Research in Astron. Astrophys. **2011** Vol. **11** No. **8**, 974–980
*http://www.raa-journal.org* *http://www.iop.org/journals/raa*

***R**esearch in*
***A**stronomy and*
***A**strophysics*

# Strong pulses from pulsar PSR J0034−0721 *

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Received 2010 November 16; accepted 2011 March 24

**Abstract** We present an analysis of strong single pulses from PSR J0034−0721. Our observations were made using the Urumqi 25-m radio telescope at a radio frequency of 1.54 GHz. A total of 353 strong pulses were detected during eight hours of observing. The signal-to-noise ratios of the detected pulses range from 5 to 11.5. The peak fluxes of those pulses are 17 to 39 times that of the average pulse peak. The cumulative distribution of the signal-to-noise ratios of these strong pulses has a rough power-law distribution with a slope of $4.4 \pm 0.5$. Ten of the strong pulses arrived approximately 23 to 40 ms earlier than the average profile peak. This suggests the possibility that there are two strong pulse-emitting regions.

**Key words:** pulsars: PSR J0034−0721, individual pulses: strong pulses

## 1 INTRODUCTION

We define a "strong pulse" from a radio pulsar as an individual pulse that has a peak flux exceeding the peak of the average pulse (AP) profile by a factor of ten or more. Such strong pulses have been previously discussed in the literature as "giant pulses" (hereafter, GPs) (Hankins et al. 2003), sporadic bursts of emission detected from rotating radio transients (McLaughlin et al. 2006; Esamdin et al. 2008) and rare strong radio bursts from PSR B0656+14 (Weltevrede et al. 2006).

GPs are short-duration, burst-like, sporadic increases of intensity and were first detected in the Crab pulsar (Staelin 1970). Typical GPs are very short (Hankins et al. 2003) and their peak flux densities can exceed hundreds or even thousands of times that of regular pulses. The typical GP phenomenon has only been detected in two pulsars with small characteristic ages (the Crab pulsar and PSR B0540−69; Kostyuk et al. 2003 and Johnston & Romani 2003) and in five millisecond pulsars. The five millisecond pulsars are PSRs J0218+4232 (Joshi et al. 2004), B1821+24 (Romani & Johnston 2001), B1937+21 (Backer 1995; Cognard et al. 1996), J1823−3021 (Knight et al. 2005) and B1957+20 (Joshi et al. 2004). Although these seven pulsars have very different rotational rates, all of them have a strong magnetic field in the light cylinder, $B_{\rm LC} > 10^5$ G.

Observations at 111 MHz have provided evidence for GPs occurring in four normal pulsars that do not have such strong magnetic field strengths in the light cylinder. GPs at this frequency have

* Supported by the National Natural Science Foundation of China.

been detected in PSRs J0034−0721 (Kuzmin & Ershov 2004), B1112+50 (Ershov & Kuzmin 2003), J1752+2359 (Ershov & Kuzmin 2005) and B0656+14 (Kuzmin & Ershov 2006). Observations at higher frequencies are required in order to understand the properties of these strong pulses and to determine whether they are caused by the same phenomenon that produces GPs at higher frequencies.

One of these pulsars, PSR J0034−0721, has a spin period of $P$ = 0.943 s, a relatively small dispersion measure (DM) of 11.38 pc cm$^{-3}$, a characteristic age of $3.66 \times 10^7$ yr and a magnetic field strength in the light cylinder of 7 G. GPs have been reported at 40 and 111 MHz (Kuzmin & Ershov 2004). The peak fluxes of the detected pulses at 40 MHz were 100 to 400 times stronger than the AP and 30 to 120 times stronger at 111 MHz. They showed that the intensities of the strong pulses are inversely proportional to the observational frequency and therefore such pulses may not be detectable at higher frequencies. Since the magnetic field strength in the light cylinder is relatively small, Kuzmin & Ershov (2004) suggested that the giant pulses from this pulsar may not come from the outer gap (Chiang & Romani 1992).

In this paper we report new observations of single pulses from PSR J0034−0721 at 1.54 GHz. In Section 2, we describe the observations. In Section 3 we describe our method for searching for strong single pulses. The results from this search for single pulses are described in Section 4. We describe the implications of this search for the strong pulse and for the giant pulse phenomenon in Section 5. Our work is summarized in Section 6.

