Evidence of coupling between the thermal and nonthermal emission in the gamma-ray binary LS I +61 303 through optical observations

X. Paredes-Fortuny, M. Ribó, V. Bosch-Ramon, J. Casares, O. Fors, J. Núñez, and D. del Ser Badia

Variable Galactic Gamma-ray Sources
5 May 2015, Heidelberg
1. Introduction
2. Optical photometric monitoring
3. Optical spectroscopic data
4. Results
5. Discussion
1. Introduction
2. Optical photometric monitoring
3. Optical spectroscopic data
4. Results
5. Discussion
What are Be/\(\gamma\)-ray binaries?

Be/\(\gamma\)-ray binaries where the companion is a Be star. There are three Be/\(\gamma\)-ray binaries currently known, namely LS I +61 303, PSR B1259−63 and HESS J0632+57 (Albert et al. 2006, Hinton et al. 2009, Aharonian et al. 2005, Casares et al. 2012).

What are Be stars?

Are non-supergiant fast-rotating early type stars which at some time have shown emission lines (e.g. Negueruela 1998).
Nonthermal photons from gamma-ray binaries: shocks+synchroton+IC

Thermal photons from gamma-ray binaries: star+disk

Figure 1: Sketch of the scenario of the gamma-ray binary PSR B1259–63. From NASA.
Nonthermal photons from gamma-ray binaries: shocks + synchrotron + IC

Thermal photons from gamma-ray binaries: star + disk

Figure 1: Density map from SPH simulation of PSR B1259-63, 11 days prior to periastron. From Takata et al. (2012), see also Okazaki et al. (2011).
LS I $+61\ 303$

Is a $\gamma$-ray binary composed by an optical Be (B0 Ve) star ($V \sim 10.8$) and a **compact companion** orbiting in a highly eccentric orbit with a **period of 26.496 d** (Gregory 2002).

- **Modulated emission** has been detected in radio, optical photometry, H$\alpha$ spectroscopy, X-rays, GeV, and TeV (see Moldón 2012 and references therein).

- Frail and Hjellming (1991) obtained a **distance** of $\sim 2.0 \pm 0.2$ kpc.


- Aragona et al. 2009 found an **orbital solution** that supports $e = 0.54 \pm 0.03$. Resulting in $d_{\text{apa}}/d_{\text{peri}} \sim 3$, with $d_{\text{apa}} = 0.64$ and $d_{\text{peri}} = 0.19$
Description of LS I +61 303 II

- LS I +61 303 shows a ~ 4.6 yr superorbital modulation in Radio flux and phase of the maximum (Fig.-left; from Gregory 2002) and EW$_{H\alpha}$ flux (Fig.-right; from Zamanov et. al 2013).

- This suggests that the superorbital variability is related to periodic changes in the mass-loss rate of the Be star and/or variations in the circumstellar disk.

- The superorbital variability in the microquasar scenario has also been explained using a precessing jet (see Massi & Torricelli-Ciamponi 2014 and references therein).
Figure 2: Orbit of the **compact object (black ellipse)** around the massive star **LS I +61 303 (black filled circle)**. Small circles are plotted every 0.1 orbital phases. From Moldón (2012).
Description of LS I +61 303 III

Figure 2: Orbit of the compact object (black ellipse) around the massive star LS I +61 303 (black filled circle). Small circles are plotted every 0.1 orbital phases. From Moldón (2012).
Description of LS I +61 303 III

Figure 2: Orbit of the compact object (black ellipse) around the massive star LS I +61 303 (black filled circle). Small circles are plotted every 0.1 orbital phases. From Moldón (2012).
Figure 2: Orbit of the compact object (black ellipse) around the massive star LS I +61 303 (black filled circle). Small circles are plotted every 0.1 orbital phases. From Moldón (2012).
Outline

1. Introduction
2. Optical photometric monitoring
3. Optical spectroscopic data
4. Results
5. Discussion
Observations with TFRM I

Telescope Fabra ROA Montsec (TFRM)

The optical photometric observations of this project are currently made with the robotic telescope TFRM, installed at the Observatori Astronòmic del Montsec (Lleida, Spain) (Fors et al. 2013)\(^1\).

