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Observational Characteristics of Giant Pulses and Related Phenomena

H. S. Knight [†] [⋆]

Centre for Astrophysics and Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn VIC 3122, Australia

Abstract Evidence now exists that at least 14 pulsars emit distinctive pulses that are stronger and narrower than the average pulse. I review observations of these pulses in an effort to determine which sources share a common emission-mechanism. All of the giant pulses emitted by millisecond pulsars have power-law energy-statistics and occur in narrow phase-windows that coincide with those of X-ray emission. The giant pulses of millisecond pulsars therefore probably originate from a single process. They are always unresolved at microsecond timescales, and therefore the emission is likely to arise from the superposition of a small number of nano-shots. Most are actually very weak when compared to the average pulse. They are only "giant" when examined in terms of their ultra-high brightness temperatures. Giant pulses from other sources have a variety of widths, shapes, and energy distributions. The giant pulses from the Crab pulsar have intrinsic sub-microsecond timescales like the giant pulses of the millisecond pulsars, and therefore probably originate from the same mechanism. Other phenomena, such as giant micro-pulses from young pulsars and giant pulses from slow pulsars have not been shown to have such short timescales. These phenomena likely arise from other mechanisms.

Key words: pulsars: general — pulsars: individual (PSR B1937+21, PSR B1821−24, PSR J1823−3021A, PSR B1957+20, PSR J0218+4232, Crab pulsar, PSR B0540−69, PSR J0437−4715, PSR B1112+50, PSR B0031−07, PSR J1752+2359, PSR B0950+08, Vela pulsar, PSR B1706−44)

1 INTRODUCTION

Soon after the discovery of pulsars, Staelin & Reifenstein (1968) observed two sources of intermittent pulses in the direction of the Crab nebula. Further studies revealed that both had underlying periodicities and were therefore classified as pulsars. Lundgren et al. (1995) subsequently presented evidence that the Crab pulsar emits both these "giant pulses" (GPs), and weaker pulses that can only be detected through phase-coherent summation of thousands of pulses.

Johnston & Romani (2003) discovered a population of GPs from PSR B0540−69, a young pulsar in the LMC. The similarity in the characteristics of PSR B0540−69 and the Crab pulsar suggests their GPs originate from a common physical mechanism. However, other pulsars with very different characteristics to the Crab pulsar also emit strong pulses. Do these pulses originate from the same physical mechanism? In this article I review the observational literature so as to clarify the key characteristics of "giant pulse" emission phenomena.

[†] Affiliated with the Australia Telescope National Facility, CSIRO
[⋆] E-mail: hknight@astro.swin.edu.au

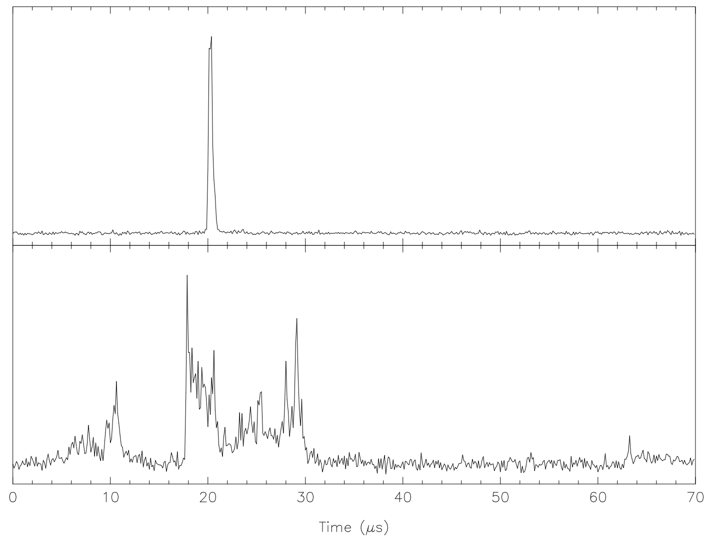

Fig. 1 The total intensity of two GPs from the Crab pulsar at a center frequency of 1373 MHz.