## 2 OBSERVATIONS

Observations were performed from 2009 November 19 to 2010 January 13 using the Urumqi 25-m radio telescope. A total of eight hours of data were collected in four observational runs. The duration of each observation was about two hours. The Urumqi 25-m radio telescope is equipped with a dual-channel cryogenic receiver that receives orthogonal linear polarizations at the central observing frequency of 1540 MHz. The receiver noise temperature is less than 20 K. After mixing down to an intermediate frequency, the two polarizations are each fed into a filter bank of 128 contiguous channels (Wang et al. 2001), each with width 2.5 MHz. The outputs from the channels are then square-law detected, filtered and one-bit sampled at a 0.25 ms interval. The data streams of all 256 channels are written to a disk for subsequent off-line processing. The start time of each observation is recorded, which enables the site arrival time of any pulse to be determined. As we search for single pulses with a signal-to-noise ratio ($R_{\rm SN}$) above $5\sigma$, the minimum peak flux density of the detected signal is

$$S_{\rm min} = \frac{2R_{\rm SN}\beta k(T_{\rm rec} + T_{\rm sky})}{\eta A\sqrt{n_p \tau \Delta f}}, \tag{1}$$

where $R_{\rm SN} = 5$ is the threshold, $\beta = \sqrt{\frac{\pi}{2}}$ is a factor accounting for losses due to one-bit digitization (Lorimer & Kramer 2005), $k$ is Boltzmann's constant, $T_{\rm rec}$ and $T_{\rm sky}$ are the receiver and sky noise, respectively ($T_{\rm rec} + T_{\rm sky}$ ~27 K), $n_p = 2$ is the number of polarizations summed, $\tau$ = 0.25 ms is the sampling interval, $\Delta f = 320$ MHz is the observational bandwidth, $\eta = 57\%$ is the antenna efficiency at 1540 MHz and $A = 490.87\,{\rm m}^2$ is the area of the antenna. We calculated a minimum detectable pulse amplitude of $\sim 4.1$ Jy for our $5\sigma$ detection threshold.

## 3 THE DETECTION OF STRONG SINGLE PULSES

Radio waves propagating through ionized plasma in the interstellar medium experience a frequency-dependent delay due to the dispersive effects of the plasma. In order to detect short bursts from celestial sources, this frequency-dependent delay has to be removed. Some of our observational data were contaminated by radio frequency interference (RFI). The frequency-dispersion property of signals can also assist in distinguishing between signals of celestial origin and locally generated impulsive RFI (Cordes & McLaughlin 2003).

The data processing was performed in two steps in order to detect the dispersed strong pulses from PSR J0034−0721. The observational data were first de-dispersed by delaying successive channels in time corresponding to the nominal DM (11.38 pc cm$^{-3}$) of the pulsar and then searching for all pulses above a $5\sigma$ signal-to-noise threshold as signal candidates through the de-dispersed time-series. Secondly, in order to ensure that the observed signals came from the pulsar, we applied a series of de-dispersions to each signal candidate again. The de-dispersion procedure was performed from zero DM to 45.52 pc cm$^{-3}$ in steps of 1.38 pc cm$^{-3}$. With this method, a DM-time distribution of the candidate signal is obtained. We can then analyze the evolution of signal intensity and width in the DM-time space to distinguish the impulse RFI from the strong pulses of the pulsar. The pulse signal from the pulsar is concentrated around the pulsar's nominal DM and the pulse gradually broadens and becomes weak with the DM either increasing or decreasing from the nominal DM. The impulsive RFI signal is spread from zero DM to several nearby DMs and the signal gradually broadens and becomes weak with the DM increasing.

Using the search method mentioned above, a total of 353 single pulses were detected during eight hours of observing. We compare the phases of these single pulses by comparing the residuals of the pulse arrival time obtained by using the single-pulse timing method. In order to compare the phases of the single pulses with the AP profile of this pulsar, we folded the individual pulses with respect to the pulse period and generated the AP profile.

## 4 RESULTS

In eight hours of observational data, we detected a total of 353 strong pulses from PSR J0034−0721 with signal-to-noise ratios ($R_{\rm SN}$) above the $5\sigma$ threshold. The $R_{\rm SN}$ of the strongest pulse is 11.5.

