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LS I +61° 303 and LS5039: New Fermi LAT results

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The Fermi Large Area Telescope (LAT) has made the first definitive GeV detections of the binaries LS I +61°303 and LS 5039 in the first year after its launch in August 2008. These detections were unambiguous because, apart from a reduced positional uncertainty, the γ-ray emission in each case was orbitally modulated with the corresponding orbital period. The LAT results posed new questions about the nature of these objects, after the unexpected observation of an exponential cutoff in the GeV γ-ray spectra of both LS I +61°303 and LS 5039, at least along part of their orbital motion. We present here the analysis of new data from the LAT, comprising 2 years of observations through which LS I +61°303 continues to provide some surprises. We find a sudden increase in flux in March 2009 and a steady decrease in the flux fraction modulation. The LAT now detects emission up to 30 GeV, where prior datasets led to upper limits only. At the same time, contemporaneous TeV observations either no longer detected the source, or found it -at least in some orbits- close to periastron, far from the usual phases in which the source usually appeared at TeV energies. The on-source exposure of LS 5039 has also drastically increased along the last years, and whilst our analysis shows no new behavior in comparison with our earlier report, the higher statistics of the current dataset allows for a deeper investigation of its orbital and spectral evolution.

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1. Introduction

To date there are only five X-ray binaries that have been detected at high (HE; 0.1-100 GeV) or very high-energies (VHE; $>$100 GeV): LS I +61°303 [1, 2, 3]; LS 5039 [4, 5], PSR B1259-63 [6], Cyg X-3 [7], and Cyg X-1 [8, 9]. Of these sources, only LS I +61°303 and LS 5039 exhibit a non-transient behavior at high-energies and consequently, have been detected as persistent, albeit variable, sources of γ-ray emission. They also share the property of being (together with PSR B1259-63, see [10]) sources detected at both GeV and TeV energies. The other systems mentioned have been unambiguously detected only in one band, either at GeV or at TeV. Indeed, in the case of Cyg X-3, one can see the upper limits imposed at TeV by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) in the work by [11]. In the case of Cyg X-1, with the TeV detection itself being at the level of 4σ, claims of detection by the Astrorivelatore Gamma a Immagini Leggero (AGILE) were not confirmed with concurrent LAT observations.[1] It is yet uncertain whether these spectral energy distribution (SED) differences reflect an underlying distinct nature.

The early LAT reports of GeV emission from LS 5039 and LS I +61°303 were based upon 6–9 months of survey observations [3, 5]. Both sources were detected at high significance and were unambiguously identified with the binaries by their flux modulation at the corresponding orbital periods, 26.4960 for LS I +61°303 [12] and 3.90603 days for LS 5039 [13]. The modulation patterns were consistent with expectations from inverse Compton scattering models, and were anti-correlated in phase with pre-existing TeV measurements (e.g., [14, 15]). The anti-correlation of GeV–TeV fluxes is in fact a generic feature embedded in inverse Compton models describing the TeV fluxes, where the GeV emission is enhanced (reduced) when the highly relativistic electrons seen by the observer encounter the seed photons head-on (rear-on); (e.g., [16, 17]). Fermi measurements provided a generic confirmation for these inverse Compton models.

Both sources presented exponential cutoffs in their high-energy spectra, at least along part of the orbit. To be precise, an exponential cutoff was a better fit to the SED –as compared with a pure power-law– in phases surrounding the inferior conjunction (INFC) of LS 5039, and when taking into account the average spectrum of LS I +61°303 along its whole orbit. Statistical limitations with the used amount of data prevented the determination or the ruling out of an exponential cutoff in any orbital cut of LS I +61°303 or in the superior conjunction (SUPC) of LS 5039. The spectral energy distributions with the exponential cutoffs that were reported were reminiscent of the many pulsars the LAT has discovered since launch [18], although this was far from a proof of an LS 5039 or LS I +61°303 pulsar nature. No pulsations has been found at GeV energies.

Since Fermi was launched, both MAGIC and the Very Energetic Radiation Imaging Telescope Array (VERITAS) have made observations of LS I +61°303. No TeV detection has been reported since summer 2008 (see, e.g., the summary by [19]), until the source re-appeared at periastron, emphasizing the variability of the TeV maximum phase-position [20].

In this work we present the results of the analysis of 2 years of LAT survey observations of both LS I +61°303 and LS 5039. We investigate any long-term flux variations of the sources and explore too the possible spectral variability for both systems. We expect that our analysis will constrain future theoretical studies on these interesting objects.

