X-ray Studes of the High-Magnetic Field Radio Pulsar J1119-6127: Any Link to Magnetars?

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PSR J1119-6127 is a high magnetic field (B=4.1E13 Gauss), young (<=1,700 year-old), and slow (P~408 ms) rotation-powered pulsar associated with the supernova remnant G292.2-0.5. The first Chandra observation allowed the detection of the X-ray counterpart of the radio pulsar and provided the first evidence for a compact and faint pulsar wind nebula (PWN). XMM-Newton observations revealed pulsed thermal X-ray emission from the pulsar with an unusually high pulsed fraction. We here present the results of a deep Chandra observation of the system which allowed an imaging and spectroscopic study of the pulsar and PWN independently of each other. We discuss our results in the context of the X-ray manifestation of high-magnetic field pulsars in comparison with the rotation-powered pulsars and magnetars. In particular, we compare the properties of PSR J1119-6127 to PSR J1846-0258, a high magnetic field X-ray pulsar with spin properties remarkably similar to those of PSR J1119-6127, and which recently revealed itself as a magnetar.

On PSR J1119-6127

- **Discovered in the radio with the Parkes multi-beam pulsar survey (*Camilo et al. 2000*)**
- **P = 407.6 ms, Pdot = 4.0 x 10^{-12}**
- **Characteristic age = P/2Pdot = 1,600 years**
- **Surface Dipole magnetic field B=3.2x10^{19} (P Pdot)$^{0.5}$ = 4.1x10^{13} G**
- **Pulsar braking index n = 2.9, Spin-down energy, Edot=2.3 x 10^{36} erg/s**
- **Near the center of G292.2-0.5 (*Crawford et al., Pivovaroff et al. 2001*), a 15'-diameter SNR**
- **Distance ~ 2.4-8.4 kpc. We here use a distance of 8.4 kpc (the SNR distance, *Caswell et al. 2004*)**
- **Chandra detection of the PSR and discovery of a compact pulsar wind nebula (PWN, *Gonzalez & Safi-Harb 2003*)**
- **XMM-Newton detection of a high pulsed fraction (74+/-14%) in the soft X-ray band (*Gonzalez et al. 2006*)**

Why is J1119-6127 an interesting pulsar?

- **Slow pulsar despite it being the 4th youngest among the rotation-powered pulsars**
- **Characterized by the 2nd highest B (excluding magnetars), which is interestingly close to the critical QED value of 4.4 x 10^{13} G**
- **The youngest pulsar that a) displays pulsed thermal X-rays (with a high kT and a high pulsed fraction), b) lacks a radio PWN, and c) powers a compact and faint X-ray PWN**
- **Its spin properties (P, B) are very similar to the Kes 75 pulsar (PSR J1846-0258), long thought to be a Crab-like pulsar, but which recently revealed itself as a magnetar (*Kumar & Safi-Harb 2008, Gavriil et al. 2008*)**
- **To date it is not clear whether PSR J1119-6127 should display more Crab-like or magnetar-like properties**
- **We here present a deep Chandra observation that allow a detailed and deep imaging and spectroscopic study of the pulsar, *independently* of its PWN. The morphology of the PWN is also revealed for the 1st time.**

Observations and Data Reduction

- **J1119-6127 was observed with Chandra ACIS-S on 2002 March 31-April 1 (AO3 data published in *Gonzalez & Safi-Harb 2003* and *Gonzalez & Safi-Harb 2005*), and during AO5 on 2004 Nov. 2-3 and Oct. 31-Nov 1**
- **All 3 datasets were positioned at the aimpoint of the back-illuminated S3 chip, in the 'timed' and 'vfaint' modes, at a CCD temperature of -120 C.**
- **We reduced the data using the standard CIAO routines (v4.0). The total effective exposure time is 136.2 ksec.**
- **The spectral analysis was performed with XSPEC v12.4.0.**

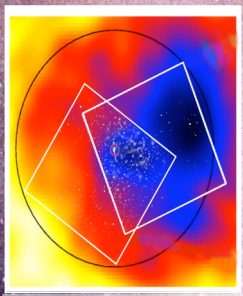


Figure 1: ASCA 2-10 keV image of SNR G292.2-0.5 with the ACIS-S3 chips from the AO3 (west) and AO5 (east) observations overlaid. The central circle indicates the position of PSR J1119-6127.

