High Energy Emission

from Supernova Remnants
SNRs: The (very) Basic Structure

- **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
Shocks in SNRs

- Expanding blast wave moves supersonically through CSM/ISM; creates shock
  - mass, momentum, and energy conservation across shock give (with $\gamma = 5/3$)

$$
\rho_1 = \frac{\gamma + 1}{\gamma - 1} \rho_0 = 4 \rho_0\\
V_1 = \frac{\gamma - 1}{\gamma + 1} V_0 = \frac{V_0}{4}\\
V_{ps} = \frac{3V_s}{4}
$$

- Shock velocity gives temperature of gas
  - can get from X-rays (modulo NEI effects)

- If cosmic-ray pressure is present the temperature will be lower than this
  - radius of forward shock affected as well

$$
T_1 = \frac{2(\gamma - 1) \mu}{(\gamma + 1)^2 k} m H v_0^2 = 1.3 \times 10^7 v_{1000}^2
$$

Patrick Slane (CfA)
TeV Unidentified Sources Workshop - PSU (4–5 June 2008)
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• Particles scatter from MHD waves in background plasma
  - pre-existing, or generated by streaming ions themselves
  - scattering mean-free-path

Maximum energies determined by either:

age – finite age of SNR (and thus of acceleration)

\[ E_{\text{max}}(\text{age}) \sim 0.5v^2_t B_{\mu G}(\eta R_J)^{-1} \text{TeV} \]

radiative losses (synchrotron)

\[ E_{\text{max}}(\text{loss}) \sim 100v^2_t (B_{\mu G}\eta R_J)^{-1/2} \text{TeV} \]

escape – scattering efficiency decreases w/ energy

\[ E_{\text{max}}(\text{escape}) \sim 20B_{\mu G}\lambda_{17} \text{TeV} \]

High B \Rightarrow High \ E_{\text{max}}

High B \Rightarrow Low \ E_{\text{max}} \text{ for } e^+^-

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\[ \lambda = \eta r_g = \eta E / eB \]

(i.e., most energetic particles have very large \( \lambda \) and escape)

\[ \eta = \left( \frac{\delta B}{B} \right)^{-2} \geq 1 \]

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Electrons:
- large \( B \) lowers max energy due to synch. losses

Ions:
- small \( B \) lowers max energy due to inability to confine energetic particles

Current observations suggest high \( B \) fields

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**γ-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 γ-ray energies
  - CMB, plus local emission from dust and starlight, provide seed photons

- **High B-field can flatten IC spectrum; low B-field can reduce \( E_{\text{max}} \) for \( \pi^0 \) spectrum**
  - Difficult to differentiate cases; GLAST observations crucial to combine with other λ's and dynamics
The expected $\pi^0 \rightarrow \gamma\gamma$ flux for an SNR is

$$F(> E_{\text{TeV}}) \approx 5 \times 10^{-11} \varepsilon E_{51} d_{\text{kpc}}^{-2} n E_{\text{TeV}}^{1-\alpha} \text{phot cm}^{-2} \text{s}^{-1}$$

where $\varepsilon$ is the efficiency, $\alpha$ is the spectral index of the particles, and $n$ is the ambient density (Drury et al. 1994)

- nearby SNRs should be strong TeV sources, particularly in regions of high density

Efficient acceleration can result in higher values for I-C $\gamma$-rays

- spectra in TeV band can constrain the emission mechanism
- high sensitivity needed for distant SNR

(Note that efficiency can be $>>0.1$)
Broadband Emission from SNRs

- **synchrotron** emission dominates spectrum from radio to x-rays
  - shock acceleration of electrons (and protons) to $> 10^{13}$ eV
  - $E_{\text{max}}$ set by age or energy losses
  - observed as spectral turnover

- **inverse-Compton** scattering probes same electron population; need self-consistent model w/ synchrotron

- **pion production** depends on density
  - GLAST/TeV observations required
• Elongated hard X-ray structure extends southward of pulsar
  - clearly identified by HESS
  - this is not the pulsar jet (which is known to be directed to NW)
  - presumably relic nebula that has been disturbed by (asymmetric) passage of reverse shock

• Similar extended structures seen offset from field pulsars
  - deep TeV studies needed
# VHE Emission from SNRs

