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Giant Pulses of Pulsars Radio Emission

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Abstract A brief review of observational manifestation of pulsars with giant pulses radio emission, based on reference data and our detections of three new pulsars with giant pulses.

Key words: stars: neutron — pulsars: general

1 INTRODUCTION

Giant pulses (GPs) are short-duration burst-like sporadic increases of intensity of individual radio pulses from pulsars.

This is a most striking phenomenon of pulsar radio emission. For normal pulsars, the intensity of single pulses varies by no more then one order of magnitude (Hesse & Wielebinski 1974; Ritchings 1976). GPs peak flux densities can exceed hundreds and even thousands of times the peak flux density of regular pulses.

GPs are the brightest sources of radio emission observed in the Universe. The brightness temperature may be as high as 10^{39} K.

This rare phenomenon has been detected only in 10 pulsars out of more than 1500 known ones. The firsts of them to be discovered were Crab pulsar PSR B0531+21 (Staelin & Reifenstein 1968; Argyle & Gower 1972; Gower & Argyle 1972) and the millisecond pulsar PSR B1937+21 (Wolsczcan, Cordes, & Stinebring 1984). Giant pulses of these pulsars were detected associated with the interpulse as well as with the main pulse.

For over 20 years only these two pulsars were known to emit GPs. In the last decade GPs emission from a further 8 pulsars has been detected. They are millisecond pulsars PSR J0218+42 (Joshi et al. 2004), PSR B0540–69 (Johnston & Romani 2003), PSR B1821–24 (Romani & Johnston 2001), PSR J1823–3021 (Knight et al. 2005), and PSR B1957+20 (Joshi et al. 2004), and ordinary pulsars PSR B0031–07 (Kuzmin et al. 2004), PSR B1112+50 (Ershov & Kuzmin 2003), and PSR J1752+2359 (Ershov & Kuzmin 2005).

Giant pulses are distinguished by a number of characteristic features. They possess a very large excess of flux and energy of radio emission relative to average pulses, the energy distribution of GPs has a power-law statistic, GPs occur in a narrow-phase window of an average pulse (except of the Crab pulsar for which GPs can occur anywhere within the average pulse) and have a short pulse time-scale as compare to an average pulse.

The shape of GPs at low frequencies may be governed by the scatter broadening of a pulse due to multi-path propagation in the interstellar plasma. Therefore a pulse width may not be a working definition of giant pulses.

2 OBSERVATIONS

Giant pulses are observed as very strong pulses of pulsar radio emission standing out of the noise background and underlying ordinary weak individual pulses. An example of one GP of the Crab pulsar observed at frequency 111 MHz inside of 150 pulsar periods is demonstrated in Figure 1.

GPs occurs both as a single spike as well as groups of several strong pulses.

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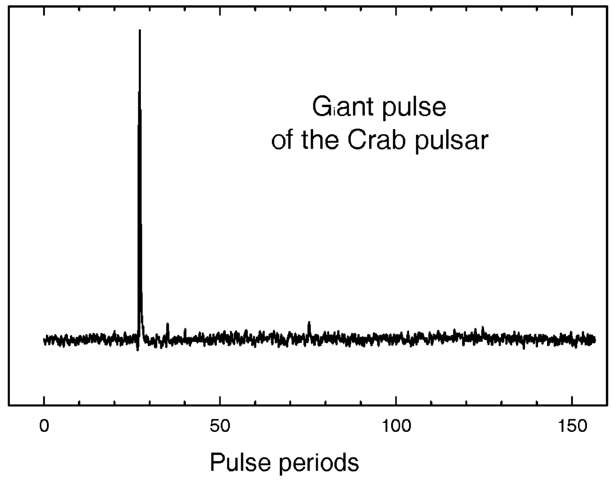

Fig. 1 An example of a GP of the Crab pulsar inside of 150 pulsar periods.

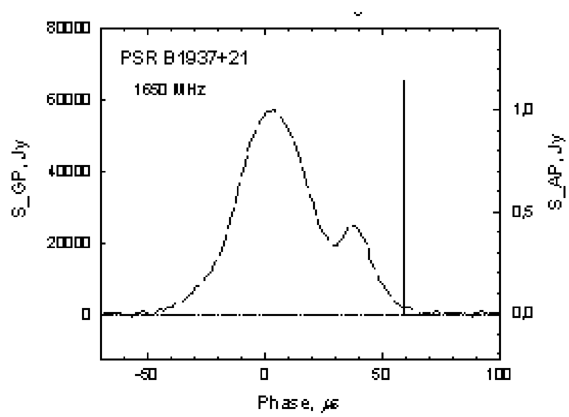

Fig. 2 An example of a giant pulse (solid line) in comparison with an average pulse (dotted line) of the pulsar PSR B1937+21. *(After Soglasnov et al. 2005).* Note different y-scales for a giant pulse (left) and an average pulse (right).

