New Views of Pulsar Winds in TeV Gamma-rays

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Pulsar Wind Nebulae

• All pulsars are slowing down
  
  \[ E = I \omega \dot{\omega} = 10^{32} - 10^{39} \text{ ergs s}^{-1} \]

• Where does this energy go?
  - usually negligible energy in pulses
  - relativistic magnetized particle wind

• Shock where wind terminates

  \[ \rightarrow \text{ pulsar wind nebula (PWN)} \]
  
  - direct calorimeter for energy loss processes
  
  - laboratory for studying relativistic shocks & interaction with surroundings (GRBs, AGN)

  - unambiguous signpost for young, energetic neutron stars

Crab Nebula (Hester et al. 2002)
Expansion into Unshocked Ejecta

- Assume continuous energy injection produces synchrotron nebula
- PWN expands supersonically into low-$P$ environment, $R_{\text{PWN}} \propto t^{6/5}$
- Sound speed high: PWN stays centered on pulsar

SNR G21.5-0.9 with PWN and pulsar (X-rays; Matheson & Safi-Harb 2005)

SNR G11.2-0.3 with PWN and pulsar (X-rays; Kaspi et al. 2001)
The Multi-Wavelength Crab Nebula

Radio (VLA; NRAO)
The Multi-Wavelength Crab Nebula

Optical (*HST*; NASA / ESA / J. Hester / A. Loll / ASU)
The Multi-Wavelength Crab Nebula

Soft X-rays (*Chandra*; Weisskopf et al. 2000)
The Multi-Wavelength Crab Nebula

TeV gamma-rays (HESS; Aharonian et al. 2006 / J. Braun)
Gamma-rays From Crab Nebula

- EGRET spectrum of Crab Nebula shows upturn at $E \sim 1$ GeV
  - modelled as synchrotron + synchrotron-self-Compton

Atoyan & Aharonian (1996)
Gamma-rays from Other PWNe

- Several pulsar wind nebulae now seen in TeV gamma-rays
  - inverse Compton emission from CMB, starlight, IR from dust

PWN G0.9+0.1 (HESS/VLA; Aharonian et al. 2005)

Broadband spectrum of G0.9+0.1 (Aharonian et al. 2005)
How Do Pulsars Accelerate Particles?

- Theory says unshocked wind has $\gamma \sim 10^6$
- X-ray & $\gamma$-ray synchrotron emission in PWNe
  - termination shock accelerates particles to $\gamma > 10^9$
- Data at $E > 100$ TeV needed to measure IC roll-off
  - knowing $\gamma_{\text{max}}$ as fn. of pulsar parameters constrains mechanism

Crab Nebula  
(Chandra; Weisskopf et al. 2000)

PWN around PSR B1509-58  
(INTEGRAL; Forot et al. 2006)

Spectrum of Crab Nebula  
(Atoyan & Aharonian 1996)
Inverse Compton in PWNe

- Synchrotron is convolution of $N(E)$, $B$
- IC depends on $N(E)$, photon field
- Spatial distribution of synch., IC
  - spatially resolved map of $B$
  - particle content, injection rate
  - $\sigma = E_{\text{fields}}/E_{\text{particles}}$
- Pulsed IC from unshocked wind?
  (Ball & Kirk 1999; Bogovalov & Aharonian 2000)
Nucleons in Pulsar Winds

- Ions in wind will produce macroscopic shock structure
  - generate magnetosonic waves which can accelerate $e^-$ (Hoshino et al. 1992)
  - may explain appearance and evolution of “wisps” in Crab Nebula & B1509-58
    (Gallant & Arons 1994; Spitkovsky & Arons 2004)

- Do we see $\pi^0$ decay from relativistic ions accelerated in PWNe?

Vela X (HESS; Aharonian et al. 2006)  
Vela X (Horns et al. 2006)
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Interaction with SNR Reverse Shock

- Reverse shock crushes PWN after time \( t \sim 7M_{10M_{\text{sun}}}^{5/6}E_{51}^{-1/2}n_0^{-1/3} \) kyr
- Compression & reverberation; synchrotron burn-off at high energies
- Asymmetric collision for moving pulsar or ISM gradient
- Pulsar now at one edge of “relic” radio PWN

van der Swaluw et al. (2004)  
SNR G327.1-1.1 (radio + X-rays; Gaensler & Slane 2006)
Offset Gamma-Ray PWNe

• HESS sees large TeV nebulae to one side of several energetic pulsars
  - energy dependence confirms IC mechanism
  - reverse shock interaction with SNR? (Gaensler et al. 2003; Aharonian et al. 2005)
  - TeV systems must have expanded rapidly, age ~ 10,000 - 40,000 years (e.g., de Jager & Venter 2005)

• Implies possible molecular cloud interactions?
  - confirmed by $^{12}$CO detections (Lemiére et al. 2006)

• Approx. 25 “Vela-like” pulsars known (Kramer et al. 2003)
  - expect large number of offset PWNe
    → particle transport, magnetic fields, diffusion, interaction with ISM/CSM
New Pulsar Wind Nebulae

- Extended TeV source HESS J1813-178
  - radio reveals very young SNR, G12.8-0.0
New Pulsar Wind Nebulae

- Extended TeV source HESS J1813-178
  - radio reveals very young SNR, G12.8-0.0
  - matches X-ray source AX J181336-1749
    (Brogan, Gaensler et al. 2005; Ubertini et al. 2005)
  - XMM images show central X-ray nebula
    (Funk et al. 2006)

- TeV source HESS J1640-465
  - matches X-ray source AX J164042-4632
  - matches catalogued SNR G338.3-0.0
    (Aharonian et al. 2006)

Red: VLA; Blue: HESS; Contours: ASCA (Brogan et al. 2005)

HESS J1640-465 (HESS; Aharonian et al. 2006)
Surveys & Discovery

- > 1000 missing supernova remnants in Galaxy
- Young pulsars without supernova remnants or pulsar wind nebulae
  - PWNe & SNRs invisible in synchrotron if $B$ is low
    ... but inverse Compton independent of $B$
- Many new PWNe & SNRs still to be found, especially for $|l| < 45^0$

35 new SNRs in 1st Galactic quadrant (Brogan et al. 2006)
7000 year old pulsar B1610-50 (Stappers et al. 1999)
Summary

- TeV data yield distribution, injection rate, evolutionary history of fields + particles in PWNe
- TeV data reveal later stages of PWN evolution, and probe interaction with ambient gas / photons
- TeV data can help complete Galactic sample of PWNe & SNRs