Observations of Pulsar Winds and Jets

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Outline

• Observed Structure of PWNe
• Properties of Pulsar Jets
• Broadband Emission from PWNe
• Evolution of PWNe in SNRs
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; particles accelerated at forward shock generate magnetic turbulence; other particles scatter off this and receive additional acceleration
• Poynting flux from outside pulsar light cylinder is concentrated in equatorial region due to wound-up B-field
  - termination shock radius decreases with increasing angle from equator (Lyubarsky 2002)

• For sufficiently high latitudes, particle flow is deflected back inward
  - collimation into jets may occur
  - asymmetric brightness profile from Doppler beaming

• Collimation is subject to kink instabilities
  - magnetic loops can be torn off near TS and expand into PWN (Begelman 1998)
  - many pulsar jets are kinked or unstable, supporting this picture

See talk by N. Bucciantini
Pulsar Jets – and Lots of Them

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  - the more we look the more we find, though evidence is weak for some
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  - many more show toroidal structures or extended tails (possibly also jets)

- Sizes vary from <0.1 pc (CTA 1) to >10 pc (PSR B1509-58)
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- Typical photon index \( \Gamma \approx 1.6 - 2 \)
  - generally, uncooled synchrotron spectrum (Vela jets appears even harder)

- Where known, outflow velocities are subsonic: \( v_{\text{flow}} \approx 0.1 - 0.5c \)
Curved Jets and Instabilities

- Jet in PSR 1509-58 is **curved**, like in Crab
  - variations in structure seen on timescale of several months ($v \sim 0.5c$)

- Jet in Vela is wildly unstable, showing variations on timescales of weeks to months
  - changes in morphology suggest kink or sausage instabilities (Pavlov et al. 2003)
• Bright wind nebula powered by PSR J1846-0258 ($dE/dt = 10^{36.9}$ erg/s)
  - jet-like structure defines rotation axis

• Deep Chandra observation reveals inner/outer jet features, clump in north, and abrupt jet termination in south
  - jet spectrum is harder than surrounding regions, ➔ high-velocity (uncooled) flow
  - clumps along jet axis vary in brightness over time
Broadband Emission from PWNe

- Spin-down power is injected into the PWN at a time-dependent rate
  \[ L(t) = L_0 \left[ 1 + \frac{(n-1)P_0^2L_0t}{4\pi^2I} \right]^{-\frac{n+1}{a-1}} \]

- Based on studies of the Crab Nebula, there appear to be two populations – relic radio-emitting electrons and electrons injected in wind (Atoyan & Aharonian 1996)
  \[ Q(\varepsilon_e, t) = \begin{cases} Q_0(t)(\varepsilon_e/E_b)^{-\alpha_1}, & \text{if } \varepsilon_e < E_b \\ Q_0(t)(\varepsilon_e/E_b)^{-\alpha_2}, & \text{if } \varepsilon_e \geq E_b \end{cases} \]

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• More completely, assume wind injected at termination shock, with radial particle distribution and latitude-dependent magnetic component
  - Evolve nebula considering radiative and adiabatic losses to obtain time- and spatially-dependent electron spectrum and B field (e.g. Volpi et al. 2008)

See talk by O.C. de Jager
A Point About Injection: 3C 58

- 3C 58 is a bright, young PWN
  - morphology similar to radio/x-ray; suggests low magnetic field
  - low-frequency spectral break suggests possible injection break

- PWN and torus region observed in Spitzer/IRAC and CFHT observations
  - jet structure not seen above diffuse emission

Slane et al. 2004
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PRELIMINARY

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• 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
Evolution in an SNR: Vela X

- XMM spectrum shows nonthermal and ejecta-rich thermal emission from cocoon
  - reverse-shock crushed PWN and mixed in ejecta?

- Radio, X-ray, and γ-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 γ-ray flux
  - much larger X-ray coverage of Vela X is required to fully understand structure

LaMassa et al. 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. Lyβ/Lyα → kT, Heα[F]/[R] → 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
• Radio and VHE spectrum for entire PWN suggests presence of two distinct electron populations
  - radio-emitting particles may be relic population, or a complicated injection spectrum...

• Maximum energy of radio-emitting electrons not well-constrained
  - this population will generate IC emission in GLAST band; spectral features will identify emissions from distinct up-scattered photon populations and constrain the underlying particle spectrum
Conclusions

• Recent X-ray observations show that jet/torus structures around pulsars are common
  - jet sizes and luminosities span a huge range; structure can be highly variable and unstable

• PWNe are reservoirs of energetic particles injected from pulsar
  - synchrotron and inverse-Compton emission places strong constraints on the underlying particle spectrum and magnetic field

• Modeling of broadband emission constrains evolution of particles and B field
  - modeling form of injection spectrum and full evolution of particles still in its infancy

• Reverse-shock interactions between SNR and PWNe distort nebula and may explain TeV sources offset from pulsars
  - multiwavelength observations needed to secure this scenario (e.g. Vela X)