Evolution of the Extended X-Ray Emission from the PSR B1259–63/LS 2883 Binary in the 2014–2017 Binary Cycle

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Abstract

We have performed a series of Chandra X-ray Observatory observations of the gamma-ray binary LS 2883, which is composed of a young pulsar (PSR B1259–63) orbiting a massive Be star with a period of 1236.7 days. The system was observed in five epochs, spanning a range from 352 to 1175 days after the periastron passage on 2014 May 4. The observations confirmed the recurrent nature of the high-speed ejecta that appear as an extended X-ray structure (clump) moving away from the binary. Compared to the results of the previous monitoring campaign (between the 2010 and 2014 periastron passages), this time we find evidence suggesting that the clump is accelerated to a projected velocity $v_\parallel \approx 0.15c$ with an acceleration $a_\parallel = 47 \pm 2$ cm s$^{-2}$ (for uniformly accelerated motion), assuming that it was launched near periastron passage. The observed X-ray properties of the clump are consistent with synchrotron emission from pulsar wind (PW) particles accelerated at the interface between the PW and the clump. We have also performed contemporaneous observations with the Hubble Space Telescope, which are used to set an upper limit on the optical flux of the extended emission.

Key words: pulsars: individual (B1259–63) – stars: early-type – stars: individual (LS 2883) – stars: neutron – X-rays: binaries

1. Introduction

High-mass $\gamma$-ray binaries (HMGBs) consist of a massive early B- or late O-type star and either a neutron star (NS) or a black hole (BH). Only seven such sources have been discovered to date. In two of these systems, LS 2883/PSR B1259–63 (B1259 hereafter) and MT91 213/PSR J2032+4127, radio pulsars were detected, while the nature of compact object is still unknown in the other systems. The most studied of these binaries is B1259. The pulsar has a spin period $P = 47.8$ ms, spin-down power $\dot{E} = 8.3 \times 10^{35}$ erg s$^{-1}$, dipolar magnetic field $B_{\text{PSR}} = 3.3 \times 10^{11}$ G, and characteristic age $\tau_{\text{PSR}} = P/(2\dot{P}) = 330$ kyr (Johnston et al. 1992). The high-mass star in this system is a fast-rotating Be star with a luminosity $L_\text{B} = 6.3 \times 10^8 L_\odot$ and mass $M_\text{B} = (15-31)M_\odot$ (Negueruela et al. 2011; Miller-Jones et al. 2018). The companion star is believed to have an equatorial decretion disk, inclined by $\approx 35^\circ$ to the orbital plane (Melatos et al. 1995; Shannon et al. 2014).

B1259 has an orbital period $P_{\text{orb}} = 1236.7$ days and large eccentricity $e = 0.87$ (Johnston et al. 1992). Recently, precise astrometric radio measurements of the system have allowed Miller-Jones et al. (2018) to accurately determine the orbital parameters and annual parallax of B1259. The updated parameters for the system are an inclination $i = 153^\circ \pm 3^\circ$ (implying that the pulsar orbits its companion in the clockwise direction), argument of periastron $\omega = 138^\circ \pm 7^\circ$, and deprojected semimajor axis $a \approx 6\,\text{au}$ (Miller-Jones et al. 2018). The measured parallax places the system at a distance $d = 2.6^{+0.4}_{-0.3}\,\text{kpc}$, after correcting for the Lutz–Kelker bias (Lutz & Kelker 1973; Miller-Jones et al. 2018).

This system has been observed many times in X-rays over several binary cycles and has shown variations in the flux, photon index, and hydrogen-absorbing column density, which are dependent on the orbital phase of the observation (Chernyakova et al. 2006, 2009, 2015). The detected X-ray emission is nonpulsed and is thought to be due to either synchrotron or inverse Compton (IC) radiation from relativistic leptons from a pulsar wind (PW) being accelerated at the shock between the stellar wind and PW (Tavani & Arons 1997; Chernyakova & Illarionov 1999, 2000).

At GeV energies B1259 has been detected as a transient source appearing near the 2010, 2014, and 2017 periastron passages, with the emission peaking after (or during) the time of the second disk crossing (Abdo et al. 2011; Cianiandro et al. 2015; Johnson et al. 2018; Tam et al. 2018). The GeV flares exhibited similar spectra but different variability timescales during each orbital cycle (Cianiandro et al. 2015; Johnson et al. 2018) and were not accompanied by simultaneous TeV or X-ray flares (H.E.S.S. Collaboration et al. 2013; Chernyakova et al. 2015). For instance, in 2010 and 2017 GeV emission was detected $\sim 10$ days after periastron passage and then was not detected again until $\sim 40$ days later, while in 2014 GeV emission was not detected until 31 days after periastron passage. These flares lasted $\sim 30–40$ days before decaying back below the detection limit. The luminosity of the GeV flare seen after the 2017 periastron passage has exceeded the spin-down luminosity of the pulsar. Additionally, rapid variability (on timescales of 1.5 minutes) was detected for the first time during the 2017 GeV flare.

The physical origin of the GeV flares remains unknown, with various scenarios involving, e.g., IC scattering of soft photons (of different origins) off PW electrons (Khangulyan et al. 2012; Dubus & Cerutti 2013; Takata et al. 2017; Yi & Cheng 2018), reconnection in the PW (Mochol & Kirk 2013), interactions
between the PW and clumpy stellar wind (de la Cita et al. 2017), or synchrotron radiation Doppler-boosted in the bow shock tail (Tam et al. 2011; Kong et al. 2012). Recently, a marginal ($\sim 3\sigma$) detection of B1259 in its “quiescent” state (i.e., far from periastron) has been reported in the Fermi-LAT 5–300 GeV band, apparently dependent on the orbital phase (Xing et al. 2016).

At TeV energies, emission from B1259 has been detected by H.E.S.S. (Aharonian et al. 2005, 2009; H.E.S.S. Collaboration et al. 2013) around the periastron passages. Combined data from three subsequent binary cycles indicate a double-peak profile of the TeV light curve reminiscent of that seen at X-ray energies (Romoli et al. 2017). The TeV emission could be due to either IC scattering of stellar photons off ultrarelativistic electrons (Khangulyan et al. 2007; Aharonian et al. 2009) or hadronic interactions between the PW and the companion’s dense decretion disk (Aharonian et al. 2009).

B1259’s pulsed radio emission disappears for nearly 1 month near periastron, suggesting that it becomes eclipsed by the dense stellar wind and the decretion disk of the Be-type companion star (Johnston et al. 2005). Nonpulsed radio emission peaks ≈5 days before and ≈20 days after periastron passage and varies in relative intensity between orbital cycles. This emission has been interpreted as synchrotron radiation from electrons accelerated by the passage of the pulsar through the decretion disk (Ball et al. 1999). The X-ray and TeV light curves also show peaks when the pulsar enters and exits the disk, ≈20–4 days before periastron and ≈10–50 days after periastron, respectively (H.E.S.S. Collaboration et al. 2013; Chernyakova et al. 2015).

