Analysis of the 2021 GeV flare of PSR B1259-63

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Abstract: PSR B1259-63/LS 2883 is a gamma-ray binary in which the compact object (a pulsar) crosses the disk of the massive companion twice during its 3.4 years orbit, when it is close to periastron. The GeV flare detected by *Fermi*-LAT around 30-40 days after the periastron passage in 2010, 2014 and 2017 was not detected until 60 days after the most recent periastron on 9th February 2021 and lasted more than the previous flares. An unbinned likelihood analysis was performed with the Python 3 version of the *Fermi*-Tools, HEAsoft 6.28 and making use of pass 8 *Fermi*-LAT data obtained up to 112 days after periastron (1st June 2021). Modelling PSR B1259-63 with a power law, a photon index of 2.76 ± 0.09 and a Test Statistics significance level of 170.3 were obtained during the flare, similar to the values in papers referring to the previous flares. Although several models have been proposed to explain this phenomenon that is likely related to the pulsar crossing the disk, the origin of the GeV is still unclear.

I. INTRODUCTION

Gamma-ray binaries are a special class of X-ray binary systems (two-star systems that emit X-ray radiation) that have non-thermal emission peaks in the gamma-ray region of the electromagnetic spectrum (above 1MeV) in a νF_ν diagram, where F_ν is the specific flux. They consist of a compact object that could be either a neutron star or a black hole and an O or Be massive star of more than 10 solar masses and $\approx 10R_\odot$. In most systems, the nature of the compact object is still unknown [6].

The detection of gamma-ray binaries follows the development of the Cherenkov technique iniciated in the 1970s, in which the Cherenkov light is used to detect the electromagnetic showers caused very high energy (VHE) gamma rays in the atmosphere. In the mid-2000s and 2010s, a series of Cherenkov telescopes (HESS, MAGIC, VERITAS) increased the number of known VHE sources to more than two hundred (as of today) [6]. At the time of writing, according to TeVCat (an online catalog for Tev astronomy), only 11 of those sources are binaries.

PSR B1259-63/LS 2883 is a gamma-ray binary that consists of a 47.76ms radio pulsar and a massive main sequence Be star, LS 2883, of $31M_\odot, 9.2R_\odot$ and a photosphere temperature of 33500K. Its compact object is one of the few that has been identified as a neutron star ($\approx 1.4M_\odot$). It's also known as HESS J1302-638, since it was first detected in VHE gamma-rays in 2004 by the HESS (High Energy Stereoscopic System) collaboration, but it had already been found as a radio pulsar [6]. Its J2000 equatorial coordinates are (RA,DEC)=(195.699,-63.8357)deg according to the *Fermi*-LAT data base.

The orbit of the pulsar is thought to be inclined $\approx 10^o - 40^o$ with respect to the equatorial disk of the companion, allowing it to cross the disk twice in an orbit. Every time the two stars are close to each other, as a result of the shock interaction between the relativistic pulsar wind and the stellar wind, there are multiwavelength non-thermal unpulsed emissions in radio, X-ray and TeV γ-ray [3].

Parameter	PSR B1259-63
orbital period (P_{orb}) [days]	1236,72432(2)
eccentricity (e)	0.8698872(9)
ω [^{o}]	138.66591(1)
binary inclination (i) [^{o}]	19-31
distance to Earth (d) [kpc]	2.3(4)
periastron [AU]	0.94
apastron [AU]	13.4

Table I: Orbital parameters of PSR B1259-63 [6].

Close to the periastron, there are radio, X-ray and TeV peaks usually explained as a result of the shock acceleration between the pulsar wind and the stellar disk. However, around a month after 2010, 1014 and 2017 periastrons, at the time when the pulsar moved out of the stellar disk for the second time, unexpected GeV flares that do not have other wavelength counterparts were observed by *Fermi*-LAT [10].

The radiation mechanisms of both the broadband radiation and GeV flares are unclear: synchrotron radiation produced by electrons, Inverse Compton scattering of photons, Doppler boosting... have been proposed [10].

As noted in [5], "the only effect coinciding in time with a GeV flare is a rapid decrease of the H_α equivalent width [...], usually interpreted as a measure of the companion's disk", presumably meaning that the disk is destroyed during the passage of the pulsar. It coincides with the evidence of clumps that are being ejected with speeds of 0.1c at least once per binary period, around the periastron passage.

More information about the models for PSR B1259-63's multiwavelenght emissions can be found in [4].