2 TYPES OF STRONG PULSES

2.1 Crab-like Emission

Two GPs from the Crab pulsar observed using the CPSR2 recorder at the Parkes radio telescope are shown in Figure 1. It can be seen that the Crab pulsar emits both GPs that appear impulse-like and GPs that have substructure over timescales of order 100 μs. Hankins et al. (2003) resolved the substructure as highly circularly polarized "nano-pulses". These have intrinsic timescales as short as 2 ns and brightness temperatures of up to 10^{37} K. The GPs exhibit power-law statistics that are distinct from the Gaussian statistics that ordinary pulses are thought to follow (Argyle & Gower 1972; Cordes 1976). The probability of a GP having energy greater than E_0 can be expressed as:

$$P(E > E_0) = KE_0^{-\alpha}. \tag{1}$$

Here E_0 is in units of the mean pulse-energy. Estimates for the power-law indices (α) for the Crab pulsar range from 2.1–2.8 (Argyle & Gower 1972; Lundgren et al. 1995; Jessner et al. 2005). Although GPs are probably present for all radio components, they are most readily visible in the main-pulse and inter-pulse phase-windows (Lundgren et al. 1995; Jessner et al. 2005). The main-pulse and inter-pulse components of the radio pulse-profile align with optical, X-ray, and γ-ray emission peaks (Lundgren et al. 1995). Optical pulses contemporaneous with GPs are on average 3% brighter, possibly due to enhanced plasma density (Shearer et al. 2003). No such correlation is seen for γ-ray emission. Some GPs are broadband — Kostyuk et al. (2003) observed 22 GPs simultaneously at 594 and 2228 MHz. However, the spectral indices of individual GPs vary from –2.2 to –4.9 (Sallmen 1998), and different components have different spectral properties.

The GPs from PSR B0540$-$69 also follow power-law statistics with α ranging between 1.5 and 2.1 (Johnston et al. 2004). They align in phase with the integrated profile in the radio and X-ray bands. An effective sampling rate of 400 μs meant that Johnston & Romani (2003) were unable to place strong constraints on intrinsic emission-timescales or the presence of substructure.

Both the Crab pulsar and PSR B0540$-$69 emit GPs at a high rate. At 800 (1390) MHz one in 120 (800) pulses from the Crab pulsar (PSR B0540$-$69) is stronger than twenty times the average pulse energy ($\langle E \rangle$) (Lundgren et al. 1995; Johnston et al. 2004). No other young pulsars have been shown to emit such strong pulses.

2.2 Giant Micro-pulses

Johnston et al. (2001) discovered that the Vela pulsar emits a population of moderately strong pulses. They dubbed the pulses as "giant micro-pulses" on account of their $\sim$50 μs widths resembling those of micro-pulses and their intensities being much higher than the average pulse. Johnston et al. did not consider them to be true GPs because none exceeded $10\langle E\rangle$.

The young pulsar B1706$-$44 and PSR B0950+08 also emit giant micro-pulses (Johnston & Romani 2002; Cairns, Johnston, & Das 2004). The giant micro-pulses from the Vela pulsar and PSR B0950+08 occur on the leading part of the profile; those from PSR B1706$-$44 occur on the trailing edge.

Kramer, Johnston, & van Straten (2002) state that the giant micro-pulses from the Vela pulsar are narrower than the average micro-pulse. The pulses from PSR B1706$-$44 have widths of $\sim$1 ms, which is much narrower than the average pulse but much broader than the GP emission from the Crab pulsar. The emission from both pulsars follows power-law statistics with α in the range of 2.7–2.9. Extrapolation implies that PSR B1706$-$44 emits a $20\langle E\rangle$ pulse every 3.7×10^6 periods.

