of giant pulses from these pulsars over a wide frequency range from 20 MHz to 5 GHz, single and multi frequency/station. The observations were made in collaboration with many observatories and observers: Kalyazin observatory with 64-m dish, Yu. Ilyasov V. Oreshko; Arecibo 305-m telescope, T. Hankins; 100-m GBT, Yu. Kovalev, F Ghigo (NRAO GB); ARO (40-m dish in Canada), N. Bartel, W. Cannon, A. Novikov (York University); WSRT, B. Stappers (NFRA); UTR-2 decametric telescope, O. Ulyanov, V. Zakharenko (Ukrainian Institute of Radio Astronomy). An important feature of these observations is a long time continuous record with high time resolution (the latter is necessary because giant pulses are very short, see below, paragraph 2.2). We used standard VLBI terminals Mk5A (Kovalev et al. 2005), Canadian S2 and Japanese K5 as high performance and large capacity data acquisition systems. They provide time resolution 8–16 ns and 6–12 hours continuous record. Raw data were then encoded and processed for coherent dedispersion.

In section 2 we describe briefly main results of these observations, the most important is that the peak flux density of giant pulse may reach improbable huge value $10^5 - 10^6$ Jy more. The interaction of such strong EM wave with plasma particles is very specific (section 3.1). In particular, a strong wave may work as effective particles accelerator. In the sections 3.2, 3.3 we discuss a probable origin of giant pulses and their role in physical processes inside magnetosphere.

2. Observational properties

2.1. Waveform and time duration

Giant pulses from MSP B1937+21 initially are extremely short, less than 10 ns (Kondratiev et al. 2006, Soglasnov et al. 2004). Their apparent waveform and time duration are caused completely by interstellar scattering. Only several pulses from the analyzed few thousands can be suspected as having some structure other than scattering waveform (Fig. 1).

Waveform and duration of the Crab giant pulses depend on their strength. Weak and medium GPs generally have complex structure. The total duration may reach few decades of microseconds (Fig. 2). However, giant pulses with peak flux density exceeding some critical value (300 kJy at 1.4 GHz) are also very short. They consist of one or two narrow peaks, sometimes with weaker pedestal of $1 - 2 \mu s$ duration (Fig. 3, 4).
2.2. Intensity

Obviously power law distribution of giant pulse intensity can not be continued up to zero as well as to the infinity, it must have cutoff both at low and high energies (or, at least, strong break in power index: flattening at low and steepening at high energies). Low intensity flattening of the distribution for Crab giant pulses was recently detected by Popov & Stappers [2006]: $E_{\text{break}} = 1000 - 3500 \text{ Jy} \cdot \mu \text{s at } 1.2 \text{ GHz}$.

In case of MSP the limit is far below GP detection threshold, since it cannot be observed directly. However, it may be derived under adoption that power law distribution is valid up to this limit (Soglasnov et al. 2004): $S_{\text{min}} = 16 \text{ Jy (main pulse)}$, $S_{\text{min}} = 5 \text{ Jy (interpulse)}$ at 1.2 and 1.6 GHz.

As for high intensity limit, the situation seems to be rather intriguing. Now there are no indications on the deviation from power law distribution up to the improbable high intensity. Giant pulses from the Crab pulsar with peak flux density exceeding million jansky (1 M Jy) were detected at 2.2 and 1.4 GHz in observations conducted in 2005 year (Fig. 1, 2). Such events are not something exclusive, they normally occurred in each session if the observing time was sufficiently long, in accordance with power law distribution. At the moment we have caught a half of hundred “millionaires” over total 30 hours. It is difficult to provide much more longer observing time which is needed to detect more intense pulses, because of huge volume of data. We tested at Kalyazin the system for long time multi frequency monitoring of the Crab total power without any dispersion removal, which can provide detection the strongest giant pulses. Few days of probe observations show that the system works properly. We plan to start regular monitoring at 5, 1.4 and 0.6 GHz in September 2006.

2.3. Polarization

The emission of narrow giant pulses is strongly polarized, up to 100 % of linear, circular (may be of both signs), elliptical, either pure or variously mixed. In itself it is not very surprisingly, because their extremely short duration means that the emission originates from very compact region, since particles are emitting under the same physical conditions. What is really marvelous, that giant pulses show rapid changes of polarization over a very short time interval. Thus, two peaks separated by only few decades of nanoseconds (since close spatially) may have quite different polarization (Fig. 4, 5). Moreover, polarization may change rapidly inside a single narrow component, from circular to linear and opposite, or/and circular polarization may change the sign. It seems improbable that the conditions change considerably at so small scale ($\sim 1 - 10 \text{ m}$). The only explanation we can propose at the moment is that the emission may be produced by stratified particles of opposite sign of charge (e.g. electrons and positrons), as a result, few spikes alternatively RCP and LCP polarized are generating, many of them are undistinguishable with our time resolution. Similar picture was observed by Hankins et al. (2003) at higher frequencies.

