Supernova Remnants and Pulsar Wind Nebulae in the Fermi Era

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PWNe and 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
  - self-generated turbulence by streaming particles, along with magnetic field amplification, promote diffusive shock acceleration of electrons and ions to energies exceeding 10–100 TeV

Gaensler & Slane 2006
**Gamma-Ray Emission from SNRs**

- **Neutral pion decay**
  - Ions accelerated by shock collide with ambient protons, producing pions in process: \( \pi^0 \rightarrow \gamma \gamma \)
  - Flux proportional to ambient density; **SNR-cloud interactions particularly likely sites**

- **Inverse-Compton emission**
  - Energetic electrons upscatter ambient photons to \( \gamma \)-ray energies
  - CMB, plus local emission from dust and starlight, provide seed photons

- **Fermi observations**, in combination with multi-\( \lambda \) data, will help differentiate between the two different mechanisms

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Ellison et al. 2007
Gamma-Ray Emission from SNRs

Gamma-ray emission depends on (and thus constrains):

- SNR age (need time to accumulate particles)
- acceleration efficiency (can be extremely high)
- electron-proton ratio in injection
- magnetic field (evidence suggests large amplification)
- ambient density (large density increases $\pi^0$-decay emission)
- maximum energy limits (age, escape, radiative losses)
Young SNRs

- Young SNRs have fast shocks that clearly accelerate particles to high energies
  - X-ray observations reveal multi-TeV electrons, and dynamical measurements imply efficient acceleration of ions as well

- But...
  - young SNRs generally haven’t encountered high densities
  - maximum energies may be age-limited

- Thus, while very young SNRs should be γ-ray sources, they are not likely to be exceptionally bright

See talk by Stefan Funk
G347.3-0.5/RX J1713.7-3946

- X-ray observations reveal a nonthermal spectrum everywhere in G347.3-0.5
  - evidence for cosmic-ray acceleration
  - based on X-ray synchrotron emission, infer electron energies of >50 TeV

- SNR detected directly in TeV $\gamma$-rays
  - $\gamma$-ray morphology very similar to X-rays; suggests I-C emission
  - spectrum suggests $\pi^0$-decay, but lack of thermal X-rays is problematic

Acero et al. 2009
G347.3-0.5/RX J1713.7-3946

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• Spectrum in Fermi band very different for leptonic and hadronic scenarios
  - if the γ-rays are hadronic in origin, the emission in the Fermi LAT should be bright; weak or non-detection will favor a leptonic origin

See talk by Stefan Funk
SNRs in Dense Environments

- The expected $\pi^0 \rightarrow \gamma\gamma$ flux for an SNR is
  
  \[ F(> 100\text{MeV}) \approx 4.4 \times 10^{-7} \theta E_{51} d_{\text{kpc}}^{-2} n \text{ phot cm}^{-2} \text{ s}^{-1} \]

  where $\theta$ is a slow function of age (Drury et al. 1994)
  - this leads to fluxes near sensitivity limit of EGRET, but only for large $n$

- Efficient acceleration can result in higher values for I-C $\gamma$-rays
  - SNRs should be detectable with Fermi for sufficiently high density; favor SNRs in dense environments or highly efficient acceleration
  - expect good sensitivity to SNR-cloud interaction sites (e.g. W44, W28, IC 443)

1 yr sensitivity for high latitude point source
SNRs in Dense Environments

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See talk by Takaaki Tanaka
G349.7+0.2

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• HI absorption measurements indicate a distance of 22 kpc
  - one of the most luminous SNRs in the Galaxy
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- HI absorption measurements indicate a distance of 22 kpc
  - one of the most luminous SNRs in the Galaxy
- CO emission reveals nearby MC
  - OH masers at $v = 16 \text{ km s}^{-1}$ confirm SNR shock-cloud interactions

**X-ray spectrum is dominated by bright thermal emission** (Lazendic et al. 2005)
- consistent with interaction with high density surroundings
- high temperature suggestions fast shocks $\Rightarrow$ efficient particle acceleration
Fermi LAT detects emission associated with G349.7+0.2 (Castro et al. – in prep) - likely evidence of $\pi^0$-decay $\gamma$-rays from $p$-$p$ collisions in molecular cloud
Gamma-Ray Emission from PWNe

