MULTIWAVELENGTH (RADIO, X-RAY, AND $\gamma$-RAY) OBSERVATIONS OF THE $\gamma$-RAY BINARY LS I +61 303

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ABSTRACT

We present the results of the first multiwavelength observing campaign on the high-mass X-ray binary LS I +61 303, comprising observations at the TeV regime with the MAGIC telescope, along with X-ray and radio interferometric observations with the MERLIN, EVN, and VLBA arrays, in 2006 October and November. From our MERLIN observations, we can exclude the existence of large-scale (~100 mas) persistent radio jets. Our 5.0 GHz VLBA observations display morphological similarities to previous 8.4 GHz VLBA observations carried out at the same orbital phase, suggesting a high level of periodicity and stability in the processes behind the radio emission. This makes it unlikely that variability of the radio emission is due to the interaction of an outflow with variable wind clumps. If the radio emission is produced by a milliarcsecond scale jet, it should also show a stable, periodic behavior. It is then difficult to reconcile the absence of a large-scale jet (~100 mas) in our observations with the evidence of a persistent relativistic jet reported previously. We find a possible hint of temporal correlation between the X-ray and TeV emissions and evidence for radio/TeV noncorrelation, which points to the existence of one population of particles producing the radio emission and a different one producing the X-ray and TeV emissions. Finally, we present a quasi-simultaneous energy spectrum including radio, X-ray, and TeV bands.

Subject headings: gamma rays: observations — X-rays: binaries — X-rays: individual (LS I +61 303)

Online material: color figures

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1. INTRODUCTION

LS I +61 303 is a high-mass X-ray binary consisting of a low-mass (M ~ 1–4 M☉) compact object orbiting around an early-type B0 Ve star along an eccentric (e = 0.7) orbit (Casares et al., 2005, and references therein). The modulation of both the radio (Gregory & Taylor, 1978; Gregory, 2002) and X-ray (Taylor et al., 1996; Paredes et al., 1997) emissions display a period of P_{orb} = 26,496 days, attributed to the orbital motion. The position of the maximum of the radio emission along the orbit, as well as its intensity, are modulated with a superorbital period of P_{sup} = 1667 ± 8 days (Gregory, 2002). LS I +61 303 is positionally coincident with an EGRET γ-ray source (Kniffen et al., 1997). Moreover, variable emission at TeV energies has been recently detected with the MAGIC telescope (Albert et al., 2006a). These authors found that the peak flux at TeV energies occurs at orbital phase φ_{orb} ≈ 0.65, while no high-energy emission is detected around periastron passage (φ_{orb} ≈ 0.23). From ~50 mas resolution radio images of LS I +61 303 obtained with MERLIN, Massi et al. (2004) suggested the existence of a precessing relativistic (β ≈ 0.6) jet up to angular scales of ~0.1′′, which led them to interpret LS I +61 303 within the framework of the microquasar scenario (Bosch-Ramon et al., 2006; Romero et al., 2007). However, recent VLBA imaging obtained by Dhawan et al. (2006) over a full orbit of LS I +61 303 has shown the radio emission to come from angular scales smaller than about 7 mas (projected size 14 AU at an assumed distance of 2 kpc). This radio emission appeared cometary-like, interpreted to be pointing away from the high-mass star within a particular scenario, and no relativistic motion, nor halos, nor larger scale structures were detected at any phase of the orbit. Based on these findings, Dhawan et al. (2006) concluded that the radio and TeV emissions from LS I +61 303 are originated by the interaction of the wind of a young pulsar with that of the stellar companion (Maraschi & Treves, 1981; Dubus, 2006).

In this article, we present and discuss the results of a multiwavelength campaign including radio, X-ray, and TeV γ-ray observations of LS I +61 303, with the aim of shedding light on the physical processes going on in the system, as well as yielding useful input for a detailed, time-dependent modeling of this relevant scenario. Moreover, bad weather conditions did not allow us to get any in-situ observations. The period November 16–20 included only MAGIC and MERLIN observations. The range of observed orbital phase in the October campaign was φ_{orb} = 0.6–0.7, for which the TeV maximum has previously been detected (Albert et al., 2006a), and φ_{sup} = 0.44–0.57 in the November campaign. The superorbital phase for both campaigns was φ_{sup} = 0.4.

