New insight into the origin of the GeV flare in PSR B1259-63 from the 2017 periastron passage.

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Received <date> ; in original form <date>

ABSTRACT
PSR B1259-63 is a gamma-ray binary system hosting a millisecond radio pulsar orbiting around a O9.5Ve star, LS 2883, with a period of \( \sim 3.4 \) years. The interaction of the pulsar wind with the LS 2883 outflow leads to unpulsed broad band emission in the radio, X-rays, GeV and TeV domains. While the radio, X-ray and TeV light curves show rather similar behaviour, the GeV light curve appears very different with a huge outburst about a month after a periastron. The energy release during this outburst seems to significantly exceed the spin down luminosity of the pulsar and the GeV light curve and energy release varies from one orbit to the next.

In this paper we present for the first time the results of optical observations of the system in 2017, and also reanalyze the available X-ray and GeV data. We present a new model in which the GeV data are explained as a combination of the bremsstrahlung and inverse Compton emission from the unshocked and weakly shocked electrons of the pulsar wind. The X-ray and TeV emission is produced by synchrotron and inverse Compton emission of energetic electrons accelerated on a strong shock arising due to stellar/pulsar winds collision. The brightness of the GeV flare is explained in our model as a beaming effect of the energy released in a cone oriented, during the time of flare, in the direction of the observer.

1 INTRODUCTION
Gamma-ray binary systems are composed of a compact object, either a black hole or a neutron star, orbiting a massive O or B type star. They are distinguished from X-ray binaries of a similar nature by non-thermal emission that peaks at energies \( \gtrsim 1 \) MeV (Dubus et al. 2017). Of all \( \gamma \)-ray binaries the only systems where the nature of the compact object is known are PSR B1259-63 and PSR J2032+4127, both of which are millisecond radio pulsars. In PSR B1259-63 the pulsar has a spin period of 47.76 ms and is orbiting a O9.5Ve star (LS 2883) with a period of \( \sim 1236.7 \) days in a highly eccentric orbit (e \( \sim 0.87 \)) (Johnston et al. 1992; Negueruela et al. 2001; Shannon, Johnston & Manchester 2014). Based on the parallax data in the Gaia DR2 Archive (Gaia Collaboration et al. 2018) the distance to the system is 2.39 ± 0.19 kpc.

The optical spectrum of the companion shows evidence of an equatorial disc, which is thought to be inclined with respect to the orbital plane by \( \sim 10 – 40^\circ \) (Melatos, Johnston & Melrose 1995), which causes the pulsar to cross the disc twice during the periastron passage. The interaction of the pulsar wind with the companion’s outflow leads to the generation of the unpulsed non-thermal emission in radio, X-ray, GeV and TeV energies. X-ray emission is observed throughout the orbit but the unpulsed radio, GeV and TeV radiation occurs only within a few months before and after the periastron (e.g. Johnston et al. 1999; Chernyakova et al. 2015; Johnson et al. 2018; H. E. S. Collaboration et al. 2020).

The unpulsed radio and X-ray emission exhibits a similar two peak light curve with the peaks occurring during the time when the pulsar crosses the disc of the companion. Current H.E.S.S. observations indicate that TeV emission can have a similar behaviour (H. E. S. Collaboration et al. 2020), but more sensitive observations are needed to confirm this. Hopefully CTA will address this issue in the very near future (Chernyakova et al. 2019). The GeV emission, however, shows a very different behaviour and is characterised by a strong flare, which started about \( \sim 30 \) days after the 2010 and 2014 periastron passages (Abdo et al. 2011; Caliandro et al. 2015) and has no obvious flaring counterparts at other wavelengths.

The only visible effect coinciding in time with a GeV flare is a rapid decrease of the H\( \alpha \) equivalent width (Chernyakova et al. 2015), usually interpreted as a measure of the companion’s star disc. The destruction of the disc is also evident in Chandra observations of the source far away from the periastron (Pavlov, Chang & Kargaltsev 2011; Pavlov et al. 2015; Pavlov, Hare & Kargaltsev 2019). This data demonstrates the presence of X-ray emitting clumps moving away from the binary with speeds of about 0.1 of the speed of light. The clumps are being ejected at least once per bi-
nary period, 3.4 years, presumably around binary periastra and are probably associated with the destruction of the companion’s disc.

