Pulse variation of the optical emission of Crab pulsar

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Abstract

The stability of the optical pulse of the Crab pulsar is analyzed based on the 1 µs resolution observations with the Russian 6-meter and William Hershel telescopes equipped with different photon-counting detectors. The search for the variations of the pulse shape along with its arrival time stability is performed. Upper limits on the possible short time scale free precession of the pulsar are placed. The evidence of pulse time of arrival (TOA) variations on 1.5-2 hours time scale is presented, along with evidence of small light curve (shape and separation of main and secondary peaks) changes between data sets, on time scale of years. Also, the fine structure of the main pulse is studied.

Key words: Pulsars, Photometric, polarimetric, and spectroscopic instrumentation
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1. Introduction

Over the last 30 years the Crab pulsar has been extensively studied. The reasons for it are clear – it is the brightest pulsar seen in optics, it is nearby and young. However, the most popular groups of contemporary theories of the Crab high-energy emission, the “polar cap” (Daugherty et al. 1996) and “outer gap” (Cheng et al. 2000) ones, can’t explain the whole set of observational data.

One of the main properties of the Crab emission is the relatively high stability of its optical pulse shape despite the secular decrease of the luminosity, related to the spin rate decrease (Pacini 1971; Nasuti et al. 1998). At the same time the pulsars in general and the Crab itself are unstable. The instabilities manifest themselves as glitches, likely related to the changes of the neutron star crust, timing noise, powered by the collective processes in the superfluid internal parts of it, magnetospheric instabilities, results of the wisps around the pulsar, precession, etc. All these factors may influence the optical pulse structure and change it on various time scales, both in periodic and stochastic way.

However, it has been found early that the variations of the Crab optical light curve, in contrast with the radio ones, are governed by the Poissonian statistics (Kristian et al. 1970). A number of observations show the absence of non-stationary effects in the structure, intensity and the duration of the Crab optical pulses, and the restrictions on the regular and stochastic fine structure of its pulse on the time scales from 3µs to 500µs (Beskin et al. 1983; Percival et al. 1993), the fluctuations of the pulse intensity (Kristian et al. 1970).

Along with the increase of the observational time spans and the accuracy of measurements, small changes of the optical pulse intensity, synchronous with the giant radio pulses, have been detected (Shearer et al. 2003). Also, the evidence for the short time scale precession of the pulsar has been found by studying its optical light curve (Cadez et al. 2001).

All this raises the importance of monitoring the Crab optical emission with high time resolution.

The article is organized as follows. In Section 2 we briefly describe the observation process and instruments used, in Section 3 the method of phase stability analysis is described and used to study the Dec 1999 and Jan 2007 data sets, in Section 4 the light curves of different data sets are compared, in Section 5 the possible fine structure of the main pulse peak is discussed, and Section 6 gives the conclusions.

2. Observations and data reduction

We analyzed the sample of observational data obtained by our group over the time span of 12 years on different tele-
Table 1
Log of observations

| Date        | Telescope | Instrument                                      | Duration | Spectral range |
|-------------|-----------|-------------------------------------------------|----------|----------------|
| Dec 7, 1994 | BTA, Russia | Four-color photometer with photomultipliers     | 2400     | U + B + V + R  |
| Dec 2, 1999 | WHT, Canary Islands | Avalanche photo-diode | 6600     | 4000-7500      |
| Jan 9, 2000 | BTA, Russia | Panoramic photometer with position-sensitive detector | 7900     | U + B + V + R  |
| Nov 15, 2003| BTA, Russia | Avalanche photo-diode                          | 1800     | 4000-7500      |
| Jan 25, 2007| BTA, Russia | Panoramic photometer                           | 10500    | B + R          |
| Jan 26, 2007| BTA, Russia | with position-sensitive detector                | 6500     | B + R          |

The details of observations are summarized in Table 1. The equipment used were a four-color standard photometer with diaphragms based on photomultipliers, a fast photometer with avalanche photo-diodes (Shearer et al., 2003) and a panoramic photometer based on position-sensitive detector (Debur et al., 2003; Plokhotnichenko et al., 2003). All devices are photon counters which record the photon time of arrivals with accuracy better than at least 1 µs, and the final observational data are the lists of these times. In case of panoramic photometer (Debur et al., 2003) only photons arrived in 3” aperture around the pulsar location has been considered.

The photon lists of all observational sets have been processed in the same way by using the same software to exclude the systematic differences due to data analysis inconsistencies. Photon arrival times of 1999, 2003 and 2007 years sets have been collected with absolute time scale calibration by means of GPS receivers. So, they have been corrected to the barycenter of the Solar System using the adapted version of axBary code by Arnold Rots. The accuracy of this code has been tested with detailed examples provided by Lyne et al. (2003) and is found to be better than at least 2 µs.

