Chandra Observations of Radio Pulsars

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X-ray observations of spin-powered pulsars (PSRs) provide valuable diagnostics of emission mechanisms and acceleration processes operating in pulsar magnetospheres and winds. We present the results from ACIS observations of several radio pulsars that belong to different categories of the diverse pulsar population. These include the 5-Myr-old "nulling" pulsar B1133+16, 200-kyr-old PSR J1825-1446, 20-kyr-old PSR B1800-21 with a pulsar-wind nebula (PWN), the famous 1-Gyr-old PSR B1257+12 with a planetary system, and a few others. The pulsars exhibit different X-ray spectral slopes suggesting that the contribution of polar cap thermal emission may become more important as pulsar ages. Although the pulsar X-ray luminosities generally correlate with the spin-down power Edot, a strong scatter in the L_X vs. Edot dependence suggests that other factors (e.g., the magnetic field geometry and orientation of magnetic and spin axes) are equally important. A compact 10''-size PWN around PSR B1800-21 shows a bow-shock-like morphology reminiscent of those found for several other PWNe. To provide a more complete picture, we compare our results with those from other Chandra observations of spin-powered pulsars.

1. Vela-like Pulsar: B1800-21

- **B1800-21 parameters:**
  Period = 133.6 ms
  Edot = 2.2 × 10^36 erg/s
  Age = 16 kyrs
  DM distance = 3.9 kpc

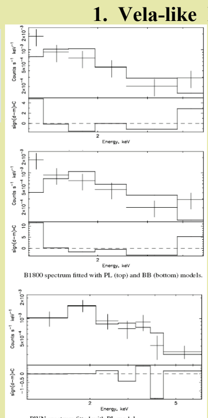
cf.

- Vela pulsar parameters:
  Period = 89.3 ms
  Edot = 6.9 × 10^36 erg/s
  Age = 11 kyrs
  Distance = 350±20 pc

- **The PWN spectrum fits well with a power-law (PL) model (Γ≈1.5). Similar to the Vela PWN, the PWN around B18200-21 is underluminous : $L_{X,PWN} \approx 8.5 \times 10^{-5}$ Edot (in 0.3-8 keV)**

- **B1800-21 PWN morphology is different from that of the Vela PWN (see figs.). Possibly, B1800 is moving faster than Vela pulsar => PWN is more compact and elongated. The bow shock stand-off distance of 1'' corresponds to ~0.02 pc (@ d=3.9 kpc) => $v_p \approx (\mathrm{Edot} / 4\pi c p r^2) \approx 280$ km/s. This is a factor of 4 faster then Vela pulsar.**

- **The pulsar spectrum does not fit well with PL or black-body (BB) models unless one assumes that n_H is much lower than that obtained from the PL fit to the PWN spectrum. Possibly, PSR spectrum has both thermal and non-thermal components (similar to the Vela PSR). In this case a good fit can be obtained with the PL+BB model; however, the fit parameters have large uncertainties due to the small number of counts. It is possible that the non-thermal component comes from the unresolved PWN close to the pulsar.**



B1800 spectrum fitted with PL (top) and BB (bottom) models.

PWN spectrum fitted with PL model.

BEST-FIT PARAMETERS FOR PL AND BB MODELS FITTED TO *Chandra* SPECTRUM OF B1800-21 AND ITS PWN

Model	$n_{H,21}$	$\mathcal{N}$[a] or/and Area[b]	Γ or/and kT[c]	C/dof	L_X or/and L_{bol}[d]
PWN PL	$1.50^{+0.76}_{-0.65}$	14.5 ± 3.1	1.51 ± 0.20	0.7/4	$18.8^{+3.0}_{-2.7}$
PSR PL	1.50	16.7 ± 4.5	2.54 ± 0.41	2.6/4	$14.1^{+12.5}_{-5.4}$
PSR BB	1.50	$11.4^{+8.0}_{-4.4}$	$0.58^{+0.06}_{-0.07}$	5.6/4	1.4 ± 0.3
PSR BB+PL	1.50	5.6 / (5.3 × 10^5)	1.5 / 0.105	1.4/2	7 / 56

[a]Spectral flux in 10^{-6} photons cm^{-2} s^{-1} keV^{-1} at 1 keV
[b]Projected area of the emitting region for the BB model (in 10^3 m^2).
[c]BB temperature in keV.
[d]Unabsorbed luminosity in 0.3-8 keV band or bolometric luminosity in 10^{31} erg s^{-1}. The pulsar and PWN absorbed fluxes in 0.3-8 keV band are 3.6 and 9.7×10^{-14} erg cm^{-2} s^{-1}.

