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Discovery of the microquasar LS I +61 303 at VHE gamma-rays with MAGIC

Núria Sidro[*] [†]
Institut de Física d'Altes Energies
Edifici Cn Universitat Autònoma de Barcelona
08193 Bellaterra (Barcelona) Spain
Tel.: +34 93 581 2834
Fax: +34 93 581 1938

E-mail: `nuria.sidro@ifae.es`

Here we report the discovery of very high energy (>100 GeV) γ-ray emission from the radio emitting X-ray binary LS I +61 303 with the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope. This high energy emission has been found to be variable, detected 4 days after the periastron passage and lasting for several days. The data have been taken along different orbital cycles, and the fact that the detections occur at similar orbital phases, suggests that the emission is periodic. Two different scenarios have been involved to explain this high energy emissions: the microquasar scenario where the gamma rays are produced in a radio-emitting jet; or the pulsar binary scenario, where they are produced in the shock which is generated by the interaction of a pulsar wind and the wind of the massive companion.

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[*]Speaker.
[†]for the MAGIC Collaboration

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1. Introduction: The MAGIC Telescope

The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope is a telescope for very high energy (VHE, $E \geq 50-100$ GeV) γ-ray observation exploiting the Imaging Air Cherenkov (IAC) technique. It is located on the Canary Island of La Palma (Spain) at, $28^{\circ}45'30''$N, 17° $52'$ $48''$W and 2250 m above sea level.

This kind of instrument images the Cherenkov light produced in the particle cascade initiated by a gamma ray in the atmosphere. MAGIC has a 17 m diameter, and a parabolic reflector, to minimize the time spread of Cherenkov light flashes on the focal plane (total surface of 234 m^2). This is currently the largest single-dish telescope in this energy band, yielding the lowest energy threshold ($\sim$50 GeV). The telescope frame is made of carbon fiber tubes, providing a very short slewing time aimed at observing the γ-ray prompt emission of GRBs. It is equipped with a 576-pixel photomultiplier camera, recording the reflected Cherenkov photons with a 3.5°-3.8° field of view.

MAGIC's sensitivity above 100 GeV is $\sim 2.5\%$ of the Crab nebula flux, the calibration standard candle for VHE telescopes, in 50 hours of observations. The energy resolution above 200 GeV is better than 30%. The angular resolution is $\sim 0.1^{\circ}$, while source localization in the sky is provided with a precision of $\sim 2'$.

Note also that MAGIC is unique among IAC telescopes by its capability to operate during moonshine and twilight under moderate illumination. The duty cycle can increase by a factor 1.5, thus allowing a better sampling of variable sources.

The physics program developed with the MAGIC telescope includes both, topics of fundamental physics and astrophysics. In this paper we present the results regarding the observations of the object LS I +61 303. Results from other galactic observations are presented elsewhere in these proceedings [22].

2. The γ-ray binary LS I +61 303

LS I +61 303 belongs, together with LS 5039 [2] and PSR B1259-63 [1], to a new class of objects, the so-called γ-ray binary systems, whose electromagnetic emission extends up to the TeV domain. In section 2.3 we will describe the possible VHE emission scenarios for this object: it was proposed as microquasar candidate, but also thought to be in a pulsar binary scenario. Thus, the question of whether the three known γ-ray binaries produce TeV emission by the same mechanism, and by which one, is currently object of an intense debate [20].

2.1 Description of the object

This γ-ray binary system is composed of a B0 main sequence star with a circumstellar disc, i.e. a Be star, located at a distance of $\sim$2 kpc. A compact object of unknown nature (neutron star or black hole) is orbiting around it, in a highly eccentric ($e = 0.72 \pm 0.15$) orbit.

The orbital period –with associated radio [13] and X-ray [25] outbursts– is 26.496 days and periastron passage is at phase 0.23 ± 0.02 [9].

Radio outbursts are observed every orbital cycle at phases varying between 0.45 and 0.95 with a 4.6 years modulation [14].

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High-resolution radio imaging techniques have shown extended, radio-emitting structures with angular extension of ∼0.01 to ∼0.1 arc-sec, interpreted within the framework of the microquasar scenario, where the radio emission is originated in a two-sided, possibly precessing, relativistic jet ($\beta/c = 0.6$) [19]. However, the two-sided jets were not completely resolved and no solid evidence of the presence of an accretion disk (i.e. a thermal X-ray component) has been observed. There are hints of variability of the γ-ray flux [24].