- Corrector plate of 0.5 m aperture and 0.78 m primary mirror.
- Refurbished Baker-Nunn Camera.
- Focal ratio f/0.96.
- 4.4° × 4.4° field of view with a pixel scale of 3.9′′/pixel.
- Passband filter \(\lambda > 475\) nm. The QE of the CCD is 60% at 550 nm.

---

\(^1\) We want to thank all the TFRM team for preparing and carrying out the optical observations.
Observations with TFRM II

- We report data between **July 2012** and **March 2015** (2.6 yr), in 19 different orbital cycles.

- The exposure time ranges from **5.0 to 8.0 s** ($V \sim 10.8$).

- LS I +61 303 has been **observed** around **20 times per night**.

- **Observed** in good atmospheric conditions for a total of **101 nights** ($\sim 2400$ science images + calibration images!).

- We have used **10 reference stars** (optical photometric calibration), obtaining a photometric **precision of $\sim 7 \text{ mmag}$** at $1 \sigma$ confidence level.
We have developed a **pipeline written in Python** to reduce and analyze the data through **differential photometry**.

The main steps are: **image calibration, quality control, astrometric reduction** and **photometric extraction** for all the stars in the image.
• We have used the following algorithm to correct the lightcurves:

1. For each image (i) and star (j), we compute its magnitude difference with respect to the first image: $\Delta m_{i,j} = m_{i,j} - m_{1,j}$

2. We perform a weighted ($w_j = 1/\sigma_j^2$) average of $\Delta m_{i,j}$ using all the stars, obtaining: $\Delta \overline{m}_i$ (image correction)

3. We correct the non-corrected photometry for each image (i) using $\Delta \overline{m}_i$

4. We compute the new $\sigma_j$ using the corrected photometry

5. We select the 10 reference stars with lowest $\sigma$ (at angular distance $< 0.4^\circ$ with respect to LS I +61 303). We iterate until the selected stars do not change

6. We assign to the mean magnitude the value of 10.7

• We compute nightly averages with the photometry of individual images for each night. The uncertainty is obtained with the standard deviation of the photometry of the individual images for each night.
Outline

1. Introduction
2. Optical photometric monitoring
3. Optical spectroscopic data
4. Results
5. Discussion
We also considered contemporaneous $EW_{\text{H}\alpha}$ data obtained using the FRODOspec spectrograph on the robotic 2.0 m Liverpool telescope at the Observatorio del Roque de Los Muchachos (La Palma, Spain).

- LS I +61 303 has been observed with one 600 s exposure per night.
- The data span from July 2012 to December 2014 (2.4 yr), in 17 different orbital cycles.
- Observed in good atmospheric conditions for a total of 136 nights.
- The $EW_{\text{H}\alpha}$ precision is of $\sim1$ Å (individual $EW_{\text{H}\alpha}$ uncertainties are assumed at 10% level).
- The data have been obtained and reduced as in Casares et al. (2012)
1. Introduction
2. Optical photometric monitoring
3. Optical spectroscopic data
4. Results
5. Discussion
Results of the *Optical photometry* and *EW_{H\alpha} spectroscopy*:

- LS I +61 303 has been observed in 3 different observational campaigns centered at autumn of 2012, 2013 and 2014. Hereafter Seasons 1, 2 and 3, respectively.

- Results on Seasons 1 and 2 have already been published in Paredes-Fortuny et al. (2015).

- Results on Season 3 are presented here for the first time.
Results of the *Optical photometry* and *EW*$_{\text{H}\alpha}$ *spectroscopy*:

- LS I +61 303 has been observed in 3 different observational campaigns centered at autumn of 2012, 2013 and 2014. Hereafter **Seasons 1, 2 and 3**, respectively.

- Results on **Seasons 1 and 2** have already been published in *Paredes-Fortuny et al. (2015)*.

- Results on **Season 3** are presented here for the first time.
Results of the *Optical photometry* and *EW$_{\text{H}\alpha}$ spectroscopy*:

- LS I +61 303 has been observed in 3 different observational campaigns centered at autumn of 2012, 2013 and 2014. Hereafter *Seasons 1, 2 and 3*, respectively.

- Results on *Seasons 1 and 2* have already been published in Paredes-Fortuny et al. (2015).

- Results on *Season 3* are presented here for the first time.
• The photometry shows a broad maximum just after apastron.