The most recent periastron of PSR B1259-63 (September 22, 2017; \( t_p = \text{MJD 58018.1} \)) presents another opportunity to examine the nature and mechanics of the GeV flare using the available broadband observations. The GeV behaviour of PSR B1259-63 turned out to be very different from previous periastra. The flare only started 40 days after the periastron and reveals variability on hour timescales (e.g. Johnson et al. 2018; Tam et al. 2018; Chang et al. 2018).

In this paper we present for the first time the results of the optical observations of the system in 2017, discuss the available multiwavelength data (optical, X-ray and GeV) and propose a new model to explain the origin of the GeV flare and how its observed luminosity apparently exceeds the spin-down luminosity. In section 2 of this paper we describe the details of the data analysis, in section 3 we present our model, and give our conclusions in section 4.

2 DATA ANALYSIS

2.1 Optical observations and analysis

Optical observations during the 2017 periastron passage were limited because of the position of the source relative to the Sun, and PSR B1259-63/LS 2883 was only visible for a short period just after sunset, allowing limited observations before periastron. The system was observed with the SAAO 1.9-m telescope between 2017 August 24 and 2017 September 04 (\( \tau \sim -28\) d to \( \tau \sim -17\) d; where \( \tau \) is the time from periastron) using the SpUpNic grating spectrograph (Crause et al. 2016).

The spectroscopic observations with SpUpNic were performed using a 1200 lines mm\(^{-1}\) grating, with a spectral resolution of \( \sim 1\) Å, covering a wavelength range of \( \sim 6150 - 7150\) Å. Each night, multiple exposures of the target were taken with a typical exposure time of 60 seconds, while the source was high enough to be observed. Arc observations of a CuNe arc lamp were taken before and after every science exposure. Dome flats where taken to be observed. Arc observations of a CuNe arc lamp were taken before and after every science exposure. Dome flats where taken to be observed. Arc observations of a CuNe arc lamp were taken before and after every science exposure. Dome flats where taken to be observed.

As previously reported, the spectrum shows a strong Hα emission line that remains single peaked through all observations. The double peaked He i (\( \lambda 6678\)) line is also present in the observations and the V/R variation of the line was measured.

Further photometric observations in the Hα filter were undertaken using the Watcher Robotic Telescope (French et al. 2004) from 2017 September 04 to 2017 September 21 (\( \tau \sim -17\) to \( \sim -0.4\) d). Multiple 30 second exposure in the Hα filter were taken per night. All images on the same night were combined to increase the signal to noise and differential photometry, using stars on the same field of view, was performed.

The results are shown in Fig. 1 (and also bottom panel of Fig. 2) and compared to the observations around the 2014 periastron passage (Chernyakova et al. 2014; van Soelen et al. 2016). The top panel shows that the Hα equivalent width follows the same trend as the previous periastron passage, with the line strength increasing towards the point of the first disc crossing. While the spectroscopic observations could not be taken beyond this, the photometric Hα observations (middle panel, shown in arbitrary flux units) show that the line continues to follow the same trend; the line strength decreases after the first disc crossing, then continues to grow towards periastron. This confirms the strong interaction between the pulsar and the circumstellar disc around the periastron. This is also shown by the V/R variation (bottom panel) which follows a similar trend, though at a lower scale, with the V component increasing towards the first disc crossing. The optical spectroscopic results are given in Table 1.

