Fermi LAT Observations of LS I +61°303: First detection of an orbital modulation in GeV Gamma Rays

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***Abstract*. The first results from the observations of LS I +61°303 using Large Area Telescope data from the *Fermi Gamma-Ray Space Telescope* between 2008 August and 2009 March are presented here. Our results indicate variability that is consistent with the binary period, with the emission being modulated at 26.6 ± 0.5 days. This constitutes the first detection of orbital periodicity in high-energy gamma rays (>20 MeV, HE). The light curve is characterized by a broad peak after periastron, as well as a smaller peak just before apastron. The spectrum is best represented by a power law with an exponential cutoff, yielding an overall flux above 100 MeV of 0.82 ± 0.03(stat) ± 0.07(syst) 10^{-6} ph cm^{-2} s^{-1}, with a cutoff at 6.3 ± 1.1(stat) ± 0.4(syst) GeV and photon index Γ = 2.21 ± 0.04(stat) ± 0.06(syst). There is no significant spectral change with orbital phase. These results suggest the link between HE and VHE gamma rays is nontrivial.**

***Keywords*: Binaries, Fermi, LS I +61°303**

I. INTRODUCTION

LS I +61°303 is an unusual binary system exhibiting strong variable emission from the radio to X-ray and TeV energies. At radio wavelengths the source has been shown to exhibit radio outbursts that are modulated on an orbital period of 26.4960 ± 0.0028 days (Taylor & Gregory, 1982; Gregory, 2002). The phase of radio maximum has also been shown by Gregory (2002) to vary with a super-orbital period of 1667 ± 8 days. Observations of orbital modulation in the optical constrain the binary system parameters. The binary has an eccentric orbit (e=0.55-0.72) and the Be star radial velocity is consistent with a neutron star companion or, if the orbital inclination is $\leq 25°$, with a $\geq 3M_{\odot}$ black hole (Hutchings & Crampton, 1981; Casares et al., 2005). Significant uncertainty still exists in key parameters of the orbital solution of the system (Grundstrom et al., 2007; Aragona et al., 2009).

The MAGIC telescope detected a variable very high-energy (VHE >100 GeV) gamma-ray source coincident with LS I +61°303 (Albert et al., 2006); a result that has been independently confirmed by the VERITAS collaboration (Acciari et al., 2008). More recently, the MAGIC collaboration has further reported that the VHE emission is periodic at the 26.5 day orbital period of the system (Albert et al., 2009).

II. DATA REDUCTION AND RESULTS

The *Fermi Gamma-ray Space Telescope* was launched on 2008 June 11, from Cape Canaveral, Florida. The Large Area Telescope (LAT) is an electron-positron pair production telescope, featuring solid state silicon trackers and cesium iodide calorimeters, sensitive to photons from ~ 20 MeV to > 300 GeV (Atwood et al., 2009). Relative to earlier gamma-ray missions the LAT has a large ~ 2.4 sr field of view, a large effective area (~ 8000 cm^2 for >1 GeV on axis) and improved angular resolution or point spread function (PSF, better than 1° for 68% containment at 1 GeV). The *Fermi* survey mode operations began on 2008 August 4. The dataset for this analysis spanned 2008 Aug 4, through 2009 Mar 24. Thus LS I +61°303 was observed for approximately 9 orbital periods.

The data were reduced and analysed using the *Fermi* Science Tools v9r8 package[1]. The standard onboard filtering, event reconstruction, and classification were applied to the data (Atwood et al., 2009), and for this analysis the high-quality (”diffuse”) event class is used. Time periods when the region around LS I +61°303 was observed at a zenith angle greater than 105° were also excluded to avoid contamination from Earth albedo photons. With these cuts, a photon count map of a 10° region around the binary is shown in Fig. 1. The alignment of the LAT pointing direction with the celestial frame was calibrated using a large set of high latitude gamma-ray sources to better than 10″ (Abdo et al., 2009b). The position of LS I +61°303 was found to be R.A. = 02^{h}40^{m}22^{s}.3, Dec. = 61°13′ 30″ (J2000) with a 95% error of 0.069°; in agreement with the accepted position (Dhawan, Mioduszewski, & Rupen, 2006). More details of the analysis are available in (Abdo et al., 2009c).