2.1 Flux Density, Energy, Spectra, Intensity Distribution.

Giant pulses are the most extremal phenomena of pulsar radio emission. Their peak flux densities can exceed hundreds and even thousands of times the peak flux density of an average pulse (AP). An example of a giant pulse in comparison with an AP of the millisecond pulsar PSR B1937+21 is shown in Figure 2. The peak flux densities $S_{\rm peak}$ of giant pulses from this pulsar at 1650 MHz has reached 60 000 Jy, that exceed the peak flux density of regular pulses these pulsars by a factor of 3×10^5. The radiation energy of the strongest GPs $E = S_{\rm peak} \times \tau$ exceeds the energy of the average pulse by a factor of 60 (Soglasnov et al. 2004).

The peak flux densities of giant pulses from the Crab Nebula pulsar (PSR B0531+21) at 8600 MHz often exceed 100 Jy for extremely brief intervals, so that they stand out as one of the brightest objects in radio sky (Hankins 2003).

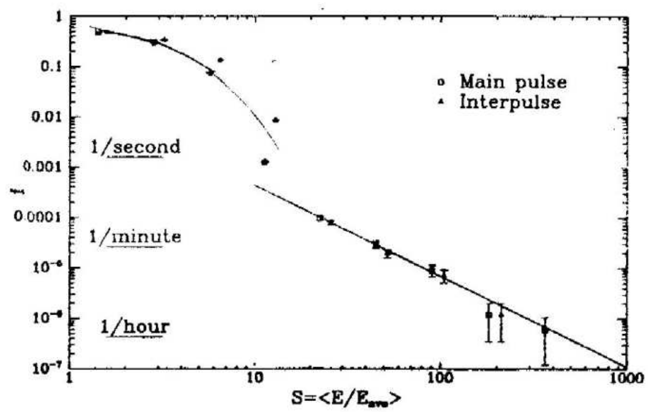

Fig. 3 Cumulative distribution of GPs amplitudes of PSR B1937+21 measured in units of the average pulse (*after Cognard et al. 1996).*

The peak flux densities of giant pulses in this pulsar at 2228 MHz exceed the peak flux density of an average pulse up to factor of 10^5 (Kostyuk et al. 2003). An energy $E = S_{\rm peak} \times \tau$ of the GPs exceeds the energy of the average pulse by a factor of 80 (Kostyuk et al. 2003).

GPs of the Crab pulsar have been detected in a very wide frequency range from 23 MHz (Popov et al. 2005 Azh, submitted) up to 15 GHz (Hankins 2000). Radio spectra of these GPs were studied by simultaneous multi-frequency observations by Sallmen et al. (1999) and Popov et al. (2005). Sallmen et al. (1999) observations at two frequencies 1.4 and 0.6 GHz show that the GPs spectral indices fall between –2.2 and –4.9, which may be compared to the average pulse value for this pulsar –3.0. Popov et al. (2005, AZh, submitted) observations at three frequencies 600, 111, and 43 MHz show that the GPs spectral indices fall between –1.6 and –3.1 with mean value –2.7, that also may be compared to the average pulse value for this pulsar. A big scatter in values of the individual GPs and a large number of unidentified GPs indicate that the spectra of individual GPs do not follow a simple power law.

Kinkhabwala et al. (2000) have estimated the average spectral properties of the GPs emission of the pulsar PSR B1937+21. Using the top eight GPs at three frequencies 430, 1420, and 2380 MHz, they find a somewhat steeper slope of –3.1 for the GPs spectrum, compared the –2.6 slope for the normal emission spectrum of this pulsar. Simultaneous two-frequency observations of GPs from PSR B1937+21 at 2210–2250 and 1414–1446 MHz (Popov & Stappers 2003) don't reveal any GPs which occur simultaneously in both frequency ranges. They conclude that radio spectra of detected GPs are limited in frequency at a scale of about $\Delta\nu/\nu < 0.5$.

