Extended X-ray object ejected from the PSR B1259-63/LS 2883 binary

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IAU XXIX General Assembly Honolulu, HI – August, 2015
High-mass binary LS 2883 with PSR B1259-63

Fast-spinning, massive (M~30 M☉, L=6×10^4L☉) star with a strong wind.

The wind is dense and slow in the decretion disk, tenuous and fast outside the disk.

**Pulsar B1259-63:**
- Spin period = 48 ms
- $Edot = 8\times10^{35}$ erg/s
- Spin-down age = 330 kyr
- Should emit pulsar wind

X-ray flux varies with orbital period.
Gamma-ray flashes near periastron, apparently when the pulsar interacts with the decretion disk during 2nd passage.

**Orbit:**
- 3.4 yr orbital period
- 7 AU (3 milliarcsec) max. separation
- 0.87 eccentricity
## Imaging observations with Chandra ACIS

4 observations, May 2009 – Feb 2014

<table>
<thead>
<tr>
<th>ObsID</th>
<th>MJD</th>
<th>$\theta^a$</th>
<th>$\Delta t^b$</th>
<th>Exp.$^c$</th>
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</table>

$^a$True anomaly counted from periastron.

$^b$Days since latest preceded periastron.

$^c$Exposure corrected for deadtime.

$^d$Total (gross) counts.

![Graphical representation of observations with Chandra ACIS](image)
1st Observation (2009 May 14)

Short 25.6 ks ACIS-I exposure near apastron, $\theta = 182$ deg

$\sim 4\sigma$ detection of asymmetric extended emission

(Pavlov et al 2011)
2nd Observation (2011 Dec 17)

56.3 ks ACIS-I exposure before apastron, $\theta = 169$ deg

Clear asymmetric extended emission
3rd Observation (2013 May 19)

56.3 ks ACIS–I exposure after apastron, $\theta = 192$ deg

Extended emission moved further outward
2nd and 3rd observations compared

$1''.8 \pm 0''.5$ shift corresponds to the apparent proper motion

$\mu = 1.27 \pm 0.35$ arcsec yr$^{-1}$

$V = (0.046 \pm 0.013)c$

at $d = 2.3$ kpc

(Kargaltsev et al. 2014)
4th Observation (2014 February 8 - 9)

57 ks ACIS-I exposure approaching periastron

Extended emission moved farther from the binary, apparently faster than expected from the previous 2 observations
Between 3rd and 4th observations the extended structure moved by $2.5'' \pm 0.5''$.

This corresponds to the apparent proper motion

$$V = (0.13 \pm 0.03)c$$

at $d = 2.3$ kpc

Apparent acceleration (?)

$90 \pm 40$ cm s$^{-2}$
Distance of the extended source from the binary versus time

**Linear fit:** \( V = (0.07 \pm 0.01)c \)

If there is no (or little) acceleration, the cloud was ejected from the binary around periastron of 2010 Dec 14
Luminosities and spectra of extended emission

In 3 last observations $0.5 - 8$ keV fluxes are

$$F = 8.5 +\/- 0.5, \quad 3.6 +\/- 0.4, \quad 1.9 +\/- 0.4 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1},$$

corresponding luminosities $L \sim (0.2 - 1) \times 10^{31} \text{ erg/s}$ at $d = 2.3$ kpc, ~0.7% - 3% of the binary’s luminosity.

The spectra can be fitted with thermal bremsstrahlung, $kT > 6$ keV, $n \sim 100 \text{ cm}^{-3}$, $m_{\text{ej}} \sim 10^{28} - 10^{29} \text{ g}$ -- much larger than the mass supplied by the massive star wind during one orbital period, $P_{\text{orb}} \dot{M} \sim 10^{26} \left(\dot{M}/10^{-8} \text{ M}_{\odot}/\text{yr}\right) \text{ g}$, or a reasonable mass of disk, $m_{\text{disk}} \sim 10^{24} - 10^{26} \text{ g}$.

Kinetic energy $\sim 10^{46} - 10^{47} \text{ erg}$, improbably large.

The scenario with hot hadronic plasma cloud radiating via bremsstrahlung does not look plausible.
The spectra are also consistent with power laws, photon indices $\Gamma = 1.2\pm0.1, 1.3\pm0.2, \text{ and } 0.8\pm0.4$ (no softening!)

