Suzaku Observation of the Supernova Remnant W51C

Submitted to PASJ

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Cosmic-Ray Acceleration in SNRs

**SNRs accelerate cosmic rays!**

- Detection of TeV gamma-ray emission (e.g., RX J1713.7-3946; Aharonian+04)
- GeV gamma rays from the SNRs interacting with molecular clouds naturally explained by CR origin (e.g., W51C; Abdo+09, W44; Abdo+10).
SED of Nonthermal Emission

- X-rays
- GeV γ-rays
- TeV γ-rays

Energy $E^2 \frac{dF}{dE}$ vs. Energy

- Synchrotron
- Brems
- $\pi^0$
- IC
Example: SNR W44

AGILE: Giuliani+11
- Interacting w/ molecular clouds
- Age: ~2x10^4 yr

\( \pi^0 \)-decay dominated

Bremsstrahlung and IC scenarios cannot represent the observed spectrum.
Cosmic-Ray Acceleration in SNRs

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But, evolution of CR acceleration after the Sedov phase is unclear.

Theoretical expectation

- Acceleration ends at the early Sedov phase by decreasing the turbulence of magnetic field arising from CR streaming instability as the shock velocity decreases (e.g., Volk+88).
- Moderate acceleration lasts after the Sedov phase and TeV particles are accelerated (Sturner+98, Nakamura+12).

Detailed investigation of middle-aged SNRs are needed.
Strategy in X-rays (I)

★Synchrotron X-ray emission from high energy electrons

Cooling time of TeV electrons is short.

\[ t_{\text{syn}}(E) = 1250 \text{ yr} (E/100 \text{ TeV})^{-1} (B_d/10 \text{ } \mu \text{G})^{-2} \]

Can easily obtain the information of acceleration site than protons.

*Protons: Cooling time is much longer unless the density of ambient matter is extremely high.

\[ t_{pp} \sim 6 \times 10^7 (1 \text{ cm}^{-3} / n_H) \text{ yr} \]

Observation of hard X-ray band is required to avoid the contamination of thermal emission from SNR plasma.
Strategy in X-rays (II)

★ Plasma diagnosis
Over-ionized plasma is possibly formed by ionization of suprathermal particles (Kato+92). → Gamma-ray emitting SNRs are good target.

**Particle distribution**

<table>
<thead>
<tr>
<th>Thermal</th>
<th>Suprathermal</th>
<th>Nonthermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log(Particle Flux)</td>
<td>~1 keV</td>
<td>~1 MeV</td>
</tr>
</tbody>
</table>

Log(Energy)

It is necessary to study the soft X-ray spectrum obtained by the detector with superior energy resolution.
SNR W51C

Located in the W51 complex including star-forming regions W51A & W51B.

**SNR W51C**
- **Age:** $\sim 3.0 \times 10^4$ yr (Koo+95)
- **Distance:** $\sim 6$ kpc
- **Interacting with the molecular clouds of W51B** (Koo+97a).
- **Gamma-ray emissions** has been detected around the shocked region.

X-rays are dim due to the absorption of MC.

Even though ROSAT, ASCA, Chandra etc. observed so far, the statistic of the spectra are not sufficient.
Hard X-rays around W51C

ASCA 2.5-6.0 keV
Contours (VLA 1.4GHz)

○: HII regions
○: PWN candidates

Hard X-ray emission has been detected around the MC of W51B (ASCA; Koo+02, Chandra; Koo+05). But the origin is unclear because the detailed analysis was not performed.

We observed Suzaku/XIS with superior energy resolution and large effective area even in hard X-ray band.

44 ks × 2 point (red square), Observation period: 2010/03/28-03/30
Suzaku/XIS Image

Vignetting corrected

**Cal source**
0.5-2.5 keV

**3.5-8.0 keV**

Black: Analysis regions
Green: Cal source, HII regions
Src A, Src B: PWN candidates

Contours
Black: 12CO(J=2-1) 60-70km/s 10,20,40%
Red: shocked HI 85-144km/s 40,80%
Plasma Property of W51C

Reg 1

Reg 2

✓ No significant feature of over-ionized plasma.
✓ Under-ionized plasma \((n_e \tau \sim 2 \times 10^{11} \text{ cm}^{-3} \text{ s})\) with a temperature of 0.7 keV.
✓ The abundance of Mg is significantly larger than one solar whereas those of Si and S is smaller than the solar values → Implying Mg rich ISM.

*Gaussian* component to compensate the lack of Fe-L \((n>5)\) lines in SPEX code
*Background was estimated by scaling the emission of nearby blank sky.
Can be represented by thermal or non-thermal emission model.

