Complexities of a Mid-Life Crush:

A Study of the Pulsar Wind Nebula Vela X

Collaborators:
J. Blondin
C. Kolb
T. Temim
and many others…
Composite SNRs: Shock Structure

See, also, Kolb et al. 2017
Radio morphology suggests PWN interaction with SNR reverse shock.

Chandra observations show offset compact source w/ trail of nonthermal emission extending to radio PWN.

- Compact source shows extent and is embedded in bow shock structure
G327.1-1.1: SNR RS Interaction

- Radio morphology suggests PWN interaction with SNR reverse shock.
- Chandra observations show offset compact source w/ trail of nonthermal emission extending to radio PWN.
  - Compact source shows extent and is embedded in bow shock structure
Morphology Comparison

- Displacement of “relic” PWN ➔ orientation of density gradient
- Orientation of trail ➔ combination of gradient and pulsar motion direction
- Trail thickness ➔ pulsar’s spin-down luminosity
- ISM density gradient
- Pulsar velocity

References:
- Temim et al. 2015
• Semi-analytic model for radiative evolution of the PWN (Gelfand et al. 2009)
• Input parameters from observational constraints and HD model
  → $B = 11 \mu G$ and an electron energy break at 300 GeV
Age of Injected Particles at 17,000 yrs

\[ \tau_{\text{syn}} \approx 820 \frac{E_{e,100}^{-1} B_{10}^{-2}}{} \text{ yr} \]

\[ \Delta \Gamma = 0.5 \]

Photon index in the trail steepens from 1.76 to 2.28:

\[ \Delta \Gamma = 0.52 \pm 0.17 \]
• Nearby SNR evolving in density gradient
• Middle-aged pulsar with disrupted PWN (Vela X)
• Nearby SNR evolving in density gradient

• Middle-aged pulsar with disrupted PWN (Vela X)

• “Cocoon”-like structure extending southward from pulsar (Markwardt & Ögelman 1995)
Vela SNR and its PWN

- Nearby SNR evolving in density gradient
- Middle-aged pulsar with disrupted PWN (Vela X)
- "Cocoon"-like structure extending southward from pulsar (Markwardt & Ögelman 1995)
- Radio/X-ray/γ-ray emission suggests complex particle spectrum
- Possible breaks or particle escape
Vela SNR and its PWN

- Nearby SNR evolving in density gradient
- Middle-aged pulsar with disrupted PWN (Vela X)
- “Cocoon”-like structure extending southward from pulsar (Markwardt & Ögelman 1995)

- Radio/X-ray/γ-ray emission suggests complex particle spectrum
- Possible breaks or particle escape
  - Possibly more rapid diffusion from radio nebula than from cocoon
• XMM observations reveal filamentary structure along cocoon
  - both nonthermal emission and thermal emission from ejecta observed
Vela X: XMM Observations

- XMM observations reveal filamentary structure along cocoon
  - both nonthermal emission and thermal emission from ejecta observed
- TeV and GeV $\gamma$-rays seen from Vela X
  - emission centroids appear offset

Patrick Slane
Crushing Vela X
TeVPA 2017
Vela X: XMM Observations

• XMM observations reveal filamentary structure along cocoon
  - both nonthermal emission and thermal emission from ejecta observed

• TeV and GeV $\gamma$-rays seen from Vela X
  - emission centroids appear offset

• Spectra show ejecta component within Vela X has higher $kT$ along cocoon
XMM observations reveal filamentary structure along cocoon
- both nonthermal emission and thermal emission from ejecta observed

TeV and GeV $\gamma$-rays seen from Vela X
- emission centroids appear offset

Spectra show ejecta component within Vela X has higher kT along cocoon
- distribution of O VII and O VIII is consistent with this picture
• XMM observations reveal filamentary structure along cocoon
  - both nonthermal emission and thermal emission from ejecta observed

