A search for giant pulses in Vela-like pulsars

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ABSTRACT
We have carried out a survey for ‘giant pulses’ in 6 young, Vela-like pulsars. In no cases did we find single pulses with flux densities more than 10 times the mean flux density. However, in PSR B1706–44 we have detected giant micro-pulses very similar to those seen in the Vela pulsar. In PSR B1706–44 these giant micro-pulses appear on the trailing edge of the profile and have an intrinsic width of ~1 ms. The cumulative probability distribution of their intensities is best described by a power-law. If the power-law continues to higher intensities, then 3.7 × 10^6 rotations are required to obtain a pulse with 20× the mean pulse flux. This number is similar to the giant pulse rate in PSR B1937+21 and PSR B1821–24 but significantly higher than that for the Crab.

Key words: pulsars: individual (PSR B1706–44)

1 INTRODUCTION
Despite three decades of intensive study, the mechanism producing pulsar radio emission is poorly understood. Fluctuations in the intensity of the radio radiation provide important constraints on plausible mechanisms. Single-pulse studies of bright pulsars detect a variety of patterns in the intrinsic intensity fluctuations, including nulling and drifting phenomena. The distribution of integrated pulse energies, however, has only a modest dispersion. Johnston et al. (2001) showed that in the Vela pulsar, 99.5% of all pulses are within a factor of 3 of the mean flux density, ⟨S⟩. The probability distribution of their intensities is best described by a power law. If the power-law continues to higher intensities, then 3.7 × 10^6 rotations are required to obtain a pulse with 20× the mean pulse flux. This number is similar to the giant pulse rate in PSR B1937+21 and PSR B1821–24 but significantly higher than that for the Crab.

In contrast, the Crab pulsar emits pulses with flux densities > 20 × ⟨S⟩, extending up to > 2 × 10^4 ⟨S⟩ (Lundgren et al. 1993) which were instrumental in the original detection of the Crab (Staelin & Reifenstein 1968). These giant pulses are typically broadband (Moffet 1977; Sallmen et al. 1999) and of short duration, with widths of order a few μs and structure down to 10 ns (Jankins 1996). They are localized to the main and interpulse phase windows and follow an intensity distribution best characterized as a power law with index ~ 3 – 3.5.

The discovery of similar pulses from the millisecond pulsar PSR B1937+21 (Sallmen & Backer 1993; Cognard et al. 1996) was surprising. The pulses are extremely short (τ < 0.3μs) events confined to small phase windows trailing the main pulse and interpulse, again with an approximately power-law distribution of pulse energies (Kinkhabwala & Thorsett 2000). Since PSR B1937+21 is the only known radio pulsar with an estimated magnetic field at the light cylinder larger than that of the Crab, it has been suggested that this is a key parameter controlling the giant pulse phenomenon (Cognard et al. 1996).

Johnston et al. (2001) have recently found that a small subset of pulse phases from the Vela pulsar have a very wide distribution of peak fluxes. The pulses are localized to a phase window ~1 ms prior to the bulk of the integrated pulse emission, are of short duration and are highly polarized. Johnston et al. (2001) called these giant micro-pulses. It is not clear if these events are related to true giant pulses; the largest Vela pulses observed to date have S < 10⟨S⟩, but these narrow pulses have peak fluxes exceeding 40× the integrated peak intensity. Kramer, Johnston & Van Straten (2001) have shown that these giant micro-pulses have a power-law distribution and the extended tail of the distribution may continue into the true giant pulse regime. Cairns, Johnston & Das (2001), in contrast, recently showed that a log-normal distribution provided an excellent fit to the flux densities in individual phase bins across the main peak of the Vela profile. It seems likely that the same distribution is also applicable to other pulsars. Therefore a potential discriminator of giant pulse activity is the change from a log-normal distribution to a power-law one.

To explore the connection between the giant pulses in the Crab and PSR B1937+21 and the large individual pulses in the Vela pulsar, we obtained fast time-sampled data for several young and millisecond pulsars. In an earlier paper (Romani & Johnston 2001) we reported the detection of giant pulses from the millisecond pulsar with the next highest known light cylinder field, PSR B1821–24. In this paper...
we report on our survey of young pulsars focussing on the results obtained for PSRs B1046–58 and B1706–44.

