Exceptionally Bright TeV Emission From the Binary LS I +61° 303

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ABSTRACT

The TeV binary system LS I +61° 303 is known for its regular, although not entirely understood, non-thermal emission pattern, which traces the orbital period of the compact object in its 26.5 day orbit around its Be star companion. When active in the TeV regime, the system typically presents elevated emission around apastron passage with flux levels in the $5-15\,\%$ Crab Nebula range (above 350 GeV). In this article, VERITAS observations of LS I +61° 303 taken in late 2014 are presented, in which bright TeV flares around apastron at flux levels peaking above 30% of the Crab Nebula flux were detected. This is the brightest such activity ever seen in the TeV regime. Low-level TeV emission is also detected close to periastron. The strong outbursts have rise times of $1-2$ days and a typical $1-2$ day duration; during the 2014 observations LS I +61° 303 was seen to go from a quiescent TeV state to one in which $> 10\,$TeV emission was detected from the system. This short acceleration time for particles (for galactic scale objects) provides strong constraints on the nature of the accelerating mechanism in LS I +61° 303.

Subject headings:

1. Introduction

The current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) has opened up the study of high mass X-ray binary star systems which also present TeV emission on various timescales. The class of TeV binaries is quite sparse, consisting of only a handful of sources: LS 5039, PSR B1259-63, LS I +61° 303, HESS J0632+057 and HESS J1018-589. Of these, only the compact object of PSR B1259-63 has been firmly identified as a pulsar; there is still a large degree of ambiguity concerning the nature of the compact object within the other systems, and consequently, the fundamental setup which produces the TeV emission along with its characteristic variability on the orbital period timescale. For instance, the presence of a pulsar within a given TeV binary indicates that the emission in the system is generated by the shock formed at the interface between the pulsar and stellar winds. The orbital variability is therefore driven principally by the varying density of the stellar wind that the pulsar encounters in its orbit. In the case of a black hole companion, the emission is driven by an accretion-powered jet.

The orbital periods of these objects vary from several days (LS 5039) to several years (PSR B129-63), and as a result, the various sources may only present short windows during which they can be studied in the TeV regime. Of the TeV binaries, LS I +61° 303 is the only known source in the Northern Hemisphere which has a short enough orbital period (26.5 days) to allow for regular study with TeV instruments. This has made it an excellent target for Northern Hemisphere TeV observatories.

LS I +61° 303, located at a distance of ~ 2 kpc, is composed of a B0 Ve star and a compact object (Hutchings & Crampton 1981; Casares et al. 2005). The observed radio through TeV emission is variable and modulated with a period of $P \approx 26.5$ days, believed to be associated with the orbital structure of the binary system (Albert et al. 2006; Esposito et al. 2007; Acciari et al. 2008;

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Abdo et al. 2009; Li et al. 2012; Massi et al. 2015). Radial velocity measurements show the orbit to be elliptical ($e = 0.537 \pm 0.034$), with periastron passage occurring around phase $\phi = 0.275$, apastron passage at $\phi = 0.775$, superior conjunction at $\phi = 0.081$ and inferior conjunction at $\phi = 0.313$ (Aragona et al. 2009). However, the inclination of the system is not exactly known, leading to some uncertainty of the orbital parameters.

As a TeV source, LS I +61° 303 has presented puzzling behavior. Initial detections in 2006 – 2007 by both the MAGIC (Albert et al. 2006) and VERITAS (Acciari et al. 2008) collaborations over many orbital cycles showed the source to be a variably bright TeV source, with emission peaking around apastron passage. Subsequent observations in 2008 – 2010 (Acciari et al. 2011) showed no evidence for emission during these previously detected phases, instead only detecting the source at a lower TeV flux near the periastron passage of a single orbit.

However, VERITAS observations taken in Nov – Dec 2011 showed the source to be highly active around apastron again (Aliu et al. 2013), similar to the behavior observed in 2006 – 2007. Since 2011, observations of LS I +61° 303 by VERITAS have only revealed typical emission levels, i.e., 5 – 15% of the Crab Nebula flux, with emission peaking around apastron. In this work we present the results of the VERITAS campaign on LS I +61° 303 in the Fall of 2014. During this time, VERITAS observed historically bright flares from LS I +61° 303 around apastron, with the source exhibiting flux levels a factor of 2 – 3 times higher than previously seen.

2. Observations

The VERITAS IACT array, located at the base of Mt. Hopkins, AZ (1.3 km a.s.l., 31°40' N, 110°57' W) consists of four 12 m diameter Davies-Cotton design optical telescopes. VERITAS is sensitive from 85 GeV to 30 TeV, and has the ability to detect a 1 % Crab Nebula source in approximately 25 hours[1]. For a full description of the hardware components and analysis methods utilized by VERITAS, see Holder et al. (2008); Kieda, D., for the VERITAS Collaboration (2013); Acciari et al. (2008), and references therein.