Figure 1 shows a strong pulse (solid line) detected through the observations and the AP of the pulsar (dotted line). The pulse is located at an earlier phase than that of the AP peak by about 25.7 ms. The $R_{\rm SN}$ of the pulse is 10.5.

The AP is obtained by folding 15 270 single pulses from four hours of observational data. The $R_{\rm SN}$ of the AP is about 36 and the full width at half maximum (FWHM) of the profile is $W_{50} = 36.3$ ms. The $R_{\rm SN}$ values of the 353 detected pulses range from 5 to 11.5; correspondingly, their peak fluxes are approximately 17 to 39 times that of the AP.

Figure 2 compares the phase of the detected pulses with the AP. The upper panel of Figure 2 shows the phase-$R_{\rm SN}$ distribution of the detected pulses. The AP profile is shown in the lower panel. The vertical dotted line in Figure 2 indicates the phase of the AP's peak.

Figure 2 shows that most of the strong pulses from this pulsar detected at 1.54 GHz are clustered in a narrow region close to the AP peak. However, at least ten strong pulses, with $R_{\rm SN}$ ratios greater than six, were detected in a phase range that leads the AP's peak phase by 22.5 to 40 ms. The middle point of this range is roughly 31 ms earlier than the AP's peak.

Kuzmin & Ershov (2004) noted that the AP of the pulsar at 40 MHz is comprised of two components. The leading component is weak and separated from the stronger component by 100 ms. Only one component is detected in the AP at 111 MHz, but the strong single pulses are concentrated in two different regions. The separation is about 55 ms.

Similar to the results at 111 MHz, the AP obtained at 1.54 GHz has only one component. The distribution of the strong pulses shows that they may also be concentrated in two different phase regions with about 31 ms of phase separation. These may strongly suggest the presence of two separate strong-pulse emitting regions in the radiation window of the pulsar. We must note that the strong pulse detecting ratio in the earlier phase is much smaller than that in the region close to the peak of the AP.

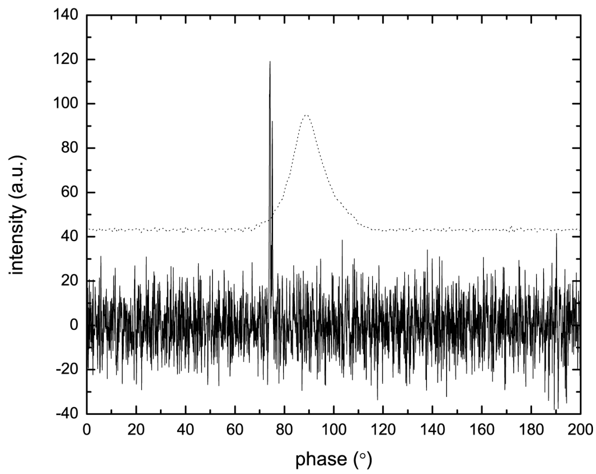


**Fig. 1** A strong pulse (*solid line*) located at a phase earlier than that of the AP (*dotted line*) peak by about 25.7 ms. The $R_{\mathrm{SN}}$ of the pulse is 10.5.

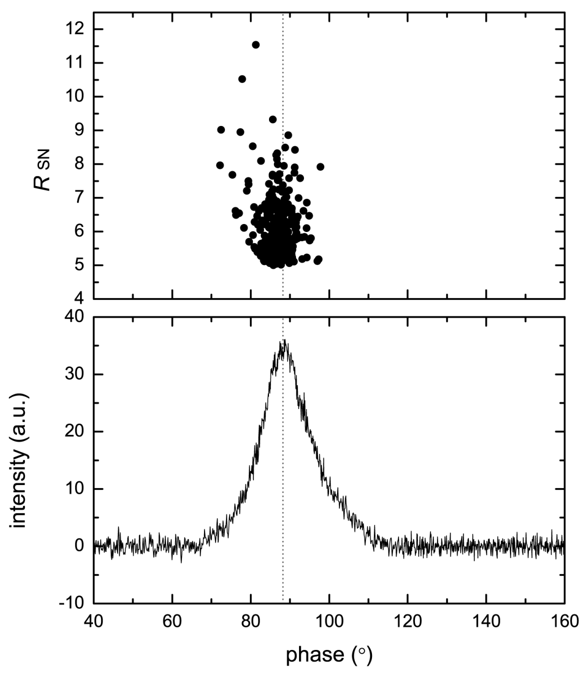


**Fig. 2** Phase-$R_{\mathrm{SN}}$ distribution of 353 detected single pulses (*upper*) and the AP (*bottom*). The *dotted lines* indicate the phase of the AP peak.