• The $EW_{H\alpha}$ spectroscopy shows a broad maximum just before apastron.

• The lightcurves exhibit a large scatter.
Results III

![Graphs showing ORBITAL PHASE and m (mag) vs. MJD](image)

**ORBITAL PHASE**

\(P = 26.4960\ d, \ JD_0 = 2,443,366.775\)

**m (mag)**

![Graphs showing EW H α (Å) vs. MJD](image)

**EW H α (Å)**

\(P = 26.4960\ d, \ JD_0 = 2,443,366.775\)
Results III

$\begin{array}{l}
\text{MJD} \\
10.62 \\
10.64 \\
10.66 \\
10.68 \\
10.70 \\
10.72 \\
10.74 \\
10.76 \\
\hline
m \text{ (mag)} \\
0.0 \\
0.5 \\
1.0 \\
1.5 \\
2.0 \\
\end{array}$

$\begin{array}{l}
\text{EW H} \alpha \text{ (Å)} \\
0.0 \\
0.5 \\
1.0 \\
1.5 \\
2.0 \\
\end{array}$

$\begin{array}{l}
\text{MJD} \\
56200 \\
56400 \\
56600 \\
56800 \\
57000 \\
\hline
\text{ORBITAL PHASE} \\
(P = 26.4960 \text{ d}, \text{JD}_0 = 2,443,366.775) \\
\end{array}$

$\begin{array}{l}
\text{MJD} \\
56200 \\
56400 \\
56600 \\
56800 \\
57000 \\
\hline
\text{ORBITAL PHASE} \\
(P = 26.4960 \text{ d}, \text{JD}_0 = 2,443,366.775) \\
\end{array}$
Results III

\begin{align*}
\text{ORBITAL PHASE} & \quad (P = 26.4960 \text{ d}, JD_0 = 2,443,366.775) \\
\text{EW H}_\alpha (\text{Å}) & \quad \text{gap!}
\end{align*}
Results IV

$$m = -\text{Acos}(2\pi(\phi - \phi_0)) + C$$

- **Season 1:**
  - A = 0.029 ± 0.003 mag, \(\phi_0 = 0.69 ± 0.02\), C = 10.704 ± 0.002 mag
- **Season 2:**
  - A = 0.021 ± 0.003 mag, \(\phi_0 = 0.85 ± 0.02\), C = 10.698 ± 0.002 mag
- **Season 3:**
  - A = 0.029 ± 0.003 mag, \(\phi_0 = 0.97 ± 0.02\), C = 10.698 ± 0.002 mag

$$EW_{\text{H}_\alpha} = \text{Acos}(2\pi(\phi - \phi_0)) + C$$

- **Season 1:**
  - A = 1.4 ± 0.2 A, \(\phi_0 = 0.54 ± 0.02\), C = 11.2 ± 0.1 A
- **Season 2:**
  - A = 1.3 ± 0.2 A, \(\phi_0 = 0.76 ± 0.03\), C = 13.0 ± 0.2 A
- **Season 3:**
  - A = 0.3 ± 0.1 A, \(\phi_0 = 0.62 ± 0.10\), C = 11.4 ± 0.1 A

---

X. Paredes-Fortuny (UB)
Results IV

\[ m = -\text{Acos}(2\pi[\phi - \phi_0]) + C \]

Season 1:
- \( A = 0.029 \pm 0.003 \) mag, \( \phi_0 = 0.69 \pm 0.02 \), \( C = 10.704 \pm 0.002 \) mag

Season 2:
- \( A = 0.021 \pm 0.003 \) mag, \( \phi_0 = 0.85 \pm 0.02 \), \( C = 10.698 \pm 0.002 \) mag

Season 3:
- \( A = 0.029 \pm 0.003 \) mag, \( \phi_0 = 0.97 \pm 0.02 \), \( C = 10.698 \pm 0.002 \) mag

\[ EW_{H\alpha} = \text{Acos}(2\pi[\phi - \phi_0]) + C \]

Season 1:
- \( A = 1.4 \pm 0.2 \) A, \( \phi_0 = 0.54 \pm 0.02 \), \( C = 11.2 \pm 0.1 \) A

Season 2:
- \( A = 1.3 \pm 0.2 \) A, \( \phi_0 = 0.76 \pm 0.03 \), \( C = 13.0 \pm 0.2 \) A