2. MULTIWAVELENGTH OBSERVATIONS

Table 1 and Figure 1 summarize our observations of LS I +61 303, carried out during 2006 October and November. In particular, we set up a simultaneous multiwavelength campaign on LS I +61 303 for 2006 October 25 and 26 using the MERLIN, EVN, and VLBA interferometers (radio), and the TNG (infrared), Chandra (X-rays), and MAGIC TeV γ-ray telescopes. Unfortunately, bad weather conditions did not allow us to get any infrared data, nor did we get useful data from the MAGIC telescope coincident in time with simultaneously scheduled Chandra observations. The period November 16–20 included only MAGIC and MERLIN observations.

The range of observed orbital phase in the October campaign was φ_{orb} = 0.6–0.7, for which the TeV maximum has previously been detected (Albert et al., 2006a), and φ_{sup} = 0.44–0.57 in the November campaign. The superorbital phase for both campaigns was φ_{sup} = 0.4.

2.1. Radio Observations

We observed LS I +61 303 with several radio interferometric arrays during 2006 October 25–26, including the Multi-Element Radio Linked Interferometer (MERLIN) in the UK, the European VLBI Network (EVN), and the Very Long Baseline Array (VLBA) in the US, all of which observed at 5.0 GHz. In addition, we also monitored the flux and large angular scale structural and flux density variations of LS I +61 303 using MERLIN at 5.0 GHz on 2006 October 27 and 28, and at 6.0 GHz for the period from 2006 November 16 to 20.

The MERLIN array included six antennas (Deford, Cambridge, Knockin, Darnhall, Jodrell Bank [MK II], and Tabley) for most of our observations, yielding synthesized beams of about 50–70 mas (corresponding to projected linear sizes of 100–140 AU). The EVN observations on 2006 October 26, which were the first ever carried out for LS I +61 303 using the e-VLBI technique (Szomoru et al., 2006), included five antennas spread over Europe (Cambridge, Jodrell Bank MK II, Medicina, Torun, and the Westerbork phased array), yielding a synthesized beam of about 7 mas (or 14 projected AU). The data were directly spread over the US, yielding a beam size of 4.6 × 2.1 mas, corresponding to a projected linear resolution of ~9.2 AU and ~4.2 AU in right ascension and declination, respectively.

All three interferometric arrays observed LS I +61 303 in phase-referenced mode. LS I +61 303 and the bright (S_{5GHz} ≈ 600 mJy), nearby International Celestial Reference Frame (ICRF) source J0244+6228 were alternately observed through each observing run, the phases of J0244+6228 being transferred to the position of LS I +61 303 in the post-observation data analysis. J0244+6228 also served as amplitude calibrator for our observations. We performed standard calibration and data reduction within the NRAO Astronomical Imaging Package System (AIPS;
We also used standard hybrid mapping techniques within AIPS to obtain the flux densities shown in Figure 1 and Table 1, and the radio images shown in Figures 2 and 3.

2.2. X-Ray Observations

We obtained Chandra X-ray observations of LS I +61 303 on 2006 October 25 through the Director Discretionary Time program (Chandra ObsId 8273). The observations were carried out using ACIS-I for a total exposure time of 20.0 ks. At the time of the observation, LS I +61 303 was expected to be in a high state, and its high X-ray brightness could have resulted in an excessively high count rate, producing appreciable pile-up in the observations. In order to minimize pile-up effects, LS I +61 303 was offset by 8'$ from the ACIS-I aim point, thus smearing its image and reducing the count rate at the source peak. We further used 1/4 subarray, reducing the exposure time of individual frames from the nominal exposure time of 3.2 s down to 0.8 s.

Data reduction of the X-ray observations of LS I +61 303 has been performed using the Chandra X-ray Center software CIAO V3.4. The data reduction included the application of standard filters and rejection of events with bad grades and those originating from bad pixels. The background count rate is consistent with the quiescent background (Markevitch 2001), and no time intervals of enhanced background needed to be removed. The processed observations have a useful exposure time of 19.1 ks. Due to the high count rate of LS I +61 303, out-of-time events were not negligible and produced a noticeable streak along the columns.