Extended X-ray emission near B1259 was first reported by Pavlov et al. (2011), who found a faint, asymmetric extension observable up to ≈4′ south–southwest from the location of the binary in a 26 ks Chandra X-ray Observatory (Chandra) observation taken near apastron. During the next orbital cycle, two deeper (56 ks exposures) Chandra observations were taken 370 and 886 days after periastron, respectively. In these observations, a variable and extended (~4″) feature, nicknamed the “clump,” was discovered and had shifted by 1″8 ± 0″5 between the observations (Kargaltsev et al. 2014 hereafter). This shift allowed K+14 to measure the corresponding projected velocity $v_{\perp} = (0.052 ± 0.015)c$ of the clump assuming $d = 2.6$ kpc. To better constrain the motion of the clump, a Director’s Discretionary Time (DDT) Chandra observation was undertaken. This allowed Pavlov et al. (2015, P+15 hereafter) to further track the motion of the extended feature and calculate a projected velocity of $v_{\perp} \approx (0.08 \pm 0.01)c$ at $d = 2.6$ kpc. Surprisingly, the extended feature showed no signs of decelerating and actually showed marginal signs of acceleration (albeit at a low significance). If a constant velocity is assumed, then the clump’s launch time was consistent with both periastron passage and the GeV flare.

The flux of the clump faded over time, but the photon index did not soften, implying no cooling of the clump’s matter (P+15). The large projected velocity, lack of spectral softening, and launch time being consistent within $\sim 0.5$ days of periastron led P+15 to suggest that the clump is launched owing to an interaction of the pulsar with the decretion disk of the Be star. They then suggested that the clump is moving in (and possibly accelerated by) the unshocked PW and that the X-ray emission can be understood as synchrotron radiation from the PW shocked by the collision with the clump.

Here we report on a Chandra campaign to determine whether this phenomenon is repeating, by searching for a newly launched clump after the 2014 periastron passage on 2014 May 4. We also obtained Chandra and Hubble Space Telescope (HST) DDT observations to help constrain the clump’s motion and its multiwavelength spectral energy distribution (SED) and to test different energy emission mechanisms. In Section 2 we describe the observations and data reduction, in Section 3 we discuss the X-ray data analysis, and in Section 4 we discuss the implications that the new observations impose on the previously suggested models. Finally, we summarize our findings in Section 5.

2. Observations and Data Reduction

2.1. Chandra Observations

In our latest Chandra campaign B1259 was observed seven times (ObsIDs 16822, 16823, 18744, 19280, 20054, 19281, 20116) with the Advanced CCD Imaging Spectrometer (ACIS) between 2015 April and 2017 July. Because observations 16823 and 18744, as well as 19281 and 20116, were carried out with very small time intervals between them, 4 and 3 days, respectively, each of these two pairs can be considered as a single observation, i.e., the binary was observed in five epochs. The pulsar’s orbital position during each observation can be seen in Figure 1, while the specific observation dates, exposure times, days after periastron at time of observation, and true anomaly of the pulsar for each observation can be seen in Table 1. Similar to our previous observations reported in K+14 and P+15, we imaged B1259 on the front-illuminated ACIS-I3 chip in timed-exposure mode. The data were telemetered in the “very faint” format, and a 1/8 subarray was used to reduce the frame time to 0.4 s in order to lessen the effect of pileup. The largest count rate from the binary was 0.05 counts per
The pipeline-produced Level 2 event files were used for all analyses. There were no episodes of anomalously high background rates occurring during any of these observations. In order to reduce the background contribution, all event files were filtered to only contain photon energies in the 0.5–8 keV energy range. The detector responses for spectral analyses were produced with the CIAO Interactive Analysis of Observations (CIAO, ver. 4.9) tools using the standard procedures and calibration database (CALDB ver. 4.7.5). The spectral fitting was done using XSPEC (ver. 12.9.1; Arnaud 1996).

2. HST Observations

The Space Telescope Imaging Spectrograph (STIS) on board the HST has a wide-filter imaging mode, which can be used to take optical coronagraphic images with an occulting mask (50CORON). STIS has a 52′′ × 52′′ field of view, a 0′05 pixel size, and operates in the 2000–10300 Å waveband. STIS observed B1259 on 2017 July 24 (MJD 57,959) for four orbits (HST program number 14932) shortly after the final Chandra observation (see Table 1). Each of the four observations was split into four shorter exposures of 648 s long (i.e., CR-SPLIT = 4) to allow for the rejection of cosmic rays. The bright companion (V ∼ 10 mag) star was placed on the WEDGB2.5, which has an occultation width of 2′′.5. We observed B1259 with four different roll angles: ORIENT = 68′′.056, 71′′.056, 74′′.0559, and 77′′.0559, one per orbit.

This is used to remove the bright diffraction spikes in the point-spread function (PSF) wings of the companion star while searching for extended optical emission from the clump (see Section 3.3).

### Table 1

| ObsID  | MJD  | \( \theta^a \) | \( \Delta^b \) | Exp. | Ctc\(^c\) | \( F_{\text{obs}}^d \) | \( F_{\text{err}}^e \) | \( N_{\text{br}}^f \) | \( \Gamma^g \) | \( \chi^2/\text{dof}^h \) |
|--------|------|---------------|---------------|------|--------|----------------|----------------|----------------|--------------|-----------------|
| 16822  | 57,133 | 169 | 352 | 58.3 | 6167 | 1.48^{+0.3}_{-0.2} | 1.85^{+0.3}_{-0.2} | 3.4(3) | 1.57(4) | 2.9(2) | 3.8 | 178.0/176 |
| 16823+18744\(^i\) | 57,401 | 180 | 620 | 32.4 | 4315 | 1.01^{+1.0}_{-1.2} | 1.23^{+1.2}_{-1.1} | 2.7(4) | 1.59(5) | 2.0(1) | 3.8 | 132.4/145 |
| 19280  | 57,759 | 198 | 978 | 55.4 | 5191 | 1.24(3) | 1.72(2) | 3.4(3) | 1.94(5) | 3.7(2) | 3.8 | 161.6/148 |
| 20054  | 57,867 | 208 | 1086 | 59.0 | 7382 | 1.81(3) | 2.32(3) | 3.2(3) | 1.70(4) | 4.1(2) | 3.8 | 247.5/193 |
| 19280+20116\(^j\) | 57,956 | 227 | 1175 | 35.5+19 | 6267 | 1.78(3) | 2.13(3) | 2.6(3) | 1.52(4) | 3.2(2) | 3.8 | 206.7/200 |
| 19280+20116\(^j\) | 57,956 | 227 | 1175 | 35.5+19 | 6267 | 1.78(3) | 2.13(3) | 2.6(3) | 1.52(4) | 3.2(2) | 3.8 | 206.7/200 |

Notes. For each ObsID the upper and lower rows correspond to the binary core and extended emission, respectively. The 1σ uncertainties of the last significant digits are shown in parentheses. Fluxes and counts are in the 0.5–8 keV range. An asterisk indicates that the hydrogen absorption column density was fixed to the value of the corresponding point-source fit. For observations that were fit simultaneously, we provide the mean values of the date, true anomaly, and days after periastron.

