The \textit{Fermi}-LAT detection of magnetar-like pulsar PSR J1846–0258 at high-energy gamma-rays

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ABSTRACT

We report the detection of the pulsed signal of the radio-quiet magnetar-like pulsar PSR J1846–0258 in the high-energy $\gamma$-ray data of the \textit{Fermi} Large Area Telescope (\textit{Fermi}-LAT). We produced phase-coherent timing models exploiting \textit{RXTE} PCA and \textit{Swift} XRT monitoring data for the post- (magnetar-like) outburst period from 2007 August 28 to 2016 September 4, with independent verification using \textit{INTEGRAL} ISGRI and \textit{Fermi} GBM data. Phase-folding barycentric arrival times of selected \textit{Fermi}-LAT events from PSR J1846–0258, resulted in a 4.2\,$\sigma$ detection (30–100 MeV) of a broad pulse consistent in shape and aligned in phase with the profiles that we measured with \textit{Swift} XRT (2.5–10 keV), \textit{INTEGRAL} ISGRI (20–150 keV) and \textit{Fermi} GBM (20–300 keV). The pulsed flux (30–100 MeV) is $(3.91 \pm 0.97) \times 10^{-9}$ photons cm\(^{-2}\) s\(^{-1}\) MeV\(^{-1}\). Declining significances of the \textit{INTEGRAL} ISGRI 20–150 keV pulse profiles suggest fading of the pulsed hard X-ray emission during the post-outburst epochs. We revisited with greatly improved statistics the timing and spectral characteristics of PSR B1509–58 as measured with the \textit{Fermi}-LAT. The broad-band pulsed emission spectra (from 2 keV up to GeV energies) of PSR J1846–0258 and PSR B1509–58 can be accurately described with similarly curved shapes, with maximum luminosities at 3.5 $\pm$ 1.1 MeV (PSR J1846–0258) and 2.23 $\pm$ 0.11 MeV (PSR B1509–58). We discuss possible explanations for observational differences between \textit{Fermi}-LAT detected pulsars that reach maximum luminosities at GeV energies, like the second magnetar-like pulsar PSR J1119–6127, and pulsars with maximum luminosities at MeV energies, which might be due to geometric differences rather than exotic physics in high-B fields.

Key words: radiation mechanisms: non-thermal – stars: neutron – pulsars: individual: PSR J1846–0258 – pulsars: individual: PSR B1509–58 – pulsars: individual: PSR J1119–6127 – gamma-rays: general

I INTRODUCTION

PSR J1846–0258 was discovered as a 0.3 s X-ray pulsar (Gotthelf et al. 2000), located at the centre of supernova remnant (SNR) Kes 75 (Helfand et al. 2003). It is a young (characteristic age $\tau \sim 723$ yr) radio-quiet (e.g. Archibald et al. 2008) rotation-powered pulsar, with $P \sim 324$ ms. Its surface magnetic field strength of $4.9 \times 10^{13}$ G is above the quantum critical field strength of $4.413 \times 10^{13}$ G. \textit{RXTE} monitoring before 2006 June showed that PSR J1846–0258 behaved as a very stable rotator (Livingstone et al. 2006). With \textit{INTEGRAL} a hard X-ray point-source (pulsar plus the surrounding diffuse pulsar wind nebula) and pulsed emission were detected. For details about the pulsed and total high-energy spectrum across the $\sim$ 2-300 keV band we refer to Kuiper & Hermsen (2009).

Most intriguingly, PSR J1846–0258 was the first rotation-powered pulsar that exhibited magnetar-like behaviour, starting with a dramatic brightening of the pulsar in \textit{Chandra} observations of Kes 75 during 2006 June 7-12 (Kumar & Safi-Harb 2008). Furthermore, Gavriil et al. (2008) reported that this radiative event lasted for about 55 d and discovered five short magnetar-like bursts during the outburst. In a followup study, Kuiper & Hermsen (2009) discovered that the onset of the radiative event was accompanied by a strong glitch in the rotation behaviour of the pulsar. Using multi-year \textit{RXTE} and \textit{INTEGRAL} observations, they concluded that PSR J1846–0258 exhibited before its magnetar-like outburst over many years a very stable behaviour, both temporally and spectrally, and continued after its outburst again as a young stable energetic rotation-powered X-ray pulsar. At higher energies, Parent et al. (2011) did not detect the pulsed signal of PSR J1846–0258 for energies above 100 MeV, analysing about 20 months of \textit{Fermi}-LAT data.
Recently, a magnetar-like outburst has been detected from a second high-B rotation-powered pulsar, namely the radio pulsar PSR J1119–6127 (Camilo et al. 2000, \(\tau \sim 1.6\) ky), with very similar characteristics as observed during the outburst of PSR J1846–0258. Particularly, an equally strong spin-up glitch followed by a radiative outburst accompanied by a few short magnetar-like bursts (Archibald et al. 2016). Different from PSR J1846–0258, Parent et al. (2011) reported PSR J1119–6127 to be a Fermi high-energy gamma-ray source with maximum luminosity at GeV energies, typical for the population of Fermi-detected gamma-ray pulsars. This is in contrast to the spectrum of the young high-B-field soft gamma-ray pulsar, PSR B1509–58 (aka PSR J1513–5908; \(\tau \sim 1.6\) ky), which has after the Crab pulsar the highest flux at hard X-ray energies, and has been detected up to the GeV band of the Fermi LAT, but reaches its maximum luminosity at MeV energies (Kuiper & Hermsen 2015).

PSR J1846–0258 and PSR B1509–58 have very similar spectral shapes of the pulsed emissions in the X-ray band above 2 keV (also the pulse shapes are similar). If the spectral shapes remain similar across the full X-ray / gamma-ray band, then a \(5-10 \times \) smaller 30-100 MeV flux is expected for PSR J1846–0258 relative to that of PSR B1509–58. However, if the gamma-ray luminosity peaks at GeV energies, like detected for the second “magnetar-like” pulsar PSR J1119–6127 then a stronger high-energy gamma-ray source should be observed.

Currently, there are more than 8 years of Fermi LAT data available and the events are reconstructed adopting a new strategy called ‘Pass 8’, which greatly enhances the sensitivity at lower gamma-ray energies (\(\lesssim 300\) MeV), compared to e.g. earlier attempts to detect a pulsed signal from PSR J1846–0258 (Parent et al. 2011). The combination of long exposure times and the enhanced sensitivity at lower gamma-ray energies allow deeper quests to the expected high-energy gamma-ray spectral tail of the pulsed emission of PSR J1846–0258. However, no radio-ephemerides can be derived for this pulsar, what would have made pulse-phase folding of the arrival times of the Fermi events a routine task. But, PSR J1846–0258 is a relatively bright X-ray pulsar, and, because of its unique properties, it is almost continuously monitored at X-rays since its discovery as a pulsar in 1999. First with the PCA aboard RXTE till 2012 January and beyond with the XRT instrument aboard Swift. These X-ray monitoring observations allow the construction of reliable timing models.

In this work we aim to detect pulsed high-energy gamma-ray emission from PSR J1846–0258 in the Fermi LAT passband using all available (Pass-8) data. For this purpose we had to generate phase-coherent timing models (ephemerides) for PSR J1846–0258 using RXTE PCA and Swift XRT monitoring observations across the post-outburst/giant-glitch period MJ 54340–57635 (2007 August 28 – 2016 September 4). Because of the complexity of the ephemeris construction from Swift XRT data (period beyond 2012 January) we verified the resulting timing models using (independent) INTEGRAL ISGRI and Fermi GBM data. After the validity checks we applied the appropriate timing models in Fermi LAT data-folding procedures. Furthermore, we derived the total pulsed hard-X-ray to gamma-ray spectrum of PSR J1846–0258 for comparison with those of PSR J1119–6127 and PSR B1509–58. For the latter comparison, we revisited and significantly improved the published high-energy gamma-ray spectrum of PSR B1509–58 by exploiting the higher sensitivity of Fermi LAT Pass-8 data and additional observations.

In Section 2 we present all X-ray and gamma-ray instruments used in this analysis. Section 3 describes the tedious analysis of the multi-instrument X-ray data to arrive at phase-coherent timing models that are used in Section 4 for the Fermi LAT timing analysis. In Section 4 we also (re)derive the pulsed hard-X-ray – gamma-ray spectra of PSR J1846–0258 and PSR B1509–58. Finally, in Sections 5 and 6 we summarize and discuss our results.

