High-speed ejecta from the high-mass gamma-ray binary PSR B1259-63/LS 2883

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Binary parameters: Orbital period 3.4 yrs, semi-major axis 6 au (3 mas), eccentricity 0.87, inclination 153°. Recent periastrons: 2010 Dec 14, 2014 May 4, 2017 Sep 22.

PSR B1259-63: Spin period 48 ms, spin-down age 330 kyr, $E_{\text{dot}} = 8 \times 10^{35}$ erg/s, $B = 3 \times 10^{11}$ G

LS 2883: $M = 15 - 31 \, M_\odot$, $L = 6 \times 10^4 \, L_\odot$, $d = 2.6 \, \text{kpc}$, fast-spinning Be (late O) star, stellar wind -- dense and slow in the equatorial disk (inclined by $\sim 35^\circ$ to the orbital plane), tenuous and fast outside the disk.
Collision of pulsar wind with stellar wind → intrabinary shock → particle acceleration → nonthermal emission from radio to γ-rays

Pulsar wind (PW) is confined by stellar wind if the thrust ratio

$$\eta = \frac{E_{\text{dot}}}{(M_{\text{dot}} v_w c)} < 1$$

(vice versa if $\eta > 1$).

(Tavani & Arons 1997)

Either shocked or unshocked PW can leave the binary and interact with the ISM forming a pulsar wind nebula (PWN)

We proposed to look for a PWN outside the binary, using the excellent angular resolution of Chandra.
First high-res observation

25 ks ACIS-I exposure

2009 May 14

(Pavlov et al 2011)

~4σ detection of asymmetric extended emission. Termination shock of PW?
Three observations in binary cycle 2011 - 2014

~60 ks ACIS-I exposures

2011 Dec 17

Extension is seen clearly
Three observations in binary cycle 2011 - 2014

2013 May 19

Extended object separated from the binary?

(Kargaltsev et al 2014)
Three observations in binary cycle 2011 - 2014

2014 Feb 8 (DDT)

Extended object is moving!

(Pavlov et al 2015)
Extended object moving from the binary along its major axis, fading with increasing distance.

High apparent velocity, $v \sim 0.1 \, c$, perhaps with acceleration.
No evidence of deceleration.

(Kargaltsev et al. 2014; Pavlov et al. 2015)
Five observations in the next binary cycle: Apr 2015 – Jul 2017

ACIS-I exposures 60-65 ks

2015 Apr 21

19281+20116

20054

19280

16822

16823+18744

(Hare et al 2019)
Five observations in the next binary cycle: Apr 2015 – Jul 2017

(Hare et al 2019)

2016 Jan 12

A hint of extended emission
Five observations in the next binary cycle: Apr 2015 – Jul 2017

(Hare et al 2019)

Separated extended object with “whiskers”!
Five observations in the next binary cycle: Apr 2015 – Jul 2017

2017 Apr 24 (DDT)

Unexpected brightening!
Different shape.
Second “clump” emerging?

(Hare et al 2019)
Five observations in the next binary cycle: Apr 2015 – Jul 2017

ACIS-I exposures 60-65 ks

(Hare et al 2019)

Brightening disappeared. Clump moved further, Yet another shape. Second clump disappeared
New clump detected moving in same direction with similar velocity

Shows strange “whiskers” in Jan 2017, brightening and 2nd clump [?] in Apr 2017
Clump separation from the binary vs time

Two binary cycles

2011-2014

2014-2017

Distance, arcseconds

Days since MJD 55544.7

1 arcsec = 3.4×10^{16} \text{ cm}

Characteristic size of the “clump” ≈ 3''≈ 10^{17} \text{ cm}
Clump separation from the binary vs time

\[ V_{\text{app}} = (0.07 \pm 0.01)c \]
Clump separation from the binary vs time

\[ V_{\text{app}} = (0.07 \pm 0.01)c \]

\[ V_{\text{app}} = (0.12 \pm 0.02)c \]
Accelerated motion: a better model

If the clump was launched at 2014 periastron with a low speed, the acceleration is

\[ a = 47 \pm 2 \text{ cm/s}^2 = 14,800 \pm 600 \text{ km/s/yr} \]

\[ V_{\text{app}} \approx 0.16c \text{ at } t = P_{\text{orb}} = 3.4 \text{ yr} \]

\[ V \approx 0.2 \text{ c} \text{ if motion in orbital plane} \]
Power-law spectra (confidence contours)

Normalization vs photon index $\Gamma$, with lines of constant flux (0.5-8 keV)

2011-2014 2017 Jan - Jul

Variations of $\Gamma$ are statistically insignificant; average $\Gamma = 1.45 \pm 0.11$. 
0.5 – 8 keV flux evolution in 2 binary cycles

Luminosities

\[ L_X \sim (2 - 9) \times 10^{31} \text{ erg/s} \]

at \( d = 2.6 \text{ kpc} \); 

\(~0.7\% - 3\%\) of the binary’s X-ray luminosity far from periastron.
Most likely emission mechanism is **synchrotron radiation** from a cloud of e\(^+\)/e\(^-\) supplied by pulsar (Inverse Compton would require too many e\(^+\)/e\(^-\)).

