Pulsar Wind Nebulae

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General outlook
Chandra results
Polarization in radio and optical
X-ray polarization
Pulsar Wind Nebulae:

• extended objects around spin-powered pulsars
• seen from radio to gamma-rays, most easily observed in radio and X-rays
• smooth, power-law-like spectra
• synchrotron emission from shocked pulsar wind

Simple model (Rees & Gunn 1974, Kennel & Coroniti 1984):

Isotropic pulsar wind, comprised of relativistic electrons/positrons and electromagnetic field, is shocked at a distance $R_S$ where the wind pressure $E_{\text{dot}}/(4\pi c R_S^2)$ equals pressure of the ambient medium: $R_S = (E_{\text{dot}}/4\pi c p_{\text{amb}})^{1/2}$. Properties of the shock and post-shock flow depend on “magnetization parameter” $\sigma = (\text{Poynting flux})/(\text{KE flux})$. 
The shock is “strong”, and the PWN is bright, if $\sigma \ll 1$ before the shock. (However, $\sigma \gg 1$ near the light cylinder, at $R=R_L=c/\omega$ --- “$\sigma$ paradox”.)

Earlier observations are crudely consistent with this model (e.g., $\sigma \sim 0.003$ for Crab PWN), but the flow is equatorial rather than radial [$4\pi \rightarrow \Omega$; $R_S = (E_{\text{dot}}/4\pi c\rho_{\text{amb}})^{1/2} \rightarrow R_S = (E_{\text{dot}}/\Omega c\rho_{\text{amb}})^{1/2}$]
High-resolution **Chandra observations** → more complicated picture: some PWNe show ~axial symmetry, others look asymmetric
Famous example: The Crab PWN

Chandra ACIS image (Weisskopf et al 2000)

Ring(s), jets, torus, wisps…

Inner ring: termination shock

Approximate axial symmetry, around the PSR rotation axis (jet direction)

Pulsar wind is anisotropic, with polar and equatorial components
The outer nebula is asymmetric
Vela PWN: Deep ACIS image

6’x5.5’ = 0.52pc x 0.48 pc @ d=300 pc

Dim outer jet along direction of proper motion and very dim outer counter-jet

Asymmetric faint nebula SW of the PSR
PWN around PSR B1509-58 in MSH 15-52 (G320.4-1.2)

1.5’ = 2.2 pc @ d=5.1 kpc

“Jelly-fish” PWN, with a long jet SE of PSR,
Two arc (wisps?)

RCW 89
(North of PSR)
apparently powered by PSR wind

(Gaensler et al. 2002)
More examples of \textasciitilde symmetric PWNe

In \textbf{N157B} (LMC), PSR J0537-6909

In \textbf{G21.5-0.9}, pulsar undetected
More examples…

MSH 15-56

PSR B1706-56

G54.1+0.3
PSR J1930+1852

PSR J2229+6114
Not so clear symmetry..

- **G11.2-03**: SN 386? PSR J1811-1926, 1.5 pc
- **3C 58**: SN 1181? PSR J0205+6449, 0.5 pc
- **CTB 80**: PSR B1951+32, 0.6 pc
- **G0.9+0.1**: 3 pc
PWNe are dynamic objects

Crab: moving wisps, etc (Mori, Burrows, Hester 2002)

8 observations separated by ~3 weeks

Speeds of outgoing wisps $\sim 0.5c$

Motions in torus $\sim 0.15c$
PWNe are dynamic objects

**Vela: variable outer jet** (Pavlov et al. 2003)

- Variability:
  1. Sideways shifts/bends; ~ month
  2. Outward moving blobs; $v \sim 0.6c$
  3. Blobs brightness varies; ~ week

- Luminosity $L_X \sim 10^{30}$ erg/s

- Spectrum: power-law, photon index $\Gamma = 1.4 \pm 0.1$

- Synchrotron emission in magnetic field $B \sim 100 \mu$G
X-ray luminosity of a PWN is a small fraction, $10^{-4} - 10^{-1}$, of $E_{\text{dot}}$

$L_{\text{PWN}}$ correlated with $E_{\text{dot}}$

Even better correlated with $L_{\text{PSR}}$
X-ray spectra: power laws with $\Gamma = 1 - 2.5$

Generally, spectra soften with increasing distance from PSR

G21.5-0.9 (Safi-Harb et al. 2001)

