Hard X-ray timing and spectral characteristics of the energetic pulsar PSR J0205+6449 in supernova remnant 3C58

An RXTE PCA/HEXTE and XMM-Newton view on the 0.5-250 keV band

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ABSTRACT

Aims. PSR J0205+6449 is a young rotation-powered pulsar in SNR 3C 58. It is one of only three young (< 10,000 year old) pulsars which are so far detected in the radio and the classical X-ray bands, as well as at high X-rays above 20 keV and at high-energy (> 100 MeV) y-rays. The other two young pulsars are the Crab and PSR B1509-58. Our aim is to derive the timing and spectral characteristics of PSR J0205+6449 over the broad X-ray band from ~ 0.5 to ~ 270 keV.

Methods. We used all publicly available RXTE observations of PSR J0205+6449 to first generate accurate ephemerides over the period September 30, 2000 - March 18, 2006. Next, phase-folding procedures yielded pulse profiles using data from RXTE PCA and HEXTE, and XMM-Newton EPIC PN. All profiles have been phase aligned with a radio profile derived from the Jodrell Bank Observatory data, and the time-averaged timing and spectral characteristics of the pulsar X-ray emission have been derived.

Results. While our timing solutions are consistent with earlier results, our work shows sharper structures in the PCA X-ray profile. The X-ray pulse profile consists of two sharp pulses, separated in phase by 0.488 ± 0.002, which can be described by 2 Lorentzians, each with the rising wing steeper than the trailing wing, and full-width-half-maximum 1.41 ± 0.05 ms and 2.35 ± 0.22 ms, respectively. We find an indication for a flux increase by a factor of 3.5σ above the time-averaged value, for the second, weaker pulse during a two-week interval, while its pulse shape did not change. The spectrum of the X-ray emission is of non-thermal origin, exhibiting a power-law shape with photon index Γ = 1.03 ± 0.02 over the energy band ~ 0.5 to ~ 270 keV. In the energy band covered with the PCA (~ 3 – 30 keV) the spectra of the two pulses have the same photon index, namely, 1.04 ± 0.03 and 1.10 ± 0.08, respectively. Comparisons of the detailed timing and spectral characteristics of PSR J0205+6449 in the radio, hard X-ray and gamma-ray bands with those of the Crab pulsar, PSR B1509-58 and the middle-aged Vela pulsar do reveal more differences than similarities.

Key words. Stars: neutron – pulsars: individual PSR J0205+6449, PSR B1509-58, Crab, Vela – X-rays: general – Gamma rays: observations – Radiation mechanisms: non-thermal

1. Introduction

PSR J0205+6449 is a young rotation-powered pulsar of which the pulsations were first discovered in X-rays in a 2002 Chandra X-ray Observatory (CXO) observation, reported by Murray et al. (2002) together with a confirmation in an analysis of archival Rossi X-Ray Timing Explorer (RXTE) data. Subsequently, the weak radio signal was detected by Camilo et al. (2002). PSR J0205+6449 is a young, 65 ms pulsar located in the center of supernova remnant/pulsar wind nebula (PWN) 3C 58. It is one of the most energetic pulsars in the Galaxy with a spin-down luminosity $E \sim 2.7 \times 10^{33}$ erg s⁻¹, and characteristic age $\tau \sim 5.4$ kyr. This characteristic age, estimated with the values of the period and period derivative, puts in doubt the possible association with 3C 58, which coincides positionally with the historical 828 yr old supernova SN1191 (Stephenson & Greer, 2002). However, an age of several thousand years for 3C 58, closer to the characteristic age of the pulsar, can be derived from the velocities of the radio expansion of the PWN (Bietenholz, 2006) and of optical knots (Fesen et al., 2008).

Recently, Livingstone et al. (2009) presented for PSR J0205+6449 phase-coherent timing analyses using X-ray data from the Proportional Counter Array (PCA; 2-60 keV) aboard RXTE and radio data from the Jodrell Bank Observatory and the Green Bank Telescope (GBT), spanning together 6.4 yrs. This work revealed timing noise and two spin-up glitches. Furthermore, they presented detailed characteristics of the X-ray profile, which was detected up to ~40 keV. Their X-ray profile template consisted of two Gaussian-shaped pulses, a narrow
(full-width-half-maximum (FWHM) ~ 1.6 ms), more intense pulse and a broader (FWHM ~ 3.8 ms) weak pulse separated 0.505 in phase, the single radio pulse leading the main X-ray pulse by φ = 0.10 ± 0.01. Earlier results from an analysis of part of the RXTE and GBT data were reported by Ransom et al. (2004). These authors also presented spectral fits over the energy band 3–16 keV for both pulses: the best fit power-law photon indices were hard, namely Γ = 0.84±0.06 for the main pulse and Γ = 1.07±0.03 for the second (weaker) pulse.

Finally, high-energy γ-ray pulsations (≥ 0.1 GeV) from PSR J0205+6449 were discovered with the Large Area Telescope (LAT) aboard the Fermi Gamma-ray Space Telescope (Abdo et al., 2009), folding the γ-ray arrival times with the radio rotational ephemeris from, again, the GBT and Jodrell Bank. The γ-ray light curve for energies ≥ 0.1 GeV shows also two peaks with intensities differing by a factor ~ 2, aligned with the X-ray peaks. However, the main X-ray pulse coincides in phase with the weakest γ-ray pulse which has the softest spectrum of the two at high-energy γ-rays. The total pulse γ-ray spectrum exhibits a simple power-law shape with index Γ ~ 2.1 and exponential cutoff at ~ 3.0 GeV. PSR J0205+6449 is now one of only three young (< 10,000 year old) pulsars which are detected in the classical X-ray band and at hard X-rays above 20 keV, as well as at high-energy (> 0.1 GeV) γ-ray energies, the others being the Crab pulsar and PSR B1509-58 (PSR J1513-5908). The Crab pulsar has been studied over the total high-energy band already in great detail (see for a coherent high-energy picture from soft X-rays up to high-energy γ-rays Kuiper et al., 2001), with even a detection of pulsed γ-rays above 25 GeV (Aliu et al., 2008).

The detection of pulsed emission above 100 MeV from PSR B1509-58 had to wait for the new generation of currently operational γ-ray telescopes (Pellizzoni et al., 2009). However, these three young pulsars have very different timing and spectral characteristics. This makes it particularly interesting to determine the timing and spectral characteristics of PSR J0205+6449 in more detail over the high-energy band of the electro-magnetic spectrum in order to compare these with those of Crab and PSR B1509-58 and for confrontation with theoretical predictions. In this work our aim is to extend the coverage in the hard X-ray band to higher energies, exploiting the data of the High Energy X-ray Timing Experiment (HEXTE; 15-250 keV) aboard RXTE, and to extend the energy window to lower energies by analysing data from XMM-Newton. We will present the results from our timing study exploiting only the multi-year PCA/RXTE monitoring data, which we performed in parallel to the work reported by Livingstone et al. (2009). Our timing solutions are consistent with those of the latter authors, but our work revealed sharper structures in the PCA X-ray pulse profile. Furthermore, we derive the spectral characteristics over the total X-ray band. In the discussion we compare our findings with the characteristics of PSR J0205+6449 reported in the radio band and at high-energy γ-rays, as well as with the timing and spectral characteristics of the Crab pulsar, PSR B1509-58 and the middle-aged Vela pulsar.