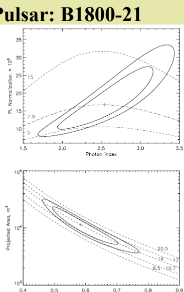


FIG. 4.— Confidence contours (68% and 90%) for the blackbody (bottom) and power-law (top) model fits to the spectrum of B1800. The BB normalization (vertical axis) is the projected emitting area in units of m^2, for d = 3.9 kpc. The PL normalization is in units of 10^{-6} photons cm^{-2} s^{-1} keV^{-1} at 1 keV. The lines of constant bolometric luminosity (bottom panel; for a polar cap close to the center of stellar disk, in units of 10^{30} erg s^{-1}) and constant flux (top panel; in units of 10^{-14} erg cm^{-2} s^{-1}; in 0.3–8 keV band) are plotted as dashed lines, for fixed $n_{H,22} = 1.5$.

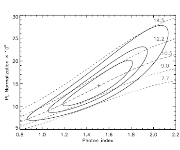
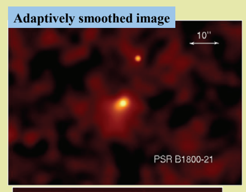
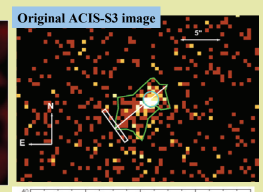


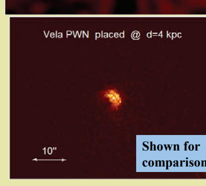
FIG. 5.— Confidence contours (68% and 90%) for the PL model fitted to the PWN spectrum. The PL normalization is in units of 10^{-6} photons cm^{-2} s^{-1} keV^{-1} at 1 keV. The lines of constant flux (in units of 10^{-14} erg cm^{-2} s^{-1}; in 0.3–8 keV band) are plotted as dashed lines, for fixed $n_{H,22} = 1.5$.

Adaptively smoothed image



Original ACIS-S3 image





Shown for comparison

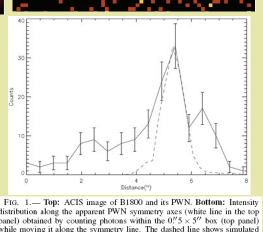


FIG. 1.— **Top:** ACIS image of B1800 and its PWN. **Bottom:** Intensity distribution along the apparent PWN symmetry axes (white line in the top panel) obtained by counting photons within the 0.''5 × 5'' box (top panel) while moving it along the symmetry line. The dashed line shows simulated ACIS PSF.

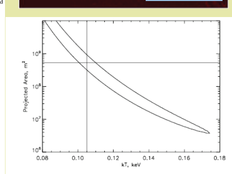


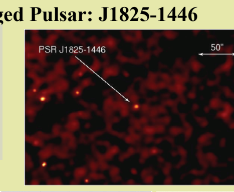
FIG. 6.— Confidence contour (68%) for the blackbody component of the BB+PL fit (see Table 1). The straight lines correspond to the canonical 13 km radius of the NS.