A. Spectral Analysis

The `gtlike` likelihood fitting tool was used to perform the spectral analysis, with ”Pass 6 v3” (P6_V3) instrument response functions (IRFs); the P6_V3 IRFs are a post-launch update to address gamma-ray detection inefficiencies that are correlated with trigger rate. The 10 degree region around the source was modeled for Galactic and extragalactic diffuse emission, and included

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

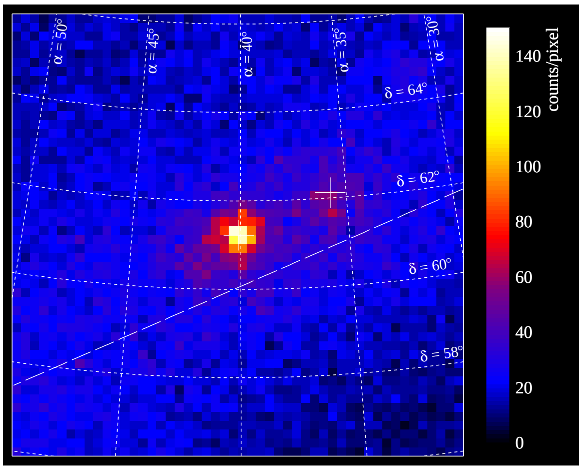

Fig. 1: 10° counts map for 100 MeV–300 GeV in (RA,Dec) around the LS I +61°303 location. The exposure varies by less than 2.5% across the field at a representative energy of 10 GeV. The source is bright and fairly isolated, sitting on a background of Galactic and extragalactic diffuse emission. A fit to the source yields a significance of more than 70 σ. The dashed line indicates the Galactic equator (b =0); the crosses indicate the location of LS I +61°303 (the brighter source) and a faint nearby point source.

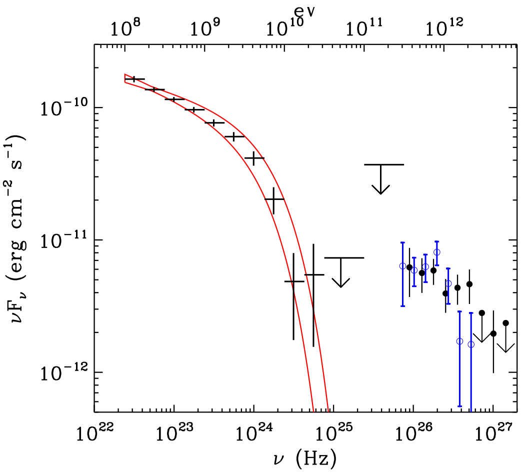

Fig. 2: Fitted spectrum of LS I +61°303. The solid red lines are the $\pm 1\sigma$ limits of the *Fermi* cutoff power law; blue (open circle) data points from MAGIC, black (filled circle) data points from VERITAS. Data points in the *Fermi* range are likelihood fits to photons in those energy bins. Note that the data from the different telescopes are not contemporaneous, though they do cover multiple orbital periods.

one nearby point source at (R.A., Dec) of (35.8°, 62.0°), too faint to be found in the 3-month Bright Source List (Abdo et al., 2009a). This source contributed approximately 13% to the flux at the location of LS I +61°303. The 10° region was chosen to capture the broad PSF obtained at 100 MeV. An alternate fitting method using

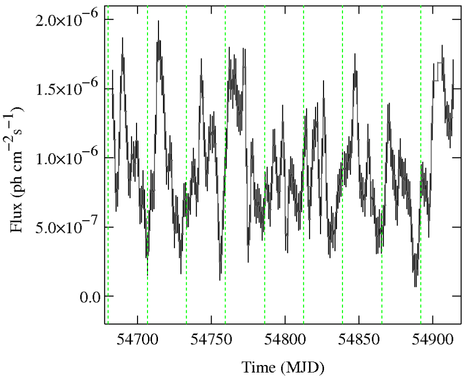

Fig. 3: The 100 MeV to 20 GeV light curve of LS I +61°303 covering the period 2008 August 4 through 2009 March 24. The vertical lines indicate the zero phase from Gregory (2002). The light curve has been rebinned and smoothed from its original 11,478s time resolution to enable variability to be seen.

energy-dependent regions of interest was used, yielding compatible results that were folded into the systematic errors.