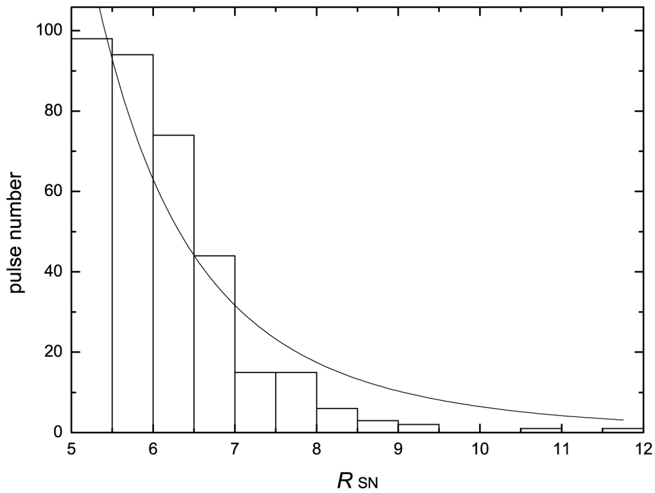


**Fig. 3** Cumulative distribution of the $R_{\rm SN}$ values for the 353 single pulses. The histogram has a rough power-law distribution with a slope of $\alpha = -4.4 \pm 0.5$.

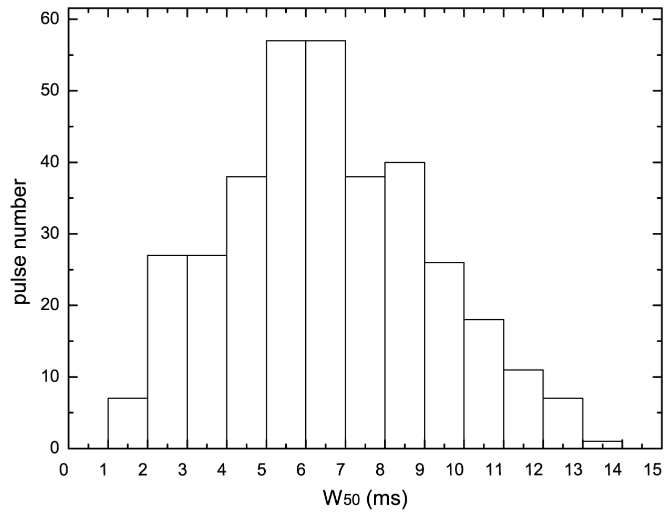


**Fig. 4** Distribution of $W_{50}$ for 353 single pulses.

Figure 3 shows the cumulative distribution of the $R_{\rm SN}$ values for the 353 single pulses. This distribution has a rough power-law distribution and the best-fit slope has an exponent of $\alpha = -4.4 \pm 0.5$. Kuzmin & Ershov (2004) also derived power-law indexes of –4.5 at 40 MHz and –4.8 at 111 MHz, which are close to the values in our work.

Figure 4 presents the distribution of $W_{50}$ for 353 single pulses. The $W_{50}$ of these pulses range from 1.5 to 13.1 ms, with an average value of 6.5 ms.

## 5 DISCUSSION

A typical GP is a broadband phenomenon whose intensity can exceed hundreds or even thousands of times the intensity of the AP. The results derived from the three observational frequencies imply that the peak fluxes of the detected strong pulses from this pulsar are much lower than those of typical GPs.