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II. *FERMI*-LAT

The *Fermi* γ-ray Space Telescope is a satellite observatory that detects photons with an energy range between 8keV and over 300GeV. One of its mean instruments, the Large Area Telescope (LAT), detects photons of 20MeV to over 300GeV via pair production: γ-rays pass freely through a thin plastic layer that rejects the background charged cosmic rays until they interact with an atom in a tungsten foil inside the instrument. Once there it produces an electron and a positron pair that keep travelling and creating ions in thin strip detectors made of silicon that allow their trajectories to be tracked. They finally stop in a calorimeter that measures the total energy deposited (https://www-glast.stanford.edu/instrument.html). The other mean instrument, the Gamma-ray Burst monitor (GBM), is not relevant for this project. More information can be found in the LAT web page https://fermi.gsfc.nasa.gov/science/eteu/about/ .

The spacecraft orbits the Earth every 96 minutes with the LAT pointing upward, rocking to the left and right on alternate orbits to cover the whole sky and allowing constant monitoring of γ-ray sources in time scales of over a day. Eventually it can focus on a certain region to get more data during important events.

A. Data analysis: *Fermi* Tools

Both LAT data and software to analyse it (known as *Fermi* Tools) are public and can be obtained from the *Fermi*-LAT web page (see: *Fermi* Tools Cicerone https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/). In this case, the most recent version were the Python 3 version of the *Fermi* Tools from the Conda environment, HEAsoft 6.28 and Pass 8 data, with the instrument response functions P8R3_SOURCE_V3, the Galactic diffuse model gll_iem_v07.fits, isotropic background emission model iso_P8R3_SOURCE_V3_v1.txt and the known sources in the 4FGL catalog (a catalog based on the first eight years of *Fermi*-LAT data) [1].

The first step after downloading the desired event and spacecraft data is to make a selection of the region, time and energy intervals and type of events, using 'gtselect' to cut the data files. After that, 'gtmktime' creates good time intervals (GTIs) using the data from the spacecraft file. It filters out the data contaminated by photons coming from the Earth's atmosphere or the Sun.

Counts maps can be then created with the [cmap] algorithm of 'gtbin' to visually identify the sources in the region of interest (ROI).

Light curves can be created in two different ways: aperture photometry (AP) and a likelihood analysis. AP is less computing demanding, as it requires fewer steps and is independent of the model. To analyse just the source that we want to study and avoid counting the background, the data has to be cut to $\approx 1^o$ around the source. It also enables the use of shorter time bins. On the other hand, the likelihood analysis is more rigorous and leads to more accurate measurements, since the background and the source can both be modeled.

To get the light curve with AP, the 'gtbin' tool has to be run with the LC algorithm and the desired time bins. Afterwards, the exposure of each time bin has to be calculated with 'gtexposure'. The light curve can be obtained representing the rate between the counts and the exposure (flux in $photons/cm^2s$) per time bin.

To get it with the likelihood analysis one has two other options: unbinned likelihood for short time periods (small number of events per bin) and binned likelihood for larger time periods (more events and bright background sources). Due to issues with the software only the unbinned analysis will be performed in this work. The following paragraphs describe this analysis, that gives the flux as an output and enables the creation of the light curve by repeating this procedure for every time bin.

A livetime cube and an exposure map have to be created with 'gtltcube' and 'gtexmap' respectively. As described in the usage description of the tools, the livetime is "the accumulated time during which the LAT is actively taking event data", since "the LAT instrument response functions depend on the angle between the direction to a source and the instrument z-axis" (inclination or off-axis angle). This tool calculates it as a function of sky position and inclination.

To create the model for the source, the make4FGLxml python module is used with the previously stated Galactic diffuse model gll_iem_v07.fits, isotropic background emission model iso_P8R3_SOURCE_V3_v1.txt and the known sources in the 4FGL catalog. As noted in the 4FGL catalog paper [1], PSR B1259-63 is not included in the catalog because it is only a bright LAT source during a small part of the 3.4 years binary period (3FGL catalog [2]), and therefore it has to be included manually in the xml file of the model. The sources outside a certain radius can be fixed, so the analysis only fits the data to the model inside the region of interest.

To continue the unbinned likelihood analysis, 'gtdiffrsp' is used to calculate the integral over the solid angle of the diffuse sources in the model and 'gtlike' performs the analysis. Once it is finished, 'gttsmap' calculates test-statistic maps for detecting and localizing sources based on their significance. As described in the Cicerone, the Test Statistic (TS) is defined as:

$$TS = -2\ln\left(\frac{L_{max,0}}{L_{max,1}}\right), \tag{1}$$

where $L_{max,1}$ and $L_{max,0}$ are the maximum likelihood values for a model that has the additional source at a specific location and one where it is not present. Large TS values indicate that the source is really present, and the square root of the TS is an approximation of the detection significance for the source.