LS I +61 303 was considered as one of the two microquasar candidates positionally coincident with EGRET γ-ray sources [17], and the only one located in the Northern Hemisphere –hence a suitable target for MAGIC. The large uncertainty of the position of the EGRET source did not allow an unambiguous association.

2.2 MAGIC observations

LS I +61 303 was observed with MAGIC for 54 hours (after standard quality selection, discarding bad weather data) between October 2005 and March 2006 [6]. As mentioned above, MAGIC is able to operate in moderate moon conditions, and in particular, 22% of the data used in this analysis were recorded under moonlight. The data analysis was carried out using the standard MAGIC reconstruction and analysis software [3, 5, 4].

The reconstructed γ-ray map is shown in Figure 1. The data were first divided into two different samples, around periastron passage ($\Phi = 0.2-0.3$) and at higher ($\Phi = 0.4-0.7$) orbital phases. No significant excess in the number of γ-ray events is detected around periastron passage, whereas there is a clear detection (9.4σ statistical significance) at later orbital phases.

The distribution of γ-ray excess is consistent with a point-like source located at (J2000): $\alpha = 2^{\mathrm{h}}40^{\mathrm{m}}34^{\mathrm{s}}$, $\delta = 61^{\circ}15'25''$, with statistical and systematic uncertainties of $\pm 0.4'$ and $\pm 2'$, respectively. This position is in agreement with the position of LS I +61 303. In the natural case in which the VHE emission is produced by the same object detected at EGRET energies, this result identifies a γ-ray source that resisted classification during the last three decades.

Our measurements show that the VHE γ-ray emission from LS I +61 303 is variable. The γ-ray flux above 400 GeV coming from the direction of LS I +61 303 (see Figure 2) has a maximum corresponding to about 16% of the Crab nebula flux, and is detected around phase $\Phi = 0.6$. The combined statistical significance of the 3 highest flux measurements is 8.7σ, for an integrated observation time of 4.2 hours. The probability for the distribution of measured fluxes to be a statistical fluctuation of a constant flux (obtained from a χ^2 fit of a constant function to the entire data sample) is 3×10^{-5}. The fact that the detections occur at similar orbital phases hints at a periodic nature of the VHE γ-ray emission.

Contemporaneous radio observations of LS I +61 303 were carried out at 15 GHz with the Ryle Telescope covering several orbital periods of the source. The peak of the radio outbursts was at phase 0.7, i.e. between 1 and 3 days after the increase observed at VHE γ-rays flux (see Figure 3).

The VHE spectrum derived from data between ∼200 GeV and ∼4 TeV at orbital phases between 0.4 and 0.7 is shown in Figure 4. The obtained spectrum is fitted well ($\chi^2/ndf = 6.6/5$) by a power law function:

$$dN_{\gamma}/(dA/dt/dE) = (2.7\pm0.4\pm0.8)\times10^{-12}\times E^{(-2.6\pm0.2\pm0.2)} \quad \mathrm{cm^{-2}s^{-1}TeV^{-1}} \tag{2.1}$$

