Giant radio pulses from the Crab pulsar revisited

N. LEWANDOWSKA, C. WENDEL, V.KONDRATIEV, D. ELSAESSER, K. MANNHEIM
University of Wuerzburg
Natalia.Lewandowska@physik.uni-wuerzburg.de
DOI: 10.7529/ICRC2011/V07/1148

Abstract: Apart from its regular pulses, the Crab pulsar represents also a known source of apparently aperiodic giant pulse (GP) emission. The amplitudes of GPs exceed those of the regular pulses by a factor of at least 1000, and their widths range from nano- to microseconds, appearing spontaneously at random pulse phases. Ideas have been put forward that the GPs originate from reconnection zones near the light cylinder which could also act as energy reservoir to power high- energy outbursts as the one observed in 2010 by Fermi-LAT, and which was accompanied by structural changes in the anvil region of the nebula apparently due to a relativisitc beam of particles. Testing this theory, we examine the properties of the GPs after the major outburst, using results from our observations with the Westerbork Synthesis Radio Telescope (WSRT), and constrain the energetics of the flare event via photometric studies of archival HST images of the anvil region.

Keywords: stars - pulsars - Crab pulsar - giant pulses - Crab Nebula - regular pulses - flux densities - pulse widths

1 Introduction

Located in the central part of the supernova remnant SN 1054 the Crab pulsar represents a unique source of pulsar radio emission. Its pulsed emission profile is visible over the entire electromagnetic spectrum ranging from radio to GeV energies and reveals three components in the radio waveband known as the main pulse (P1), the interpulse (P2) and the precursor ([1]). Among the regular pulses appearing at the phase ranges of P1 and P2, radio GPs are known as a special and exotic form of pulsar radio emission. Since the detection of the Crab pulsar through its GPs ([2]), several properties were discovered which extinguish them from regular pulses. The flux densities of GPs are at least a thousand times higher in comparison with the ones of regular pulses ([3]), while the pulse widths of GPs vary from a few microseconds down to two nanoseconds ([4]). Crab GPs have been detected at a wide frequency range from 23 MHz ([5]) to 15.1 GHz ([6], [7]) occuring at the phases of P1 and P2, but also at the high frequency components HFC 1 and HFC 2 ([8], [6]). No GPs have been confirmed at the phase of the precursor yet. Hence they are apparently phase bounded and their appearance at different phases cannot be excluded.

The characteristics of radio GPs were studied extensively by [9]. Since no offset was found between the arrival times of GPs and regular pulses, it was assumed that both kinds of pulses result from the same location. A different outlook on the origin of the P1 and P2 pulse was given by [10] who confirmed the detection of different time and frequency patterns of GPs at the phases of P1 and P2. According to this GPs at P1 exhibit narrow-band nanopulses, while GPs at P2 consist of narrow emission bands with microsecond duration. These results imply different emission mechanisms of P1 and P2 which challenges all current pulsar emission models.

The theoretical considerations of possible GP emission mechanisms are laid out broadly ([12], [13], [4], [14], [15]).

The emission bands of GPs at P2 ([10]) were reconstructed with the Lyutikov model ([11]) which refers to a higher particle density on closed magnetic field lines in contrast with the Goldreich-Julian standard model. When this density dissipates due to magnetic reconnection events near the last closed magnetic field line, a high energy Lorentz beam developes which moves along the closed field line and dissipates by curvature radiation.

The central emission mechanism and origin of radio GPs is currently not clarified.

With regard to the recently detected flares of the Crab nebula ([16]), we carried out an analysis of three Hubble Space Telescope (HST) exposures gained from the HST archive [1]. The central aspect of this analysis was to examine the synchrotron emission power output of the so called Anvil region located approximately 10 arcseconds away from the Crab pulsar in which an increase of brightness was detected after the Flare in September 2010. Since the whole nebula is thought to be powered solely by the pulsar, the brightness increase of this region raises the question if the pulsar contributes to the apparently sporadically

1. http://archive.eso.org/archive/hst/

occuring Crab nebula flares and if radio GPs, caused probably by magnetic reconnection processes near the light cylinder, are affected by this.

2 Data Analysis

2.1 Optical Data

For our analysis three exposures taken with the HST in combination with the ACS camera and the F550M filter[2] were selected in which the anvil region was defined as a spherical shape with a radius of 0.034 pc. The frequency-dependent synchrotron emission power of this region was determined via several steps. The energy distribution of the electrons and positrons emitted by the pulsar can be described by a power law

