Back to Quiescence: Postoutburst Evolution of the Pulsar J1119–6127 and Its Wind Nebula

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Abstract

We report on the analysis of a deep Chandra observation of the high-magnetic-field pulsar (PSR) J1119–6127 and its compact pulsar wind nebula (PWN) taken in 2019 October, three years after the source went into outburst. The 0.5–7 keV postoutburst (2019) spectrum of the pulsar is best described by a two-component blackbody plus power-law model with a temperature of 0.2 ± 0.1 keV, photon index $\Gamma = 1.8 \pm 0.4$, and X-ray luminosity of $1.9^{+0.3}_{-0.2} \times 10^{33}$ erg s$^{-1}$, consistent with its preburst quiescent phase. We find that the pulsar has gone back to quiescence. The compact nebula shows a jet-like morphology aligned in the north–south direction, similar to the preburst phase. The postoutburst PWN spectrum is best fit by an absorbed power law with a photon index $\Gamma = 2.3 \pm 0.5$ and a flux of $3.2^{+0.3}_{-0.2} \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (0.5–7 keV). The PWN spectrum shows evidence of spectral softening in the postoutburst phase, with the preburst photon index $\Gamma = 1.2 \pm 0.4$ changing to $\Gamma = 2.3 \pm 0.5$ and the preburst luminosity of $1.5^{+0.3}_{-0.2} \times 10^{32}$ erg s$^{-1}$ changing to $2.7^{+0.3}_{-0.2} \times 10^{32}$ erg s$^{-1}$ in the 0.5–7 keV band, suggesting magnetar outbursts can impact PWNs. The observed timescale for returning to quiescence, of just a few years, implies a rather fast cooling process and favors a scenario where J1119 is temporarily powered by magnetic energy following the magnetar outburst, in addition to its spin-down energy.

Unified Astronomy Thesaurus concepts: Magnetars (992); Radio pulsars (1353)

1. Introduction

Neutron stars, the evolutionary end-points of massive stars, are extremely compact remnants endowed with strong magnetic fields ($B$) ranging from $\sim 10^9$–$10^{15}$ G. They are a diverse population, both in their observational and physical properties. Rotation-powered pulsars (RPPs) and magnetars are two different manifestations of the neutron star population. RPPs are mostly observed as rapidly spinning, pulsating radio sources and are powered by their spin-down energy ($E$). Their periods $P$ span the range from 1 ms to 8 s and their $B$-field strengths range from $\sim 10^9$ to $10^{13}$ G. Magnetars, on the other hand, are believed to be the strongest magnets in the universe with long $P \sim 1$–12 s and inferred surface dipole $B$ fields of $10^{14}$–$10^{15}$ G, although some of them can have relatively weaker surface fields of $\gtrsim 10^{12}$ G (see Kaspi & Beloborodov 2017; Esposito et al. 2021 for reviews). They are characterized by intense episodes of X-ray and gamma-ray bursts, ranging from a few millisecond duration to major month-long outbursts, followed by timing and spectral changes. Magnetar emission is believed to be powered by the decay of enormous internal magnetic fields, with indications that their magnetosphere is highly dynamic and characterized by a complex nondipolar geometry (Thompson & Duncan 1996). It is also expected that magnetars might be able to accelerate charged particles and produce extended, nebular outflows known as a magnetar wind nebula (MWN), which can provide important information on the composition and energetics of injected particles. Many observational results in recent years, including the discovery of MWNe around the magnetar Swift J1834.9–0846 (Youenes et al. 2016), have demonstrated that the above properties are not exclusive to magnetars, thereby bridging the gap between different neutron star classes.

