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Letter to the Editor

A microquasar shot out from its birth place

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Abstract. We show that the microquasar LS I +61° 303 is running away from its birth place in a young complex of massive stars. The supernova explosion that formed the compact object shot out the X-ray binary with a linear momentum of 430 ± 140 $M_{\odot}$ km s^{-1}, which is comparable to the linear momenta found in solitary runaway neutron stars and millisecond pulsars. The properties of the binary system and its runaway motion of 27 ± 6 km s^{-1} imply that the natal supernova was asymmetric and that the upper limit for the mass that could have been suddenly ejected in the explosion is ~ 2 $M_{\odot}$. The initial mass of the progenitor star of the compact object that is inferred depends on whether the formation of massive stars in the parent stellar cluster was coeval or a sequential process.

Key words. stars: individual: LS I +61° 303, 2CG 135+01, 3EG J0241+6103 – X-rays: binaries: stars – gamma-rays: observations – gamma-rays: theory

1. Introduction

Neutron stars are known to have large transverse motions on the plane of the sky which are believed to result from natal kicks imparted by supernova explosions. But the distances of solitary neutron stars are usually uncertain and it is not possible to determine the motion along the line of sight. To constrain the strength of the natal kick imparted to a particular neutron star, the distance and actual runaway space velocity in three dimensions must be known. If a compact object is accompanied by a mass-donor star, it is possible to determine the radial velocity, proper motion, and distance of the system. Then one can derive the space velocity, track the path in the sky, and estimate the strength of the natal kick, after correcting for the peculiar streaming motion of the parent cluster of stars.

This kinematic method together with the development of astrometric facilities at radio (VLBI) and optical (e.g. GAIA) wavelengths will provide in the future powerful observational tests for models of the evolution of massive stars in binary systems and collapsars. Presently, the most accurate proper motions of X-ray binaries can be obtained following at radio wavelengths with Very Long Baseline Interferometry (VLBI) the motion in the sky of compact microquasar jets, as done recently for some X-ray binaries (e.g. Mirabel et al. 2001; Ribó et al. 2002; Mirabel & Rodrigues 2003a,b).

2. LS I +61°303 and its kinematics

LS I +61°303 (Gregory & Taylor 1978) is a high mass X-ray binary (HMXB), classified as a Be/X-ray system (Gregory & Taylor 1978; Bignami et al. 1981). The compact object is a neutron star or black hole (Massi 2004) of 2 ± 1 $M_{\odot}$ orbiting around a 14 ± 4 $M_{\odot}$ donor star in an eccentric orbit with a period of 26.5 days (see Table 1). LS I +61°303 is of particular interest because it is located inside the 95% confidence radius of an unidentified high energy source observed with EGRET on board the Compton Gamma-Ray Observatory (Kniffen et al. 1997). The variable radio counterpart of LS I +61°303 (Gregory et al. 1979) has been resolved at milliarcsecond scales as a rapidly precessing relativistic compact jet (Massi et al. 2001, 2004).

The motion in the sky of the X-ray binary has been determined with high precision by VLBI astrometry of the compact jet (Lestrade et al. 1999). Figure 1 shows that LS I +61°303 is near the cluster of massive stars and HII region IC 1805, which is part of the Cas OB6 association. As indicated in Table 1, the estimated distances of the X-ray source and the star cluster are the same, despite the use of different observational techniques. An independent indication of the cluster membership of LS I +61°303 is that the apparent magnitude and colors of the donor star are consistent with those of the massive stellar members of the cluster. That is, the apparent magnitude and color of the donor star place it on the main sequence in the Hertzsprung-Russell (HR) diagram of IC 1805. Moreover, the X-ray binary and the stellar cluster are both falling towards the Galactic plane. Therefore, LS I +61°303 may have been born in the cluster IC 1805.

At a distance of 2.3 kpc from the sun (Frail & Hjellming 1991; Steele et al. 1998) the X-ray binary is at a projected

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Table 1. Basic data on the microquasar LS I +61°303 and the cluster IC 1805.

