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Superorbital variability of the gamma-ray binary LS I +61 303 studied with MAGIC

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Abstract. The gamma-ray binary LS I +61 303 has been detected from radio up to very high–energy gamma rays. Its emission is likely originated by the interaction of the stellar wind and a relativistic outflow. The broadband emission shows a periodicity of about 26.6 days, coincident with the orbital period. A long-term periodicity of 1667 ± 8 days was discovered in radio and confirmed in optical and high–energy gamma rays. Here we will present the results of a four-year campaign performed by MAGIC together with archival data. In this campaign, we search for a long-term signature in the VHE emission from LS I +61 303. We will focus on the search for super orbital modulation of the VHE emission, similarly to the one observed at other wavelengths, and on the search for (anti-)correlation between the TeV emission and the extension of the circumstellar disk, measured using optical data.

1. Introduction

Of those currently known, LS I +61 303 is one of the most powerful and complex gamma-ray binaries. This system is comprised of a young main sequence B0 Ve star and a compact object orbiting it with a period of $P_{\rm orb} = 26.4960 \pm 0.0028$ d (Gregory 2002) and an eccentricity of $e = 0.72 \pm 0.15$ (Casares et al. 2005). The system is located at 2.0 ± 0.2 kpc (Frail & Hjellming 1991), and the periastron passage takes place in the orbital phase range 0.23–0.28 (Casares et al. 2005; Aragona et al. 2009), using $\mathrm{JD}_0 = 2\,443\,366.775$. Extended emission at mas scales (∼1–100 AU) has been reported at GHz frequencies, showing morphological changes along the orbit (Massi et al. 2004; Dhawan et al. 2006; Moldón 2012).

The emission of LS I +61 303 is orbitally modulated from radio to gamma-rays. At radio frequencies, the spectrum is produced by synchrotron emission. The 1–10 GHz radio light-curve of the source shows a clear outburst on each orbital cycle that increases the $\lesssim 50$ mJy steady flux density emission up to $\sim$100–200 mJy. These outbursts are periodic, although changes in their shape and intensity have been reported from cycle to cycle (Paredes et al. 1990; Ray et al. 1997). A similar periodicity ($\sim$26.5 d) has been detected at optical and infrared bands (Mendelson & Mazeh 1989; Paredes et al. 1994), at X-rays (Paredes et al. 1997; Torres et al. 2010), at high energies (HE; 100 MeV–20 GeV) by *Fermi-LAT* (Abdo et al. 2009), and at very high energies (VHE; 20 GeV–TeV) by MAGIC (Albert et al. 2009).

A long-term modulation is also observed, from radio to HE wavelengths, the so-called superorbital modulation, with a period of $P_{\rm so} = 1\,667 \pm 8$ d or $\simeq$4.6 yr (Gregory 2002). This modulation was first found at GHz radio frequencies (Paredes 1987; Gregory et al. 1989; Paredes et al. 1990), affecting the amplitude of the non-thermal periodic outbursts and the orbital phases at which the onset and peak of these outbursts take place, drifting from orbital phases of $\sim$0.45 to $\sim$0.95 (Gregory 2002). The source exhibits the minimum activity at GHz frequencies during the superorbital phase range of $\phi_{\rm so} \sim$ 0.2–0.5, whereas the maximum activity takes place at $\phi_{\rm so} \sim$ 0.78–0.05 (using the same $\rm JD_0$ quoted above). This $\simeq$4.6 yr modulation has also been observed at optical (Zamanov et al. 2013), X-rays (Chernyakova et al. 2012; Li et al. 2014), and HE by *Fermi-LAT* (Ackermann et al. 2013). In order to determine if this modulation is also present at VHE energies, we carried out a multi-year campaign with MAGIC.

The origin of the superorbital modulation was proposed to be related to periodic changes in the circumstellar disc and the mass-loss rate of the Be star (Zamanov et al. 2013), although other interpretations within the framework of a precessing jet have been also discussed (see Massi & Torricelli-Ciamponi 2014, and references therein).

2. Observations

A four-year (August 2010–September 2014) campaign was carried out with the MAGIC telescopes together with the Liverpool optical telescope. With the aim of detecting a possible long-term modulation, LS I +61 303 was observed with MAGIC during the orbital phase range $\phi_{\rm orb} = 0.5$–0.75, where the TeV emission outburst peak is present. Furthermore, in order to search for (anti-)correlation between the Be star mass-loss rate and the TeV emission, contemporaneous observations with MAGIC and Liverpool telescope were performed during the orbital phase range $\phi_{\rm orb} = 0.75$–1.0, where the TeV emission does not present yearly periodic variability (Aleksic et al 2012). For technical details of the observations and the analysis and data reduction see Ahnen et al. (2016).