Among the RPPs, there is a peculiar class referred to as the high-magnetic-field pulsars (hereafter, high-$B$ pulsars) with inferred surface $B$ fields $\gtrsim 4.4 \times 10^{13}$ G, the quantum critical field limit. There are seven high-$B$ pulsars, most of which have been discovered in the radio, except for the pulsar PSR J1846–0258, discovered in X-rays with no known radio counterpart. The high-$B$ pulsars further showed X-ray properties consistent with other lower-$B$ RPPs of comparable age as well as magnetars in quiescence, which led to the suggestion that these sources could be magnetars in disguise (e.g., Kaspi & McLaughlin 2005; Safi-Harb & Kumar 2008). Over the last two decades, different observational results proved that high-$B$ pulsars could indeed show magnetar-like bursts. The first such behavior was observed from PSR J1846–0258 in 2006 (Gavriil et al. 2008; Kumar & Safi-Harb 2008), followed by PSR J1119–6127 in 2016 (Archibald et al. 2016), which is the subject of study here. These results, along with the detection of bursts from other classes of neutron stars (e.g., the central compact object 1E 161348–5055 in the supernova remnant (SNR) RCW 103; Rea et al. 2016), further suggested that magnetars are more widely distributed than originally thought.

The high-$B$-field pulsar, PSR J1119–6127 (hereafter J1119), was discovered in the Parkes multibeam 1.4 GHz pulsar survey with a spin period $P = 408$ ms and is associated with the SNR
G292.2–0.5 (Camilo et al. 2000). The period, \( P \), and the spin-down rate, \( \dot{P} = 4 \times 10^{-12} \text{ s}^{-1} \), imply a characteristic age \( \tau_c \sim 1.9 \text{ kyr} \), a spin-down luminosity \( \dot{E} = 2.3 \times 10^{36} \text{ erg s}^{-1} \), and a dipolar surface magnetic field \( B = 4.1 \times 10^{13} \text{ G} \). Observations performed with Chandra in 2002 detected the X-ray counterpart of J1119 and unveiled a faint, compact (\( \sim 3'' \times 6'' \)) wind nebula around it (Gonzalez \\& Safi-Harb 2003). No radio PWN has yet been detected around the pulsar. Only in 2004, when new Chandra observations were carried out, was it possible to study the PSR and the PWN independently (Safi-Harb \\& Kumar 2008). The pulsar spectrum was well modeled by the combination of a blackbody (BB) of temperature \( kT \sim 0.2 \text{ keV} \) and a power law (PL) characterized by the spectral index \( \alpha \) or photon index \( \Gamma = \alpha + 1 \) of \( \sim 2 \) to account for nonthermal emission above \( 3 \text{ keV} \). The PWN showed elongated jet-like features extending at least \( \gtrsim 7'' \) north and south of the pulsar and its emission was described by a PL with \( \Gamma = 1.1 \sim 1.4 \) (Safi-Harb \\& Kumar 2008). XMM-Newton observations of the source showed strong pulsations below 2.5 keV, with a pulsed fraction of \( 74\% \pm 14\% \) (Gonzalez et al. 2005). Furthermore, the pulsar has shown sporadic, or rotating radio transient-like behavior, preceded by large-amplitude glitch-induced changes in the spin-down parameters in the radio wavelengths (Weltevrede et al. 2011).

Remarkably, on 2016 July 27, J1119 exhibited several short (0.02–0.04 s), energetic hard X-ray bursts detected by the Fermi Gamma-ray Burst Monitor and Neil Gehrels Swift Observatory (hereafter Swift) Burst Alert Telescope, which marked the onset of a magnetar-like outburst (Archibald et al. 2016; Göğüş et al. 2016). In the few days following these bursts, observations with the Swift X-ray Telescope (XRT) and NuSTAR showed that the unabsorbed \( 0.5–10 \text{ keV} \) X-ray flux of J1119 had increased by a factor of \( \sim 200 \), and strong X-ray pulsations were detected above 2.5 keV for the first time. The pulsar spectrum was dominated by a BB component with temperature \( kT \) rising from 0.9 to 1.05 keV during the first two weeks of the outburst and a PL component with \( \Gamma = 1.2 \) (Archibald et al. 2016, 2018). A hard X-ray component also suddenly appeared with emission extending at least up to \( \sim 70 \text{ keV} \), a spectral behavior previously well established in many magnetars. The pulsar also underwent a contemporaneous spin-up glitch (Archibald et al. 2016). The radio emission was affected by the magnetar-like activity, initially becoming undetectable as a radio pulsar, and then returning with a steeper radio spectrum and a changed, multicomponent pulse shape (Majid et al. 2017). The spin-down rate and X-ray flux increased by a factor of \( 5 \sim 10 \) before recovering toward the preburst rate (Archibald et al. 2018; Dai et al. 2018; Lin et al. 2018; Wang et al. 2020). Thus, J1119 displayed a classic magnetar-like outburst, despite its normal appearance as a radio pulsar in the two decades since its discovery.