Season 3:
- \( A = 0.3 \pm 0.1 \) A, \( \phi_0 = 0.62 \pm 0.10 \), \( C = 11.4 \pm 0.1 \) A

**Graphs:**
- **Left Graph:**
  - \( m \) vs. ORBITAL PHASE
  - \( P = 26.4960 \) d, \( JD_0 = 2443.366775 \)
- **Right Graph:**
  - \( EW_{H\alpha} \) vs. ORBITAL PHASE
  - \( P = 26.4960 \) d, \( JD_0 = 2443.366775 \)
Results IV

\[ m = -A \cos(2\pi(\phi - \phi_0)) + C \]

- Season 1:
  \[ A = 0.029 \pm 0.003 \text{ mag}, \quad \phi_0 = 0.69 \pm 0.02, \quad C = 10.704 \pm 0.002 \text{ mag} \]
- Season 2:
  \[ A = 0.021 \pm 0.003 \text{ mag}, \quad \phi_0 = 0.85 \pm 0.02, \quad C = 10.698 \pm 0.002 \text{ mag} \]
- Season 3:
  \[ A = 0.029 \pm 0.003 \text{ mag}, \quad \phi_0 = 0.97 \pm 0.02, \quad C = 10.698 \pm 0.002 \text{ mag} \]

\[ EW_{H\alpha} = A \cos(2\pi(\phi - \phi_0)) + C \]

- Season 1:
  \[ A = 1.4 \pm 0.2 \text{ A}, \quad \phi_0 = 0.54 \pm 0.02, \quad C = 11.2 \pm 0.1 \text{ A} \]
- Season 2:
  \[ A = 1.3 \pm 0.2 \text{ A}, \quad \phi_0 = 0.76 \pm 0.03, \quad C = 13.0 \pm 0.2 \text{ A} \]
- Season 3:
  \[ A = 0.3 \pm 0.1 \text{ A}, \quad \phi_0 = 0.62 \pm 0.10, \quad C = 11.4 \pm 0.1 \text{ A} \]
• The red and blue crosses correspond to the **phases of the maxima** of the sinusoidal fits to the orbital variability of the Optical and $EW_{H\alpha}$, respectively.

• The color lines represent the **orbital phase drift** of the emission peaks caused by the **super-orbital variability** for the Optical, $EW_{H\alpha}$, Radio, and X-rays.

• The Radio and X-ray drifts are taken from Fig. 3 of Chernyakova et al. (2012) using data of the previous superorbital cycle.
Outline

1. Introduction
2. Optical photometric monitoring
3. Optical spectroscopic data
4. Results
5. Discussion
Orbital variability:

- The circumstellar disk is likely to be perturbed by tidal forces and the putative pulsar wind ram pressure. After periastron passage at $\phi_{\text{per}} = 0.23$:
  
1. There is first a maximum in X-rays (tracer of nonthermal emission)

2. Followed by a maximum in $EW_{H\alpha}$ (tracer of the outer disk conditions) and in Radio emission (produced mainly outside the binary system)

3. Finally a maximum in the Optical flux is observed (variability from inner circumstellar disk)

- Optical flux shows $\sim 0.06$ mag modulation (in 1st season), or $\sim 6\%$ in total flux. The Be disk represents the 35% of the flux (Casares et al. 2005). Variability is $\sim 16\%$ in disk flux

- $EW_{H\alpha}$ shows $\sim 25\%$ variability (1st season): external parts of the disk are more perturbed

- There is a $\sim 0.1$ phase lag between the Optical and $EW_{H\alpha}$: the external parts are perturbed (and recover) before the internal parts
Superorbital variability:

- $EW_{\text{H}\alpha}$ superorbital variability is associated with **periodic changes on the Be star** (e.g., Zamanov et al. 1999)

- This secular evolution could be linked to the presence of a **moving one-armed spiral density wave in the disk** (Negueruela et al. 1998)

- We detect an orbital phase drift in the optical as that seen in Radio and X-rays.

- **Empirical coupling between the thermal (optical) and nonthermal (X-ray and radio) emission**

Future work:

- Continue the observations of LS I +61 303.

- Build a toy model (precessing disk or density wave) to explain the thermal behaviour.