These have been corrected using the CIAO task acisreadcorr. Finally, we note that as of CALDB v3.1.0 (2005 June), the CIAO task acis_process_events is routinely used by the level 1 processing pipeline to mitigate the charge transfer inefficiency (CTI) that affects the Chandra ACIS-I front-illuminated chips. Therefore, no further CTI correction was applied. Light curves and spectra of LS I +61 303 were obtained using standard CIAO tasks and analyzed using HEASARC FTOOLS and XSPEC v11.2.0 routines (Arnaud 1996).

2.3. VHE γ-Ray Observations

Observations in the very high energy (VHE) γ-ray band ($E_\gamma > 100$ GeV) were scheduled with the MAGIC telescope on 2006 October 26–28 and November 16–19 (see Table 1). These observations are part of an extensive, stand-alone observing campaign carried out between 2006 September and December (J. Albert et al. 2008, in preparation). Bad weather conditions at the Observatorio del Roque de los Muchachos, however, prevented us from obtaining useful data on 2006 October 26 and 28.

The observations were carried out in the false-source track (wobble) mode (Fomin et al. 1994), with two directions at 24' distance and opposite sides of the source direction, which allows for a reliable estimation of the background with no need for extra observation time. The data were analyzed using the standard MAGIC calibration and analysis software (Albert et al. 2006b; Gaug et al. 2005). Data runs with anomalous event rates were discarded from further analysis. Hillas variables (Hillas 1985) were combined into an adimensional $\gamma$/hadron discriminator ("hadronness") and an
3. RESULTS

In this section we present the results obtained from the different multiwavelength observations we have performed, and put them into the context of the past measurements in the different bands. They are summarized in Table 1 and Figure 1.

3.1. Radio Results

The total radio flux density obtained with MERLIN shows a decline between October 26 ($\phi_{\text{orb}} = 0.66$) and October 28 ($\phi_{\text{orb}} = 0.70$), from $\sim 35$ to $\sim 30$ mJy, and a peak on 18 November ($\phi_{\text{orb}} = 0.50$) at $\sim 80$ mJy. At the superorbital phase of the observations ($\phi_{\text{sup}} = 0.4$), the radio source is in the weak state. The predicted flux of the radio flux is between 50 and 100 mJy at the orbital phases $\phi_{\text{orb}} \sim 0.9$. We therefore measure a flux compatible with the predicted one, although at a much earlier phase value. However, for the weak state, secondary peaks of comparable flux show up at other orbital phase values (see, e.g., Dhawan et al. 2006).

In Figure 2 we show the radio images corresponding to October 25–26, where all three arrays observed simultaneously LS I +61 303. In Figure 3 we show the MERLIN images obtained on 2006 October 27 and 28 at a frequency of 5.0 GHz, and on 2006 November 16, 17, 18, 19, and 20 at a frequency of 6.0 GHz. Radio contours are drawn at (3, 3$^{1/3}$, 9, . . .) times the off-source rms (see Table 1). Note that the shape of the radio brightness distribution of LS I +61 303 genuinely follows the synthesized beam for each epoch (upper left inset in each panel).

The coordinates of the peak of radio brightness distribution of LS I +61 303, as obtained from our VLBA observations (using task IMFIT), were R.A. = 02h40m31.6638756 s, decl. = 61°45′45.592235″ on October 25, and R.A. = 02h40m31.6638756, decl. = 61°45′45.592496″ on October 26, with and estimated accuracy of 12 $\mu$as and 7 $\mu$as in R.A. and decl., respectively. This shift of the brightness peak corresponds to a day-to-day projected speed of $904 \pm 60$ km s$^{-1}$, in excellent agreement with the typical value of $\sim 1000$ km s$^{-1}$ found by Dhawan et al. (2006) along a complete orbital cycle.