Typical GPs are extremely short with durations of several microseconds to a few nanoseconds. As shown in Figure 4, the $W_{50}$ of the pulses detected at 1.54 GHz range from 1.5 to 13.1 ms. Their widths seem to be much wider than those of typical GPs, as detected from several pulsars (Hankins et al. 2003). We should note that the dispersion, scattering and the sampling time of the observation will cause the observed pulse width to be wider than the intrinsic pulse width. The broadening of the pulse is given by

$$W = (W_i^2 + t_{\rm samp}^2 + \Delta t_{\rm DM,ch}^2 + \Delta t_{\rm scatt}^2)^{1/2}, \quad (2)$$

where $t_{\rm samp}$ is the sampling interval, $\Delta t_{\rm DM,ch}$ is the dispersion smearing across one frequency channel and $\Delta t_{\rm scatt}$ is the broadening of the pulse due to interstellar scattering.

$$\Delta t_{\rm DM,ch} = (8.3\mu{\rm s}){\rm DM}\Delta f_{\rm MHz} f_{\rm GHz}^{-3}, \quad (3)$$

where DM = 11.38 pc cm$^{-3}$ is the dispersion measure, $\Delta f_{\rm MHz}$ is the one frequency channel bandwidth in MHz, and $f_{\rm GHz}$ is the central frequency in GHz.

$$\Delta t_{\rm scatt} = \left(\frac{\rm DM}{1000}\right)^{3.5} \left(\frac{400}{f_{\rm GHz}}\right)^{4} ({\rm s}). \quad (4)$$

The sampling time in our observations is 0.25 ms. The influence of dispersion and scattering of pulse broadening can be neglected because the DM of this pulsar is too small. So the pulse is only broadened by about 0.25 ms from the above effects. The $W_{50}$ distribution in Figure 4 may fairly represent the distribution of the intrinsic pulse width of the strong pulses detected at 1.54 GHz. Although these strong pulses are narrower than the AP profile by approximately a factor of six, the widths of the detected strong pulses are much wider than those of typical GPs.

Typical GPs were detected from seven pulsars with extremely strong magnetic fields in the light cylinder $B_{\rm LC} > 10^5$ G. It is suggested that GPs were inherent in pulsars with extremely strong magnetic fields in the light cylinder, and they may originate near the light cylinder region (Lyutikov 2007). However, PSR J0034−0721 has relatively low magnetic fields in the light cylinder $B_{\rm LC}$=7 G. This is in contrast with the suggestion that GPs occur in pulsars with a strong magnetic field in the light cylinder. Kuzmin & Ershov (2006) suggested that the strong pulses from the pulsar may not come from the outer gap near its light cylinder, but instead they may originate from the inner gap of the magnetic polar region.

As shown in Figure 2, more than ten strong pulses are detected at the leading edge of the AP. The distribution of the strong pulses suggests that they may come from two different emission regions. The separation of the two emission regions at 1.54 GHz is approximately 31 ms. At 40 and 111 MHz, Kuzmin & Ershov (2004) also detected strong pulses at the AP's leading edge, which is separated from the AP peak by about 100 and 55 ms respectively. The observational results from three radio frequencies strongly suggest the presence of two strong-pulse emitting regions in the radiation window of this pulsar.

## 6 SUMMARY

Observations of pulsar J0034−0721 were made using the Urumqi 25-m radio telescope at 1.54 GHz. Using the single-pulse searching method, we detected a total of 353 strong pulses through eight hours of observational data. The pulse detection rate is approximately 1.2% in our observations.

The peak fluxes of the 353 detected strong pulses are approximately 17 to 39 times that of the AP. The cumulative distribution of intensities of the strong pulses is roughly a power-law relation, and the best fit for the slope is $\alpha = -4.4 \pm 0.5$. The $W_{50}$ of these pulses ranges from 1.5 to 13.1 ms, with an average value of 6.5 ms.

At 1.54 GHz, although the AP reveals only one component, the strong pulses are concentrated in two longitudinal regions in the radiation window. One is at a region close to the peak of the AP, while the other is leading the peak of the AP by about 31 ms. The detection ratio of the strong pulse at the earlier phase is approximately 0.03%, much smaller than that in the region close to the peak of the AP.

The intrinsic widths and strengths of the pulses imply that the strong pulses detected in PSR J0034−0721 at 1.54 GHz may be a special kind of strong pulse, which is different from the normal single pulses of the pulsar and also different from those of typical GPs.

**Acknowledgements** We thank the referee for the very helpful comments. The authors are supported by the National Natural Science Foundation of China (Grant No. 10973026) and the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No. KJCX2-YW-T09).

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