2 OBSERVATIONS AND DATA ANALYSIS

Table 1 lists the relevant parameters for the pulsars observed in this survey. The pulsars were chosen on the criteria of small spin periods and/or small age coupled with a reasonably high flux density at 1500 MHz. The link between high energy emission and giant pulses seems a strong one (Romani & Johnston 2001), hence we also chose pulsars which have been detected at high energies. PSRs B1046–58, B1706–44 and J1105–6107 are not known to pulse in the X-ray and their X-ray emission is likely dominated by a surrounding nebula (Pivovaroff, Kaspi & Gotthelf 2000; Becker, Brazier & Trümper 1995; Gotthelf & Kaspi 1998). The first two are are pulsed in γ-rays (Kaspi et al. 2000; Thompson et al. 1992), the latter is a γ-ray detection but a search for pulses has as yet proved unsuccessful (Kaspi et al. 2000). PSR B1509–58 is pulsed at both X-ray and γ-ray wavelengths (Ulmer et al. 1993; Rots et al. 1998). PSRs J1420–6048 and J1617–5055 are pulsed in the X-ray and may also be associated with γ-ray sources (Roberts, Romani & Johnston 2001; Gotthelf, Petre & Hwang 1997).

Observations were made on 20-22 May 2001, with the Parkes 64-m radio telescope. We used the center beam of the 21-cm multi-beam system at an observing frequency of 1517.5 MHz. The receiver has a system equivalent flux density of 30 Jy on cold sky. The back-end consisted of a filter-bank system containing 512 channels per polarization each of width 0.5 MHz for a total bandwidth of 256 MHz. The data were then de-dispersed at the pulsar’s nominal dispersion measure (DM). The mean and rms of groups of 8192 samples (0.65 s) were examined and those which showed obvious signs of interference were discarded. The data could then be folded synchronously with the pulsar’s topocentric period to produce a pulse profile. Our nominal 5-σ sensitivity in 80 µs is 1.3 Jy. In practice, even after removal of high sigma points (clipping), we experienced substantially larger background fluctuations and the rms exceeded our expected rms by a factor of 1.5-3.

To confirm that we could detect conventional giant pulses, we made short observations of the Crab pulsar, during which giant pulses were detected with high significance. Short integrations with the Vela pulsar off-axis, producing an effective continuum flux of only 0.6 mJy, confirmed that we could detect the largest individual Vela-type giant micro-pulses at faint continuum flux levels. Finally, we observed PSR B1937+21, obtaining 1784 s of integration (1.15 × 10⁶ pulses). Our sampling provides only 19 bins across the pulse profile, but we clearly detect the giant pulse distributions in both the main and interpulse components. In both components the giant pulse peaks occur ~ 1 sample after the corresponding peak of the integrated pulse profile. The largest main component giant pulse obtained had an energy 445 Jyµs, the third largest had 230 Jyµs. The phasing and intensity distribution are well matched to the 1.4 GHz results reported by Kinkhabwala & Thorsett (2000).

3 RESULTS

3.1 PSR B1046–58

PSR B1046–58 has a mean flux density of 5.9 mJy. It has a narrow pulse profile with a peak flux of 150 mJy, the highest of any of the pulsars in our sample. We re-sampled the 80 µs data to produce 256 phase bins across the pulsar period and examined ~8200 single pulses. The rms per phase bin is 85 mJy; in ~82000 pulses we expect the largest noise sample to be 4.3σ. On both the leading edge and trailing edges of the pulse we see a number of large amplitude pulses, where the peak flux exceeds 20 × the integrated flux in these phase bins. Examples of these pulses are shown in Figure 1. This behaviour is reminiscent of the Vela pulsar, where Krishnamohan & Downs (1983) showed that the strong pulses were confined to the rising edge of the profile. Kramer et al. (2001) showed that the distribution of fluxes on the rising edge of the Vela pulsar has a log-normal distribution with a relatively large sigma of 0.6 in the log, in contrast to the giant micro-pulses which occur even earlier in phase and which have a power-law distribution of fluxes. In PSR B1046–58 the situation is less extreme. Figure 2 shows the distribution of fluxes on the rising edge of the pulse and their cumulative probability distribution. These are consistent with a log-normal fit with a sigma of 0.33 in the log. The trailing edge of the pulse shows rather similar behaviour. The best fit to these data is also log-normal with slightly larger sigma of 0.45 in the

![Figure 1](image_url)
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Figure 2. Top panel: Histogram of flux densities on the leading edge of the pulse of PSR B1046–58. The solid line denotes the best fit to the data after convolving a gaussian noise distribution of width 32.0 mJy with a log-normal pulsar distribution with mean of 36.5 mJy and sigma (in the log) of 0.33. Bottom panel: Cumulative probability distribution of the data (binned) and best fit (solid line).

log. In contrast, the centre of the pulse is best fit with a log-normal distribution with sigma of 0.25.