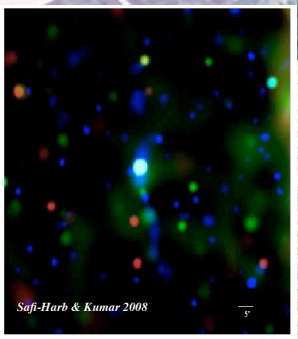


Figure 2 (right): Tri-color energy image of the Chandra field surrounding the pulsar (the brightest source near the centre). The image shows the compact PWN and the 1st evidence for an *extended jet to the south* with a (7+/-2) σ detection (0.5-7 keV).

Red: 0.5-1.15 keV

Green: 1.15-2.13 keV

Blue: 2.3-10 keV

Zooming on the pulsar wind nebula

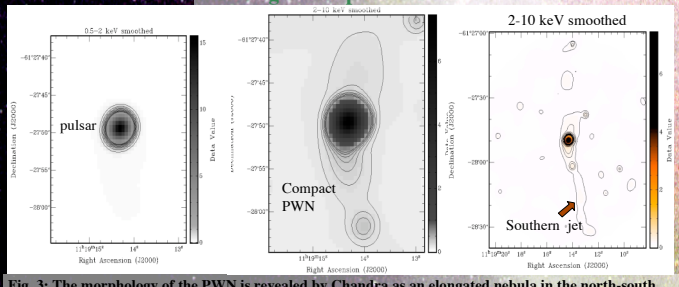
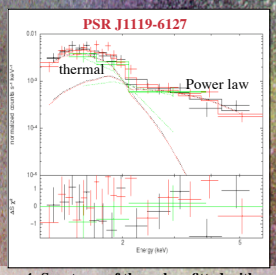


Fig. 3: The morphology of the PWN is revealed by Chandra as an elongated nebula in the north-south direction. The compact nebula appears as "jet"-like (extending ~10" north and south of the pulsar, which corresponds to ~0.4 pc at 8.4 kpc; middle panel). The PWN is evident only in the *hard band*. There is also evidence for a faint, long (~30" or 1.2 pc at 8.4 kpc) and hard jet-like structure south of the pulsar (right-most image). The images have been adaptively smoothed using a Gaussian with σ=1" for a significance of detection greater than 5 and up to σ=3" for a significance of detection down to 2.

Spectral Results and Comparison with the Kes 75 pulsar



Parameter	PL	BB+PL	NSA+PL[a]	
N_H (10^{22} cm^{-2})	$1.2^{+0.6}_{-0.5}$	$1.8^{+1.5}_{-0.8}$	1.6 ± 0.2	
Γ	$3.0^{+0.5}_{-0.5}$	$1.9^{+1.1}_{-0.9}$	1.5 ± 0.8	
Norm[b](PL)	$5.7^{+4.2}_{-2.3}\times10^{-5}$	$1.5^{+2.3}_{-0.8}\times10^{-5}$	$8.4^{+4.5}_{-3.0}\times10^{-6}$	PSR
kT_{BB}(keV)	...	0.21 ± 0.01	$0.14^{+0.02}_{-0.02}$	
Norm[b](BB)	...	$3.5^{+4.3}_{-1.8}\times10^{-6}$	1.42×10^{-6} (frozen)	
$F_{0.5-8}$(PL)[c]	$1.7^{+1.3}_{-0.7}\times10^{-13}$	$6.2^{+4.7}_{-2.8}\times10^{-14}$	$6.1^{+3.2}_{-2.3}\times10^{-14}$	
$F_{0.5-8}$(thermal)	...	$2.2^{+0.9}_{-0.8}\times10^{-13}$	$1.8^{+0.9}_{-0.7}\times10^{-13}$	
L_X[d](10^{33}erg s^{-1}	$1.4^{+1.1}_{0.6}$	$2.4^{+0.8}_{-0.5}$	$2.1^{+0.8}_{-0.6}$	
χ^2_ν (*dof*)	1.356 (31)	0.948 (29)	0.977 (30)	

Table 1: Spectral fits to the pulsar. All models are modified by interstellar absorption with a column density N_H. PL denotes a power-law model, BB denotes a blackbody, and NSA refers to the neutron star H atmospheric model in XSPEC version 12.4.0.