## 2 INSTRUMENTS

In this section we briefly present the instruments aboard RXTE, Swift, INTEGRAL and Fermi, which we used in this work. For their general characteristics we refer to the descriptions by the respective instrument teams, referenced below.

### 2.1 RXTE PCA

RXTE was launched on 1995 December 30 and ended its observations on 2012 January 5. We used its PCA (Jahoda et al. 1996) which consists of five collimated Xenon proportional counter units (PCUs), sensitive to photons with energies in the range 2-60 keV. All PCA data used in this study have been collected from observations in GoodXenon mode allowing high-time resolution (0.9\(\mu\)s) analyses in 256 spectral bins.

### 2.2 Swift XRT

The Swift satellite (Gehrels et al. 2004) was launched on 2004 November 20. Swift carries three co-aligned instruments: the wide-field coded aperture mask Burst Alert Telescope (BAT, 15-150 keV), the narrow field (23′′6 × 23′′6) grazing incidence Wolter-1 X-Ray Telescope (XRT; 0.2-10 keV) and the Ultraviolet/Optical Telescope (UVOT). We used data of PSR J1846–0258 gathered by the XRT (Burrows et al. 2005) from regular monitoring observations that commenced on 2011 July 25. The XRT has several operation modes of which we only used the Windowed-Timing (WT) mode with a time resolution of 1.7675 ms, amply sufficient for pulse timing studies of PSR J1846–0258.

### 2.3 INTEGRAL ISGRI

The INTEGRAL spacecraft (Winkler et al. 2003), launched on 2002 October 17, carries two main \(\gamma\)-ray instruments: a high-angular-resolution imager IBIS (Ubertini et al. 2003) and a high-energy-resolution spectrometer SPI (Vedrenne et al. 2003). In this work, guided by sensitivity considerations, we only used data recorded by the INTEGRAL Soft Gamma-Ray Imager ISGRI (Lebrun et al. 2003), the upper detector system of IBIS, sensitive to photons with energies in the range \(\sim 15\) keV – 1 MeV (effectively about 300 keV). The timing accuracy of the ISGRI time stamps recorded on board is about 61\(\mu\)s. The time alignment between INTEGRAL and RXTE is better than \(\sim 50\mu\)s, verified using data from simultaneous RXTE and INTEGRAL observations of the accretion-powered millisecond pulsar IGR J00291+5934 (Falanga et al. 2005).

### 2.4 Fermi

The Fermi gamma-ray space telescope was launched on 2008 June 11. It comprises two science instruments, the Large Area Telescope (LAT), sensitive to gamma-rays with energies between \(\sim 20\) MeV and 300 GeV, and the Gamma-ray Burst Monitor (GBM) covering the \(\sim 8\) keV – 40 MeV energy band. The spacecraft orbits...
the Earth in about 96.5 min at a height of about 550 km above the Earth’s surface. After a checkout phase nominal science operations started on 2008 August 4 with a one year all sky survey. Till 2013 December the LAT scanned the sky, providing all-sky coverage every two orbits. Since then the observing strategy has been modified combining sky survey observations with pointed observations including target-of-opportunity observations.

2.4.1 Fermi LAT

The Large Area Telescope aboard Fermi is an imaging, wide field-of-view (FoV \( \sim 2.4 \) sr), high-energy \( \gamma \)-ray telescope, covering the energy range from below 20 MeV to more than 300 GeV (Atwood et al. 2009). It is a pair-conversion telescope with a precision tracker and calorimeter, each consisting of a \( 4 \times 4 \) array of 16 modules, a segmented anticoincidence detector that covers the tracker array, and a programmable trigger and data acquisition system. The time stamps of the registered events are accurately \( (\lesssim 1 \mu s) \) derived from GPS clocks aboard the satellite. Since 2015 June 24, LAT events are available from a new event reconstruction and event selection strategy called Pass 8, allowing better sensitivity and acceptance at lower energies than previous reconstructions (Atwood et al. 2013a,b).

2.4.2 Fermi GBM

The Gamma-ray Burst Monitor (Bissaldi et al. 2009; Meegan et al. 2009) comprises a set of 12 sodium iodide (NaI(Tl)) detectors sensitive across the 8 keV to 1 MeV band, and a set of 2 bismuth germanate (BGO) detectors covering the 150 keV to 40 MeV band, and so overlapping with the Fermi LAT passband. The set of non-imaging detectors provides a continuous view on each unblocked (by Earth) hemisphere. During the first four years of the operations, the timing accuracy was insufficient to perform timing studies for fast \( (P < 512 \) ms) energetic pulsars. However, since 2012 November 26 (MJD 56257), the GBM is operated in a nominal data-taking mode that provides time-tagged events (TTE) with \( 2 \mu s \) precision, synchronized to GPS every second, in 128 spectral channels, allowing now detailed timing studies at milli-seconds accuracy. For this work we exploited this much improved timing capability.

3 TIMING ANALYSIS

A timing analysis starts, irrespective the high-instrument involved, with the conversion of (selected) event arrival times registered at the satellite to arrival times at the Solar system barycentre. This process uses the instantaneous spacecraft ephemeris (position and velocity) information (DE200) and an accurate source position (see Helfand et al. 2003) to convert the recorded satellite times\(^1\) from Terrestrial Time-scale (TT or TDT, which differs from Coordinated Universal Time (UTC) by a number of leap seconds plus a fixed offset of 32.184 s) into Barycentric Dynamical Time (TDB) scale, a time standard for Solar system ephemerides.

\(^1\) The on-board-registered event-time stamps of the (selected) events are corrected for known instrumental (fixed), ground station(s) and general time delays in the on-board-time versus Terrestrial-Time (TT) correlation and internal clock/oscillator-drifts (fine clock corrections).

3.1 Phase-coherent timing models

Accurate timing models (ephemerides) are required to describe every revolution of the spinning neutron star accurately, otherwise a potential pulsed signal is washed-out. These models are often composed of a limited number of Taylor series expansion components around epoch time \( t_0 \) in terms of spin frequency \( \nu \), frequency derivative \( \dot{\nu} \), second order derivative \( \ddot{\nu} \) etc.

3.1.1 RXTE PCA

In this work we have used post-outburst RXTE PCA monitoring observations of PSR J1846–0258, covering the period 2007 August 28 till 2011 December 11 (the last RXTE observation of PSR J1846–0258 before decommissioning at 2012 January 5) i.e. MJD range 54340–55906, to construct these so-called phase coherent ephemerides. The method, which is extensively described in section 4.1 of Kuiper & Hermsen (2009), is based on Time-of-Arrival (ToA) determinations involving a high-statistics pulse profile of PSR J1846–0258 as correlation template. The RXTE monitoring based ephemerides are listed in Table 1 as entries 1–6.

3.1.2 Swift XRT

In anticipation of the decommissioning of RXTE in 2012 January Swift XRT started monitoring PSR J1846–0258 on 2011 July 25, and so there is about 5 months overlap in RXTE and Swift monitoring. In this work we used the (still ongoing) Swift XRT monitoring observations up to and including 2016 September 3 i.e. Swift observations 00032031001 – 00032031148 covering the period MJD 55767 – 57635. In total, 147 XRT observations in WT mode have been processed and analysed, totalling an exposure time of \( \sim 876 \) ks.

Because of the spectral hardness of the pulsed emission of PSR J1846–0258 in the X-ray band long exposure times, typically lasting for 15–20 ks, are required for Swift XRT to detect the pulsed signal (in WT mode) at \( \geq 3\sigma \) confidence levels at energies above \( \sim 2.5 \) keV, selecting Grade 0 events from a 30° aperture around the position of the PSR J1846–0258 X-ray counterpart. These exposures cannot be accommodated in a single observation given other observational constraints, and therefore we (initially) combined observations less than 5–10 d apart.

Initially, we attempted to augment the 2011 RXTE PCA ToA’s with Swift XRT based ToA’s. Inspite the poor quality of the latter ToA’s we were able to add six new Swift ToA’s, bridging the 2011–2012 data gap due to Swift and RXTE observational constraints, and to construct a combined RXTE / Swift phase-coherent timing model up to and including 2012 September 15, covering the range MJD 55588–56185 (see entry 7 in Table 1).