**Thermal:** Temperature $\sim 5$ keV

**Non-thermal:** Index $\sim 2.2$

Column density: $\sim 1 \times 10^{22}$ cm$^{-2}$ $< $ Throughout the Galaxy ($\sim 3 \times 10^{22}$ cm$^{-2}$)

Luminosity $L_x(0.5-10$ keV$): \sim 1 \times 10^{34}$ erg/s $>>$ Sum of point sources

$L_x \sim 1 \times 10^{33}$ erg/s

Suggesting the Galactic source with diffuse nature
Discussion

1. Contribution of Suprathermal Electrons to Ionization of Thermal Plasma

2. The Origin of Hard X-ray Emission
   - Stellar winds from OB stars in star-forming region W51B
   - Supernova remnant W51C
Ionization Due to Suprathermal Electrons

No significant feature of over-ionized plasma is detected.

Elapsed time of ionization of suprathermal electrons (~10 keV) is shorter than the characteristic time?

\[
\text{Characteristic timescale of ionization by suprathermals } < \sigma v >^{-1}
\]

Assuming the electron energy is 10 keV, the timescale is calculated to be \(~5 \times 10^{10} \text{ cm}^{-3} \text{ s}\) (\(\sigma\) for H-like Mg)

\[
\text{Ionization timescale of thermal electrons: } n_e t \sim 2 \times 10^{11} \text{ cm}^{-3} \text{ s}
\]

\[
\frac{n'_e}{n_e} \sim 10^{-3} \text{ (SN1006; Bamba+03)}
\]

\[
n'_e t' \sim 2 \times 10^8 \text{ cm}^{-3} \text{ s} < \text{Characteristic timescale of suprathermals}
\]

Consistent with a possibility that CR acceleration still ongoing.
**Thermal Scenario:** Might no be origin

- **Thermal energy:** \(\sim 2 \times 10^{50}\) erg
- **Required energy supply:** \(\sim 6 \times 10^{36}\) erg/s\(\therefore\) The age of HII region: \(\sim 1\) M yr (Kim+07)
- **Typical kinetic power of OB star:** \(10^{33}-10^{35}\) erg/s

**Non-thermal Scenario:** Probably not interpreted

- Brems. & IC: Expected photon index (< 1.5) is harder than observed
- Synchrotron emission: 100 OB stars are required to explain the amount of non-thermal electrons (\(\sim 10^{47}\) erg) considering the cooling time of TeV electrons.
Origin of Hard X-rays: SNR W51C

**Thermal emission**

Obtained temperature 5 keV is higher than the typical SNR plasma’s (a few keV).
→ Less likely to be the origin.

**Nonthermal emission**

- Brems. & IC: Ruled out in terms of the X-ray spectral index
- Synchrotron emission

**Case 1) CR acceleration ends at the early Sedove phase:** Cannot explain the X-rays
  - TeV electrons cannot survive due to the cooling loss.
  - Emission from secondary electrons is fairly dim in X-rays (e.g, G8.7-0.1; Ajello+12).

**Case 2) CR acceleration takes place over the SNR age**
  - Tens of TeV electrons can exist! (Sturner+97, Nakamura+12)

★ Alternative Scenario: W51C in a tenuous environment
  - Long-lasting CR acceleration without the deceleration of shock

Such environment is provided by core-collapse SN before the birth of W51C.
SN with the mass of 20-25 $M_{\odot}$ produces the large amount of Mg (Tsujimoto+95)
→ Consistent with the property of the SNR plasma.
Origin of Hard X-rays: SNR W51C

Thermal emission

Obtained temperature 5 keV is higher
→ Less likely to be the origin.

Nonthermal emission

• Brems. & IC: Ruled out in terms of the X-ray spectral index
• Synchrotron emission
  
  Case 1) CR acceleration ends at the early Sedov phase:
  ▶ TeV electrons cannot survive due to cooling loss.
  ▶ Emission from secondary electrons is fairly dim in X-rays (e.g., G8.7-0.1; Ajello+12).

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Obtained temperature 5 keV is higher → Less likely to be the origin.

**Nonthermal emission**

- Brems. & IC: Ruled out in terms of the observations
- Synchrotron emission

Case 1) CR acceleration ends at the early Sedov phase:
  - TeV electrons cannot survive due to the cooling loss
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→ Consistent with the property of the SNR plasma.
Summary

- We observed the middle-aged SNR W51C to study the CR acceleration after the Sedov phase.

- The SNR plasma is well represented by an under-ionized one with the temperature of 0.7 keV and the enhanced Mg abundance.

- No significant feature of over-ionized plasma is detected.
  - Consistent with a possibility that CR acceleration is still ongoing.

- The hard X-ray emission is thought to be galactic origin with diffuse nature. The spectrum is represented by a thermal plasma with the temperature of ~5 keV and a powerlaw model with the index of ~2.2.
  - The stellar winds from OB stars in W51B is less likely to be the origin.

- Can be interpreted with the synchrotron emission from TeV electrons accelerated in W51C after the Sedov phase.