### 2. Instruments and observations

#### 2.1. RXTE

In this study extensive use is made of data from monitoring observations of PSR J0205+6449 with the two non-imaging X-ray instruments aboard RXTE, the Proportional Counter Array (PCA; 2-60 keV) and the High Energy X-ray Timing Experiment (HEXTE; 15-250 keV). The PCA (Jahoda et al., 1996) consists of five collimated Xenon proportional counter units (PCUs) with a total effective area of ~ 6500 cm² over a ~ 1° (FWHM) field of view. Each PCU has a front Propane anti-coincidence layer and three Xenon layers which provide the basic scientific data, and is sensitive to photons with energies in the range 2-60 keV. The energy resolution is about 18% at 6 keV. All data used in this work have been collected from observations in GoodXenon or GoodXenon1/2/3/4/5 mode allowing high-time-resolution (0.1 μs) studies in 256 spectral channels.

The HEXTE instrument (Rothschild et al., 1998) consists of two independent detector clusters A and B, each containing four Na(TI)/ CsI(Na) scintillation detectors. The HEXTE detectors are mechanically collimated to a ~ 1° (FWHM) field of view and cover the 15-250 keV energy range with an energy resolution of ~ 15% at 60 keV. The collecting area is 1400 cm² taking into account the loss of the spectral capabilities of one of the detectors. The best time resolution of the tagged events is 7 μs. In its default operation mode the field of view of each cluster is switched on and off source to provide instantaneous background measurements. Due to the co-alignment of HEXTE and the PCA, both instruments simultaneously observe the same field of view.

RXTE observed PSR J0205+6449 for the first time on Sept. 30, 1997 (MJD 50721) for about 17 ks. Data from this observation were used by Murray et al. (2002) to confirm the pulsation discovered with Chandra. A dedicated much deeper observation was performed in the period August 17-19, 2001 (MJD 52138-52141), yielding about 80 ks good exposure time. Next, a monitoring campaign started on March 10, 2003 (MJD 52343) which ended on April 23, 2003 (MJD 52752). The total (good) exposure time for this period was about 269 ks. A second monitoring round commenced on Feb. 28, 2004 and continued till March 18, 2006 (MJD 53063-53813) yielding a total (good) exposure time of about 572 ks. A summary of all RXTE observations of PSR J0205+6449 is given in Table 1. The total good-time exposure (after screening; see Sect. 3.1) amounts 938.23 ks.

#### 2.2. XMM-Newton

We searched the XMM-Newton observation database for observations of the field around PSR J0205+6449 in which the EPIC-PN camera (Strüder et al., 2001) operated in Small-Window (SW) mode. This mode (4′.4 x 4′.4 field of view) offers sufficient time resolution (~ 5.67 ms) to sample the pulse-profile of PSR J0205+6449 over the ~ 0.3-12 keV range. We found two observations (observation ids. 0004010101/0004010201) both performed on February 22, 2001 at 12 offset from PSR J0205+6449 with durations of about 9.2 and 23.6 ks, respectively.

| Obs. id. | Date begin | Date End | MJD     | Exposure (ks) |
|----------|------------|----------|---------|---------------|
| 20259    | 30-09-1997 | 30-09-1997 | 50721-50722 | 16.96         |
| 60130    | 17-08-2001 | 19-08-2001 | 52138-52141 | 80.35         |
| 70089    | 10-03-2002 | 23-04-2003 | 52343-52572 | 268.95        |
| 90080    | 28-02-2004 | 03-03-2005 | 53063-53432 | 243.23        |
| 91063    | 12-03-2005 | 18-03-2006 | 53441-53813 | 328.74        |

* Screened (GTI) exposure for PCA unit-2

(continued)
3. Timing

3.1. RXTE PCA timing analysis

The first step in the RXTE PCA data analysis was the screening of the data. We generated good-time intervals (GTI) for each PCU by including only time periods when the PCU in question is on, and during which the pointing direction is within 0.05 from the target, the elevation angle above Earth’s horizon is greater than 5°, a time delay of 30 minutes since the peak of a South-Atlantic-Anomaly passage holds, and a low background level due to contaminating electrons is observed. These good time intervals have subsequently been applied in the screening process to the data streams from each of the PCUs (e.g. see Table 1 for the resulting screened exposure of PCU-2 per observation run).

Next, we selected event data from all three Xenon layers of each PCU allowing us to better characterize the hard (> 10 keV) X-ray properties of PSR J0205+6449. The TT (Terrestrial Time) arrival times of the selected events (for each sub-observation and for each PCU unit) have been converted to arrival times at the solar system barycenter (in TDB time scale) using 1) the JPL DE200 solar system ephemeris, 2) the instantaneous spacecraft position and 3) the sub-arcsecond celestial position of PSR J0205+6449. The position used is: \( \alpha, \delta = (02^h 05^m 37^s 92, +64^\circ 49' 42'' 78) \) for epoch J2000 (Slane et al., 2002), which corresponds to \( (l, b) = (130.71931, 3.08456) \) in Galactic coordinates.

3.2. Timing solutions: ephemerides

We generated pulsar timing models (ephemerides) specifying the rotation behaviour of the pulsar over a certain time stretch. The pulse frequency and its first two time derivatives \( (\nu, \dot{\nu}, \ddot{\nu}) \) were determined from PCA X-ray data solely, demanding a maximum RMS value of only 0.01 period in the time-of-arrival (TOA) analysis. This requirement resulted in 13 timing models with validity intervals of typically 100 days. The ephemerides are listed in Table 2. In the TOA analysis we followed the steps outlined in Section 4 of Kuiper & Hermsen (2009), in this case, however, we made a high-statistics correlation template (showing clearly the two X-ray pulses) from the 80 ks observation during run 60130. Our models are fully consistent with those derived by Livingstone et al. (2009), who used a combination of X-ray (RXTE PCA) and radio (GBT and JBO) data. Also, we found evidence for the presence of two timing glitches using solely X-ray data, one occurring somewhere between MJD 52515 and 52571 and a much stronger one occurring in the RXTE monitoring gap between MJD 52752 and 53063 (see Livingstone et al., 2009 for more details on these glitches which they report to have fractional magnitudes \( \Delta v/v \sim 3 \times 10^{-7} \) and \( \Delta v/v \sim 3 \times 10^{-6} \), respectively). The frequency evolution history over the RXTE observation time stretch MJD 52138-53813 is shown in Fig. 1.