[1] See for instance http://fermisky.blogspot.com/2010/03/lat-limit-on-cyg-x-1-during-reported.html

2. Observations and data reduction

The *Fermi Gamma-ray Space Telescope*, launched on 2008 June 11, carries onboard the Large Area Telescope (LAT). The LAT is an electron-positron pair production telescope, featuring solid state silicon trackers and cesium iodide calorimeters, sensitive to photons from $\sim$20 MeV to $>$300 GeV [22]. It has a large field of view with $\sim$2.4 sr (at 1 GeV) and an effective area of $\sim$8000 cm^2 for $>$1 GeV.

The Fermi survey mode operations began on 2008 August 4; in this mode, the observatory is rocked north and south on alternate orbits to provide a more uniform coverage, so that every part of the sky is observed for 30 minutes every 3 hours. Therefore, the two sources of interest were monitored all the time without significant breaks, allowing us to draw a complete picture of their behavior in γ-rays along the last two years. The full dataset used for this analysis spans 2008 August 4, through 2010 December 4.

The data were reduced and analyzed using the Fermi Science Tools v9r17 package.[1] The standard onboard filtering, event reconstruction, and classification were applied to the data [22]. The high-quality "diffuse" event class was used. Throughout the analysis the recommended "Pass 6 v3 Diffuse" instrument response functions (IRFs) were applied. Time periods when the target source was observed at a zenith angle greater than 105° and for observatory rocking angles of greater than 43° were excluded to avoid contamination from Earth albedo photons. Where required in the analysis, models for the Galactic diffuse emission (*gll_iem_v02.fit*) and isotropic backgrounds currently recommended by the LAT team were used.[2]

The binned maximum-likelihood method of `gtlike`, which is part of the ScienceTools, was used to determine the intensities and spectral parameters presented in this paper. We used all photons with energy $>$100 MeV within a $20^\circ \times 20^\circ$ region of interest (ROI) centered at the position of LS I +61°303 and LS 5039. For source modeling, the 1FGL catalog [23], derived from 11 months of survey data, was used. The energy spectra of point sources included in the catalog within our ROI are modeled by simple power-laws

$$\frac{\mathrm{d}N}{\mathrm{d}E} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \tag{2.1}$$

with the exception of known γ-ray pulsars, which were modeled by power-laws with exponential cutoffs described by

$$\frac{\mathrm{d}N}{\mathrm{d}E} = E^{-\Gamma} \exp\left[-\left(\frac{E}{E_{\mathrm{cutoff}}}\right)\right]. \tag{2.2}$$

The spectral parameters were fixed to the catalog values except for the sources within 3 degrees of the candidate location. For these latter sources, the flux normalization was left free. Obviously, all spectral parameters of the two subject binaries were left free for the fit too. The folded lightcurves were derived by performing `gtlike` fits for each phase bin.

[1] See the Fermi Space Science Centre (FSSC) website for details of the Science Tools: http://fermi.gsfc.nasa.gov/ssc/data/analysis/

[2] Descriptions of the models are available from the FSSC: http://fermi.gsfc.nasa.gov/

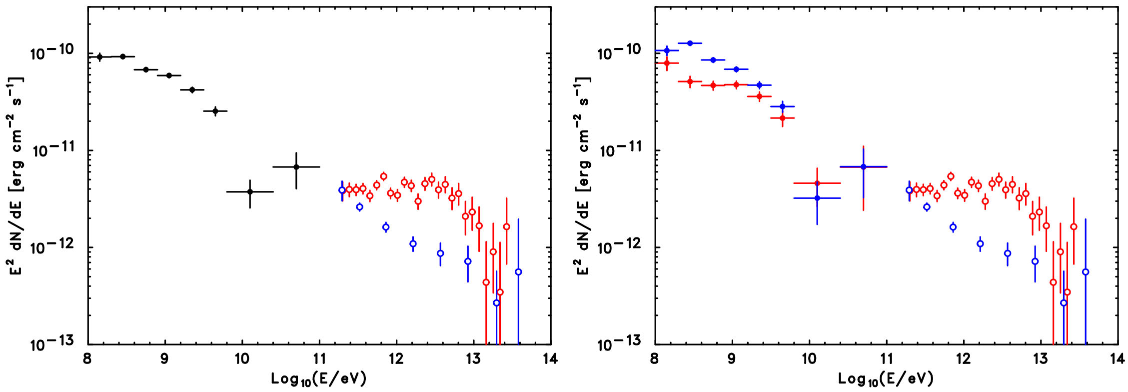

Figure 1: LS 5039 *Left:* The overall spectrum over 2 years of data are shown in black. Also, very high-energy data points from H.E.S.S. are plotted, but one has to keep in mind that they are not simultaneous. The red points correspond to inferior conjunction of the system and the blue ones to superior conjunction. *Right:* Spectra for inferior (red) and superior (blue) conjunction of the system. Note that all plots are preliminary.