Giant micro-pulses appear to differ from the true "giant" pulses of the Crab pulsar in that substructure with very short timescales has not been observed in the giant micro-pulses. In their study of the Vela pulsar Johnston et al. (2001) used a baseband recorder that could achieve sub-microsecond time resolution. Despite this, the shortest timescales reported were $\sim$50 μs. The presence of similar emission from PSR B1706$-$44 without structure on timescales $\lesssim 1$ ms suggests that the nano-shots of the Crab pulsar do not make up this emission. High time-resoution observations are needed to investigate this hypothesis further, particularly with respect to the role scattering has in determining pulse widths.

2.3 Emission from Ordinary Pulsars

Strong pulses with relatively short timescales have also been observed at 40–111 MHz from the relatively slowly rotating PSRs B1112+50, B0031$-$07, and J1752+2359 (Ershov & Kuzmin 2003; Kuzmin, Ershov, & Losovsky 2004; Kuzmin & Ershov 2004; Ershov & Kuzmin 2005). Power-law fits to the pulse-energy distributions give α as 4.5, $\sim$3.6, and 3.0 for each of the pulsars respectively. These power-law slopes are steeper than those seen for the Crab pulsar and PSR B0540$-$69.

On average the strong pulses are 1–10 ms wide and around 5–30 times narrower than the average pulse. The strongest pulses seen from each of the three pulsars respectively had peak flux-densities 80, 400, and 260 times that of the mean pulse.

All three emit bursts of several strong pulses in a row, and PSR B0031$-$07 emits dual-component giant pulses. Lewandowski et al. (2004) report that at 430 MHz PSR J1752+2359 has significantly different pulse statistics. It spends 70%–80% of its time in a "quasi-null" state. Its "on-state" occurs every 400–600 pulses and exponentially decays over $\sim$100 periods. No such deviation from Poisson statistics has been observed for other types of strong pulses (see e.g. Lundgren et al. 1995).

2.4 Emission from Millisecond Pulsars

The solitary millisecond pulsar (MSP) PSR B1937+21 has a characteristic age of 237 Myr and spins $\sim$20 times faster than the Crab pulsar (Manchester et al. 2005). It emits GPs that occur in narrow phase-windows that trail its main-pulse and inter-pulse components (Soglasnov et al. 2004). Substructure has been seen for some pulses, but only on timescales of $\lesssim 1\,\mu$s. Other GPs are as narrow as 16 ns. The GPs are highly circularly polarized (Popov et al. 2004), and show a power-law energy dependence with α in the range of 1.4–1.8 (Cognard et al. 1996; Soglasnov et al. 2004). On average the GPs have a steeper spectral index than other emission (Kinkhabwala & Thorsett 2000). At 430 MHz a $20\langle E\rangle$ pulse is emitted every $\sim$7000 pulses — around 60 times less than the rate of the Crab pulsar at 800 MHz. The strongest GP seen by Soglasnov et al. had an inferred brightness temperature of 5×10^{39} K. Such ultra-high brightnesses are not easily explained by the Lorentz factors expected of the potential drop in the polar cap (Gil & Melikidze 2005). From consideration of the pulse profile Soglasnov et al. determined the GPs of PSR B1937+21 occur at energies lower than 0.03$\langle E\rangle$. Consequently the vast majority of "giant" pulses are in fact very weak. The X-ray pulses of PSR B1937+21 are narrow (29$\pm$2 and 51$\pm$21 μs), likely have a non-thermal origin, and occur at approximately the same phase as the GPs (Cusumano et al. 2003).

Knight et al. (2006) observed a population of intrinsically narrow pulses from PSR J0218+4232 that are scatter-broadened to microsecond timescales. Figure 2 shows that these pulses occur about the min-