Another way to visualize the results of the likelihood analysis is to plot a spectrum with the fitted model, comparing the spectrum of each source with the sum of all of them and finally to the counts data. More frequent than that is the butterfly plot, consisting in the differential flux multiplied by E^2 in order to get the spectrum in [MeV/cm^{2}s] for every energy. It can include the 1 sigma contours and the counts data from the source (counts spectrum).

There are programs known as user contributions (see: https://fermi.gsfc.nasa.gov/ssc/data/analysis/user/) developed by external scientists to help with the *Fermi* data analysis in creating those plots. However, some of them are not updated and are not compatible with the latest software upgrade or with pass 8 data.

III. 2021 PERIASTRON PASSAGE AND GEV FLARE

According to ATel #14399 [9], the most recent periastron passage of PSR B1259-63 was on $T_0 = 09/02/2021$. The corresponding GeV flare was expected about 40 days afterwards o a few days later, following the tendency of the previous flares: from a delay of 30-32 days in 2010 and 2014 to 40 days in 2017 [8]. However, no significant emission was detected until at least 60 after the periastron, with the biggest flare around 85 days after the periastron. The following analysis uses the data from the *Fermi*-LAT Data Base obtained with the constraints sumarized in Table III.

Parameter	Value
Equatorial coordinates (deg)	(195.699,-63.8357)
Time range (MET[11])	(634435205,644284805)
Time range (Gregorian)	(2021-02-08 00:00:00, 2021-06-02 00:00:00)
Energy range (MeV)	(30,300000)
Search radius (degrees)	20

Table II: data from the *Fermi*-LAT data base on PSR B1259-63 for the analysis discussed in this work.

Fig.(1) provides a preliminar analysis of the flux from the day of the periastron ($T_0 = 09/02/2021$) to the end of May to visualize the GeV flare. It was obtained filtering the data of 112 days after T_0 to 0.9^o around PSR B1259-63 in order to avoid photons from the background, with 1 day time bins, using a photon index of 2.76 based on previous passages (around 2.74 in 2010, 20.78 in 2014 and 2.58 in 2017 in [3]) and the first results of the likelihood analysis.

To be accurate, the aperture photometry was first performed with a photon index of 2.58 based on the 2017 periastron passage to identify the days of the 2021 flare, and after the unbinned likelihood analysis was performed to those days, Fig.(1) was plotted with the obtained 2.76 index.

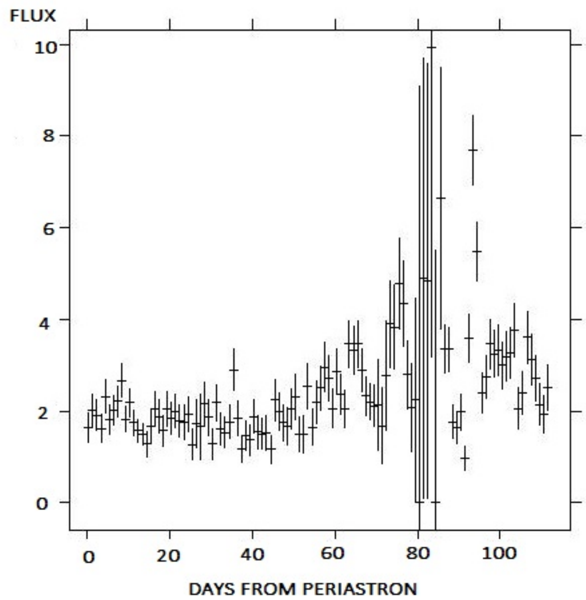

FIG. 1: Light curve obtained with aperture photometry between 09/02/2021 and 01/06/2021. The flux is in 10^{-6}photons/cm^{2}s.

As described in ATel #14612 [7], the high error bars of 80-85 days after T_0 can be explained by "a reduction in exposure towards B1259-63 due to the observatory's modified rocking profile [that] prevented sensitive measurements between 2021-04-30 and 2021-05-05, UTC".

The start of the flare is not clear and can be considered to be around the 60th day after T_0, 10/04/2021, and its end on the final days of this analysis, at the end of May. Therefore the likelihood analysis has to be performed between those dates, when the source is brighter and has a greater statistical significance.

Fig.(2) displays a counts map of a region of 20^o around PSR B1259-63 useful to get an idea of the relevant sources in the region and visualize the analysed data. As shown in this figure, PSR B1259-63 is in the galactic plane and surrounded by a lot of brighter sources, both diffuse and point-like. The ones that have the biggest contribution in addition to PSR B1259 and the background in the spectrum obtained with the likelihood analysis (not included in the current paper) are 4FGL J1303.0-6312e, 4FGL J1309.1-6223, 4FGL J1244.3-6233 and 4FGL J1317.5-6316. More sources and a detailed description of their properties can be found in the 4FGL catalog [1].