2.2 X-ray data

A full overview of the X-ray flux and spectral slope for the observations around 2004, 2007, 2010, 2014 and 2017 years are presented in the panels (b) and (c) of Fig. 2. Historical data in this figure are taken from Chernyakova et al. (2015)

2.2.1 Swift/XRT

The 2017 periastron passage of PSR B1259-63 was closely monitored by the Swift satellite (Gehrels et al. 2004). We have analysed all available data taken from March, 26th, 2017 to January, 6th, 2018.
The data was reprocessed and analysed as suggested by the Swift/XRT team with the xrtpipeline v.0.13.5 and heasoft v.6.27 software package. The spectral analysis of Swift/XRT spectra was performed with XSPEC v.12.11.0. The spectrum was extracted from a circle of radius 36′ around the position of PSR B1259-63 and the background estimated from a co-centred annulus with inner/outter radii of 60′/300′.

During the spectral analysis we noticed that the quality of the Swift/XRT data does not allow the hydrogen column density to be firmly determined in each individual observation and thus we chose to fix it to the mean value. To do this we have fitted all the data with an absorbed power law model with a common value of column density in all the observations. The resulting value of \( N_H = 0.55 \times 10^{22}\text{cm}^{-2} \) is in good agreement with previous observations (see e.g. Chernyakova et al. 2015, and references therein). This data was also presented in the paper of Tam et al. (2018), but in that work the value of the column density was fixed in a rather model-dependent way.

### 2.2.2 Chandra

We accompanied our analysis with the analysis of historic, publicly available Chandra data taken during the 2014 and 2017 periastron passages (February to June 2014, ObsIds: 16563, 16583, 16624, 16625 and July 2017, ObsIds: 19281, 20116).

We analyzed the data using the most recent CIAO v.4.12 software and CALDB 4.9.0. The data was reprocessed with the chandra_repro utility. The source and background spectra, with corresponding RMFs and ARFs, were extracted with the specextract tool. We note that two Chandra observations of PSR B1259-63 in June 2014 (ObsIds: 16624, 16625) were performed in asic-cc (continuous clocking) mode, in which only 1-dimensional spatial information is available. In this case, to extract the source and background spectra, we used box-shaped regions\(^1\) centred on PSR B1259-63 and on a nearby source-free region, respectively. For the rest of observations we utilized standard circular regions.

### 2.3 Fermi/LAT Observations and Analysis

The analysis of Fermi/LAT data was performed using FermiTools version 1.2.23 (released 11th February 2020). For the analysis of the 2017 periastron passage and the combined periastron data the analysis was carried out using the latest Pass 8 reprocessed data (P8R3) from the SOURCE event class. All gamma-ray photons used for this analysis were within the energy range 0.1 – 100 GeV and within a circular region of 15′ around the ROI centred on PSR B1259-63. The selected maximum zenith angle was 90′. The spatial-spectral model built in order to perform the likelihood analysis included the Galactic and isotropic diffuse emission components and the known gamma-ray sources within 20′ of the ROI centre from the 4FGL catalogue (Abdollahi et al. 2020). A likelihood analysis was applied to each observation data set twice to achieve the best model for that time span and energy range. The first likelihood run frees the normalization of every source within 15′ of the ROI centre and the index of PSR B1259-63. The second run fixes the normalization of all sources outside 5′ of PSR B1259-63 to the value calculated from the first likelihood fit. The output

\(^1\) See e.g. the Swift/XRT User’s Guide

\(^2\) See caveats of asic-cc mode data analysis.
The GeV emission after the periastron (prfl2) has a higher flux before periastron (prfl1) is well described with a simple power law. The spectrum points correspond to the spectrum of the source averaged over 20 days before and after the periastron correspondingly. The spectrum of unshocked electrons was selected to be a power law (PLSuperExpCutoff) model to match the shape of the GeV peak spectra; see Table 3 for the best-fit parameters. Spectral fitting was done twice, the first time with all the parameters free, and second time with $y_2$ fixed to the value of the first fit to better constrain the other model parameters.

The spectral shape of the GeV emission turned out to be very different before and after the periastron, see Fig. 3. Blue and red points correspond to the spectrum of the source averaged over 20 days before and after the periastron correspondingly. The spectrum before periastron (prfl1) is well described with a simple power law. The GeV emission after the periastron (prfl2) has a higher flux in the 0.1 – 2 GeV energy range and is characterised by a strong cut-off, see Table 3. This noticeable difference in spectral characteristics between different time periods of the preflare implies that around periastron there is a change of the spectrum of electron population responsible for the GeV production.

