Chandra and NuSTAR Observations of SNR RX J1713.7–3946

Naomi Tsuji, Yasunobu Uchiyama, Dmitry Khangulyan, Ryota Higurashi (Rikkyo University) David Berge (U. of Amsterdam), Felix Aharonian (DIAS, MPI-K)
Cosmic Ray Spectrum

* Cosmic Rays; CRs
- High energy particles traveling in space
- CR spectrum has two breaks: knee and ankle
- Consists of protons (~90%), He nuclei (~10%), electrons, heavy nucleon...

**Origin of CRs**
- \(<\ text{knee} \rightarrow \text{Galactic SNRs}\)
- knee–ankle \(\rightarrow\) Unknown
- \(>\ text{ankle} \rightarrow \text{Extragalactic?}\)

Supportive ideas
- Energy budget
  - once/\sim 100 \text{ yr}, \(E_{\text{SN}} \sim 10^{51} \text{ erg}, E_{\text{CR}}/E_{\text{SN}} \sim 10\%\)
  - \(\rightarrow\) CR energy density (1 eV/cm³)
- Spectral shape
  - Standard DSA \(\rightarrow\) Power-law distribution

Issues
- Max energy of accelerated particles
- Acceleration mechanism (DSA)
- … etc.
SNR spectra (in Gamma-ray, young to old)

Old SNRs
\(~10000-40000\) yr

Young SNRs
\(~1000-4000\) yr

Young SNRs
\(~300-400\) yr

\(>10\) TeV gamma-rays → High energy particles

(Funk 2015)
**Supernova Remnant RX J1713.7–3946**

**keV X-ray w/ Suzaku**
(Tanaka et al., 2008)

**GeV γ-ray w/ Fermi**
(Abdo et al., 2011)

**TeV γ-ray w/ H.E.S.S.**
(H.E.S.S. collab., 2016)

<table>
<thead>
<tr>
<th>Age</th>
<th>1600–2100 yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>~1 kpc (Fukui et al. 2003)</td>
</tr>
<tr>
<td>Size</td>
<td>65′×55′</td>
</tr>
<tr>
<td>Coord.</td>
<td>17ʰ13ᵐ33.1ˢ-39°45′44″</td>
</tr>
</tbody>
</table>

**Features**
- Shell-like structure
- X-ray dominated by synchrotron radiation
- Observed in GeV and TeV γ-ray
- Particles accelerated up to ~10–100 TeV
- Interacting with molecular cloud

Spatial correlation between TeV γ-ray and molecular gas

Color map: Proton column density
Contour: H.E.S.S. (Fukui+ 2012)
Properties

- Launch: Jul. 23rd, 1999
- Energy band: 0.4–10 keV
- FoV: 16.9′×16.9′
- Angular resolution: 0.5′
- Energy resolution: 130 eV @1.49 keV, 285 eV @5.9 keV (FWHM)
- Instruments: HRMA (X-ray telescope), ACIS (X-ray detector), etc.

Dataset

- 7 times observations of NW in 11 yrs

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Start date [yyyy-mm-dd]</th>
<th>Pointing position [α2000.0, δ2000.0]</th>
<th>Exposure [ks]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12671</td>
<td>2011-07-01</td>
<td>17h11m47.5s, −39°33′41″2</td>
<td>89.9</td>
</tr>
<tr>
<td>10092</td>
<td>2009-09-10</td>
<td>17h11m46.1s, −39°33′51″6</td>
<td>29.2</td>
</tr>
<tr>
<td>10091</td>
<td>2009-05-16</td>
<td>17h11m46.3s, −39°32′55″7</td>
<td>29.6</td>
</tr>
<tr>
<td>10090</td>
<td>2009-01-30</td>
<td>17h11m44.4s, −39°32′57″1</td>
<td>28.4</td>
</tr>
<tr>
<td>6370</td>
<td>2006-05-03</td>
<td>17h11m46.6s, −39°33′12″0</td>
<td>29.8</td>
</tr>
<tr>
<td>5560</td>
<td>2005-07-09</td>
<td>17h11m45.5s, −39°33′40″0</td>
<td>29.0</td>
</tr>
<tr>
<td>736*</td>
<td>2000-07-25</td>
<td>17h11m49.9s, −39°36′14″7</td>
<td>29.6</td>
</tr>
</tbody>
</table>

