Constraining Pulsar Emission Physics through Radio/Gamma-Ray Correlation of Crab Giant Pulses

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To constrain the giant pulse (GP) emission mechanism and test the model of Lyutikov of GP emission, we are carrying out a campaign of simultaneous observations of the Crab pulsar between $\gamma$-rays (Fermi) and radio wavelengths. The correlation between times of arrival of radio GPs and high-energy photons, whether it exists or not, will allow us to choose between different origins of GP emission and further constrain the emission physics. Our foremost goal was testing whether radio GPs are due to changes in the coherence of the radio emission mechanism, variations in the pair creation rate in the pulsar magnetosphere, or changes in the beaming direction. Accomplishing this goal requires an enormous number of simultaneous radio GPs and $\gamma$-photons. Thus, we organized a radio observations campaign using the 42-ft telescope at the Jodrell Bank Observatory (UK), the 140-ft telescope, and the 100-m Robert C. Byrd Green Bank Telescope (GBT) at the Green Bank Observatory (WV). While the observations with the two first ones are ongoing, here we present the preliminary results of 20 hrs of observations with the GBT at the high frequency of 8.9 GHz. These particular observations were aimed to probe the model of GP emission by Lyutikov which predicts that GPs at frequencies $> 4$ GHz should be accompanied by $\gamma$-ray photons of energies of 1-100 GeV.

1. Introduction

The Crab pulsar was discovered by Staelin & Reifenstein in 1968 by its remarkably bright giant pulses (GPs). These relatively rare bursts of intense radio emission last a few nanoseconds to a few microseconds, and are clearly a special form of pulsar radio emission [e.g. 3, 4]. GPs generally occur only in certain narrow ranges of pulse phase that are often coincident with pulses seen at X-ray and $\gamma$-ray energies [5]. Popov et al. propose that all radio emission from the Crab (except for that in the precursor) is composed entirely of GPs, consistent with the alignment of the GP and high-energy components seen in other GP pulsars [6, 7].

Crab pulsar shows pulsed emission across the entire electromagnetic spectrum (see Fig. 1 left), reflecting different radiation processes in pulsar magnetosphere — from coherent curvature or synchrotron (radio) to incoherent synchrotron (optical and X-ray) and incoherent curvature ($\gamma$-ray). Similar to other sporadic, variability phenomena in pulsar radio emission, represented by nulling pulsars [e.g. 8], intermittent pulsars [9], and rotation radio transients [10], GP emission can be due to changes in the coherence of the radio emission, variations in the pair creation rate in the magnetosphere, or changes in the beaming direction. If GP phenomenon is due to changes in the coherence of the radio emission mechanism, one would expect little correlation of the radio GPs with the high-energy emission. However, if the GPs are due to changes in the actual rate of pair creation in the pulsar magnetosphere, one would expect an increased flux at high energies at the time of the GPs. Similarly, because the radio GP and $\gamma$-ray components are aligned, one expects that they come from the same place in the pulsar magnetosphere. Therefore, if a GP occurs from a beam direction alteration, one would expect to see an increase also in the high-energy flux.

The attempt to carry out simultaneous radio/$\gamma$-ray observations (50-220 keV energy range of CGRO/OSSE) and correlate time of arrivals (TOAs) of GPs was undertaken before by Lundgren et al. [5]. They did not have enough sensitivity to correlate TOAs for single events and averaged their data in 2-min intervals. They were only able to put an upper limit on $\gamma$-ray flux increase of a factor of 2.5 concurrent with radio GPs. This suggested that GP mechanism is largely based on changes in coherence and not changes in pair production rates or beaming.
Yet, Shearer et al. [12] performed simultaneous radio/optical observations of the Crab pulsar, and they found a weak correlation, that optical pulses coincident with radio GPs were on average 3% brighter than others. In contrast to the Lundgren et al. work, this observation clearly points to variations in magnetospheric particle density as the cause of the radio giant pulses.

Also, Lyutikov [1] proposed a more specific, quantitative model of GP emission in which Crab GPs are generated on closed magnetic field lines near the light cylinder via anomalous cyclotron resonance on the ordinary mode. One clear prediction of this model is that radio GPs (at least those at radio frequencies $>4$ GHz) should be accompanied by $\gamma$-ray photons, as the high energy beam is expected to produce curvature radiation at energies $\sim h \gamma^3 \Omega \sim 1$–$100$ GeV, depending on the exact value of the Lorentz factor $\gamma$. These energies fall perfectly into the energy range of the Fermi mission, and so this hypothesis can also be tested through high-frequency radio observations concurrent with Fermi.

In Sections 2 and 3 below we describe performed radio observations and Fermi data used in further analysis. Section 4 presents the obtained preliminary results. We describe the correlation analysis between radio GPs and Fermi photons in Section 4.1. Conclusions are made in Section 5.