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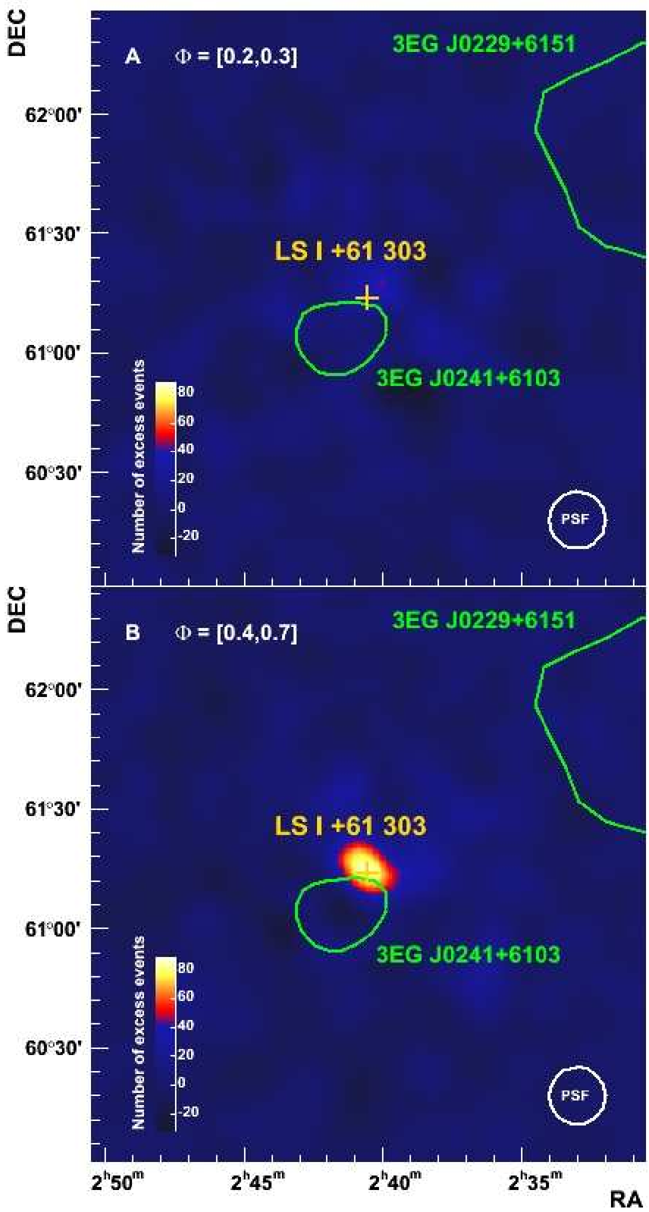

Figure 1: Smoothed maps of γ-ray excess events above 400 GeV around LS I +61 303. (A) Observations over 15.5 hours corresponding to data around periastron (i.e., between orbital phases 0.2 and 0.3). (B) Observations over 10.7 hours at orbital phase between 0.4 and 0.7. The number of events is normalized in both cases to 10.7 hours of observation. The position of the optical source LSI +61 303 (yellow cross) and the 95% confidence level contours for the EGRET sources 3EG J0229+6151 and 3EG J0241+6103 (green contours) are also shown. The bottom right circle shows the size of the point spread function of MAGIC (1σ radius). From Albert *et al.* [6].

