Using IXO to Probe
The Nature of Pulsar Winds
Key Science Points

• PWNe are unique laboratories for studying the life cycle of energy
  - Rotational energy is converted into high energy radiation and energetic particles, allowing us to study the properties of:
    - outflows and jets
    - termination shocks
    - acceleration efficiency
  - We know more about the underlying conditions (mass, spin, magnetic field strength and geometry) than for any other systems

• PWNe (and their absence) are signposts for young neutron stars
  - Their properties place constraints on initial spin and magnetic fields
  - What is the full census of PWNe in the Galaxy?

• The evolution of PWNe probes the progenitor structure and environment
  - Shocked ejecta reveals composition; Doppler-broadened lines provide expansion velocities that constrain densities and evolution
  - Nonthermal structure connects emission from radio to TeV bands
PWNe and Their SNRs

Pulsar Wind
- sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms
- ejecta spectrum constrains expansion velocity and progenitor type/structure

Supernova Remnant
- sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN; PWN/RS interaction mixes ejecta into relic PWN

Patrick Slane (CfA)  Exploring the Hot Universe with IXO (MPE/Garching)  18 Sept 2008
PWN Expansion w/ IXO: 3C 58

Measurements of PWN evolution and swept-up mass constrain initial spin and its evolution.

Energy input and swept-up ejecta mass.
PWN Expansion w/ IXO: 3C 58

- Chandra reveals complex structure of wind shock zone and surroundings

- Spectrum reveals ejecta shell with enhanced Ne and Mg
  - PWN expansion sweeps up and heats cold ejecta
PWN Expansion w/ IXO: 3C 58

Chandra reveals complex structure of wind shock zone and surroundings.

Spectrum reveals ejecta shell with enhanced Ne and Mg.

- PWN expansion sweeps up and heats cold ejecta.
Con-X baseline gives \( \sim 16000 \) counts in Ne line in a 100 ks observation.

- thus, we will get 100 counts from this line in a resolution element 12 arcsec on a side
- Measure velocity broadening to determine age based on size
  - connect with evolution to determine initial spin and spindown properties

- Maximum velocities in optical are 900 km s\(^{-1}\)
  - to detect broadening we need resolution of about 2.7 eV
• Vela X is the PWN produced by the Vela pulsar
  - located primarily south of pulsar
  - apparently the result of relic PWN being disturbed by asymmetric passage of the SNR reverse shock

• Elongated “cocoon-like” hard X-ray structure extends southward of pulsar
  - clearly identified by HESS as an extended VHE structure
  - this is not the pulsar jet (which is known to be directed to NW); presumably the result of reverse shock interaction
MM spectrum shows nonthermal and ejecta-rich thermal emission from cocoon reverse-shock crushed PWN and mixed in ejecta?

Radio, X-ray, and $\gamma$-ray measurements appear consistent with synchrotron and I-C emission from power law particle spectrum w/ two spectral breaks. Density derived from thermal emission 10x lower than needed for pion-production to provide observed $\gamma$-ray flux. Much larger X-ray coverage of Vela X is required to fully understand structure.

Patrick Slane (CfA)  
Exploring the Hot Universe with IXO (MPE/Garching) 
18 Sept 2008
Thermal properties of ejecta in/around Vela X constrain the PWN/RS interaction. Expect additional compression and heating as RS meets PWN.

IXO will easily determine plasma parameters (temperature, density, abundances, and ionization state) in short exposures (e.g. Ly\( \beta \) /Ly\( \alpha \) \( \Rightarrow \) kT, He\( \alpha \) [F]/[R] \( \Rightarrow \) n\(_e\)t). Line diagnostics will trace evolution of ejecta mixed into Vela X. Similar studies will be enabled for other (much fainter) known systems of this type.
Nearly half of the detected TeV sources are thought to be PWNe:
- no known pulsars associated with most sources
- X-ray observations reveal faint, extended nebulae for some
- large FOV and collecting area needed to identify counterparts

→ ideal for IXO in relatively short (~10-100 ks) exposures

Large TeV/X-ray size ratio suggests low magnetic field systems, perhaps post-RS PWNe:
- sensitive observations required to establish counterparts, and to produce X-ray flux and spectral maps
- magnetic field related to flux ratio
Impacts on IXO Design Requirements

- **High throughput and spectral resolution** will allow us to detect the thermal gas at very faint levels, even in the presence of synchrotron emission.

- Line ratios will give temperature; modeling leads to density.
  - constrain CSM \(\rightarrow\) progenitor properties

- Velocity broadening gives expansion velocity.

- **Issues:**
  - field of view – prominent sources are 5 arcmin or more in size (may not be a problem with mosaic pointings)
  - angular resolution – need to resolve small structure in PWNe
  - effective area – thermal emission is faint; require large areas
  - spectral resolution – need to detect velocities of < 1000 km s\(^{-1}\)