Multi-waveband study of Supernova remnants (SNRs)

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Randoll Smith (CFA)

9th EAMA@ NCU, Taiwan Oct. 14-18, 2013
Discovery of SNRs in China

SNR G108.2-0.6 (Tian et al. 2007)

SNR G353.6-0.7/HESS J1731-347 (Tian et al. 2008)
SNRs: What?

Progenitor of an SNR has mass in $8-25 \, M_\odot$: SNR G21.5-0.9 / PSR J1833-1034

**Evolution Phase**
- I
- II
- III

<table>
<thead>
<tr>
<th>Phase</th>
<th>Mass swept up ($M_\odot$)</th>
<th>Velocity (km/s)</th>
<th>Radius (pc)</th>
<th>Time (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$&lt;5$</td>
<td>$&lt;10,000$</td>
<td>$&lt;1$</td>
<td>$&lt;2,000$</td>
</tr>
<tr>
<td>II</td>
<td>tens</td>
<td>$~200$</td>
<td>$~10$</td>
<td>$~40,000$</td>
</tr>
<tr>
<td>III</td>
<td>$\sim 1000$</td>
<td>$\sim 20$</td>
<td>$\sim 30$</td>
<td>$\sim 100,000$</td>
</tr>
</tbody>
</table>

Phase IV represents disappearance of remnant.
# SNR classification

<table>
<thead>
<tr>
<th>type</th>
<th>Radio</th>
<th>X-ray</th>
<th>SN</th>
<th>SNR evolution phase</th>
<th>Observed fraction</th>
<th>examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>shell</td>
<td>$\alpha \sim -0.5$</td>
<td>Most thermal</td>
<td>Ia</td>
<td>Free expansion/Sedov</td>
<td>~90%</td>
<td>Tycho</td>
</tr>
<tr>
<td>plerions</td>
<td>$\alpha \sim -0.2\ldots -0.1$</td>
<td>Non-thermal</td>
<td>Ib/c, II</td>
<td></td>
<td>&lt;10%</td>
<td>Crab</td>
</tr>
<tr>
<td>hybrid</td>
<td>Multi-component</td>
<td>Non-thermal</td>
<td>Ib/c, II</td>
<td></td>
<td>&lt;10%</td>
<td>Vela</td>
</tr>
</tbody>
</table>

![Tycho](image1.png)  ![Crab](image2.png)  ![Vela](image3.png)
SNR deficiency

• Observations
  – PSR: 2213 (ATNF 2013)
  – SN: 726 (Li et al. 2011)
    274 Ia, 116 Ibc, 324 SNe II
  – SNR: 274 Galactic (Green 2009)

• Prediction
  • Faint
  • limit of coverage

~1000 SNR distribution (Li et al. 1991)

Selection effect function (Li et al. 1991)
Five-hundred-meter aperture spherical *radio telescope* (FAST)

1. How SNRs affect their environment and how the environment affect SNRs’ evolution
2. How the magnetic fields of SNRs change their shapes with time?
3. Are SNRs responsible for the origination of Galactic cosmic rays

(Nan et al. 2009)
SKA Pathfinders

Where are they?

- Low-Frequency Array (LOFAR)
  - Netherlands (core), Europe (outstations), 2012
- 21-Centimetre Array (21-CMA)
  - Xinjiang region, China, 2006
- Murchison Widefield Array (MWA)
  - Western Australia, 2012
- Square Kilometre Array - Low frequency (SKA)
  - Western Australia, 2020

How big are they?

- The larger the number of antennas, the fainter the objects that can be seen
  - PAPER 64
  - LWA II 256
  - MWA 2048
  - 21-CMA 10,000
  - LOFAR 20,000
  - SKA ~1 million
- The longer the maximum baseline*, the smaller the objects that can be resolved
  - LWA 110m
  - PAPER 1km
  - MWA 3km
  - 21-CMA 3km
  - LOFAR 100km (1000km with outstations)
  - SKA 200km

* the longest distance on the ground covered by antennas

broad frequency coverage (70MHz -- 25 GHz)

(Peter et al. 2009)

Progenitor of SN Ia (Poster 24—Wang et al.)