The key issue here is that log-normal distribution provides an excellent fit to the data at all pulse phases (Cairns et al. 2001). There is no evidence of any power-law distribution at any phase. The variations seen in sigma across pulse phase is consistent with the statement that the modulation index is large towards the outside of the pulse and small in the centre, a trend which has been known since the mid-1970s (Taylor, Manchester & Huguenin 1975; Krishnamohan & Downs 1983).

3.2 PSR J1105–6107

The integrated flux density of this pulsar is 1.49 mJy. The pulse profile is double-peaked with a peak flux density of 60 mJy. We subdivided the pulse period into 256 phase bins for a time resolution of 250 µs and examined the ∼168000 pulses. The effective rms was 100 mJy per phase bin. Only phase bins towards the centre of the pulse had a flux density in excess of that expected from the noise fluctuations. The distribution of intensities in the peak flux bin was consistent with a log-normal distribution with sigma of 0.3 in the log convolved with gaussian statistics for the noise. There was no evidence of a power-law tail to the distribution in any phase bin.

3.3 PSR J1420–6048

The pulsar was observed for a total of 4 hr, split into two separate observations. The integrated flux density for both observations is only 0.95 mJy. The pulsar has large duty cycle; as a result its peak flux is only 12 mJy. No large samples were detected at any pulse phase. Subdividing the pulse into 256 phase bins and examining the single pulses yielded statistics which were consistent with the noise level of 90 mJy. One pulse out of ∼210000 had, however, a peak flux of 800 mJy, this is the only sample in the entire data set with a flux greater than 5 times the noise rms (450 mJy). This high point is located on the leading edge of the second peak, where the integrated flux density is only 2.1 mJy. However, re-examination of individual 80 µs samples, revealed that this high flux is entirely due to one sample. As the DM of the pulsar ensures that any real signal should be smeared by ∼7 samples, we therefore believe this does not originate from the pulsar but is likely to be interference or an instrumental glitch.

3.4 PSR B1509–58

The integrated flux density during our 3 hr observation was only 0.96 mJy. This pulsar has a broad single component with a peak flux density of only 8 mJy. The DM is large, effectively smearing our time resolution to 400 µs. No large samples were detected during the observation. We then subdivided the pulse period into 256 phase bins for a time resolution of 3650 µs and examined the ∼65000 single pulses. The effective rms was 70 mJy per phase bin, no single phase bin had a flux density in excess of 5σ.

3.5 PSR J1617–5055

The pulsar is very weak with a flux density of only 0.15 mJy in our 3 hour observation. The pulsar is significantly scatter-broadened at this frequency and the peak flux is only 1.5 mJy. We subdivided the pulse period into 128 phase bins and examined each of the ∼150000 pulses. No single phase bin of any pulse was in excess of 400 mJy or 5× the noise level. This is consistent with Kaspi et al. (1998) who also reported a lack of giant pulses from this pulsar.
Johnston & Romani

Figure 4. Cumulative probability distributions for two phase bins. The solid line is the expected distribution from Gaussian noise with an rms of 90 mJy. The right panel shows an extra solid line representing a power-law of slope –2.7. The dashed line is the reciprocal of the number of pulses.

3.6 PSR B1706–44

This pulsar was observed twice, each observation was 1.5 hr in length. The integrated flux densities were 8.63 and 7.70 mJy in the two observations. This pulsar has a profile which consists of a single component with a peak flux of ~100 mJy. Analysis of each 80 µs sample revealed that many strong samples were detected in a small phase window located far into the wings of the trailing edge of the profile. No such samples were detected on the leading edge and only a few at the peak of the pulse profile. It was clear that the large pulses were resolved on this timescale. We then divided the pulse period into 256 phase bins and the ~46000 single pulses from each observation were examined. The rms per bin is 92 mJy. Figure 3 shows the pulse with the largest peak flux density. The flux density in this phase bin is 500× the flux density in the integrated profile at this phase, but the integrated flux is only 4 times that of the integrated profile (i.e. it would not be classified as a true giant pulse). The pulse is clearly resolved with a half width of ~1 ms. This width must be intrinsic; the DM smearing is only 120 µs and the scattering time at this frequency is negligible (Johnston, Nicastro & Koribalski 1998). Of the ~93000 pulses collected, 52 had a peak flux density in excess of 50× the integrated flux density at a given phase. All these pulses are located between phases 0.06 and 0.095.