The barycentered photon lists then have been folded independently using both Jodrell-Bank radio ephemerides (Jordan, 2006) and our own fast-folding based method of timing model fitting (Plokhotnichenko, 1993). The declared accuracy of Jodrell-Bank ephemerides frequency and derivatives provide the folding precision of at least 1 µs, and the base epoch – of at least 5 µs (Jordan, 2006), so we decided to fold the light curves with 5000 bin (6.6 µs) resolution.

The observations of 1994 and 2000 have been performed without absolute time scale calibration, using non-stabilized frequency generators, so these data can’t be converted to the barycenter correctly. So, we divided the whole data set into several pieces short enough to be well fitted with a 3rd order timing model (up to second frequency derivative), performed an independent timing model fit for each, folded and combined it together, compensating the phase shift between separate pieces. The accuracy of such procedure is proved to provide similar time resolution, so we use the same number of bins in its analysis.

The observations of 1994 and 2000 have been performed in standard Johnson-Cousins U, B, V and R photometric bands, 2007 – in B and R bands, while 1999 and 2003 – without filters, but with the same detector, described by Ryan et al. (2006) (avalanche photodiode with broad spectral sensitivity in the 4000-7500 Å peaked at ~ 7000 Å).

3. Study of phase stability

We performed the search for timing model residuals (“phase shifts”) using two longest continuous data sets of 1999 and 2007 years.

3.1. Computation of timing residuals

The photon list of 1999 data set has been divided into segments of 100 pulsar periods (with duration of approximately 3.3 s), which resulted in 1677 segments with mean number of photons of 10546.5 each. They then have been folded separately using the same Jodrell-Bank radio ephemerides, and each fold have been cross-correlated with the template, which has been built by folding the entire data set. The estimation of the segment phase shift in respect to template is then derived by approximating the peak of cross-correlation function (in a phase window of 0.02 period width) with the Gaussian, and analytically computing its maximum position. The steps of the procedure are illustrated in Fig. 1. The resulting phase shifts are plotted in upper panel of Fig. 3.

The formal accuracy of the maximum of Gaussian approximation of cross-correlation function estimation is much better than the spreading of real data values (basi-
Fig. 1. Method of estimation of phase shift of the sample folded light curve in respect to the template one. Upper panel – sample light curve of 1999 data set with 5000 bins resolution and 100 pulsar periods long (approximately 3.3 sec). Superimposed is the template profile, derived by folding the whole data set. Middle panel – cross-correlation of the sample and the template light curves, with Gaussian fit superimposed. Lower panel – cross-correlation residuals after subtraction of Gaussian fit. The real accuracy of phase shift estimation is much worse than the one of determining the cross-correlation peak position due to influence of original light curve errors and its systematic deviation from the Gaussian approximation. However, it may be shown that it does not lead to the statistical biasing of the estimate.

Fig. 2. Dependence of the estimation of phase shift mean value of simulated data on the set length. The simulated data have the same parameters (template profile, number of lightcurve bins and mean number of photons per sample) as the 1999 set. No significant biasing is seen, and the deviation from zero decreases with the increase of set length. It proves that the estimation of phase shifts is statistically unbiased and reliable.

cally, the error bars are hidden inside the dots in Fig 3. This is partly due to neglecting of original light curve errors while computing the cross-correlation. Also, the lower panel of Figure 4 demonstrates that the Gaussian estimation for the cross-correlation function is not perfect, as it shows systematic deviations from it. To ensure that these facts are not spoiling the results and to test the statistical quality of the method used we performed the numerical simulation by generating the set of sample Poisson-distributed light curves based on the average profile of the 1999 data set with the same mean number of photons per segment, and processing them in the same manner as the real data. The computed phase shifts of simulated data are shown in the lower panel of Fig. 3. The RMS of the simulated and observed data are roughly the same ($\sigma \approx 5.5 \cdot 10^{-4}$), which is consistent with the statistical nature of phase shift values scatter. Also, we performed the test whether the estimated phase shifts are unbiased and statistically reliable by studying the behaviour of the mean value of simulated data phase shift and its RMS in dependence of number of segments. The results of this simulation are shown in Fig. 2. It may be easily seen that the mean value of the estimation along with its RMS, both converge to zero with the increase of the number of segments, which
proved the statistical reliability of the method used. Also, it permits to increase the determination of systematic phase shifts accuracy by averaging it over long phase segments.