The main difference between our work and that performed by Livingstone et al. (2009) is that we chose for an accurate (RMS < 0.01) description of the rotation behaviour of the pulsar with at most 3 timing parameters over a limited time stretch in stead of using many more timing parameters over a much wider time interval. In the latter approach the need for the (unphysical) higher order timing parameters reflects the presence of (strong) timing noise.

Table 2. Phase-coherent ephemerides for PSR J0205+6449 as derived from RXTE PCA (monitoring) data.

| Entry | Start MJD | End MJD | Epoch MJD,TDB | \( \nu \) [Hz] | \( \dot{\nu} \times 10^{-11} \) Hz/s | \( \ddot{\nu} \times 10^{-21} \) Hz/s² | \( \Phi_0 \) | Validity range (days) |
|-------|-----------|---------|---------------|-------------|-----------------------------|-----------------------------|---------|------------------------|
| 0     | 50721     | 50722   | 50721.0       | 15.230153881(92) | -4.489 (fixed) | 0.0 (fixed) | 0.2931 | 2                      |
| 1     | 52138     | 52141   | 52138.0       | 15.224659006(16) | -4.489(16) | 0.0 (fixed) | 0.5389 | 4                      |
| 2     | 52343     | 52343   | 52343.0       | 15.223863557(3)  | -4.49065(13) | +1.96(38) | 0.6540 | 91                     |
| 3     | 52433     | 52515   | 52433.0       | 15.225141035(8)  | -4.49086(20) | -7.98(62) | 0.7751 | 83                     |
| 4     | 52639     | 52752   | 52639.0       | 15.2227187742(4) | -4.51063(1) | 0.0 (fixed) | 0.4147 | 114                    |
| 5     | 53063     | 53173   | 53063.0       | 15.2211188258(7) | -4.56381(2) | 0.0 (fixed) | 0.4814 | 111                    |
| 6     | 53173     | 53312   | 53173.0       | 15.220651395(13)| -4.55932(4) | +5.80(8)  | 0.3170 | 140                    |
| 7     | 53323     | 53401   | 53323.0       | 15.2201380229(35)| -4.54739(19) | +1.36(49) | 0.3458 | 90                     |
| 8     | 53401     | 53469   | 53401.0       | 15.2197884405(37)| -4.5444(25) | +12.0(9)  | 0.3273 | 69                     |
| 9     | 53469     | 53546   | 53469.0       | 15.2195216777(26)| -4.5304(15) | +7.18(47) | 0.1970 | 78                     |
| 10    | 53546     | 53637   | 53546.0       | 15.2192204400(23)| -4.5213(12) | +1.85(32) | 0.6030 | 92                     |
| 11    | 53637     | 53726   | 53637.0       | 15.2188658017(24)| -4.5195(12) | +28.5(3)  | 0.1413 | 90                     |
| 12    | 53726     | 53813   | 53726.0       | 15.2185183927(26)| -4.5030(14)| +16.8(4)  | 0.2436 | 88                     |
| 13*   | 53726     | 53764   | 53745.0      | 15.2184445054(20)| -4.4990(14) | -10.3(61) | 0.1147 | 39                     |
| 14*   | 53750     | 53814   | 53782.0      | 15.2183007045(13)| -4.4950(28) | +29.1(16) | 0.6055 | 65                     |

1 A glitch occurred between MJD 52515 and 52571 (see Livingstone et al., 2009, for more information). This entry describes the last part of the glitch recovery period. Its validity is questionable given the low number of TOA’s, namely 4, translating to 1 degree of freedom in the TOA fit procedure.

2 Ephemeris from Jodrell Bank radio data

3 \( \Phi_0 \) is the phase offset to be applied to obtain consistent radio-alignment (see Equation 1 in Sect. 4.3).
3.3. X-ray/radio pulse profile phase alignment

The Jodrell Bank observatory (JBO) made observations at a radio frequency of 1.4 GHz from MJD 53725 to 54666, and therefore overlaps for about 89 days with the second RXTE monitoring cycle in the period MJD 53725 to 53813. For two time segments in this interval, MJD 53726-53764 (number of TOAs, 28) and MJD 53750-53814 (number of TOAs, 29), accurate (RMS < 0.01) timing models are constructed with 3 timing parameters (see also Table 2). The 1.4 GHz single-pulse radio profile (in 400 bins) is shown in Fig. 3a with a fiducial point (defining radio-phase 0.0) corresponding to the centre of gravity of the single pulse (just before the pulse maximum). Folding the barycentered X-ray time tags from period MJD 53726 to 53813 upon these radio-ephemerides put the main X-ray pulse (pulse-1) at phase 0.089 ± 0.001 (statistical error only), consistent with the value quoted for the JBO-PCA offset in Livingstone et al. (2009), namely 0.085 ± 0.010. Next, we determine through correlation analysis the phase shifts to be applied to the X-ray pulse profiles from the data periods of entries 0-12 of Table 2 to align these to the radio-aligned X-ray profile of period MJD 53726-53813. These shifts ($\Phi_0$) are given in Table 2.

3.4. Combined X-ray event matrix from PCA observations

Barycentered PCA X-ray event times are finally folded upon an appropriate timing model composed of $v$, $\dot{v}$, $\ddot{v}$ and the epoch $t_0$, as shown in Table 2. Proper X-ray/radio phase alignment, $\Phi(t)$, is obtained by subtracting $\Phi_0$ as shown in the following formula:

$$\Phi(t) = v \cdot (t - t_0) + \frac{1}{2} \dot{v} \cdot (t - t_0)^2 + \frac{1}{6} \ddot{v} \cdot (t - t_0)^3 - \Phi_0$$

Combining the radio-aligned phase information for all PCA-data covered with a proper ephemeris (see Table 2) yielded an event matrix $N(\Phi, E)$ of (180x256) elements. For this purpose we binned the pulse-phase interval [0,1] into 180 phase bins for all 256 PCA PHA channels. From this matrix a high-statistics pulse-phase distribution was extracted for the PHA channels 5-44 (~2-20 keV). This distribution is shown in Fig. 2.