While there is a notable distinction in the characteristics between the time periods of the preflare, such a difference was not observed in the analysis of the flare periods. The spectra of both the average flare period (avfl) and the peaks of the flare (pkfl) are quite similar (see Figure 6 and Table 3), and differ mainly by the normalisation.

### 3 DISCUSSION

The energy release in PSR B1259-63 is known to be extremely efficient, for example around periastron more than 10% of the spin-down luminosity is released in the 1 – 10 keV energy band alone (e.g. Chernyakova et al. 2017). The energy release during the GeV flare is even larger, reaching values higher than 50% of the spin-down luminosity in 2010 and 2014, without considering possible beaming effects (Caliandro et al. 2015). The GeV flare in 2017 differs a lot from the previous ones, as it starts about 10 days later and consists of a number of short individual flares, more intensive than previously observed (Tam et al. 2018; Johnson et al. 2018). The brightness of these flares allows their structure to be reconstructed on timescales shorter than 1 day, and even to find 15 minute long sub-flares. The energy release during these sub-flares reached a value exceeding the spin-down luminosity by a factor of 30, with no clear counterparts at other wavelength (Johnson et al. 2018). This makes it clear that the GeV flare is produced as a separate and highly anisotropic component.

In what follows we propose a new model, which suggests the presence of two populations of relativistic electrons: (i): electrons of the unshocked and weakly shocked pulsar wind and (ii): strongly shocked electrons.

The spectrum of unshocked electrons was selected to be a power law with the slope $–2$ in energy range $E_\gamma = 0.6 – 1$ GeV. A small fraction of electrons are additionally accelerated at the strong shock near the apex to $E_\gamma \sim 500$ TeV energies with the similar slope $\Gamma_\gamma = -2$ on a characteristic timescale (see Fig. 5)

$$t_{acc} \approx 0.1 \left( E_\gamma / 1 \text{ TeV} \right) \eta (B_0 / 1 \text{ G})^{-1} \, \text{s}$$

where $B_0$ is a magnetic field in the region and $\eta \geq 1$ is the acceleration efficiency (see e.g. Khangulyan, Aharonian & Bosch-Ramon 2008, for the details).

The rest of the electrons flying into the shock direction will

![Figure 3. Daily-binned light curve of the 2017 periastron passage. The highlights indicate the time periods that were used for spectral analysis and modelling; the details are given in Table 2. The different periods are shown as: prfl1 = Red, prfl2 = Magenta, avfl = Yellow, pkfl = Green.](image-url)

| Data Set | Time period (MJD) | $t-t_p$ (days) |
|----------|------------------|----------------|
| prfl1    | 55524.7 – 55544.7, 56761.4 – 56781.4, 57998.1 – 58018.1 | -20 – 0 |
| prfl2    | 55544.7 – 55564.7, 56781.4 – 56801.4, 58018.1 – 58038.1 | 0 – 20 |
| avfl     | 58058.1 – 58090.1 | 40 – 72 |
| pkfl     | 58059.1, 58074.1, 58076.1, 58088.1 | 41, 56, 58, 70 |

| Data Set | $\gamma_1$ | $E_0$ (GeV) | $\gamma_2$ | Photon Flux ($10^{-6}$ cts/cm²/s) |
|----------|------------|-------------|------------|-----------------------------------|
| prfl1    | -2.9 ± 0.3 | -           | -          | 0.26 ± 0.05                       |
| prfl2    | -1.5 ± 0.4 | 0.50 ± 0.08 | 3.0        | 0.28 ± 0.04                       |
| avfl     | -2.4 ± 0.3 | 0.65 ± 0.10 | 5.0        | 0.34 ± 0.05                       |
| pkfl     | -2.3 ± 0.1 | 1.86 ± 0.43 | 3.0        | 3.39 ± 0.38                       |
be reverted to flow along the shock at the surface of stellar-pulsar wind interaction cone far from the apex, and could be additionally mildly accelerated on a weak shock. This leads to a power law tail in the spectrum of diverted electrons with a slope $\sim -3$ which continues above 1 GeV to at least $E_\gamma \sim 5$ GeV. This slope is characteristic of particles acceleration on weak shocks (see e.g. Bell 1978; Blandford & Eichler 1987). Hereafter we will refer to these diverted electrons as weakly shocked electrons.

