Irregularities in the rate of generation of giant pulses from the Crab pulsar observed at 111 MHz

A. N. Kazantsev\(^1\), V. A. Potapov\(^1\), M. S. Pshirkov\(^2,3,4\),
\(^1\)P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Pushchino Radio Astronomy Observatory, Pushchino 142290, Russia
\(^2\)Sternberg Astronomical Institute, Moscow State University, 119992, Universitetskiy Prospekt, 13, Moscow, Russia
\(^3\)Institute for Nuclear Research of the Russian Academy of Sciences, 117312, Moscow, Russia

Abstract

In this paper we present our results concerning the rate of generation of the giant radio pulses (GPs) from the Crab pulsar (B0531+21). One of the main goal of this investigation was to search for a possible connection between pulsar glitches and the process of GP generation. We used for our analysis results of 9 years of daily observations at frequency 111 MHz at the Large Phased Array radio telescope of Pushchino Radio Astronomy Observatory. It was shown that the observed rate of GPs is quite unstable during the entire span of observations. We have found a significant increase in the rate of GPs with flux density larger than 80 Jy around the epoch MJD 58064, when the largest glitch ever observed in the Crab pulsar happened. Although a considerable fraction of this enhancement could have been caused by the propagation effects that have taken place in the nebula itself, we have found indications that the pulsar had demonstrated rather high degree of intrinsic irregularity in the emission of the GPs, especially the stronger ones.

1 Introduction

Averaged profiles obtained from the thousands or even millions of individual pulses are highly stable for the majority of pulsars. However, their individual pulses could vary very much in shape, duration and strength due to fluctuations in the process of pulse emission in pulsar’s magnetosphere and to the effects

\(^1\)E-mail:kaz.prao@bk.ru (ANK)
\(^1\)E-mail:potap@prao.ru (VAP)
\(^4\)E-mail:pshirkov@sai.msu.ru (MSP)
arising during propagation of signal through the interstellar medium. The peak flux density and fluence of individual pulses can change in extremely wide limits. These strong fluctuations of flux were already noticed in pioneer works about the Crab pulsar [1]. Soon it was found that this pulsar regularly emits strong individual pulses with flux densities which exceed average by at least order of magnitude [2]. Subsequently these pulses were dubbed as Giant Pulses (GPs).

The GPs are one of the most intriguing phenomena in pulsar astrophysics. The brightest GPs of the Crab pulsar observed to date had flux density larger than 2 MJy at 9.25 GHz and width less than 0.4 ns [3]. The Crab pulsar is a known prolific source of regularly generated GPs which allows to investigate their characteristics in fine details [4, 5, 6].

In order to build comprehensive set of strong GPs and investigate their properties, especially the evolution of the production rate, we used almost 9 years (2010 Feb – 2018 Nov, MJD 55240 – 58440) of daily observations of the Crab pulsar at frequency of 111 MHz at the Large Phased Array radio telescope (LPA FIAN) of the Pushchino Radioastronomy Observatory of P.N.Lebedev Physical Institute. We were particularly interested in possible correlation of the GPs intensity and production rate with glitching activity which is another well-known property of this young pulsar. The glitch process is a rapid increase of rotational frequency which is followed by gradual decay and almost complete recovery of pre-glitch values of frequency and its time derivative [3]. Most likely these phenomena are caused by the processes taking place inside the neutron star itself, such as unpinning of superfluid vortices from the crust [7]. The largest glitch in almost 50 years of observations with a relative increase in frequency $\delta \nu / \nu = 5.2 \times 10^{-7}$ occurred around 2017 November 08 (MJD=58064) and although no changes in the pulse profile shape were observed near the glitch epoch [8], we used the possibility to check for possible changes in the GP properties. Without specifying any certain theoretical model we wanted to check whether the catastrophic glitch event might cause some secondary long-lasting perturbations in the magnetosphere structure, which would subsequently lead to a significant change in the process of generation of individual pulses and, particularly, GPs.

The paper is organized as follows: in Section 2 we describe the data and the method of data analysis, Section 3 contains our results and discussion, and we draw conclusions in Section 4.