In the period 2012 October 6 – November 15 three additional XRT observations were taken, lasting each \( \sim 9-10 \) ks, for which 3–4\( \sigma \) pulsed-signal significances were found; however, phase connection with previous ToA’s failed. The loss of coherence is also reported in Archibald et al. (2015) and is possibly due to a glitch.

For the 2013-and-beyond Swift XRT observations, we developed and employed a new strategy for the construction of phase coherent timing models, given the poor quality of the ToA’s and so questioning the reliability of the ephemerides. In the new method the \( Z^2 \)-test statistics (Buccheri et al. 1983)\(^2\), which is a function

\(^2\) The RXTE PCA pulse-phase distribution for the \( \sim 2 - 30 \) keV band
Table 1. Phase-coherent post-outburst ephemerides for PSR J1846–0258 as derived from RXTE PCA and Swift XRT (monitoring) data covering the time period MJD 54340–57635 (2007 August 28 – 2016 September 4).

| Entry # | Start [MJD] | End [MJD] | t0, Epoch [MID,TDB] | ν [Hz] | ̇ν ×10^{-11} Hz s^{-1} | ̈ν ×10^{-21} Hz s^{-2} | RMS | Φ₀ | Validity range (days) |
|---------|-------------|-----------|---------------------|--------|------------------------|------------------------|-----|-----|----------------------|
| 1       | 54340       | 54440     | 54340.0             | 3.064967014(15) | -6.6999(7)            | 27(2)                  | 0.032 | 0.7992 | 101                  |
| 2       | 54559       | 55070     | 54559.0             | 3.063702807(2)  | -6.67156(2)            | 3.130(9)               | 0.036 | 0.4319 | 512                  |
| 3       | 55056       | 55175     | 55056.0             | 3.060840893(19) | -6.66518(8)            | 12.3(1.6)              | 0.050 | 0.4575 | 120                  |
| 4       | 55154       | 55222     | 55154.0             | 3.059885948(3)  | -6.65645(4)            | 1.83(29)               | 0.033 | 0.6181 | 195                  |
| 5       | 55348       | 55541     | 55348.0             | 3.058322717(6)  | -6.64875(7)            | 2.5(7.8)               | 0.040 | 0.4528 | 194                  |
| 6       | 55488       | 55906     | 55488.0             | 3.056502936(2)  | -6.63946(2)            | 3.58(2)                | 0.033 | 0.7669 | 419                  |
| 7       | 55588       | 56185     | 55811.0             | 3.0565029360(7) | -6.639410(6)           | 3.67(1)                | 0.034 | 0.7713 | 598                  |
| 8       | 56338       | 56967     | 56652.0             | 3.051688239(5)  | -6.61345(3)            | 3.28(7)                | ----- | 0.5898 | 630                  |
| 9       | 56940       | 57458     | 57199.0             | 3.048566201(6)  | -6.59866(3)            | 3.17(9)                | ----- | 0.6503 | 519                  |
| 10      | 57267       | 57635     | 57451.0             | 3.047130268(11) | -6.59106(9)            | 3.71(37)               | ----- | 0.6461 | 369                  |

Notes. a Entries 1–6 are RXTE PCA ToA based, entry 7 is based on a combination of RXTE PCA and Swift XRT ToA's, and entries 8–10 are Swift XRT based using a Simplex optimization algorithm. Solar system planetary ephemeris DE200 has been used in the barycentering process.

b This entry provides an update on entry 9 of Table 2 of Kuiper & Hermsen (2009)

c Combined RXTE PCA / Swift XRT ephemeris bridging the 2011/2012 data gap

d An equivalent ephemeris, based solely on Swift XRT data, is shown in Table 1 of Archibald et al. (2015)

Figure 1. Rotation behaviour of PSR J1846–0258 from its first RXTE detection at 1999 April 18 up to 2016 September 4. The spin frequency (solid lines represent phase coherent timing models, while data points denote incoherent measurements) is shown with respect to the last phase coherent pre-outburst ephemeris (MJD 53464 - 53880; see entry 5 of table 2 of Kuiper & Hermsen 2009). The solid, dashed-dotted and dashed vertical lines indicate the times of the start of nominal science operations of the Fermi LAT instrument at MJD 54682.655 (2008 August 4), the decommissioning of RXTE at MJD 55931 (2012 January 5) and the start of default TTE mode operation of the Fermi GBM at MJD 56257 (2012 November 26). The shaded bands coincide with data gaps due to observational constraints for either RXTE or Swift.

The rotation is illustrated in Figure 1. For each of the selected epochs, the best fit model is found by maximizing the signal-to-noise ratio of the phased data for the given epoch t₀ and the pulse phase Φ. The model parameters e.g. those from a previous coherent solution, the scheme converges to the global maximum of Z². We applied this method to the Swift XRT observations taken between MJD 56338–56966 (2013 February 15 – 2014 November 5; ending just before the 2014–2015 data gap), for which an equivalent ToA-based ephemeris exists (see Archibald et al. 2015, Table 1; second solution). The solution is shown in Table 1 as entry 8, and the parame-
ters are fully consistent with those shown in Archibald et al. (2015).
In this manner we extended the phase-coherent ephemerides set of
PSR J1846–0258 with two new (partially overlapping) entries by adding
Swift XRT observations from 2015 February 25 to 2016
September 4 (Table 1 entries 9 and 10). It was also possible to phase
connect across the 2014–2015 and 2015–2016 data gaps.

In Table 1 all phase-coherent post-outburst ephemerides of
PSR J1846–0258 are summarized, valid from MJD 54340 up to
57635 (2007 August 28 – 2016 September 4). The RMS column
indicates the mean deviation of the model and data (in phase unit)
for the ($\chi^2$-based) ToA methods, whereas the phase-zero, $\Phi_0$, column
specifies the offset value to be applied to the phase calculation
(see equation 1) of every selected event to obtain consistent align-
ment with the master template.

A graphical representation of the evolution of the rotation fre-
quency of PSR J1846–0258 since its discovery with respect to the
last pre-outburst ephemeris is shown in Fig. 1. RXTE and Swift data
gaps are indicated by shaded vertical bands, whereas some impor-
tant dates for this analysis are shown as solid (start nominal Fermi
science operations), dashed-dotted (decommissioning of RXTE) and
dashed (start Fermi GBM TTE data taking mode) lines. The loss
of phase coherence between MJD 56185 and 56338 during the
Swift XRT monitoring period is clearly visible in this plot (note
that Fermi GBM starts in this period its TTE data taking mode). It
is also clear that the post-outburst spin behaviour, while smoothly
evolving, is not recovering to its pre-outburst characteristics, indi-
cating permanent changes in the rotation behaviour after the 2006
June outburst/glitch.

3.1.3 Verification of the phase-coherent timing models using
INTEGRAL ISGRI and Fermi GBM

We cross checked the validity of the RXTE PCA and Swift XRT
based ephemerides listed in Table 1 by making pulse-phase dis-
tributions through pulse-phase folding the selected PCA or XRT
events i.e. converting the event barycentered arrival time $t$ to pulse-
phase $\Phi$ according to

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

(1)

and subsequently sorting the pulse-phases in histograms (see e.g.
the Swift XRT pulse-phase histogram in the top panel of Fig. 6 for energies between 2.5 and 10 keV combining all available data).

However, in this procedure we use exactly the same win-
dow function, reflecting the observation time-line of the source for
the involved instrument, as used in the generation of the models
and so hidden inconsistencies could still be present. Therefore, we
searched for independent data taken by high-energy instruments on
different spacecrafts using a completely different observation time-
line.

For this purpose we have used INTEGRAL ISGRI data col-
lected on PSR J1846–0258 during the 2008–2015 period (cover-
ing INTEGRAL revolutions 655 – 1611; 2008 February 23 – 2015
November 18)\(^3\), and the (continuous) all-sky GBM NaI detectors aboard Fermi for the period 2012 November 26 – 2016 September
4. The observation log details for the INTEGRAL observations used
in this work are shown in Table 2.