In the 2014 season, VERITAS observations of LS I +61° 303 were taken from October 16 (MJD 56946) to December 12 (MJD 57003), obtaining a total of 24.7 hours of quality selected livetime. These observations covered three separate orbital periods of LS I +61° 303, sampling the orbital regions of $\phi = 0.5 - 0.2$ (see Figure 1). Over the entire set of observations, a total of 449 excess events above background were detected, equivalent to a significance of 21σ calculated using Equation 17 of Li & Ma (1983).

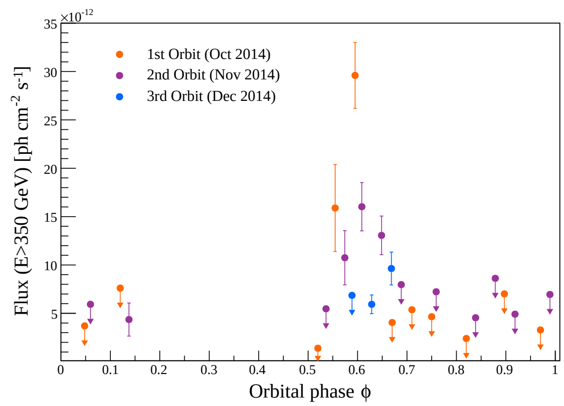

Fig. 1.— Light curve of LS I +61° 303 during the 2014 observation season **Describe axes and the UL criteria.**

During the first orbit observed (in October), the source presented the largest of its flares (hereafter "F1"), beginning on 17 October 2014 (MJD 56947, $\phi = 0.55$) with emission reaching a peak of $3.0 \pm 0.3 \times 10^{-11}$ photons cm^{-2} s^{-1} (>350 GeV) on October 18 (MJD 56948). This flare peaked at approximately 30% of the Crab Nebula flux in the same energy range, representing the largest flux ever detected from the source. Unfortunately, observations were limited by poor weather conditions for two nights following this peak and only recommenced on October 20 (MJD 56950), by which time the source had already quietened down. As can be seen in Figure 1, this flare is rather sharply defined: only one night before the flare began, the source was in a quescient state with a 99% confidence upper limit of emission of 1.4×10^{-11} photons cm^{-2} s^{-1} (>350 GeV). **This short variabil-**

[1]http://veritas.sao.arizona.edu/about-veritas-mainmenu-81/veritas-specifications-mainmenu-111

ity fast confirms the result of (Aliu et al. 2013).

During the November observation (second orbital passage), VERITAS detected another period of high activity for the source at similar orbital phases ($\phi = 0.5 - 0.6$) with similar flux levels detected. Follow-up observations conducted by VERITAS during the next month (2014 December 10−12) covered the orbital phases of $\phi = 0.59 - 0.67$ and detected the source at a lower flux level of $\sim 1.7 \times 10^{-11}$ photons cm^{-2} s^{-1} (>350 GeV).

During the 2014 observing season, the differential energy spectrum of LS I +61° 303 was consistent with past observations, i.e., the emission in the 0.2 − 25 TeV range is well fit by a power-law described by $(1.70 \pm 0.69_{\rm stat}) \times 10^{-12} \cdot \left(\frac{E}{1\rm TeV}\right)^{-2.35 \pm 0.32_{\rm stat}}$ cm^{-2} s^{-1} TeV^{-1}, as can be seen in Figure 2.

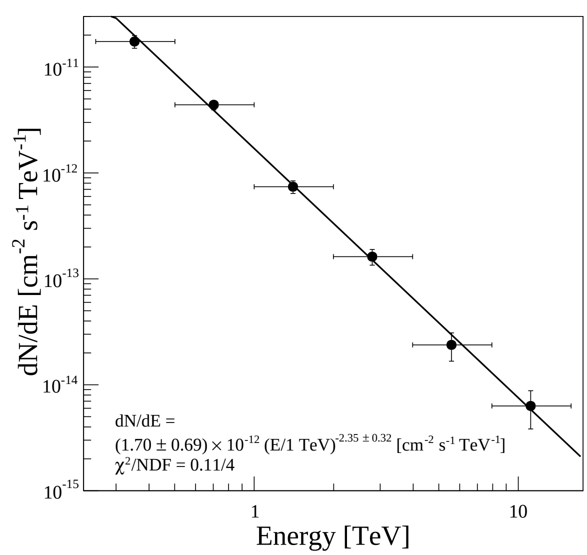

Fig. 2.— Average differential energy spectrum of LS I +61° 303.

