Comparison of Giant Radio Pulses in Young Pulsars and Millisecond Pulsars

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Abstract. Pulse-to-pulse intensity variations are a common property of pulsar radio emission. For some of the objects single pulses are often 10–times stronger than their average pulse. The most dramatic events are so-called giant radio pulses (GRPs). They can be thousand times stronger than the regular single pulses from the pulsar. Giant pulses are a rare phenomenon, occurring in very few pulsars which split into two groups. The first group contains very young and energetic pulsars like the Crab pulsar, and its twin (PSR B0540-69) in the Large Magellanic Cloud (LMC), while the second group is represented by old, recycled millisecond pulsars like PSR B1937+21, PSR B1821-24, PSR B1957+20 and PSR J0218+4232 (the only millisecond pulsar detected in gamma-rays). We compare the characteristics of GRPs for these two pulsar groups. Moreover, our latest findings of new features in the Crab GRPs are presented. Analysis of our Effelsberg data at 8.35 GHz shows that GRPs do occur in all phases of its ordinary radio emission, including the phases of the two high frequency components (HFCs) visible only between 5 and 9 GHz.

1. Introduction

The ‘giant pulses’ term is reserved for individual radio pulses that are 10–20 or more times stronger than the mean pulse energy. The Crab pulsar was discovered through showing this phenomenon \textit{(Staelin & Reifenstein, 1968)}. For a long time it was the only pulsar known to emit giant radio pulses (GRPs). Within the group of \(\sim 1700\) already known radio pulsars only a few pulsars are found to emit GRPs. These pulsars belong to two different groups of pulsars, some represents the classical pulsars, some of them the millisecond pulsars.

2. Young pulsars

\textit{The Crab Pulsar}

The occurrence of sporadic radio emission of very strong pulses by NP 0532 (the very first name of the Crab pulsar) has been known since its discovery by \textit{Staelin & Reifenstein, 1968}. They discovered the dispersed pulse signals from the Crab Nebula. These strong pulses were not periodic, therefore the rotational period of the Crab was not established. However, considering the source as a periodic one, they were able to give the upper limit of 0.13 s for its period. A single pulse of average flux density can not be detected because of the high radio emission from the plerionic nebula. The strongest pulses exceed the total radio emission from the nebula itself by an order of magnitude. The average pulse profile is determined by averaging the data from thousands of sequentially recorded single pulses. Following studies of its pulse shape as a function of radio frequency have shown that Crab is very unique (see e.g. Moffett & Hankins, 1996, Figs. 1 and 2; hereafter MH96). The results show that the averaged radio pulse profile consists of two main components: an intense but narrow ‘main pulse’ (MP), lasting about 250 \(\mu\)s with respect to the 33 ms pulsar period, and a broader and weaker ‘interpulse’ (IP) following the MP by 13.37 milliseconds. These two main components have counterpart non-thermal emission from the infrared to the gamma-ray energies. IP does not occur exactly between successive main pulses; the phase separation between the MP and the IP is \(\sim 0.4\) and decreases nearly continuously as a function of energy (Eikenberry & Fazio, 1997). At lower radio frequencies (300–600 MHz) another broad and weak component is visible. It precedes the MP by 1.6 milliseconds and is called a ‘precursor’ (P). In the average pulse shape at 1.4 GHz the precursor vanishes, due to its steep spectral index, leaving only MP, IP, and a weak but distinct low frequency component (LFC). It is \(\sim 36^\circ\) ahead of the MP, therefore it is not coincident with the position of the precursor apparent at lower frequency. New and additional profile components were discovered by MH96. They appear in the profiles obtained for frequencies between 5 and 8 GHz. These two broad components with nearly flat spectrum are referred to as high frequency component 1 and 2, i.e. HFC1 and HFC2, respectively. The existence of the extra components at high frequency and their strange, frequency-dependent behaviour is unlike anything seen in other pulsars. It can not easily be explained by emission from a simple dipole field geometry.
For over 25 years, only the Crab pulsar was known to emit GRPs. Its individual GRPs might last just a few nanoseconds (Hankins et al. 2003). However, they rank among the brightest flashes in the radio sky reaching peak flux densities of up to 1500 Jy even at high radio frequencies. Already four years after its discovery it has been reported that GRPs occur not only at the MP, but also at the IP phases (Gower & Argyle 1972).