The pulsar’s spectrum, obtained with Chandra three months after the outburst onset, was best described by a single PL model with \( \Gamma = 2.0 \pm 0.2 \), softer than the value measured at the peak (Blumer et al. 2017). The pulsar luminosity was higher by a factor of \( \sim 22 \) compared to its pre-outburst level, \( L_{\text{X,Y}} \sim 2 \times 10^{39} \text{ erg s}^{-1} \) (0.5–7 keV). The PWN’s spectrum also softened from a photon index of 1.2 to 2.2. The compact nebula also appeared brighter than its preburst state: the unabsorbed flux increased from \( 2.3 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \) to \( 2.2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \) (0.5–7 keV).

Moreover, we noticed a change in the PWN post-burst morphology, with a faint equatorial torus-like structure (\( \sim 10'' \times 2'' \)) along the southeast–northwest direction running perpendicular to a jet-like structure (\( \sim 1.5'' \times 3.5'' \)) southwest of the pulsar, while the preburst image showed a compact \( \sim 6'' \times 15'' \) PWN primarily extending along the north–south direction and visible only in the hard X-ray band (2.0–7.0 keV).

In this paper, we report on a detailed study of the postoutburst evolution of J1119 and its associated nebula with Chandra, along with a reanalysis of all archived Chandra observations for consistency and for studying the evolution of the pulsar and its PWN. J1119 is associated with the SNR G292.2–0.5 at a distance of 8.4 kpc (Caswell et al. 2004); therefore, we scale all derived quantities in units of \( d_{4.4} = D/8.4 \text{ kpc} \). The paper is organized as follows: Section 2 describes the observation and data reduction. We present the details of the X-ray imaging analysis in Section 3 and spectral fitting in Section 4. The results are discussed in Section 5, including modeling the observations in light of the recently introduced model discussing the effect of magnetar bursts on the nebula (Martín et al. 2020). Finally, we summarize our findings in Section 6.

### 2. Observation and Data Reduction

J1119 was previously observed with the Chandra X-ray observatory in 2002 and 2004, during its quiescence, and in 2016, three months after the onset of magnetar-like outburst. We obtained a deep new observation of J1119 in 2019, split into four pointings between October 18–26, three years after the source went into outburst. All the observations were positioned at the aimpoint of the back-illuminated S3 chip of the Advanced CCD Imaging Spectrometer (ACIS). The standard processing of the data was performed with the Chandra Interactive Analysis of Observations software package (CIAO version 4.12; Fruscione et al. 2006) and the calibration files in the CALDB database (version 4.9.1). The event files were reprocessed (from level 1 to level 2) to remove pixel randomization and to correct for CCD charge transfer efficiencies. An examination of the background light curves did not show any strong flares. We have also similarly reprocessed all previous observations of J1119 obtained with Chandra. The resulting effective exposure times for the observations are given in Table 1.

| ObsID | Date       | Exposure (ks) |
|-------|------------|---------------|
| 2833  | 31 March 2002 | 56.79         |
| 4676  | 31 October 2004 | 60.54       |
| 6153  | 2 November 2004 | 18.90        |
| 19690 | 27 October 2016 | 55.50        |
| 22422 | 18 October 2019 | 52.56        |
| 22877 | 21 October 2019 | 44.47        |
| 22883 | 24 October 2019 | 17.82        |
| 22884 | 26 October 2019 | 19.80        |

Note. Exposure represents the effective exposure times obtained after following the CIAO routines.
3. Imaging Analysis

Figure 1 shows the 0.5–7 keV image of PSR J1119–6127 and its surrounding PWN (in logarithmic scale) for the preburst (left), burst (middle), and postoutburst (right) Chandra data. The preburst image was obtained by combining the 2002 and 2004 observations while the postoutburst image was made by combining all four observations in 2019. The images are exposure corrected and smoothed using a Gaussian function of radius 2 pixels. North is up and east is to the left.