		LS I +61°303		IC 1805	
l	[°]	135.68	(1)	134.73	(2)
b	[°]	+1.09	(1)	+0.92	(2)
$\mu_\alpha \cos\delta$	[mas yr^{-1}]	0.97 ± 0.26	(1)	−1.02 ± 0.4	(2)
μ_δ	[mas yr^{-1}]	−1.21 ± 0.3	(1)	−0.88 ± 0.4	(2)
D	[kpc]	2.3 ± 0.4	(3, 4)	2.3 ± 0.1	(5)
V_{helio}	[km s^{-1}]	−55 ± 4	(6)	−41.2 ± 3	(2)
U	[km s^{-1}]	37.7 ± 4.1		42.9 ± 4.4	
V	[km s^{-1}]	−37.0 ± 4.1		−11.8 ± 4.5	
W	[km s^{-1}]	−1.8 ± 3.4		−6.9 ± 4.0	
Lifetime/Age	[Myr]	<20		<5	(5, 7)
M_x	[$M_\odot$]	2 ± 1	(6, 8)	–	
M_{Be}	[$M_\odot$]	14 ± 4	(6, 8)	–	
Spect. type		B0Ve	(5, 6, 9)	–	
Bin. eccentr.		0.7 ± 0.1	(8, 12)	–	
Binary mean sep.	[$R_\odot$]	46	(10)	–	
Binary period	[days]	26.5	(10, 11)	–	

Note: (1) Lestrade et al. (1999); (2) Dambis et al. (2001); (3) Frail & Hjellming (1991); (4) Steele et al. (1998); (5) Massey et al. (1995); (6) Hutchings & Crampton (1981); (7) Dennison et al. (1997); (8) Martí & Paredes (1995); (9) Paredes & Figueras (1986); (10) Taylor et al. (1992); (11) Gregory (2002); (12) Casares et al. (2004).

distance on the sky of ~40 pc from the center of IC 1805, and it is moving away from the cluster with a relative spatial speed of 27 ± 6 km s^{-1}. Given the relative transverse motion and using the angular extent of the cluster it is inferred that the X-ray binary could have been ejected from the cluster by a supernova explosion 1.7 ± 0.7 Myr ago. From the mass of the X-ray binary and its space velocity, it is computed that the energetic trigger imparted LS I +61°303 with a runaway linear momentum of 430 ± 140 $M_\odot$ km s^{-1}, which is a typical value for runaway neutron star binaries (Toscano et al. 1999).

3. The asymmetric natal supernova

Following the analysis by Brandt & Podsiadlowski (1995) and Nelemans et al. (1999) for symmetric mass ejection in the formation of compact objects, and from the properties of LS I +61°303 (Table 1) we estimate the maximum amount of mass that could have been suddenly ejected to accelerate the binary to a runaway speed of 27 ± 6 km s^{-1}. Assuming that the binary period and eccentricity did not change considerably since the SN event, and using Eqs. (5) and (7) of Nelemans et al. (1999) it is found that the mass that could have been suddenly ejected in a spherically symmetric SN explosion (which is the maximum possible) is $\Delta M_{SN} = 2.0 \pm 1.0\ M_\odot$. As expected for a SN that took place ≥1 Myr ago, no associated SN remnant in the X-rays and/or radio wavelengths is found.

Van den Heuvel et al. (2000) have shown that a sudden spherically symmetric mass loss ΔM_{SN} from a binary system of total mass M_{sys} would induce an orbital eccentricity $e = \Delta M_{SN} \times {M_{sys}}^{-1}$. Since $\Delta M_{SN} = 2.0 \pm 1.0\ M_\odot$ and $M_{sys} = 16 \pm 4\ M_\odot$, this implies that a symmetric explosion would have produced an orbital eccentricity $e = 0.12$, which is much lower than the actual eccentricity $e = 0.7 \pm 0.1$ (Table 1). Therefore, the SN explosion was asymmetric. The asymmetric natal explosion imparted a kick to the compact object, which caused a smaller runaway velocity of the system $V_{run} = 27 \pm 6$ km s^{-1}, since the compact object had to drag its companion of 14 ± 4 $M_\odot$.