<table>
<thead>
<tr>
<th>Name</th>
<th>Flux(_{\text{TeV}}) (cm(^{-2}\text{s}^{-1}\text{TeV}^{-1}))</th>
<th>(\Gamma)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J1713.7-3946</td>
<td>2.0 \times 10^{-11}</td>
<td>2.32 +/- 0.01</td>
<td>G347.3.-0.5; nonthermal X-rays</td>
</tr>
<tr>
<td>RX J0852.0-4622</td>
<td>1.9 \times 10^{-11}</td>
<td>2.2 +/- 0.3</td>
<td>Vela Jr.; nonthermal X-rays</td>
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<tr>
<td>Cas A</td>
<td>1 \times 10^{-12}</td>
<td>2.4 +/- 0.2</td>
<td>Nonthermal X-ray filaments</td>
</tr>
<tr>
<td>IC443</td>
<td>5.8 \times 10^{-13}</td>
<td>3.1 +/- 0.3</td>
<td>PWN? SNR? MC interaction?</td>
</tr>
<tr>
<td>RCW 86</td>
<td>2.7 \times 10^{-12}</td>
<td>2.5 +/- 0.1</td>
<td>Nonthermal X-rays</td>
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<tr>
<td>W28</td>
<td>7.5 \times 10^{-13}</td>
<td>~2.6</td>
<td>MC interactions; masers</td>
</tr>
<tr>
<td>CTB 37A</td>
<td>8.7 \times 10^{-13}</td>
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<td>CTB 37B</td>
<td>6.5 \times 10^{-13}</td>
<td>2.65 +/- 0.19</td>
<td></td>
</tr>
<tr>
<td>HESS J1834-087</td>
<td>3.7 \times 10^{-12}</td>
<td>2.5 +/- 0.2</td>
<td>SNR W41?</td>
</tr>
<tr>
<td>HESS J1804-216</td>
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<td>2.7</td>
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IC443: What is the Source of Emission?

- SNR age is \(~30\) kyr; large diameter suggests modest shock speeds
  - probably not highly efficient accelerator at present, so leptonic emission may be weak

- A molecular cloud lies at the edge of the remnant
  - enhanced density provides significant target material for \(\gamma\)-rays from \(\pi^0\) decay

Albert et al. 2007
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• SNR contains PWN which could be a source of TeV emission
  - PWN is outside of \(\gamma\)-ray error circle, and X-ray tail points away from \(\gamma\)-ray source, so not likely candidate
\(\gamma\)-rays from 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 \(\sim 50\) TeV

- This SNR is detected directly in TeV gamma-rays, by HESS
  - \(\gamma\)-ray morphology very similar to x-rays; suggests I-C emission
  - spectrum seems to suggest \(\pi^0\)-decay

**WHAT IS EMISSION MECHANISM?**

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Modeling the Emission

- Joint analysis of radio, X-ray, and γ-ray data allow us to investigate the broad band spectrum.
  - Data can be accommodated by synch. emission in radio/X-ray and pion decay (with some IC) in γ-ray.
  - However, two-zone model for electrons fits γ-rays as well, without pion-decay component.

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  - But, implied densities appear in conflict with thermal X-ray upper limits.

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or a Northern IceCube...
Aside: Evidence for CR Ion Acceleration

- Efficient particle acceleration in SNRs affects dynamics of shock
  - for given age, FS is closer to CD and RS with efficient CR production

- This is observed in Tycho’s SNR
  - “direct” evidence of CR ion acceleration
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Thin Filaments: B Amplification?

- Thin nonthermal X-ray filaments are now observed in many SNRs, including SN 1006, Cas A, Kepler, Tycho, RX J1713, and others
  - observed drop in synchrotron emissivity is too rapid to be the result of adiabatic expansion

- Vink & Laming (2003) and others argue that this suggests large radiative losses in a strong magnetic field

\[ B \sim 200v_8^{2/3}\left(\frac{l}{0.01pc}\right)^{-2/3} \mu G \]

- Diffusion length upstream appears to be very small as well (Bamba et al. 2003)
  - we don’t see a “halo” of synchrotron emission in the upstream region

\[ l_D \sim \sqrt{kt_{syn}} \propto B^{-3/2} \]

- Alternatively, Pohl et al (2005) argue that field itself confined to small filaments due to small damping scale
Rapid Time Variability: B Amplification?

- Along NW rim of G347.3-0.5, brightness variations observed on timescales of ~1 yr.
  - if interpreted as synchrotron-loss or acceleration timescales, B is huge: B ~ 1 mG

\[ t_{\text{syn}} \sim 1.5 B_{\text{mG}}^{-3/2} \epsilon_{\text{keV}}^{-1/2} \text{yr} \]

\[ t_{\text{acc}} \sim 9 B_{\text{mG}}^{-3/2} \epsilon_{\text{keV}}^{1/2} v_{1000}^{-2} \text{yr} \]

- This, along with earlier measurements of the nonthermal spectrum in Cas A, may support the notion of magnetic field amplification \( \Rightarrow \) potential high energies for ions.

- Notion still in question; there are other ways of getting such variations (e.g. motion across compact magnetic filaments); more investigation needed.
Time Variations in Cas A

- Cas A is expanding rapidly

- Significant brightness variations are seen on timescales of years
  - ejecta knots seen lighting up as reverse shock crosses

- Variability seen in high energy continuum as well
  - similar to results from RX J1713.7-3946

- Uchiyma & Aharonian (2008) identify variations along region of inner shell, suggesting particle accelerations at reverse shock
  - many more observations needed to understand this!
Summary

• SNRs are efficient accelerators of cosmic ray electrons and ions
  - X-ray spectra reveal multi-TeV electrons
  - X-ray dynamics indicated strong hadronic component

• Several lines of argument lead to conclusion that the magnetic field is amplified to large values in shock
  - thin filaments
  - rapid variability
  => this could allow acceleration of hadrons to ~knee

• Other explanations for above exist, without large B
  - further study needed
  - GeV/TeV studies will help resolve question of hadron acceleration
  - neutrino observations will weigh in on this as well