3. Results

The VHE spectrum for the different campaigns follows a power-law with spectral index α. Figure 1 shows the dependence of α with the phase of the superorbital period of 1667 days. The values of α obtained are compatible with a constant value of 2.43 ± 0.04. The spectral index also does not show variability for each of the different observational campaigns, for orbital intervals $\phi_{\rm orb} = 0.5$–0.75 and $\phi_{\rm orb} = 0.75$–1.0, and for epochs when the source was in high– or low–flux states.

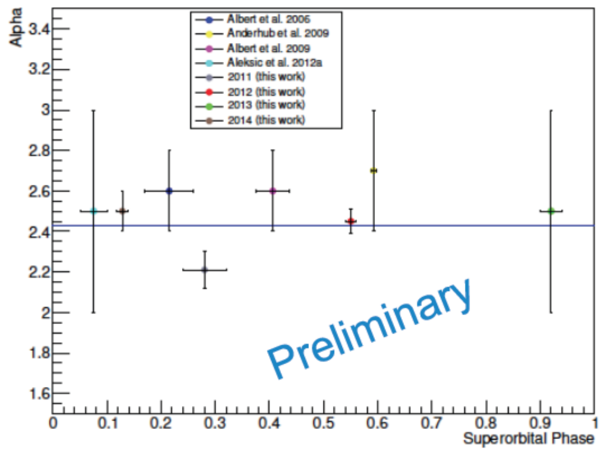

Figure 1. Spectral index dependence of all MAGIC campaigns with the superorbital period (1667 d). The average value of all MAGIC data is represented by the blue line.

In order to have enough data to search for superorbital modulation at VHE, we have added to our four-year campaign archival data from MAGIC obtained since its detection in 2006 (Albert et al. 2008; Anderhub et al. 2009; Albert et al. 2009; Aleksic et al. 2012), and data from VERITAS (Acciari et al. 2008, 2009, 2011; Aliu et al. 2013). Figure 2 shows the peak integrated flux above 300 GeV for each orbit folded into the superorbital period. The data were fit with a sinusoide and a constant function, being the probability for a constant flux negligible (4.5×10^{-12}), and for a sinusoidal signal 8%. This seems to indicate that there is a superorbital signature in the TeV emission of LS I +61 303 and that it is compatible with the 4.5-year radio modulation seen at other frequencies.

We have explored possible correlations between the H_α parameters (EW, FHWM, profile centroid velocity) measured by the Liverpool telescope, and the TeV flux measured by MAGIC, for data in the orbital phase range $\phi_{\rm orb} = 0.75$–1.0. No significant correlation was found from the statistical test performed on the sample within this phase interval. Figure 3 shows the EW, FHWM, and profile centroid velocity as a function of the TeV flux.

4. Discussion and Conclusions

In this paper we presented the first detection of superorbital variability in the TeV regime using new MAGIC data and archival MAGIC and VERITAS data. The detection of superorbital variability at TeV/VHE energies is consistent with the predicted long-term behavior of the flip-flop model (Zamanov et al. 2001, Torres et al. 2012, Papitto et al. 2012) that considers LS I +61 303 as a pulsar-Be star binary that changes (driven by the influence of matter) from a propeller regime in periastron to an ejector regime in apastron. This result also confirms the earlier observational hints for this phenomenology discovered using smaller samples of TeV data (Li et al. 2012).