• TeV and GeV $\gamma$-rays seen from Vela X
  - emission centroids appear offset

• Spectra show ejecta component within Vela X has higher kT along cocoon
  - distribution of O VII and O VIII is consistent with this picture
**Vela X: XMM Observations**

- XMM observations reveal filamentary structure along cocoon
  - both nonthermal emission and thermal emission from ejecta observed

- TeV and GeV $\gamma$-rays seen from Vela X
  - emission centroids appear offset

- Spectra show ejecta component within Vela X has higher kT along cocoon
  - distribution of O VII and O VIII is consistent with this picture

- Power law index steepens with distance from pulsar, though slowly along cocoon
  - emission at Fermi peak somewhat harder
Solutions by Truelove & McKee (1999) show evolution of FS/RS radius for different values of explosion energy, ambient density, and ejecta mass/profile.

Explore parameter space to arrive at scenario for Vela SNR

\[ E_{51} = 1, \ M_{ej} = 8 \ M_\odot, \ n = 12 \]

\[ n_{0,SW} = 0.05 \ \text{cm}^{-3}, \ n_{0,NE} = 0.15 \ \text{cm}^{-3} \]

Note: actually, evidence of engulfed clouds suggests a higher mean density.
Evolution of SNR into density gradient with contrast of ~4 results in asymmetric crushing similar to that observed in Vela X.

- As RS sweeps over pulsar, a channel of ejecta-rich material is formed, similar in structure to cocoon.
- Rapid advection may explain hard spectrum in cocoon.
n_0^N = 1 \text{ cm}^{-3}

Pulsar:
- P = 89 ms
- \dot{E} = 10^{36.8} \text{ erg/s}
- \tau_c = 10^{4.05} \text{ yr}

n_0^S = 0.06 \text{ cm}^{-3}

Hydro simulations reproduce overall structure

“Cocoon” created by RS interaction
- RS sweeps ejecta into PWN, creating channel of mixed gas

PWN gas still fills much of nebula, but ejecta mixing occurs throughout
- consistent w/ observations, though fast diffusion may be required

3D modeling and study of broadband emission in progress
Hydro simulations reproduce overall structure

“Cocoon” created by RS interaction
- RS sweeps ejecta into PWN, creating channel of mixed gas

PWN gas still fills much of nebula, but ejecta mixing occurs throughout
- consistent w/ observations, though fast diffusion may be required

3D modeling and study of broadband emission in progress
• Hydro simulations reproduce overall structure

• “Cocoon” created by RS interaction
  - RS sweeps ejecta into PWN, creating channel of mixed gas
  - lower $\rho$ in cocoon $\Rightarrow$ higher $kT$

• PWN gas still fills much of nebula, but ejecta mixing occurs throughout
  - consistent w/ observations, though fast diffusion may be required

• 3D modeling and study of broadband emission in progress
Summary

- Multiwavelength studies of PWNe reveal unique information on the conversion of spin-down power into relativistic outflows, providing views of shocks and interactions with supernova ejecta.
  - Hydrodynamical simulations, constrained by observations, provide important tool for unfolding the evolution and properties of PWNe within SNRs.

- Vela SNR shows distinct signatures of evolution into a non-uniform CSM, resulting in disruption of its PWN by an asymmetric reverse shock.

- X-ray studies of Vela X reveal ejecta mixed into disrupted PWN.
  - Hard nonthermal X-rays observed along cocoon, and also near GeV peak.
  - Enhanced ejecta observed along cocoon.
  - HD modeling suggests cocoon may result from instabilities dragging ejecta into disrupted PWN.
  - Higher advection speed may reduce synchrotron losses in cocoon region.

- Ongoing efforts include 3D simulations with post-processed emission characteristics, applied to these and other evolving systems.
Inferring Pulsar Kicks

- Cross-hair indicates original pulsar position.
- Interpreting pulsar motion based on tail geometry and distance from apparent SNR center is misleading.