The spectrum of PSR B1259-63 can be modelled with a power law [10]:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma}, \quad (2)$$

where Γ is the photon index and N_0 the flux normalization factor. In the likelihood analysis, the scale E_0 is fixed to 100MeV but the prefactor N_0 and the index $\gamma = -\Gamma$

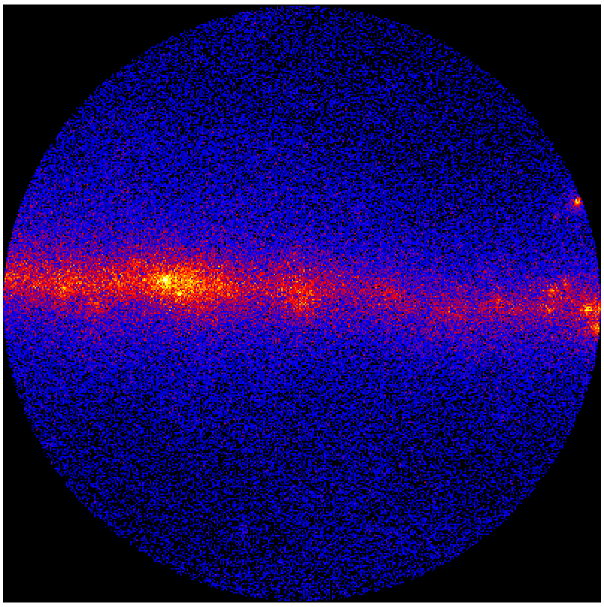

FIG. 2: Counts map of the data from Table 2 in a square root scale.

are left free to fit the data. The model for the likelihood analysis is created as described in the Data analysis: *Fermi* Tools subsection, adding PSR B1259 manually with the previous power law. Filtering the data to a ROI of 10^o around PSR B1259-63 and fixing all the sources further 5^o from the center, the results shown in Table III are obtained.

Parameter	Value	Error
Index	2.76	0.09
Prefactor	$1.1 \cdot 10^{-7}$	$2 \cdot 10^{-8}$
Test Statistic (TS)	170.3	-
$\sqrt{TS}$	13.05	-
Flux	$6.5 \cdot 10^{-7}$	$1.0 \cdot 10^{-7}$
Test Statistic (TS)	17.8	-
Significance ($\sqrt{TS}$)	4.22	-
Flux	$1 \cdot 10^{-8}$	$5 \cdot 10^{-8}$

Table III: results from the likelihood analysis during the flare (top) and before the flare (bottom) of the *Fermi*-LAT data.

The TS value during the flare is much higher than the one obtained performing a similar analysis (ROI of 5^o, sources beyond 2^o fixed) to the data from T_0 to 60 days after, right before the flare. Therefore, PSR B1259-63 is a more significant source during the GeV flare, and is usually negligible during the rest of its orbit. The photon index and prefactor are not included in Table III because they are not relevant outside the flare.

To make sure that this is the most significant source during the flare two TS maps of the region can be represented, one with it and one without it, as displayed in Fig. 3.

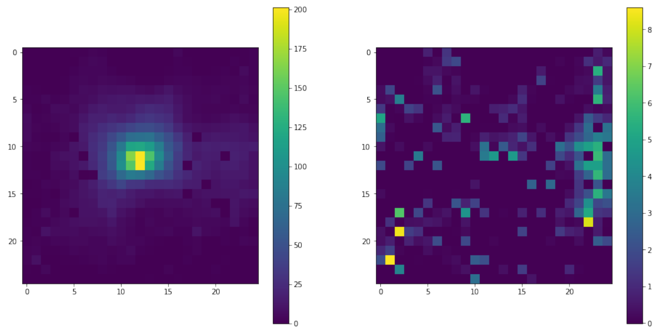

FIG. 3: TS maps of the studied region, with PSR B1259-63 (left) and without it (right).

Even though there are more sources in Figure 3 (bottom), they are not relevant compared to PSR B1259-63 because their TS values range up to 8, very lower than the 200 TS obtained for the γ-ray binary.

Fig.(4) is obtained using the contribution to *Fermi* Tools like_lc.pl (V 2.1) by R. Corbet. The flux of various time bins is calculated with a likelihood analysis and plotted to a light curve if its TS value is greater than 2, so only the days when PSR B1259 is a significant source are represented. The same figure includes the photon index of those days.