3.2. Fourier analysis of phase shifts

In order to search for periodic components of the phase shift we performed the Fourier analysis of the data set according to the method described in Scott et al (2003), i.e. computed the power-density spectrum $P$ using the time-domain Hann window $w_i \propto \sin^2 (\pi i / N)$ to suppress the power leakage (which lowers the spectral resolution approximately by two).

The resulting power density spectrum is shown in Fig. 4 in comparison with results of radio data analysis of Scott et al (2003). The accuracy of our data is not sufficient to reach the level of extrapolated power-law timing noise seen in the radio band.

Moreover, it is possible to derive upper limits for the sinusoidal variable components of timing noise on $3.3\ s - 50$ minutes time scale. Indeed, for the purely white noise process the value $2P/(P)$ is distributed as $\chi^2$ with 2 degrees of freedom (Leahy et al. 1983) and has mean and standard deviations of 2. The probability $Q$ for this quantity to exceed some threshold value $2\langle P \rangle$ by chance is

$$Q \left( \chi^2_0 = \frac{2P_0}{\langle P \rangle} \right) = \int_{\chi^2_0}^{\infty} p(\chi^2) d\chi^2$$

For the significance level $SL = 0.01$ (which corresponds to the 99% confidence probability) the threshold value $P_0$, determined by solving

$$Q \left( \chi^2_0 = \frac{2P_0}{\langle P \rangle} \right) = c ,$$

is $P_0 = 4.6\langle P \rangle$, where $\langle P \rangle$ is the mean “noise” level of power density spectrum. By combining it with the spectral amplitude $P_A = \frac{\chi^2}{2\nu}$ (where $\delta\nu = 1/T$ is the spectral resolution) of sinusoidal signal, we have

$$\frac{A^2}{2\Delta\nu} < 4.6\langle P \rangle$$

and for the upper limit for amplitude

$$A < \sqrt{0.2\langle P \rangle \Delta\nu}$$

For our data, the mean “noise” level of power density is $\langle P \rangle = 2.2\cdot 10^{-11}$ cycles$^{-2}$•day$^{-1}$ and $\Delta\nu = 15.3$ day$^{-1}$, which leads to the limit for amplitude of periodic component of timing residuals $A < 5.6 \cdot 10^{-5}$ cycles (1.8 $\mu$s) in this frequency range.

3.3. Secular behaviour of phase shifts

To test the phase stability of the Crab light curve on time scales comparable with the total length of observations we first computed the power density spectrum of phase shifts without any time domain window. The result, shown in Figure 5, demonstrates significant deviation (with significance level $SL = 2.4 \cdot 10^{-4}$) of the first bin from noise mean value, which suggests the presence of variations on time scale of the data set length.

To check these variations in time domain we divided the data set into 10 equal time segments 562 seconds long, and computed the mean and variance of phase shifts in it. The results (shown in Figure 5) indeed show the presence of significant variations on 1.5 hours time scale with $(3 \pm 1) \cdot 10^{-4}$ (9.3 $\mu$s) amplitude.

We performed similar analysis of the data of Jan 25-26, 2007. The signal to noise ratio in this set is smaller,
Fig. 7. Phase shifts of the Jan 25, 2007 data set (upper panel, each point corresponds to 33 seconds of data) and its averaging in 10 time segments 1050 seconds long (lower panel). The vertical error bars correspond to the standard deviations of values in segments. Also, the approximation of phase shifts with 7-rd order polynomial is shown. Characteristic time scale of variations is 1-2 hours with amplitude $\sim (3 \pm 1) \cdot 10^{-4}$ (9±3 µs).

Fig. 8. Phase shifts of the Jan 26, 2007 data set (upper panel, each point corresponds to 33 seconds of data) and its averaging in 5 time segments 1300 seconds long (lower panel). The vertical error bars correspond to the standard deviations of values in segments. Also, the approximation of phase shifts with 3-rd order polynomial is shown.

so we computed the phase shifts using 1000 period long segments of light curve (roughly 33 seconds). The results (see Figures 7 and 8) also show variations on 1.5-2 hours time scale with similar amplitude.

4. Pulse shape

We performed the comparison of pulse profile shapes of data sets of 1994, 1999, 2000, 2003 and 2007 years in a way similar to the one used in [Jones, Smith & Nelson, 1980]. As there are evidences that the Crab profile depends on wavelength [Eikenberry et al., 1996; Golden et al., 2000; Beskin, Komarova & Plokhotnichenko, 2000; Romani et al., 2001], we compared the data acquired in the same wave bands, i.e. 1994 vs 2000 and 2007, and 1999 vs 2003 data sets.