The peak flux density varied significantly between our two VLBA observing runs, decreasing from 24.3 mJy beam$^{-1}$ on October 25 to 15.4 mJy beam$^{-1}$ on October 26. The total 5 GHz flux density varied from 39.5 ± 0.2 mJy [radio luminosity $L_R = (9.5 \pm 0.1) \times 10^{29}$ ergs s$^{-1}$] to 32.7 ± 0.2 mJy [$L_R = (7.8 \pm 0.1) \times 10^{29}$ ergs s$^{-1}$].
We therefore suggest that the drop seen in the total radio flux density of LS I +61 303 between our two consecutive VLBA observations is directly related to the change in the peak flux density, which hints toward a physical link with structural variations in the innermost (≤3 mas projected radius, or 6 AU at a distance of 2 kpc) region of the source, which our observations cannot resolve.

3.2. X-Ray Results

LS I +61 303 is clearly detected in our Chandra observation, with a background-subtracted averaged count rate of \(1.067 \pm 0.008\) counts s\(^{-1}\) in the energy band 0.5–10.0 keV. This count rate would have indeed resulted in considerable pile-up for a standard observational setup. The X-ray spectrum (Fig. 4) shows a broad peak at \(\sim 1.6\) keV and a hard energy tail that extends up to 9 keV. Assuming a foreground interstellar absorption with solar abundances and the absorption cross sections of Balucinska-Church & McCammon (1992), the X-ray spectrum of LS I +61 303 can be reasonably well fitted by either an absorbed power law, or an absorbed bremsstrahlung model (Fig. 4). The best-fit parameters, goodness of the fit (reduced \(\chi^2\)), and implied source flux and luminosity in the energy range of 0.5–10.0 keV for these two models are listed in Table 2. In both cases, the unabso

![](image)

**Fig. 4.** Chandra ACIS-I spectrum of LS I +61 303 overplotted with the best-fit absorbed power-law (solid histogram) and bremsstrahlung (dotted histogram) models (see Table 3 for details). The lower panel shows the relative residuals of the fits (\(\Delta I\)) in terms of the bin standard deviation (\(\sigma\)) for both the absorbed power-law (filled circles) and bremsstrahlung (open circles) models. The errors bars in both the spectra and residual plots are 1 \(\sigma\). The insets show the \(\chi^2\) plots as a function of the power-law index, \(\Gamma\), and \(N_h\) (upper inset), and of the plasma temperature, \(kT\), and \(N_h\) (lower inset) of the spectral fits to the Chandra ACIS-I spectrum of LS I +61 303 using absorbed power-law and bremsstrahlung models, respectively. The contours represent 68\%, 90\%, and 99\% confidence levels. [See the electronic edition of the Journal for a color version of this figure.]

| TABLE 2 |
|---|---|---|
| **X-RAY SPECTRUM BEST-FIT PARAMETERS** | | |
| Parameter | Power-Law | Bremsstrahlung |
| --- | --- | --- |
| \(\chi^2/\text{dof}\) | 413.95/370 = 1.12 | 428.24/370 = 1.16 |
| \(N_h\) \((10^{21} \text{ cm}^{-2})\) | 5.5 ± 0.5 | 4.8 ± 0.4 |
| \(\Gamma\) or \(kT\) | 1.53 ± 0.07 | 17^{+9}_{-5} \text{ keV} |
| \(f_{\text{obs}}^\text{0.5–10.0 keV}\) | 1.87 ± 0.16 | 1.84 ± 0.05 |
| \(f_{\text{obs}}^\text{8–50 keV}\) | 1.18 ± 0.11 | 1.11 ± 0.04 |

**Notes.** — Best-fit parameters to the X-ray spectrum for LS I +61 303 obtained using absorbed power-law and bremsstrahlung models. The flux between 0.5 and 10.0 keV is expressed in \(10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}\), and the luminosity in \(10^{34} \text{ ergs s}^{-1}\) and for an assumed distance of 2 kpc.