*PI: P. Slane. (PI: Y. Uchiyama for the other observations.)
Proper motion measurement (Tsuji & Uchiyama, 2016)

Expansion direction

Outer edge → Forward shock

0.5-5 keV
Chandra flux image

<table>
<thead>
<tr>
<th>box ID</th>
<th>Angular velocity ($\dot{\theta}$) [&quot;/yr]</th>
<th>Velocity (V) [km/s]</th>
<th>Radius ($\theta$) [arcmin]</th>
<th>Rsidus (R) [pc]</th>
<th>$\dot{\theta}/\theta$</th>
<th>Corrected velocity ($V_{cor}$) [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>box (a)</td>
<td>0.82 ± 0.06</td>
<td>3900 ± 300</td>
<td>29.8</td>
<td>8.68</td>
<td>0.459</td>
<td>—</td>
</tr>
<tr>
<td>box (b)</td>
<td>0.25 ± 0.06</td>
<td>1200 ± 300</td>
<td>29.6</td>
<td>8.62</td>
<td>0.141</td>
<td>1200 ±300</td>
</tr>
<tr>
<td>box (c)</td>
<td>0.30 ± 0.05</td>
<td>1400 ± 200</td>
<td>23.5</td>
<td>6.84</td>
<td>0.213</td>
<td>1800 ±300</td>
</tr>
<tr>
<td>box (d)</td>
<td>0.61 ± 0.05</td>
<td>2900 ± 200</td>
<td>22.3</td>
<td>6.50</td>
<td>0.456</td>
<td>3900±300</td>
</tr>
<tr>
<td>box (e)</td>
<td>0.17 ± 0.06</td>
<td>800 ± 300</td>
<td>20.1</td>
<td>6.11</td>
<td>0.135</td>
<td>1100 ±400</td>
</tr>
</tbody>
</table>
**Properties**

- **Launch**: Jun. 13th, 2012
- **Energy band**: 3–79 keV
- **FoV**: 12.45′×12.45′
- **Angular resolution**: 58″ (HPD), 18″ (FWHM)
- **Energy resolution**: 0.4 keV@6 keV, 0.9 keV@60 keV (FWHM)
- **Instruments**: 2 X-ray telescopes (OMA, OMB)

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**Dataset**

- Two times observations of RX J1713 NW (P1, P2) in AO-1.

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ObsID</td>
<td>40111001002</td>
<td>40111002002</td>
</tr>
<tr>
<td>Start-date</td>
<td>2015-09-27</td>
<td>2016-03-30</td>
</tr>
<tr>
<td>Exposure time [ks]</td>
<td>50</td>
<td>57</td>
</tr>
<tr>
<td>Effective time [ks]</td>
<td>43</td>
<td>51</td>
</tr>
<tr>
<td>RA Pointing [deg]</td>
<td>257.8546</td>
<td>257.9298</td>
</tr>
<tr>
<td>Position Angle [deg]</td>
<td>343.286</td>
<td>165.5761</td>
</tr>
<tr>
<td>PI</td>
<td>Y. Uchiyama</td>
<td>Y. Uchiyama</td>
</tr>
</tbody>
</table>

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**XMM-Newton (0.5–8 keV)**
NuSTAR spectra

![Image of NuSTAR spectra](image)