\(^a\) True anomaly counted from periastron.

\(^b\) Days since 2014 periastron passage (MJD 56,781).

\(^c\) Exposure corrected for dead time.

\(^d\) Total (gross) counts.

\(^e\) Observed flux.

\(^f\) Extinction-corrected flux calculated using Chandra WebPIMMS [http://cxc.harvard.edu/toolkit/pimms.jsp].

\(^g\) Normalization in photons s^{-1} cm^{-2} keV^{-1} at 1 keV.

\(^h\) Area of the extraction region.

\(^i\) If the data were fit by minimizing C-stat instead of \( \chi^2 \), then the C-stat/dof is reported and denoted by (C).

\(^j\) The spectra from the two observations were fit simultaneously.

The sequence of five Chandra images obtained in the 2014–2017 binary cycle shows a new X-ray-emitting clump moving away from the binary and allows one to track the clump’s motion up to a distance of \( ∼ 7'' \) (see Figure 2). In the last three observations, once the clump was clearly detached from the binary, we measured the positions and corresponding statistical uncertainties of the binary and the clump using CIAO’s `celldetect` tool and then calculated their separation.

To analyze the image structure more carefully, particularly in the cases where the presence of extended emission was not obvious (like in the first two observations), we used the Lucy–Richardson deconvolution algorithm (Richardson 1972; Lucy 1974). This algorithm deconvolves the PSF from the brightness distribution intrinsic to the source and is implemented by the CIAO tool `arestore`. An accurate PSF must be provided to `arestore`, so the PSFs of the observations are modeled using the Chandra Ray Tracer (ChaRT) and projected onto the ACIS-I detector plane using the MARX package (Davis et al. 2012; Carter et al. 2003). The best-fit spectral model for the emission from the binary (see Table 1) was used in the PSF simulation.

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\(^*\) See [http://www.stsci.edu/hst/stis/documents/handbooks/currentHIB/c12_special12.html](http://www.stsci.edu/hst/stis/documents/handbooks/currentHIB/c12_special12.html).

\(^\dagger\) See [http://cxc.harvard.edu/ciao/ahelp/arestore.html](http://cxc.harvard.edu/ciao/ahelp/arestore.html).
The inspection of ObsID 16822 does not show any credible extended emission, so we can only place an upper limit of \( \approx 1.5 \) on the distance of any object that is detached from the binary (see Figure 3), assuming that the emission is as bright as or brighter than that seen in the next observation.

The first evidence of extended emission can be seen in the merged images of ObsIDs 16823 and 18744 (618 and 622 days after the 2014 periastron passage, respectively). It appears as an extended feature around 1.7 ± 0.5 south/southwest from the binary in the merged deconvolved image (see the inset in the second panel of Figure 2). We examined the location of the mirror asymmetry for this observation and found it to be imaged southeast of the binary, away from the extended emission (see the green regions in the inset in the second panel of Figure 2).

The next observation, taken 978 days after periastron passage (ObsID 19280), clearly reveals a clump of extended emission, which is separated from the binary. There appears to be some substructure to this extended emission that was not seen in the previous observations (see Figure 2 in P+15). Most notably, there is a linear structure that extends perpendicular to the direction of the clump’s apparent motion, which we nickname the “whiskers” (shown by a white arrow in Figure 2). This observation shows that the clump has traveled 3.8 ± 0.7 away from the binary.

8 CIAO’s celldetect could not detect the extended feature because it is too close to the binary, so we calculate the distance to the feature using the peak in the counts distribution for the binary and clump. The uncertainty is equal to one-half of the width of the feature.

9 See http://cxc.harvard.edu/ciao/caveats/psf_artifact.html for more details.
Once the clump had been detected, a Chandra DDT observation (ObsID 20054) was taken 1086 days after periastron passage to better constrain the clump’s motion and to monitor its flux evolution. Surprisingly, the new observation showed a clear brightening of the clump and a change in morphology, in which it resembles a bow-shock-like shape. The clump was $5.5' \pm 0.7''$ away from the binary. Further, the image shows a second clump of emission detaching from the binary in the same direction as the first clump. It lies at a distance of $2.2' \pm 0.7''$ from the binary (see Figure 4 and Section 4).

The final observations (ObsIDs 19281+20116) of the campaign were carried out 1173 and 1176 days after periastron passage, respectively. These observations revealed the apparent dispersing and dimming of the clump. In the latest observation, the clump appears to be $6.7' \pm 1.9''$ away from the binary. The second clump detected in ObsID 20054 is not detected in this observation or in its deconvolved image.

Images from the last three observations are combined, with different colors, in the sixth panel of Figure 2. We see that the clump was moving along a straight line at a position angle of $230^\circ$ (north through east), similar to the $215^\circ$ angle measured in the previous binary cycle (P+15). The excellent angular resolution of Chandra allowed us to observe changes in the clump’s morphology and brightness, which are much more drastic than those of the clump observed in the previous cycle (P+15).

3.2. Projected Motion of the Extended Emission

We fit a linear model to the data, $r(t) = \mu(t - t_0) + r_0$, to determine the projected velocity of the clump. We chose $t_0 = 964.25$ days as the reference time, which is the mean value of the time intervals that have passed between periastron passage and each of the observations. The best-fit parameters are $r_0 = 4'4.4 \pm 0'.3$ and $\mu = 0''.008 \pm 0''.001$ day$^{-1}$ or $3''0 \pm 0''.5$ yr$^{-1}$, which corresponds to a projected velocity $v_\perp = (0.12 \pm 0.02)c$ at a distance $d = 2.6$ kpc. However, the launch time (defined as $r(launched) = 0$) is $t_{launched} = 420^{+103}_{-82}$ days for this fit. At this launch time, the pulsar is far away (>9 au) from its stellar companion (see ObsID 16822 in Figure 1) and has long since passed through periastron and its companion’s disk. Therefore, we consider this to be an unlikely scenario because it is difficult to imagine a mechanism that could launch the clump with such a large initial velocity with minimal interaction between the pulsar and companion’s winds. In the previous observations, the launch time was consistent with periastron passage and the disk crossings (P+15; see Figure 3 below).

If we assume that the launch time of the clump should occur near periastron passage, we can restrict our models to uphold this criterion. We first fit a linear model $r(t) = \mu t$, assuming $r_0 = 0$. The best-fit proper motion for this model is $\mu = 0''.0044 \pm 0''.006$ day$^{-1}$ or $1''.6 \pm 0''.2$ yr$^{-1}$, corresponding to a projected velocity $v_\perp = (0.066 \pm 0.009)c$ with a $\chi^2$ for 3 degrees of freedom (dof). Due to the poor fit of this model, we also fit a model with an acceleration term: $r(t) = r_0 + v_{0,\perp}(t - t_0) + a(t - t_0)^2/2$, with $r_0 = 0$, $v_{0,\perp} = 0$, and $t_0 = 0$, i.e., $r(t) = a(t)^2/2$. The best-fit acceleration is $a = (9.0 \pm 0.4) \times 10^{-6}$ arcsec day$^{-2}$ or $47 \pm 2$ cm s$^{-2}$ or $14,800 \pm 600$ km s$^{-1}$ yr$^{-1}$ with $\chi^2 = 0.80$ for 3 dof (see Figure 5).