The folding results of post-outburst ISGRI data (20–150 keV)
for the 2008–2011 (using RXTE based entries 2–6 of Table 1) and

\(^3\) During 2016 and up to 2016 December 6, no INTEGRAL observations
have been performed with PSR J1846–0258 within 14\(^\circ\)5 from the pointing axis.

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### Table 2. Characteristics of INTEGRAL observations of PSR J1846–0258 for the 2008–2016 period

| Revs. | Date begin | Date end | MJD | GTI\(^a\) exposure (Ms) | Effective\(^b\) exposure (Ms) | # Scw\(^c\) |
|-------|------------|----------|-----|------------------------|-----------------------------|----------|
|       |            |          |     |                        |                             |          |
|       |            |          |     |                        |                             |          |
|       |            |          |     |                        |                             |          |
|       |            |          |     |                        |                             |          |
|       |            |          |     |                        |                             |          |
|       |            |          |     |                        |                             |          |

Post-outburst observations: 2008–2011

|       | 0655-0741 | 23-01-2008 | 07-11-2008 | 54488-54777 | 1.7926 | 0.7265 | 759 |
|-------|-----------|------------|-----------|-------------|--------|--------|-----|
|       | 0782-0865 | 10-03-2009 | 13-11-2009 | 54900-55148 | 1.6514 | 1.0019 | 849 |
|       | 0899-0988 | 22-02-2010 | 17-11-2010 | 55249-55517 | 1.3718 | 0.8727 | 648 |
|       | 1025-1106 | 06-03-2011 | 03-11-2011 | 55626-55868 | 0.7924 | 0.2831 | 334 |

Post-outburst observations: 2012–2015

|       | 1145-1235 | 29-02-2012 | 24-11-2012 | 55986-56255 | 0.8281 | 0.3499 | 432 |
|-------|-----------|------------|-----------|-------------|--------|--------|-----|
|       | 1265-1351 | 22-02-2013 | 08-11-2013 | 56345-56604 | 0.9050 | 0.4327 | 406 |
|       | 1386-1480 | 20-02-2014 | 29-11-2014 | 56708-56990 | 1.0170 | 0.5802 | 382 |
|       | 1508-1611 | 16-02-2015 | 18-11-2015 | 57069-57344 | 0.9055 | 0.5092 | 420 |

Post-outburst observations: 2008–2015

|       | 0655-1611 | 23-01-2008 | 18-11-2015 | 54488-57344 | 9.2638 | 4.7562 | 4230 |

Notes. \(^a\) Total Good-Time-Interval exposure of the used observations
\(^b\) Effective exposure on PSR J1846–0258 corrected for off-axis sensitivity reduction
\(^c\) Number of used Science Windows, see Sect. 2.3
2012–2015 (using Swift based entries 7–10 of Table 1) epochs are shown in the middle and lower panels of Fig. 2, respectively. The top panel of Fig. 2 is adapted from Fig. 3 of Kuiper & Hermsen (2009) and refers to the pre-outburst ISGRI lightcurve. It is clear from this graph that the basic (aligned) structure of the pulse-profile of PSR J1846–0258 is clearly reconstructed in the folding process for the 2008–2011 post-outburst epoch, proving the validity of ephemerides entries 2–6 of Table 1. However, the measured pulsed-signal significance $Z_2^1$ of 5.9σ is lower than expected (c.f. the pre-outburst pulse-profile shown in the top panel of Fig. 2) has a 9.6σ significance for an effective exposure of 2.9797 Ms comparable to the 2008–2011 post-outburst value of 2.8842 Ms. This is partially due to an increased background level for the 2008–2011 set of mosaicked/combined observation pointings, which differs from the pre-outburst one.

We investigated the $Z_2^2$-test statistics of the 2008-2011 post-outburst and 2003–2006 pre-outburst epochs further by simulating pulse-phase distributions for the 20–150 keV band adopting various input strengths for the pulsed signal superposed on a (huge) dominating flat background. It turns out that, assuming a constant pulsed signal strength during the 2003–2006 and 2008–2011 epochs, a ‘genuine’ (parent) pulsed flux of $\sim 85\%$ of the measured 2003–2006 epoch flux (i.e. just $1.5\sigma$ lower than measured) can statistically just explain both the 9.6σ and 5.9σ $Z_2^1$-measured values for the 2003–2006 (in the positive tail of the $Z_2^2$ distribution) and 2008–2011 (in the negative tail of the $Z_2^2$ distribution) epochs, respectively. Therefore, time variability (flux reduction during the first post-outburst epoch) of the 20–150 keV pulsed flux can statistically not be claimed.

For the second epoch, 2012–2015, employing only Swift XRT based ephemerides, the shape consistency and alignment of the 20–150 keV ISGRI profile (see bottom panel of Fig. 2) demonstrates the likely validity of the used ephemerides (entries 7–9 of Table 1). However, the achieved pulsed-signal significance of merely $\sim 2.4\sigma$ is again (much) lower than expected, even when taking into account the considerably reduced effective exposure time on PSR J1846–0258 of 1.872 Ms for this epoch compared to the earlier epochs. In this case simulations demonstrate that the 20–150 keV pulsed flux should be $\lesssim 60\%$ of the measured pre-outburst flux to explain the small $Z_2^2$ significance of 2.4σ. This would indicate that the pulsed hard X-ray/soft γ-ray emission has faded during the post-outburst period. A deeper study on this issue other high-energy instruments like Swift BAT, Fermi GBM or NuSTAR, is required, but this is outside the scope of this work.

Fortunately, for the 2012–2015 epoch Fermi GBM TTE data have come available as of 2012 November 26, providing another way to validate the timing models. We have used in the event folding procedure only TTE data from the twelve NaI-detectors, which have been collected for the 12 NaI-detectors. Since we are not dealing with imaging detectors, event selections can only be made on observational conditions like imposing constraints on the following: a) source - detector pointing angle $\alpha$; b) Earth zenith - detector pointing angle $\zeta$; c) Source - Earth zenith angle $\Psi$ and the period when the spacecraft is within/around the South Atlantic Anomaly (SAA).

In this work we applied the following maximum angles of $58^\circ$, $128^\circ$ and $105^\circ$ for selection on $\alpha$, $\zeta$ and $\Psi$, respectively. The values for the first two maximum angles, valid for energies between $\sim 12 – 100$ keV, have been determined using (CTIME) data on high-mass X-ray binary pulsar Her X-1 as ‘calibration’ source. Above $\sim 100$ keV the source - detector pointing angle $\alpha$ widens up to $84^\circ$. The maximum value for the $\Psi$ angle ensures that the source is never blocked by the Earth disc which has an angular extension of about $70^\circ$ as viewed from the orbit of the spacecraft. Finally, we extended the anticipated SAA duration by $\pm 300$ s at egress and ingress to avoid further periods of background activation.

Because the full 2µs time resolution is not necessary, given the pulse period of $P \sim 328$ ms of PSR J1846–0258, to speed up the barycentering process we first produce lightcurves (counts versus TT time) in 10 ms bins for each of the 128 spectral channels of each NaI detector and convert these lightcurve TT (mid bin) times to TDB times, and these subsequently to pulse-phases. We have used data from the twelve Sodium Iodide detectors, which have been collected for Fermi mission weeks 246–430 i.e. MJD 56337–57631; 2013 February 14 – 2016 August 31. The total GBM (NaI detectors) exposure with PSR J1846–0258 in the field of view under the applied observational constraints is, averaged per detector, 19,689 Ms (32.6 weeks equivalent).

The folding process using (Swift XRT based) ephemerides 7–10 (see Table 1) yielded the phase-distribution (10 bins per cycle) shown in Fig. 3. The expected profile shape and alignment

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Figure 2. Pulse profiles of PSR J1846–0258 for the 20–150 keV band as measured by INTEGRAL ISGRI during the pre-outburst epoch (2003–2006; upper panel; see fig. 3 of Kuiper & Hermsen 2009) and two different post-outburst epochs (middle panel, 2008–2011; lower panel, 2012–2015) analysed in this work.
Figure 3. Pulse profiles of PSR J1846–0258 as measured by the twelve Fermi GBM NaI detectors in three energy bands: 20-100 keV (top), 100-300 keV (middle) and 20-300 keV (bottom). Data collected during mission weeks 246–430 (MJD 56337–57631; 2013 February 14 – 2016 August 31) has been used in the folding process. The $Z^2_2$ significances are $6.4\sigma$, $4.2\sigma$ and $7.6\sigma$ for the distributions shown in the top, middle and bottom panels, respectively.

of PSR J1846–0258 is nicely revealed in this plot, yielding for the first time even a significant detection in the 100–300 keV band of $4.2\sigma$ applying a $Z^2_2$ test. These results prove the validity of the Swift XRT based ephemerides 7–10 listed in Table 1.