The preburst image was made by combining the 2002 and 2004 observations and shows a compact nebula of size 6″ × 15″ in the north–south direction (Safi-Harb & Kumar 2008). The 2016 burst image clearly shows a brighter nebula and small-scale fine structures (∼10″) around the pulsar (see Blumer et al. 2017 for details). The postoutburst image was made by combining all the four observations in 2019 and features a much fainter PWN, with elongated jet-like features along the north–south direction, similar to its preburst phase.

To further investigate the PWN morphological differences between the three epochs, we extracted the radial profile of the observed (0.5–7 keV) surface brightness up to a radial distance of 15″ from J1119 in the 0.5–7 keV energy range. The simulated PSFs are shown in black for an aspect blur value of 0.28. See Section 3 for details.

4. Spectral Analysis

The spectra were extracted for the source and background regions, and the corresponding response files were created using specextract and analyzed with the XSPEC (v12.10.1f; Arnaud 1996) fitting package. The contributions from background point sources were removed prior to the extraction of spectra. We then combined the spectra created for each ObsID in the preburst (2002+2004) and postoutburst (2019) phase (see Table 1) using the CIAO tool combine_spectra to make a single data set for each epoch, which has the advantage of increasing the signal-to-noise ratio for spectral analysis. The
resulting combined spectra were rebinned to have at least 10 counts per spectral bin, and errors are at the 90% confidence level. The spectral analysis was restricted to the 0.5–7 keV band, where the pulsar and PWN signal-to-noise ratio was higher. We used the tbabs model (Wilms et al. 2000) to describe photoelectric absorption by the interstellar medium.

The spectrum of J1119 was extracted from a 1″ radius circular region centered on the source, which encompasses more than ~90% of the encircled energy for a point source observed on axis with Chandra at 1.49 keV. The background was chosen from an annular ring of 3″–5″ centered on the source. We also estimated the impact of photon pileup in all the Chandra observations using WebPIMMS (version 4.10) and the jdpileup model of the Chandra spectral fitting software Sherpa (Freeman et al. 2001; Doe et al. 2007) convolved with an absorbed PL or BB model to the pulsar spectrum. The 2016 data were affected by 10% pileup, while all other data had negligible pileup. Therefore, we included a pileup model (Davis 2001) as implemented in XSPEC for the 2016 data during spectral fitting.

The pulsar spectra for all three epochs were simultaneously fit with different one- and two-component models. The column density $N_H$ was tied between the epochs, leaving all other parameters to vary during the fit. As found by Safi-Harb & Kumar (2008), a single-component BB model did not yield a good fit to the spectrum of the pulsar in quiescence. We confirm that a hard PL component in addition to the BB component was needed to fit both the preburst (2002+2004) and the most recently acquired (2019) spectra. The 2016 (burst) data were however adequately fitted by a single-component PL model, as illustrated in Blumer et al. (2017). The results of the spectral fits are shown in Table 2. We obtained consistent results when fitting the spectra individually. Figure 3 (left) shows the best-fit preburst (BB+PL; black), burst (PL; red), and postburst (BB+PL; green) pulsar spectra.

To extract the photons from the PWN, we followed the same procedure as in Blumer et al. (2017) and selected an annular region of 2″ to 10″ radii to ensure that all small-scale features were included. The background was extracted from a nearby source-free elliptical region. To model the PWN emission and investigate any spectral variations between the epochs, we fit the three spectra simultaneously with an absorbed PL model, tying only the $N_H$ among the data sets and allowing the PL photon indices and normalizations to vary. The absorption $N_H$ was found to be $(2.2 \pm 0.8) \times 10^{22} \text{cm}^{-2}$, consistent within errors to that obtained for the pulsar. The PWN spectral parameters are listed in Table 1. The spectral fits were also explored with different annular and elliptical backgrounds and binning, and the spectral parameters agree within the errors to those reported in Table 1. Figure 3 (right) shows the best-fit PL model for the PWN.

