

Research Note

LS I +61°303 in the context of microquasars

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Abstract. LS I +61°303 is one of the most observed Be/X-ray binary systems because, peculiarly, it has periodical radio and X-ray emission together with strong, variable gamma-ray emission. This source remains, however, quite enigmatic. Some properties of this system can be explained assuming that the unseen companion is a non-accreting young pulsar with a relativistic wind strongly interacting with the wind of the Be star. On the contrary, other properties of LS I +61°303 fit a model where the companion is accreting even with two events of super-critical accretion along the orbit. The very recent discovery of a radio jet extending ca. 200 AU from both sides of a central core has definitely proved the occurrence of accretion-ejection processes in this system. Therefore it is of great interest to combine this result with previous observations at other wavelengths within the framework of the two-peak accretion (ejection) model. Concerning the first ejection, we show that the observed gamma-ray variations might be periodic with outbursts confined around the periastron passage (i.e. where the first accretion-rate peak occurs and high-energy emission but no radio emission is predicted). Concerning the second ejection, with radio bursts, we point out that it can be also traced in the X-ray data, both in episodes of hardening of the X-ray emission and in a transition from soft- to hard-states at the onset of radiobursts. Both hardening and transitions between spectral states are related to the dramatic change in the structure of the accretion disk preceding the ejection. Finally, we explore the nature of the accretor and we conclude that on the basis of the present optical data a black hole cannot be ruled out.

Key words. stars: individual: LS I +61°303 – stars: individual: 2CG 135+01 – X-rays: binaries – radio continuum: stars – gamma-rays: observations – gamma-rays: theory

1. Introduction

The X-ray binary stellar system LS I +61°303 has excited particular interest because of its two peculiarities: on the one hand being the probable counterpart of the variable gamma ray source 2CG 135+01 (Gregory & Taylor 1978; Tavani et al. 1998) and on the other hand being a periodic radio source (Taylor & Gregory 1982, 1984).

The binary system is composed of a compact object in an eccentric orbit around a rapidly rotating B0–B0.5 main-sequence star, undergoing mass loss through an equatorial disk (Hutchings & Crampton 1981). The orbital period is assumed to be of 26.496 days determined on a radio data base of over 20 years (Hutchings & Crampton 1981; Gregory et al. 1999; Gregory 2002).

High radio outbursts always peak near phase 0.6, where $\Phi = 0$ has been set at Julian Date 2 443 366.775 (Taylor & Gregory 1982; Paredes et al. 1990). However, lower intensity radio outbursts occur within the broad distribution $\Phi_{\text{radio}} = 0.45\text{--}0.95$, due to variations of the equatorial disk in the Be star (Paredes et al. 1990; Gregory et al. 1999; Zamanov & Martí 2000; Gregory et al. 2002; Gregory & Neish 2002). From optical and near-infrared observations the periastron passage is estimated to be in the range $\Phi_{\text{periastron}} = 0.2\text{--}0.5$

(Hutchings & Crampton 1981; Martí & Paredes 1995). One of the fundamental questions concerning the periodic radio outbursts of LS I +61°303 therefore has been: why are the radio outbursts shifted with respect to the periastron passage?

The X-ray emission is also periodic with period estimates of $P = 26.7 \pm 0.2$ by Paredes et al. (1997) and $P = 26.42 \pm 0.05$ by Leahy (2001), clearly in agreement with the radio period. Quite surprising, however, is that the X-ray outbursts are off-set from the radio ones. In fact, the two available simultaneous X-ray and radio observations by Taylor et al. (1996) and by Harrison et al. (2000) during an orbital period show that the X-ray emission peaks in the phase interval $\Phi_{\text{X-ray}} = 0.43\text{--}0.47$ (recalculated by Gregory 2002) while the radio outburst is off-set by several days.