• Core collapses SNe

1. How do the massive progenitor stars of core collapse SNe evolve in the thousands of years prior to their explosion?
2. What are the physical processes of the absorbing medium of the early radio emission?
3. Do these SNe simply transition smoothly into SNRs or is there a fading as they overrun their CSM and later re-brightening as the blast wave begins to encounter the ISM

• Type Ia SNe

White dwarf + (from MS to RG) VS Double white dwarf

*High sensitivity radio observation can help to answer these questions!*
SNR G353.6-0.7: hard X-ray

Suzaku : 33ks
XMM-Newton : 25 ks
Chandra : 30 ks
Non-thermal shell (power law with $SI \sim -2.2$) in radio, X-rays, Gamma-rays

A compact source (XMMS J173203-344518) within the SNR: AXP

XMM-Newton, Tian et al. 2010
Chandra, Halpern & Gotthelf 2009

Acero et al., 38th COSPAR, 2010
SNR W51C: Chandra ACIS image (0.5-8keV)

Fermi LAT counts map in 2–10 GeV around SNR W51C

Addo et al. 2009

<table>
<thead>
<tr>
<th>Sequence Number</th>
<th>Date</th>
<th>Instrument</th>
<th>Field Center $(\alpha_{2000.0}, \delta_{2000.0})$</th>
<th>Exposure (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500318</td>
<td>2003 Jun 3</td>
<td>ACIS-I</td>
<td>(19 22 28.0, 14 05 00)</td>
<td>29.9</td>
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<tr>
<td>500319</td>
<td>2002 Dec 8</td>
<td>ACIS-I</td>
<td>(19 23 00.0, 14 15 00)</td>
<td>11.76</td>
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<tr>
<td>500320</td>
<td>2002 Dec 8</td>
<td>ACIS-I</td>
<td>(19 23 30.0, 14 05 00)</td>
<td>12.12</td>
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</table>

(Koo et al 2005)
XMM-Newton Observations W51C

<table>
<thead>
<tr>
<th>Obs.ID</th>
<th>EPIC</th>
<th>RGS</th>
<th>Target</th>
<th>RA</th>
<th>Dec</th>
<th>Start Date</th>
<th>End Date</th>
<th>Dur.</th>
<th>Target Type</th>
<th>PI name</th>
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<tbody>
<tr>
<td>0554690501</td>
<td>N/A</td>
<td>N/A</td>
<td>W51C center</td>
<td>19h 23m 31.84s</td>
<td>+14d 07' 19.70''</td>
<td>2009-04-08 10:58:21</td>
<td>2009-04-08 12:23:49</td>
<td>5128</td>
<td>SNR FILLED-CENTER TYPE II</td>
<td>Lee, Jae-Joon</td>
</tr>
</tbody>
</table>
Spectra SNR W51C and new source

<table>
<thead>
<tr>
<th>source</th>
<th>model</th>
<th>$N_H$ $(10^{22} cm^{-2})$</th>
<th>$kT$ (keV)</th>
<th>$[Mg]/[Mg]_c$</th>
<th>$[Si]/[Si]_c$</th>
<th>$[Ni]/[Ni]_c$</th>
<th>re-$\chi^2$</th>
<th>snr</th>
<th>pholindex</th>
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</thead>
<tbody>
<tr>
<td>SNR inner left</td>
<td>wabs*vequil</td>
<td>1.28±0.03</td>
<td>0.57±0.02</td>
<td>1.90±0.18</td>
<td>1.00</td>
<td>1.00</td>
<td>1.852</td>
<td>4.0</td>
<td>-</td>
</tr>
<tr>
<td>SNR inner right</td>
<td>wabs*vequil</td>
<td>1.48±0.03</td>
<td>0.57±0.01</td>
<td>1.75±0.12</td>
<td>1.63±0.11</td>
<td>4.54±0.90</td>
<td>1.813</td>
<td>4.0</td>
<td>-</td>
</tr>
<tr>
<td>SNR inner whole</td>
<td>wabs*vequil</td>
<td>1.41±2.74</td>
<td>0.57±0.01</td>
<td>1.72±0.10</td>
<td>1.41±9.52</td>
<td>3.06±0.72</td>
<td>2.031</td>
<td>4.0</td>
<td>-</td>
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<tr>
<td>SNR outer whole</td>
<td>wabs*vequil</td>
<td>1.53±0.14</td>
<td>0.90±0.07</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.042</td>
<td>2.0</td>
<td>-</td>
</tr>
<tr>
<td>CXO¹</td>
<td>wabs*(vequil+PL)</td>
<td>1.48±0.03</td>
<td>0.57±0.01</td>
<td>1.75±0.12</td>
<td>1.63±0.11</td>
<td>4.54±0.90</td>
<td>1.005</td>
<td>4.0</td>
<td>1.70±0.16</td>
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<tr>
<td>New source</td>
<td>wabs*PL</td>
<td>0.94±0.27</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.911</td>
<td>3.0</td>
<td>2.09±0.35</td>
</tr>
</tbody>
</table>
SNR RCW 103