5. Discussion

Thanks to the prompt response and dedicated follow-up programs of Chandra and other X-ray satellites, the past decade has seen great success in detecting many magnetar outbursts and studying their postoutburst emission mechanisms. The spectacular angular resolution of Chandra has allowed us to collect an unprecedented data set for the high-$B$ pulsar J1119 and its compact nebula covering the period from 2002 to 2019. This has enabled us to accurately characterize the behavior of the source over a long time span of ~17 yr. We discuss the implications of our findings below.

The persistent soft X-ray spectrum of magnetars usually comprises a thermal (BB temperature $kT \sim 0.3$–0.6 keV) and a nonthermal (photon index $\Gamma \sim 2$–4) component. According to the twisted-magnetosphere model of magnetars, the thermal emission originates from heating within the star due to the decay of strong internal magnetic fields (Thompson et al. 2002). Magnetospheric currents, which circulate in localized bundles of magnetic field lines, scatter the thermal surface photons to higher energies. These currents provide a source of surface heating in the form of a return current. The flux increase that accompanies a magnetar outburst is suggested to be due to rapid heating originating from the magnetospheric, internal, or crustal reconfiguration of the neutron star (Thompson et al. 2002; Beloborodov 2009). The twisted magnetosphere does not remain static and gradually untwists, dissipating magnetic energy and producing radiation.

The quiescent spectrum of J1119 is well described by a BB of temperature $kT = 0.2 \pm 0.1 \text{keV}$ and PL of index $\Gamma = 1.7 \pm 0.5$, which made this pulsar the youngest with detected

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Figure 3. Left: X-ray spectra of PSR J1119–6127. The preburst (black) and postoutburst (green) data are best fit by a BB+PL model while the burst data (red) are fit by a PL model. Right: X-ray spectra of the compact PWN fitted with a PL model. The topmost, middle, and bottom spectra represent the preburst (black), burst (red), and postburst (green), respectively. The lower panel shows the ratio of data to plotted model.
The spectra of magnetars generically show a hardening at the time of outburst, while the number of hard photons is consistent with the number of soft photons for the postoutburst epoch with respect to the pre-outburst phase, while the number of hard photons is consistent between the two epochs. These results further confirm the spectral softness observed in the PWN, which is likely impacted by the outburst.

Whether magnetars and high-\(B\) pulsars power PWNe or MWNe is an open and interesting question. Magnetars are believed to produce relativistic particle outflows, either steady or during bursting episodes (Harding et al. 1999). Clear evidence for temporary magnetar outflows has also been seen in the form of transient extended radio emission following two giant flares (Gaensler et al. 2005). However, MWNe are considered long-lived and result from continuous particle outflow even when the magnetar is in quiescence. The most compelling case of an MWN is an asymmetrical X-ray structure around the magnetar Swift J1834.9–0846 (Younes et al. 2016), where the extended emission remained fairly constant in flux and spectral shape across 9 yr of observations. In the X-ray range, where diffuse emission has been seen around several magnetars, the identification of an MWN is complicated by the formation of a dust-scattering halo.
accompanying a magnetar burst due to the large interstellar absorption and high X-ray luminosity of these sources. J1119 had not shown any magnetar-like bursts since 2016, and hence, we do not expect to see any scattering halo in the new Chandra observations. Small-scale variabilities are expected in PWNe; however, the photon index of J1119’s nebula has remained softer even after 3 yr of magnetar-like activity.