We compensated the phase shifts of 1999 and 2007 data described above by approximating it with high-order polynomials and adding it to the timing models. Also, to compensate possible phase shifts between light curves of different data sets (due to, for example, systematic errors in radio ephemerides base epochs) we determined the phase shift between them by the method described in Section 3 and re-folded them with base epoch shifted according to it. This procedure has been performed iteratively until the phase shift became smaller than at least $10^{-4}$, i.e. less than half of a bin size used.

Then we normalized each light curve $y_i$ to the same template profile $y_{0,i}$ (we used the one of Nov 2003 data set as it has the largest number of photons) by means of linear transformation $y'_i = ay_i + b$ with parameters $a$ and $b$ maximizing the likelihood

$$L' = \sum_{i=0}^{N-1} \left( y_i \ln \lambda_i - \ln (y_i!) - \lambda_i \right),$$

of $y_i$ to be the instance of Poissonian distribution with $\lambda_i =$
Fig. 10. Crab profile change in B and R filters between 2000 and 2007 data sets. Both bands demonstrate peaks (primarily – first one) shape change without significant phase shift.

Then we rebinned them in blocks with roughly equal number of photons and plotted the difference between them. The results are presented in Figures 9-12.

To check whether it may be due to uncompensated phase shift we simulated shifted light curves, computed their differences and plotted them in Figure 6. The simulated effect has different shape and different ratio of positive and negative residuals, which argues for the reality of the detected variation.

The effects seen in Figs 9-12 may be interpreted as a some combination of systematic “phase shift”, variation of main peak shape and change of the distance between primary and secondary peaks. Unfortunately, its exact nature can’t be revealed by the methods used – it is impossible to correctly define the “phase shift” of two profiles with different shape, and the procedure of light curves phasing devours some part of the shape change effect. However, it may only lower the significance of detected residuals – so the presence of the effect itself is undoubtful.

5. Pulse fine structure

For the data set of Nov 2003, which has the largest number of photons collected, we performed the search for the fine structure of the peak of main pulse. We approximated its shape by means of low-pass Fourier filter with characteristic frequency of 0.05 bin$^{-1}$, which effectively smoothes the light curve with sinc-like window with $\sim 40$ bins FWHM. The peak data, fit and residuals are shown in Figure 13. We do not detect any significant spike-like fine structure on the level of 0.5% (1 $\sigma$) with 6.6 $\mu$s time resolution.

However, there is a single “absorption-like” feature with
6. Discussion

Optical emission of Crab pulsar has been detected soon after its radio one (Staelin & Reifenstein, 1968; Cocke, Disney & Taylor, 1969), and since then it has been observed a number of times (Kristian et al, 1970; Cocke & Ferguson, 1974; Peterson et al, 1978; Percival et al, 1993; Beskin, Komarova & Plukhotnichenko, 2000; Golden et al, 2000). Being the brightest (~16m) among 5 known optical pulsars, it demonstrates relatively high stability of light curve shape against a background predicted secular luminosity changes (Pacini, 1971; Nasuti et al, 1996). At the same time, it exhibits the timing noise in pulse time of arrivals in radio, optical and x-ray spectral bands on time scales from several days to tens of years (Cordes, 1980; Boynton et al, 1972; Kuiper et al, 2003; Rots, Jahoda & Lynd, 2004). Also, the variation of primary and secondary peaks intensity ratio in gamma rays has given the hint of 13-year periodicity (Nolan et al, 1993; Ulmer et al, 1994). Similar behaviour has been observed in radio on months and years time scales (Jones, 1988; Lyne, Pritchard & Smith, 1988; Scott et al, 2003). On the other hand, the search for time of arrival residuals on short (seconds to hours) time scale has not been practically performed. The one exception seems to be the result of Cadez & Galicic (1996) and Cadez et al (2001), who detected the 60-seconds periodicity of pulsar intensity.

We analyzed the data of several sets of optical observations with high temporal resolution of the Crab pulsar performed by our group over the last 12 years.

No evidence for periodic short time scale variations of pulse time of arrivals (like 60-sec free precession claimed by Cadez et al (2001)) is detected on the 3.3 s – 50 minutes time scale on Dec 2, 1999. The upper limit for their amplitude is $A < 5.6 \cdot 10^{-5}$ cycles (1.8 $\mu$s) (significance level 0.01). Note that no periodic features has also been detected in the Crab light curve on these frequencies in previous work of Golden et al. (2000).