3.3. HST Image Analysis

The HST STIS CCD images of the clump region are shown in Figure 6 (middle and right panels), together with the nearly contemporaneous Chandra ACIS image (left panel). In order to eliminate the small-scale artifacts (e.g., pixels with abnormally large values seen in the summed image), and to reduce the impact of the bright diffraction spikes associated with the PSF, we have produced both the min/max filtered image (middle) and summed image (right). For the min/max filtered image, we retained two out of the four values (corresponding to the four observations) for each pixel by throwing out the minimum and maximum values. Note that, although the filtering somewhat improved the image, we were unable to subtract the wings of the bright star’s PSF at the location of the X-ray clump owing to the asymmetric shape of the PSF, which has multiple fainter diffraction spikes (in addition to the brightest four spikes). We also note that the PSF is asymmetric with respect to the line drawn through the middle of the occulting wedge in the image, possibly because the center of the star was slightly offset from this line. The latter issue prompted us to choose the source and background regions on the same side of the occulting wedge,
where both regions encompass a similar PSF structure (see Figure 6).

In order to estimate the impact of small-scale nonuniformities caused by the remaining fainter narrow diffraction spikes, we performed multiple (10 for each region) source and background measurements by shifting the source and background regions, respectively, in the 5176 s exposure. For comparison, we found (30.8 ± 0.4 × 10^5) counts (within the same exposure time) in an aperture of the same size placed at randomly chosen locations far away from any bright stars. The net number of counts in the source region is n_s = 3.4 × 10^5, and its standard deviation is σ_s = 3.3 × 10^3. Therefore, we conclude that the clump is not detected in our HST observations. The 3σ upper limit on the source count rate of 1.9 counts s~1 translates into an unabsorbed (dereddened) spectral flux of 280 nJy (or an observed spectral flux of 29 nJy) at ν = 5.2 × 10^14 Hz (λ = 5769 Å). These estimates were obtained using the Synphot package, assuming a power-law spectrum, F_ν ∝ ν^−0.45, with the same slope as the clump’s X-ray spectrum (see Section 3.4) and a color excess of E(B − V) = 0.85 (Negueruela et al. 2011).

We have also produced an image where we have subtracted the emission of the bright star (see Figure 7) following the procedures typically used for exoplanet detections (see, e.g., Kalas et al. 2013). Here we briefly describe the procedure. We started with the pipeline-processed (flat-fielded, bias- and dark-subtracted, CR-rejected) images. As a first step, we applied a median spatial filter to each of the four images using a 2 × 2 pixel (one pixel is 0′′05) box to remove any remaining pixel-scale artifacts (e.g., noisy, bad, flaring pixels). In the next step, we produced a median-combined image out of the four images registered to the telescope’s reference frame. Since the telescope was rotated by 3° per observation, this step removes most of the stars in the image and produces a clean image of the PSF from the bright star occulted by the coronagraph. The median image of the PSF is then rotated to coincide with the telescope orientation during each individual observation and is then subtracted from each individual image. Finally, the resulting images are added together, producing a single deep image with the bright star subtracted out (see Figure 7). There are no noticeable extended structures within the area with the size of the X-ray clump (the white ellipse in Figure 7), suggesting that its emission is not detected by HST. However, we do not use this image for the upper limit estimation because the azimuthal extent of the clump in the X-ray images (∼2′′) significantly exceeds the ∼0′′3 shifts (due to the telescope’s rotation) between the individual images at the 6′′ distance between the star and clump. Therefore, the clump’s emission is being partly subtracted from itself while making the median-combined image of the central star. This method could be more beneficial in the future if the clump is farther from the star, is more compact, or the angle increments of the telescope’s rotation are larger.

### 3.4. Chandra Spectral Analysis

The spectra from both the binary core and the clump were extracted for each observation, but those obtained from either of the ObsIDs 16823+18744 or ObsIDs 19281+20116 were fit simultaneously. Spectra from the binary were taken from an r = 1″1 radius circle placed at the binary center and then grouped to contain 25 counts per spectral bin. An absorbed power-law model, using the XSPEC tbabs absorption model, was used to fit the spectra from both the binary and the clump. The fit parameters obtained from each observation and subsequent fit can be seen in Table 1.

The clump was not seen in ObsID 16822, and it was too close to the binary to extract an uncontaminated spectrum in ObsIDs 16823+18744, so they have been omitted. To fit the spectra of the clump, we used C-statistics10 (Cash 1979). The hydrogen absorption column density (N_H) was fixed for each spectral fit to the value obtained from the fit of the binary core. All best-fit parameters are provided in Table 1. Figure 8 shows the 1σ and 2σ confidence contours in the normalization (N) versus photon index (Γ) plane for all observations where it was possible to extract a spectrum. Interestingly, the flux of the clump increases by a factor of ∼1.5 in between ObsIDs 19280 and 20054 and then dims in the final observation (ObsIDs 19281+20116). This implies brightening on timescales of ∼100 days, which was not seen in the previous observations (see Figure 9, K+14, P+15).

The photon index of the clump remains consistent across all observations and is also consistent with the previous observations (K+14, P+15). Therefore, we fit all extracted spectra from the 2014–2017 orbital cycle simultaneously. The hydrogen absorption column density was frozen to the mean value (N_H = 3.1 × 10^17 cm~2) of the observations for which spectra of the clump were extracted. The normalizations of each spectrum were left free, since the clump changes its brightness. This fit gives us a more constrained photon index

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10 See https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSappendixStatistics.html.
(Γ = 1.45 ± 0.11), assuming that the photon index does remain constant across all observations. The unabsorbed 0.5–8 keV luminosity of the clump is \( \sim (3–6) \times 10^{33} \text{ erg s}^{-1} \) at \( d = 2.6 \text{ kpc} \), which is a few percent of the binary’s X-ray luminosity.

**4. Discussion**

The appearance of the clump after periastron passage led P+15 to suggest that the clump, composed of fragments of the massive star’s decretion disk, is launched when the pulsar interacts with the disk. However, if the clump is moving in the stellar wind of the high-mass companion, it should experience a large drag force with a characteristic deceleration time of \( \sim 10 \text{ s} \) (see K+14). Yet, the clumps observed in both orbital cycles show no signs of deceleration on timescales of several years. In order to overcome this difficulty, P+15 suggested that the clump is moving in (and being propelled by) the fast-streaming PW. In the scenario proposed by P+15, the clump is moving along the periastron-to-apastron direction in the unshocked PW, which is dynamically dominant, i.e., \( \eta > 1 \), where \( \eta \equiv E/(M_{\text{w}} v_{\text{w}} c) \) is the ratio of pulsar to stellar wind momentum fluxes, \( M_{\text{w}} \) is the companion’s mass-loss rate due to its isotropic wind, and \( v_{\text{w}} \) is the companion wind’s velocity. Alternatively, the simulations of Barkov & Bosch-Ramon (2016) have shown that the accelerated motion of the clump in the PW, which is shocked near (or even within) the binary, is still possible for \( \eta < 1 \), i.e., when the stellar wind is dynamically dominant. This is because a “channel” in the stellar wind is carved out by the PW streaming in the apastron direction (because the pulsar spends most of the time near apastron).