3.5. X-ray pulse profile characterization

Initially, we fitted, analogous to Livingstone et al. (2009), our high-statistics RXTE PCA pulse profile shown in Fig. 2 with a model consisting of 2 Gaussians, each with free scale, width and position, plus background. However, this model rendered a poor/unsatisfactory fit ($\chi^2 = 265.48$ for 180 - 7 degrees of freedom). Next, we tried a double symmetric Lorentzian model plus background in order to give more weight to the wings of the pulses. This model provided a better description of the measured pulse-phase distribution ($\chi^2 = 239.13$ for 180 - 7 degrees of freedom), but is still poor. Finally, we abandoned the description in terms of symmetric functions and used a combination of 2 asymmetric Lorentzians plus background. This model (9 free parameters) is specified below:

$$N(\phi; B, p_1, p_2) = B + N_1(\phi; p_1) + N_2(\phi; p_2)$$

In this formula $p_1$ represents the 4 model parameters, $(N_1, \phi_1, \Gamma_{1v}, \Gamma_{1c})$, of the first asymmetric Lorentzian, $p_2$ the
Table 3. X-ray pulse profile characterization of PSR J0205+6449 from a fit involving two asymmetric Lorentzians plus background

| Parameter | Value       | 1σ-error |
|-----------|-------------|----------|
| Pulse-1   |             |          |
| \(\Phi^1\) | 0.0831 ± 0.0004 |
| \(\Gamma^1_{\ell}\) | 0.0175 ± 0.0009 |
| \(\Gamma^1_r\) | 0.0252 ± 0.0011 |
| Pulse-2   |             |          |
| \(\Phi^2\) | 0.5709 ± 0.0015 |
| \(\Gamma^2_{\ell}\) | 0.0214 ± 0.0036 |
| \(\Gamma^2_r\) | 0.0502 ± 0.0056 |
| Derived quantities | | |
| \(\Phi^2 - \Phi^1\) | 0.488 ± 0.002 |
| \(N^1/N^2\) | 3.72 ± 0.23 |
| \(I^1_l\) | 0.688 ± 0.011 |
| \(I^1_r\) | 0.312 ± 0.014 |
| \(R = I^1_l/I^2\) | 2.2 ± 0.1 |
| \(\Gamma^1 = (\Gamma^1_{\ell} + \Gamma^1_r)/2\) | 0.0214 ± 0.0007 |
| \(I^1 = 1.41 ± 0.05\) ms |
| \(\Gamma^2 = (\Gamma^2_{\ell} + \Gamma^2_r)/2\) | 0.0358 ± 0.0034 |
| \(R = I^1_l/I^2\) | 2.35 ± 0.22\) ms |

a Statistical error only, the systematic error is of the order of 0.01 (see Livingstone et al., 2009)

b Relative contribution of the integrated flux in pulse-1 to the total pulsed flux

equivalent parameters, \((N^1, \phi^2, \Gamma^2_{\ell}, \Gamma^2_r)\), describing the second asymmetric Lorentzian and \(B\) is the value of the background level. The first asymmetric Lorentzian is described by the following expression:

\[
N^1(\phi; p^1) = \begin{cases} 
\frac{N^1_1}{(\phi - \phi^1) / \Gamma^1_{\ell}} + 1 & \phi \leq \phi^1 \\
\frac{N^1_1}{(\phi - \phi^1) / \Gamma^1_r} + 1 & \phi > \phi^1 
\end{cases}
\]

(3)

In this description \(N^1_1\) is the maximum value of pulse-1 reached at \(\phi^1\), the location of the maximum of pulse-1, \(\Gamma^1_{\ell}/2\) is the width of the left wing of the pulse-1, and finally \(\Gamma^1_r/2\) is the width of the right wing of the pulse-1. A similar expression and equivalent definitions hold for the second asymmetric Lorentzian.

This composite model provided an excellent fit, \(\chi^2 = 199.47\) for 171 degrees of freedom, with best-fit parameters and their 1σ error estimates listed in Table 3 (see also the best-fit model superposed on the data in Fig. 2). A description in terms of two asymmetric Lorentzians plus background provides a 7.7σ improvement over the two-Gaussians-plus-background model and a 6σ improvement over the two-Lorentzians-plus-background model, taking into account the two (=9-7) additional degrees of freedom in both cases. Therefore, our analysis does not support the assumption made by Livingstone et al. (2009) of an underlying double Gaussian shape for the X-ray profile. We find the X-ray pulses to be sharper, especially for pulse-2. For both pulses the rising wings are significantly steeper than the trailing wings.

The X-ray peak separation \(\phi^2 - \phi^1\) derived in this work is 0.488(2), significantly smaller than the value estimated by Livingstone et al. (2009), but consistent with the separation of 0.49±0.01±0.01\(\gamma\)-rays by Abdo et al. (2009a) measured at high-energy \(\gamma\)-rays by Abdo et al. (2009a) using Fermi LAT > 100 MeV data. The comparison of the shapes and absolute phases of the JBO radio, our RXTE-PCA X-ray and the Fermi-LAT profiles is shown in Fig. 3. The main X-ray pulse (P1) appears to be the sharpest pulse in this comparison.

3.6. X-ray pulse profile variability

We investigated the stability of the X-ray pulse-shape as a function of time. Therefore, we fitted the measured X-ray pulse-phase distribution (PHA range [4,27] ~ 2-11 keV) for 15 time periods in terms of a constant background and the shapes of pulse-1 and pulse-2, separately. The times of these data points correspond to those of the X-ray timing models shown in Table 2 (entries 0 to 11; 12 points), added with two measurements during the last RXTE monitoring period, MJD 53726-53813, covering entry #12 and finally, with a data point covering the post-glitch-1 period MJD 52544-52607, yielding eventually 15 independent measurements. The splitting of period MJD

2 The first error specifies the statistical error and the second the systematical error (see Abdo et al. 2009a, for more details)
53726–53813 into the intervals MJD 53736–53749 (2 RXTE sub-observations) and MJD 53760–53813 (5 sub-observations) was driven by the detection of a “timing anomaly” in the former interval during the phase-coherent timing analysis. At a later stage of this work it turned out that this “anomaly” was caused by incorrect RXTE clock corrections just after the introduction of a leap second on 2006, January 1.

The profile fitting procedure yields the flux ratio \( R = I_1/I_2 \) (see for the definition Table 3) for each time interval. The results, \( R(t) \) vs. \( t \), are shown in Fig. 3 with superposed as long-dashed line the P1/P2-flux ratio from the time-averaged high-statistics profile \( R = 2.2 \pm 0.1 \); see Table 3 along with its 1-\( \sigma \) error region (shaded area). One data point, corresponding to the “anomaly” period, deviates \( \sim 3.5\sigma \) from the time-averaged value. Taking into account the number of trials (15) its significance reduces to 2.7\( \sigma \), still indicating an interesting hint for variability. The pulse-phase distribution during the “anomaly” period is shown in Fig. 5. In this figure we also superposed as dotted line the best fit model in which the shapes (two asymmetric Lorentzians) for each of the two pulses are identical to those derived for the time-averaged profile in Fig. 2 and detailed in Table 3.

Compared to the other measurements, where P2 is sometimes hardly visible, we see strongly enhanced P2 emission during this period. From spectral analysis of the P1 and P2 emissions during the “anomaly” period it turns out that the P1 flux is comparable to its time-averaged value contrary to the P2 flux, which shows a clear enhancement by almost a factor 2.

This leads to the conclusion that we see an interesting indication for flux variability for P2 without a change of its pulse shape. Finally, we checked the JBO radio profile assembled during the “anomaly” period for possible morphology changes e.g. the appearance of a new feature, but we found none.