## 2 Data and methods

The observations were carried out in 2010–2018 using the first beam of the LPA FIAN transit radio telescope. The effective area of the telescope varied during observations from 20000 ± 1300 m$^2$ (2010 - 2017.5 data) to 35000 ± 2000 m$^2$ (2017.5 - 2018 data). A digital receiver with 512 channels ($\delta f = 5$ kHz in each frequency channel) was used. The central frequency of observations was 111 MHz, the full bandwidth of observations was about 2.3 MHz, as there were used

\[\text{http://www.jb.man.ac.uk/pulsar/glitches/gTable.html}\]
only 460 channels. Observation session was equal to the duration of passage of the Crab nebula across the antenna beam (taken as full width of half-maximum in the intensity), which was equal to 198 sec. The sampling frequency was 2.4576 ms that was a good compromise between the radiometric gain and the time resolution of scattered pulsar profile. A single linear polarization was used.

The data reduction was made in several steps (see Fig. 1). First, the effect of the frequency dispersion of pulse in the interstellar medium was removed ("dedispersion"), second, in each session we corrected for the geometrical beam factor. Usually the antenna response for the beam factors produces the unnormalized \textit{Sinc}^2(x) function, but for a substantial part of our data the influence of ionospheric effects was significant, leading to the noticeable distortion of the theoretical antenna response. We used the spline regularization to correct these distortions. At this stage we introduce absolute flux normalization using the Crab nebula as a calibrating source – the baseline level was set at 1720 Jy [9, 10]. Scattering poses severe problem at this low frequency, broadening pulse widths to \( O(10) \) ms which are by several orders of magnitude larger than the intrinsic pulse duration \( O(\mu s) \) [11, 12]. We took \( W_{50} \) – a value of full width at half maximum, as an estimate of the pulse width and, assuming the exponential shape of the broadened pulse estimated scattering time \( \tau_d = 1.44W_{50} \). Large pulse widths makes mitigation of radio frequency interference very difficult and we were compelled to limit ourselves with a subset of stronger pulses, with peak fluxes larger than 80 Jy. An example of a GP is presented in Fig. 2. Finally the candidate pulses were visually rechecked. The total amount of detected pulses was equal to 1117 in 1922 good quality observational sessions which were performed during our time span of observations (Fig. 3).

3 Results and Discussion

The evolution of observed rate of bright GPs is presented in Figs. 4 and 8. A very sharp peak around epoch MJD\( \sim 58100 \) can be easily seen. It would be tempting to connect it to a very strong glitch which took place at approximately that time (MJD 58064), however it could be just a coincidence and should be discussed in more details. First, not every glitch in the studied timespan was accompanied by a corresponding increase in the production rate, although it should be noted that it can be explained by low amplitudes of other glitches – apart from one at MJD 55875 all of them were weaker by more than two orders of magnitude. Second, there was strong ‘orphan’ increase of activity at MJD 56700-57200 which was unaccompanied by any glitch. On the other hand, there are some indications on non-standard rotational behavior of the Crab pulsar during this epoch [13]. Thus it can be said that there are only weak evidences of correlation between glitch activity and GP production rate at the very best except the fact that the maximum of GPs is delayed by \( \sim 50 \) days with respect to the glitch epoch MJD 58064.

Still non-uniform rate of detection shall be explained. The most obvious explanation would be instrumental effects produced by the telescope, but it is
rather difficult to reconcile with our absolute calibration technique and thorough visual checks of candidate pulses. Additionally, the variations in effective area of the telescope, that if unaccounted for could potentially affect the signal-to-noise ratio and therefore the number of detected strong pulses, were controlled using a set of several calibrating sources and showed no anomalies which correlate with the rate of detections.

Propagation effects, especially strong at low frequencies, could also be responsible for the observed anomaly. We used the cut based on the observed peak flux and this value could be easily influenced by the scattering. Indeed, even if the generation rate of the GRPs with some fixed fluence $F$ was absolutely stable, peak flux $S \propto F/\tau_d$ would be modulated by the changing behavior of $\tau_d$ (or, equivalently, $W_{50}$) [10]. As it can be seen in Figs. 4 and 5 there exists a certain level of anticorrelation between the production rate and scattering strength, the sharpest peak coincides with a strong, although not the strongest one, decline in pulse widths in MJD 58100-58140 interval – our explanation seems to be valid. Also this explanation is supported by the shapes of distributions of fluxes and fluences. We have selected three regions, corresponding to regions of increased activity in 2014-2015 (MJD 56668-57252, 523 GPs), 2017-2018 (MJD 58000-58200, 378 GPs), and the remaining one (216 GPs), where the apparent rate was lower (Figs. 6-7). It could be seen that the flux distributions resemble each other pretty close, small overabundance of brighter pulses in 'regions of activity' can be linked to larger statistics of pulses in these regions. Nevertheless the fluence distributions are markedly different, the pulses in 'off region' have generally higher fluence.