[a]The NSA model assumes a magnetic field of 10^{13} Gauss, a neutron star radius of 10 km and mass of 1.4 $M_\odot$. The distance is also fixed at 8.4 kpc (thus the normalization of 1.4×10^{-6}).
[b]PL normalization at 1 keV in units of photons cm^{-2} s^{-1} keV^{-1}. BB normalization in units of L_{39}/D_{10}^2 where L_{39} is the luminosity in units of 10^{39} erg s^{-1} and D_{10} is the distance in units of 10 kpc.
[c]0.5-7.0 keV unabsorbed flux (ergs cm^{-2} s^{-1}).
[d]0.5-7.0 keV total luminosity (assuming isotropic emission).

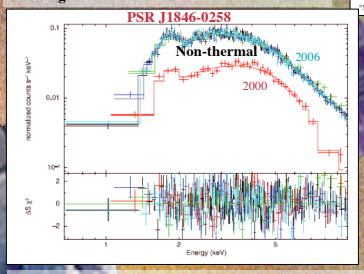
Parameter/PWN Region	Compact PWN	Southern 'Jet'	
Γ	$1.1^{+0.9}_{-0.7}$	$1.4^{+0.8}_{-0.9}$	PWN
Norm[a]	$(2.2^{+1.5}_{-1.2})\times10^{-6}$	$(3.5^{+1.6}_{-1.3})\times10^{-6}$	
χ^2_ν(*dof*)	1.23 (17)	1.16 (17)	
f_{unabs} (0.5-7 keV) ergs cm^{-2} s^{-1}	$(1.9^{+0.5}_{-0.4})\times10^{-14}$	$(2.4^{+0.5}_{-0.4})\times10^{-14}$	

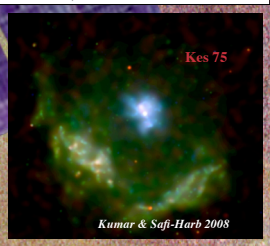
Table 2: Power law spectral fits to the PWN. The compact PWN refers to the 6"×15" structure elongated in the north-south direction (see Fig. 4). The southern 'jet' corresponds to the new faint and extended jet-like structure (~6"×20") shown in Fig. 5. N_H is frozen to 1.8×10^{22} cm^{-2}. Errors are 2σ.

[a]Normalization at 1 keV in units of photons cm^{-2} s^{-1} keV^{-1}.

Figure 4: Spectrum of the pulsar fitted with a two-component thermal+power law model. See table above for a summary of parameters.

Figure 5 (below): Spectrum of PSR J1846-0258 (associated with the SNR Kes 75 shown to the right) displaying variability and spectral softening between 2000 and 2006.





Conclusions and Discussion

- **Thanks to Chandra, we have for the 1st time resolved the pulsar's spectrum from that of the PWN. We reject a single absorbed blackbody model. A power law model is needed to account for the hard X-rays. No variability was detected from the pulsar using the available data, unlike what's observed for the high-B pulsar PSR J1846-0258 (Fig.5).**
- **A two-component thermal blackbody (T~2.5MK) or a NS atmospheric model (T~1.2MK) plus a power law component (modified by interstellar absorption with N_H ~1.8x10^{22} cm^2) provides an excellent fit to the PSR's spectrum, with an unabsorbed non-thermal flux of ~20-35% that of the thermal flux.**
- **For a distance of 8.4 kpc, the blackbody radius is ~2.7 km, suggesting polar cap emission from the neutron star's surface. The pulsar's luminosity (assuming isotropic emission) is ~2x10^{33} erg/s.**
- **We have unveiled the morphology of the PWN as an elongated compact nebula in the N-S direction, with jet-like structures showing up only in the *hard band*, and extending to 10"-15" (0.4-0.6 pc at 8.4 kpc) from the pulsar. The new observation shows evidence for a hard longer jet (extending to ~30" or ~1.2 pc south of the pulsar). A deeper observation is needed to confirm this.**
- **The PWN is well described by a PL model with a hard photon index (~1.1 for the compact PWN, and ~1.4 for the southern jet--for a column density of 1.8x10^{22} cm^{-2}), and with an X-ray luminosity of ~4x10^{32} erg/s (0.5-7 keV). This is ~20% of the pulsar's luminosity, and ~0.02% (2x10^{-4}) of Edot.**
- **Assuming the non-thermal emission from the PWN is due to synchrotron radiation in X-rays (no radio PWN has been detected so far), we estimate an equipartition B_{PWN} >~4.5 x 10^{-5} Gauss.**
- **The 0.5-7 keV total non-thermal luminosity of PSR+PWN is 5x10^{-4} x Edot (scales as $D_{8.4}^2$).**