Also, no signature of extended timing noise spectral features (like power-law one observed on lower frequencies) is seen on this time scale.

However, the data of Dec 2, 1999 and Jan 25-26, 2007 sets both show significant phase variations on 1.5 – 2 hours time scale with $2 \cdot 10^{-4}$ cycles ($6 – 16$ $\mu$s) amplitude. This effect is most likely not truly periodic. Moreover, it is difficult to explain it as a precession of a rotating rigid body, as it requires too large difference of neutron star axes ($\Delta R/R \sim 10^{-5}$) (Akgüm et al, 2006). Possible manifestations of noise processes, related to either superconducting vortices inside the neutron star, or magnetospheric effects, on the short time scales of minutes to hours has yet to be analyzed. These effects has been usually involved in explanation of timing noise observed on time scales of days to years (Cordes & Greenstein, 1981; Alpar et al, 1984; Cheng et al, 1987a,b). However, the amplitude of the effect we discovered significantly exceeds the power-law extrapolation of timing noise spectrum (Scott et al, 2003) (see Fig.3).

Only one observed effect is currently known to occur on similar time scale – the giant radio pulses (Lundgren et al, 1995), which have inverse power-law intensity distribution and randomly appear in all phases of light curve occupied by “normal” radio emission except for precursor (Jessner et al, 2005). Moreover, it has been recently suggested that all radio emission except for the precursor con-
sists of giant pulses only (Popov et al., 2006). Their origin is most likely due to changes of either coherence conditions or electron density in the magnetosphere. In the latter case, it may influence the optical emission region too. The slight correlation between giant radio pulses and increase of optical emission has been discovered in (Shearer et al., 2003). As giant pulses appear randomly in phase, they may lead to changes of optical pulse shape, and so mimic the time of arrival variations.

Also, it may in principle be attributed to polar cap current-pattern drifting, which may occur on a very broad range of time scales (Ruderman & Gil, 2006).

The non-detection of this effect in ongoing radio observations may be attributed to its lower resolution (according to Lyne, Pritchard & Smith (1993), the accuracy of pulse time of arrival determination in Jodrell Bank observations is 20 μs for 10 min integration time).

We discovered the variation of pulse shape between different sets of our observations, i.e. on time scale of several years. It presents and has similar properties in all studied spectral bands, and cannot be attributed to well-known effect of shape dependence on wavelength (Eikenberry et al., 1996; Golden et al., 2000; Beskin, Komarova & Plokhotnichenko, 2000; Romani et al., 2001). Due to limitations of data analysis methods used it is impossible now to specify the exact nature of the variation – it may only be empirically described as a combination of systematic phase shift, main and secondary peaks shape change and variation of peak separation. Also, it is not clear whether the variation periodic, systematic or irregular. However, the effect is similar to the one marginally detected in (Jones, Smith & Nelson, 1980) on time scale of 7 years.

There are several possible physical mechanisms able to produce such pulse shape variations on time scale of years. First is the suspected precession of Crab on ~ 568 days (Scott et al., 2003). Indeed, at least one other pulsar – PSR B1828-11 – exhibits the precession accompanied by the changes of a radio pulse profile on a similar time scale (Stairs, Lyne & Shemar, 2000). For Crab, however, due to difference in rotational frequencies, such precession period implies much smaller wobble angle, and so – smaller pulse profile variations. Also, polar cap current-pattern drifting may mimic the precession and result in the same phase shift and profile change effects on years time scale. (Ruderman & Gil, 2006).

Another possibility is the incomplete post-glitch relaxation (Dziembowski & Prószyński, 1983; Lyne, Pritchard & Smith, 1993; Wong, Backer & Lyne, 2001), as all our observations have been separated by glitches of different power (Lyne et al., 2003). In Crab, it manifests itself as a persistent change of frequency derivative, and may be attributed to small changes of the angle between the magnetic dipole and the rotation axis (Link & Epstein, 1997; Allen & Horvath, 1997; Link et al., 1998), which inevitably leads to pulse profile variation. Also, pulse profile variations in hard energy band are often observed in anomalous x-ray pulsars (Kaspi et al., 2003; Morii, Kawai & Shibazaki, 2004), however, it is still not clear whether they result directly from glitches.

We do not detect any spike-like fine structure of the main pulse maximum on the level of 0.5% (1 σ) with 6.6 μs time resolution.

All the proposed explanations of discovered variations of pulse shape and time of arrival are qualitative only and are in no sense complete. The observations have to be continued, and the theoretical analysis still has to be performed. We hope the study of such variations can help to elaborate the theory of pulsar emission.

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