4. Birth place in the cluster IC 1805

More massive stars evolve to the SN stage faster, and the initial mass of the progenitor of the compact object in LS I +61°303 could in principle be estimated assuming that it was contemporary of the massive stars presently being observed in the cluster. IC 1805 is one of the best studied clusters in the Milky Way (Guetter & Vrba 1989; Sung & Lee 1995; Massey et al. 1995; Shi & Hu 1999). It contains 10 main sequence stars with masses in the range of 20−85 $M_\odot$ that were formed in the last $1{-}3 \times 10^6$ years. However, the HR diagram of Guetter & Vrba (1989) and Massey et al. (1995) leave room for the possibility of an older population of stars in IC 1805, with ages of 10–20 Myr. Since it is not clear whether these stars belong to IC 1805 or to a foreground population, at present the initial mass and age of the progenitor of the neutron star is uncertain.

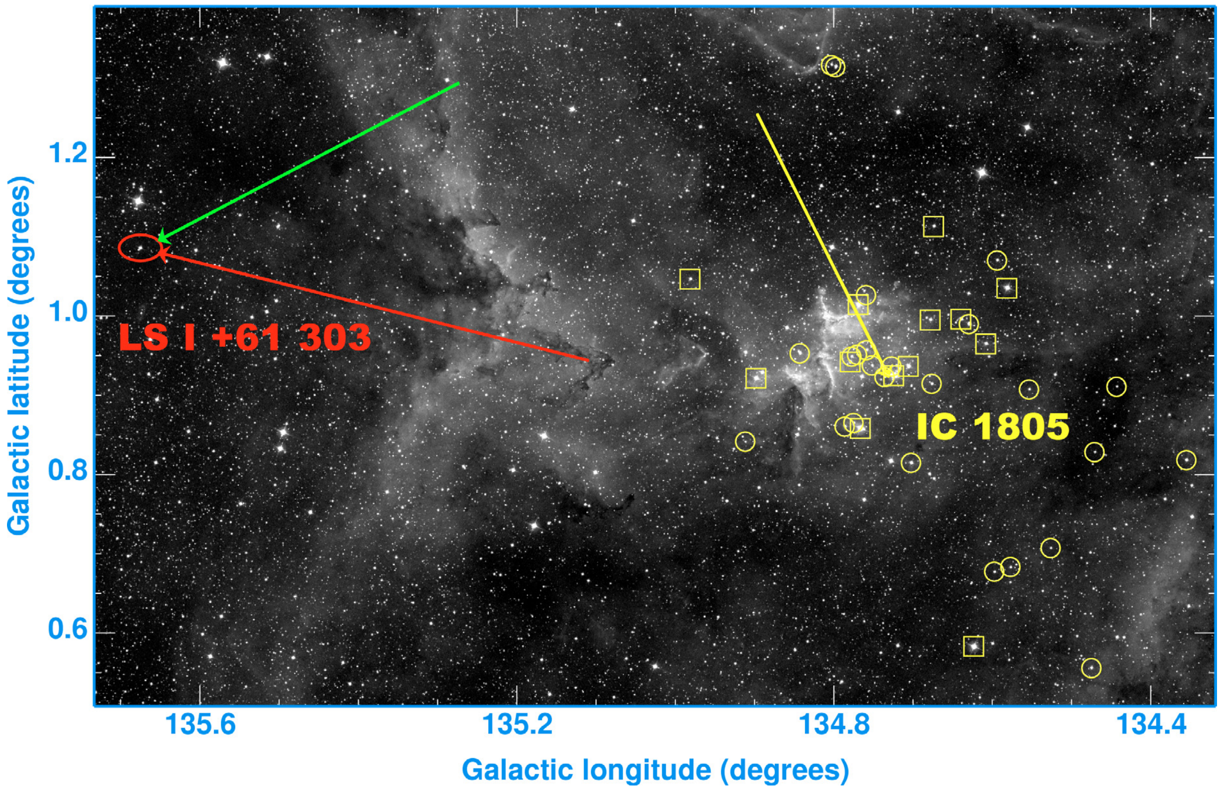

Fig. 1. The microquasar LS I +61°303 shot out at a velocity of 27 ± 6 km s^{-1} from the stellar cluster IC 1805 by the kick imparted to the compact object in a natal asymmetric supernova explosion. In this optical image (DSS, *R* filter) of the sky, LS I +61°303 is shown inside the red ellipse, and the confirmed member stars of IC 1805 with masses in the range of 7–85 $M_{\odot}$ (Massey et al. 1995; Shi & Hu 1999) are shown inside yellow symbols. The green arrow represents the motion in the sky of the radio counterpart of LS I +61°303 for the last 1 million years. The yellow arrow represents the average Hipparcos motion of the 13 brightest stars of the cluster in the Hipparcos catalog (Dambis et al. 2001), which are shown here inside yellow squares. The red arrow shows the motion of the X-ray binary relative to the cluster of massive stars for the last 1 million years.

If the cluster was formed in the last 4–5 × 10^6 years and LS I +61°303 was ejected from it ≥1 Myr ago, the progenitor of the compact object had a lifetime ≤4 Myr before it exploded as a SN. From current models of stellar evolution (Schaller et al. 1992) it is inferred that only stars of ≥60 $M_{\odot}$ have such short lifetimes before collapse. This would be a lower limit for the progenitor mass since stars with masses of up to 