ACIS Exposure: 30.23 ks
PSR: 48 cts
PWN: 117 cts

2. Middle-Aged Pulsar: J1825-1446

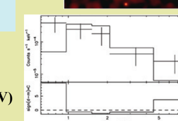
Radio data:

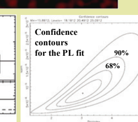
- DM distance: 5 kpc
- Edot = 4.1 × 10^34 erg/s
- Edot/(4πd²) =1.2 × 10^-11 erg/s/cm²
- Age is about 200 kyrs
- Period 279 ms



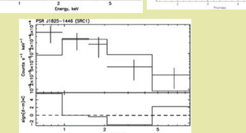
ACIS Exposure: 30 ks
PSR: 17 cts

- **PL fit:**
  $n_{H,22}$= 1.1
  Γ = 3.0 ±0.3
  $L_X \approx 1.2 \times 10^{32}$ erg/s (0.3-8 keV)
  C / dof = 5.0 / 3



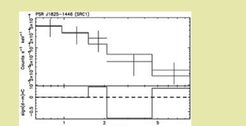


- **BB fit:**
  $n_{H,22}$= 1.1
  kT = 0.64 ±0.07 keV, R=40 ± 8 m
  $L_{bol} \approx 9 \times 10^{30}$ erg/s (bolometric)
  C / dof = 6.1 / 3



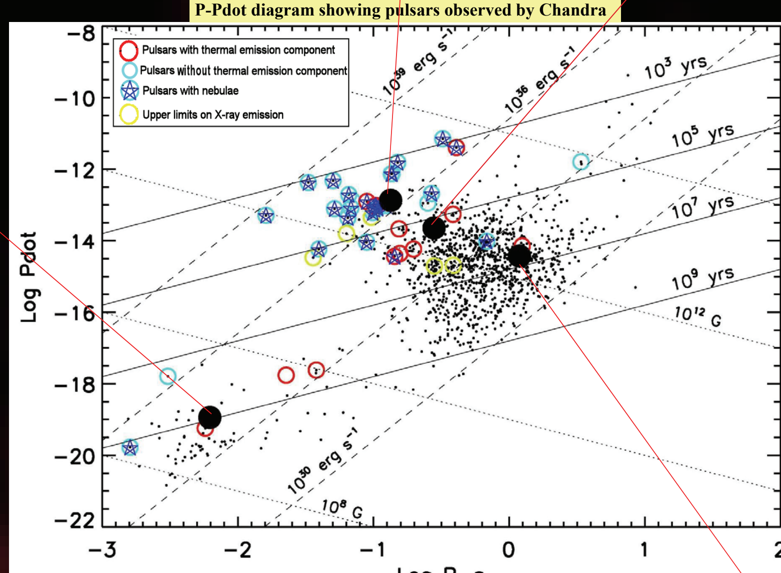
Better fit with two-component model:

- **PL+BB fit:**
  $n_{H,22}$= 1.1
  Γ = 1.3 ±0.8
  $L_X \approx 3 \times 10^{31}$ erg/s (0.3-8 keV)
  kT = 70 eV, R=13 km
  $L_{bol} \approx 1.3 \times 10^{32}$ erg/s (bolometric)
  C/ dof = 0.46 / 3



Two-component fit gives reasonable parameters (cf. B0656+14, Geminga), however more counts are needed to be sure.

P-Pdot diagram showing pulsars observed by Chandra



3. Recycled Planetary Pulsar: B1257+12

- **Radio data**
  Period = 6.2 ms
  Edot = 1.9 × 10^34 erg/s
  Age = 0.86 Gyr
  DM distance = 770 pc

ACIS Exposure: 20 ks
PSR: 19 cts

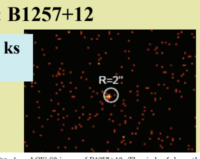


FIG. 1.— ACIS S3 image of B1257+12. The circle of shows the radio position of PSR B1257+12.

BEST-FIT PARAMETERS FOR PL AND BB MODELS FITTED TO *Chandra* SPECTRUM OF B1257

Model	$n_{H,21}$	$\mathcal{N}$[a] or Area[b]	Γ or kT[c]	C/dof	L_X or L_{bol}[d]
PL	0.32	$(1.66 \pm 0.5) \times 10^{-6}$	2.73 ± 0.5	1.9/2	$5.6^{+2.5}_{-2.3} \times 10^{29}$
BB	0.32	$5.4^{+6.0}_{-3.0}$	$0.204^{+0.016}_{-0.025}$	0.55/2	$1.0^{+0.6}_{-0.5} \times 10^{29}$

[a]Spectral flux in photons cm^{-2} s^{-1} keV^{-1} at 1 keV
[b]Projected area of the emitting region for the BB model (in 10^3 m^2).
[c]BB temperature in keV.
[d]Unabsorbed luminosity in 0.3-8 keV band or bolometric luminosity. The absorbed flux in 0.3-8 keV band is 6.4×10^{-15} erg cm^{-2} s^{-1}.