As was expected, even though the data covers all the days from periastron to 1st June (see Table III for the exact dates), most of the relevant points are after the 60th day, thus during the flare. It's interesting to remark that the flux is lower than in Fig. 1, which means that the AP includes not only photons from PSR B1259 but also from the background.

IV. CONCLUSIONS

The main objective of this project was to analyse the *Fermi*-LAT data of the most recent periastron passage of PSR B1259-63, since the GeV flare was happening during the time the project took place. After studying the bibliography related to this source and its last periastron passages, familiarizing with the analysis software (following the available data analysis tutorials and applying their steps to the 2017 flare LAT data) and finally analysing the most recent data, I reached the following conclusions:

- The 2021 GeV flare was even more delayed than the 2017 one, up to 60 days after periastron instead of $\approx 30 - 40$ days.
- The flare lasts more than the usual ≈ 40 days, but new data should be studied to cover more days (June 2021) and see exactly when it is over and if there are other subflares. This was not possible before the deadline of this project due to the required computing time.

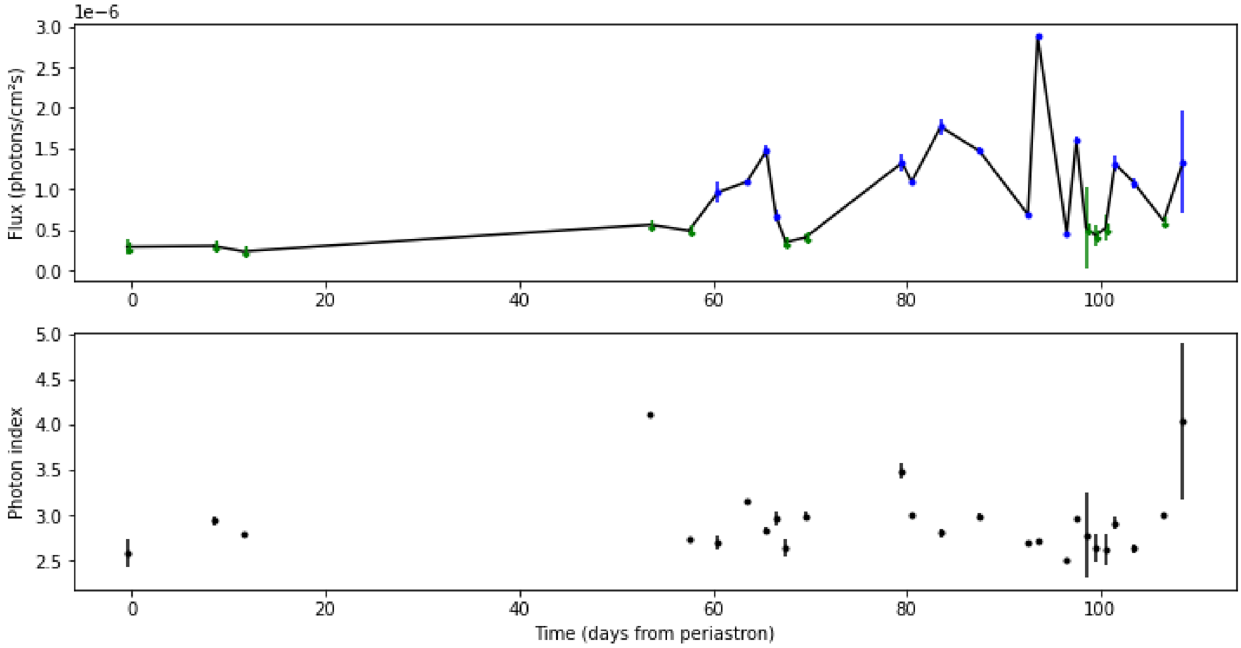

FIG. 4: Likelihood light curve (top) and photon index (bottom) during the 2021 flare. The blue points have a $TS > 4$ and the green downwards arrows (upper limits) a $2 < TS < 4$.

- Since it is still periodic (a few days after the periastron passage in the 3.4 years orbit), the GeV flare is likely associated with the crossing of the disk by the pulsar, supporting the similar conclusion on the discussion by [10].
- If the temporal evolution of the flare changes with each passage, following the same tendency to extend as in 2017, and it is associated with the pulsar crossing the disk, the disk must be modified with each passage in a way that it does not completely return to an equilibrium before the next orbit is completed. This hypothesis should be confirmed or discarded by measures at other energy ranges, a more accurate analysis of the current data, and the study of posterior flares.
- Similar analysis on shorter timescales are outstanding to study sub-structures in the flare.

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