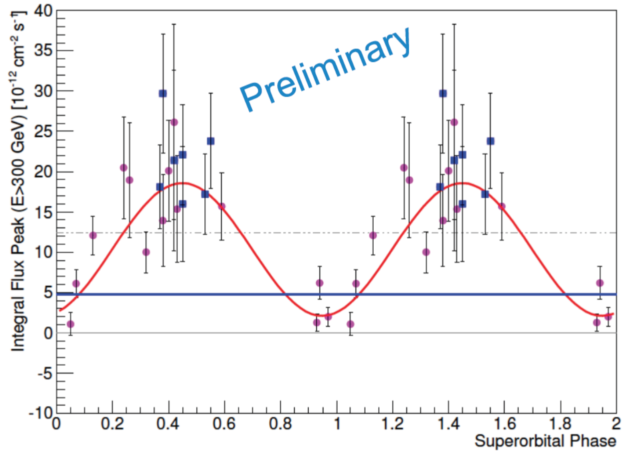

Figure 2. VHE peak flux emitted during orbital phases 0.5 − 0.75 in different orbital periods folded into the superorbital 1667 d period. MAGIC data are magenta dots and VERITAS data blue squares. The solid red line represents the fit with a sinusoidal function and the blue line the fit with a constant. The 10% of the Crab Nebula flux is represented by a grey dashed line whereas the grey solid line marks the zero level.

No statistically significant correlation between the H_α parameters and the TeV emission has been found. However, this lack of (anti-)correlation could be due to the fast and extreme changes in the H_α data of the source (Zamanov et al. 2013), and the vastly different integration times (minutes vs. several hours) in both frequencies may blur finding any possible trend.

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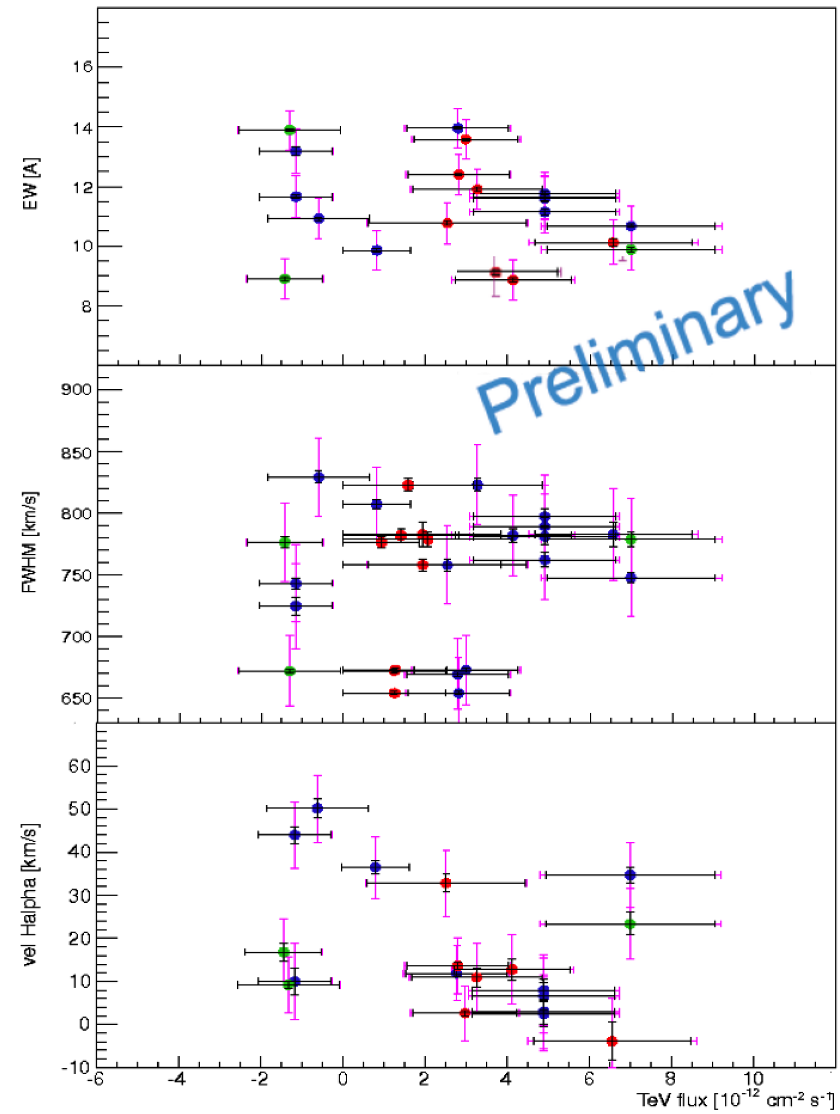

Figure 3. Correlations between the TeV flux obtained by MAGIC and the H_α parameters (EW, FWHM and velocity) measured by the Liverpool telescope, for the extended orbital interval $0.75 - 1.0$. Optical data corresponds to 10 minutes observation whereas TeV data has a variable integration time. The different color means that the optical and TeV data were taken nightly (blue), contemporary (red) and strictly simultaneous (green).

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