Taylor et al. (1992) and Martí & Paredes (1995) have modelled the properties of this system in terms of an accretion rate $\dot{M} \propto \frac{\rho_{\text{wind}}}{v_{\text{rel}}^3}$, (where ρ_{wind} is the density of the Be star wind and v_{rel} is the relative speed between the accretor and wind) which develops two peaks for high eccentricities: the highest peak corresponds to the periastron passage (highest density), while the second peak occurs when the drop in the relative velocity v_{rel} compensates (because of the inverse cube dependence) the decrease in density. From typical parameters of

LS I +61°303 derived from near infrared data, Martí & Paredes (1995) have shown that both peaks are above the Eddington limit and therefore one expects that matter is ejected perpendicular to the plane of the accretion disk. Near the periastron the short distance to the Be star enhances inverse Compton losses: X-ray or/and gamma-ray outbursts are expected but no radio bursts. At the second accretion peak, the compact object is much farther away from the Be star, so that the electrons can propagate out of the orbital plane: an expanding double radio source should be observed with a radio interferometer (Taylor & Gregory 1984; Taylor et al. 1992; Massi et al. 1993; Martí & Paredes 1995; Gregory et al. 1999).

The main problem concerning this model is that the luminosity of LS I +61°303 in the X-ray range is only $L_X \approx 10^{34} \text{ erg s}^{-1}$. That is several orders of magnitude lower than the Eddington limit, even for a neutron star, and in addition the bulk of the energy output seems to be shifted from X-ray to γ -ray wavelengths with $L_\gamma \approx 10^{36} \text{ erg s}^{-1}$ (Paredes et al. 1997). The difficulty of interpreting these results in the context of a super-accretion model has led to an alternative young pulsar model where a population of relativistic electrons are produced at the shock boundary between the relativistic wind of the young pulsar and the wind of the Be star (Maraschi & Treves 1981; Tavani 1995; Harrison et al. 2000; Hall et al. 2003). As a matter of fact such a model fits the time-variable high-energy emission observed near periastron from the Be/pulsar system PSR B1259-63 (Tavani & Aaron 1997).

However, the recent discovery of a radio emitting jet extending ca. 200 AU to both sides of a central core (Massi et al. 2004) has shown the occurrence of accretion-ejection processes in LS I +61°303. Therefore, this source seems very similar to the microquasar LS 5039 (Paredes et al. 2000) also subluminal in the X-ray range and also having $L_\gamma > L_X$. The quite stable gamma-ray emission in that case is explained due to upscattered stellar photons via inverse Compton process from the relativistic electrons of the persistent jet. If that is true for LS I +61°303 (Taylor et al. 1996; Massi et al. 2001; Kaufman Bernadó et al. 2002), do the periodic outbursts of this source imply periodic gamma-ray bursts? And in this case at which $\Phi_{\gamma\text{-ray}}$? Moreover, recent developments in the theory of the accretion-ejection processes show that magneto-rotational instabilities are able to accelerate and to collimate a part of the disk material into a double jet only after thermal instabilities in the accretion disk have inflated and transformed it into a geometrically thick disk (Meier 2001). As shown by Belloni et al. (1997) structural changes of the disk are associated with changes in the X-ray spectral states. Is it possible to discern a change of state in available X-ray data? And in this case: are changes of state and radio outburst related to each other as expected in an accretion-ejection process? The aim of this paper is to try to answer these questions. Section 2 analyses and discusses gamma-ray data while Sect. 3 deals with X-ray and optical results. The conclusions are given in Sect. 4.

2. EGRET data analysis

The EGRET gamma-ray data presented by Tavani et al. (1998) extend over a period of 1300 days. During that long interval