2. Radio observations

The radio observations were carried out during the September 2009 with the 100-m Robert C. Byrd Green Bank Telescope (GBT) using the new Green Bank Ultimate Pulsar Processor (GUPPI) at a frequency of 8.9 GHz. The total bandwidth of 800 MHz was split into 256 frequency channels, and the total intensity was recorded with the sampling interval 2.56–3.84 $\mu$s. There were 10 observing sessions for a total of $\sim$20 hrs. The raw data from every session were dedispersed with the current DM of the Crab Pulsar using the PRESTO package, and searched for all the single-pulse events. The lists of events were presented in TEMPO format and converted to barycentric reference frame for further analysis with Fermi data. Figure 1 right shows the average profile (top) of the Crab Pulsar together with the subintegrations during the course of observations for the most fruitful session on Sep 25. The interpulse (IP) and high-frequency components (HFCs) are clearly seen, with the weak peak after HFC2 being the main pulse (MP).

3. Fermi data

For each observing radio session we extracted LAT data for diffuse class of events. Photons with energies above 100 MeV and with the angular separation $\theta < \text{Max}(1.6 - 3 \log(E/1000 \text{ MeV}), 1.3)^\circ$ from the nominal pulsar position were selected (e.g. [13]). Total number of photons per 8 hrs of simultaneous observations is 70 (11 above 1 GeV). Photons were barycentered with TEMPO2 using the same ephemeris as for radio GPs.

4. Results

The number of detected radio GPs stronger than $7\sigma$ and $\gamma$-photons with the energies above 100 MeV during contemporaneous time for each observing session is given in the Table. Taking into account the contribution from the Crab nebula, the $1\sigma$ sensitivity in our observations was about 480 mJy. In total, we found more than 85,000 GPs stronger than $7\sigma$, with about simultaneous 39,450 GPs with Fermi. The corresponding total number of photons detected is 70.

Figures 2 and 3 present the flux density of radio GPs and energy of Fermi photons and their histograms versus the phase of their occurrence within the Crab period. It is evident that most of GPs occurred at the phases of the MP and IP. In agreement with Hankins & Eilek [14] radio GPs occur more frequently at the phases of IP, while GPs in MP are stronger. Due to small photons sample, no definitive conclusion can also be put forward, whether there is an average increase in counts rate in Fermi profile during the events of radio
Figure 2: Flux density of GPs and energy Fermi photons vs. the phase of their occurrence within the Crab period. The radio profile from one of the GBT sessions is shown in the background (gray).

Table I Observations summary. The columns are as follows: the day in September when observations were happened; \( T_{\text{radio}, \gamma} \), the duration of radio session simultaneously with Fermi; \( N_{\text{GPs}} \), the number of detected GPs stronger than 7\( \sigma \) during contemporaneous time with Fermi; \( N_\gamma \), the number of Fermi photons occurred with energy > 100 MeV.

| Day (Sep 2009) | \( T_{\text{radio}, \gamma} \) (s) | \( N_{\text{GPs}} \) (> 7\( \sigma \)) | \( N_\gamma \) (> 100 MeV) |
|---------------|-----------------|-----------------|-----------------|
| 12            | 1551            | 4               | 7               |
| 14            | 3304            | 4166            | 11              |
| 19            | 3077            | 4096            | 7               |
| 20            | 1779            | 1069            | 2               |
| 21            | 1801            | 154             | 2               |
| 22            | 3871            | 1567            | 6               |
| 23            | 4710            | 9764            | 10              |
| 24            | 1260            | 264             | 1               |
| 25            | 7446            | 18299           | 19              |
| 28            | 2795            | 65              | 5               |
| Total:        | 31594           | 39448           | 70              |

GPs. Several pulses, either giant pulses or regular single pulses, were also detected at the phases of HFCs and even MP precursor. Though such pulses were reported by Jessner et al. [15] as well, their GP nature is to be checked, and they could only represent strong single pulses of regular emission.

At high radio frequency of 8.9 GHz GPs occur in bursts or clumps due to scintillations with a characteristic scintillation time of about 10-20 min. However, scintillations can mask the intrinsic flux variability inherent to the pulsar. Hence, if so and there is a correlation between time of arrivals of radio GPs and high-energy photons, one would expect Fermi photons also come within clumps of GPs. Figure 4 shows the time series of radio GPs and Fermi photons for every observing session. Apparently photons do also have a tendency to occur in clumps, and in some cases during the increase of the flux in radio. The latter, however, does require an additional analysis.

4.1. Correlation Analysis

For every photon we searched for a GP within the set of different time windows between 1 ms and 10 s. Since the rate of GPs varies significantly from session to session (see Fig. 4), the search was performed for each day separately. The results are presented in the Table II. It is obvious, that the higher the average GP rate and/or length of correlation time window, the more matches between radio GPs and Fermi photons.

To estimate the probability \( P \) of getting the same number of matches by pure chance (i.e. when there is no true correlation), we performed a Monte-Carlo simulation assigning a random time of arrival for each \( \gamma \)-photon for every observing session. Then, we calculated the number of matches between real radio GPs and simulated photons and repeated this procedure \( N_{\text{sim}} = 10,000 \) times. Knowing the real number of matches \( k \) for every observing session and every time window, we calculated \( P \) as \( N^k / N_{\text{sim}} \), where \( N^k \) is the number of performed simulations with \( k \) matches.