- **Very underluminous pulsar !**
  For PL fit:
  $L_X \approx 5.6 \times 10^{29}$ erg/s (0.3-8.0 keV, @ d=770 pc), which is only ~ 3 × 10^-5 Edot

If thermal, the radiation is not expected to be strongly beamed =>low X-ray efficiency can be due to an intrinsic X-ray absorber (e.g., interplanetary dust)

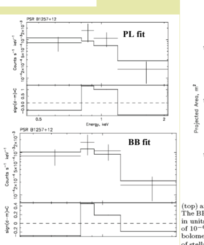
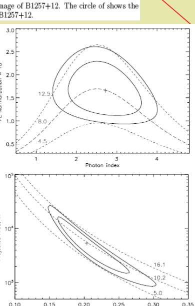
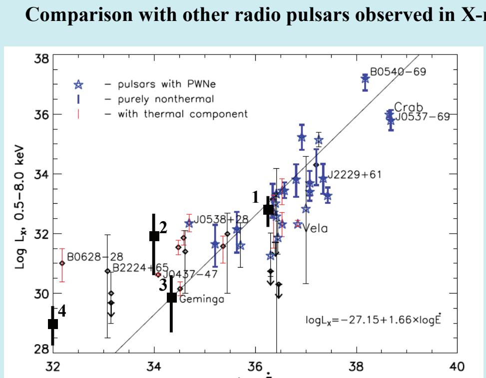


FIG. 2.— X-ray spectrum of B1257 fitted with PL (top) and BB (bottom) models.

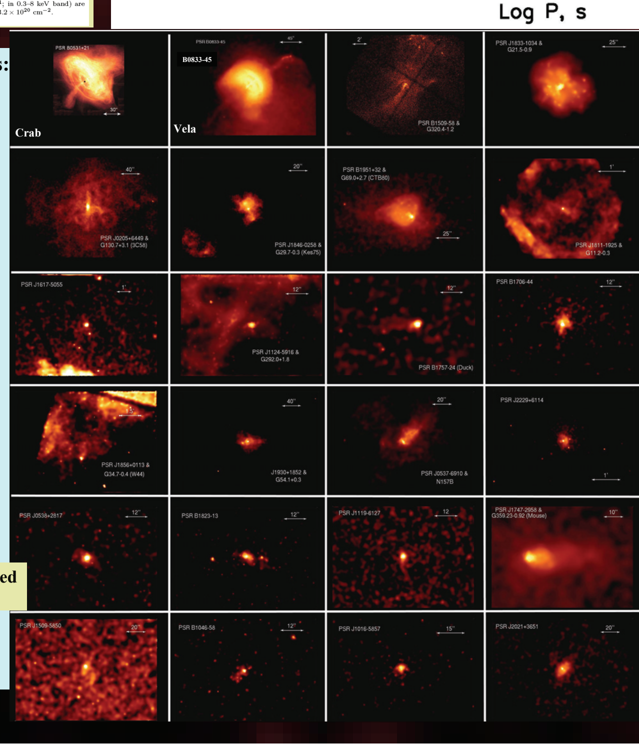


Confidence contours (68% and 90%) for the power-law (top) and blackbody (bottom) model fits to the spectrum of B1257. The BB normalization (vertical axis) is the projected emitting area in units of m^2, for d = 0.77 kpc. The PL normalization is in units of 10^{-6} photons cm^{-2} s^{-1} keV^{-1} at 1 keV. The lines of constant bolometric luminosity (top panel; for a polar cap close to the center of stellar disk, in units of 10^{28} ergs s^{-1}) and constant flux (bottom panel; in units of 10^{-15} ergs cm^{-2} s^{-1}; in 0.3–8 keV band) are plotted as dashed lines, for fixed $n_H = 3.2 \times 10^{20}$ cm^{-2}.