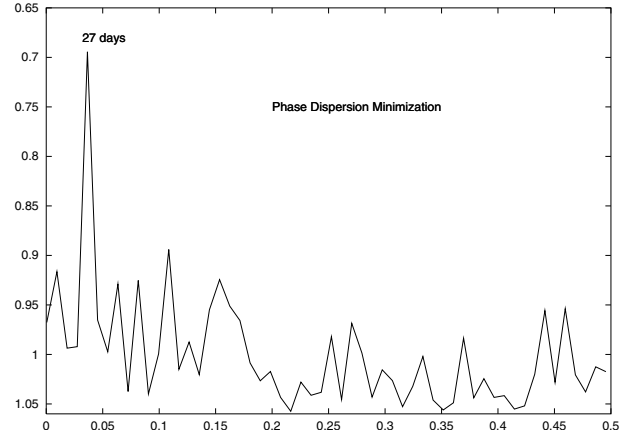


Fig. 1. Result of the Phase Dispersion Minimization analysis of the EGRET data. Note that the analysis provides the most probable period as a minimum (Stellingwerf 1978) and the vertical scale is here shown reversed. The dominant feature is at $P = 27.4 \pm 7.2$ days.

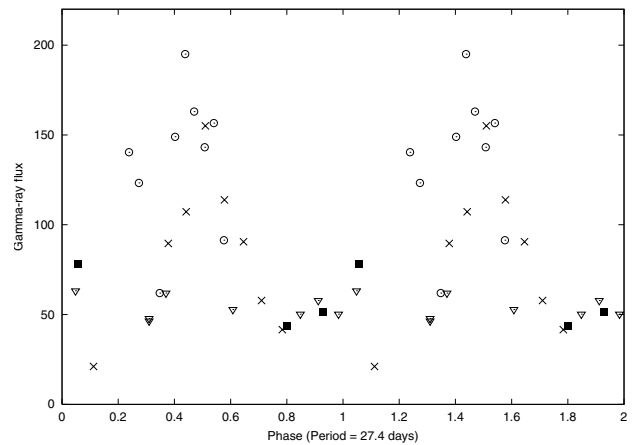


Fig. 2. Gamma-ray observations from Tavani et al. (1998) folded with a period of 27.4 days. The phase is computed with respect to $t_0 = 2443\,366.775 \text{ JD}$ (Gregory 2002). The circles correspond to the data set “a”, the full squares to the data set “b”, the crosses to the data set “c” and the triangles to the upper limits.

there are three data sets “a, b”, and “c” lasting for 10, 7 and 22 days, respectively. To search for eventual periodicities we used the Phase Dispersion Minimization (PDM) method which is very efficient on irregularly spaced data (Stellingwerf 1978). We used the PDM algorithm of the UK Starlink software package, PERIOD (<http://www.starlink.rl.ac.uk/>).

As shown in Fig. 1 the PDM results in a dominant feature at $P = 27.4 \pm 7.2$. The folding of the EGRET data with this period results in a clear clustering of the gamma-ray emission (Fig. 2).

The statistical significance of the period is calculated in PERIOD following the method of Fisher randomization as outlined in Nemec & Nemec (1985). The advantage of using a Monte-Carlo- or randomization-test is, that it is distribution-free and that it is not constrained by any specific noise models (Poisson, Gaussian etc.). The fundamental assumption is: if there is no periodic signal in the time series data, then the measured values (gamma-ray flux in our case) are independent of their observation times and are likely to have occurred in any

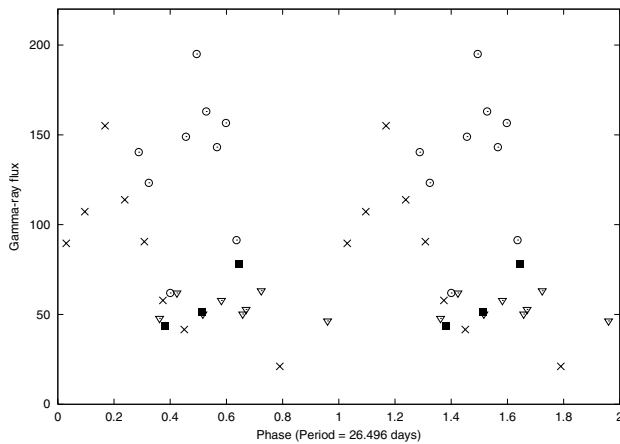


Fig. 3. Gamma-ray observations from Tavani et al. (1998) folded with the radio period of 26.496 days.

