Nonthermal Supernova Remnants with Suzaku

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0.1. cosmic rays

high energy particles in the universe
\( p, e, \ldots \) up to \(10^{20}\) eV

\( u_{\text{CR}} \sim 1\text{eV/cc} \)

c.f. CMB
- stellar light < 0.3 eV/cc
- magnetic field 0.3 eV/cc
- turbulence 0.3 eV/cc
- thermal energy 0.01 eV/cc

galactic? extra-galactic?

Origin and Acceleration mechanism of cosmic rays are still unknown

knee = \(10^{15.5}\text{eV}\)

the common element in Galaxy

ankle = \(10^{18.5}\text{eV}\)
0.2. Cosmic ray acceleration and SNRs

Who and how to accelerate cosmic rays up to knee? diffusive shock acc. in shocks? = biggest problem!

difficulties: \( r_g \sim \text{pc} \) in interstellar B

- \( \rightarrow \) we cannot point out accelerators

How to search for accelerators?

TeV electron IS B. (\( \sim \mu \text{G} \)) \( \rightarrow \) synchrotron X-rays

IC (e) or pion decay (p) \( \rightarrow \) TeV gamma-rays

hard X-rays obs. is the best for the electron accelerator search.
0.3. Tasks for Suzaku

Koyama+ discovered sync. X-rays from the shells of SN1006

What is the NEXT issue?

1. Detailed spectra of sync. X-rays
cut-off? \( \rightarrow E_{\text{max}} \) of e, B
difference of spectra between regions

2. spectra above 10 keV
Sync. spectra free from thermal X-rays
efficient acceleration?

3. Searching for new SNRs with sync. X-rays
More and more samples we need!
Samples with thermal and nonthermal X-rays
are especially important.

- good stat. w. XIS
- low bgd of HXD
- both XIS & HXD
1. Detailed spectra of sync. X-rays

cut-off ? -> $E_{\text{max}}$ of $e, B$
difference of spectra between regions

We need spectra with good statistics
Let’s see SN1006
1.1. Suzaku observations of SN 1006

- **src**: 4pointing
- **bg**: 2pointing
- **total**: 200ks

**FOV of XIS**

**FOV of HXD/PIN**
Suzaku images

He-like O line band

3 - 5 keV band

clear rim and inside emission
1.2. XIS spectra of SN 1006(1)

lines + hard emission
3 temp. thermal (Yamaguchi+ 2008, A48) + power-law

large residuals

(Bamba+ 2007)
XIS spectra of SN 1006 (2)

3 temp. + srcut model

 sync. emission from e
 w. power-law + exp. spectra
 a = 0.57 is fixed

no residual!

(Bamba+ 2007)

nonthermal emission has clear bending!

5.69 (5.67-5.71) x 10^{16} Hz
1.3. XIS/HXD spectra of SN 1006

The most tight upper limit
(2.7x10^{-5} ph/cm^2/s in 10-15 keV)
1.4. XIS spectrum of each rim

**NE rim**

Cut-off freq.

$6.66(6.58-6.69) \times 10^{16}$ Hz

**SW rim**

$4.68(4.64-4.73) \times 10^{16}$ Hz

Larger cut-off in the NE rim
1.5. What determine the cutoff energy? (Bamba+ 2008)

\[ \text{cutoff freq.} = 1.6 \times 10^{16} \left( \frac{B}{1 \mu \text{G}} \right) \left( \frac{E}{10 \text{TeV}} \right)^2 \text{ [Hz]} \]

B: magnetic field   E: the maximum E of e   (Reynolds 1998)

Assumption: B=40$\mu$G (10$\mu$G outside of the SNR) (Bamba+ 2003)

\[ \rightarrow E = 9.4 \text{ TeV} \]

The diff. of cutoff freq. in NE and SW

\[ \text{difference of B, E?} \]
\[ \rightarrow \text{diff. of acceleataion eff.?} \]

If B=40$\mu$G

E = 10 TeV @ NE
E = 8.5 TeV @SW

More precise model is needed!
2. spectra above 10 keV

Sync. spectra free from thermal X-rays
efficient acceleration?
We need several samples above 10 keV
(RXJ1713 and Vela Jr. will be presented
by Uchiyama-san and Tanaka-san)
2.1. Tycho Remnant

\[ \chi^2 / \text{dof} = 185.9 / 173 \]

Bremss+Power-law

\[ kT = 4.7(3.7-5.7) \text{ keV} \]
\[ \Gamma = 2.7(1.4-2.9) \]

(Tamagawa+, A52)
(Hayato+, A53)

2 kT plasma requires too high kT (>10 keV)

-> The Tycho rim really emits nonthermal X-rays!