Depending on the scenario (i.e., \( \eta > 1 \) vs. \( \eta < 1 \)), the fraction of the PW that interacts with the clump will vary. If the PW is isotropic and dynamically dominant (\( \eta > 1 \)), then only a fraction \( \xi_0 = (r_{\text{ap}}/2r)^2 \approx 0.04 \) of the PW is intercepted by the clump, where \( r_{\text{ap}} \) is the radial size of the clump and \( r \) is the distance between the clump and the binary. On the other hand,
if the PW is confined to a channel and the clump fills the entire cross section of the channel, then all of the PW interacts with the clump (i.e., $\xi_{\Omega} = 1$). In reality, this factor $\xi_{\Omega}$, which accounts for the geometry of the PW flow, is likely to be in between these two limits, so we carry it through our estimates.

4.1. Radiation Mechanism

Once the dense clump is entrained into the very fast PW, a shock is expected to form at the PW-clump interface, regardless of the value of $\eta$ or whether the PW is shocked or unshocked by the time it reaches the clump.\footnote{However, the details of this interaction (e.g., particle acceleration at the shock) may be different for large and small $\eta$.} If the X-ray emission of the clump is indeed powered by the PW, then the X-ray luminosity can be expressed as $L_{X,cl} = \xi_X \xi_{\Omega} \dot{E}$, where $\xi_X$ is the X-ray efficiency. The observed luminosities of the clump, $L_{X,cl} \approx (3-6) \times 10^{31} d_{17}^2$ erg s$^{-1}$, where $d = 2.6 d_{17}$ kpc is the distance to the binary, correspond to $\xi_X \xi_{\Omega} \sim (4 - 7) \times 10^{-5}$. This implies an X-ray efficiency, $\xi_X \sim 10^{-4} - 10^{-3}$, of the same order of magnitude as those of synchrotron pulsar wind nebulae observed around isolated young pulsars (Kargaltsev & Pavlov 2008).

Another source of energy that could, in principle, power the clump’s X-ray emission is the radiation field of the massive star. The star’s luminosity, $L_\star = 2.4 \times 10^{38}$ erg s$^{-1}$, is a factor of 300 larger than the pulsar’s $\dot{E}$. The energy density of the radiation field, $u_{rad} = L_\star / (4\pi r^2) = 6.4 \times 10^{-8} n_{17}^2$ erg cm$^{-3}$, exceeds the magnetic field energy density, $u_B = B^2 / 8\pi = 4.0 \times 10^{-8} (B/1$ mG$)^2$ erg cm$^{-3}$, for $B < 1.3 n_{17}^{-1}$ mG, where $n_{17}$ is the clump’s distance from the binary in units of $10^{17}$ cm.

Below we discuss both sources of power and conclude that, although the star produces more energy than the pulsar, it is unlikely to contribute significantly to the X-ray emission or the dynamics of the clump at the observed separations from the binary.

We first consider whether the scattering of stellar photons off relativistic electrons in the clump could power the observed X-ray emission. Electrons with Lorentz factors exceeding $\gamma_{KN} = m_e c^2 / 4\epsilon \sim 10^4$, where $\epsilon \sim 10$ eV is the typical energy of the most abundant UV photons produced by the star, will upscatter photons in the Klein–Nishina (KN) regime, while those with $\gamma < \gamma_{KN}$ will scatter in the Thomson regime (see, e.g., Blumenthal & Gould 1970). The broadband SED of the electrons is not known, but if the clump’s X-ray emission is due to IC upscattering of UV photons, it can only be due to upscattering by electrons with $\gamma \sim 10$–100 in the Thomson
regime. Electrons with larger $\gamma$ will produce $^{12}$ photons with energies $\gtrsim 10$ keV.

Assuming that the dominant emission mechanism is IC, we can crudely estimate the lower limit on the number of IC emitting electrons as $N_e > L_x / P_{IC} = 1.4 \times 10^{50} \left( F_2 / 4 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \right) (\gamma / 10)^{-2/7} d_{2.6}^{-2} \mu G$, where $P_{IC} = (4/3) \sigma_T c E_{\gamma}^{-2/3} \dot{m}_{\text{rad}}$ is the total IC power emitted by a single electron that upscatters stellar photons in the Thomson regime, and $F_2$ is the observed X-ray flux of the clump in the 0.5–8 keV band. However, such a large number of particles is problematic because the pulsar is expected to only supply $\dot{N}_e = 4\pi^2 B_d^2 \kappa_{\text{pair}} (e\gamma)^{-1} 2\kappa_{\text{pair}} = 4 \times 10^{22} \kappa_{\text{pair}}$ electrons s$^{-1}$, where $B_d = 3.3 \times 10^{11}$ G is the dipolar field at the NS equator, $R_{\text{NS}} \sim 10$ km is the NS radius, and $\kappa_{\text{pair}} \gtrsim 10^3$ is the pair cascade multiplicity (Timokhin & Harding 2015, 2019). Therefore, the maximum number of electrons injected by the pulsar since the launch of the clump is $\dot{N}_e t \sim 3 \times 10^{44} (\kappa_{\text{pair}} / 10^5)(t/1000 \text{ days})$.

Lastly, even if the clump contains the mass of the entire decretion disk ($m_{\text{decretion}} \sim 10^{-3} - 10^{-6}$ g; Chernyakova et al. 2014, and references therein), the clump would contain $< 6 \times 10^{49}$ electrons, and only a very small fraction of them could be accelerated to $\gamma \sim 10$–100. Therefore, we conclude (in agreement with Pavlov et al. 2011 and P+15) that the IC mechanism is unlikely to be responsible for the observed X-ray emission at distances of a few arcseconds away from the binary and that the clump’s X-ray emission is produced via synchrotron radiation.