During these observations, the source was also monitored by *Fermi*-LAT (0.1−300 GeV), *Swift*-XRT (0.2−10 keV), and both the RATAN and AMI radio instruments (4/6−15 Ghz). In addition, H-alpha monitoring of the system took place with the Ritter Observatory in Toledo, Ohio (USA). After the second flare (November) was detected by VERITAS, Atel #6785 **ref** was released, notifying the astronomical community of the historic flux levels and triggering more intense observations with the existing multiwavelength partners, as well as additional observations with the MAGIC TeV observatory. The results of this campaign are under analysis and will be presented in an upcoming publication.

3. Discussion and Interpretation

Following number calculated from ED analysis - need numbers from VEGAS for the final version!

- The VHE light curve is inconsistent with a constant flux at $14.6\,\sigma$
- Orbit 1 is inconsistent with a constant flux at $8.3\,\sigma$
- Orbit 2 is inconsistent with a constant flux at $8.4\,\sigma$
- No evidence for intra-night variability
  - Peak night of F1 fit with constant flux model, $\chi^2/NDF = 8.186/2$, $P = 0.01669$, → inconsistent with model at $2.4\,\sigma$
  - Peak night of F2 fit with constant flux model, $\chi^2/NDF = 7.539/4$, $P = 0.11$, → inconsistent with model at $1.6\,\sigma$
  - ⇒ accept model for both cases
- Orbit 1 and 2 (in daily bins, as now we know there is not intra-night variability) fit with a constant + a Gaussian to accommodate a flare superimposed on a base line flux
  - Orbit 1: Fixed mean of Gaussian to 56947.8 (highest measured flux point), as the fit did not converge otherwise. Obtained $\chi^2/NDF = 16.97/8$, $P = 0.03046$, with a $FWHM = 0.665 \pm 0.0987$ for a rise and fall time of ~ 2 days.
  - Orbit 2: All parameters remained free, mean of Gaussian naturally converged to highest measured flux point. Obtained $\chi^2/NDF = 6.298/8$, $P = 0.6139$, with a $FWHM = 0.853 \pm 0.112$ for a rise and fall time of ~ 2.5 days.

- Shortest significant flux variability timescale is 1.8 days, at $7.15\,\sigma$ (between 1st and 3rd night of F1)
  - 1-day variability at $3.56\,\sigma$ (this is max sigma for 1-day var, measured between 1st and 2nd night of F1)
- Average ED spectrum: $8.6 \times 10^{-12} \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-2.24\pm0.19}$
- ED spectrum on peak night of F1: $7.1 \times 10^{-12} \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-2.41\pm0.17}$
- ED spectrum on peak night of F2: $1.9 \times 10^{-12} \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-2.56\pm0.08}$
- $\Rightarrow$ some evidence for spectral hardening during high flux - also seen with VEGAS?
- The highest energy photon is $\sim 10\,\mathrm{TeV}$
  - Look at model from Khangulyan et al. (LS 5039) 2008
  - Scattering is in deep KN regime where $\sim 100\%$ of the electron energy is transferred to the photon $\Rightarrow$ have at least 10 TeV electron accelerated in system
  - B-field comes out at $\sim 1\,\mathrm{G}$
  - Acceleration time is $\sim 10\eta\,\mathrm{s}$, which is a few hundred seconds
  - This is much less than our measured minimum var time, which is dominated by the data sampling
- Optical depth?
- Could short-term var be due to sudden changes in transparency?

REFERENCES

Abdo, A., et al. 2009, ApJ, 701, L123

Acciari, V., et al. 2008, ApJ, 679, 1427

Acciari, V. A., Aliu, E., Arlen, T., et al. 2011, ApJ, 738, 3

Albert, J., et al. 2006, Science, 312, 1771

Aliu, E., Archambault, S., Behera, B., et al. 2013, ApJ, 779, 88

Aragona, C., et al. 2009, ApJ, 698, 514

Casares, J., et al. 2005, MNRAS, 360, 1105

Esposito, P., Caraveo, P. A., Pellizzoni, A., et al. 2007, A&A, 474, 575

Holder, J., et al. 2008, American Institute of Physics Conference Series, 1085, 657

Hutchings, J., & Crampton, D. 1981, PASP, 93, 486

Kieda, D., for the VERITAS Collaboration. 2013, in Proceedings of the 33rd International Cosmic Ray Conference (ICRC2013)

Li, J., et al. 2012, ApJ, 744, L13

Li, T.-P., & Ma, Y.-Q. 1983, The Astrophysical Journal, 272, 317

Massi, M., Jaron, F., & Hovatta, T. 2015, A&A, 575, L9