Gamma-ray emission depends on (and thus constrains):

- PWN age

- maximum particle energy (depends on properties of both pulsar and nebula)

- magnetic field (decreases with time, allowing high-E particles injected at late phases to persist; also introduces loss breaks)

- ambient photon field (synchrotron self-Compton can be important)

- breaks in injection spectrum
Broadband Emission from PWNe

- Get **synchrotron** and **IC emission** from electron population & evolved B field

- Spin–down power is injected into PWN at time–dependent rate
  - results in spectral break that propagate to lower energy with time

- Based on studies of Crab Nebula, there may be two distinct particle populations
  - relic radio–emitting electrons and those electrons injected in wind

- Fermi observations can provide constraints on maximum particle energies via synchrotron radiation, and on lower energy particles via IC emission
Connecting the Synchrotron and IC Emission

- Energetic electrons in PWNe produce both synchrotron and inverse-Compton emission
  - for electrons with energy $E_{\text{TeV}}$,
    \[
    \varepsilon_{\text{keV}}^{s} \approx 2 \times 10^{-4} E_{\text{TeV}}^2 B_{-5} \quad \text{synchrotron}
    \]
    \[
    \varepsilon_{\text{TeV}}^{\text{ic}} \approx 3 \times 10^{-3} E_{\text{TeV}}^2 \quad \text{inverse-Compton}
    \]
- Magnetic field strength links IC photons with synchrotron photons from same electrons
  \[
  \varepsilon_{\text{keV}}^{s} \approx 0.06 \varepsilon_{\text{TeV}}^{\text{ic}} B_{-5}
  \]
- For low $B$, $\gamma$-ray emission probes electrons with lower energies than those that produce X-rays
  - $\gamma$-ray studies fill crucial gap in broadband spectra of PWNe
Fermi Studies of 3C 58

- Low-frequency break suggests possible break in injection spectrum

- Torus spectrum requires change in slope between IR and X-ray bands
  - challenges assumptions for single power law for injection spectrum

- Fermi LAT band probes CMB IC emission from ~0.6 TeV electrons
  - this probes electrons from the unseen synchrotron region around $E_{\text{syn}} = 0.4$ eV where injection is particularly complex
• Vela X is the PWN produced by the Vela 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
• Broadband spectrum for PWN suggests two distinct electron populations and very low magnetic field (~5 μG)
  - radio-emitting population will generate IC emission in LAT band
  - spectral features may identify distinct photon population and determine cut-off energy for radio-emitting electrons

See Talk by Marianne Lemoine-Goumard
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

Patrick Slane (CfA)
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• Fermi LAT reveals extended emission associated with source (Castro et al. – in prep.)
  - flux appears consistent with PWN model predictions
Conclusions

• SNRs are efficient particle accelerators, leading to $\gamma$-ray emission from both hadronic and leptonic processes
  - the associated spectra strongly constrain fundamental parameters of particle acceleration processes; Fermi LAT observations will help differentiate between emission mechanisms

• SNRs interacting with dense clouds are particularly strong candidates for $\gamma$-ray emission
  - Fermi has already detected several, and more are being uncovered

• 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

• Fermi LAT has sensitivity and resolution to probe underlying electron spectrum in crucial energy regimes
  - observations of PWNe will complement multi-$\lambda$ studies to constrain the structure and evolution of PWNe
• Broadband spectrum for PWN suggests two distinct electron populations
  - radio-emitting population will generate IC emission in LAT band
  - spectral features will identify distinct photon population and determine cut-off energy for radio-emitting electrons

• XMM large project (400 ks) to study ejecta and nonthermal emission now underway; images reveal considerable structure and spectral variation
The Surrounding Ejecta: 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
- Mass and temperature of swept-up ejecta suggests an age of ~2400 yr and a Type IIp progenitor, similar to that for Crab (Chevalier 2005)
- Temperature appears lower than expected based on radio/optical data