Figure 4b shows the cumulative probability distribution of the intensities at phase 0.079. The mean flux density at this phase is 4 mJy, therefore only pulses with intensities greater than 80× this can be detected at the 3-σ level. The distribution clearly deviates from that expected from gaussian noise and at high flux levels can best be described with a power law with index –2.7. This power law index is very similar to that seen in the Crab pulsar and PSR B1937+21. In contrast Figure 4a shows intensities for a bin on the rising edge of the profile with the same integrated flux density as for phase 0.079. No large intensities are seen and the distribution is consistent with noise.

There are no true giant pulses seen in our data set for PSR B1706–44. The maximum flux density of any single pulse was only ~4× the mean integrated flux density. Figure 5 shows the distribution of fluxes summing over all phase bins. The fluxes have been normalised to take into account the effects of interstellar scintillation. The width of the distribution is essentially determined by the receiver noise. However, there is an excess of counts at high fluxes - there are 782 pulses with flux densities greater than 2.4× the mean flux density but only 490 pulses with flux densities less than -0.4× the mean. This indicates the pulsar flux is likely log-normally distributed.

It is our belief that the power-law distribution shown in Figure 3b is indicative of giant pulse behaviour. If this power law continues to larger fluxes, then 3.7 × 10⁶ rotations are needed before reaching a pulse with 20 times the mean flux density. This number of rotations is within a factor of 10 of
the giant pulse rate in both PSR B1937+21 and B1821–24 but significantly higher than that of the Crab.

4 DISCUSSION

In the Vela pulsar, log-normal statistics are adequate to fit the distribution of flux across the bulk of the pulse profile (Kramer et al. 2001, Cairns et al. 2001) but the width of the distribution is significantly larger at the edge of the profile than in the middle. In addition to this, there are giant micro-pulses which occur well before the main pulse phase. These giant micro-pulses have a half-width of \( \sim 200 \mu s \), and are not at a fixed phase, but have an inherent ‘jitter’ of about 1 ms (Johnston et al. 2001). Their distribution is best described by a power-law (Kramer et al. 2001). We have found new examples of both these phenomena in our current survey.

PSR B1706–44 shows an additional example of giant micro-pulses. This time, however, the giant micro-pulses are located on the trailing edge of the pulse, and are somewhat wider then in Vela with a half-width close to 1 ms. Again there is some phase jitter as to the location of the pulse maximum. For this pulsar also, the distribution of fluxes is clearly power-law at high amplitudes.

In PSR B1046–58 we clearly see large amplitude pulses on both the leading and trailing edges of the integrated pulse profile. The intensity distribution at these phases, however, is moderately described by a log-normal distribution with a width of 20× the mean flux density but there is no evidence for a power-law tail to the distribution. In this regard they are similar to the fluctuations seen on the rising edge of the Vela pulsar.

No giant micro-pulses are detectable in PSRs J1105–6107, J1420–6048, B1509–58 or J1617–5055. However, the sensitivity to giant micro-pulses in these pulsars is not as good as for PSR B1706–44 or B1046–58. To demonstrate this, let’s assume that any giant pulses would be similar to those seen in PSR B1706–44; i.e. they would have an intrinsic width of 0.5 ms, a power-law index of –3.0 and occur every 107 rotations. The brightest giant pulse in the observing time for PSRs J1105–6107, J1420–6048, B1509–58 and J1617–5055 would therefore be less than 500 mJy (in 0.5 ms) and not detectable in the noise. Giant pulses could only be detected in these pulsars if they were intrinsically very narrow, and/or occurred much more frequently than in either Vela or PSR B1706–44.

We find, as in previous studies (e.g. Taylor et al. 1975), that the modulation of pulse intensity is larger in the wings of the profile of Vela-like pulsars. PSR B1046–58 is a good example of this behaviour: its phase resolved intensity distributions are well described by a log-normal distribution whose width increases towards the profile edge. The giant micro-pulses in Vela and now PSR B1706–44 appear to represent a distinct pulse population, with emission phases well separated from the bulk of the integrated pulse profile. Both of these phenomena represent enhanced intensity fluctuations.