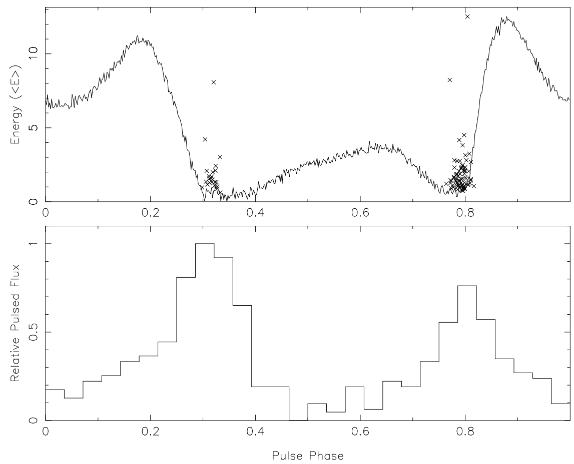

Fig. 2 Top: Phases and energies of pulses detected from PSR J0218+4232 superimposed on an integrated pulse profile. These data were acquired using the CGSR2 recorder at the Green Bank Telescope at a center frequency of 857 MHz. Bottom: The Chandra HRC-S 0.08–10 keV pulse profile of PSR J0218+4232 (Kuiper, Hermsen, & Stappers 2004) has been phase-aligned with the radio profile using the absolute timing of Rutledge et al. (2004). Figure reproduced from Knight et al. (2006).

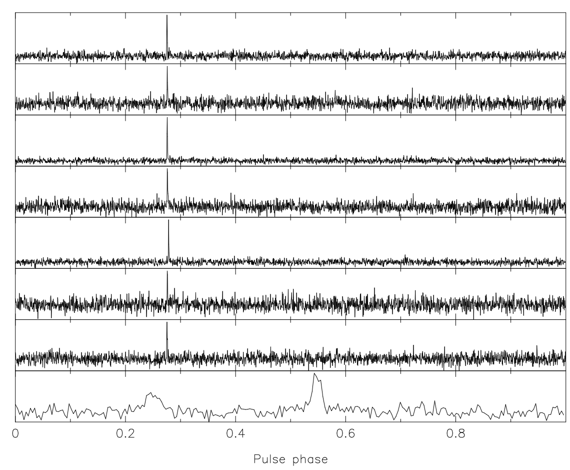

Fig. 3 Total-intensity pulse-profiles for seven GPs from PSR B1821−24 are shown in the top seven panels. The bottom panel shows an integrated pulse-profile. All the GPs occur within a 9 μs phase window and are scatter-broadened to widths of 2 μs. These data were acquired using the CPSR2 recorder at a center frequency of 1405 MHz.

ima of the integrated pulse-profile and correlate in phase with its X-ray components. The γ-ray profile of PSR J0218+4232 as presented by Kuiper, Hermsen, & Stappers (2004) peaks at a different phase. The GPs follow power-law statistics with α in the range of 1.5–1.9. The emission occurs at a low rate similar to that of PSR B1706−44 — at 857 MHz only one in 4×10^6 pulses surpasses $20\langle E\rangle$. Otherwise it is similar in nature to that of PSR B1937+21. The majority of the "giant" pulses seen by Knight et al. were comparable to, or weaker than, the average pulse.

Romani & Johnston (2001) found ~30 Myr MSP B1821−24 emits GPs. These occur on the extreme trailing side of the leading component (see Figure 3). A non-thermal X-ray peak with a width of 34 μs is seen at this phase (Rots et al. 1998; Rutledge et al. 2004).