The results of this simulation are presented on Figure 5. It is clear that the probability of getting the recorded number of matches between GPs and \( \gamma \)-
5. Conclusions

No obvious correlation was found between Fermi photons of energies > 100 MeV and radio giant pulses at the frequency of 8.9 GHz.

Due to a small number of contemporaneous photons, no definitive inference can be made about an average increase in counts rate in Fermi profile during the events of radio GPs. Current preliminary results indicate that fraction of photons closely accompanying high-frequency GPs is certainly less than 10%. In order to estimate this value more precisely, one needs to continue simultaneous observations, accumulating more photons and registering more GPs. Such a campaign of Fermi/radio observations using 140-ft telescope at Green Bank Observatory (WV) and 42-ft
Figure 5: The probability that the number of matches between GP and $\gamma$-photon within given time window is due to pure chance (no correlation). Each line corresponds to different observation date. The simulation was performed for each observing session separately due to different rates of radio GPs.

Table II Correlation results between radio GPs and Fermi photons for each observing session. Column 1 shows the day in September 2009 when observation was happened, column 2 gives the average GP rate during the session, and columns 3–7 give the number of matches between radio GPs and Fermi photons for different time windows from 1 ms to 10 s.

| Day (Sep 2009) | GP rate (s$^{-1}$) | 1 ms | 10 ms | 100 ms | 1 s | 10 s |
|---------------|-------------------|------|-------|--------|-----|------|
| 12            | 0.0026            | –    | –     | –      | –   | –    |
| 14            | 1.26              | 1    | 1     | 4      | 9   | 10   |
| 19            | 1.33              | –    | –     | 2      | 5   | 7    |
| 20            | 0.6               | –    | –     | –      | –   | 2    |
| 21            | 0.0855            | –    | –     | –      | –   | 1    |
| 22            | 0.4               | –    | –     | –      | 1   | 4    |
| 23            | 2.073             | –    | 1     | 4      | 7   | 9    |
| 24            | 0.21              | –    | –     | 1      | 1   | 1    |
| 25            | 2.458             | –    | –     | 6      | 13  | 15   |
| 28            | 0.023             | –    | –     | –      | 2   | 2    |

telescope at Jodrell Bank Observatory at low frequencies is ongoing now. Non-correlation, if indeed true, may favor for coherence change as a reason for GP emission rather than variations in pair creation rate in the pulsar magnetosphere, or changes in beaming direction. In particular, the model of Lyutikov predicts correlation between high-energy photons and radio GPs at frequencies 4-10 GHz. Again, if radio and $\gamma$-rays are indeed not correlated, then model either has to be tweaked, or such correlation exists only for very high energy photons $\gtrsim 100$ GeV. At this energy range Fermi, though sensitive, can not provide extensive sample of photons in reasonable time for correlation, so Cherenkov detectors are much more promising.

Simple identification of time of arrivals of photons shows that they also come in groups similarly to radio GPs. Though in case of GPs this is caused by scintillations, they could potentially mask the flux variability intrinsic to the Crab pulsar as well. Then, we would expect groups of photons to concentrate with fraction of stronger GPs. And in fact, we do see the tendency of some groups of photons to cluster around strong GPs (Fig. 4). Using the current dataset, we are planning to do a more thorough analysis of TOA correlation between individual photons and radio GPs. There could be a time delay between time of arrival of Fermi photon and corresponding GP due to, for instance, different travel paths in the pulsar magnetosphere, or non-simultaneity in emitting radio and gamma-ray. We will introduce the delay between photon and GP time series and run the correlation analysis for many such trials. Also, $\gamma$-photons may accompany only the brightest GPs or the clump of giant pulses as a whole.

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References

[1] Lyutikov, M. 2007, MNRAS, 381, 1190
[2] Staelin, D. H., & Reifenstein, E. C. 1968, Science, 162, 1481
[3] Knight, H. S. et al. 2006, ApJ, 640, 941
[4] Popov, M. V. & Stappers, B. 2007, A&A, 470, 1003
[5] Lundgren, S. et al. 1995, ApJ, 453, 433
[6] Popov, M. V. et al. 2006, Ast. Rep. 83, 660
[7] Cusumano, G. et al. 2003, A&A, 410, L9
[8] Moffett, D. A., & Hankins, T. H. 1996, ApJ, 468, 779
[9] Herfindal, J. L., & Rankin, J. M. 2009, MNRAS, 393, 1391
[10] Kramer, M., Lyne, A. G., O’Brien, J. T., Jordan, C. A., & Lorimer, D. R. 2006, Science, 312, 549
[11] McLaughlin, M.A. et al. 2006, Nature, 439, 817
[12] Shearer, A., et al. 2003, Science, 301, 493
[13] Fermi Collaboration, & Pulsar Timing Consortium, RICAP Proceedings 2009 (arXiv:0909.0862)
[14] Hankins, T. H., & Eilek, J. A. 2007, ApJ, 670, 693
[15] Jessner, A., Slowikowska, A., Klein, B., Lesch, H., Jaroschek, C. H., Kanbach, G., & Hankins, T. H. 2005, Advances in Space Research, 35, 1166