### 3.8. RXTE HEXTTE timing analysis

HEXTE operated in its default rocking mode during the observations listed in Table 1 allowing the collection of real-time background data from two independent positions \( \pm 1.5^\circ \) to either side of the on-source position. For the timing analysis we selected only the on-source data from both clusters. Good-time intervals have been determined using similar screening filters as used in the case of the PCA. The selected on-source HEXTE event times have subsequently been barycentered and folded upon the ephemerides listed in Table 2, taking into account proper radio-phase referencing. Thus, we obtained time-averaged HEXTE pulse phase distributions in 256 spectral channels (15 - 250 keV) for the combination of observations listed in Table 1. The total dead-time corrected exposure time collected for clusters A and B amounts, 400.6 ks and 426.3 ks, respectively. Pulse profiles for the band 14.7-28 and 33.1-132.6 keV, are shown in panels c and d of Fig. 6. Fitting a model, comprising the (asymmetric) Lorentzians shapes of Pulses 1 and 2 and a flat background, to these phase distributions yielded detection significances of 7.8\( \sigma \) and 3.8\( \sigma \) for the 14.7-28 and 33.1-132.6 keV bands, respectively (2.9\( \sigma \) for the band, 64.1-132.6 keV). Therefore, pulsed emission of PSR J0205+6449 has been detected up to \( \sim 132 \) keV, well above the sensitivity band of the PCA.

### 3.8. XMM-Newton timing analysis

The XMM EPIC-PN data were screened for solar (soft proton) flares by creating a light curve for events with energies in excess of 10 keV. From the resulting count rate distribution, assumed to be Gaussian in absence of any flares, we could identify periods during which the rate exceeds its mean value plus three times the width of the distribution. These periods are ignored in subsequent analysis. Next, we selected events from a sufficiently large circular region centered on PSR J0205+6449 with a radius of 60” to ensure that all pulsar counts are included and barycentered the event times of these events. Because the XMM-Newton observations have been performed before the 80 ks RXTE observation (60130) no valid ephemeris was available for the XMM data period. Therefore, we performed a limited periodicity search around the predicted frequency value based on

\[ R = I_1/I_2 \]

Fig. 4. The ratio of the integrated flux in pulse-1 over pulse-2 as a function of time for the PCA energy band \( \sim 2-11 \) keV. One data point at time interval MJD 53736–53749 (i.e. the “anomaly” period) deviates \( \sim 3.5\sigma \) (single trial) from the time-averaged value of \( 2.2 \pm 0.1 \).

Fig. 5. The pulse profile of PSR J0205+6449 (60 bins) in the \( \sim 2-11 \) keV band during the “anomaly” interval (MJD 53736–53749; 2 RXTE sub-observations). Strongly enhanced P2 emission is detected. The best fit model, composed of a background plus two asymmetric Lorentzians of the same shapes as shown in Fig. 2, is superposed as dashed line.
庭 our X-ray pulse profile variability study shown in Sect. 3.6 to the measured pulse-phase distribution, \(N(\Phi)\), in various user-selected energy bands:

\[
N(\Phi) = b + c_1 \times T_1(\Phi) + c_2 \times T_2(\Phi)
\] (4)

In this formula \(b\) represents the (constant) unpulsed/DC level, \(c_1\) and \(c_2\) the scales of the two asymmetric Lorentzian templates, \(T_1\) and \(T_2\) (both normalized to 1), respectively (see Sect. 3.5). This model provided statistically good fits to all PCA and HEXTED profiles. Good fits could be derived for the EPIC-PN profiles after convolving the Lorentzian templates with the poorer time resolution.

For each instrument the pulsed excess counts in the various energy bands for the first (P1) and the second pulse (P2) and the sum (=total pulsed, TP) can be translated to photon fluxes provided that proper energy response matrices are used.

In the case of the PCA we constructed time-averaged energy response matrices for each PCU separately taking into account the different (screened) exposure times of the involved PCU’s during the time period of interest. For this purpose we used the fools version 6.4 programs pcarsp and ardfgen. To convert PHA channels to measured energy values, E(\(\Phi\))E, for PCA combined/stacked products we also generated a weighted PCU-combined energy response matrix.

For HEXTED we employed cluster A and B energy-response matrices separately, taking into account the different screened on-source exposure times and the reduction in efficiency in case of off-axis observations. The on-source exposure times for both clusters have been corrected for considerable dead-time effects.

Finally, we created energy response files (effective area (arf) and energy redistribution matrix (rmf)) for the EPIC-PN operating in small window mode taking into account the reduction in effective area given the 15\(^{\circ}\) source extraction radius used. For this purpose we employed the XMM SAS (vrs. 7.1.0) software tools arfgen 1.73.3 and rmfgen 1.55.1.

We assume simple power-law models in the form, \(F_E = K \times (E/E_0)^{-\Gamma}\) with \(\Gamma\) the photon-index and \(K\) the normalization in ph/cm\(^2\)/s/keV at the pivot energy \(E_0\), for the underlying photon spectra of P1, P2 and its sum TP. We fixed the absorbing interstellar Hydrogen column \(N_H\) to 3.4 \(\times\) 10\(^{22}\) cm\(^{-2}\) (see the “PL-model for neutron star” entry in Table 2 of Slane et al., 2004). These models have been fitted in a forward folding procedure using the appropriate response matrices to obtain the optimum spectral parameters, \(K\) and \(\Gamma\), and the reconstructed spectral flux points from the observed pulsed count rates. We verified that the measured high-statistics RXTE-PCA spectrum, as well as the EPIC-PN spectrum and the total spectrum including also HEXTED data are fully consistent with this non-thermal simple power-law model. There is in the pulsed X-ray spectrum above \(0.5\) keV no indication for a thermal black-body component, a conclusion also reached for the total emission from the compact source by Slane et al. (2002) and Slane et al. (2004), who reported a power-law spectral index of \(\sim 1.7\). We note that Kargaltsev & Pavlov (2008) in their Table I erroneously mark this pulsar to have a black-body component. Furthermore, in this work we only show the unabsorbed spectra i.e. the interstellar absorption has been modeled out.

In Table 4 the best fit values are listed of the spectral parameters for the total pulsed emission TP, and emissions of P1 and P2 using PCA data only, and for TP using the EPIC PN, PCA and HEXTED combination over the extended energy band 0.56 to 267.5 keV. All spectra have a consistent shape with index \(\sim 1.03\). We note for comparison, that for energies > 100 MeV the Fermi

![Fig. 6. XMM-Newton EPIC-PN pulse profiles (30 bins) of PSR J0205+6449 for the 0.5-3 and 3-12 keV energy bands (panels a,b). Panels c and d show the RXTE HEXTED profiles (60 bins) for the 14.7-28 and 33.1-132.6 keV energy bands. Significant pulsed emission is detected up to \(\sim 130\) keV and down to \(\sim 0.95\) keV.](image-url)
consistent with the value $0.49$.

The X-ray pulse profile consists of two sharp pulses which we determined in the radio domain and the high-energy ($\sim 3$ GeV [Abdo et al., 2009a]), and that P2 exhibits at high-energy $\gamma$-rays a significantly harder spectrum than P1.