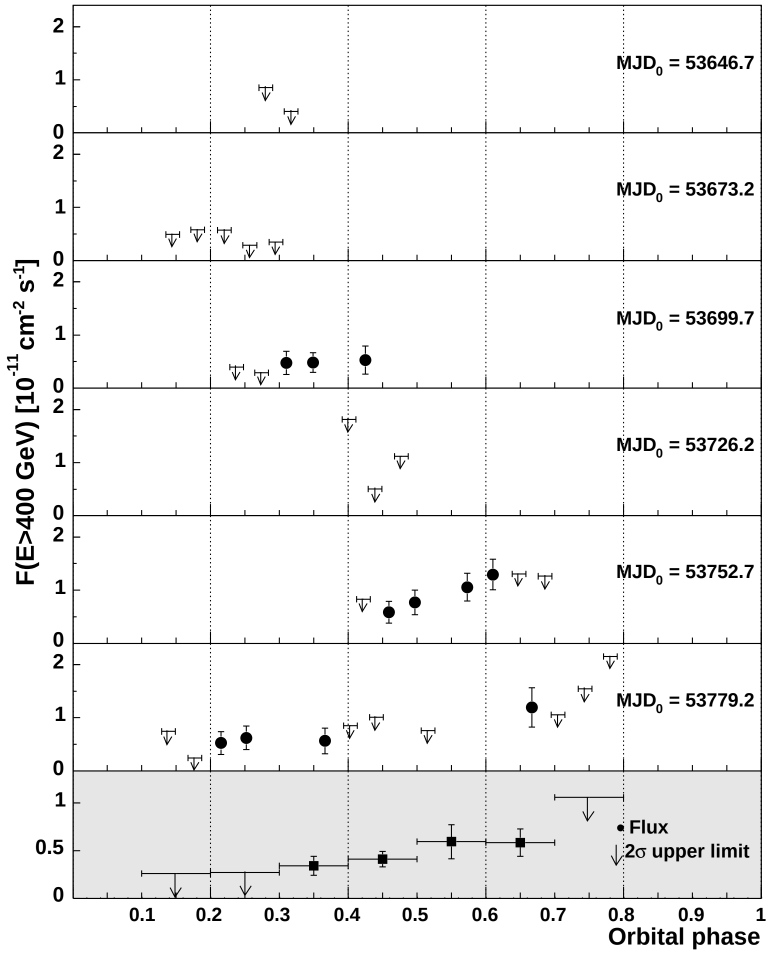

Figure 2: VHE γ-ray flux of LS I +61 303 as a function of orbital phase for the six observed orbital cycles (six upper panels, one point per observation night) and averaged for the entire observation time (bottom panel). Vertical error bars include 1σ statistical error and 10% systematic uncertainty on day-to-day relative fluxes. Only data points with more than 2σ significance are shown, and 2σ upper limits [23] are derived for the rest. The modified Julian date (MJD) corresponding to orbital phase 0 is indicated for every orbital cycle. From Albert *et al.* [6].

where N_γ is the number of gamma rays reaching the Earth per unit area A, time t and energy E (expressed in TeV). Errors quoted are statistical and systematic, respectively. This spectrum is consistent with that measured by EGRET for a spectral break between 10 and 100 GeV.

We estimate that the flux from LS I +61 303 above 200 GeV corresponds to an isotropic luminosity of $\sim 7 \times 10^{33}$ erg s^{-1} (assuming a distance to the system of 2 kpc [12]). The intrinsic luminosity is of the same order of that of the similar object LS 5039 [2], and a factor ~ 2 lower than the previous experimental upper limit ($< 8.8 \times 10^{-12}$ cm^{-2} s^{-1} above 500 GeV) obtained by Whipple [11]. LS I +61 303 displays more luminosity at GeV than at X-ray energies, a behavior shared also by LS 5039.

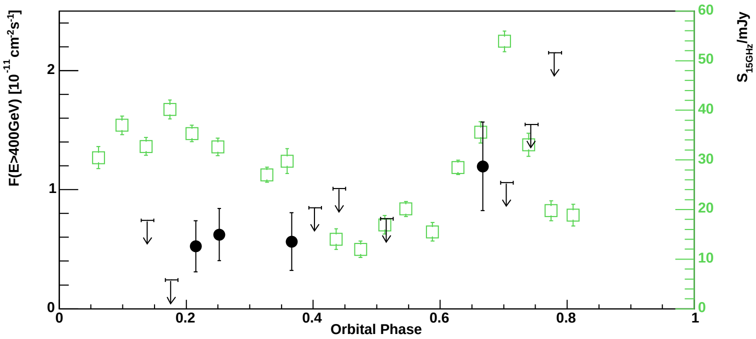

Figure 3: LS I +61 303 radio flux density at 15 GHz measured with the Ryle Telescope (green squares, right axis) and results from the last orbital cycle observed by MAGIC (black dots, left axis), from 14 February to 8 March 2006. The MJD corresponding to orbital phase 0 is indicated. From Albert *et al.* [6].

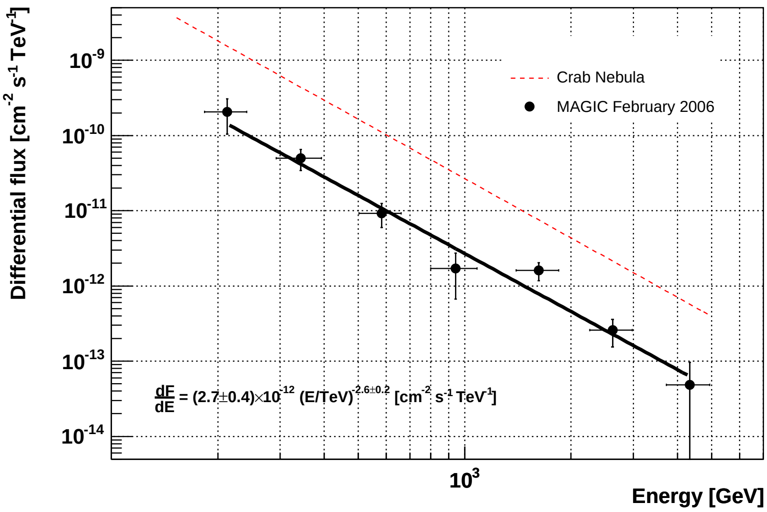

Figure 4: Differential energy spectrum of LS I +61 303 for energies between 200 GeV and 4 TeV and averaged for orbital phases between 0.4 and 0.7, measured by MAGIC. The error bars show the 1σ statistical uncertainty. The dashed, red line corresponds to the Crab nebula differential spectrum also measured by MAGIC. The solid, black line is a fit of a power law (also expressed mathematically in the inset) to the measured points. From Albert *et al.* [6].