3. LS 5039 Results

LS 5039 is located in a complicated region toward the inner Galaxy with high Galactic diffuse emission and many gamma-ray sources. In an earlier publication about this source [5] we derived that a power law plus an exponential cutoff describes best the data (with an expression given by Eq. 2.2). The photon index was $\Gamma = 1.9 \pm 0.1_{\rm stat} \pm 0.3_{\rm syst}$; the 100 – 300 GeV flux was $(4.9 \pm 0.5_{\rm stat} \pm 1.8_{\rm syst}) \times 10^{-7}\,{\rm ph\,cm^{-2}\,s^{-1}}$ and the cutoff energy was found to be $2.1 \pm 0.3_{\rm stat} \pm 1.1_{\rm syst}$ GeV.

3.1 Orbitally averaged spectrum

Firstly, we analyzed the orbitally-averaged data of LS 5039. As spectral models for LS 5039, we used a power law as well as a power law with an exponential cutoff, and compared likelihood obtained to test the significance of a spectral cutoff. The likelihood ratio between the power-law and cutoff power-law cases clearly indicates that the power-law assumption is rejected.

Spectral points at each energy band were obtained by dividing the data set into each energy bin and performing maximum likelihood fits for each of them. Resulting spectral energy distribution (SED) is plotted in Figure 1.

3.2 Phase-resolved analysis

Following the H.E.S.S. analysis by [15] and our previous analysis, the whole data set was divided into two orbital intervals: superior conjunction (SUPC; $\phi < 0.45$ and $0.9 < \phi$) and inferior conjunction (INFC; $0.45 < \phi < 0.9$). The SUPC and INFC data were analyzed in the same way as the orbitally averaged data. Being consistent with our previous paper, the power-law assumption for the SUPC spectrum is rejected. Although a single power law was not rejected for INFC in our previous analysis using 10-month data, a cutoff power law is preferred also for INFC with the present data set. The corresponding SED is shown in Figure 1.

4. LS I +61°303 Results

4.1 Orbitally-averaged spectral analysis

In our earlier publication [3], we have reported that the orbitally averaged (i.e., without any orbital cuts) LAT data of LS I +61°303 from August 2008 through February 2009 were well fitted by a power-law plus an exponential cutoff. The photon index was found to be $\Gamma = 2.21 \pm 0.04_{\rm stat} \pm 0.06_{\rm syst}$; the flux above 100 MeV was $(0.82 \pm 0.03_{\rm stat} \pm 0.07_{\rm syst}) \times 10^{-6}\,{\rm ph\,cm^{-2}\,s^{-1}}$ and the cutoff energy was $6.3 \pm 1.1_{\rm stat} \pm 0.4_{\rm syst}$ GeV.

The currently obtained spectral points and the best-fit averaged over all the orbital phases of the LS I +61°303 system are shown in the left panel of Figure 2, together with the previously derived results from the LAT and the higher-energy, non-simultaneous data points obtained by the Cherenkov telescope experiments. As one can see there, the LAT data along the whole orbit are still best described by a power-law with an exponential cutoff. The relative TS value [24] comparing a fit with a power-law and a fit with a power-law with an exponential cutoff clearly favors the latter. We have also tested a broken power-law shape as an a priori assumption to fit the data, but a power-law with exponential cutoff is still prefered.