other order. One thousand randomized time-series are formed and the periodograms calculated. The proportion of permutations that give a peak power higher (for the PDM: a trough lower) than that of the original time series would then provide an estimate of p , the probability that no periodic component is present in the data. A derived period is defined as significant for $p < 0.01$, and a marginally significant one for $0.01 < p < 0.10$ (Nemec & Nemec 1985). As compared with other tests, the randomization test is more rigorous in rejecting peaks that might contain some oscillatory signal; on the other hand there is no doubt that the peaks that it finds significant represent an oscillation (Muglach 2003). For the period $P = 27.4$ days we got $p = 0.009$ which implies an almost zero probability that the observed time series oscillations could have occurred by chance. From the extreme case of complete exclusion from the data analysis of the upper limits the result is that the period of $P = 27.4$ days is still determined as a dominant period in a noisier periodogram with $p = 0.099$.

The gamma-ray emission is predicted to be produced via inverse Compton scattering of stellar photons by the relativistic electrons of the jet at each periastron passage (Taylor et al. 1992, 1996). Are the two gamma-ray peaks in the EGRET data indeed located around periastron passage? To determine the orbital phase of the gamma-ray emission we have folded the data with the period $P = 26.496$. As shown in Fig. 3 the two gamma-ray peaks occur at $\Phi_{\gamma\text{-ray}} = 0.2\text{--}0.5$.

3. X-ray and optical observations

Variations in the structure of the accretion disk around a compact object in a X-ray binary system can be revealed by X-ray data when they show a transition of the spectral state from the high/soft state to the low/hard state (Tanaka 1997). In their high/soft state, systems hosting black holes have a power-law component $E^{-\Gamma}$ (Tanaka 1997, his Table 3) with $\Gamma \geq 2$. When the high/soft state evolves into a low/hard state the value of Γ for the power law becomes $\Gamma \sim 1.6$ (in this case for both X-ray binary systems containing black holes or neutron stars) (Tanaka 1997). The spectral transition from high/soft to low/hard corresponds to a change in the disk structure (Tanaka 1997). The

radio emission from microquasars with steady jets is always correlated to low/hard states (Fender 2004).

Changes of the hardness ratio in the source GRS 1915+105 have been shown to correspond to a drastic change of the inner radius of the accretion disk (Belloni et al. 1997) followed by the onset of synchrotron radiation, first at infrared wavelengths and afterwards at radio wavelengths (Mirabel et al. 1998).

Figure 2-top in Greiner & Rau (2001) shows the resulting photon index Γ of RXTE data of LS I +61°303. The range for Γ is 2.0–2.4 except at one point where the photon index is $\Gamma = 1.6$. This point at $\Gamma = 1.6$ is clearly below the average and therefore assumed to be affected by unknown systematic uncertainties. In the context of microquasars this value corresponds – like the change in the hardness ratio as discussed above – to a variation in the accretion disk followed by the ejection of matter. And indeed the simultaneous radio observations show (Fig. 2-bottom in Greiner & Rau 2001) that the photon index value $\Gamma = 1.6$ coincides with the onset of a radio outburst.

The error bars in the photon index are large and there is only one critical point where the transition takes place. However, Taylor et al. (1996) also noticed a hardening of the X-ray emission at the onset of a new radio outburst. Moreover, Leahy et al. (1997) report two X-ray observations, both with power-law indices in the range 1.63–1.90 at orbital phases 0.2 and 0.42. While for the first value we can only speculate that it might be coincident with the first accretion rate peak (no simultaneous gamma-ray observations are available), the second value is certainly coincident with the onset of a radio outburst (Fig. 3 in Harrison et al. 2000).

In conclusion, the fit by Greiner and Rau (2001) suggests that 1) LS I +61°303 with its power-law component with $\Gamma \geq 2$ is mainly in the high/soft state typical for systems hosting black holes, and 2) it changes this state into a low/hard state just before/during (it is difficult to determine the exact time delay) the onset of a radio outburst.