Changes in flux are, however, noticeable beyond doubt. Three months after the burst, the PWN was ∼10 times brighter than in its pre-outburst state. However three years after the burst, the PWN returned to its preburst flux level. This raises the question of whether the rise and decrease of the flux level at the PWN before and after the outburst of 2016 is indeed physically connected with it or not. We cannot rule out the idea that the PWN X-ray flux increase could be the result of a process of releasing energy, magnetic field, and particles that started before the detection of the pulsar burst itself. This idea, although possible in principle, is less testable (and less appealing) because it implies a total disconnect between the rise and decay times of the magnetar burst observed in 2016 and the PWN phenomenology following it. In what follows, then, we consider that the most natural scenario is that the recent PWN phenomenology is indeed related to the influence of the 2016 burst.

In recent work, Martín et al. (2020) explored the possible effects of magnetar bursts on the radio, X-ray, and gamma-ray fluxes of PWNe assuming either that the burst injects electron–positron pairs or powers the magnetic field. Similar to gamma-ray bursts (GRBs), they considered that the magnetar flare could be associated with an outflow carrying kinetic and magnetic energy that collides with the PWN, driving a forward shock and accelerating electrons to higher energies. The magnetic field in the forward shock region would also be enhanced with respect to the original PWN field, e.g., due to shock compression and/or Weibel instability in the shock downstream. Martín et al. (2020) considered that a significant amount of relativistic particles is injected in the PWN as a result of a magnetar burst—happening roughly instantaneously in comparison to the dynamical timescales of the PWN. For instance, in an injection of particles during 1 s with a total energy $E_{\text{out}}$ of $10^{45}, 10^{46}$, and $10^{47}$ erg, when particles reach the termination shock, the luminosity is increased by factors of 20 in X-rays in the most extreme cases. From the perspective of the flux increase, this could work. However, the loss timescales for particles are too large in comparison to a decay of a few years, as in the case of J1119. In fact, we expect such an enhanced luminosity to remain high for several kyr. The same happens if the energy of the burst is considered to power the magnetic field, which then decays via adiabatic losses with the PWN expansion velocity (see Equation (15) of Martín et al. 2020).

Shorter decay times can be approached by considering that the evolution equation of the magnetic field energy of the perturbation $E_{\Delta B}$ is

$$\frac{dE_{\Delta B}}{dt} = \eta' L'(t) - \frac{E_{\Delta B}}{R} \frac{dR}{dt},$$

where $R$ is the radius of the perturbation wave, which we take as $R \approx ct$, and we assume that the injection has the form

$$L'(t) = L'_0 e^{-t/t_{\text{decay}}},$$

where $t_0$ is the time when the injection starts, $t_{\text{decay}}$ the decay injection timescale, and $L'_0$ the initial injection luminosity. If the total energy injected is $E_{\text{out}}$, a fraction $\eta'$ of such energy will sustain the magnetic perturbation. To determine the value of $L'_0$, we can use energy conservation:

$$E_{\text{out}} = \int_0^\infty L'_0 e^{-t/t_{\text{decay}}} dt,$$

resulting in $L'_0 = \eta'E_{\text{out}}/t_{\text{decay}}$, which assuming for simplicity $\eta' = 1$ yields

$$L'(t) = \frac{E_{\text{out}}}{t_{\text{decay}}} e^{-t/(t_{\text{decay}})},$$

Taking into account that $E_{\Delta B} = V_{\text{pwn}}\Delta B^2/(8\pi)$, the evolution of the perturbation can be written as

$$\frac{d(\Delta B)}{dt} = \frac{3\eta' L'(t)}{c^3 \Delta B t^3} - \frac{2\Delta B}{t},$$

where $\Delta B$ is the magnetic field due to the additional injection, i.e., the total field being $B_{\Delta B} = B_{\text{pwn}} + \Delta B$. Because in this phenomenological approach the additional field injected has a faster evolution in time than the original one residing in the nebula, the decay time of the PWN flux is shorter.