For relativistic particles accelerated within the clump (e.g., shocked at the interface between the PW and the decretion disk material in the clump) the synchrotron emissivity depends on the magnetic field in the shock (possibly carried by the magnetized PW), the relativistic electron number density, and the Lorentz factors of the emitting electrons. There are no significant spectral changes observed as the clump travels away from the binary. This, together with the relatively hard X-ray spectrum, suggests that synchrotron cooling does not have a noticeable impact on the radiating electrons up to the distances where the clump is seen. This can happen either because of continuous reacceleration or if the synchrotron cooling time, $\tau_{\text{syn}} = 22 (B/100 \mu G)^{-3/2} (E_{\text{syn}}/3 \text{ keV})^{-1/2}$ yr, exceeds the dynamical time (i.e., the clump travel time$^{14}$) of $t \sim 3.4$ yr. The latter condition implies $B \lesssim 240 (E_{\text{syn}}/10 \text{ keV})^{-1/3} \mu G$, assuming that the magnetic field is constant or slowly varying over most of the dynamical time. On the other hand, the gyroradius of electrons must not exceed the (essentially unresolved) width of the “whiskers” in the ObsID 19280 image, implying $B \gtrsim 30 (E_{\text{syn}}/1 \text{ keV})^{-1/3} d_{2.6}^{-2/3} \mu G$.

These limits comfortably accommodate $B \approx 80 \kappa_{\text{m}}^{2/7} d_{2.6}^{-2/3} \mu G$ estimated by K+14 from the clump’s surface brightness (where $\kappa_{\text{m}}$ is the unknown ratio of the magnetic field energy density to the energy density of the relativistic particles). Therefore, for a plausible magnetic field, $q \equiv u_{\text{rad}} / u_B \approx 150 \Gamma_1^{-2} (B/100 \mu G)^{-2} \gg 1$, which, according to Equations (8) and (9) from Moderski et al. (2005), implies that synchrotron losses dominate IC losses for $\gamma > \gamma_2 \approx 3.5 \times 10^4 (B/100 \mu G)^{-4/3} \gamma_1^{-4/3}$. The Lorentz factors, $\gamma_1 \sim 3 \times 10^4 (B/100 \mu G)^{-1/2}$ and $\gamma_2 \sim 10^4 (B/100 \mu G)^{-1/2}$, of electrons that produce the 1–10 keV synchrotron photons are much larger than both $\gamma_{\text{syn}} \sim 10^4$ and $\gamma_2$, implying that any IC scattering must occur in the KN regime and that the synchrotron losses dominate the IC losses.

The uncooled synchrotron interpretation of the observed X-ray spectrum also implies that the slope $p$ of the electron SED, $dN_e(\gamma) = K_{\gamma} \gamma^{-p} d\gamma$, (where $\gamma_{\text{m}} < \gamma < \gamma_{\text{M}}$), is $p = 2\Gamma - 1 \approx 1.4$–2.2. The photon index derived from fitting all three clump X-ray spectra simultaneously is $\Gamma = 1.45 \pm 0.11$, corresponding to $p = 1.90 \pm 0.22$. Although there are substantial uncertainties associated with the measurements of $\Gamma$ (see Table 1), the obtained $p$ values are below the value of $p \approx 2.2$ typically expected for Fermi-type shock acceleration (Achterberg et al. 2001). This may suggest that an acceleration mechanism other than shock acceleration (e.g., magnetic reconnection) is responsible for the X-ray emission.

Furthermore, in the synchrotron emission scenario the decreasing flux of the clump observed in the previous binary cycle (see Figure 9) may be attributed to the decreasing magnetic field as a function of distance from the pulsar. In this case the flux should be $\propto B^{p+\Gamma/2}$ and the magnetic field should be $B \propto r^{-1}$. For $p \approx 2$ we find that the flux evolution during the 2010–2014 orbital cycle is compatible with $B \propto r^{-1}$. Unfortunately, the episode of brightening in the 2014–2017 binary cycle makes it difficult to constrain the flux decay rate.

An alternative possibility consistent with the observed photon index ($\Gamma = 1.45$ ) is that the electrons are in the fast cooling regime, where $\Gamma$ is expected to be 1.5. In this regime the synchrotron cooling time for the lowest-energy electrons is much smaller than the dynamical (residence) time of the X-ray-emitting electrons (see, e.g., Sari et al. 1998; Piran 2004). However, for this scenario to be plausible, the minimum Lorentz factor must exceed $\gamma_\text{m} \gtrsim 10^3$ and the magnetic field must be at least several hundred microgauss. These parameters (especially the lack of lower-energy electrons) would be unusual for the shocked PW from an isolated pulsar similar to B1259 but cannot be entirely excluded for the interacting winds in this binary. Since we consider this scenario less plausible, we only consider the uncooled synchrotron case below.

The number of electrons emitting synchrotron radiation with a luminosity $L_{\text{syn}}(E_1, E_2) \equiv L_x$ in the photon energy range $(E_1, E_2)$ can be estimated as $N_e(\gamma_1, \gamma_2) = N_{X} = L_{X} / P_{\text{syn}} (\gamma_1, \gamma_2)$. where $\gamma_1 \sim (E_1 / E_{\text{cycl}})^{-2} = 2.9 \times 10^7 (E_1 / 1 \text{ keV})^{-2/3} (B/100 \mu G)^{-2/3}$ is the Lorentz factor of electrons that provide the main contribution to radiation at energy $E_1$, $E_{\text{cycl}} = heB/(2em_e c)$ is the cyclotron energy, and $P_{\text{syn}}(\gamma_1, \gamma_2) = (4/3) \sigma_T c u_B (\gamma_2^2)$ is the mean synchrotron power per electron in the $(\gamma_1, \gamma_2)$ range. For the assumed power-law SED, the mean square of the Lorentz factor is $\langle \gamma^2 \rangle = C_{1-p} (\gamma_1, \gamma_2) / C_{1-p} (\gamma_1, \gamma_2)$, where $C_q(\gamma_1, \gamma_2) = (\gamma_2^q - \gamma_1^q) / q$. For instance, for $E_1 = 0.5 \text{ keV}$, $E_2 = 8 \text{ keV}$, and $p = 1.9$, we have

$^{12}$ Indeed, if IC upscattering proceeds in the Thomson regime, then the UV photon energy is boosted by $\gamma^2$ (but remains a small fraction of $\nu m_e c^2$), while if it occurs in the extreme KN regime (i.e., where $\gamma > \gamma_{\text{KN}}$), then the typical energy gained by the photon in a single collision is a sizable fraction of $\nu m_e c^2$ (Blumenthal & Gould 1970).

$^{13}$ Although the expression we used for $P_{\text{IC}}$ is only valid for an isotropic photon field, it should be the same for the average scattered power (per electron) if the electrons come from an isotropic electron distribution (even if the radiation field is anisotropic as it happens to be in this case).

$^{14}$ We assume that the clump is launched around the time of periastron passage.