Hard X-ray obs. are essential to distinguish thermal and nonthermal emission
2.2. RCW 86

the oldest historical SNR (SN184)
sync. X-rays from shells
below 10 keV (Bamba+ 2000)
Efficient acceleration? (Vink+ 2006)

HXD/PIN detected
X-rays < 30 keV
Γ > 10keV ~ Γ < 10keV
2.3. Cas A - very bright SNR in hard X-rays

Chandra 4-6 keV

extrapolate to 11-14 keV
Smooth w. Suzaku PSF

Suzaku 11-14 keV

The first image above 10 keV
Hard X-rays come from RS? (Maeda+, in prep)

Courtesy of E.A. Helder
Excess from power-low ??

 Photon index is ~3 in 4-80 keV
3 obs. detected the excess, but only 1% of the bgd.

Preliminary !
Maeda+. in prep
What is the excess (if it is true detection)?

nonthermal brems (Allen+, A45, Vink+ private comm.)?

if the density is enough large, it should be observed other components?

secondary e, p, ... (e.g., Yamazaki+, 2006)

change from the test particle spectrum?

Direct measurement of p and/or acc. efficiency ??

personal question:
Why the $\Gamma$ is same in <10 keV and >10 keV??

We need more precise bgd and statistics

RCW86: Vink+ 2006
3. Searching for new SNRs with sync. X-rays

How many SNRs accelerate particles? X-ray surveys of Galactic plane have been done with previous missions. The number is still limited. Many have only nonthermal X-rays, especially we need samples with nonthermal and thermal X-rays in other wavelength?
3.1. How to search new CR accelerators?

**HESS discovered many new sources**

On the Galactic plane
Some are diffuse accelerate particles > TeV

Galactic accelerators

However, they have no counterpart!

They are not known PSRs, PWNe known SNRs known star-forming regions ...

“TeV unID sources”
Deep follow up!

(Aharonian+ 2006)
3.2. Suzaku follow-ups of TeV unID sources

**HESS J1837-069**

Many TeV unIDs do not have direct counterparts in X-ray
(Puehlhofer+, A41)

off-set PWN?
Some PWNe have off-set between X-ray and TeV
(e.g. Mori+ A43)

real dark particle accelerator?
(e.g. Matsumoto+, 2007)

X-ray sources are just superposed?

Suzaku follow-ups revealed us it is not simple

Diffuse TeV + compact and offset X-ray

(Anada+, A42)
3.3. A New SNR with TeV and sync. X-rays

CTB 37B

a bright shell-like SNR in radio in a star forming region?
Young? (AD393: Stephenson+ 2002)
No X-ray information

TeV emission is found
(Aharonian+ 2006)
TeV flux: only 2% of the Crab nebula

New CR accelerating SNR?
Between SN1006 and RXJ1713?
(T/NT X-rays) (NT X and TeV)
Deep X-ray follow-up is needed
Suzaku Image and spectrum of CTB 37B (Nakamura+ A46)

Hard X-rays are detected from the radio shell  
The position is consistent with TeV gamma-rays

Gray scale: 2-10 keV X-ray  
Red contour: radio  
Green contour: TeV

spectrum:  
NEI plasma + power-law  
(\(\Gamma = 3.0^{+0.2}_{-0.2}\))

new sample of CR acc. SNR young plasma (t~1400 yrs)

The first sample with T/NT X-rays and TeV

Suzaku will discover more and more accelerators.
4. Summary

We discussed 3 topics using Suzaku capability.

- Suzaku achieved detailed analysis of nonthermal emission. The spectrum of SN1006 has clear bending. The maximum E of e is 9.4 TeV with assumption of B=40 microG. NE accelerate particles more efficiently?
- More precise model!

- Suzaku detected hard X-rays (>10 keV) from several SNRs Tycho, RCW86, Cas A, ...
- We might be able to detect other component/eff. acc.
- More statistics are needed

- TeV unIDs may be new CR accelerators. Many have no direct counterpart in the X-ray band. CTB 37B is the first sample w. T/NT X-rays and TeV. Suzaku will discover more and more counterparts.
Papers and posters cited in this presentation

Bamba+ 2008
Yamaguchi+ 2008, A48
Tamagawa+, A52
Hayato+, A53
Puehlhofer+, A41
Anada+, A42
Mori+, A43
Matsumoto+ 2007
Nakamura+, A46

SN1006 (nonthermal)
SN1006 (therermal)
Tycho (nonthermal)
Tycho (thermal)
HESS unIDs
HESS J1837
Vela X
Dark particle accelerator
CTB37B