$$n'(\gamma)d\gamma = K'\gamma^{-q}d\gamma$$

with n being the derivative of the number density per unit energy-interval, the power law index q, the Lorentz factor γ and the deviation of the normalisation coefficient K. The latter one is not constant, but wavelength dependent. From [17] several values of K were derived together with a total energy integrated number density of 2 x 10^{-8} cm^{-3}.
The emitted electrons and positrons from the pulsar move into the nebula which is assumed to have a magnetic field strength of B $\approx 10^{-7}$ T ([17], [18]). Depending upon their velocities they are urged on circular orbits by Lorentz Force and emit electromagnetic radiation caused by gyration. The power of all electrons and positrons gyrating in the magnetic field of the Crab nebula was determined by multiplying the power of a single relativistically gyrating electron ([19], [20]) with the number of electrons with the energy E. This results in the total emitted power per unit volume and frequency of:

$$p(f) = \int_0^\infty P(f, \gamma(E))KE^{-q}dE$$

The normalisation coefficient K was determined in a subsequent computational analysis. To filter out the synchrotron emission at optical wavelengths, border values for the Lorentz factor γ were set. This way and via further numerical calculations of several coefficients the energy distribution of the electrons and protons emitting at optical wavelengths was determined.
Since all discussed HST exposures were taken through the F550M filter, we included its transmittance into the determined energy distribution (Figure 1).
The resulting total synchrotron emission power of an ensemble of electrons and positrons from the anvil region was determined to $P_{em} \approx 10^{33}$ erg s^{-1} while including the filter function the power amounts to $P_{filter} \approx 10^{31}$ erg s^{-1}. The optical emission power was determined to $P_{em} \approx 10^{32}$ erg s^{-1}. It is generally expected that electrons with a power law distribution inherit an energy of $\sim 10^{42}$ erg.

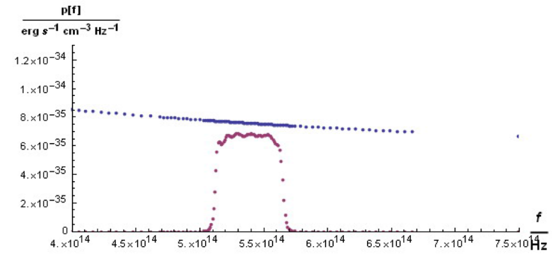

Figure 1: Spectral power density of an ensemble of electrons and positrons (blue) and with the contribution of the F550M filter (magenta) at optical wavelengths

2.2 Radio Data

All radio observations presented here were carried out with the Westerbork Synthesis Radio Telescope (WSRT) at a frequency of 1.38 GHz and the PuMaII pulsar backend ([21]). The radio data was coherently dedispersed using the open source pulsar data processing software package DSPSR[3] and the dispersion measure provided by Jodrell Bank[4].
Since GPs occur aligned in phase with regular pulses, a subdivision was done by putting up the treshold to 7 σ. This resulted in a total amount of over 1500 GPs (Figure 3).
All GPs are flux calibrated with the modified radiometer equation ([22]).
In the following part of the analysis several properties of radio GPs are examined and compared with already published values. At first the separation times between single GPs are determined to examine variation of GP rates (one GP every 0.803 seconds according to [25]). A detailed analysis of the GP rates could verify differences in the rotation period which would be a possible hint at a contribution of the pulsar in the observed flares.
Radio GPs are known to emit intensities which display a power law distribution ([23]) in contrary to the Gaussian distribution of the intensities of regular pulses ([24]). Within the framework of our analysis we examine the brightest ones contributing to the power law tail of the distribution being in search for a possible decrease.
Short width GPs are already known to exhibit the highest flux densities ([26], [4]). For a test of a variation of their fluxes, the width distribution of all detected GPs is examined.

2. http://acs.pha.jhu.edu/instrument/filters/data/
3. http://dspsr.sourceforge.net/
4. http://www.jb.man.ac.uk/∼pulsar/crab.htm

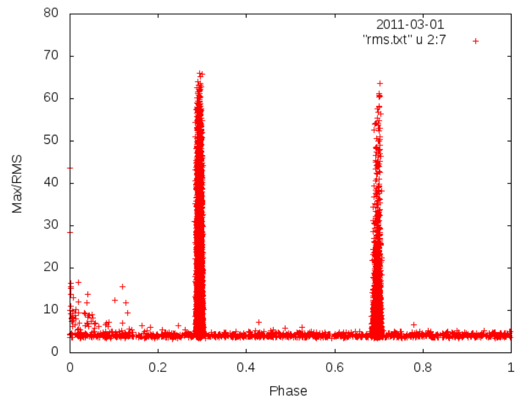

Figure 2: Phase diagram of all pulses observed with the WSRT on March 1th 2011

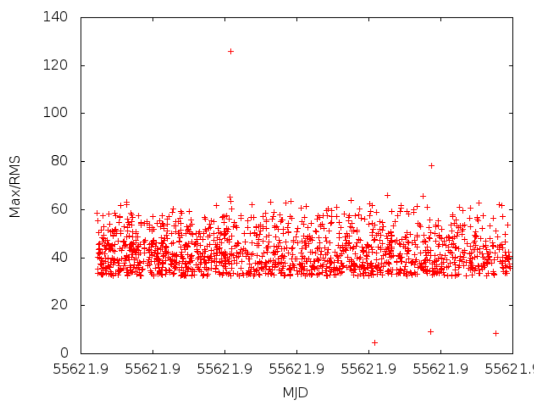

Figure 3: Selected GPs from WSRT observations from March 1th 2011

3 Summary

We present an extended analysis of radio GPs from the Crab pulsar observed with the WSRT. Coming from the results of an optical analysis of HST exposures verifying an increase in the synchrotron emission, we are searching for changes in the energetics of Crab pulsar GPs together with a difference in its rotation period to examine a possible connection between the Crab pulsar and the recently detected Crab nebula flares. Properties of GPs like pulse widths, pulse intensity distributions and GP rates are examined.

