Pulsar Wind Nebulae:

A Multiwavelength Perspective

Patrick Slane (CfA)  Workshop on High Energy Galactic Physics  New York, NY 2010

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**PWNe and Their SNRs**

- **Pulsar Wind**
  - sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms

- **Supernova Remnant**
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN; energy distribution of particles in nebula tracks evolution; instabilities at PWN/ejecta interface may allow particle escape

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Gaensler & Slane 2006

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- IR emission is from freshly-formed ejecta dust heated by stars
  - Extended IR clump has enhanced temperature and density; possibly compressed by jet

Temim et al. 2010
Broadband Emission from PWNe

• Spin-down power is injected into the PWN at a time-dependent rate

\[ \dot{E} = I\Omega \dot{\Omega} = \dot{E}_0 \left( 1 + \frac{t}{\tau} \right)^{-n+1} \]

• Assume power law input spectrum:

\[ Q(t) = Q_0(t)(E_e / E_b)^{-\alpha} \]

- note that studies of Crab and other PWNe suggest that there may be multiple components

• Get associated synchrotron and IC emission from electron population evolved nebula

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- joint fitting of synchrotron and IC spectra give \( B \)
• PIC simulations of particle acceleration in relativistic shocks show build-up of energetic particles (Spitkovsky 2008)

• Multi-component input spectrum: Maxwellian + power law
  - and possibly more complex if conditions differ at different acceleration sites
Broadband Observations of 3C 58

- 3C 58 is a bright, young PWN
  - morphology similar to radio/x-ray; suggests low magnetic field
  - PWN and torus observed in Spitzer/IRAC

- Low-frequency break suggests possible break in injection spectrum
  - IR flux for entire nebula falls within the extrapolation of the X-ray spectrum
  - indicates single break just below IR

- Torus spectrum requires change in slope between IR and X-ray bands
  - challenges assumptions for single power law for injection spectrum
• XMM spectrum shows nonthermal and ejecta-rich thermal emission from cocoon
  - reverse-shock crushed PWN and mixed in ejecta?

• Broadband measurements consistent with synchrotron and I–C emission from PL
electron spectrum w/ two breaks, or two populations
Evolution in an SNR: Vela X

- XMM large project to map cocoon and much of remaining nebula underway
HESS J1640-465

- Extended source identified in HESS GPS
  - no known pulsar associated with source
  - may be associated with SNR G338.3-0.0

- XMM observations (Funk et al. 2007) identify extended X-ray PWN

- Chandra observations (Lemiere et al. 2009) reveal neutron star within extended nebula
  - $L_x \sim 10^{33.1} \text{ erg s}^{-1} \Rightarrow \dot{E} \sim 10^{36.7} \text{ erg s}^{-1}$
  - X-ray and TeV spectrum well-described by leptonic model with $B \sim 6 \mu\text{G}$ and $t \sim 15 \text{ kyr}$
  - example of late-phase of PWN evolution: X-ray faint, but $\gamma$-ray bright
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- Fermi LAT reveals emission associated with source

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• GeV emission can also be fit w/ pion model
  - requires $n_0 > 100 \text{ cm}^{-3}$, too large for G338.3–0.3
G327.1-1.1: More (Reverse) Shocking Results

- G327.1-1.1 is a composite SNR for which radio morphology suggests PWN/RS interaction

- Chandra observations show an offset compact source w/ trail of nonthermal emission extending back to radio PWN
  - compact source is extended and embedded in bowshock-structure
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And...
Probing Composite SNRs With Fermi

- Watch for studies of this and other such systems with Fermi
Summary

• Multiwavelength studies of PWNe reveal:
  - spin properties of central engines
  - geometry of systems
  - spatially-resolved spectra
  - interaction with supernova ejecta
  - presence of freshly-formed dust.

• These lead to constraints on:
  - particle acceleration in relativistic shocks
  - formation of jets
  - physics of pulsar magnetospheres
  - nature of progenitor stars
  - early and late-phase evolution of pulsar winds

• Current advances are being made across the electromagnetic spectrum, as well as in theoretical modeling, and point the way for investigations in virtually every wavelength band.