Another distinguishing characteristic of pulsars with GPs, as demonstrated in Figure 3, is their two-mode pulse intensity distribution. At low intensities of ordinary pulses, the pulse strength distribution is Gaussian one, but above a certain threshold the pulse strength of GPs is roughly power-law distributed (Argyle & Gower 1972; Cognard et al. 1996) .

2.2 Size and Brightness Temperature of an Emitting Region.

The next peculiarity of GPs, as demonstrated in Figure 2 for PSR B1937+21, is a much shorter time-scale of GPs as compare to APs. The width of this GP is $\tau \leq 15$ ns (Soglasnov et al. 2005).

Hankins (2003) found in pulsar PSR B0531+21 pulse structure as short as 2 ns. If one interprets this pulse duration in terms of the maximum possible size of emitting region $l \leq c \times \tau$, where c is the speed of light, the time-scale τ =2 ns corresponds to a light-travel size of emitting body l of only 60 cm, the smallest object ever detected outside our solar system.

The brightness temperature of the GPs is

$$T_{\rm B} = S_{\rm peak} \lambda^2 / 2k\Omega \ ,$$

where $S_{\rm peak}$ is the peak flux density, λ is the radio wavelength, k is the Boltzmann's constant, and $\Omega \simeq (l/d)^2$ is the solid angle of the radio emission region.

For observed peak flux density of 10^3 Jy at 5.5 GHz with $\tau = 2$ ns (Hankins 2003) the brightness temperature of GPs in Crab pulsar is as high as 10^{37} K.

Soglasnov et al. (2004) have proved that the majority of GPs from the millisecond pulsar PSR B1937+21 are shorter than 15 ns. At a frequency of 1.65 GHz, a peak flux density of 65×10^3 Jy with $\tau = 15$ ns shows that the brightness temperature of GPs in this pulsar is $T_B \geq 5 \times 10^{39}$ K, the brightest radio emission observed in Universe.

However, these evaluations of size and brightness temperature of an emitting body are not unambiguous. Gil & Melikidze (2004) argued that the apparent duration of the observed impulse $\tau_{\rm obs}$ may be shorter[1] than the duration of the emitted one $\tau_{\rm rad}$ as $\tau_{\rm obs} = \tau_{\rm rad} \times \gamma^{-2}$. For Lorentz factor $\gamma \approx 100$, the time-scale of pulse structure for B1937+21 will transformed from observed $\tau_{\rm obs}$= 2 ns to emitted $\tau_{\rm rad}$ =20 μs.

Since also as $T_{\rm B} \propto \Omega^{-1} \propto \tau^{-2}$, the brightness temperature will be reduced to $T_{\rm B} \approx 10^{31}$ K. This aspect needs a further refinement.

GPs are clustered around a small phase window (except of Crab pulsar, for which GPs can occur anywhere within the average pulse). An example of such clustering for pulsar PSR B0031–07 is shown in Figure 4.

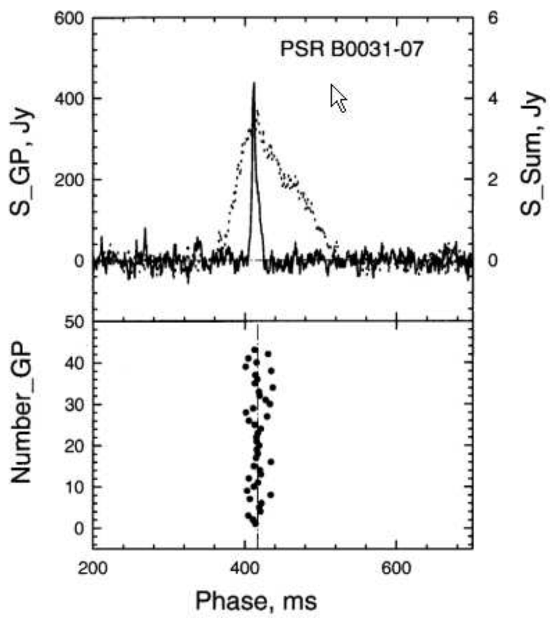

Fig. 4 *Top:* Giant pulse (solid line) in comparison with an average pulse (dotted line) of the pulsar PSR B0031–07; *Bottom:* Phases of 43 observed GPs are clustered around a small phase window *(after Kuzmin, Ershov, & Losovsky 2004)* .