$^{15}$ Assuming that the dynamical (residence) time is the observed lifetime of the clump ($\sim 1000$ days).
Following P+15, the acceleration can be estimated as $a_c \sim \mathcal{F}_{\text{pw}} m_{\text{cl}}^{-1}$, where $\mathcal{F}_{\text{pw}} = \rho_{\text{pw}} A = (E/c) \xi_\Omega^{-1} \xi_{\Omega} = 2.8 \times 10^{25} \xi_{\Omega} \xi_{\Omega} \text{ dyn}$ is the PW ram force, $\xi_{\Omega} < 1$ is a filling factor (which takes into account that the clump can consist of separate fragments), $\xi_{\Omega}$ is the fraction of PW that interacts with the clump (see above), and $m_{\text{cl}}$ is the mass of the clump. Using the estimated $a_c \approx 50 \text{ cm s}^{-2}$, we obtain an upper limit on the clump’s mass, $m_{\text{cl}} \lesssim 6 \times 10^{23} \xi_{\Omega} \xi_{\Omega}$ g, and kinetic energy, $E_{\text{kin}} \lesssim 6 \times 10^{42} (m_{\text{cl}}/6 \times 10^{23} \text{ g})(0.15c)^2 \text{erg}$, at the time of the last observation. This upper limit corresponds to the pulsar’s rotational energy losses over the period of $\approx 80$ days, which is comparable to the time that the pulsar spends interacting with the disk (see, e.g., Figure 3 in Chernyakova et al. 2006).

In the above estimate, we assume that the accelerating force is due to the pressure of the PW. However, the pressure of the radiation produced by the luminous companion star could represent an additional force. To understand the relative contribution of the radiation force, let us first consider nonrelativistic electrons that can be associated with the ejected fragment of the decretion disk (assuming that it is ionized). In this case, the X-ray emission can still be synchrotron emission attributed to a small number of ultrarelativistic electrons accelerated in the shock at the interface between the PW and the clump.

For Thomson scattering, the average optical thickness of the clump can be estimated as $\tau \sim n_e \sigma_T \xi_\Omega \approx 1 \times 10^{-9} (m_{\text{cl}}/10^{26} \text{ g}) (\xi_\Omega/10^2 \text{ cm}^{-2}) (B/100 \text{ G})^{-1}$. The number of electrons in this case is substantially smaller than the $>10^{50}$ required in the IC case (see above).

Detecting the clump at lower frequencies could constrain the broadband SED shape and provide a more precise measurement of the spectral slope (if the SED has a power-law shape). Unfortunately, we did not detect the clump in the HST images, with the upper limit being above the continuation of the PL spectrum with the slope inferred from the X-ray spectra (see Figure 10). Observations with sensitive radio observatories may be more successful because of their excellent angular resolution and the relative faintness of the massive star at longer wavelengths. In fact, Moldón et al. (2011) reported extended radio emission on $\approx 50$ mas scales at 2.3 GHz just after the 2007 periastron passage. More recently, ALMA observations of B1259 were undertaken up to $\approx 84$ days after the 2017 periastron passage, but no evidence of extended emission was reported (Fujita et al. 2019). Therefore, it is still unclear whether the extended radio emission reported by Moldón et al. (2011) could be related to the X-ray-emitting clump.

4.2. Clump’s Dynamics: Accelerated Motion

The data from our earlier campaign corresponding to the preceding binary cycle provided only marginal evidence of the clump being accelerated, assuming that it was launched with a small (compared to the observed) velocity near periastron passage. P+15 speculated that the PW ram pressure could be responsible for the rapid acceleration. Subsequent numerical simulations confirmed that, indeed, the clump can be accelerated to large velocities by the PW in the $\eta < 1$ scenario (see Figure 2 in Barkov & Bosch-Ramon 2016). However, the new data reported here provide more direct evidence of accelerated motion, with the acceleration continuing to be present on timescales of hundreds of days after the clump’s launch near the periastron passage (see Figure 3).

Although in the case of $\eta > 1$ we expect $\xi_\Omega$ to be similar to $\xi_{\Omega}$ (introduced above for the PW), in the opposite, $\eta < 1$, case $\xi_{\Omega} \sim 1$, while $\xi_{\Omega}$ remains the same as in the $\eta > 1$ case.
\[
d{N}_{\gamma}/d\gamma = K_{\gamma} \gamma^{-p} \, d\gamma \quad (\gamma_{\text{m}} < \gamma < \gamma_{\text{M}})
\]
Taking into account that \(\gamma_{\text{M}} >> \gamma_{\text{KN}}\) in our case, there is always a contribution from IC scattering in the KH regime, \( \propto \gamma_{\text{KN}}^{-p} \max(\gamma_{\text{KN}}^{-\epsilon_{\text{A}}}, \gamma_{\text{m}})^{\epsilon_{\text{A}}} \) (for \( p > 1 \) and \( \gamma_{\text{M}} >> \gamma_{\text{m}}\)), while the Thomson regime term, \( \propto \gamma_{\text{KN}}^{3-p} \) (for \( p < 3 \)), only contributes at \( \gamma_{\text{m}} \ll \gamma_{\text{KN}}\). Thus, at a given \( \gamma_{\text{KN}}\) and \( 1 < p < 3 \), the radiative force does not depend on \( \gamma_{\text{m}}\) at \( \gamma_{\text{m}} \ll \gamma_{\text{KN}}\) and decreases \( \propto (\gamma_{\text{KN}}/\gamma_{\text{m}})^{p-1} \) at \( \gamma_{\text{m}} >> \gamma_{\text{KN}}\).

Assuming \( \gamma_{\text{m}} \ll \gamma_{\text{KN}}\) and expressing the electron SED normalization in terms of the X-ray synchrotron luminosity, \( K_x = L_x (4/3) \sigma_{\text{B}} c G_{-3-p}(\gamma_{1}, \gamma_{2})^{-1} \) (see Section 4.1), we obtain an order-of-magnitude estimate for the radiative force

\[
F_{\text{rad}} \sim \xi_x L_x \gamma_{\text{KN}}^{3-p} / C_{3-p}(\gamma_{1}, \gamma_{2}),
\]

where \( q = u_{\text{rad}}/u_{\text{th}}\). The ratio of this force to the PW ram force is \( F_{\text{rad}}/F_{\text{sw}} \sim (\xi_x/\xi_A) q \gamma_{\text{KN}}^{3-p} / C_{3-p}(\gamma_{1}, \gamma_{2})\), where \( \xi_x = L_x / (\xi_0 E) \) is the X-ray efficiency (see Section 4.1). For \( p = 1.9\), we obtain \( F_{\text{rad}}/F_{\text{sw}} \sim \alpha \times 10^{-3} (\xi_x/10^{-3})^{-1} \gamma_{\text{A}}^{-2} \gamma_{\text{KN}}^{3-p}/(100 \mu G)^{-1.45} \). This ratio becomes even smaller (by a factor of \( (\gamma_{\text{m}}/\gamma_{\text{KN}})^{0.9} \)) if \( \gamma_{\text{m}} >> \gamma_{\text{KN}}\). Thus, although the mean radiative force per electron is larger than in the nonrelativistic case, the number of relativistic electrons required to provide the observed synchrotron luminosity is relatively small, so the contribution of the radiative force to the clump acceleration is negligible.\(^{17}\)

4.3. Comparison to the Previous Binary Cycle

The differences in the clump properties between the two binary cycles could be related to the difference in the GeV flares, if the flares are associated with the disk fragmentation and the destroyed disk fragments can be considered as clump “seeds.” The different structure of the 2010 and 2014 GeV light curves likely reflects different masses and initial speeds of the disk fragments, which would ultimately result in different clumps. For instance, the latter appearance of the resolved clump and longer acceleration time (but about the same final velocity) in the 2014–2017 binary cycle could be linked to the flatter GeV flare light curve caused by a longer and more gradual process of disk destruction and a larger mass of the fragment (Caliandro et al. 2015). Since the 2017 GeV flare light curve (Johnson et al. 2018) was very different from the 2010 and 2014 light curves (larger fluence, longer delay, higher peak), we can expect an even larger difference in the clump properties in the 2017–2021 binary cycle. Future Chandra observations will test this hypothesis.