4 Acknowledgement

The Westerbork Synthesis Radio Telescope is operated by the ASTRON (Netherlands Institute for Radio Astronomy) with support from the Netherlands Foundation for Scientific Research (NWO).

We would like to thank Roy Smith, Gyula Jozsa, Gemma Janssen and the whole Westerbork crew for their essential support in carrying out and processing the radio observations.

References

[1] Moffett, D.A., Hankins, T.H., Astrophysical Journal, 1996, **Volume** (468): page 779

[2] Staelin, D.H., Reifenstein, Edward C., III, Science, 1968, **Volume 162** (3861): page 1481-1483

[3] Soglasnov, V., Proceedings of the 363. WE-Heraeus Seminar on Neutron Stars and Pulsars 40 years after the discovery, 2007, **MPE-Report 291**: page 68

[4] Hankins, T.H., Nature, 2003, **Volume 422** (6928): page 141-143

[5] Popov, M. V.; Kuzmin, A. D.; Ulyanov, O. M.; Deshpande, A. A.; Ershov, A. A.; Kondratiev, V. I.; Kostyuk, S. V.; Losovsky, B. Ya.; Soglasnov, V. A.; Zakharenko, V. V., On the Present and Future of Pulsar Astronomy, 26th meeting of the IAU, Joint Discussion 2, 2006

[6] Hankins, T.H., Proceedings of the 177th Colloquium of the IAU held in Bonn, 2000, **Volume 202**: page 165

[7] Jessner, A., Popov, M. V., Kondratiev, V. I., Kovalev, Y. Y., Graham, D., Zensus, A., Soglasnov, V. A., Bilous, A. V., Moshkina, O. A., Astronomy and Astrophysics, 2010, **Volume 524** (id.A60)

[8] Jessner, A., Slowikowska, A., Klein, B., Lesch, H., Jaroschek, C. H., Kanbach, G., Hankins, T. H., Advances in Space Research, 2005, **Volume 35** (6): page 1166-1171

[9] Lundgren, S. C., Cordes, J. M., Ulmer, M., Matz, S. M., Lomatch, S., Foster, R. S., Hankins, T., Astrophysical Journal, 1995, **Volume 435** (6928): page 433

[10] Hankins, T.H., Eilek, J.A., Astrophysical Journal, 2007, **Volume 670** (1): page 693-701

[11] Lyutikov, M., Monthly Notices of the Royal Astronomical Society, 2007, **Volume 381** (3): page 1190-1196

[12] Mikhailovskii, A. B., Onishchenko, O. G., Smolyakov, A. I., SOVIET ASTR.LETT.(TR:PISMA), 1985, **Volume 11** (NO.2/MAR/APR): page 78

[13] Weatherall, J.C., Astrophysical Journal, 2001, **Volume 559** (1): page 196-200

[14] Petrova, S. A., Astronomy and Astrophysics, 2004, **Volume 424**: page 227-236

[15] Istomin, Y. N., Astronomical Society of the Pacific, 2004, page 369

[16] Tavani et al.,The Astronomer's Telegram, 2010, **2855**

[17] Moroz, V. I., Soviet Astronomy, 1960, **Volume 4** : page 250

[18] Oort, J.H., The Observatory, 1956, **Volume 76**: page 137-138

[19] Longair, M.S., High energy Astrophysics, Cambridge University Press 2002

[20] Rybicki, A.P., Lightman, Radiative processes in Astrophysics, John Wiley & Sons 1979
[21] Karuppusamy, R., Stappers, B., van Straten, W., 2008, **arXiv:0802.2245**
[22] Lorimer, D.R., Kramer, M., Handbook of Pulsar Astronomy, Cambridge University Press 2005
[23] Argyle, E., Gower, J.F.R., Astrophysical Journal, 1972, **Volume 175** : page L89
[24] Hesse, K. H., Wielebinski, R., Astronomy and Astrophysics, 1974, **Volume 31** : page 409
[25] Karuppusamy, R., Stappers, B., van Straten, W., Astronomy and Astrophysics, 2010, **Volume 515** (id.A36)
[26] Sallmen, S., Backer, D. C., Hankins, T. H., Moffett, D., Lundgren, S., Astrophysical Journal, 1999, **Volume 517** : page 460-471