The photon spectrum ($\nu F_{\nu}$ representation) over the 0.56 - 267.5 keV energy band of the total pulsed emission combining XMM-Newton EPIC-PN, RXTE-PCA and HEXTE data, as derived in this work, is shown in Fig. 7 in a much wider energy frame (0.1 keV-10 GeV) by including the best fit and its uncertainty range measured by Fermi for energies $> 100$ MeV [Abdo et al., 2009a]. The luminosity of the pulsed emission of PSR J0205+6449 apparently reaches a maximum in the MeV band. For comparison are also shown the total pulsed emission spectra of the Crab, PSR B1509-58 as well as the “middle-aged” Vela pulsar.

5. Summary
In this paper we derived for the young rotation-powered pulsar PSR J0205+6449 the timing and spectral characteristics over the broad X-ray band from $\sim 0.5$ to $\sim 270$ keV, using data from the RXTE-PCA and HEXTE, and XMM-Newton EPIC PN. These X-ray characteristics complement our knowledge about this pulsar in the radio domain and the high-energy $\gamma$-ray band for energies above 100 MeV.

Our phase-coherent ephemerides (see Table 2) are consistent with those derived by Livingstone et al. (2009) with the main difference that we used solely X-ray data (from the RXTE PCA) and fitted at most three timing parameters ($\nu, \dot{\nu}, \ddot{\nu}$) over more limited time intervals.

The X-ray pulse profile consists of two sharp pulses which can be described with two asymmetric Lorentzians, each with the rising wing steeper than the trailing wing, and full-width-half-maximum $1.41 \pm 0.05$ ms and $2.35 \pm 0.22$ ms, respectively. These profiles are sharper than reported by Livingstone et al. (2009).

The first X-ray pulse lags the single radio pulse in phase by $0.089 \pm 0.001$ (statistical error); the phase separation between the two X-ray pulses amounts $0.488 \pm 0.002$, fully consistent with the value $0.49 \pm 0.01 \pm 0.01$ (statistical and systematic errors) reported for high-energy $\gamma$-rays above 100 MeV [Abdo et al., 2009a].

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We find an indication for a flux increase by a factor $\sim 2$, $\sim 3.5\sigma$ above the time-averaged value, for the second, weaker pulse during a two-week time interval, while its pulse shape did not change. During this time window, the morphology of the JBO radio profile of PSR J0205+6449 did not change, notably, there was no indication for a second pulse.

We detected the pulsed signal significantly for the first time down to $\sim 0.95$ keV with XMM-Newton EPIC PN, and up to $\sim 130$ keV by analysing RXTE HEXTE data. The morphologies of the EPIC PN (taking into account the coarser timing resolution) and the HEXTE profiles are consistent with that measured with the PCA.

The spectrum of the pulsed X-ray emission is of non-thermal origin, exhibiting a power-law shape with photon index $\Gamma = 1.06 \pm 0.03$, fitting just the high-statistics PCA data, and $\Gamma = 1.03 \pm 0.02$, fitting over the broader energy band from $\sim 0.5$ to $\sim 270$ keV by including also the EPIC-PN and HEXTE flux values. There is no indication for a black-body component in the soft X-ray spectrum above 0.5 keV.

We do not see a spectral difference between the spectra of the two X-ray pulses in the PCA data. Both spectral photon indices are fully consistent with the time averaged value for the total pulsed emission (see Table 3). Note that the relative strengths of P1 and P2 in the X-ray and high-energy $\gamma$-ray windows reverse (see Fig. 3); the spectrum of P2 has to harden significantly with respect to that of P1 between a few hundred keV and 100 MeV.

6. Discussion and Conclusions
In the introduction we noted that PSR J0205+6449 is now one of only three young (< 10,000 year old) pulsars which are detected in the classical X-ray band and at hard X-rays above 20 keV, as well as at high-energy (> 100 MeV) $\gamma$-rays, the others being the Crab pulsar and PSR B1509-58. Fig. 7 shows that these three young pulsars reach their maximum luminosities below 100 MeV, while the “middle-aged” Vela pulsar (characteristic age 11.4 kyr) reaches its maximum at GeV energies (for the latest results on the Vela pulsar for energies above 100 MeV, see the Fermi results by Abdo et al. 2009b). The latter spectrum is characteristic for older pulsars reported to be detected above 100 MeV (e.g. see the first Fermi Large Area Telescope catalog of $\gamma$-ray pulsars by Abdo et al. 2009a).

Comparing in more detail the high-energy spectra of the young pulsars in Figure 7 we notice large differences. For energies below 10 keV the flux values of PSR J0205+6449 are $\sim 4$ orders of magnitude below those of the Crab, while around 10 MeV the difference is reduced to about a factor of 10. The X-ray spectrum of PSR J0205+6449 is, thus, very much harder than that of the Crab. The total high-energy spectrum of PSR J0205+6449 appears to reach its maximum luminosity at MeV energies, like is the case for PSR B1509-58/PSR J1513-5908. The spectral break for the latter spectrum between 10 MeV and 100 MeV (see flux values in Figure 7) measured with COMPTEL and EGRET aboard the Compton Gamma-Ray Observatory by Kuiper et al. (1999) has been confirmed by Pellizzoni et al. (2009). These authors report for PSR B1509-58 a softening of the photon index $\Gamma$ from ~1.7 to ~2.5 going from tens to hundreds of MeV (but do not provide pulsed-flux values).

Interestingly, the X-ray spectrum above 2 keV of PSR J0205+6449 resembles that of the slightly older Vela pulsar (similar spectral index), but the $L_\gamma/L_\nu$ ratio for the pulsed
Table 5. Characteristics of the three young (< 10 kyr) X-ray and γ-ray emitting pulsars in comparison with the middle-aged Vela pulsar (PSR B0833-045). The luminosities of the pulsed emission $L$ are calculated as $L = 4\pi d^2 F_{\Omega}$ with values for the distance $d$ taken from the table, and the beaming fraction $f_{\Omega}$ set to 1. $F$ represent the pulsed flux.

| Source      | $d$  | $P$   | $\tau$ | $L_{sd}$ | $F_\gamma^c$ | $L_\gamma^c$ | $F_\gamma^b$ | $L_\gamma^b$ | $\eta_\gamma^c$ | $\eta_\gamma^b$ |
|-------------|------|-------|--------|----------|--------------|--------------|--------------|--------------|----------------|----------------|
| B0531+21    | 2.0  | 29.7  | 1.3    | 4.4E+38  | (5.68 ± 0.05)E-09 | (1.3 ± 0.1)E-09 | (2.72 ± 0.02)E+36 | 6.2E-3 | (6.1 ± 0.3)E+35 | 1.4E-3          |
| B1509-58    | 5.8  | 151.5 | 1.6    | 1.7E+37  | (1.46 ± 0.02)E-10 | (5.1 ± 2.5)E-11 | (5.88 ± 0.08)E+35 | 3.5E-2 | (2.1 ± 1.0)E+35 | 1.2E-2          |
| J0205+6449  | 3.2  | 65.7  | 5.4    | 2.7E+37  | (0.36 ± 0.02)E-11 | (6.7 ± 0.5)E-11 | (4.45 ± 0.20)E+33 | 1.7E-4 | (8.2 ± 0.6)E+34 | 3.0E-3          |
| B0833-045   | 0.287| 89.3  | 11.4   | 6.9E+36  | (0.88 ± 0.29)E-11 | (7.9 ± 0.3)E-09 | (8.67 ± 2.85)E+31 | 1.3E-5 | (7.8 ± 0.3)E+34 | 1.1E-2          |