- Extract spectrum from ~5'x6' box (P1)
- Detectd up to ~20 keV

<table>
<thead>
<tr>
<th>ID</th>
<th>Data</th>
<th>Model</th>
<th>(N_H) (10^{22} \text{ cm}^{-2})</th>
<th>(\Gamma/\alpha)</th>
<th>(\varepsilon_c/\varepsilon_0/\varepsilon_{\text{roll}}) (keV)</th>
<th>Flux_{0.5-7} keV (10^{-12} \text{ erg/cm}^2/\text{s})</th>
<th>Flux_{10-20} keV</th>
<th>(\chi^2) (d.o.f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chandra</td>
<td>Power law</td>
<td>0.84 ± 0.02</td>
<td>2.26 ± 0.03</td>
<td>—</td>
<td>24.5 ± 0.1</td>
<td>—</td>
<td>1.051 (441)</td>
</tr>
<tr>
<td>2</td>
<td>NuSTAR</td>
<td>Power law</td>
<td>0.84 ± 0.01</td>
<td>2.62 ± 0.04</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.217 (448)</td>
</tr>
<tr>
<td>3</td>
<td>Joint</td>
<td>Power law</td>
<td>0.93 ± 0.02</td>
<td>2.4 ± 0.02</td>
<td>—</td>
<td>23.9 ± 0.1</td>
<td>3.34 ± 0.05</td>
<td>1.311 (890)</td>
</tr>
<tr>
<td>4</td>
<td>Joint</td>
<td>Cutoff PL</td>
<td>0.79 ± 0.01</td>
<td>2.0 ± 0.01</td>
<td>11.4^{+0.7}_{-0.6}</td>
<td>24.2^{+0.1}_{-0.2}</td>
<td>2.41 ± 0.05</td>
<td>1.095 (890)</td>
</tr>
<tr>
<td>5</td>
<td>Joint</td>
<td>Smoothly CPL</td>
<td>0.73 ± 0.03</td>
<td>1.5 ± 0.1</td>
<td>1.4^{+0.4}_{-0.3}</td>
<td>24.2 ± 0.5</td>
<td>2.46 ± 0.03</td>
<td>1.180 (889)</td>
</tr>
<tr>
<td>6</td>
<td>Joint</td>
<td>Synch ZA07</td>
<td>0.78 ± 0.01</td>
<td>—</td>
<td>0.83 ± 0.05</td>
<td>24.1 ± 0.1</td>
<td>2.52^{+0.04}_{-0.05}</td>
<td>1.180 (890)</td>
</tr>
<tr>
<td>7</td>
<td>Joint</td>
<td>Srcut</td>
<td>0.8 ± 0.02; fixed</td>
<td>0.6</td>
<td>1.5 ± 0.1</td>
<td>24.1 ± 0.1</td>
<td>2.76^{+0.03}_{-0.02}</td>
<td>1.207 (890)</td>
</tr>
</tbody>
</table>

- Spectral steepening: \(\Gamma=2.6\) (NuSTAR) ← 2.3 (Chandra)
- >4σ Cutoff: CPL (\(\chi^2\)~1.10/891) ← PL (1.3/890)
Cosmic Ray Diffusion

**SNR paradigm**
(i) Acceleration at SNR shocks  
(ii) Escape from SNR  
(iii) Propagation in Galaxy

**CR motion**
Diffuse thru scattering with B-field  
→ Characterized by diffusion coefficient (D)

\[
D(p) = 10^{28} D_{28} \left( \frac{p}{10 \, \text{GeV/c}} \right)^{\alpha} \, \text{cm}^2/\text{s}
\]

<table>
<thead>
<tr>
<th>(i) SNR shock</th>
<th>(ii) SNR vicinity</th>
<th>(iii) Galaxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>accelerated CRs</td>
<td>escaping CRs</td>
<td>GCRs</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>( \sim 0.3 – 0.6 )</td>
<td>( \sim 0.3 – 0.6 )</td>
</tr>
<tr>
<td>( D_{28} )</td>
<td>( \sim 10^{-5} ? )</td>
<td>( \sim 10^{-2} – 1 ? )</td>
</tr>
</tbody>
</table>

Note:
Relation between B-field spectrum and diffusion coeff.

\[
\int_{k_0}^{\infty} dk W(k) = \eta_B = \frac{\delta B^2}{B_0^2}; \quad W(k) \propto k^{-s}
\]

\[
\delta B_z = \frac{\delta B_0^2}{B_0^2} \quad \Rightarrow \quad \alpha = 2 - s
\]

\[
D(p) = \frac{1}{3} r_L(p) v(p) \frac{1}{k_{\text{res}} W(k_{\text{res}})} \propto p^{\alpha}
\]
How to investigate diffusion type?