Until 2005 the GRP phenomenon in the Crab pulsar had been known to occur exclusively at the phases of the MP and the IP (Lundgren et al. 1995; Salinnen et al. 1999; Cordes et al. 2004). In particular, no GRPs had been detected either in the LFC or at the phases of the high radio frequency components: HFC1 and HFC2. The situation changed due to results published by Jessner et al. (2005). In our observations at 8.35 GHz the IP and both HFCs are clearly visible, whereas the LFC can be seen as a slight rise above the noise level separated by about 0.1 in phase from the MP, that is not very intense at this frequency as well. Our observations show that GRPs can be found in all phases of ordinary radio emission including HFC1 and HFC2. For all giant pulses, i.e. regardless their phases, the histogram of their peak strengths at 8.35 GHz can be described by a power-law with a slope $-3.46$ (Lundgren et al. 1994). For comparison at 800 MHz the distribution (regardless the phases of GRPs) has a slope of -3.13 ± 0.22 was found. It is consistent with the value of $-2.9$ presented by Cordes et al. (2004). The MPs from the Crab pulsar at 146 MHz are distributed according to a power-law with the exponent of $-2.5$, whereas the IPs with $-2.8$ (Argyle & Gower 1972). For comparison at 800 MHz the distribution (regardless the phases of GRPs) has a slope of -3.46 (Lundgren et al. 1995). It should be noticed that at low radio frequency the main contribution to the number of GRPs comes from the MP component. So far, there is no evidence that the distributions of numbers of GRPs for the HFC1 and the HFC2 differ from each other. However, their slopes seem to be steeper than the slope of the same distribution for the IP component. An intriguing feature of GRPs observed with the Effelsberg telescope is that sometimes they occur in a single rotation in more than one component (e.g. at the IP, HFC1, and HFC2 phases in the same rotation).

The average polarisation characteristics of about 900 GRPs at 8.35 GHz in some aspects are similar to previously published high radio frequencies observations, but in some aspects we do observe significant differences. All authors (Moffett & Hankins 1995; Karastergiou et al. 2004; Slowikowska et al. 2005, hereafter: MH99, K04, S05) find that the relative offset of the position angle (PA) between IP and HFCs is on the level of 35°−45°. However, the PA for the IP, and at the same time for the HFCs differ for all authors. They are as follow, for the IP: 30°, 0°, −30°, and for the HFCs: 60° − 70°, 45°, 5° − 10° according to MH99, K04, S05, respectively. Moreover, there is some discrepancy in the degree of polarisation. Almost 100% linear polarisation of all three components has been derived by K04, whereas for MH99 the IP is polarised in only 50% and HFCs in 80-90%. In our work (S05) all components are polarised at the same level of 70-80%. This may be due to the time varying contribution of the nebula to the rotation measure of the pulsar (Rankin et al. 1988; RM = -43 rad m$^{-2}$, MH99; RM = -46.9 rad m$^{-2}$, Weisberg et al. 2004; RM = -58 rad m$^{-2}$). No abrupt sweeps in PA are found within pulse components. The S/N ratio was too low to derive reliable values of polarisation degree and angle for the LFC and MP components. Some new and additional features of GRPs at MP and IP phases are presented by Eilek & Hankins (2006, this proceedings). They observed the GRPs with the 2.5 GHz bandwidth (8−10.5 GHz) and found that giant interpulses have totally different intensity profiles and dynamic spectra from giant main pulses.