6.67-hour periodicity
(De Luca et al. 2006)
Chandra 2009 observations

- Reduced statistic = 23.7101
- Change in statistic = 8.46608e+06
- abs1.nH = 0.516173
- a1.kT = 0.589954
- a1.norm = 0.102177

- Reduced statistic = 2.56824
- Change in statistic = 1.12116e+08
- abs1.nH = 0.835967
- a1.kT = 0.286364
- a1.norm = 0.0972665

Reduced statistic = 2.00874
Change in statistic = 3.22511e+08
abs1.nH = 1.05606
a1.kT = 0.297875
a1.norm = 0.0273112
VHE γ-ray observations: a key for CRs origin

γ-rays (its trajectories are unaffected by interstellar and Galactic magnetic fields) are an excellent tracer of CR accelerators.

Accelerated CRs produce γ-rays after interaction with interstellar material.

The key issue in SNR case:
identification of γ-ray emission mechanisms:

\[ \pi^0: \text{hadronic origin of } \gamma \text{-ray} \]
\[ \text{CRs + gas } \rightarrow \text{ pp } \rightarrow \pi^0 \rightarrow 2\gamma \]

\[ \text{IC: leptonic origin of } \gamma \text{-rays} \]
\[ e\gamma \rightarrow e\gamma \]
High-energy Gamma rays

- Counterpart of accelerated electrons (inverse Compton scattering, Bremsstrahlung)

- Is there a counterpart of accelerated hadrons? Few evidences with current data
Survey of the Gamma Sky

2 possible techniques

<table>
<thead>
<tr>
<th>Cerenkov imaging of gamma-ray showers (IACT)</th>
<th>Detection at ground of gamma-ray showers</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Cerenkov imaging" /></td>
<td><img src="image2.png" alt="Detection at ground" /></td>
</tr>
</tbody>
</table>

Ex: HESS, MAGIC, VERITAS then CTA

- High sensitivity ($\gamma$-hadron separation)
- Good spatial resolution
  
  **BUT**

- Low duty cycle
- Limited field of view

Ex: ARGO, MILAGRO, Tibet-ASY, HAWC

- 100% duty cycle
- Large field of View
  
  **BUT**

Lower rejection power

LHAASO: Detection at ground of gamma-ray showers optimizing the rejection power with large collection surface and multi-parameter measures

Olivier Deligny (Rencontres de Moriond 2013)
Tibet ASy Experiment

Tibet China (90.522°E, 30.102°N) 4300 m a.s.l., since 1989

Number of Scinti. Det. 0.5 m² x 789

Angular Resolution for gamma rays
~0.9 deg.@3 TeV
~0.5 deg.@10 TeV
~0.2 deg.@100 TeV

Energy Resolution for gamma rays
~100% @3 TeV
~60% @10 TeV
~40% @100 TeV

F.O.V. ~2 sr

Effective Area for AS ~37,000 m²
The Large High Altitude Air Shower Observatory (LHAASO)

30TeV-10PeV (Cao et al. 2009)

Fig. 1: Layout of the LHAASO array

Fig. 2: The sensitivity of the major experiments and future projects for gamma ray astronomy
TeV gamma-ray from the interaction between old SNR and MC

W41/HESS J1834-087 (Tian et al. 2007a)

SNR G18.3+0.3 (Tian et al. 2007b)
Testing SNR-MC interaction

- **Tycho 1572**: a naked TeV Ia SNR
  (Tian & Leahy, 2011)
  no interaction between Tycho shock and CO cloud

- **W51C (TeV)**: not associated with HI
  Tian & Leahy, 2013
### Galactic γ-Ray SNRs: 122 (Tian & Zhang 2013)