The behavior of the extended X-ray emission around B1259 in the 2014–2017 cycle demonstrated several other potentially important differences with respect to what was seen in the 2010–2014 cycle (P+15; Pavlov et al. 2019). In the image from ObsID 19270 (see Figure 2), the clump’s morphology evolved into an interesting linear extended feature, nicknamed the “whiskers.” This change in the clump’s shape (the whiskers are not visible in the next observation \( \approx 100 \) days later, which is roughly the light-travel time along the structure) was not seen in the previous cycle, but it may have been missed since it is not a persistent feature. The “whiskers” show that the width of the channel occupied by the PW that pushed the clump (our preferred scenario) must be rather large at these distances. In the following observation (108 days after the one where the whiskers were detected) the clump appeared to be more compact but underwent an episode of rebrightening, a behavior that was also not previously seen.

A qualitative picture explaining the whiskers and brightening could be as follows. As the pulsar passes through periastron, some amount of stellar wind becomes entrained into the PW.\(^{18}\) Then, the pulsar interacts with the companion’s decretion disk, fragmenting it and launching the clump. In the \( \eta < 1 \) scenario, this clump will then sweep up the stellar wind particles entrained in the channel as it is being accelerated by the PW ram pressure. The “whiskers” could be outflows from the clump, which is flattened by the combination of the PW ram pressure and the drag force pressure from the residual stellar matter in the channel. At some location along the channel, the medium will transition from being dominated by the PW into a mixture of the pulsar and stellar winds (see, e.g., Figure 1 in Barkov & Bosch-Ramon 2016), with a lower sound speed. Therefore, as the clump travels farther away from the pulsar, at some point its speed may become supersonic. This transition could result in a shock, which could give rise to the observed brightening (e.g., if the magnetic field is compressed), and the bow-shock-shaped morphology of the clump. The whiskers and the brightening episode are more difficult to explain in the \( \eta > 1 \) scenario. Alternatively, as briefly mentioned in Section 4.1, the rather hard SED slope \( (p = 1.90) \) and a lack of synchrotron cooling could suggest that the emitting particles are being reaccelerated via magnetic reconnection, which could in principle also contribute to the acceleration of the bulk flow (see, e.g., Lyubarsky & Kirk 2001; Beniamini & Giannios 2017). The inherently variable nature of magnetic reconnection may also explain the sudden brightening of the clump seen in the ObsID 20054 image. However, more observations with a higher cadence are necessary to probe these scenarios.

The clumps have also shown some similarities between the binary cycles. For instance, all of the observed clumps thus far have been launched in the same direction with respect to the binary. This lends more credibility to the \( \eta < 1 \) scenario, since in this scenario there could be a channel with a preferred direction in which the clump is launched.

Finally, there is solid evidence for a separate extended feature (second clump) \( \approx 2\arcsec\) away from the binary core in the image from ObsID 20054. However, it was not detected in the next observation. This suggests that it faded on timescales shorter than 120 days. Unfortunately, the second feature is too faint and too close to the bright binary to extract a reliable spectrum. However, we have revisited our older observations near this orbital phase (i.e., ObsIDs 16553+16583 occurring 1151 days after the periastron passage; see P+15 for additional details) and found evidence of a faint second feature located 3\arcsec/4 from the binary (see Figure 4). The feature has \( \approx 30 \) net counts in the combined ACIS image. The spectrum can be fitted by an absorbed PL model with \( \Gamma = 1.6 \pm 0.4 \) and unabsorbed flux \( f_\lambda = 1.1(2) \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) for fixed \( N_H = 3 \times 10^{21} \) cm\(^{-2}\). The second clump has a similar photon index and flux to the first clump, but these values are not well constrained owing to the small number of counts. Interestingly,

\(^{17}\) See also Pavlov et al. (2019).

\(^{18}\) This could happen either because the stellar wind is collimated in the apastron direction (if \( \eta > 1 \)) or (if \( \eta < 1 \)) because the channel carved out by the PW allows some stellar wind particles to leak into the channel.
this second (smaller) clump is launched in the same direction as the first (larger) clump in both orbital cycles. In order to understand the nature of these differences between the two different binary cycles, continued monitoring of this system with Chandra is needed.

5. Conclusions

The new Chandra observing campaign of B1259 during the 2014–2017 orbital cycle has allowed us to confirm the recurrent (with every binary cycle) nature of the remarkable high-velocity features (clumps) ejected from the binary. Although there were a lot of similarities with the previous binary cycle, there were also some important differences. The feature appears to detach from the binary later (i.e., more time has passed since periastron passage) than in the previous binary cycle. If the clump is ejected near periastron passage, it must be accelerated up to the observed projected velocity, \( v_r \approx 0.15c \), with a projected acceleration, \( a_r \approx 50 \text{ cm s}^{-2} \). The evidence for acceleration is present at large distances (i.e., a few arcseconds) from the binary. The acceleration measurement provides an upper limit on the mass \( (m_{\text{cl}} \lesssim 6 \times 10^{23} \text{ g}) \) and kinetic energy \( (E_{\text{kin}} \lesssim 6 \times 10^{48} \text{ erg}) \) of the clump. We find that the radiation pressure force is not sufficient to continue accelerating the clump to the observed speed at the observed separations from the star. Therefore, the accelerating force is likely provided by PW. The observed X-ray emission is likely to be synchrotron radiation from the interface between the clump material and PW. Furthermore, we show that IC upscattering is unlikely to be responsible for the X-ray emission.

The clump showed puzzling changes in morphology (developing short-lived "whiskers" in one of the images). Unlike the clump observed in the 2010–2014 orbital cycle, this clump shows an episode of brightening. In the \( \eta < 1 \) scenario, these whiskers can be explained if the clump sweeps up some stellar matter that somehow leaks into the channel, causing a flattening in the clump due to the PW ram pressure pushing the clump and the drag from the stellar wind in front of the clump. The brightening may be explained if the clump becomes supersonic as it crosses the region between the PW channel and the region filled with a mixture of pulsar and stellar wind. We also find evidence of a second (more transient) clump launched in both cycles after the first, more prominent clump. While we do not find direct observational support for either the \( \eta > 1 \) or \( \eta < 1 \) scenario, the observed variability in morphology and brightness could be more easily explained in the \( \eta < 1 \) scenario. Future Chandra observations could allow one to probe the possible connections between the GeV flares and phenomenology of the X-ray-emitting clump.

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