LS I+61 303: microquasar or not microquasar?

G. E. Romero* and M. Orellana

Instituto Argentino de Radioastronomía, C.C. 5,
(1894) Villa Elisa, Buenos Aires, Argentina
**E-mail: romero@fcaglp.unlp.edu.ar*
www.iar.unlp.edu.ar/garra

A. T. Okazaki

Faculty of Engineering, Hokkai-Gakuen University,
Toyohira-ku, Sapporo 062-8605, Japan
E-mail: okazaki@elsa.hokkai-s-u.ac.jp

S. P. Owocki

Bartol Research Institute, University of Delaware,
Newark, DE 19716, USA
E-mail: owocki@bartol.udel.edu

LS I +61 303 is a puzzling object detected from radio up to high-energy gamma-rays. Variability has recently been observed in its high-energy emission. The object is a binary system, with a compact object and a Be star as primary. The nature of the secondary and the origin of the gamma-ray emission are not clearly established at present. Recent VLBA radio data have been used to claim that the system is a Be/neutron star colliding wind binary, instead of a microquasar. We review the main views on the nature of LS I +61 303 and present results of 3D SPH simulations that can shed some light on the nature of the system. Our results support an accretion powered source, compatible with a microquasar interpretation.

Keywords: X-ray: binaries; gamma-rays: theory; stars: individual. LS I+61 303.

1. Introduction

The radio-emitting X-ray binary LS I +61 303 was discovered by Gregory & Taylor (1978). It is formed by a primary B0-B0.5Ve star with a dense equatorial disk (Paredes & Figueras 1986) and a compact object of unknown nature (Casares et al. 2005). The orbital period is 29.4960 days (Gregory 2002). The eccentricity is estimated to be high, ranging from ~ 0.55 (Grunsdstrom et al. 2007) to 0.72 ± 15 (Casares et al. 2005). The distance to the system is ~ 2 kpc (e.g. Frail & Hjellming 1991).

At X-ray energies the source presents a behavior different from other X-ray binaries: the overall level of emission is rather low ($\sim 10^{33} - 10^{34}$ erg s^{-1}) and no outbursts are observed. The whole spectral energy distribution (SED) has been recently compiled by Sidoli et al. (2006). No pulsation is observed from the compact object in any band. Thermal X-ray features are absent as well, with the spectrum following a power-law.

Recently, LS I +61 303 was detected by the MAGIC Cherenkov telescope at energies $E > 200$ GeV (Albert et al. 2006). The emission is highly variable and modulated by the orbital period. The maximum flux is observed well after the periastron passage, at phase ~ 0.6 (the periastron is at phase 0.23). The gamma-ray emission and variability have been confirmed by the VERITAS array (Maier et al. 2007). The source was also detected by EGRET at $E > 100$ MeV (Kniffen et al. 1997), with a luminosity about $\sim 10^{35}$ erg s^{-1}.

High-resolution studies of the radio morphology have shown the existence of jet-like features that change very rapidly, on timescales of days (Massi et al. 2001, 2004). These observations were first considered as supportive of a microquasar scenario (Massi 2004), but recently Dhawan et al. (2006) claimed that the changing radio morphology revealed by the VLBA along the orbit is evidence for a Be/pulsar system, powered by wind collisions as it is the case in PSR 1259-63, a well-known system that also produces high-energy emission (Aharonian et al. 2005). In this paper we discuss the nature of this peculiar source, in light of the muliwavelength observations and through detailed 3D SPH simulations of both the colliding-wind and accretion-jet scenarios.

2. Colliding winds and cometary tails

The scenario based on colliding winds for LS I +61 303 was originally proposed by Maraschi & Treves (1981), and recently revisited by Dubus (2006). Dhawan et al. (2006) claim that a jet-like feature observed during the periastron passage could be a 'cometary tail' produced by the stellar wind around the pulsar. The stellar wind, in this interpretation, would confine the pulsar wind producing a jet-like radio morphology that would point opposite to the star. Relativistic electrons, locally accelerated at the bow shock, would cool via synchrotron radiation and inverse Compton interactions in this scenario. The absence of thermal features in the X-ray spectrum is used to argue against the existence of accretion in the system. But the wind collision picture has several problems that require further investigation. For example, the 'cometary tail' points in random directions at phases other than the periastron, even in the direction of the Be star at certain phases. A spin-down luminosity of the pulsar of ($\sim 10^{36}$ erg s^{-1}) would require unrealistic efficiencies for the generation of gamma-rays in the GeV band. Larger pulsar luminosities would produce a wind that should overcome the stellar wind and would require a too-young pulsar to sustain an extremely powerful relativistic wind. Finally, in this colliding-wind scenario, it is difficult to explain the multiwavelength light curve, something that can be done in a scenario with accretion and associated ejection of unstable outflows (e.g. Bosch-Ramon et al. 2006).