4 Fermi LAT Timing and Spectral Results

The validity of the newly generated timing models paved the way to proceed with a timing analysis of the Fermi LAT high-energy $\gamma$-ray (>30 MeV) data. For this purpose we downloaded all Pass-8 Fermi LAT (see e.g. Atwood et al. 2013a,b; Laffon et al. 2015) events registered since the start of the nominal Fermi science operations at 2008 August 4 till 2016 September 1 (MJD 54682.75–57632) from a circular Region-of-Interest (ROI) of radius 11° around PSR J1846–0258. The events were barycentered using Fermi tool gtbary selecting the DE200 Solar system ephemeris file and adopting the Chandra X-ray position of PSR J1846–0258 (Helfand et al. 2003) as best location. Next, in the event selection process using Fermi tool gtselect we applied for the source analysis the following filters on source class and type of evclass = 128 and etype = 3, respectively, as recommended for Pass 8 LAT data analysis. Also, a maximum Earth Zenith angle $\zeta_{\text{max,Earth}}$ of 105° was allowed for every event arrival direction.

4.1 LAT timing

In the LAT timing analysis we further selected only events from within an energy-dependent acceptation cone $\Theta_{68\%}(E)$

Figure 4. Pulse profiles of PSR J1846–0258 as measured by Fermi LAT in two different energy bands, 30–100 MeV (top panel) and > 100 MeV (bottom panel). Significant pulsed emission at 4.2$\sigma$ confidence level has been detected in the 30–100 MeV band.

Figure 5. The evolution of the pulsed signal strength of PSR J1846–0258 in the LAT 30–100 MeV band using a stepsize of about 327 d. The dashed lines indicate the 3, 4 and 5$\sigma$ single trial confidence levels, from the bottom to top, respectively. The pulsed signal, $Z^2_1$, gradually reached a $\sim 4.2\sigma$ significance in a linear way as expected for a constant pulsed fraction.
around PSR J1846–0258 according to the average of the Pass 8 FRONT+BACK event type point spread functions (PSF), containing 68% of source counts from a point-source\(^5\). To further suppress in our sample events possibly coming from the Earth disc, which is mainly effective for events with energies below 100 MeV because of the broad PSF (larger than 10° for \(E \lesssim 50\) MeV), we applied an energy dependent Earth zenith selection according to \(\Omega_{\text{Earth}}(E) = \frac{\sigma_{\max}(E)}{\sigma_{\max}} - \cdot \Theta_{\text{Earth}}(E)\) with \(\sigma_{\max} = 2\).

Next, we sorted the events in two broad energy bands, 30–100 MeV and >100 MeV, and folded the barycentric arrival times of the selected events on the timing models shown in Table 1. Events falling within MJD 56185–56338, where phase coherence was lost, were excluded in the folding process.

The resulting pulse-phase distributions for the 30–100 MeV and >100 MeV bands are shown in Fig. 4. The 30–100 MeV pulse phase distribution, shown in the top panel of Fig. 4, deviates from uniformity, applying a \(Z_1^2\)-test, at a 4.2\(\sigma\) confidence level, representing thus the first detection (single trial) of pulsed emission from PSR J1846–0258 at high-energy \(\gamma\)-rays. Above 100 MeV (bottom panel of Fig. 4), the distribution is consistent with being uniform. This behaviour is in line with expectations if the spectral characteristics of PSR J1846–0258 are similar to those of the ‘canonical’ soft \(\gamma\)-ray pulsar PSR B1509–58 which yielded a very soft spectrum for energies above 30 MeV (Kuiper \& Hermsen 2015). It does not support a flat spectral shape (power-law index \(\sim -2\)) at high-energy gamma rays till a break at GeV energies as measured for PSR J1119–6127.

We investigated the evolution of the pulsed signal strength in the 30–100 MeV band as a function of integration time (see Fig. 5). We see a gradual linearly build-up of the pulsed signal \(\hat{\varepsilon}\) is expected for a genuine pulsed signal with a (nearly) constant pulsed fraction, because the following relation holds (de Jager 1987): \(Z_1^2(t) = (N_{\text{tot}}(t) - 1) \cdot \hat{\varepsilon}^2 + 2\), with \(\hat{\varepsilon} = N_{\text{pul}}(t)/N_{\text{tot}}(t)\) the pulsed fraction uncorrected for background, \(N_{\text{tot}}(t)\) the total number of selected events within the acceptance cone (= total number of events from PSR J1846–0258 plus events from the dominating, mainly celestial, background) as a function of time and finally \(N_{\text{pul}}(t)\) the number of pulsed counts from PSR J1846–0258 within the acceptance cone as a function of time.

From the Swift XRT (soft X-rays), Fermi GBM (hard X-rays/soft \(\gamma\)-rays) and Fermi LAT (\(\gamma\)-rays; 30–100 MeV) data we

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**Table 3.** Fermi LAT (Pass8) pulsed excess counts, exposure and pulsed flux values of PSR J1846–0258 and PSR B1509–58 for different energy bands.

| \(E_{\text{min}}\) (MeV) | \(E_{\text{max}}\) (MeV) | Pulsed Counts | \(T_{\text{exp}}\) (cm\(^2\) s) | Pulsed Flux (photons cm\(^{-2}\) s\(^{-1}\) MeV\(^{-1}\)) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(30\)          | \(100\)         | \(-3.13\)       | \(2.43305 \times 10^{10}\) | \(3.91 \pm 0.97 \times 10^{-9}\) |
| \(100\)         | \(1000\)        | \(-4.48\)       | \(1.20448 \times 10^{11}\) | \(0.34 \pm 1.28 \times 10^{-11}\) |
| \(30\)          | \(50\)          | \(-2.92\)       | \(1.80564 \times 10^{10}\) | \(2.89 \pm 0.36 \times 10^{-8}\) |
| \(50\)          | \(70\)          | \(-3.14\)       | \(4.49307 \times 10^{10}\) | \(8.13 \pm 1.00 \times 10^{-9}\) |
| \(70\)          | \(100\)         | \(-3.34\)       | \(7.81444 \times 10^{10}\) | \(2.68 \pm 0.34 \times 10^{-9}\) |
| \(100\)         | \(150\)         | \(-3.58\)       | \(1.27078 \times 10^{11}\) | \(8.79 \pm 1.15 \times 10^{-10}\) |
| \(150\)         | \(300\)         | \(-3.99\)       | \(1.92914 \times 10^{11}\) | \(2.09 \pm 0.25 \times 10^{-10}\) |
| \(300\)         | \(500\)         | \(-4.50\)       | \(2.66704 \times 10^{11}\) | \(2.27 \pm 0.72 \times 10^{-11}\) |
| \(500\)         | \(1000\)        | \(-5.13\)       | \(3.18729 \times 10^{11}\) | \(0.22 \pm 0.17 \times 10^{-11}\) |
| \(1000\)        | \(10000\)       | \(-7.51\)       | \(3.75161 \times 10^{12}\) | \(6.33 \pm 3.86 \times 10^{-14}\) |

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\(5\) For more details, see http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LATJRFs/IRF_PSF.html
compiled a pulse-profile collage showing the shape of PSR J1846–0258 as a function of energy (see Fig. 6). In this figure, the best-fitting INTEGRAL ISGRI profile (20–150 keV; see e.g. panel a of Fig. 2 and figure 3 of Kuiper & Hermsen 2009) is superposed. There is no evidence for morphology changes of the profile as a function of energy across the energy band $\sim 2.5$ keV - 100 MeV.

4.2 LAT PSR J1846–0258 pulsed-flux determination

Because the pulsed signal from PSR J1846–0258 is detected only in a narrow bandpass below 100 MeV a detailed characterization of the high-energy $\gamma$-ray spectrum is impossible. We can, however, estimate the 30–100 MeV pulsed photon flux of PSR J1846–0258 from the measured 30–100 MeV (pulsed) excess counts $N_p$ (i.e. pulsed counts above flat background; see Fig. 6c) and the LAT exposure $T_{\text{exp}}$ for the 30–100 MeV band assuming a certain photon spectral index across this band.