**Synchrotron radiation?**

Confidence contours in Photon Index – Normalization plane
Synchrotron interpretation:

magnetic field $B \sim 80 \, k_m^{2/7} \, \mu G$, where $k_m = \varepsilon_{\text{mag}}/\varepsilon_{\text{kin}}$;
electron Lorentz factor $\gamma \sim 10^7 - 10^8$,
total magnetic and electron energies $W_m \sim 5 \times 10^{40} \, k_m^{4/7}$ and $W_e \sim 5 \times 10^{40} \, k_m^{-3/7} \, \text{erg}$ in volume $V \sim 10^{50} \, \text{cm}^3$.
$W_m + W_e < \lesssim P_{\text{orb}} \, \dot{E} = 9 \times 10^{43} \, \text{erg}$ for a broad range of $k_m$ -- the energy could be supplied by the pulsar.

But, if the ejected object were an e-/e+ cloud, it would be difficult to explain the fast motion because of the drag force, $f \sim \rho_{\text{amb}} \, v^2 \, A$.
Deceleration time

$t_{\text{dec}} \sim (W_m + W_e) \, v \, f^{-1} \, c^{-2} \sim 10 \, n_{\text{amb}}^{-1} \, (k_m^{4/7} + k_m^{-3/7}) \, \text{s}$,
where $n_{\text{amb}}$ is the ambient proton number density.

To reduce the deceleration, the e-/e+ cloud must be loaded with a heavy (electron-ion) plasma, but even in this case the ejected mass should be a substantial fraction of the disk mass, if the ejected clump is moving in a stellar wind blown bubble.
Another hypothesis

**Variable termination shock in the circumbinary medium,**
similar to PWNe around isolated pulsars (Kargaltsev et al 2014)

**But,** it requires unrealistically high ambient pressure, $p_{amb} \sim 10^{-10}$ dyn cm$^{-2}$, to explain the shock size; looks artificial now.

Current explanation: Instead of the companion’s wind bubble, **ejected clump is moving in the unshocked pulsar wind**

More plausible at larger values of $\eta = \frac{E_{dot}}{(\dot{M} \cdot v_w \cdot c)} = 4.4 \left(\frac{\dot{M}}{10^{-9} M_\odot/\text{yr}}\right)^{-1} \left(\frac{v_w}{1000 \text{ km/s}}\right)^{-1}$

when the companion’s wind is confined by the pulsar wind into a narrow cone, while the unshocked pulsar wind fills the rest of the binary volume.

The X-ray emission is due to synchrotron radiation of the pulsar wind shocked by the collision with the clump.

X-ray luminosity $L_{X,cl} = \xi_X E_{dot} (r_{cl}/2r)^2, \quad \xi_X \sim 1.5 \times 10^{-3}$
The interaction with unshocked pulsar wind with ejected clump can also **accelerate** the clump: \( \text{vdot} \sim p_{pw} A m_{cl}^{-1} \).

\( m_{cl} \sim 10^{21} \text{ g} \) for the apparent (low-significance) estimated acceleration.

**The clump could be ejected due to interaction of the pulsar with the decretion disk.** When the pulsar enters the dense disk, a shock is created, with a radius exceeding the disk’s vertical size \( \Rightarrow \) Disruption of the disk in the first passage, further fragmentation in the second passage, \( \gamma \)-ray flares from shocked pulsar wind, entrainment of clumps in the pulsar wind, then acceleration by the pulsar wind ram pressure to \( \sim 0.1 \text{ c.} \)
Summary

• We discovered a new phenomenon: Ejection of an X-ray emitting clump from a high-mass γ-ray binary with a velocity $v \sim 0.1c$ and a hint of acceleration.
• The clump’s luminosity faded with time but the power-law-like spectrum ($\Gamma \sim 0.8 – 1.3$) did not show softening.
• The clump was likely ejected due to interaction of the pulsar (pulsar wind) with the equatorial decretion disk of the high-mass star.
• We suggest that the clump is moving in the unshocked pulsar wind, whose pressure accelerated the clump to the very high speed. This scenario requires large $\eta$.
• The most likely emission mechanism is synchrotron radiation of relativistic electrons ($E_e \sim 10 - 100\text{ TeV}, B \sim 10^2 \mu\text{G}$) of pulsar wind shocked in the collision with clump.
• We expect a new clump has been ejected during the recent periastron passage (May 2014), new Chandra observations are planned.