$^a$ Luminosities, fluxes and efficiencies labeled with $x$ are evaluated for the 2-100 keV band.
$^b$ Luminosities, fluxes and efficiencies labeled with $\gamma$ are evaluated for the 0.1-10 GeV band.
$^c$ The γ-ray energy flux of PSR B1509-58 in the 0.1-10 GeV band has been derived from the (total) photon flux values for the 100-300 and 300-1000 MeV bands as given in Kuiper et al. (1999) assuming a power-law shape with photon index of 2.5, and should be considered as an upper-limit to the pulsed flux of PSR B0531+21 in the 0.1-10 GeV band.

The γ-ray pulse in phase $\gamma$-ray bands are the same. We know, however, that differences in beaming fraction, while the latter components differ by a factor ~50; higher for PSR J0205+6449 (see Table 5 which is introduced below). The $L_\gamma/L_x$ ratio of PSR J0205+6449 is in between those of Vela and PSR B1509-58, namely, the $L_\gamma/L_x$ ratio for PSR J0205+6449 is a factor ~50 smaller than that for PSR B1509-58. Note, that for the quoted flux ratios it is assumed that the beaming fractions in the X-ray and γ-ray bands are the same. We know, however, that these are in many cases different. More importantly, in the X-ray spectra below e.g. 2 keV there are no indications for black-body components in the spectra of Crab, PSR B1509-58 and PSR J0205+6449. In contrast, the (pulsed) Vela spectrum exhibits below 2 keV a black-body peak (not shown in Fig. 7) see e.g. Pavlova et al. (2001), which is characteristic for middle-aged and older rotation powered pulsars. Therefore, the spectral properties of PSR J0205+6449 confirm that we are dealing with a young pulsar, and suggest a real age between those of Vela and PSR B1509-58, favouring its characteristic age of 5.4 kyr over that of SN 1181 (828 yr).

Table 5 lists for the four pulsars discussed above in order of characteristic age ($\tau = P/2P$) the spin-down luminosities $L_{sd}$ and fluxes $F$ and luminosities $L$ in the X-ray 2-100 keV and gamma-ray 0.1-10 GeV bands, as well as the corresponding efficiencies to convert spin-down energy into emission in these energy bands. The luminosities are calculated as $L = 4\pi d^2 F_{\Omega}$, with the values for the distance $d$ taken from the table, and the value for $f_{\Omega}$, which is the beaming fraction, set to 1. At first sight one could argue that there is an evident anticorrelation between characteristic age and X-ray luminosity, independent from differences in the beaming fractions, but this becomes less obvious when we consider the X-ray efficiencies instead of luminosities. In the gamma-ray band there is not any indication for a correlation. The listed gamma-ray efficiencies differ less than a factor ~10, ignoring differences in beaming fraction, while the latter differences can be substantial.

There are also large differences in the morphologies of the pulse profiles of the three young pulsars. Comparing the pulse profiles detected for Crab and PSR J0205+6449 at X-ray energies and high-energy γ-rays, then are also some similarities: both exhibit two pulses with peaks separated ~0.5 and ~0.4 in pulse phase, respectively, and the X-ray and γ-ray pulses are aligned in phase. However, the pulses in the Crab profile are significantly broader than those of PSR J0205+6449 and emission is also detected between the two Crab pulses. The latter is not the case for the X-ray profile of PSR J0205+6449, but, interestingly, emission between the pulses has been detected in the Fermi profile at the 5σ level.

Furthermore, the Crab main radio pulse is in general phase coincidence with the broad X-ray/γ-ray pulse. The peak of this main radio pulse lags that of the first X-ray/γ-ray pulse in phase by only ~0.008 or 280 µs; see for consistent estimates from INTEGRAL, RXTE and EGRET [Kuiper et al. 2003], and from Fermi [Abdo et al. 2009b]. On the other hand, the Crab radio...
precursor precedes the first, main X-ray/γ-ray pulse in phase by ∼0.09, or 3.2 ms, being located around the start of the leading wing of the high-energy pulse. In the case of PSR J0205+6449, the single radio pulse is also preceeding the first narrow X-ray/γ-ray pulse in phase by ∼0.083 or 5.4 ms, and is fully separated in phase, the radio pulse being located just before the onset of the first high-energy pulse (see Fig. 3). This strongly suggests that the analogue of the radio pulse of PSR J0205+6449 is the weak radio precursor of the Crab. Also, that there are no counterparts in the radio profile of PSR J0205+6449 to the two high-energy pulses of PSR J0205+6449, contrary to the situation for the Crab. This means that for this young pulsar exhibiting sharp non-thermal high-energy pulses, we do not see evidence for radio emission originating from the same site in the magnetosphere, e.g. in slot gaps (two-pole caustic emission, Dyks & Rudak 2003) or outer gaps (outer-magnetosphere emission, see Cheng et al. 1986; Romani 1998; Hirota, 2006 from a region close to the light cylinder). Possibly, this radio component of PSR J0205+6449 is just too weak to be detectable, but might be revealed in a search for giant radio pulses in the phase intervals of the high-energy pulses. Namely, for a number of young and milli-second radio pulsars phase coincidences between the high-energy pulses and giant radio pulses have been reported. Two examples: the Crab for which the distribution of giant radio pulses is remarkably similar to the average profile of the radio main and interpulse (Popov et al. 2006) and milli-second pulsar PSR B1937+21 for which Cusumano et al. (2003) reported the phase coincidence of two sharp high-energy X-ray pulses with two phase intervals exhibiting giant radio pulses, which trail the two normal radio pulses. The latter example might be revealed for PSR J0205+6449.

The high-energy pulse profile of PSR B1509-58 differs totally from those of Crab and PSR J0205+6449. At hard X-rays and soft γ-rays below 10 MeV the profile consists of a single structured broad pulse, which can be explained as being composed of two Gaussian pulse profiles separated ∼0.14 in phase with different spectra (Kuiper et al., 1999; Cusumano et al., 2001), the second broader pulse peaking at ∼0.35, with the main radio pulse at phase 0. Above 10 MeV, the COMPTEL profile between 10 and 30 MeV and the EGRET profile between 30 and 100 MeV suggest the presence of an additional high-energy pulse at phase ∼0.85 (Kuiper et al., 1999). The latter seems now to be confirmed in the AGILE profile of PSR B1509-58 (Pellizzoni et al. 2009), which shows the main pulse for energies above 100 MeV at phase ∼0.35, and a second possible pulse at ∼0.85. It is now ambiguous what phase difference between high-energy pulses of PSR B1509-58 (∼0.14 or ∼0.5) should be considered for comparison with the morphology of pulse profiles of the other young pulsars.