For the pulsed excess counts we derived a value of $4545 \pm 1125$ fitting a pre-defined pulse shape, the ISGRI 20-150 keV shape (cf. Fig. 3 of Kuiper & Hermsen 2009), to the measured 30–100 MeV pulse-phase histogram (see Fig. 6c). These counts have been accumulated across the MJD 54682.75–57632 period, excluding time interval MJD 56185-56338 for which phase coherence was lost.

The second quantity, $T_{\text{exp}}$, has been determined using Fermi analysis tool gtcountr, setting P8R2 SOURCE V6 as reference to instrument (Pass-8) response functions and adopting for the weighting of the exposure as a function of energy across the 30–100 MeV photon spectral index of $-3.13$. This index is consistent with the value earlier derived for PSR B1509–58 and confirmed for PSR B1509–58 and PSR J1846–0258 below in the fits to their broad-band spectra (see Section 4.2.2). The gtcountr tool also requires a counts lightcurve which has been prepared by gtbins adopting a bin size of $\frac{1}{4}$ day. We ended up with an exposure $T_{\text{exp}}$ of $2.43305 \times 10^{10}$ cm$^2$s for the 30–100 MeV band across the MJD 54682.75–57632 period (excl. MJD 56185-56338).

Now, all ingredients are available to calculate the pulsed flux, $F_{\gamma}$, from $F_{\gamma} = (N_p/f_{1\sigma}) \cdot (1/T_{\text{exp}}) \cdot (1/(E_+ - E_-))$, in which $1/f_{1\sigma}$ represents the correction factor for the (missing) flux outside the Pass-8 1$\sigma$ source-acceptance cone ($f_{1\sigma} = 0.6827$), and $E_+$ and $E_-$ represent the lower- and upper-bounds of the energy band, respectively. The resulting pulsed flux values for PSR J1846–0258 are listed in Table 3 along with those derived for PSR B1509–58 (see Section 4.2.1).

4.2.1 LAT PSR B1509–58 pulsed-fluxes revisited

The availability of Fermi LAT Pass-8 data, and the greatly increased exposure time of about 7.4 yr on the soft $\gamma$-ray pulsar PSR B1509–58 triggered us to revisit the high-energy pulsed gamma-ray emission of PSR B1509–58. This offers a verification of the earlier published results for PSR B1509–58 and allows a comparison with the derived characteristics of PSR J1846–0258 using for both Pass-8 data and response parameters. The latest $\gamma$-ray spectral results for PSR B1509–58 were published by Kuiper & Hermsen (2015) using Pass-7 LAT data and a data-collecting period of 3.4 yr. They obtained a 10.2$\sigma$ pulsed signal for photons with energies between 30 and 1000 MeV. Now, using Pass-8 data and a 7.4 yr data-collection period yields a 28.7$\sigma$ pulsed signal for the 30–100 MeV band applying appropriate and up-to-date X-ray/radio based ephemerides (see Table 4) in the timing analysis. This dramatic improvement in sensitivity makes a detailed study in differential energy bands possible. Fig. 7 shows the (Pass-8) LAT pulse profiles for four different energy bands: 30–100 MeV, 100–300 MeV, 300–1000 MeV and $> 1$ GeV, yielding pulsed signal significances ($Z^2_2$-test) of 19.5$\sigma$, 18.8$\sigma$, 5.5$\sigma$ and $< 1$ $\sigma$, respectively. Pulsed emission has been detected up to $\sim 500$ MeV!

From the pulse-phase distributions - in even smaller energy bands - we derived pulsed excess counts by subtracting the ‘un-pulsed’ level, estimated in phase interval 0.7–1.2, from the counts collected in the ‘pulsed’ phase interval covering 0.2–0.7. The derived excess counts were converted to pulsed fluxes analogous to the method employed for PSR J1846–0258, as outlined in Section 4.2. The resulting pulsed fluxes are given in Table 3.
4.2.2 Broad-band spectra of the pulsed emission of PSR J1846–0258 and PSR B1509–58

The newly derived Fermi LAT (Pass-8) pulsed-flux values for PSR J1846–0258 and PSR B1509–58 (see Table 3) are plotted in Fig. 8 as green- and purple data points (filled squares), respectively, along with pulsed flux measurements derived at lower energies (see Kuiper & Hermsen 2015, for the latter values). We fitted the broad-band pulsed emission spectra of both PSR J1846–0258 and PSR B1509–58 with a model (see Section 5.7 of Kuiper & Hermsen 2015) with the following \( E_\gamma \) dependence:

\[
F_\gamma = k \cdot \left(\frac{E_\gamma}{E_0}\right)^\beta \cdot \exp(-\left(\frac{E_\gamma}{E_c}\right)^\gamma) \tag{2}
\]

The normalization energy \( E_0 \), which minimizes the correlation between the four fit parameters, was 0.024306 MeV for the PSR J1846–0258 spectral data set. The best-fitting values were \( k = (2.05 \pm 0.03) \times 10^{-2} \) ph cm\(^{-2}\) s\(^{-1}\) MeV\(^{-1}\); \( \Gamma = -0.932 \pm 0.015; \)

\( E_c = 0.0087 \pm 0.0006 \) MeV and \( \beta = 0.245 \pm 0.007 \). For these model parameters (and uncertainties in these) the maximum luminosity of the pulsed emission of PSR J1846–0258 is reached at \( E_\gamma^{\text{max}} = E_c \cdot \left(\frac{E_\gamma}{E_c}\right)^\beta \approx 3.5 \pm 1.1 \) MeV.

The best-fitting model parameters for PSR B1509–58 were \( k = (4.81 \pm 0.03) \times 10^{-2} \) ph cm\(^{-2}\) s\(^{-1}\) MeV\(^{-1}\); \( \Gamma = -1.067 \pm 0.003; \)

\( E_c = 0.00234 \pm 0.00004 \) MeV and \( \beta = 0.2144 \pm 0.0008 \), whereas \( E_0 \) was 0.105745 MeV. This results in a \( E_\gamma^{\text{max}} \) value of 2.23 \pm 0.11 MeV, consistent with the value of \( \sim 2.5 \) MeV given in Kuiper & Hermsen (2015) and 2.6 \pm 0.8 MeV by Chen et al. (2016), who included an accurate spectrum up to \( \sim 79 \) keV analysing NuSTAR data. The best-fitting models are also superposed in Fig. 8 as green (PSR J1846–0258) and purple (PSR B1509–58) solid lines. Their shapes are remarkably similar. It is clear that both pulsars reach their maximum luminosities in the MeV band.

Comparing fig. 7 of Kuiper & Hermsen (2015) with Fig. 8 of this work it is evident that the statistical quality of the LAT pulsed flux measurements of PSR B1509–58 drastically improved, going from Pass 7 to Pass 8, and more than doubling the exposure time.

5 SUMMARY

For our successful attempt to detect and characterize the pulsed signal of the radio-quiet magnetar-like pulsar PSR J1846–0258 in the high-energy \( \gamma \)-ray data of Fermi LAT, we first had to construct an ephemeris using its pulsed X-ray emission. This complex initial step was crucial for obtaining our results.