Observations of the Crab pulsar at infra-red, optical and higher energies (e.g. Lundgren et al. 1995, Patt et al. 1999, Romani et al. 2001) show that there are no detectable intensity fluctuations in the (incoherent) high energy emission associated with the radio giant pulses. Thus we must conclude that giant pulses represent a variation in the coherence of the particle distribution. An important question is why coherence fluctuations appear to be strongest at the pulse edges.

One clue may be found in the connection of pulse width to altitude. Crudely, in a dipole polar cap of radius \( r \), the width of the edge of the open zone maps as \( \delta \propto r^{1/2} \). If interpreted as the edge of a polar zone, the leading and trailing edges of the profiles where the modulation index increases represent locations 1.5–2× higher than that of the mean pulsar emission. If we adopt the classical polar gap picture, with a pair formation front producing a dense plasma at a few stellar radii, then we can identify pulse intensity fluctuations with the growth of instabilities in the outflowing pair wind. Larger widths represent higher altitudes, and in this picture larger phase-space amplitudes for the instability-driven fluctuations, which have had more time to grow in the outflow. Alternative pictures exist, such as the slot-gap scenario of Arons (1983) for which the gap height is larger at the edge of the polar cap. Again there could be a plausible connection with increased instability.

In both PSR B1706–44 and Vela the giant micro-pulses are located far from the peak of the pulse profile, representing an emission altitude \( \sim 4 \times r \) higher. It is plausible that instability growth reaches a different regime at these heights. Clearly a true power-law intensity distribution suggests that the instabilities have left the (linear) stochastic growth regime (Cairns et al. 2001). Power-law behaviour suggests a causal connection between different intensity scales such as a cascade from one energy scale to another, or a self-similar coupling as in a saturated growth scheme. Such processes might develop late (higher) in the polar wind outflow.

The giant micro-pulse emission is however well separated from the bulk of the radio emission in these objects, suggesting instead an independent origin. There is good evidence that for the Crab and possibly PSR B1821–24, the giant pulse radio emission is co-located with high energy emission in the outer magnetosphere, where strong power law X-ray components indicate sites of dense pair production. Vela and PSR B1706–44 are also \( \gamma \)-ray emitters; in the outer magnetosphere picture this high energy emission comes from the pole opposite to that viewed in the radio. They do not show strong X-ray pulses and so it is perhaps not surprising that we have not found giant pulse emission coincident with the \( \gamma \)-rays in these objects, as the Earth line-of-sight evidently does not sample regions of dense pair production. Nevertheless, there may be a high energy connection to the giant micro-pulse emission if the outer magnetosphere above the radio pole is also actively producing pairs. The high energy emission from beyond the null charge surface would not be visible from this pole, but some pairs from the gap would be expected to flow inward past the null charge surface. We can speculate that this plasma mirrors in the converging field lines above the radio pole and that this mirrored, counter-streaming population would suffer instability growth and produce the giant micro-pulse components.

A final question concerns the asymmetry of the giant micro-pulse component. Why does it lead in the case of Vela, but lag for PSR B1706–44? For Vela, the radio pulse has a steep rise and slow fall suggesting the leading edge
of a cone; the giant micro-pulse component is at higher altitudes on the same side. For PSR B1706−44, one would then infer that the main radio pulse is the trailing edge of a cone, although this is morphologically less clear. If there is a high energy connection, then it is intriguing to note that the leading γ-ray pulse is stronger for Vela, while for PSR B1706−44, the trailing component is stronger at most high energies. More examples are clearly needed to see if the dominance of leading versus trailing giant micro-pulses has a deterministic connection with other pulsar emission and if some global asymmetry in the magnetosphere geometry controls this choice.

CONCLUSIONS

We have found evidence for giant micro-pulses in PSR B1706−44 which are very similar to those seen in the Vela pulsar. They are located in a small window of pulse phase, have a duration of ∼1 ms and significant phase jitter. Their amplitude distribution is power-law and so may extend into true ‘giant pulses’ if observed for long enough. It is unclear whether the giant micro-pulses are just another manifestation of pulsar ‘weather’ associated with the standard radio emission from pulsars or whether they are more closely related to high-energy phenomena and the classical giant pulses.

No giant pulses or any other giant micro-pulses were detected within our sensitivity limits in any of the other 5 pulsars in our survey. Where it was possible to measure amplitude distributions, these were generally log-normal as surmised by Cairns et al. (2001).

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