2.3 Are Giant Pulses Inherent to Some Special Property of Pulsars ?

The first detected pulsars with GPs, PSR B0531+21, and PSR B1937+21, are among a small group of pulsars with highest magnetic field at the light cylinder $B_{\rm LC} = 10^4 - 10^5$ G. This gave a rise to suggestion that GPs occur in pulsars with very strong magnetic field at the light cylinder and the search of GPs was oriented on those pulsars. As a result GPs were detected in five other pulsars with very strong magnetic

[1] Relativistic shortening of a pulse duration were claimed by Smith (1970) and Zheleznyakov (1971).

field at the light cylinder: PSR B1821–24 (Romani & Johnston 2001), PSR B0540–69 (Johnston & Romani 2003), PSR J0218+42 (Joshi et al. 2004), PSR B1957+20 (Joshi et al. 2004), and PSR J1823–3021 (Knight et al. 2005).

PSR J0218+42 and PSR B1821–24 have nearly the same energy excess to the energy of the average pulse as the Crab pulsar and PSR B1937+21. They are known also as having high energy X-ray emission. PSR B0540–69 is an extragalactic pulsar in the LMC.

The first exception from a strong magnetic field at the light cylinder as an inherent property of GPs, was the detection of GPs in pulsar PSR B1112+50 (Ershov & Kuzmin 2003) with a more normal magnetic field at the light cylinder of 4.1 G. The succeeding detections of GPs in pulsars PSR B0031–07 (Kuzmin, Ershov, & Losovsky 2004) and PSR J1752+2359 (Ershov & Kuzmin 2005) with ordinary magnetic field at the light cylinder of 6.9 and 4.6 G have revealed that GPs can occur in ordinary pulsars too.

These GPs exhibit all the characteristic features of the classical GPs from PSR B0531+21 and PSR B1937+21. The peak intensities of the GPs in PSR B0031–07 and PSR J1752+1359 exceed the peak intensity of the AP by factor of 400. An energy excess over that of an average pulse $E_{\rm GP}/E_{\rm AP}$ for PSR J1752+1359 of 200 is the same as for classical GPs in PSR B0531+21 and PSR B1937+21. The energy distribution has the power-law statistic. The GPs are clustered in a narrow phase window inside the integrated profile. An example of a GP of pulsar PSR B0031–07 is shown in Figure 4.

Johnson & Romani (2004) claimed that GPs may be associated with pulsars which show a high energy X-ray emission. However the association of X-ray pulses with GPs is observed only for four objects among ten known pulsars with GPs and is not a proper indication for GPs.

Knight et al. (2005) argued that GPs may be indicated by large spin-down luminosity $\dot{E} \propto P^{-3}\dot{P}$. But in fact the spin-down luminosity of the known ten pulsars with GPs differ by six orders of magnitude and is not a proper indication for GPs also.

In Table 1 we summarize the comparative data for all known pulsars with GPs, for which the data of energy $E^{\rm GP}$ or energy excess factor $E^{\rm GP}/E^{\rm AP}$ has been published or may be derived. Here PSR is a pulsar name, Freq is an observation frequency, $S_{\rm GP}$ is the peak flux density of the strongest GP, $S_{\rm GP}/S_{\rm AP}$ is the ratio of the peak flux density of the strongest GP over the peak flux density of an AP, $T_{\rm B}$ is the brightness temperature of the strongest GP, $E_{\rm GP}$ is the energy of the strongest GP, $E_{\rm GP}/E_{\rm AP}$ is the excess of the energy of the strongest GP over the energy of an AP and $B_{\rm LC}$ is the magnetic field strength at the light cylinder.