**PSR B0540-69**

GRPs were also found in the Crab-twin, i.e. PSR B0540-69 - pulsar located in the LMC ($P = 50$ ms; Johnston & Romani 2003). Pulse profiles and spectra of PSR B0540-69 and PSR B0531+21 differ significantly. The PSR B0540-69 spectrum has very similar shape as the spectral shape of the Class-II MSPs (see Sec. 3), and not as the Crab spectrum. The Crab pulse profile shows a sharp double-peak structure, whereas the profile of LMC pulsar consists of a single broad peak. However, this broad peak might be formed as a superposition of two Gaussian components separated of about 0.2 in phase (de Plan et al. 2003). The giant pulses occur 6.7 ms before and 5.0 ms after the mid-point of the X-ray profile and they follow the power-law distribution. From performed simultaneous X-ray and radio observations it is known that there is no significant increase in the X-ray pulse profile at the time of GRPs (Johnston et al. 2004).

### 3. Millisecond pulsars (MSPs)

Interestingly three millisecond pulsars showing GRPs phenomena form an individual class - the Class-II of MSPs (after Kuiper & Hermes 2003). These pulsars: B1937+12 (P= 1.56 ms), B1821-24 (P= 3.05 ms), J0218+4232 (P= 2.32 ms) have high X-ray luminosities, hard power-law shaped X-ray spectra and their X-ray pulses consist of two narrow components separated in phase by 0.5. All of these pulsars have a very high value of the magnetic field at the light cylinder, $B_{LC}$ (Cognard et al. 1996). Within the group of MSPs, the third highest $B_{LC}$ is found for the millisecond pulsar B1957+20 - being also a potential source of giant pulse emission. It has a high X-ray luminos-
ity, but no X-ray pulsation have been detected from this source so far. A new population of short-duration pulses from B1957+20 is reported by Knight et al. (2006b). They detected only four of this kind of pulses in 8003 s of observations. They have a sub-microsecond timescale, are several times stronger than the mean pulse, and are coincident with the main emission component. It is worth to mention that this pulsar has a very strong wind that ablates the gas of its companion. Recently, Knight et al. (2005) detected GRPs of up to 64 times the mean pulse energy from PSR B1823-3021A ($P = 5.4$ ms). This pulsar is located in the globular cluster NGC 6624 and has the lowest value of the characteristics age of all known MSPs, i.e 26 Myr (period derivative can be perturbed by gravitational interaction in the cluster and consequently can give different value of $\tau_{\text{cha}} = P/(2\dot{P})$, for the discussion see Knight et al. 2003. As an exception it has not been detected in X-rays. Moreover, nearly all its GRPs are distributed within the trailing half of the main component of the integrated pulse profile. This is in contrast to the location of for example GRPs from PSR B1937+21, that are clustered around the extreme trailing edge of the pulse components. Viewing geometry rather than different emission mechanism can be responsible for such a difference.

**PSR B1937+12**

The existence of large pulses from PSR B1937+21 was firstly noted by Wolszczan et al. (1984), but at that time this fact received only a little attention. About ten years later Sallmen & Backer (1993) presented the first analysis of properties of these giant pulses. They noted that GRPs are located on the trailing edges of both main pulse and interpulse. This study was later followed by a more extensive one performed by Cognard et al. (1996). The GRPs distribution has a power-law shape. These strong pulses are narrower than the averaged one and are systematically delayed by $\sim 40 - 50 \mu s$. Moreover, many of them are nearly 100% circularly polarised, while the averaged main pulse is more than 50% linearly polarised and interpulse at about 13%; both with little if any circular polarisation. Observations performed by Romani & Johnston (2001) provided only 19 bins per pulse profile, however they clearly detected GRPs distributions in both, main and interpulse, components. Again the delay of time of arrival of GRPs relative to the average emission has been confirmed. In both components GRP peaks occur approximately 1 bin after the corresponding peak of the integrated pulse profile. GRPs of PSR B1937+21 are extremely short, with duration below 15 ns, the strongest one has the flux density of 65 000 Jy (Soglasnov et al. 2004). These are the shortest pulses found so far in any pulsar after those of the Crab pulsar (Hankins et al. 2003).