The spectra of both populations will be additionally modified by radiative (IC, synchrotron or bremsstrahlung) and non-radiative (adiabatic or escape) losses operating in the system. In our calculations the resulting electron spectrum was determined by numerically calculating the radiative losses of a continuously injected spectrum of electrons, until a steady solution has been obtained. The time that electrons spend in the emitting region, $R/c$, is about a few thousand seconds, and is long enough to substantially modify the injected spectrum due to synchrotron losses (in our calculations we took $t_{es}=400$ s; see Figure 5 and Table 4).

We would like to note that the losses substantially modify the injected spectrum and thus properly accounting for such losses is important for modelling the PSR B1259-63 system. Additionally one has to account for the radiation efficiency of the considered mechanisms. This is rather low for the majority of the considered processes and subsequently an increase of the total energy of the pulsar wind is required (in comparison to 100% efficiency case).

According to our model, similar to previous works (e.g. Chernyakova et al. 2014, 2015; Chen et al. 2019), the X-ray and TeV components are explained as synchrotron and IC emission of the strongly shocked electrons. The GeV component in our model is a separate component due to the combination of the IC and bremsstrahlung emission of the less energetic, unshocked electrons interacting with the clumps of the matter from the Be-star wind which penetrated through the shock.

The modelled SEDs along with the observed keV-TeV data are shown in Figure 6. In this figure the synchrotron and IC emission of the strongly shocked electrons are shown with solid and dashed magenta curves correspondingly. The contributions of IC and bremsstrahlung emission of the unshocked and weakly shocked electrons are indicated with dashed and dashed-dot curves correspondingly, where the colours refer to the prfl1 (blue) and prfl2 (red) periods. The TeV points shown are taken from Aharonian et al. (2005), and the coloured region at TeV energies represent the range of multi-years H.E.S.S. measurements reported in Fig. 2 of H. E. S. S. Collaboration et al. (2020). The shaded region at X-ray energies represents the range of fluxes observed by Swift in 2017 before (left panel), and after (right panel) the GeV flare.

The synchrotron, bremsstrahlung and IC emission was calculated with the naima v.0.8.3 package (Zabalza 2015), which uses the approximations for the IC, synchrotron and bremsstrahlung emission from Aharonian & Atoyan (1981); Aharonian, Kelner & Prosekin (2010); Khangulyan, Aharonian & Kelner (2014); Baring et al. (1999).

To explain the observed luminosity one has to consider that for relativistic electrons both IC and bremsstrahlung radiation is strongly peaked in the forward direction and most of the energy radiated as a photon moving in the same direction as the initial electron. To explain the observed excess of the energy released during the short flares an initially isotropic pulsar wind should be reversed after the shock and confined within a cone, pointing in the direction of the observer, similar to the geometry described in Khangulyan et al. (2011).

The difference in true anomaly between days 40 and 80 af-
The periastron (period including all short flares) is about 20°. This angle is comfortably smaller than the apex angle of solid angle $4\pi/30$ needed to explain the observed luminosity during the short flares in the case of 100% efficiency. The cone of such a size is a result of the interaction of the pulsar wind with the Be star wind if the winds ram pressure ratio is $\eta = \frac{P_{\text{wind}}}{P_{\text{surf}}} = 0.05$ (Khangulyan et al. 2011).