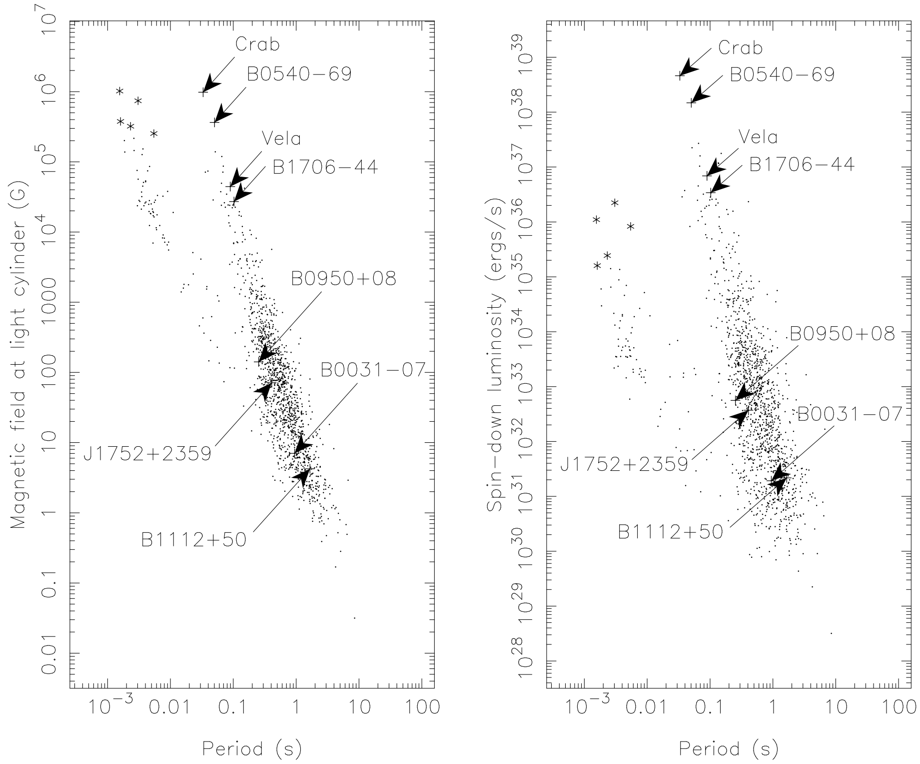

Fig. 4 Left: The Crab pulsar, PSR B0540−69, and the MSPs that emit GPs (asterisks) have much higher values of $B_{\rm LC}$ than other radio pulsars (dots). Right: The MSPs that emit GPs have higher spin-down luminosities than other MSPs, but have lower values than even the Vela pulsar and PSR B1706−44. The Crab pulsar emits GPs 2–5 orders of magnitude more frequently than the MSPs. Therefore, $B_{\rm LC}$ is a much poorer indicator than $\dot{E}$ of the rate of emission for high-field pulsars. Data for these plots were acquired using the ATNF pulsar catalogue: *http://www.atnf.csiro.au/research/pulsar/psrcat/*.

PSRs J1823−3021A and B1957+20 also emit strong and narrow pulses similar to those of PSR B1937+21 (Knight et al. 2005; Knight et al. 2006). The statistics on these pulses are poor, but they appear to occur within the windows of the ordinary emission.

Jenet et al. (1998) observed that the strongest pulses from PSR J0437−4715 are $\sim$10 μs wide and occur at the peak of the pulse profile. Jenet et al. did not consider these to be “giant” on account of their energies being less than $10\langle E\rangle$. The pulses from PSR J0437−4715 seem unlikely to be GPs, as the observations of Jenet et al. should have been able to resolve the nano-structure that GPs seem to be composed of.

3 DISCUSSION

Five MSPs are now known to show evidence for the emission of GPs. All of the pulses occur in narrow phase-windows and have sub-microsecond durations and power-law energy-distributions. Non-thermal X-ray emission occurs at the same phase as the GPs for all the MSPs with X-ray profiles.

Phenomena exhibiting power-law statistics will invariably lead to small numbers of readily-detectable, high-intensity events. The historical detection of such events from the Crab pulsar led to the strong pulses it emits being labelled as “giant”. Several MSPs now have been shown to emit “giant” pulses that are very weak. Knight et al. (2006) detected 4 individual pulses from PSR B1957+20 of 4.5–8.6$\langle E\rangle$. If these moderately-strong giant-pulses had been discovered before strong giant-pulses, they would not have been classified as “giant”. Despite this, our best definition of giant pulses from millisecond pulsars (see Knight et al. 2006) qualifies these as almost certainly arising from the GP emission mechanism of the other MSPs. The pulses of PSR B1957+20 are giant in one respect — they have ultra-high brightness-temperatures.