An exponential cutoff was used, in the form $E^{-\Gamma}\exp\left[-(E/E_{\rm cutoff})\right]$. The chance probability to incorrectly reject a power law hypothesis was found to be 1.1×10^{-9}. The best fit exponential cutoff returns a test statistic (Mattox et al., 1996) significance value of about 4770, or roughly 70σ. The photon index is Γ =2.21 $\pm$ 0.04 (stat) $\pm$ 0.06 (syst); the flux above 100 MeV is (0.82 $\pm$ 0.03 (stat) $\pm$ 0.07 (syst)) $\times10^{-6}$ ph cm^{-2} s^{-1} and the cutoff energy is 6.3 $\pm$ 1.1(stat) $\pm$ 0.4(syst) GeV (see below for a discussion of systematics). A total of 135,659 photons were found in the 10° region. Evaluating the fit parameters, 6467 $\pm$ 80 photons were observed from LS I +61°303 above 100 MeV. Fig. 2 shows the best fit cutoff power law model as well as the fluxes fit per energy bin and archival data from MAGIC (Albert et al., 2009) and VERITAS (Acciari et al., 2008).

A number of effects are expected to contribute to the systematic errors. Primarily, these are uncertainties in the effective area and energy response of the LAT as well as background contamination. These are currently estimated by using outlier IRFs that bracket our nominal ones in effective area. These are defined by envelopes above and below the P6_V3 IRFs by linearly connecting differences of (10%, 5%, 2%) at log(E/MeV) of (2, 2.75, 4) respectively. Other effects considered are: fitting technique, cuts applied (zenith angle; minimum and maximum energies), and details of the diffuse modeling, but they are all smaller than the bracketing effective area variations that are intended to give an upper limit on the systematics.

B. *Timing Analysis*

The aperture and energy band employed were independently chosen to maximize the signal-to-noise level.

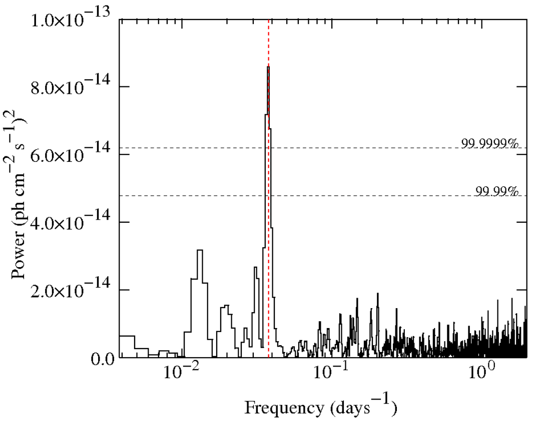

Fig. 4: Power spectrum of the light curve. The vertical line indicates the known orbital period from Gregory (2002), coinciding with a strong peak in the spectrum, while the horizontal lines indicate the marked significance levels.

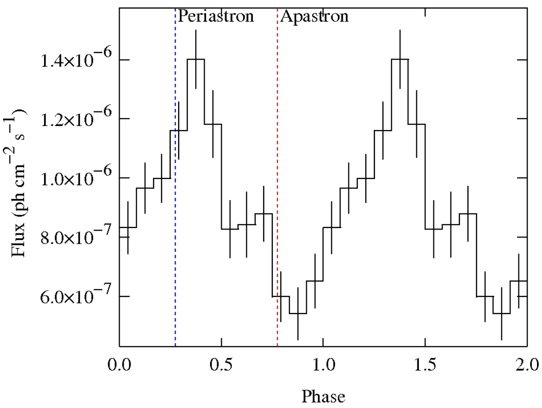

Fig. 5: Folded light curve of LS I +61°303 binned in orbital phase, see text for details.