Comparison to other PSRs

- **There are currently 7 pulsars including J1119 with B>~B_c=4.4x10^{13} G, but which are not identified as magnetars, except for J1846-0258 which recently blurred the distinction between the rotation-powered pulsars and magentars-- see Table (to the right).**
- **The X-ray properties of J1119-6127 are *most similar* to those of J1357-6429, another young rotation-powered pulsar but with a more "typical" B~8x10^{12} G (*Zavlin 2007*). Both pulsars have comparable Edot and L_X/Edot (<<1, unlike magnetars), and J1357-6429 also similarly displays a high pulsed fraction (>~50%) in the soft X-ray.**
- **Among the tabulated high-B pulsars (HBPs), J1119-6127 has *spin/B* properties *most similar* to J1846-0258, however J1854-0258 is a non-thermal X-ray pulsar and much more efficient at powering a bright PWN (L_X/Edot~2-3%), so their X-ray properties are very different. As well J1846 recently revealed itself as a magnetar (*Gavriil et al. 2008, Safi-Harb & Kumar 2008*). *Whether J1119 will reveal itself as a magnetar one day remains to be seen!***
- **Further observations of this, and other HBPs, are needed to address their connection with magnetars.**

Pulsar (PSR)	$\dot{E}$ (ergs s^{-1})	B (10^{13} G)	PWN?	L_X(PWN)/Edot	Reference
J1846−0258	8.0×10^{36}	4.9	Y (X)	$0.018-0.0325\,d_{8.4}^2$	Kumar & Safi-Harb (2008)
J1119−6127	2.3×10^{36}	4.1	Y (X)	$5\times10^{-4}\,d_{8.4}^2$	this work
J1734−3333	5.6×10^{34}	5.2	–	–	Morris et al. (2002)
J1718−3718	1.5×10^{33}	7.4	–	$0.013-4.0\,d_{2.5}^2$	Kaspi & McLaughlin (2005)
J1814−1744	4.7×10^{32}	5.5	–	$<1340\,d_{10}^2$	Pivovaroff et al. (2000)
J1819−1458[c]	2.9×10^{32}	5.0	–	$\sim12\,d_{4.0}^2$	Reynolds et al. (2006)
J1847−0130	1.7×10^{32}	9.4	–	$<18-47\,d_6^2$	McLaughlin et al. (2003)
B1800−21	2.2×10^{36}	0.4	Y(X)	$10^{-4}\,d_4^2$	Kargaltsev et al. (2007)
J1357−6429	3.1×10^{36}	0.8	Y(X)	$6.5\times10^{-5}\,d_{2.5}^2$	Zavlin et al. (2007b)

Table 3: The high-magnetic field pulsars sorted in order of decreasing spin-down power. We used the ATNF pulsar catalog in compiling the pulsar properties and only selected pulsars with $B\geq4\times10^{13}$ G (the QED value) (B is defined in footnote#4, but see footnote#13). The last two pulsars, shown only for comparison with PSR J1119−6127, are rotation-powered pulsars with a 'typical' magnetic field, but with $\dot{E}$ and X-ray properties almost identical to PSR J1119−6127. The 4th column refers to the presence (Y) or absence of a PWN in X-rays (X). Except for PSR J1846−0258, none of these pulsars has a radio PWN associated with it. The 5th column refers to the ratio of the non-thermal X-ray luminosity of the combined pulsar and associated PWN (when detected in X-rays) to the pulsar's spin down power, scaled to the distance given in units of d_x, where x is the adopted distance to the pulsar in units of kpc.

[a]the lower (upper) range corresponds to the 2000 (2006) *Chandra* data; the pulsar has brightened by a factor of ~6 in 2006.
[b]only an upper limit on the X-ray luminosity was estimated using the spectral properties of 1E 2259+586 (an AXP) as a template.
[c]pulsar classified as a rotating radio transient; the X-ray luminosity of the pulsar is uncertain by an order of magnitude.
[d]only an upper limit was estimated using AXPs 0.1012+61 or 1E 2259+586 as templates.

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