Table 4. Phase-coherent X-ray (PCA)/radio ephemeris for PSR B1509–58 covering the time period MJD 54626–57372 (2008 June 9 – 2015 December 16). Solar system planetary ephemeris DE200 adopted.

| Entry | Start [MJD] | End [MJD] | \( t_0 \), Epoch [MJD,TDB] | \( \nu \) [Hz] | \( \nu \times 10^{-11} \) Hz s\(^{-1}\) | \( \nu \times 10^{-21} \) Hz s\(^{-2}\) | \( \Phi_0 \) | Validity range (days) |
|-------|------------|-----------|--------------------------|-------------|------------------------|------------------------|--------|------------------|
| 1     | 54626      | 55075     | 54626.0                  | 6.601 176 760 (2)(3) | -6.664 902 (3) | 1.969 (2) | 0.4573 | 450              |
| 2     | 55075      | 55465     | 55075.0                  | 6.598 592 680 (2)(3) | -6.657 350 (3) | 1.884 (2) | 0.0151 | 391              |
| 3     | 55465      | 55927     | 55465.0                  | 6.596 350 488 (4)(4) | -6.650 918 (4) | 1.885 (2) | 0.4970 | 463              |
| 4     | 55939      | 56376     | 56157.0                  | 6.592 377 363 (5)   | -6.639 61 (2)  | 1.88 (7)  | 0.3375 | 399              |
| 5     | 56310      | 56708     | 56509.0                  | 6.590 588 953 (4)   | -6.633 84 (3)  | 1.88 (10) | 0.1454 | 412              |
| 6     | 56760      | 57081     | 56876.0                  | 6.588 256 398 (3)   | -6.627 83 (3)  | 1.94 (11) | 0.3758 | 438              |
| 7     | 57013      | 57372     | 57192.0                  | 6.586 447 550 (4)   | -6.622 67 (4)  | 1.89 (16) | 0.7781 | 360              |

Figure 8. The high-energy pulsed emission spectra of PSR J1846–0258 (green symbols/dashed line) and PSR B1509–58 (purple symbols/solid line) from \( \sim 2.5 \) keV up to \( \sim 1000 \) MeV. For comparison also the pulsed spectra of the Crab (red) and Vela (blue; the strongest high-energy \( \gamma \)-ray source) pulsars are shown. The \( \gamma \)-ray spectra of three other high B-field pulsars are superposed: PSR J1119–6127 (orange), PSR J1124–5916 (dark-orange/red) and PSR J1208–6238 (yellow). The total (pulsed plus unaltered) X-ray spectra based on XMM-Newton data of PSR J1119–6127 (data points/dashed line) and PSR J1124–5916 are shown as well. The pulsed (thermal) component of PSR J1119–6127 is superposed as a solid orange line.

(1) We succeeded in producing phase-coherent timing models exploiting RXTE PCA and Swift XRT monitoring data for the post-outburst period from 2007 August 28 (MJD 54340) to 2016 September 4 (MJD 57635) (see Table 1). The smoothly evolving post-outburst spin behaviour is not recovering to its pre-outburst characteristics, indicating permanent changes in the rotation behaviour after the 2006 outburst/glitch (Fig. 1).

(2) Independent verification of the ephemerides was obtained using INTEGRAL ISGRI and Fermi GBM data by making pulse-phase distributions through phase folding selected ISGRI (20–150 keV) and/or GBM (20–300 keV) events, accumulating over long time intervals (2008 February 23 – 2016 September 4, and 2013...
February 14 – 2016 August 31, respectively). The constructed broad pulse profiles were identical in shape as measured post outburst by RXTE PCA and Swift XRT and by INTEGRAL ISGRI during the pre-outburst epoch (2003–2006), confirming the correctness of the ephemerides (Figs 2 and 3).

(3) Interestingly, we found in the multi-year INTEGRAL ISGRI data an indication for fading of the pulsed hard X-ray/soft γ-ray emission during the post-outburst epoch (see Sect. 3.1.3).

(4) Taking advantage of the increased sensitivity of Fermi LAT by using Pass-8 data, and phase folding barycentric arrival times of selected events with the ephemerides produced in this work, we obtained a 4.2σ detection of a pulsed signal for energies 30–100 MeV, with a pulse consistent in shape and aligned in phase with the profiles measured at lower energies, e.g. Swift XRT (2.5–10 keV), INTEGRAL ISGRI (20–150 keV) and Fermi GBM (20–300 keV) (Fig. 6). The flux (30–100 MeV) of the broad pulse is (3.91 ± 0.97) × 10−9 photons cm−2 s−1 MeV−1.

(5) For energies above 100 MeV the γ-ray pulse could not be detected, indicative for a very soft spectral shape at high-energy γ-rays.

(6) We rederived the timing and spectral characteristics of PSR B1509–58 at high-energy γ-rays, exploiting the increased sensitivity of Pass-8 data and the greatly increased Fermi LAT exposure time (collected over about 7.4 yr), compared to our earlier report on this pulsar in Kuiper & Hermsen (2015). The shape of the published broad pulse profile and high-energy spectrum have been confirmed with greatly improved statistics (Fig. 7 and Table 3, respectively).

(7) The broad-band pulsed emission spectra (from 2 keV up to Fermi energies) of PSR J1846–0258 and PSR B1509–58 can both be accurately described with similarly curved shapes with a photon energy, $E_\gamma$, dependence as given in equation (2) (Section 4.2.2 and Fig. 8). For the best-fitting parameters, the maximum luminosity of the pulsed emission of PSR J1846–0258 is reached at 3.5 ± 1.1 MeV and for PSR B1509–58 at 2.23 ± 0.11 MeV.

6 DISCUSSION

Table 5 lists all high-magnetic-field rotation-powered pulsars with characteristic age $\lesssim 3$ ky detected by Fermi LAT. The five γ-ray pulsars listed, have rather similar rotation (and derived) characteristics, but exhibit very different characteristics at γ-ray energies. PSR J1119–6127, PSR J1124–5916 (Camilo et al. 2002) and PSR J1208–6238 (Clark et al. 2016) show two pulses in their γ-ray pulse profiles and reach their maximum luminosities in the GeV band, like most of the pulsars in the Fermi pulsar catalog. In this discussion we call these pulsars 'GeV pulsars'. On the other hand, PSR B1509–58 and PSR J1846–0258 have single broad γ-ray pulses and reach their maximum luminosities at low-energy γ-rays. These pulsars we call 'MeV pulsars'.

Interestingly, the two magnetar-like rotation-powered pulsars PSR J1119–6127 and PSR J1846–0258, looking like twins in their rotational parameters, appear to be widely different at X-rays and high-energy γ-rays. Fig. 8 shows the broad-band (pulsed-emission for PSR J1846–0258 and PSR B1509–58) spectra of all five pulsars in comparison with those of the Crab and Vela pulsars. PSR J1119–6127, PSR J1124–5916 and PSR J1208–6238 with their weak emissions at X-rays (PSR J1208–6238 not yet detected), exhibit broad-band spectra more similar to that of Vela, than that of the Crab. PSR J1846–0258 is now the second pulsar, after PSR B1509–58, shown to reach maximum luminosity at MeV energies by measuring its broad-band spectrum into the Fermi LAT band of high-energy γ-rays.

Kuiper & Hermsen (2015) presented the soft γ-ray pulsar catalog containing 18 non-recycled rotation-powered pulsars from which non-thermal pulsed emission has been securely detected at hard X-rays/soft γ-rays above 20 keV. The majority (11 members) exhibits broad, structured single-pulse profiles at soft γ-rays, like PSR J1846–0258 and PSR B1509–58 and 15 show hard power-law spectra in the hard X-ray band. PSR B1509–58 being the exception, Fermi LAT had not yet detected the pulsed emission from the remaining 14. Given the high sensitivity of the LAT above 100 MeV, it was concluded that these 14 pulsars, including PSR J1846–0258, also had to reach their maximum luminosities typically at MeV energies. Interestingly, the soft γ-rays are all fast rotators and on average an order of magnitude younger and ∼ 40 times more energetic than the Fermi LAT sample, suggesting that we are dealing with a special subset of high-energy rotation-powered pulsars. This makes it particularly interesting to decisively establish their manifestation as MeV pulsars. For PSR J1846–0258 this has been succeeded in this work.

There is still no consensus on the physics behind the deviant curved broad-band spectral shape of the MeV pulsars. This has been extensively discussed for PSR B1509–58 after the broadband high-energy spectrum was revealed by the instruments aboard the Compton Gamma-Ray Observatory (CGRO), summarized in Kuiper et al. (1999). In the latter paper, the firm detection of pulsed emission at MeV energies by CGRO COMPTEL was reported, together with low upper limits/weak detections with CGRO EGRET below 100 MeV. Harding, Baring & Gonthier (1997) proposed for the Polar Cap (PC) model, where the gamma rays are produced near the stellar surface, the quantum electrodynamic process of magnetic photon splitting, as an explanation for the apparent lack of detection at GeV energies. This process becomes important when the pulsar magnetic field near the surface approaches the quantum critical value $B_{\text{cr}} = 4.41 \times 10^{12}$ G. They concluded that photon splitting, or combined splitting and pair production, can explain the broad-band spectrum of PSR B1509–58 with the unusually low cutoff energy. Alternatively, Zhang & Cheng (2000) reproduced the cutoff in the high-energy spectrum as well as the broad pulse profile of PSR B1509–58 in the context of the Outer Gap model (OG) model, where the γ-ray radiation comes from the outer magnetosphere. The non-thermal photons are emitted by e± pairs produced by back-flow charged particles from the OG through synchrotron radiation mechanism near the stellar surface and in a finite region just above the OG through a synchrotron self-Compton mechanism.