2.3 Emission scenarios

Microquasars are a subclass of stellar, X-ray binary systems that display prominent radio emission, usually attributed to the existence of jets of relativistic particles. They are named after the similarities with active galactic nuclei (AGNs), since microquasars show the same three ingredients that make up radio-loud AGNs: a compact object, an accretion disc, and relativistic jets [21]. Hence, microquasars are galactic, scaled-down versions of an AGN, where instead of a supermassive black hole we deal with a compact object of just a few solar masses that accretes material from a donor star. The similarities with AGNs explain the large interest risen by microquasars. In fact, the short timescale variability displayed by microquasars allows to see changes in the on-going physical processes within typical time scales ranging from minutes to months, in contrast with the usual scales of years to observe such variability in AGNs. In addition, microquasars could measurably contribute to the density of galactic cosmic rays [16].

LS I +61 303 was usually thought to be a mircoquasar, similar to LS 5039, because evidence of relativistic jets has been found at radio frequencies. In this scenario, the high energy emission would be produced in shocks at the relativistic jets [21]. The observation of jets has triggered the study of different microquasar-based γ-ray emission models, some regarding hadronic mechanisms: relativistic protons in the jet interact with non-relativistic stellar wind ions, producing gamma rays via neutral pion decay; some regarding leptonic mechanisms: IC scattering of relativistic electrons in the jet on stellar and/or synchrotron photons [8].

However, no clear signal of the presence of an accretion disk (in particular a spectral feature between ~ 10 and ~ 100 keV due to the cut-off of the thermal emission) has been observed so far. Because of that, it has been alternatively proposed that relativistic particles could be injected into the surrounding medium at the shock where the wind of the young pulsar and the wind of the stellar companion collide [18], which seems to be the case of PSR B1259-63.

In the case of LS I +61 303 the resemblance of the time variability and the radio/X-ray spectra with those of young pulsars support such hypothesis. However, no pulsed emission has been detected from LS I +61 303.

Recently [10] VLBA observations extending over a whole orbital period of LS I +61 303 have been done, resolving the emission on scales of 1mas (2AU), into a cometary shape, which always points away from the high-mass star. This strongly favours the wind-wind interpretation.

Observation at VHE with MAGIC simultaneously together with other instruments at other wavelength domains –in particular radio– will help elucidate the mechanism of the TeV emission and hence the nature of γ-ray binaries.

The TeV flux measured by MAGIC has a maximum at phases 0.5-0.6 (see Figure 2), overlapping with the X-ray outburst and the onset of the radio outburst. The timescale of the TeV variability constrains the emitting region to be smaller than a few 10^{15} cm (or 0.1 arc-sec at 2 kpc), which is larger than the binary system and of the same order of the detected radio jet-like structures. The maximum flux is not detected at periastron, when the accretion rate is expected to be the largest. This result seems to favor the leptonic over the hadronic models, since the IC efficiency is likely to be higher than that of proton-proton collisions at the relatively large distances from the companion star at this orbital phase. Further, VHE γ-ray emission that peaks after periastron passage has been predicted considering electromagnetic cascading within the binary system [7]. It is also possible to explain the orbital modulation of the VHE emission in LS I +61 303 by the geometrical effect of changes in the relative orientation of the stellar companion with respect to the compact object and jet as it impacts the position and depth of the $\gamma\gamma$ absorption trough [15]. The existing data are, however, not conclusive to confirm or rule out any of the theoretical models existing in the literature.

LS I +61 303 is an excellent laboratory to study the VHE γ-ray emission and absorption processes taking place in massive X-ray binaries: the high eccentricity of the binary system provides very different physical conditions to be tested on timescales of less than one month. Future MAGIC observations will test both, the periodicity of the signal and its intra-night variability.

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