However the situation is not so clear-cut: it could be seen that the maximal production rate in 2014-2015 was at MJD 56850 and was higher than the rate during the outburst at MJD 56730. On the contrary, the scattering time in the latter epoch, 20 ms was much lower than the 30 ms value around MJD 56850. Next, over some threshold in fluence even the strongest scattering could not prevent GP from entering our set, and thus we would expect some rather uniform distribution of such pulses. In Fig. 8 we present the distribution of GRPs with $F > 7200$ Jy ms. These pulses must be detected if scattering times do not exceed 90 ms, which is true for a larger part of our observations (see Fig. 5). This additional fluence cut makes our analysis more robust to uncertainties caused by the scattering. The peak around MJD 58100 is still clearly seen along with other increases (Fig. 6) and that is quite difficult to explain with an assumption that the intrinsic rate of GRP generation is stable. This non-uniform behaviour of pulses with the largest fluences can also be seen in Fig. 5.

Taking into account typical properties of dense clouds that can contribute to quick variations in scattering and DM [14] ($n \sim 10^3$ cm$^{-3}$, $T \sim 10^4$ K, $d \sim 10^{14}$ cm) it can be estimated that optical depth to free-free absorption even at 100 MHz is much smaller than unity, so these modulations could hardly be effects of obscuration by dense plasma clouds.

Intriguingly, a strong jump in DM (and scattering) in 1997 that was later explained as an effect of interaction with a cloud in the nebula also coincided
with a weak glitch MJD 50812 [15] [16].

4 Conclusions

After analysis of almost nine years of everyday observations of the Crab pulsar we constructed a large sample of bright GPs. The distribution of detected pulses is highly non-uniform and its properties could not be fully explained by the effects of pulse scattering in the nebula meaning that the underlying distribution is intrinsically non-uniform – rate of GP generation fluctuates with time.

Finally, we still were not able to refute a hypothesis that the highest peak in the generation rate is somehow connected with the strongest glitch which precedes it by 40-50 days.

Acknowledgements

The authors are grateful to B.Ya. Losovsky for sharing the data of Crab pulsar observations for years 2011-2013. ANK and MSP acknowledge the support by the Foundation for the Advancement of Theoretical Physics and Mathematics «BASIS» grant 18-1-2-51-1. MSP acknowledges the support of Leading Science School MSU (Physics of Stars, Relativistic Compact Objects and Galaxies). This research has made use of NASA’s Astrophysics Data System.

References

[1] D. H. Staelin and E. C. Reifenstein, III. Pulsating Radio Sources near the Crab Nebula. Science, 162:1481–1483, December 1968.

[2] J. M. Sutton, D. H. Staelin, and R. M. Price. Individual Radio Pulses from NP 0531. In R. D. Davies and F. Graham-Smith, editors, The Crab Nebula, volume 46 of IAU Symposium, page 97, 1971.

[3] T. H. Hankins and J. A. Eilek. Radio Emission Signatures in the Crab Pulsar. ApJ, 670:693–701, November 2007.

[4] A. Jessner, A. Slowikowska, B. Klein, H. Lesch, C. H. Jaroschek, G. Kanbach, and T. H. Hankins. Giant radio pulses from the Crab pulsar. Advances in Space Research, 35:1166–1171, 2005.