The broad-band spectral shape of PSR B1509–58 as presented by Kuiper et al. (1999) was confirmed by Pilia et al. (2010) and Abdo et al. (2010) using the next-generation of gamma-ray instruments AGILE and Fermi, respectively. Abdo et al. (2010) used only 1 yr of survey data with Fermi LAT and detected the pulsed signal of PSR B1509–58 at the 3σ level in the energy intervals 30–100 MeV and 100–300 MeV. This was obviously a small fraction of the 7.4 years of survey data used in this work. Kuiper et al. (1999), Pilia et al. (2010) and Abdo et al. (2010) extensively discuss OG, Slot Gap and PC scenarios (see references therein) to explain the spectral and temporal characteristics of PSR B1509–58 and conclude for example, that the PC model including photon splitting is spectrally similar, but subject to the strong constraint of emission at the magnetic co-latitude of the rim, i.e. $\sim 2^\circ$ as proposed by Kuiper et al. (1999).

More recently, Wang, Takata & Cheng (2013) proposed a new version of the OG model to successfully explain the characteris-

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tics of PSR B1509–58. They explain that most pairs created in the
OG are created around the null charge surface and the gap’s elec-
tric field separates the two charges to move in opposite directions.
The region towards the light cylinder is dominated by the outflow
current, producing curvature radiation as measured from the Fermi
LAT GeV pulsars. The region towards the neutron star is domi-
nated by the inflow radiation, in which magnetic pair creation con-
verts curvature photons into pairs by the strong magnetic field. The
hard X-rays and soft gamma rays of PSR B1509–58 result from
synchrotron radiation of these pairs. They argue that the observer
viewing angle measured from the rotation axis is smaller than (or
close to) the inclination angle of the magnetic axis. For this ge-
ometry, the outward GeV emissions are missed by the observer, while
the inward emissions are observed.

In a follow-up paper Wang et al. (2014) applied this scenario
to four young pulsars, including PSR J1846–0258 with PSR J1617–5055, PSR J1811–1925 and PSR J1930+1852. These form
a subset of a preliminary version of the soft γ-ray pulsar cata-
ologue (Kuiper & Hermsen 2015) and share some emission prop-
erties with PSR B1509–58: (1) their radio emissions are dim or
quiet; (2) the pulse profile in X-rays/soft γ-rays is described by
a single broad profile; (3) no GeV emissions have been detected;
(4) the broad-band spectral shape suggests that they are all MeV
pulsars. Wang et al. (2014) underlined that the viewing geometry
is a crucial factor to discriminate between the normal GeV pul-
sars and the MeV pulsars. Furthermore, the magnetic inclination
angle of the MeV pulsars is relatively small, α ≲ 30°. For all
four pulsars, including PSR J1846–0258, and for PSR B1509–58
(Wang, Takata & Cheng 2013), broad-band spectra and pulse pro-
files were calculated that match the observed characteristics.

As we mentioned above, in the hard X-ray/soft γ-ray pulsar cata-
ologue (Kuiper & Hermsen 2015), the number of (candidate)
MeV pulsars has increased to eleven, constituting a fraction of
about 60%. This underlines the importance of understanding the
physics behind this manifestation: Are we seeing GeV and MeV
pulsars due to, for example, differences in viewing directions and
geometries in OG models as proposed by Wang et al. (2014), or
plays the signature of the exotic process of photon splitting in a
very strong magnetic field near the stellar surface a dominant role
(Harding, Baring & Gonthier 1997)? The latter scenario, however,
cannot explain the characteristics of all MeV pulsars, since some
of them, including PSR J1617–5055 and PSR J1811–1925, appear
not to possess sufficiently strong magnetic fields approaching the
quantum critical value. Furthermore, we show in Fig. 8 that Fermi
LAT has detected high B-field pulsars, including the magnetar-like
PSR J1119–6127, as GeV pulsars with their maximum luminosities
at GeV energies. For the latter arguments we are inclined to believe
more in geometrical solutions to the problem of understanding the
scenarios that explain the manifestations of the young and energetic
MeV pulsars.

In this work we probed in detail the spectral extension of the
MeV pulsars PSR J1846–0258 and PSR B1509–58 in the Fermi
LAT band, going to the bottom for PSR J1846–0258. Other promi-
sing MeV-pulsars to show spectral extensions in the GeV band are
AX J1838.0–0655 and IGR J1849.0–0000, each having stronger
pulsed emission at hard X-rays/soft γ-rays than Fermi J1846–0258
(see fig. 28 of Kuiper & Hermsen (2015)). Both pulsars, however,
are not detected at radio wavelengths, and could only be timed at
X-rays. AX J1838.0–0655 is currently (since 2017 March 19) being
monitored by Swift XRT to obtain phase coherent timing models
that will be used in turn to uncover a likely pulsed gamma-ray sig-

tial in a timing analysis of Fermi LAT data. We already have folded
Fermi LAT Pass-8 events collected during 2008 Aug. 4 and 2010
December 12, when RXTE PCA monitored the source (see table 1
of Kuiper & Hermsen 2015, for the phase coherent timing models),
and this yielded, inspite the low exposure of only 2.2 yr, encour-
gaging 2.1 − 2.4σ pulsed signal significances for the 30–1000 MeV
band.

Future high-sensitivity MeV telescopes like the proposed
AMEGO or e-ASTROGAM missions are required to make signifi-
cant progress in understanding the physics of MeV pulsars.

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Table 5. All high-magnetic-field rotation-powered pulsars with characteristic age \( \lesssim 3 \) kyr detected by Fermi LAT

| name               | \( P \) | \( \dot{P} \) | Age  | \( B_s \) | \( L_{sd} \) | Pulse shape | \( E(L_{max}) \) | Comment |
|--------------------|--------|------------|------|----------|-------------|-------------|---------------|---------|
| PSR J1119–6127 (G292.2+0.5) | 407 | 4.02      | 1.6  | 4.1      | 0.23        | two pulses\(^1\) | 600 \( r,X,\gamma \)/magnetar-like outburst |
| PSR J1124–5916 (G292.0+1.8) | 135 | 0.75      | 2.9  | 1.0      | 1.19        | two pulses\(^2\) | 520 \( r,X,\gamma \) |
| PSR J1208–6238      | 440 | 3.27      | 2.7  | 3.8      | 0.15        | two pulses\(^3\) | 1300 \( \gamma \) |
| PSR B1509–58 (MSH 15-52) | 151 | 1.53      | 1.6  | 1.5      | 1.72        | single broad   | 2.2 \( r,X,\gamma \) |
| PSR J1846–0258 (Kes 75) | 326 | 7.13      | 0.7  | 4.9      | 0.81        | single broad   | 3.5 \( X,\gamma \)/magnetar-like outburst |

Notes. Column 1 gives source name(s) and associated SNR or PWN (between brackets), when applicable.
Columns 2 and 3 give the period \( P \) and the period derivative \( \dot{P} \); Column 4 gives the characteristic age \( \tau = -0.5\nu/\dot{\nu} \).
Column 5 gives the magnetic-field strength at the surface \( B_s \); Column 6 gives the spin-down power \( (L_{sd} = 4\pi^2 I\dot{\nu}) \), in erg s\(^{-1}\).
Column 7 gives for the Fermi band above 30 MeV a description of the pulse shape; [1] Parent et al. (2011), [2] Abdo et al. (2010a), [3] Clark et al. (2016).
Column 8 gives the energy where the maximum luminosity is reached in the broad-band spectrum.
Column 9 a label \( r \), \( X \), \( \gamma \) indicates that pulsed emission has been detected at radio wavelengths, X-rays and γ-rays, respectively.
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