G0.9+0.1 (Porquet et al. 2003)

IC 443 (Bocchino & Bykov 2001)
Spectral slope correlates with morphology
(not just a function of radius)

Spectral map of **Crab PWN**
from XMM-Newton
(Willingale et al. 2001)

Blue = hardest, $\Gamma = 1.6$;
red = softest, $\Gamma = 2.4$

Spectrum generally softens
towards the PWN periphery,
but not isotropically

Fine structures (e.g., wisps)
are not seen, perhaps because
of low angular resolution
Chandra resolution $\rightarrow$ fine structure of spectral map

Spectral map of the **Vela PWN**: red = soft, $\Gamma = 1.9$, yellow = hard, $\Gamma = 1.2$

Outer jet and outer nebula are **harder** than inner PWN shell
Chandra observations have shown that PWNe have complicated morphology, often with axial symmetry (equatorial and polar outflows), associated with pulsar spin.

A model (Coroniti 1990): “striped wind” with toroidal magnetic field of alternating polarity, stripes separated by current sheets; predicts a “helical wind” along the spin axis; no model for collimated jets.

Fig. 1.—Sketch (not to scale) of a plausible magnetic topology for a relativistic MHD wind from an oblique rotator. Near the rotational equator, the toroidal magnetic field $B_\phi$ has an alternating polarity. These magnetic stripes are separated by thin current sheets ($J_\phi$). Off the equator, the magnetic flux in the toward and away stripes is unequal if the dipole obliquity is not equal to $\pi/2$. Opposite flux regions of an initially high $\sigma$ wind slowly annihilate, resulting in a low $\sigma$, thermally hot wind at large distances. Near the rotational poles, the toroidal magnetic field should be helically wound, because the flux originates in a single polar cap.
Some PWNe show very complicated structure, without a clear symmetry, perhaps due to various instabilities, nonuniformities of the ambient medium, etc.

Geometry of the magnetic field provides a clue for understanding the nature of these MHD flows.

Direct way to probe the magnetic field geometry: **Polarization measurements.**

**Polarization of synchrotron radiation:**

Linear; direction of electric vector perpendicular to magnetic field. Degree of polarization:

\[ q = \frac{\Gamma}{(\Gamma + 2/3)} \]

\[ \Gamma = 1 – 2.5 \rightarrow q = 60\% - 80\% \]
Polarization can be easily measured in radio, BUT:
• requires correction for (nonuniform) Faraday rotation
• radio is bright at larger distances from the pulsar
• strong contamination from the much brighter pulsar

Vela PWN:
pink: X-rays,
blue: radio (Dodson et al 2003)

Radio is brighter at larger distances due to synchrotron + adiabatic cooling of the anisotropic outflow
Vela PWN: X-rays vs. radio

X-ray contours follow the shape of the radio PWN:

Black dashes mark direction of polarization (i.e. perpendicular to magnetic field direction)
Crab: Radio
PWN polarization can be observed in **optical** but for very few objects.

HST/ACS observations of **Crab** (Hester et al 2004)

- Total intensity
- Polarized intensity

q up to 50%, strong depolarization at SW
**Crab**: Polarized intensity + directions of magnetic field (white lines)

Magnetic field is indeed mostly toroidal
Polarization in X-rays

Detected from Crab only; the latest observations with OSO 8 in 1976-77, 71 hours total @ 2.6 and 5.2 keV (Weisskopf et al 1976,1978).

Net result:

\[ q = 19.2 \pm 1.0\% \]
\[ \text{P.A.} = 156.4 \pm 1.4 \text{ deg} \] @ 2.6 keV

\[ q = 19.5 \pm 1.8\% \]
\[ \text{P.A.} = 152.6 \pm 4.0 \text{ deg} \] @ 5.2 keV

Generally consistent with radio/optical, given poor angular resolution (~0.5 deg) and nonuniformity of the magnetic field.
• X-ray polarization observations directly probe topology of magnetic field and are helpful in understanding PWN physics
• X-rays are more suitable than radio because Faraday rotation/depolarization is negligible
• X-rays are more suitable than optical because PWNe are relatively bright in X-rays (more PWNe can be studied)
• Energy resolution is not required, time resolution useful to separate pulsar’s contribution

BUT

• Observations with low angular resolution provide only average direction of magnetic field, not very useful for understanding fine structures

We need another Chandra, with a polarimeter