A helpful way to check the colliding wind scenario is to perform 3D time-dependent numerical simulations of the system under the assumptions made by the proponents of the Be/pulsar hypothesis. We have done such simulations (described in detail in Romero et al. 2007) using a well-tested SPH code (e.g. Okazaki et al. 2002). We assumed a rapid Be wind with a velocity of 1000 km s^{-1} and a mass loss rate of $10^{-8}\ M_{\odot}$ yr^{-1}. The ratio of momentum fluxes is then $\eta = 0.53\dot{E}_{\rm PSR}/10^{36}$ erg s^{-1}, where $\dot{E}_{\rm PSR}$ is the pulsar spin-down luminosity. The pulsar wind was assumed to have a velocity of 10^4 km s^{-1} in order to avoid the complexities of a relativistic wind, but the mass-loss rate was adjusted as to provide the same momentum as a relativistic flow. Our results, shown in Fig. 1, are in agreement with 2D non-dynamical but relativistic simulations performed by Bogovalov et al. (2007). There is no evidence of any cometary tail for a pulsar power of $\sim 10^{36}$ erg s^{-1}. Moreover, the Be stellar wind cannot confine the pulsar wind. For a lower power, the energetics of the gamma-ray emission cannot be accounted for. For a higher power, the pulsar should be too young, and the shock front would wrap around the star, not the pulsar.

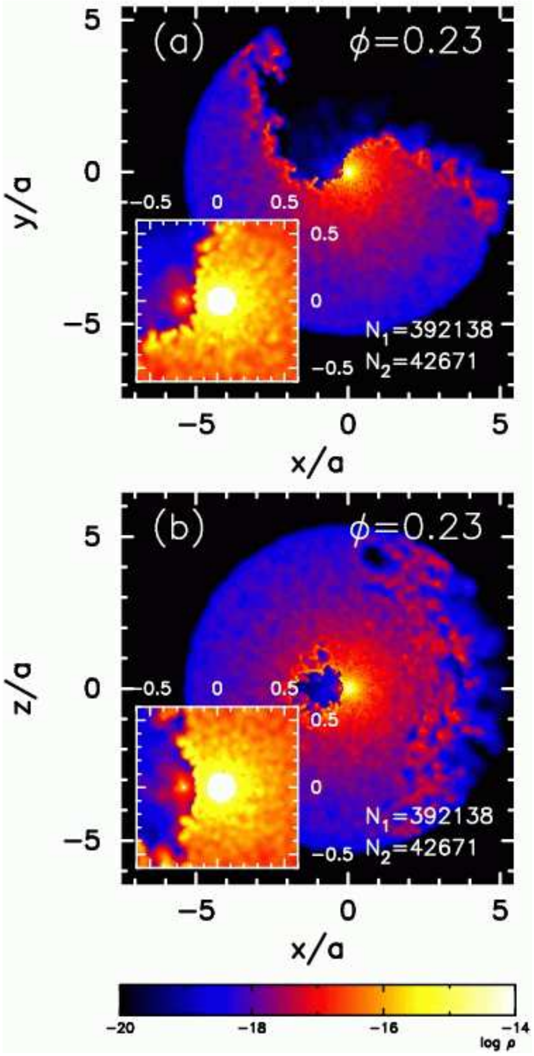

Fig. 1. Colliding wind snapshots at periastron from the 3D SPH sumulations of LS I+61 303. The bright spot is the Be star whereas the small point is the pulsar. The orbit is in the xy plane. Lengths are in units of the semi-major axis a of the orbit.

3. What is the accretion regime of LS I+61 303?

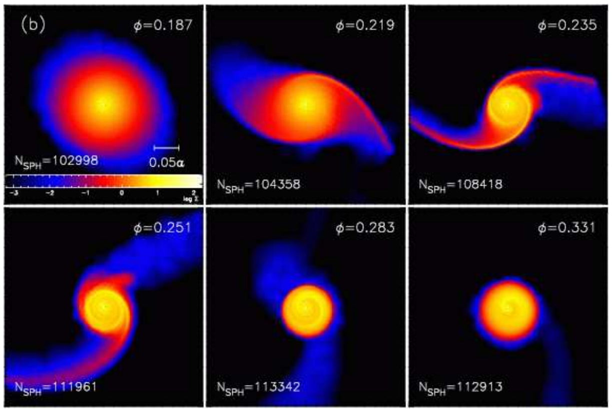

Fig. 2. Evolution of the accretion disk close to the periastron passage according to the simulations. The density wave excited by the mass transfer is clearly seen.