2.4. Spectra

In average, giant pulses have nearly power law spectra. For MSP the spectral index equals -2.8. For the Crab pulsar, the spectrum becomes slightly flattened at higher frequencies, it changes from $-2.7$ (at frequencies below 1GHz) to $-1.8$ (between 1.4$ - 2.2$GHz).

Instant spectra of single pulses, obtained in simultaneous multi frequency sessions, are very different. The spectral index change within wide limits from $+0.4$ to $-4.0$ (Popov et al. 2006b). Only one third of events occur simultaneously at widely spaced frequencies. Partially it can be explained by interstellar scintillations, but it is not a main reason, as it follows from simultaneous observations of the Crab at 600 and 111 MHz, where the receiver band-pass exceed greatly decorrelation band, since interstellar scintillations do not affect considerably on the apparent strength of GPs. Detail analysis shows that spectra of single giant pulses cover a wide frequency range but not continuously. They represent chains of spots or bands, which parameters are inconsistent with usual ISS; probably they are intrinsic giant pulse structure. The most remarkable examples are quite exclusive spectra of the Crab giant interpulses with discrete regular structure observed at Arecibo at frequencies higher than 5GHz (Eilek & Hankins 2006).

3. Giant pulses and pulsar's physics

3.1. Giant pulses as strong EM waves

Megajansky intensity of GPs detected in the Crab pulsar looks rather impressive, however, are these pulses really giant with physical point of view? There are several different criteria for the strong EM wave. The top is Schwinger’s quantum limit, when the field strength of EM wave exceeds a critical value $4.4 \times 10^{13}$ Gs. Such wave can create $e^+e^-$ pairs. It is convenient to measure the wave field strength $E_w$ in (angular) frequency units $\omega_w \equiv eE_w/m_e c = eH_w/m_e c$, then the Schwinger’s limit can be written as $\hbar \omega_w >> m_e c^2$. The next criterium is condition $\omega_w > \omega$, where $\omega$ is wave frequency. It means that the motion of charged particles under the action of EM wave becomes relativistic, such wave accelerates particles nearly up to the speed of light over a single wave cycle.

From the observed peak flux density $S_{Jy}$ we can estimate $\omega_w$ at the distance $l_{cm}$ from the region of GP emis-
Fig. 1. Example of rare occurred multi component giant pulse from MSP B1937+21, f=2.2 GHz, as it seen in two polarization channels. The first component has nearly total circular polarization of one sign (LCP). A leading edge of the second component also 100% circularly polarized, but of opposite sign (RCP). Polarization changes the sign at the middle of second component.

Fig. 2. Example of extent giant pulse from the Crab pulsar, detected at 2.2 GHz, ∆ν = 16 MHz, displayed in total intensity (blue), linear (red) and circular (magenta) polarization.

The relation is

ω_w ≈ 4.9 \cdot 10^{12} \frac{L_{kpc}}{l_{cm}} \sqrt{S_Jy \Delta \nu},

where L_{kpc} is the distance from the Earth to the pulsar in kiloparsecs, ∆ν is the frequency band. This estimate is obtained without any arbitrary adoption such as dimension of GP source, beam pattern of the emission etc., it based only on the inverse square law, which is valid at least up to the boundary of wave zone. Even strongest “MegaJansky” Crab pulses detected at 2.3 and 1.4 GHz are far below the Schwinger’s limit, however, they satisfy to the condition ω_w > ω, which is valid up to the distance 10^{10} – 10^{11} cm from the emitter, or ≃ 100 radii of the light cylinder. Since inside magnetosphere pulses are “really giant”: if suppose that they are emitted near the star’s surface, the ratio ω_w/ω ≥ 100 even at light cylinder, 10^3 – 10^6 cm near the emitter (at 10^4 – 10^6 cm). This ratio may be much more for giant pulses at low frequency 23 MHz: if adopt the true (non-scattered) pulse duration of order 1 μs, ω_w/ω ∼ 10^4 at light cylinder and ∼ 10^6 close to the emitter.

Under condition ω_w/ω > 1 the interaction between EM wave and plasma particles becomes very specific. The wave accelerates particles up to the Lorenz factor γ ∼ ω_w/ω. Particles emit secondary waves at different frequencies and in different directions than the incident wave. Thus, in the simplest case of circularly polarized wave, trajectory of particles is a circle of radius λ/2π (λ is wavelength), the plane of the circle coincides with the wavefront. Particles emit at frequency ω_{em} ∼ ω γ^2 ∼ ω^2/ω under right angle to the direction of the incident wave propagation within a small angle ∼ γ^{-1} ∼ ω/ω_w.