We assume that the X-ray emission coming from the PWN is synchrotron radiation. In a monochromatic approximation, the synchrotron power emitted by each electron (or positron) in the nebula is

$$P_{\text{syn}}(\nu, \gamma, t) = \frac{4}{3} \frac{\sigma_T}{m_e c} U_B \gamma^2 \delta(\nu - \nu_c),$$

where $\nu$ is the frequency of the emitted photon, $\gamma$ the Lorentz factor of the electron, $t$ the time, $m_e$ the electron mass, and $c$ the speed of light. The symbol $\sigma_T$ is the classical Thompson cross section for electrons, $U_B = B^2/(8\pi)$ the magnetic energy density for a magnetic field $B$, and $\nu_c = 3eB\gamma^2/(4\pi mc^2)$ is the so-called critical frequency where the maximum of power is emitted. The synchrotron luminosity for an electron–positron distribution $N(\gamma, t)$ is then

$$L_{\text{syn}}(\nu, \gamma, t) = \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} N(\gamma, t) P_{\text{syn}}(\nu, \gamma, t) d\gamma.$$

Note then that by substituting $P_{\text{syn}}(\nu, \gamma, t)$ in the latter equation we have $L_{\text{syn}} \propto U_B \propto B^2$. Note that $B$ affects also the electron–positron population through synchrotron energy losses, but for a short timescale and low magnetic fields, we can consider $N(\gamma, t)$ approximately constant. Then, if we want to detect an order of magnitude increase of the synchrotron luminosity $L_{\text{syn}}$, $f/L_{\text{syn}} \propto ((B + \Delta B)/B)^2 \approx 10$, the change we should expect in the magnetic field is $\Delta B \approx 2.16B$.

The form of the energy injection and the evolution of $\Delta B$ are described in Equations (4) and (5), respectively. The latter has an analytic solution, such that

$$\Delta B(t) = \frac{1}{(ct)^2} \sqrt{\frac{6cE_{\text{out}}}{t_{\text{decay}}} \int_0^t t e^{-t/t_{\text{decay}}} dt}$$

where we set $t_0 = 0$ to simplify. This perturbation will affect the PWN when it reaches the termination shock. Most of the high-energy particles are located close to that region, and then we
will assume that once the termination shock is affected, all particles emitting in X-rays are affected by the increase of the magnetic field. At time $t_0$, the magnetic field perturbation starts to expand from the pulsar to the PWN. To estimate when this perturbation affects the PWN, we need to gather the size of the termination shock by using the observational data available. The termination shock radius is given by (e.g., Gelfand et al. 2009)

$$R_{ts}(t) = \sqrt{\frac{\dot{E}}{4\pi \chi c P_{\text{pwn}}}}$$

where $\dot{E}$ is the spin-down luminosity of the pulsar, $P_{\text{pwn}}$ is the internal pressure of the PWN, and $\chi$ is the filling factor of the wind, which is assumed to be 1 for an isotropic wind. To calculate the internal pressure, we use the analytic function given in van der Swaluw et al. (2001):

$$P_{\text{pwn}}(t) = \frac{3}{25} \rho_{\text{ej}}(t) \left( \frac{R_{\text{pwn}}}{t} \right)^2,$$

with $\rho_{\text{ej}}(t)$ the density of the SNR ejecta defined as

$$\rho_{\text{ej}}(t) = \frac{3M_{\text{ej}}}{4\pi R_{\text{pwn}}^3(t)},$$

with $M_{\text{ej}}$ being the mass of the ejecta. We can recover $M_{\text{ej}}$ from Equations (4) and (12) in van der Swaluw et al. (2001):

$$M_{\text{ej}} = 7.04 \cdot \frac{E_{\text{out}}^{1/2}}{3R_{\text{pwn}}} \left( \frac{\dot{E}t}{E_{\text{in}}} \right)^{2/5}$$

with $E_{\text{in}} = 10^{51}$ erg. Substituting the latter expression in Equations (9) and (10), we get an expression for the radius of the termination shock as a function of observational parameters:

$$R_{ts}(t) = 1.088 R_{\text{pwn}}(t) \sqrt{\frac{P_{\text{pwn}} \dot{E}}{cE_{\text{in}}}} \left( \frac{E_{\text{out}}}{\dot{E}t} \right)^{2/5}$$

From the observations, we see that the radius of the PWN is $\sim 10^{0.5}$. Using the distance to J1119 as 8.4 kpc, we obtain $R_{\text{pwn}} \simeq 0.41$ pc. The current spin-down luminosity is $2.3 \times 10^{36}$ erg s$^{-1}$ and its characteristic age 1610 yr. Taking into account all these data, Equation (13) yields $R_{ts} \simeq 0.0084$ pc, which means that the perturbation needs, at the speed of light, $\sim 10$ days to reach the termination shock.