**PSR B1821-24**

This pulsar has a complex radio pulse morphology. It consists of three peaks (P1, P2 and P3) and emission over the whole pulse period. It pulsates in different modes. Its GRPs usually occur in the P1 and P3 phase windows and are concentrated in a narrow phase window coincident with the power-law non-thermal pulse seen in hard X-rays (Romani & Johnston 2001). In case of the radio pulse profile obtained only from GRPs the P1 emission lags that of the integrated pulse profile by $\sim 80 \mu s$. Recently, the polarisation of the GRPs has been reported by Knight et al. (2006a). The polarimetric properties of GRPs are completely different to the pulses of ordinary emission. At $\sim 1.4$ GHz the averaged emission of P1 and P2 is 72% and 96% linearly polarised, respectively. P3 is not polarised at all. No circular polarisation was found in any component. In contrast, the giant pulses of PSR B1821-24 are highly elliptically polarised, some are even 100% elliptically polarised. The average polarisation faction is 79%. Their position angles are random and seem to have no preferred orientation. This might be caused by a propagation effect, or it might be intrinsic to the emission mechanism of giant pulses.

**PSR J0218+4232**

For the first time GRPs (only three events) of PSR J0218+4232 were reported by Joshi et al. (2004); however, Knight et al. (2006b) share the opinion that they are rather controversial. The second group of authors describe the analysis of 155 such events. Again, the pulses are very narrow, and are align in phase with the non-thermal X-ray emission, i.e. they occur roughly at the minima of the integrated radio pulse profile. Therefore, they do not contribute to the ordinary radio emission. This strong correlation between phases of GRPs and X-ray maxima confirms that the two emission processes originate in similar regions of the pulsar magnetosphere. The distribution of pulse energies has a power-law shape. However, only 3 over 139 have energies greater than ten times the average. No polarisation information is available.

4. Conclusions

The Class-II MSPs together with the Crab pulsar and its twin from the LMC are among the top seven pulsars with the highest magnetic field strengths near the light cylinder (the sixth one is PSR B1957+20, and the seventh is the radio-quiet one - PSR J0537-6910; Cognard et al. 1996; Kramer 2004). However, new observations do not support very strongly the hypothesis that strong magnetic field at the light cylinder is a critical condition for giant pulse activity.

The Crab pulsar results obtained so far by us suggest that physical conditions in the regions responsible
for HFCs emission might be similar to those in the main pulse and interpulse emission regions. This idea is supported not only by our detection of GRPs phenomenon at LFC and HFCs phases, but also by their polarisation characteristics. Still, the origin of HFCs remains an open question. One of the propositions is inward emission from outer gaps which may produce two additional peaks at requested phases in the light curve of the Crab pulsar (Cheng et al. 2000).

Flux density distribution of GRPs that have been detected from different pulsars generally follows power-law statistics. GRPs are believed (to some extend) to be associated with non-thermal high energy emission (e.g. PSR B0531+21, PSR B1937+21, PSR B1821-24, and PSR B0540-69). The Crab pulsar was the best example of this association for a long time. From the group of millisecond pulsars a strong confirmation of this idea comes from the observations of PSR B1821-24 (Romani & Johnston 2001) as well as Knight et al. 2006a found that GRPs of this pulsar are concentrated in a narrow phase window coincident with the non-thermal pulses seen in hard X-rays, but occur on the trailing edges of the radio components. Recently, more and more features of pulsar radiation showing correlations between radio and high energy emission are observed. For example phase alignment between some optical polarisation features and radio intensity profile (Slowikowska 2006). Furthermore, it was found that there is a correlation between X-ray and radio pulses for Vela (Lommen et al. 2006), whereas Shearer et al. 2003 have detected a correlation between optical emission and GRPs emission in the Crab pulsar. They found that optical pulses coincident with GRPs were of about 3% brighter on average. On the other hand, the characteristics of some pulsars (PSR B1133+16; Kramer et al. 2003) and the discovery of the Crab’s giant radio pulses at phases where no high energy emission is known, do not match to this picture.

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