We have performed full simulations of the mass transfer from the Be star and its circumstellar disk to the compact object under the assumption that the latter is a 2.5 $M_\odot$ black hole (see details in Romero et al. 2007). The bulk of the mass flux onto the compact object occurs around periastron passage. The black hole gravitational pull tidally deforms the circumstellar disk and particles are captured and accreted, forming an accretion disk in which a strong density wave is excited (see Fig. 2). When the wave arrives near the central hole, around phase 0.5, there is a broad peak in the accretion rate, as shown in Fig. 3. This peak is correlated with the maximum of the gamma-ray emission in accretion/ejection models (e.g. Orellana & Romero 2007), through the standard jet/disk symbiosis assumption. The accretion rate resulting from the simulations is significantly lower (by more than two orders of magnitude) than what is obtained through simple calculations based on Bondi-Hoyle accretion into a non-perturbed circumstellar disk (Martí & Paredes 1995, Gregory & Neish 2002). It is very interesting to note that for the accretion rates obtained from the SPH simulations, the accretion regime would be advection-dominated (Narayan et al. 1999). This has important consequences, since the source should then be underluminous in X-rays, and the nonthermal emission could easily cover any thermal feature from the accretion disk.

The narrow accretion peak at the periastron might be, as explained by Romero et al. (2007), an artifact of the spatial resolution of the simulations. In any case, when opacity effects to gamma-ray propagation in the anisotropic radiation field of the star and the truncated circumstellar disk are taken into account, the high-energy emission during the periastron passage must be strongly attenuated.

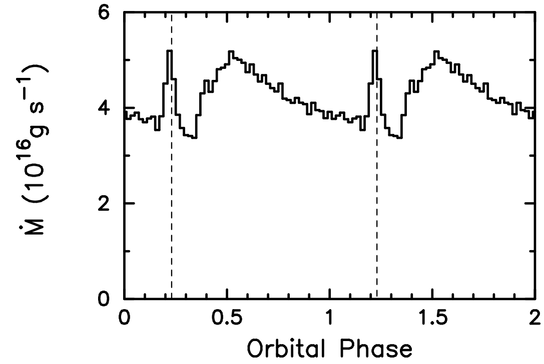

Fig. 3. Accretion rate obtained through the simulations. Notice that the accretion is sub-Eddington, in a regime where ADAF, sub-luminous, solutions exist.

4. Where are the Be/black hole binaries?

Known Be/X-ray binaries harbor pulsars and have long periods. However, Be/black hole binaries should exist in the Galaxy according to population synthesis studies (e.g. Podsiadlowski et al. 2003). They are expected to be narrow systems, with orbital periods of less than 30 days (Zhang et al. 2004). The tidal effects that truncate the Be disk described by our simulations make these systems underluminous in X-rays, and hence far more difficult to detect than longer period Be/pulsar binaries, where large X-ray outbursts use to occur. In Fig. 4 we show the effects of the tidal truncation of the Be disk. In other systems with a pulsar and a long period (e.g. PSR 1259–63), the disk has enough time to expand to large distances after the interaction with the compact object, which then moves *through* the disk in the next approach. We emphasize then that LS I +61 303 is a very different system from PSR 1259-63. We suggest that LS I +61 303 could be the first Be/black hole binary detected in the Galaxy.

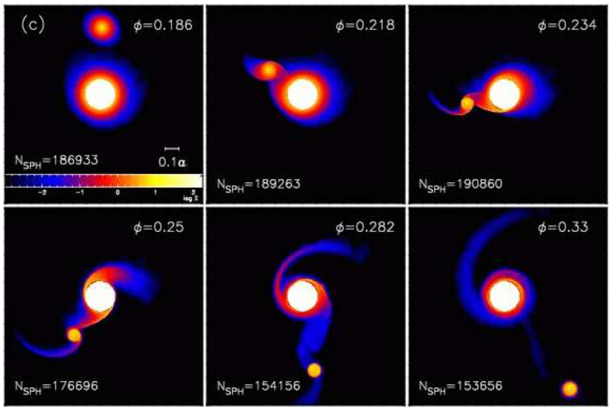

Fig. 4. Tidal interactions between the compact object and the circumstellar disk around the periastron passage.

5. Conclusions: LS I +61 303, a peculiar microquasar

The conclusion of our work, contrary to some recent claims found in the literature, is that LS I +61 303 can be classified as a microquasar because it is powered by accretion and presents radio emission produced by what seems to be an unstable jet. It is a quite different system from PSR 1259-63. The instability of the jet might be the result of the interaction of the outflow with the wind (Perucho & Bosch-Ramon 2007) or the effects of perturbations in the accretion disk and the attached magnetic fields (Romero et al. 2007). The overall picture, hence, should be similar to that discussed by Massi (2004). The mechanism behind the gamma-ray production might be hadronic (Romero et al. 2003, 2005; Orellana & Romero 2007), leptonic (Bosch-Ramon et al. 2006, Bednarek 2006), or a mixture. Neutrino observations with ICECUBE could settle this issue in the near future.

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