Comparison with other radio pulsars observed in X-rays:



L_X-Edot diagram for pulsars observed with Chandra ACIS. The best-fit correlation and the four new X-ray pulsars (numbered) are shown. ***The plot is based on our own analysis of ACIS data.***



PWNe observed by *Chandra*

4. Old Pulsar: B1133+16

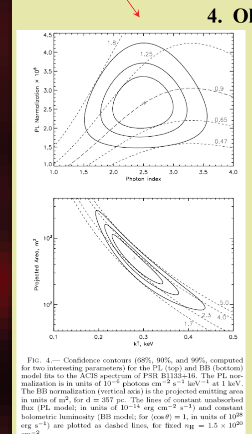


FIG. 4.— Confidence contours (68%, 90%, and 99%, computed for two interesting parameters) for the PL (top) and BB (bottom) model fits to the ACIS spectrum of PSR B1133+16. The PL normalization (vertical axis) is in units of 10^{-6} photons cm^{-2} s^{-1} keV^{-1} at 1 keV. The BB normalization (vertical axis) is the projected emitting area in units of m^2, for d = 357 pc. The lines of constant unabsorbed flux (PL model, in units of 10^{-14} erg cm^{-2} s^{-1}) and constant bolometric luminosity (BB model; for cos θ = 1, in units of 10^{28} erg s^{-1}) are plotted as dashed lines, for fixed $n_H = 1.5 \times 10^{20}$ cm^{-2}.

Parameter	Value
R.A. (J2000)	11ʰ36ᵐ03ˢ.1829(10)
Dec. (J2000)	+15°51′09″.726(15)
Epoch of position (MJD)	51,544.0
Proper motion, R.A./Dec. (mas yr^{-1})	−73.95(38)/368.05(28)
Spin period, P (s)	1.1879
Dispersion Measure, DM (cm^{-3} pc)	4.86
Distance from parallax, d (pc)	357(19)
Surface magnetic field, B_s (10^{12} G)	2.13
Spin-down power, $\dot{E}$ (10^{31} erg s^{-1})	8.8
Age, $\tau = P/(2\dot{P})$, (Myr)	5.04

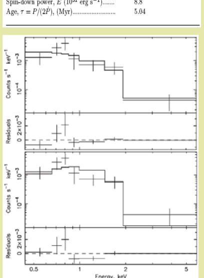
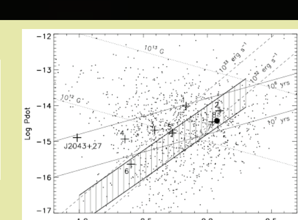


FIG. 3.— B1133 spectrum fitted with the PL (top) and BB (bottom) models. The contributions of the energy bins into the C-statistic are shown, multiplied by +1 when the number of data counts is smaller than the number of model counts.

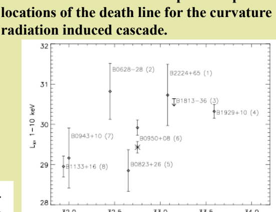
FITTING PARAMETERS FOR THE PL AND BB MODELS

Model	Norm.	Γ or kT	C/dof	Q	L_{29}
PL	$2.66^{+0.43}_{-0.41}$	$2.51^{+0.36}_{-0.33}$	6.20/5	43%	1.4 ± 0.3
BB	$0.56^{+0.42}_{-0.22}$	$0.28^{+0.04}_{-0.03}$	10.4/5	79%	$0.32^{+0.05}_{-0.06}$

ACIS Exposure: 18 ks
PSR: 33 cts



- **P-Pdot diagram showing old pulsars (τ > 1 Myr) observed in X-rays with Chandra and XMM. The hatched area represents plausible locations of the death line for the curvature radiation induced cascade.**



L_X-Edot plot for old pulsars.

The observed X-ray emission can come from hot PC (thermal) or magnetosphere (if non-thermal). Similar to B0950+08 (Zavlin & Pavlov 2005), where more counts are available for spectral analysis, both thermal and non-thermal components may be present in B1133+16 spectrum.

The work is accepted to ApJ, Kargaltsev et al. 2006, astro-ph/0510466