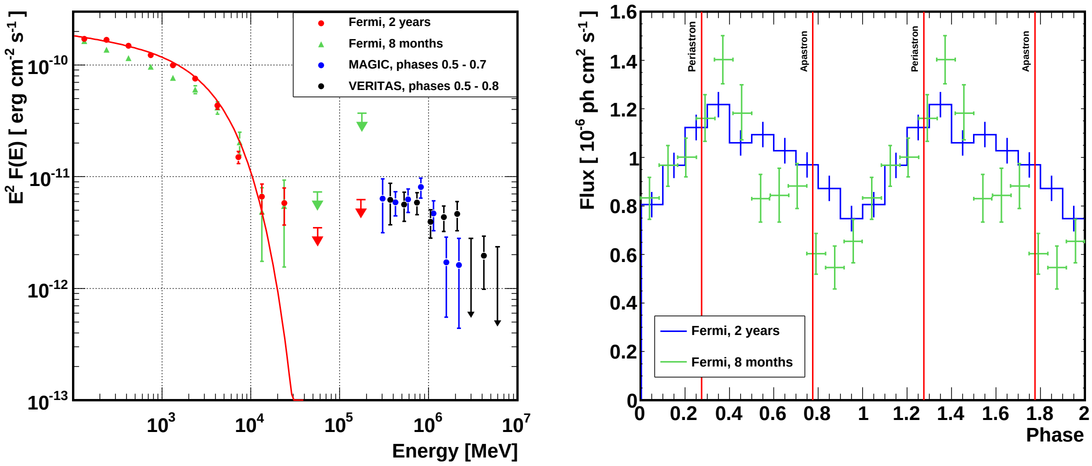

Figure 2: LS I +61°303 *Left:* The overall spectrum (red) in comparison with the earlier published one (green) over 8 months is shown. Also, very high-energy data points from MAGIC and VERITAS are plotted, but one has to keep in mind that they are not simultaneous. *Right:* The corresponding folded lightcurves for the published data set (green) and the new data set over 2 years. Note that all plots are preliminary.

4.2 Average flux change around March 2009

LS I +61°303 is one of the brightest sources in the γ-ray sky and towers above other emitters in its neighborhood. This has allowed to clearly detect, in March 2009, $\sim$40% increase on the average flux. We graphically show the flux change in Figure 3, by plotting the folded lightcurves before and after the found transition in March 2009. Before the transition, the modulation was clearly seen and is compatible with the already published phasogram, whereas afterwards, the modulation gets fainter. Note that the datasets corresponding to the reported results [3] and what we here referred to as *before the flux change* span almost exactly the same time range, with the consequence of our current analysis essentially reproducing the one previously published. The time range covered by our earlier publication coincidentally finished just prior to the flux change. The spectra derived before and after this flux change are also shown in Figure 3, where the increase in flux is also obvious. The earlier-published spectrum, based on the first 8 months of data, is shown in grey. Again, it is basically coincident with the spectrum obtained using data before the flux change (red), and can thus be barely seen in the figure.

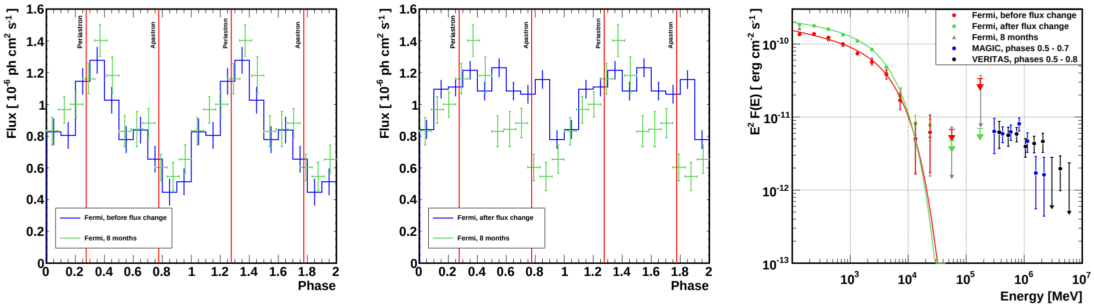

Figure 3: LS I +61°303 *Left:* Folded lightcurve before the flux change (blue), when the modulation is still clearly visible. *Middle:* Folded lightcurve after the flux change, in March 2009 (blue). The modulation gets fainter. *Right:* Comparison of the spectra derived before (red) and after (green) the flux change in March 2009. Note that all plots are preliminary.

5. Summary

After two years of continous data taking of the two binary systems LS 5039 and LS I +61°303 we confirm that their energy spectra are best described by a power law function with an exponential cutoff. For LS 5039 in comparison with earlier publications of these sources, with larger data set at hand we can extend the observed spectrum to higher energies. No significant emission of LS I +61°303 above 30 GeV has been detected with the *Fermi*-LAT yet. Furthermore, in the case of LS I +61°303 variable modulation in the folded light curves was observed. Before a flux change in March 2009, the modulation was clearly visible, whereas afterward it faints away. This behavior was not predicted by any theoretical model so far and has to be investigated further.

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