Indeed, all the giant pulses emitted by millisecond pulsars are "ultra-bright" pulses by virtue of their narrow widths.

Magnetic field at the light cylinder ($B_{\rm LC}$) and spin-down luminosity ($\dot{E}$) have both been proposed as indicators of GP emissivity (Cognard et al. 1996; Knight et al. 2006). Figure 4 shows that the Crab pulsar and PSR B0540−69 have some of the highest known values of $B_{\rm LC}$ and $\dot{E}$ of all pulsars. The MSPs that emit GPs also have high values of $B_{\rm LC}$, and higher values of $\dot{E}$ than other MSPs. If $B_{\rm LC}$ determines whether or not a pulsar emits narrow GPs, or if $\dot{E}$ helps determines the rate of narrow GP emission, then the GPs from the Crab pulsar and PSR B0540−69 are probably also caused by the same physical process as those of the millisecond pulsars. However, the $\lesssim 1\,\mu$s timescales of the GPs from PSR B1937+21 are markedly different from the $\sim$100 μs timescales for the modulation windows of some of the Crab GPs. The other MSPs that emit GPs have longer periods than PSR B1937+21. Perhaps then, high frequency observations of all the emitters could indicate a trend in the emission timescales that could be extrapolated to the characteristics of the Crab pulsar. Until such observations are performed, some uncertainty will remain as to whether a single physical process can explain both types of emission.

PSR B0540−69 has a longer spin period than the Crab pulsar. High time-resolution observations of its GPs could be used to determine the expected characteristics of similar emission from even slower pulsars like those that emit giant micro-pulses. At $\sim$10 μs and $\sim$1 ms respectively, the strong pulses of PSR J0437−4715 and giant micro-pulses of pulsars like PSR B1706−44 have much longer timescales than the GPs of PSR B1937+21. Determining that these pulses arise from an emission mechanism similar to that of the GPs from MSPs really needs observations of nano-structure. A significant null-detection of nano-pulses could rule out giant micro-pulses as simply being GPs occuring at a low rate.

A variety of pulse morphologies and widths are seen from the GPs of PSRs B1112+50 and B0031−07. Large numbers of shots probably make up these pulses. Perhaps then the GPs of PSRs B1112+50 and B0031−07 are caused by a different physical process to the ultra-bright pulses of the millisecond pulsars. The fact that the timescale for PSR J1752+2359 emitting bursts of strong pulses is different at 111 and 430 MHz implies that the high intensities of the GPs result from propagation effects. However, this need not be the case if the GPs are intrinsically a narrow-band phenomenon. High time-resolution observations at a variety of frequencies are needed to elucidate the properties of these emitters.

4 CONCLUSIONS

Giant pulses from millisecond pulsars have a uniform set of qualities — durations of microseconds or less; phase-alignment with X-ray emission; and power-law energy-statistics. As most pulses exhibiting these criteria are weak, the giant pulses from millisecond pulsars are only "giant" in the sense that their ultra-high brightness temperatures are giant compared to ordinary pulses.

The giant pulses from PSR B1937+21 appear to be composed of at most a few coherent shots of nanosecond duration spread over windows of $\lesssim 1\,\mu$s. Giant pulses from the Crab pulsar are also composed of nano-pulses, but many make up its longest ($\sim$100 μs) giant pulses. High time-resolution observations of the other millisecond pulsars that emit giant pulses are needed to see whether pulsar characteristics such as pulse period correlate in any way with substructure durations. Observations of the intrinsic timescales of giant pulses from the more slowly rotating Crab-like pulsar B0540−69 could also help elucidate whether long-duration pulses such as giant micro-pulses can be attributed to the mechanism of the giant pulses from millisecond pulsars. The giant pulses of the slow pulsars B1112+50, B0031−07, and J1752+2359 exhibit a variety of pulse morphologies and seem to occur in bursts whose durations are dependent on frequency. These properties are not shared by the giant pulses of millisecond pulsars, and so the two types of giant pulses are probably created through different physical mechanisms.

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