In Figure 6 we show Fermi/LAT spectra averaged over the total flare (green points), and over the peak of the flares only (red points). These spectra can be explained as a combination of IC and bremsstrahlung emission on the clumps with densities of about $2 \times 10^{10}$ cm$^{-3}$ and less then $1 \times 10^{9}$ cm$^{-3}$ correspondingly, see Table 4. Please note that in the Figure 6 we show only the dominant component (IC for the average flare and bremsstrahlung for the peaks) in order to make the figure more readable. Also please note that the split of the Hα light curve (rapid flares) from the 2010 and 2014 periastra, also suggests a more complicated disc behaviour, that was unfortunately not observable during the 2017 periastron passage by Fermi. We show that:

1) The optical observations show that the behaviour of the disc around the first disc crossing is similar to the previous periastron, clearly indicating the pulsar significantly disrupts the disc.

2) The observed X-ray and TeV emission both around the periastron and during GeV flare can be explained as a synchrotron and IC emission of the strongly shocked electrons of the pulsar wind.

3) The GeV component is a combination of the IC emission of unshocked/ weakly shocked electrons and bremsstrahlung emission.

4) The luminosity of the GeV flares can be understood if it is assumed that the initially isotropic pulsar wind after the shock is reversed and confined within a cone looking, during the flare, in the direction of the observer.

5) The observed softening of the spectrum close to the periastron corresponds to the shift of the break in the electrons spectrum due to the cooling losses. The position of the break is determined by the strength of the magnetic field in the emitting region, which is higher around the periastron. We foresee that the break position can be located at higher energies further from the periastron, which can lead to the detectable break in X-ray/TeV spectra. A hint of such a break was detected by Suzaku in 2007 (Uchiyama et al. 2009).

4 CONCLUSIONS

In this paper we present optical observations (spectroscopy and Hα photometry) and discuss spectral characteristics of the GeV emission both around the periastron and during the flare. We propose a new model to explain the origin of the short bright GeV flares observed during 2017 periastron passage by Fermi. We show that:

1) The optical observations show that the behaviour of the disc around the first disc crossing is similar to the previous periastron, clearly indicating the pulsar significantly disrupts the disc.

2) The observed X-ray and TeV emission both around the periastron and during GeV flare can be explained as a synchrotron and IC emission of the strongly shocked electrons of the pulsar wind.

3) The GeV component is a combination of the IC emission of unshocked/ weakly shocked electrons and bremsstrahlung emission.

ACKNOWLEDGEMENTS

Authors thank Prof. F. Aharonian for fruitful discussions. This paper uses observations made at the South African Astronomical Observatory (SAAO). This paper uses observations obtained at the Boyden Observatory, University of the Free State, South Africa. Watcher data made available through support from Science Foundation Ireland grant 07/RFP/PGYF295. The authors acknowledge support by the state of Baden-Württemberg through bwHPC. This work was supported by DFG through the grant MA 7807/2-1. The authors wish to acknowledge the DfE/DES/SFI/HEA Irish Centre for High-End Computing (ICHEC) for the provision of computational facilities and support. We would also like to acknowledge networking support by the COST Actions CA16214 and CA16104. DM acknowledges support from the Irish Research Council through grant GOIPG/2014/453.

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Figure 6. Left: Broad band spectrum emission of PSR B1259-63 during the 20 days before (blue points) and after (red points) the periastron period. Green X-ray points are NuSTAR observations of the 2014 periastron from Chernyakova et al. (2015). Right: Broad band spectrum emission of PSR B1259-63 during the GeV flare. Blue points represent the flare averaged over the whole duration, and red points correspond to the sum of peak periods. The TeV points shown are taken from Aharonian et al. (2005), and the shaded regions at TeV energies represent the range of multi-years H.E.S.S. measurements reported in Fig. 2 of H. E. S. S. Collaboration et al. (2020). The shaded regions at X-ray energies represent the range of fluxes observed by SWIFT in 2017 (left panel), and after (right panel) the GeV flare. In both panels dashed lines show an IC component, solid magenta line corresponds to synchrotron emission of strongly shocked electrons, dash-dotted line shows the bremsstrahlung component and black solid line corresponds to overall model emission.