Due to the lack of data (outside the X-ray band) on the synchrotron spectrum of the PWN, we cannot use either the full radiative model to estimate the magnetic field $B$ (e.g., Martín et al. 2012), or other rougher estimations, such as the ratio between the synchrotron and inverse Compton (IC) flux (see e.g., Aharonian et al. 1997). Thus, in order to get an estimate of the order of magnitude of $E_{\text{out}}$, we assume a mean magnetic field of 5 $\mu$G. Such a low magnetic field can be justified by the fact that the X-ray emission is really dim in comparison to other PWNe, or to the spatially coincident TeV emission ($L_X/L_v \sim 10^{-3}$; see Torres et al. 2014). Figure 4 shows the evolution of $\Delta B/B$ for $E_{\text{out}} = 10^{41}$, $10^{42}$, and $10^{43}$ erg and $t_{\text{decay}} = 0.1, 0.5, 1,$ and 2 yr. The plot can be rescaled for other values of $B$ such that $E_{\text{out}} = E_{\text{out}}(5 \mu G B/5 \mu G)^2$. Note that following our previous calculations, the ratio $\Delta B/B$ must be $\sim 2.16$ when it crosses the vertical solid red line; this is the epoch of the observations reported in by Blumer et al. (2017). There is a continuum of values for $E_{\text{out}}$ and $t_{\text{decay}}$ that accomplishes this condition, with $E_{\text{out}}$ around $10^{42}$ erg.

We note that the total energetics needed to reproduce a PWN decay time of about 3 yr, and an increase by a factor of 10 in the X-ray luminosity three months after the burst, is of course larger than the X-ray flux increase. In this model, the larger energetics is invested not only in producing the X-ray burst, but also local particles and magnetic field and perhaps the kinetic outflow itself, so that the X-ray measurement should function as a lower limit to the total power available. Among the several caveats of this simplified, but in principle working, model is that the decay timescale is governed by a damping process that is necessarily different from the one operating in the preburst PWN (and of which the equations above are just a phenomenological proxy).

### 6. Conclusions

In summary, we have conducted a deep Chandra observation of J1119 and its nebula, taken 3 yr after the source went into outburst. Our results show that the pulsar has mostly returned to quiescence with its spectrum best fit by a combination of thermal and nonthermal components. A faint PWN is clearly detected, with jet-like features in the north–south direction, similar in morphology to the preburst phase. The PWN spectrum shows evidence of spectral softening in its quiescent postoutburst phase, with the preburst photon index $\Gamma = 1.2 \pm 0.4$ changing to $\Gamma = 2.3 \pm 0.5$. In addition, its preburst luminosity of $1.5 \pm 0.5 \times 10^{32}$ erg s$^{-1}$ 3 yr following the outburst is just slightly higher at $2.7 \pm 0.3 \times 10^{32}$ erg s$^{-1}$ (0.5–7 keV band). These changes, together with the observed timescale for returning to quiescence (of just a few years), imply a rather fast cooling process and favor a scenario where J1119 is temporarily powered by its magnetic energy following the magnetar-like outburst, in addition to its spin-down energy.

Further monitoring of J1119 and its PWN with Chandra would be beneficial to monitor the spectral evolution of this system. Obviously, should a new magnetar outburst happen in J1119, or in a different pulsar for which a known PWN exists,
All recurrent observations separated at months scales would prove invaluable. That would allow us to track the increase and decrease of the nebula’s luminosity and characterize its spectrum and morphology better to test the theoretical models.

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Software: CIAO (v14.12; Fruscione et al. 2006), XSPEC (v12.10.1f; Arnaud 1996), Sherpa (Freeman et al. 2001; Doe et al. 2007), ChaRT (Carter et al. 2003), MARX (Davis et al. 2012).

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