The case of linearly polarized wave is more complicate. Particles move along trajectory of eight-like shape in the plane which is normal to the wave front, the trajectory crosses itself at the center under angle 51°. γ-factor changes along trajectory from 1.03 \omega_w/ω in the middle to 0.36 \omega_w/ω at the edges of trajectory.

Fig. 3. Example of extremely bright linearly polarized giant pulse from the Crab pulsar, S_{peak} = 5.4 MJy, detected at 2.2 GHz, ∆ν = 16 MHz, displayed in total intensity (blue), linear (red) and circular (magenta) polarization.

Fig. 4. Example of extremely bright double giant pulse from the Crab pulsar, S_{peak} = 4.2 and 7.3 MJy, detected at 2.2 GHz, displayed in total intensity (blue), linear (red) and circular (magenta) polarization. Both components have almost 100% polarization, the first circular and the second linear.
Some evidence of the existence of such “perpendicular” emission is a dramatic transformation of the Crab pulsar profile at high frequencies (Moffet & Hankins 1996) where two strong wide components HFC1 and HFC2 appear, they are spaced by $51\degree - 54\degree$ in longitude, the longitude of HFC2 is $-90\degree$ relative the main pulse. They may be interpreted as counterparts of giant pulses emitted at lower frequencies, as the sum of large number of short duration bursts (“secondary giant pulses”), in accordance with the results obtained by Sovakovska et al. (2006). Final confirmation may be obtained from polarization measurement of single pulse HFC emission with high time resolution.

In presence the magnetic field of strength $H$, in case of wave propagation along field lines (the case important for pulsars), the particles accelerated by the wave are orbiting with frequency $\omega_H \equiv eH/m_e c = 1.78 \times 10^7 H$. They emit synchrotron radiation at frequency $\omega_{em} \sim \omega_H^2 \omega / \omega^2$. Near star’s surface $H \sim 10^{12} \text{Gs (Crab)}$ and $\sim 10^{8} \text{Gs (MSP B1937+21)}$, since synchrotron quants have energy $\sim 10^{12}$ and $\sim 10^{16} \text{eV}$ correspondingly, which is far above threshold $e^+ e^-$ pair creation by quants in magnetic fields near surface of these pulsars. This mechanism is much more effective than traditional curvature radiation, because synchrotron quants are emitting under right angle to the field lines, while curvature quants are emitting along the tangent field line. Thus, giant pulse may work as effective particles’ accelerator and is able to induce cascade pair creation. Moreover, under some conditions giant pulse becomes self-generating, see below, section 3.2.

### 3.2. Where and how giant pulses are emitting

All stated above are observational results and their direct consequences. Now we concern briefly more speculative question on the origin of giant pulses. In the frame of standard model of pulsar’s magnetosphere it seems rather unlikely that giant pulses originate from the region located far from the star’s surface, where the energy of radiation per unit volume, corresponding to megajansky peak flux, exceeds by many orders the density of plasma energy. By this reason giant pulses surely cannot arise near the light cylinder. The only place where sufficient number of particles have sufficient energy to produce giant pulse is a polar cap near star’s surface. Perhaps, a cause of giant pulses is the gap discharge, they are directly observed effect of the discharge. If so, we can suppose the follow scenario. The first giant pulse may be born when the gap potential reaches some critical value, strong currents begin to run across the polar cap generating strong EM emission. As described above (in the section 3.3.1) interaction between strong EM wave (“giant pulse”) and charged particles leads in a strong magnetic field to the $e^+ e^-$ pair creation. Because this mechanism is very effective, immediately cascade pair creation develops very fast in a small volume, begetting rapidly rising volume charge, in turn, it generates strong EM emission (“secondary” giant pulse), which accelerates particles, particles emit high energy synchrotron quants which produce $e^+ e^-$ pairs, and so on.

### 3.3. What will happen afterwards

The rate of pair production drops rapidly when the wave and particles move away from the star’s surface both because of the emission dilution and decreasing the magnetic field strength. However, as before, the wave is capable to accelerate particles over the whole path inside magnetosphere up to light cylinder. It leads to the development of strong plasma instabilities, as a result, a “normal” pulsed radioemission is generating by usual plasma mechanism.

Pulsars with long period have a large light cylinder radius, the energy of EM wave (“giant pulse”) propagating over such long path, converts entirely to the “normal” pulsed emission. It is the reason why giant pulses are not observed in the majority of long period pulsars.

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