We have also investigated the short-term variability of LS I +61 303 X-ray flux and hardness ratio (defined as the ratio of the count rate between 2.0 and 10.0 keV over that between 0.5 and 2.0 keV), shown in Fig. 5. The Chandra ACIS-I count rate of LS I +61 303 in the energy band of 0.5–10.0 keV varied by a factor of 25\%, from \(\sim 1.25 \pm 0.03\) counts s\(^{-1}\) down to \(\sim 1.00 \pm 0.03\) counts s\(^{-1}\), within a timescale of 1–2 hr, showing a clear decline in the final third of the observation. The probability that this variation is a statistical fluctuation of a constant flux is less than \(10^{-12}\), as obtained from a \(\chi^2\) fit of a constant function to the data set. Fast flux variations of up to 70\% within few hours timescale have been reported by Sidoli et al. (2006). In their case, these were accompanied by variations in the hardness ratio (HR = \(2–12 \text{ keV/0.3–2 keV}\)) of about 30\%, which our data do not confirm. It must be noted, however, that assuming a linear correlation between flux and HR, we should observe less than \(\sim 10\%\) variations in the HR during our observation, which is below our statistical error.

![Image](image)

**Fig. 5.** — Temporal evolution of the Chandra ACIS-I hardness ratio (top) and count rate in the energy band 0.5–10.0 keV (bottom). The bin size is 1000 s, and the error bars are 1 \(\sigma\).
The electronic edition of the Journal for a color version of this figure.

Fig. 6.—Correlation between the X-ray flux and photon index for the existing observations of LS I +61 303 in the $\sim$1–10 keV range.

### 3.3. VHE $\gamma$-Ray Results

LS I +61 303 was detected with MAGIC only on October 27 ($\phi_{\text{orb}} = 0.66$), with a significance of 4.5 $\sigma$. For the rest of the nights, no detection above 2 $\sigma$ was found, and we derived the corresponding upper limits to the integral flux (see Table 1).

On October 27, the measured average flux above 300 GeV corresponds to 15% of the Crab Nebula flux at these energies.

The VHE $\gamma$-ray source is pointlike for the MAGIC angular resolution ($0.1^\circ$), and the location is compatible with that of LS I +61 303. The energy spectrum is well fitted by an unbroken power-law with index $\alpha = -2.7 \pm 0.5 \pm 0.2$, where the quoted errors correspond to the statistical and systematic uncertainties, respectively. No significant variations of the absolute flux were detected within that night.

Previous observations of this source with the MAGIC (Albert et al. 2006a, 2008) and VERITAS (Acciari et al. 2008) telescopes have shown a pointlike source, with a peak of $\sim$15% Crab flux intensity at orbital phase $\phi_{\text{orb}} \sim 0.65$, and a spectral index $\alpha \sim -2.6$, hence in agreement with the results derived from our observations.

### 4. DISCUSSION

The comparison between VHE $\gamma$-ray and radio data during the October campaign (see Fig. 1) shows a detection at TeV energies for $\phi_{\text{orb}} = 0.66$ with a flux level of $\sim$15% of the Crab Nebula flux, during a period when the radio emission is constant at 35 mJy. During the November campaign, however, there is no detection at TeV energies, while the radio data show a peak flux twice as high as in October. Albert et al. (2006a) reported radio and TeV peaks detected almost simultaneously, while for our campaign we see the TeV peak for a flat and low radio flux and a radio peak for no significant TeV emission. Therefore, we exclude a general TeV-radio correlation. A plausible explanation is that the emissions are produced by different particle populations. On the other hand, the detections at X-ray and TeV energies, both at particularly
The fact that the extended radio emission is produced by the interaction of steady flows (from a relativistic pulsar wind, jet and/or stellar wind) rather than by the interaction of such an outflow with wind clumps. We note that if the radio emission is produced by a milliarcsecond scale jet, the required stability and periodic behavior of such a jet is difficult to reconcile with the nonpersistent nature of a large-scale (~100 mas), putative relativistic jet, as deduced from our MERLIN observations in combination with those obtained by Massi et al. (2004).

Finally, we combine our X-ray data from 25 October, the TeV data from 26 October, and the average VLBA in both nights to produce a quasi-simultaneous multilwavelength spectrum, including radio, X-ray, and VHE \( \gamma \)-ray observations, which we display in Figure 7. However, the simultaneous data cover only a small range of the orbital phase of LS I +61 303. Given the high variability of the physical conditions of the system along the orbit, more simultaneous multilwavelength data, and particularly involving longer exposure times, orbital phase coverage, and redundancy, will shed further light in our understanding of this peculiar object.

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