The suggestion – coming from the X-ray data – of a black hole as the accreting object is appealing. Only Punsley (1999) discussed this possibility in detail and presented a model for the high-energy emission based on it. In the literature it has generally been assumed that LS I +61°303 hosts a neutron star because of an estimated mass of $M_x = 1.5 M_\odot$ by Hutchings & Crampton (1981). To derive that value Hutchings & Crampton (1981) assumed a mass function $f = 0.02$, an inclination $i \simeq 70^\circ$ ($\sin^3 i = 0.8$) and a mass for the companion star of $M = 10 M_\odot$. Below, we will show that these values are only average values from a rather large possible range.

Concerning the mass function f as noticed by Punsley (1999) the observations of Hutchings & Crampton (1991) imply a value in the range $0.0028 < f < 0.043$.

Ultraviolet spectroscopy (Hutchings & Crampton 1981) indicates that the primary star is a main sequence B0–B0.5 star ($L \sim 10^{38}$) erg s⁻¹ with a possible range for the mass of 5–10 M_\odot . Values in the range 10–16.5 M_\odot have been suggested by Punsley (1999) and values in the ranges 10–18 M_\odot by Martí & Paredes (1995).

Assuming 600 km s⁻¹ as the critical rotational velocity for a normal B0 V star and that Be stars may rotate at a velocity not exceeding 0.9 of this value (Hutchings et al. 1979), the very low

limit for the inclination of the orbit compatible with the measured value $V \sin i = 360 \pm 25 \text{ km s}^{-1}$ (Hutchings & Crampton 1981) is of 38° (Massi et al. 2001). On the other hand, the observed (Hutchings & Crampton 1981) shell absorption in the strong Balmer and He I lines for a disk sufficiently flat corresponds to a large inclination angle ($i = 90^\circ$) (Kogure 1969).

In conclusion, the uncertainties of the parameters are $0.0028 < f < 0.043$ for the mass function, $38^\circ < i < 90^\circ$ for the inclination angle and $5 M_\odot < M < 18 M_\odot$ for the mass. The chosen values of $f = 0.02$, $i \simeq 70^\circ$ and $M = 10 M_\odot$ are indeed reasonable average values. However, already assuming $i = 38^\circ$, one obtains $M_x = 2.5 M_\odot$. Assuming in addition $M = 18 M_\odot$ the result is $M_x = 3.4 M_\odot$, clearly a black hole. Finally, taking $f = 0.043$ we are faced with an even more massive object. We can conclude that on the basis of the present optical data the presence of a black hole in the system LS I +61°303 cannot be ruled out.

4. Conclusions

The emission of the gamma-ray source 2CG 135+01 is consistent with a periodic behaviour, with a period similar to the orbital/radio period of the system LS I +61°303. The gamma-ray peaks, observed at two different epochs (Tavani et al. 1998), remain confined around the periastron passage, a fact which may imply that most of the seed photons for Comptonization are indeed stellar photons (Taylor et al. 1996).

The X-ray observations along an orbital cycle (Greiner & Rau 2001) show that the system remains always in a high/soft state, characterized by a photon index $\Gamma \geq 2$. Only at the onset of radio emission is there a state transition, characterized by $\Gamma \sim 1.6$, to the low/hard state (Tanaka 1997; Fender et al. 1999). These transitions between spectral states are related to the dramatic change in the structure of the accretion disk preceding the ejection of part of it into a jet (Belloni et al. 1997; Mirabel et al. 1998; Fender et al. 1999). Good sampled simultaneous X-ray and radio observations in different outbursts would be quite important to trace (by monitoring the photon index Γ) the two accretion-ejection processes occurring in this peculiar source.

Finally, we suggest that LS I +61°30 may host a black hole, because its high/soft state has a power law component with $\Gamma \geq 2$, which is typical for systems hosting black holes. On the other hand the value of $M_x = 1.5 M_\odot$ – always quoted in the literature – is related to average values for the inclination of the orbit, mass of the Be star and mass function. The ranges for these parameters presently available are so large that a massive black hole in LS I +61°303 cannot be excluded. A new determination of all these values is desirable.

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