85 $M_{\odot}$ are presently found in IC 1805 (Sung & Lee 1995; Massey et al. 1995). The masses of the donor and compact object are 14 ± 4 $M_{\odot}$ and 2 ± 1 $M_{\odot}$ respectively, and in the explosion not more than ~2 $M_{\odot}$ were ejected. Therefore, if the progenitor was contemporary of the massive stars in IC 1805, before collapse it must have lost ≥50 $M_{\odot}$, that is ≥90% of its initial mass.

We point out that the two best studied soft gamma-ray repeaters, which are young neutron stars, are located in dust enshrouded clusters of massive stars (Mirabel et al. 2000). But unless it is known whether the massive star formation in these clusters was coeval or a continuous process, we don't know whether stars with masses ≥60 $M_{\odot}$ can end as neutron stars and black holes of low mass.

On the other hand, in the context of binary evolution models (Ergma & van den Heuvel 1998), the progenitor of the compact object in LS I +61°303 would be much older, say 10 million years, as its companion has a mass of about 14 $M_{\odot}$, and mass transfer between the components of the binary may have increased its mass. So the progenitor star might have had a smaller mass, say 15–20 $M_{\odot}$.

5. Conclusion

The compact object in LS I +61°303 was striken by an asymmetric natal supernova dragging the binary system with a runaway linear momentum of 430 ± 140 $M_{\odot}$ km s^{-1}. Large runaway linear momenta comparable to those of solitary neutron stars and millisecond pulsars were reported for the neutron star X-ray binary LS 5039 (Ribó et al. 2002) and GRO J1655-40, which contains a black hole of ≤7 $M_{\odot}$ (Mirabel et al. 2002). On the contrary, Cygnus X-1 which contains a black hole of ~10 $M_{\odot}$ was formed in situ and did not receive an energetic trigger from a supernova (Mirabel & Rodrigues 2003a). Although the number statistics is still low, these preliminary results are consistent with evolutionary models for binary massive stars (Balberg & Shapiro 2001; Fryer et al. 2002), where neutron stars and low-mass black holes form in energetic supernova explosions, whereas the black holes with the larger masses form in underluminous supernovae or even in complete darkness.

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