Table 1 Properties of the Giant Pulses

PSR	Freq MHz	$S_{\rm GP}$ kJy	$S_{\rm GP}/S_{\rm AP}$	$T_{\rm B}$ K	$E_{\rm GP}$ Jy × ms	$E_{\rm GP}/E_{\rm AP}$	$B_{\rm LC}$ G	References
B0031–07	40	1.1	400	$\geq 10^{28}$	6600	15	6.9	1
	111	0.5	120	$\geq 10^{26}$	2600	8		2
J0218+42	610				1.3	51	3×10^5	3
B0531+21	146		300				9×10^5	4
	594	150	6×10^4	$\geq 10^{36}$	75	10		5
	2228	18	5×10^5	$\geq 10^{34}$	9	80		5
	5500	1		$\geq 10^{37}$				6
B0540–69	1380		$> 5 \times 10^3$				3×10^5	7
B1112+50	111	0.18	80	$\geq 10^{26}$	900	10	4.1	8
J1752+2359	111	0.11	260	$\geq 10^{28}$	920	200	4.6	9
B1821–24	1517				0.75	81	7×10^5	10
J1823–3021A	685	0.045	680			64	2.5×10^5	11
	1405	0.02	1700			28	2.5×10^5	11
B1937+21	111	40	600	$\geq 10^{35}$	400	65	9.8×10^5	12
	1650	65	3×10^5	$\geq 5 \times 10^{39}$	1	60		13
B1957+20	400				0.9	129	4×10^5	3

References: 1) Kuzmin & Ershov 2004, 2) Kuzmin et al. 2004, 3) Joshi et al. 2004, 4) Argyle & Gower 1972, 5) Kostyuk et al. 2003, 6) Hankins et al. 2003, 7) Johnston & Romani 2003, 8) Ershov & Kuzmin 2003, 9) Ershov & Kuzmin 2005, 10) Romani & Johnston 2001, 11) Knight et al. 2005, 12) Kuzmin & Losovsky 2002, 13) Soglasnov et al. 2004.

GPs occur in various types of pulsars over a wide range of periods $P = 1.5 - 1600\,\mathrm{ms}$ and magnetic field at the light cylinder $\log B_{\mathrm{LC}} = 4 - 10^6$ G and over a wide range of radio frequencies.

3 WHERE GIANT PULSES ARE GENERATED ?

The first detected GP-pulsars PSR B0531+21 and PSR B1937+21 have the highest magnetic field at the light cylinder $B_{\mathrm{LC}} = 10^4 - 10^5$ G. This gave rise to the suggestion that the GPs emission may depend on conditions at the light cylinder, rather than close to the stellar surface. Istomin, 2004 proposes a model of GPs radio emission which is generated by the electric discharge taking place due to the magnetic reconnection of field lines in the region of the light cylinder near the zero line of the magnetic field.

Two-frequency observations of GPs in PSR B0031–07 (Kuzmin & Ershov 2004) suggests another approach to determine a location of the GP emission source. GPs in this pulsar are double and clustered around two different phase windows. This indicates that there are two emission regions of GPs. The separation of these regions at lower frequency is larger than at upper one in a similar manner to the frequency evolution of the width of the AP. This suggests that the GPs of this pulsar originate in the same region as the AP, that is in a hollow cone over the polar cap instead of the light cylinder region.

This approach is similar to that of the Gil & Melikadze (2004) model which proposed that GPs are generated by means of the coherent curvature radiation of charged relativistic solitons associated with sparking discharges of the inner gap potential drop above the polar cap. It is also similar to the suggestion of Soglasnov et al. (2004) that giant pulses are a result of the polar gap discharge generating the energetic particles.

One may suggest that there are two classes of GPs, one associated with high-energy emission from the outer gaps, the other associated with polar radio emission. GPs of PSR J0218+4332, PSR B0531+21, PSR B0540–69, PSR B1821–24, PSR J1823–3021, PSR B1937+21 and PSR B1957+20 may be of the first class. GPs of PSR B0031–07, B1112+50 and PSR J1752+2359 may be of the second class.

4 SUMMARY

Giant pulses are a special form of pulsar radio emission that is characterized by a very large excess of flux density and energy of radio emission relative to the average and has a power-law statistic of an energy distribution. Giant pulses occur in a narrow-phase window of an average pulse and have a short pulse timescale as compare to an average pulse.

The flux density of giant pulses exceeds the flux density of an average pulse by a factor of up to 5×10^5.

The ratios of giant pulses energy excess over an energy of an average pulse is $E_{\mathrm{GP}}/E_{\mathrm{AP}}$ = 50–200 and are nearly the same for different magnetic fields at the light cylinder, pulsar periods and frequencies.

The light-travel size of an emitting body indicate the smallest object ever detected outside our solar system.

Giant pulses are the brightest sources of radio emission (the brightness temperature up to 10^{39} K) among the known astronomical objects.

Giant pulses exist in various types of pulsars in a wide range of periods, magnetic field at the light cylinder and broad frequency range.

One may suggests that there are two classes of pulsars with giant pulses: one associated with emission from the outer gaps, the other associated with polar radio emission.

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