### Asy candidate sources: 18

<table>
<thead>
<tr>
<th>SNR ID</th>
<th>Name (Gamma-ray)</th>
<th>Type</th>
<th>Age (kry)</th>
<th>Distance (kpc)</th>
<th>Radio size</th>
<th>Gamma-Flux (Crab Units)</th>
<th>SNR/MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>G23.3-0.3(W41)</td>
<td>HESS J1834-087(GT)</td>
<td>S? PWN?</td>
<td>100(S)</td>
<td>3.9-4.5(S)</td>
<td>27'</td>
<td>0.08(0.2TeV)(H,MA,F)</td>
<td>Y?</td>
</tr>
<tr>
<td>G25.5+0.0</td>
<td>HESS J1837-006(T)</td>
<td>PWN?</td>
<td></td>
<td></td>
<td></td>
<td>0.132(0.2TeV)(H)</td>
<td></td>
</tr>
<tr>
<td>G40.3-0.5</td>
<td>HESS J1908-063, MGRO 1908-06(GT)</td>
<td>S</td>
<td>20(P)</td>
<td>3.2(P)</td>
<td>22'</td>
<td>0.17(1TeV)(H,V,MI,A,F)</td>
<td>Y?</td>
</tr>
<tr>
<td>G65.1+0.6</td>
<td>0FGL J1954.4+2838(GT)</td>
<td>S</td>
<td>4-14</td>
<td>9.2(S)</td>
<td>50'-90'</td>
<td>0.23(35TeV)(MI,L,F)</td>
<td></td>
</tr>
<tr>
<td>G75.2+0.1</td>
<td>MGRO J2019+37(T)</td>
<td>PWN?</td>
<td>≥10(S), 4(P)</td>
<td></td>
<td></td>
<td>0.67(35TeV)(MI)</td>
<td></td>
</tr>
<tr>
<td>G78.2+2.1</td>
<td>VER J2019+407(GT)</td>
<td>S</td>
<td>6.6(S)</td>
<td>1.5(S)</td>
<td>60'</td>
<td>?(V,F)</td>
<td>Y?</td>
</tr>
<tr>
<td>G184.6-5.8</td>
<td>Crab(GT)</td>
<td>C? PWN</td>
<td>0.958</td>
<td>1.5-2.5(S), 2(P)</td>
<td>5'-7'</td>
<td>1(H,V,MA,MI,A,F)</td>
<td>N</td>
</tr>
<tr>
<td>G189.1+3.0</td>
<td>MAGIC J0616+225(GT)</td>
<td>C</td>
<td>30(S,P)</td>
<td>0.7 - 2(S)</td>
<td>45'</td>
<td>0.03(V,MA,MI,F)</td>
<td>Y</td>
</tr>
<tr>
<td>G195.1+4.3</td>
<td>Geminga(GT)</td>
<td>C? PWN</td>
<td>0.25(P)</td>
<td></td>
<td></td>
<td>0.23(35TeV)(MI,F)</td>
<td></td>
</tr>
<tr>
<td>G26.8-0.2</td>
<td>HESS J1841-055(T)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.37(0.54-80TeV)(H)</td>
<td></td>
</tr>
<tr>
<td>G29.3+0.51</td>
<td>HESS J1843-033(T)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>?(H)</td>
<td></td>
</tr>
<tr>
<td>G34.7-0.4</td>
<td>2FGL J1855.9+0121e(G)</td>
<td>C PWN</td>
<td>≥10(S), 30(P)</td>
<td></td>
<td>27-35'</td>
<td>0.43(0)</td>
<td>Y</td>
</tr>
<tr>
<td>G44.39-.07</td>
<td>HESS J1912-101(T)</td>
<td>PWN?</td>
<td></td>
<td></td>
<td></td>
<td>0.09 (1.10TeV)(H)</td>
<td></td>
</tr>
<tr>
<td>G65.85-0.23</td>
<td>0FGL J1958.1+2848</td>
<td>PWN</td>
<td></td>
<td></td>
<td></td>
<td>0.21(Mi)</td>
<td></td>
</tr>
<tr>
<td>G79.72+1.26</td>
<td>MGRO J2031+41(T)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.39(35TeV)(MI,F,A)</td>
<td></td>
</tr>
<tr>
<td>G80.25+1.07</td>
<td>TeV J2032+4130(T)</td>
<td></td>
<td></td>
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<td>0.03(35TeV)(HE,W,ML,A)</td>
<td></td>
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<tr>
<td>G201.3+0.51</td>
<td>0FGL J0631.8-1034</td>
<td>PWN</td>
<td></td>
<td></td>
<td></td>
<td>0.29(Mi)</td>
<td></td>
</tr>
</tbody>
</table>
Multi-wavebands study

Castro et al. 2013

From left to right and upper to bottom: 2.12um, 4.5um, 8um, 12um, 22um, 100um, 1.1mm, 2.6mm, 1-9KeV, 6-30GeV, 21cm CTA 46

- Multi-wavebands observation will help us to understand the SNRs and the origin of CR.