Electron spectrum: \( \frac{dN_e}{dE} \propto E^{-s} \exp \left[ - \left( \frac{E}{E_{\text{max}}}, e \right)^{\beta} \right] \)

- **Spectral index: s**
  - Standard DSA, strong shock (Mach\(>\)1, compression rate \(r\sim4\)) \(\rightarrow s = \frac{r + 2}{r - 1} \approx 2\)
  - Synchrotron cooling is not negligible in strong B-field, \(s \geq 3\)

- **Cutoff shape parameter: \(\beta\)**
  - Depends on B-field and/or energy dependence on diffusion coefficient(\(\alpha\))
  - Energy dependent diffusion coefficient: \(D(E) \propto E^\alpha\)
    - e.g.) \(\alpha = 1\) **Bohm diffusion** ← widely accepted!
    - \(\alpha = 1/3\) Kolmogorov B-turbulence
    - \(\alpha = 1/2\) Kraichnan B-turbulence
    - \(\alpha \sim 2\) Wave damping due to ion-neutral collision

- (i.) **cooling-limited case:** \(\beta = \alpha + 1\) (Zarakashvili & Aharonian 2007)
- (ii.) **age-limited case:** \(\beta = 2\alpha\) (Kang et al., 2009)
- (iii.) **escape-limited case:** \(\beta = \alpha\) (Ohira et al., 2010)

(e.g. Yamazaki+14) “Synchrotron X-ray diagnostics of cutoff shape of nonthermal electron spectrum at young supernova remnants”
## Theoretical electron • X-ray cutoff energy

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Non-Bohm case</th>
<th>Bohm case ($\beta=2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron ($p_0$)</td>
<td>$\left[ \frac{\gamma_s^2}{u_1^2} \left(1 + \frac{1}{\sqrt{\kappa \xi}}\right)^2 \frac{b_0 D_0}{\beta} \right]^{-\frac{1}{\beta}}$</td>
<td>$\frac{1}{1 + \sqrt{\kappa}} \frac{m^2 c^2 u_1}{\gamma_s \sqrt{2 \eta q^3 B / 27}}$</td>
</tr>
<tr>
<td>X-ray ($\omega_0$)</td>
<td>$\beta \left( \frac{4}{(2+\beta)^2 + \beta} \right)^{\frac{1}{\beta}} \frac{3 q B}{2 m^3 c^3} \frac{p_0^2}{b_0 D_0}$</td>
<td>$\frac{81}{16(1 + \sqrt{\kappa})^2} \frac{mcu_1^2}{\eta \gamma_s^2 q^2}$</td>
</tr>
</tbody>
</table>

### Parameters to determine cutoff energy:
$\{u_1, \beta, B, (D_{28},) \kappa, \xi, \gamma_s, (p_c)\}$

- $\beta$ : Free
- Others : Fixed

Theoretical prediction between $\beta$ and X-ray cutoff is shown in right figure.

**Diffusion coefficient:**

$$D(E) \propto E^{\alpha}$$

**Electron spectrum:**

$$\frac{dN_e}{dE} \propto \exp \left[- \left( \frac{E}{E_0} \right)^{\beta} \right]$$

---

**Table 1:**

<table>
<thead>
<tr>
<th>Non-Bohm case</th>
<th>Bohm case ($\beta=2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D(E) \propto E^{\alpha}$</td>
<td>$\frac{1}{1 + \sqrt{\kappa}} \frac{m^2 c^2 u_1}{\gamma_s \sqrt{2 \eta q^3 B / 27}}$</td>
</tr>
<tr>
<td>$\frac{dN_e}{dE} \propto \exp \left[- \left( \frac{E}{E_0} \right)^{\beta} \right]$</td>
<td>$\frac{81}{16(1 + \sqrt{\kappa})^2} \frac{mcu_1^2}{\eta \gamma_s^2 q^2}$</td>
</tr>
</tbody>
</table>

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Nov. 9th, 2017. JSI workshop

N. Tsuji (Rikkyo Univ.)
Observational electron • X-ray cutoff energy

region: large box
model: high-energy solution
energy band: 3-20 keV (NuSTAR)

![Graph showing observational electron spectrum]

- Chandra
- NuSTAR

ZA07 model

↑ high-energy model
(β=1.3–3)