The optimum aperture radius was found to be approximately 2.4° in the energy range 100 MeV-20 GeV, with a time resolution of 11,478 s, equal to twice the *Fermi* orbital period.

The light curve, rebinned from its original time resolution and smoothed to enable variability to be seen, is shown in Fig. 3. Contributions from the nearby source and Galactic and extragalactic diffuse backgrounds were estimated based on the spectral fit and subtracted from the light curve

A search was made for periodic modulation by calculating the periodogram of the light curve (Lomb, 1976; Scargle, 1982). Since the exposure of the time bins was variable, the contribution of each time bin to the power spectrum was weighted based on its relative exposure. The periodogram of the unbinned, unsmoothed light curve is shown in Fig. 4. The vertical line marks the Gregory (2002) orbital period and a highly significant peak is detected at this period. The significance levels marked are for a "blind" search with 500 independent frequency steps, however, the effects of the tuning of the aperture radius and energy range are not taken into account. The period and its error from the LAT observations were estimated using a Monte-Carlo approach: light curves were simulated using the observed LS I +61°303 light curve and randomly shuffling the data points within their statistical errors, assuming Gaussian statistics, and yielded an associated error of 26.6 $\pm$ 0.5 days (1σ).

The binned LAT light curve folded on the Gregory (2002) period with zero phase at $\mathrm{MJD}\ 43,366.2749$ (Gregory et al., 1979) is shown in Fig. 5. The folded light curve shows a large modulation amplitude with maximum flux occurring slightly after periastron passage. In addition, Fig. 5 shows a possible secondary peak at around phase 0.7, prior to apastron. While the primary peak is seen to appear every orbit (Fig. 3), the constancy of the secondary peak is difficult to assess due to its relative weakness compared to the primary.

C. Phase resolved spectral analysis

The possibility of the spectral shape changing across the orbit was explored by running `gtlike` fits for phase-folded bins of 0.1 width. There is no significant dependence of photon index on phase; a fit to a constant value returns a reduced χ^2 /d.o.f of 1.4 for 9 d.o.f, consistent with no variation.

III. DISCUSSION AND CONCLUDING REMARKS

The *Fermi* data enable for the first time the detection of a modulation in GeV gamma rays at the orbital period of a binary system. The derived period is in excellent agreement with the radio and optical-based ephemeris Gregory (2002). The COS-B source 2CG 135+01 is now firmly identified as the gamma-ray counterpart to LS I +61°303, resolving a 30-year long suspicion that the two were associated. With the identification originally based on localization only, the detection of orbital-modulated very high-energy emission ($>$100 GeV, VHE) from LS I +61°303 by MAGIC and VERITAS (Albert et al., 2006, 2009; Acciari et al., 2008) had already provided very strong support in favour of this association.

The folded *Fermi* light curve peaks around phase 0.3, which is compatible with periastron passage (when the compact object is closest to the Be star) according to the latest radial velocity studies (Aragona et al., 2009). This contrasts with the behavior at very high energies where peak flux occurs at phases 0.6-0.7 and detections are achieved only at phases ranging from 0.5 to 0.8, before or at apastron. The folded *Fermi* light curve also suggests a secondary peak at phase 0.7, giving a possible connection to the behavior at other frequencies.

The average *Fermi* and EGRET spectra have compatible power law indices and fluxes taking into account systematics, but the *Fermi* spectrum also shows a cutoff at approximately 6 GeV. There is no evidence for a phase-dependence of the index or cutoff energy.

Continued monitoring by *Fermi* combined with dedicated campaigns by pointed instruments is needed to better constrain spectral variability and establish the multiwavelength connections: how do orbit-to-orbit variations compare in different energy ranges? Are there separate HE and VHE spectral components?

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