The above cited different models aiming to explain the production of non-thermal high-energy emission in the magnetospheres of rotation-powered pulsars do not address flux variability. Furthermore, there was also no observational evidence for such variability till the magnetar-like outburst of the high-field pulsar PSR J1846-0258 (Gavriil et al. 2008), which decayed with an 1/e-time constant of ∼55 days. It was shown by Kuiper & Hermes (2009) that the radiative outburst was triggered by a major spin-up glitch, and that, most interestingly, the shape of the X-ray pulse profile did not change during the outburst. For the flux increase by a factor of ∼2 of the non-thermal emission from the second pulse of PSR J0205+6449 during a two-week time period, we did not see a variation in pulse shape, either. However, there was no indication for glitching activity. The significance of the variability is insufficient to draw strong conclusions, but it seems warranted to start searching for such variability in the emission from the increasing sample of rotation-powered pulsars emitting non-thermal high-energy emission.

In conclusion, we accurately measured for the young rotation powered pulsar PSR J0205+6449 the morphology of the X-ray light curve and the spectrum over the broad X-ray band ∼0.5 - ≤270 keV. The PSR J0205+6449 X-ray spectrum above 2 keV has the same power-law shape (Γ ∼ 1.03) as the middle-aged Vela pulsar, but the overall high-energy spectral shape, considering also the Fermi γ-ray spectrum, resembles more the spectrum expected for a younger pulsar, i.e. no evidence for a thermal black-body component, and maximum luminosity at MeV energies and not at GeV energies.

The morphology of the double-pulse PSR J0205+6449 light curve can be explained in a conventional outer-gap scenario for a rotating dipole in vacuum assuming low-altitude radio emission, similar to the case of the Crab pulsar when taking the Crab precursor radio pulse as the counterpart of the single radio pulse detected for PSR J0205+6449. This can be verified in the “Atlas” of model γ-ray light curves simulated by Watters et al. (2009). However, see also the alternative Atlas by Bai & Spitkovsky (2009a), who point out an inconsistency in the model calculations by Watters et al. (2009) and in earlier reports, affecting particularly profile shapes calculated for the two-pole caustic model.

Furthermore, it should be realized that the sharp pulses in the high-energy profile of this young pulsar PSR J0205+6449 do not have radio counterparts like we see for the Crab, and we encourage a search for giant radio pulses in the phase intervals of these high-energy pulses. Recent model calculations by Bai & Spitkovsky (2009b) using a force-free field instead of the vacuum dipole field show that alternative scenarios such as their annular-gap model are required to produce over a wide range of parameters two sharp high-energy pulses as exhibited by PSR J0205+6449. More extensive 3-D simulations including the physics of the production processes are required for more detailed comparisons with the spectral and timing characteristics.

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References
Abdo, A.A. et al. 2009a, ApJ, 699, L102
Abdo, A.A. et al. 2009b, ApJ, 696, 1084
Abdo, A.A. et al. 2009c, astro-ph, arXiv:0910.1608
Abdo, A.A. et al. 2010, ApJ, 708, 1254
Aliu, E., Andritschke, H., Antonelli, L.A. et al. (The MAGIC Collaboration) 2008, Science, 322, 1221
Bai, X.-N. & Spitkovsky, A., 2009a, submitted to ApJ, arXiv:0910.5740
Bai, X.-N. & Spitkovsky, A., 2009b, submitted to ApJ, arXiv:0910.5741
Bietenholz, M.F. 2006, ApJ, 645, L180
Buccheri, R., Bennett, K., Bigman. G., et al. 1983, A&A, 128, 245
Camilo, F., Stairs, I.H., Lorimer, D.R., et al. 2002, ApJ, 571, L41
Cheng, K.S., Ho, C., & Ruderman, M.A., 1986, ApJ, 300, 522
Cusumano, G., Mineo, T., Massaro, E., et al., 2001, A&A, 375, 379
Cusumano, G., Hermes, W., Kramer, M., et al., 2003, A&A, 410, L9
Dyks, J., & Rudak, B., 2003, ApJ, 598, 1201
Fesen, R., Rudie, G., Hurford, A., & Soto, A. 2008, ApJS, 174, 379
Gavriil, F.P., Gonzales, M.E., Gotthelf, E.V. , et al., 2008, Science, 319, 1802
Hirotani, K., 2006, ApJ, 652, 1475
Jahoda, K., Swank, J.H., Giles, A.B., et al. 1996, Proc. SPIE, 2808, 59
Kargaltsev, O. & Pavlov, G.G. 2008, AIP Conf. Proc. 983, 171
Kuiper, L., Hermes, W., Krijger, J.M. et al. 1999, A&A, 351, 119

L. Kuiper et al.: Hard X-ray characteristics of the energetic pulsar PSR J0205+6449 in 3C58
Kuiper, L., Hermsen, W., Cusumano, G., et al. 2001, A&A, 378, 918
Kuiper, L., Hermsen, W., Walter, R., & Foschini, L. 2003, A&A, 411, L31
Kuiper, L. & Hermsen, W. 2009, A&A, 501, 1031
Livingstone, M.A., et al. 2009, ApJ, 706, 1163
Murray, S.S., Slane, P.O., Seward, F.D., et al. 2002, ApJ, 568, 226
Pavlov, G.G., Zavlin, V.E., Sanwal, D., et al., 2001, ApJ, 552, L129
Pellizzoni, A., Pilia, M., Possenti, A., et al. 2009, ApJ, 695, L115
Popov, M., Soglasnov, V., Komrat’ev, V., et al., 2006, Astronomy Letters, 50, 55
Ransom, S., Camilo, F., Kaspi, V., et al. 2004, in AIP Conf. Proc. 714, X-ray Timing 2003: Rossi and Beyond, eds. P. Kaaret, F.K. Lamb & J.H. Swank
Romani, R.W., 1996, ApJ, 470, 469
Rothschild, R.E., Blanco, P.R., Gruber, D.E., et al. 1998, ApJ, 496, 538
Slane, P.O., Helfand, D.J., and Murray, S.S. 2002, ApJ, 571, L45
Slane, P.O., Helfand, D.J., van der Swaluw, E., and Murray, S.S. 2004, ApJ, 616, 403
Stephenson, F.R., & Green, D.A. 2002, Historical Supernovae and Their Remnants (Oxford:Clarendon)
Strüder, L., Brinkmann, U., Dennerl, K., et al. 2001, A&A, 365, L18
Watters, K., Romani, R.W., Weltevrede, P. & Johnston, S. 2009, ApJ, 695, 1289