<table>
<thead>
<tr>
<th>Energy, ε (keV)</th>
<th>e^2dN/de (erg/cm^2/s/arcmin^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^0</td>
<td>10^{-12}</td>
</tr>
<tr>
<td>10^1</td>
<td>10^{-13}</td>
</tr>
</tbody>
</table>

- ZA07 c1: (ε_0=0.81 keV)
- J at high 2: (β, ε_0)=(2.0, 0.4)
- J at high 2: (β, ε_0)=(1.5, 0.15)
- J at high 2: (β, ε_0)=(1.33, 0.08)
- J at high 2: (β, ε_0)=(3.0, 1.02)
- RXJ1713_large1

Obervational β v.s. ε₀

- Bohm
- Kraichnan
- Kolmogorov

wave dumping

Observational constraint (high model)
**β v.s. ε₀**

Diffusion coefficient:

\[ D(E) \propto E^\alpha \]

\[ \beta = \alpha + 1 \]

Electron spectrum:

\[ \frac{dN_{e}}{dE} \propto \exp \left[ -\left( \frac{E}{E_0} \right)^{\beta} \right] \]

Theoretical prediction

Observational constraint

\[ \beta \sim 2 \]

Bohm-type diffusion

Future work
- Develop synchrotron X-ray model
- Apply for other SNRs

region: large box
model: high-energy solution
energy band: 3-20 keV

Future work
- Develop synchrotron X-ray model
- Apply for other SNRs

**D(Bohm)**

\[ D_{\text{Bohm}} = \frac{1}{3} \eta r_{g} c = \frac{\eta c^2}{3qBp} \]
**ε₀ V.S. V_{shock} (Bohm diffusion)**

1. Cutoff depends on shock speed

\[ \varepsilon_0 = 0.93 \left( \frac{v_{sh}}{3900 \text{ km/s}} \right)^2 \eta^{-1} \text{ keV} \]

e.g.) box (a): \( v_{sh} \sim 3900 \text{ km/s}, \varepsilon_0 \sim 1.1 \text{ keV}, B=10-20 \mu \text{G} \rightarrow E=30-45 \text{ TeV} \)

→(a) and (d), \( \eta \sim 1 \) (Bohm limit)

2. Strong B-field?

\[ \varepsilon_c = 0.543 \left( \frac{B}{100 \mu \text{G}} \right) \left( \frac{E}{10 \text{ TeV}} \right)^2 \text{ keV} \]

→(b), (c), (e)

Locally enhanced magnetic field?

Notes:

- open markers are projection-corrected speed (Tsuji et al., in prep.)
**HXC (Hard X-ray component) with NuSTAR**

10–20 keV image

- Extremely hard component detected
  - Photon Index $\sim 1.5\pm0.5$ ($>6$ keV)
  - Not contaminated by stray light from X-ray objects
  - Spatially extended: $\sim68''$ (1/e)
  - No time variability

- Hard X-ray emission mechanism?
  - Synchrotron from secondary electrons
  - Thermal bremsstrahlung
  - etc.

Not confirmed

follow-up observation required
Summary

✦ Broadband synchrotron X-ray spectrum of SNR RX J1713.7–3946 NW, taken with Chandra and NuSTAR, are used to determine the cutoff shape of accelerated electrons.

✦ Extending Zirakashvili & Aharonian (2007) model, we can obtain analytical expression of electron and synchrotron X-ray in the case of arbitrary diffusion.

✦ Comparing the theoretical and observational relation between X-ray cutoff energy ($\varepsilon_0$) and energy dependence on diffusion coefficient ($\beta$), Bohm diffusion ($\beta \sim 2$) seems to be favored.

✦ If Bohm diffusion is the case, the relation between observational shock speeds and cutoff X-ray energy implies:

1. edge-like structure; (a), (d) … described well by the theoretical curve with $\eta=1–2$ → the site of effective (Bohm limit) particle acceleration

2. others; (b), (c), (e) … cutoff energies are higher than expected from the theoretical curve → presence of locally enhanced B-field?

✦ Hard X-ray component is newly found in NuSTAR 10–20 keV image, motivating us to perform follow-up observation.