[5] M. V. Popov, A. D. Kuz’min, O. M. Ul’yanov, A. A. Deshpande, A. A. Ershov, V. V. Zakharenko, V. I. Kondrat’ev, S. V. Kostyuk, B. Y. Losovskii, and V. A. Soglasnov. Instantaneous radio spectra of giant pulses from the crab pulsar from decimeter to decameter wavelengths. Astronomy Reports, 50:562–568, July 2006.
[6] M. B. Mickaliger, M. A. McLaughlin, D. R. Lorimer, G. I. Langston, A. V. Bilous, V. I. Kondratiev, M. Lyutikov, S. M. Ransom, and N. Palliyaguru. A Giant Sample of Giant Pulses from the Crab Pulsar. *ApJ*, 760:64, November 2012.

[7] B. Haskell and A. Melatos. Models of pulsar glitches. *International Journal of Modern Physics D*, 24:1530008, January 2015.

[8] B. Shaw, A. G. Lyne, B. W. Stappers, P. Weltevrede, C. G. Bassa, A. Y. Lien, M. B. Mickaliger, R. P. Breton, C. A. Jordan, M. J. Keith, and H. A. Krimm. The largest glitch observed in the Crab pulsar. *MNRAS*, 478:3832–3840, August 2018.

[9] M. F. Bietenholz, N. Kassim, D. A. Frail, R. A. Perley, W. C. Erickson, and A. R. Hajian. The Radio Spectral Index of the Crab Nebula. *ApJ*, 490:291–301, November 1997.

[10] T. V. Smirnova and S. V. Logvinenko. Giant pulses of PSR B0531+21 at 112 MHz. *Astronomy Reports*, 53:334–342, April 2009.

[11] N. D. R. Bhat, S. J. Tingay, and H. S. Knight. Bright Giant Pulses from the Crab Nebula Pulsar: Statistical Properties, Pulse Broadening, and Scattering Due to the Nebula. *ApJ*, 676:1200–1209, April 2008.

[12] B. Y. Losovskii. The dynamics and structure of plasma inhomogeneities in the Crab Nebula. *Astronomy Reports*, 61:187–192, March 2017.

[13] M. Vivekanand. A non-glitch speed-up event in the Crab Pulsar. *A&A*, 597:L9, January 2017.

[14] A. Kuzmin, B. Ya. Losovsky, C. A. Jordan, and F. G. Smith. Correlation of the scattering and dispersion events in the Crab Nebula pulsar. *A&A*, 483(1):13–14, May 2008.

[15] D. C. Backer, T. Wong, and J. Valanju. A Plasma Prism Model for an Anomalous Dispersion Event in the Crab Pulsar. *ApJ*, 543:740–753, November 2000.

[16] A. G. Lyne, R. S. Pritchard, and F. Graham-Smith. Pulsar reflections within the Crab Nebula. *MNRAS*, 321:67–70, February 2001.
Figure 1: Upper panel: an example of typical Crab transit. Lower panel: the same observation corrected for the beam factor and influence of ionospheric effects. The baseline is normalized to 1720 Jy level. Several strong pulses could be easily seen.
Figure 2: A typical GP with peak flux density about 350 Jy and scattering broadening of pulse due to interstellar scattering $\tau_d \approx 40$ ms.
Figure 3: Fraction of good quality observational sessions. Bins are 30-days long.
Figure 4: The rate of GPs with peak flux $S$ larger than 80 Jy. Positions of glitches at MJD 55875.5, 57839.92, and 58237.357 are shown by black vertical lines. By far the strongest glitch at MJD 58064.55 is shown by a vertical bold blue line. Bin size is equal to 30 days and the rate is corrected for average number of good observational sessions in respective bins (see Fig. 3).
Figure 5: Average scattering time $\tau_d = 1.44W_{50}$ in 30-day long bins. Error bars represent standard deviation of scattering times in respective bins.
Figure 6: Distribution of peak fluxes for GPs in three selected regions: enhanced activity in 2014-2015 and 2017-2018 and the remaining ‘off-region’.
Figure 7: Distribution of pulse fluences in three selected regions.
Figure 8: The rate of GPs with total fluence exceeding 7200 Jy ms. Identically to Fig. positions of glitches at MJD 55875.5, 57839.92, and 58237.357 are shown by black vertical lines. By far the strongest glitch at MJD 58064.55 is shown by a vertical bold blue line.
Figure 9: Fluences for all GPs with peak flux exceeding 80 Jy.
Figure 10: Peak fluxes for all GPs with peak flux exceeding 80 Jy.