**Physical parameters:** \(B_{eq} \sim 100 \ \mu\text{G}, \quad E_{\text{electron}} \sim 10 – 100 \ \text{TeV},\)

total energy \(W \sim 10^{41} \ \text{erg} \) in volume \(\sim 10^{51} \ \text{cm}^3;\)
\(W << P_{\text{bin}} \ E_{\text{dot}} = 7 \times 10^{42} \ \text{erg}\)

**Problem:** Isolated e\(^-\)/e\(^+\) clump would be immediately **decelerated** and **destroyed** by drag force in the interstellar medium: \(f \sim \rho_{\text{amb}} v^2 A, \) but clumps show **no deceleration**!

Likely, they are **loaded with ions from the stellar wind disk** and move in a very **low density medium**

If the **acceleration** is real, it could be **due to ram pressure of pulsar wind** (but not a ‘Compton rocket’)

Possible scenario:

During most part of the binary period the shocked PW leaves the binary in the apastron direction and carves a low-density channel in ambient medium.

When the pulsar crosses the disk, a clump of mixed disk matter and relativistic electrons (clump mass $\sim 10^{21}$ g) is formed and ejected into the channel.

The clump is pushed “from behind” and perhaps accelerated by the shocked PW along the channel until the clump speed approaches the shocked PW speed, $\sim 0.1c – 0.3 c$.
Such a scenario was supported by numerical simulations (Barkov & Bosch-Ramon 2016).

Density distribution (colors) and velocities (arrows) in the orbital plane 680 d after periastron.

Azimuthally averaged radial velocities for two sectors of orbital plane at different times.
Open Questions

• Are the clumps indeed launched near *periastron passages*?

• Do they indeed move with a nearly constant *acceleration*? Why could the acceleration be different in different cycles?

• Is the clump *brightening* due to *internal* processes (e.g., magnetic field reconnection in turbulent plasma) or *external* ones (e.g., collision with a previously launched clump)? How long do the brightening episodes last, what are the peak luminosities?

• What is the origin of the *whiskers*? Instabilities in the clump plasma? How fast do they evolve?
Open Questions

• What is the nature of the *apparent 2\textsuperscript{nd} clump* observed on 2017 Apr 24?

Possible ejection of another, slower moving clump?

Or launched at a later date, well after periastron?

Or a projection effect (different clumps are launched in different directions and fade with different rates)?

Possible new clump 2” from binary

Not seen in next observation 97 days later
Open Questions

• How clump parameters are connected with the post-periastron γ-ray flares?


The flares after 2017 periastron had higher photon flux and fluence ($L_γ > E_{\text{dot}}$ in some of them), faster variability (~1.5 min), lasted longer (up to 90 day after periastron) – Johnson et al 2018.

Such differences can affect clump ejection and properties – higher clump mass, lower velocity, higher brightness, larger size in 2017-2021 cycle?

To answer these questions, we should keep monitoring this system with Chandra with short enough cadence.
Three observations in the 2017-2021 binary cycle

We see extended emission (perhaps a nascent slow-moving clump) but it is not separated from the binary yet. New observations are needed in the most interesting part of the orbit.
Summary of findings:

- New (so far unique) phenomenon discovered: Ejection of X-ray emitting clumps from a high-mass gamma-ray binary, accelerated to an apparent velocity $V_{\text{app}} \sim 0.1c$

- Typical clump sizes up to 10,000 a.u. Clumps change their shape and brightness. X-ray luminosity up to $10^{32}$ erg/s, power-law spectra with $\Gamma \sim 1.2 – 1.6$, no softening with time

- Clumps showed somewhat different behavior in two binary cycles (e.g., different speed/acceleration, steady fading vs occasional brightening)

Possible interpretations:

- Clumps consisting of relativistic electrons and stellar (disk) matter are ejected during periastrons passages due to interaction of the pulsar wind with the equatorial disk of the high-mass star

- Clumps are possibly moving in the pulsar wind, whose ram pressure accelerates them to the very high speed

- X-ray emission mechanism is likely synchrotron radiation of relativistic electrons of the shocked pulsar wind mixed with stellar matter; possible internal shocks within the clump
Thank you!